# Table of Contents

1. Introduction ................................................................. 3  
   1.1. Document Conventions ............................................. 3  

2. Fundamentals ............................................................... 5  
   2.1. Host and Device Environment .................................... 5  
   2.2. Execution Model .................................................... 5  
   2.3. Object Model ....................................................... 7  
   2.4. Application Binary Interface ..................................... 11  
   2.5. Command Syntax and Duration ................................... 12  
   2.6. Threading Behavior ............................................... 13  
   2.7. Errors .............................................................. 22  
   2.8. Numeric Representation and Computation ....................... 39  
   2.9. Fixed-Point Data Conversions .................................... 41  
   2.10. Common Object Types ........................................... 42  

3. Initialization ............................................................... 45  
   3.1. Command Function Pointers ...................................... 45  
   3.2. Instances .......................................................... 48  

4. Devices and Queues ....................................................... 54  
   4.1. Physical Devices ................................................... 54  
   4.2. Devices ............................................................ 73  
   4.3. Queues ............................................................. 83  

5. Command Buffers ........................................................ 90  
   5.1. Command Buffer Lifecycle ...................................... 90  
   5.2. Command Pools .................................................... 92  
   5.3. Command Buffer Allocation and Management .................. 98  
   5.4. Command Buffer Recording ..................................... 103  
   5.5. Command Buffer Submission .................................... 108  
   5.6. Queue Forward Progress ........................................ 121  
   5.7. Secondary Command Buffer Execution ......................... 121  
   5.8. Command Buffer Device Mask .................................. 125  

6. Synchronization and Cache Control .................................. 128  
   6.1. Execution and Memory Dependencies ......................... 128  
   6.2. Implicit Synchronization Guarantees ......................... 142  
   6.3. Fences ........................................................... 144  
   6.4. Semaphores ......................................................... 165  
   6.5. Events ............................................................ 191  
   6.6. Pipeline Barriers ................................................ 204  
   6.7. Memory Barriers .................................................. 210  
   6.8. Wait Idle Operations ............................................ 218
6.9. Host Write Ordering Guarantees .................................................. 220
6.10. Synchronization and Multiple Physical Devices ........................... 220

7. Render Pass ................................................................................... 221
7.1. Render Pass Creation ................................................................... 222
7.2. Render Pass Compatibility ........................................................... 268
7.3. Framebuffers .............................................................................. 268
7.4. Render Pass Commands ............................................................... 277

8. Shaders ......................................................................................... 298
8.1. Shader Modules ......................................................................... 298
8.2. Shader Execution ....................................................................... 301
8.3. Shader Memory Access Ordering .................................................. 301
8.4. Shader Inputs and Outputs ............................................................ 302
8.5. Vertex Shaders ......................................................................... 302
8.6. Tessellation Control Shaders ........................................................ 303
8.7. Tessellation Evaluation Shaders ..................................................... 303
8.8. Geometry Shaders ..................................................................... 304
8.9. Fragment Shaders ....................................................................... 304
8.10. Compute Shaders ..................................................................... 305
8.11. Interpolation Decorations ............................................................ 305
8.12. Ray Generation Shaders .............................................................. 306
8.13. Intersection Shaders ................................................................. 306
8.15. Closest Hit Shaders .................................................................. 307
8.16. Miss Shaders ............................................................................ 307
8.17. Callable Shaders ...................................................................... 308
8.18. Static Use ................................................................................. 308
8.19. Scope ......................................................................................... 308
8.20. Group Operations ..................................................................... 311
8.21. Quad Group Operations ............................................................... 313
8.22. Derivative Operations ................................................................. 313
8.23. Helper Invocations .................................................................. 314

9. Pipelines ......................................................................................... 315
9.1. Compute Pipelines ..................................................................... 316
9.2. Graphics Pipelines ..................................................................... 324
9.3. Pipeline destruction .................................................................... 337
9.4. Multiple Pipeline Creation ............................................................ 338
9.5. Pipeline Derivatives .................................................................... 338
9.6. Pipeline Cache ............................................................................ 338
9.7. Specialization Constants ............................................................... 345
9.8. Pipeline Libraries ....................................................................... 349
9.9. Pipeline Binding ......................................................................... 350
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.10. Dynamic State</td>
<td>352</td>
</tr>
<tr>
<td>9.11. Pipeline Shader Information</td>
<td>352</td>
</tr>
<tr>
<td>9.12. Ray Tracing Pipeline</td>
<td>360</td>
</tr>
<tr>
<td>10. Memory Allocation</td>
<td>372</td>
</tr>
<tr>
<td>10.1. Host Memory</td>
<td>372</td>
</tr>
<tr>
<td>10.2. Device Memory</td>
<td>379</td>
</tr>
<tr>
<td>11. Resource Creation</td>
<td>420</td>
</tr>
<tr>
<td>11.1. Buffers</td>
<td>420</td>
</tr>
<tr>
<td>11.2. Buffer Views</td>
<td>427</td>
</tr>
<tr>
<td>11.3. Images</td>
<td>431</td>
</tr>
<tr>
<td>11.4. Image Layouts</td>
<td>451</td>
</tr>
<tr>
<td>11.5. Image Views</td>
<td>454</td>
</tr>
<tr>
<td>11.6. Resource Memory Association</td>
<td>469</td>
</tr>
<tr>
<td>11.7. Resource Sharing Mode</td>
<td>496</td>
</tr>
<tr>
<td>11.8. Memory Aliasing</td>
<td>498</td>
</tr>
<tr>
<td>11.9. Acceleration Structures</td>
<td>500</td>
</tr>
<tr>
<td>12. Samplers</td>
<td>513</td>
</tr>
<tr>
<td>12.1. Sampler Y'CbCr conversion</td>
<td>520</td>
</tr>
<tr>
<td>13. Resource Descriptors</td>
<td>529</td>
</tr>
<tr>
<td>13.1. Descriptor Types</td>
<td>529</td>
</tr>
<tr>
<td>13.2. Descriptor Sets</td>
<td>532</td>
</tr>
<tr>
<td>13.3. Physical Storage Buffer Access</td>
<td>590</td>
</tr>
<tr>
<td>14. Shader Interfaces</td>
<td>593</td>
</tr>
<tr>
<td>14.1. Shader Input and Output Interfaces</td>
<td>593</td>
</tr>
<tr>
<td>14.2. Vertex Input Interface</td>
<td>597</td>
</tr>
<tr>
<td>14.3. Fragment Output Interface</td>
<td>597</td>
</tr>
<tr>
<td>14.4. Fragment Input Attachment Interface</td>
<td>598</td>
</tr>
<tr>
<td>14.5. Shader Resource Interface</td>
<td>599</td>
</tr>
<tr>
<td>14.6. Built-In Variables</td>
<td>605</td>
</tr>
<tr>
<td>15. Image Operations</td>
<td>625</td>
</tr>
<tr>
<td>15.1. Image Operations Overview</td>
<td>625</td>
</tr>
<tr>
<td>15.2. Conversion Formulas</td>
<td>628</td>
</tr>
<tr>
<td>15.3. Texel Input Operations</td>
<td>630</td>
</tr>
<tr>
<td>15.4. Texel Output Operations</td>
<td>645</td>
</tr>
<tr>
<td>15.5. Normalized Texel Coordinate Operations</td>
<td>647</td>
</tr>
<tr>
<td>15.6. Unnormalized Texel Coordinate Operations</td>
<td>652</td>
</tr>
<tr>
<td>15.7. Integer Texel Coordinate Operations</td>
<td>653</td>
</tr>
<tr>
<td>15.8. Image Sample Operations</td>
<td>654</td>
</tr>
<tr>
<td>15.9. Image Operation Steps</td>
<td>657</td>
</tr>
<tr>
<td>16. Queries</td>
<td>658</td>
</tr>
<tr>
<td>16.1. Query Pools</td>
<td>658</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>22.4. Geometry Shader Primitive Ordering</td>
<td>795</td>
</tr>
<tr>
<td>23. Fixed-Function Vertex Post-Processing</td>
<td>796</td>
</tr>
<tr>
<td>23.1. Flat Shading</td>
<td>796</td>
</tr>
<tr>
<td>23.2. Primitive Clipping</td>
<td>796</td>
</tr>
<tr>
<td>23.3. Clipping Shader Outputs</td>
<td>799</td>
</tr>
<tr>
<td>23.4. Coordinate Transformations</td>
<td>799</td>
</tr>
<tr>
<td>23.5. Controlling the Viewport</td>
<td>800</td>
</tr>
<tr>
<td>24. Rasterization</td>
<td>805</td>
</tr>
<tr>
<td>24.1. Discarding Primitives Before Rasterization</td>
<td>808</td>
</tr>
<tr>
<td>24.2. Rasterization Order</td>
<td>808</td>
</tr>
<tr>
<td>24.3. Multisampling</td>
<td>809</td>
</tr>
<tr>
<td>24.4. Sample Shading</td>
<td>811</td>
</tr>
<tr>
<td>24.5. Points</td>
<td>812</td>
</tr>
<tr>
<td>24.6. Line Segments</td>
<td>812</td>
</tr>
<tr>
<td>24.7. Polygons</td>
<td>815</td>
</tr>
<tr>
<td>25. Fragment Operations</td>
<td>821</td>
</tr>
<tr>
<td>25.1. Early Per-Fragment Tests</td>
<td>821</td>
</tr>
<tr>
<td>25.2. Scissor Test</td>
<td>821</td>
</tr>
<tr>
<td>25.3. Sample Mask</td>
<td>823</td>
</tr>
<tr>
<td>25.4. Early Fragment Test Mode</td>
<td>823</td>
</tr>
<tr>
<td>25.5. Late Per-Fragment Tests</td>
<td>824</td>
</tr>
<tr>
<td>25.6. Multisample Coverage</td>
<td>824</td>
</tr>
<tr>
<td>25.7. Depth and Stencil Operations</td>
<td>825</td>
</tr>
<tr>
<td>25.8. Depth Bounds Test</td>
<td>826</td>
</tr>
<tr>
<td>25.9. Stencil Test</td>
<td>828</td>
</tr>
<tr>
<td>25.10. Depth Test</td>
<td>834</td>
</tr>
<tr>
<td>25.11. Sample Counting</td>
<td>835</td>
</tr>
<tr>
<td>25.12. Coverage Reduction</td>
<td>835</td>
</tr>
<tr>
<td>26. The Framebuffer</td>
<td>836</td>
</tr>
<tr>
<td>26.1. Blending</td>
<td>836</td>
</tr>
<tr>
<td>26.2. Logical Operations</td>
<td>844</td>
</tr>
<tr>
<td>26.3. Color Write Mask</td>
<td>845</td>
</tr>
<tr>
<td>27. Dispatching Commands</td>
<td>847</td>
</tr>
<tr>
<td>28. Sparse Resources</td>
<td>857</td>
</tr>
<tr>
<td>28.1. Sparse Resource Features</td>
<td>857</td>
</tr>
<tr>
<td>28.2. Sparse Buffers and Fully-Resident Images</td>
<td>858</td>
</tr>
<tr>
<td>28.3. Sparse Partially-Resident Buffers</td>
<td>859</td>
</tr>
<tr>
<td>28.4. Sparse Partially-Resident Images</td>
<td>859</td>
</tr>
<tr>
<td>28.5. Sparse Memory Aliasing</td>
<td>867</td>
</tr>
<tr>
<td>28.7. Sparse Resource API</td>
<td>869</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>28.8. Examples</td>
<td>894</td>
</tr>
<tr>
<td>29. Window System Integration (WSI)</td>
<td>900</td>
</tr>
<tr>
<td>29.1. WSI Platform</td>
<td>900</td>
</tr>
<tr>
<td>29.2. WSI Surface</td>
<td>900</td>
</tr>
<tr>
<td>29.3. Presenting Directly to Display Devices</td>
<td>912</td>
</tr>
<tr>
<td>29.4. Querying for WSI Support</td>
<td>932</td>
</tr>
<tr>
<td>29.5. Surface Queries</td>
<td>936</td>
</tr>
<tr>
<td>29.6. Device Group Queries</td>
<td>950</td>
</tr>
<tr>
<td>29.7. WSI Swapchain</td>
<td>954</td>
</tr>
<tr>
<td>30. Deferred Host Operations</td>
<td>989</td>
</tr>
<tr>
<td>30.1. Requesting Deferral</td>
<td>989</td>
</tr>
<tr>
<td>30.2. Deferred Host Operations API</td>
<td>990</td>
</tr>
<tr>
<td>31. Ray Traversal</td>
<td>995</td>
</tr>
<tr>
<td>31.1. Ray Intersection Candidate Determination</td>
<td>995</td>
</tr>
<tr>
<td>31.2. Ray Intersection Culling</td>
<td>997</td>
</tr>
<tr>
<td>31.3. Ray Intersection Confirmation</td>
<td>999</td>
</tr>
<tr>
<td>31.4. Ray Closest Hit Determination</td>
<td>1000</td>
</tr>
<tr>
<td>31.5. Ray Result Determination</td>
<td>1001</td>
</tr>
<tr>
<td>32. Ray Tracing</td>
<td>1002</td>
</tr>
<tr>
<td>32.1. Shader Call Instructions</td>
<td>1002</td>
</tr>
<tr>
<td>32.2. Ray Tracing Commands</td>
<td>1004</td>
</tr>
<tr>
<td>32.3. Shader Binding Table</td>
<td>1013</td>
</tr>
<tr>
<td>32.4. Acceleration Structures</td>
<td>1015</td>
</tr>
<tr>
<td>32.5. Host Acceleration Structure Operations</td>
<td>1042</td>
</tr>
<tr>
<td>33. Extending Vulkan</td>
<td>1051</td>
</tr>
<tr>
<td>33.1. Instance and Device Functionality</td>
<td>1051</td>
</tr>
<tr>
<td>33.2. Core Versions</td>
<td>1051</td>
</tr>
<tr>
<td>33.3. Layers</td>
<td>1053</td>
</tr>
<tr>
<td>33.4. Extensions</td>
<td>1057</td>
</tr>
<tr>
<td>33.5. Extension Dependencies</td>
<td>1060</td>
</tr>
<tr>
<td>33.6. Compatibility Guarantees (Informative)</td>
<td>1061</td>
</tr>
<tr>
<td>34. Features</td>
<td>1065</td>
</tr>
<tr>
<td>34.1. Feature Requirements</td>
<td>1093</td>
</tr>
<tr>
<td>35. Limits</td>
<td>1094</td>
</tr>
<tr>
<td>35.1. Limit Requirements</td>
<td>1116</td>
</tr>
<tr>
<td>36. Formats</td>
<td>1126</td>
</tr>
<tr>
<td>36.1. Format Definition</td>
<td>1126</td>
</tr>
<tr>
<td>36.2. Format Properties</td>
<td>1165</td>
</tr>
<tr>
<td>36.3. Required Format Support</td>
<td>1170</td>
</tr>
<tr>
<td>37. Additional Capabilities</td>
<td>1187</td>
</tr>
<tr>
<td>37.1. Additional Image Capabilities</td>
<td>1187</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Appendix C: Compressed Image Formats</td>
<td>1252</td>
</tr>
<tr>
<td>Block-Compressed Image Formats</td>
<td>1253</td>
</tr>
<tr>
<td>ETC Compressed Image Formats</td>
<td>1254</td>
</tr>
<tr>
<td>ASTC Compressed Image Formats</td>
<td>1255</td>
</tr>
<tr>
<td>Appendix D: Core Revisions (Informative)</td>
<td>1256</td>
</tr>
<tr>
<td>Version 1.1</td>
<td>1256</td>
</tr>
<tr>
<td>Appendix E: Layers &amp; Extensions (Informative)</td>
<td>1266</td>
</tr>
<tr>
<td>List of Current Extensions</td>
<td>1266</td>
</tr>
<tr>
<td>List of Provisional Extensions</td>
<td>1389</td>
</tr>
<tr>
<td>List of Deprecated Extensions</td>
<td>1405</td>
</tr>
<tr>
<td>Appendix F: API Boilerplate</td>
<td>1466</td>
</tr>
<tr>
<td>Vulkan Header Files</td>
<td>1466</td>
</tr>
<tr>
<td>Window System-Specific Header Control (Informative)</td>
<td>1469</td>
</tr>
<tr>
<td>Provisional Extension Header Control (Informative)</td>
<td>1470</td>
</tr>
<tr>
<td>Appendix G: Invariance</td>
<td>1472</td>
</tr>
<tr>
<td>Repeatability</td>
<td>1472</td>
</tr>
<tr>
<td>Multi-pass Algorithms</td>
<td>1472</td>
</tr>
<tr>
<td>Invariance Rules</td>
<td>1472</td>
</tr>
<tr>
<td>Tessellation Invariance</td>
<td>1474</td>
</tr>
<tr>
<td>Glossary</td>
<td>1476</td>
</tr>
<tr>
<td>Common Abbreviations</td>
<td>1499</td>
</tr>
<tr>
<td>Prefixes</td>
<td>1501</td>
</tr>
<tr>
<td>Appendix H: Credits (Informative)</td>
<td>1502</td>
</tr>
<tr>
<td>Working Group Contributors to Vulkan</td>
<td>1502</td>
</tr>
<tr>
<td>Other Credits</td>
<td>1508</td>
</tr>
</tbody>
</table>
This Specification is protected by copyright laws and contains material proprietary to Khronos. Except as described by these terms, it or any components may not be reproduced, republished, distributed, transmitted, displayed, broadcast or otherwise exploited in any manner without the express prior written permission of Khronos. Khronos grants a conditional copyright license to use and reproduce the unmodified Specification for any purpose, without fee or royalty, EXCEPT no licenses to any patent, trademark or other intellectual property rights are granted under these terms.

Khronos makes no, and expressly disclaims any, representations or warranties, express or implied, regarding this Specification, including, without limitation: merchantability, fitness for a particular purpose, non-infringement of any intellectual property, correctness, accuracy, completeness, timeliness, and reliability. Under no circumstances will Khronos, or any of its Promoters, Contributors or Members, or their respective partners, officers, directors, employees, agents or representatives be liable for any damages, whether direct, indirect, special or consequential damages for lost revenues, lost profits, or otherwise, arising from or in connection with these materials.

This Specification has been created under the Khronos Intellectual Property Rights Policy, which is Attachment A of the Khronos Group Membership Agreement available at https://www.khronos.org/files/member_agreement.pdf, and which defines the terms 'Scope', 'Compliant Portion', and 'Necessary Patent Claims'. Parties desiring to implement the Specification and make use of Khronos trademarks in relation to that implementation, and receive reciprocal patent license protection under the Khronos Intellectual Property Rights Policy must become Adopters and confirm the implementation as conformant under the process defined by Khronos for this Specification; see https://www.khronos.org/adopters.

This Specification contains substantially unmodified functionality from, and is a successor to, Khronos specifications including OpenGL, OpenGL ES and OpenCL.

Some parts of this Specification are purely informative and so are EXCLUDED from the Scope of this Specification. The Document Conventions section of the Introduction defines how these parts of the Specification are identified.

Where this Specification uses technical terminology, defined in the Glossary or otherwise, that refer to enabling technologies that are not expressly set forth in this Specification, those enabling technologies are EXCLUDED from the Scope of this Specification. For clarity, enabling technologies not disclosed with particularity in this Specification (e.g. semiconductor manufacturing technology, hardware architecture, processor architecture or microarchitecture, memory architecture, compiler technology, object oriented technology, basic operating system technology, compression technology, algorithms, and so on) are NOT to be considered expressly set forth; only those application program interfaces and data structures disclosed with particularity are included in the Scope of this Specification.

For purposes of the Khronos Intellectual Property Rights Policy as it relates to the definition of Necessary Patent Claims, all recommended or optional features, behaviors and functionality set forth in this Specification, if implemented, are considered to be included as Compliant Portions.
Where this Specification includes normative references to external documents, only the specifically identified sections of those external documents are INCLUDED in the Scope of this Specification. If not created by Khronos, those external documents may contain contributions from non-members of Khronos not covered by the Khronos Intellectual Property Rights Policy.

Vulkan and Khronos are registered trademarks of The Khronos Group Inc. ASTC is a trademark of ARM Holdings PLC; OpenCL is a trademark of Apple Inc.; and OpenGL and OpenGL ES are registered trademarks of Hewlett Packard Enterprise, all used under license by Khronos. All other product names, trademarks, and/or company names are used solely for identification and belong to their respective owners.
Chapter 1. Introduction

This document, referred to as the “Vulkan Specification” or just the “Specification” hereafter, describes the Vulkan Application Programming Interface (API). Vulkan is a C99 API designed for explicit control of low-level graphics and compute functionality.

The canonical version of the Specification is available in the official Vulkan Registry (https://www.khronos.org/registry/vulkan/). The source files used to generate the Vulkan specification are stored in the Vulkan Documentation Repository (https://github.com/KhronosGroup/Vulkan-Docs). The source repository additionally has a public issue tracker and allows the submission of pull requests that improve the specification.

1.1. Document Conventions

The Vulkan specification is intended for use by both implementors of the API and application developers seeking to make use of the API, forming a contract between these parties. Specification text may address either party; typically the intended audience can be inferred from context, though some sections are defined to address only one of these parties. (For example, Valid Usage sections only address application developers). Any requirements, prohibitions, recommendations or options defined by normative terminology are imposed only on the audience of that text.

Note
Structure and enumerated types defined in extensions that were promoted to core in Vulkan 1.1 are now defined in terms of the equivalent Vulkan 1.1 interfaces. This affects the Vulkan Specification, the Vulkan header files, and the corresponding XML Registry.

1.1.1. Normative Terminology

Within this specification, the key words must, required, should, recommended, may, and optional are to be interpreted as described in RFC 2119 - Key words for use in RFCs to Indicate Requirement Levels (https://www.ietf.org/rfc/rfc2119.txt). These key words are highlighted in the specification for clarity. In text addressing application developers, their use expresses requirements that apply to application behavior. In text addressing implementors, their use expresses requirements that apply to implementations.

In text addressing application developers, the additional key words can and cannot are to be interpreted as describing the capabilities of an application, as follows:

can
This word means that the application is able to perform the action described.

cannot
This word means that the API and/or the execution environment provide no mechanism through which the application can express or accomplish the action described.

These key words are never used in text addressing implementors.
There is an important distinction between \textit{cannot} and \textit{must not}, as used in this Specification. \textit{Cannot} means something the application literally is unable to express or accomplish through the API, while \textit{must not} means something that the application is capable of expressing through the API, but that the consequences of doing so are undefined and potentially unrecoverable for the implementation (see \textit{Errors}).

Unless otherwise noted in the section heading, all sections and appendices in this document are normative.

\subsection*{1.1.2. Technical Terminology}

The Vulkan Specification makes use of common engineering and graphics terms such as \textit{Pipeline}, \textit{Shader}, and \textit{Host} to identify and describe Vulkan API constructs and their attributes, states, and behaviors. The \textit{Glossary} defines the basic meanings of these terms in the context of the Specification. The Specification text provides fuller definitions of the terms and may elaborate, extend, or clarify the \textit{Glossary} definitions. When a term defined in the \textit{Glossary} is used in normative language within the Specification, the definitions within the Specification govern and supersede any meanings the terms may have in other technical contexts (i.e. outside the Specification).

\subsection*{1.1.3. Normative References}

References to external documents are considered normative references if the Specification uses any of the normative terms defined in \textit{Normative Terminology} to refer to them or their requirements, either as a whole or in part.

The following documents are referenced by normative sections of the specification:


Chapter 2. Fundamentals

This chapter introduces fundamental concepts including the Vulkan architecture and execution model, API syntax, queues, pipeline configurations, numeric representation, state and state queries, and the different types of objects and shaders. It provides a framework for interpreting more specific descriptions of commands and behavior in the remainder of the Specification.

2.1. Host and Device Environment

The Vulkan Specification assumes and requires: the following properties of the host environment with respect to Vulkan implementations:

- The host must have runtime support for 8, 16, 32 and 64-bit signed and unsigned twos-complement integers, all addressable at the granularity of their size in bytes.
- The host must have runtime support for 32- and 64-bit floating-point types satisfying the range and precision constraints in the Floating Point Computation section.
- The representation and endianness of these types on the host must match the representation and endianness of the same types on every physical device supported.

Note
Since a variety of data types and structures in Vulkan may be accessible by both host and physical device operations, the implementation should be able to access such data efficiently in both paths in order to facilitate writing portable and performant applications.

2.2. Execution Model

This section outlines the execution model of a Vulkan system.

Vulkan exposes one or more devices, each of which exposes one or more queues which may process work asynchronously to one another. The set of queues supported by a device is partitioned into families. Each family supports one or more types of functionality and may contain multiple queues with similar characteristics. Queues within a single family are considered compatible with one another, and work produced for a family of queues can be executed on any queue within that family. This Specification defines four types of functionality that queues may support: graphics, compute, transfer, and sparse memory management.

Note
A single device may report multiple similar queue families rather than, or as well as, reporting multiple members of one or more of those families. This indicates that while members of those families have similar capabilities, they are not directly compatible with one another.

Device memory is explicitly managed by the application. Each device may advertise one or more heaps, representing different areas of memory. Memory heaps are either device local or host local,
but are always visible to the device. Further detail about memory heaps is exposed via memory types available on that heap. Examples of memory areas that may be available on an implementation include:

- **device local** is memory that is physically connected to the device.
- **device local, host visible** is device local memory that is visible to the host.
- **host local, host visible** is memory that is local to the host and visible to the device and host.

On other architectures, there may only be a single heap that can be used for any purpose.

A Vulkan application controls a set of devices through the submission of command buffers which have recorded device commands issued via Vulkan library calls. The content of command buffers is specific to the underlying implementation and is opaque to the application. Once constructed, a command buffer can be submitted once or many times to a queue for execution. Multiple command buffers can be built in parallel by employing multiple threads within the application.

Command buffers submitted to different queues may execute in parallel or even out of order with respect to one another. Command buffers submitted to a single queue respect submission order, as described further in the synchronization chapter. Command buffer execution by the device is also asynchronous to host execution. Once a command buffer is submitted to a queue, control may return to the application immediately. Synchronization between the device and host, and between different queues is the responsibility of the application.

### 2.2.1. Queue Operation

Vulkan queues provide an interface to the execution engines of a device. Commands for these execution engines are recorded into command buffers ahead of execution time. These command buffers are then submitted to queues with a **queue submission** command for execution in a number of **batches**. Once submitted to a queue, these commands will begin and complete execution without further application intervention, though the order of this execution is dependent on a number of implicit and explicit ordering constraints.

Work is submitted to queues using queue submission commands that typically take the form `vkQueue*` (e.g. `vkQueueSubmit`, `vkQueueBindSparse`), and optionally take a list of semaphores upon which to wait before work begins and a list of semaphores to signal once work has completed. The work itself, as well as signaling and waiting on the semaphores are all **queue operations**.

Queue operations on different queues have no implicit ordering constraints, and may execute in any order. Explicit ordering constraints between queues can be expressed with **semaphores** and **fences**.

Command buffer submissions to a single queue respect submission order and other implicit ordering guarantees, but otherwise may overlap or execute out of order. Other types of batches and queue submissions against a single queue (e.g. sparse memory binding) have no implicit ordering constraints with any other queue submission or batch. Additional explicit ordering constraints between queue submissions and individual batches can be expressed with **semaphores** and **fences**.

Before a fence or semaphore is signaled, it is guaranteed that any previously submitted queue operations have completed execution, and that memory writes from those queue operations are
available to future queue operations. Waiting on a signaled semaphore or fence guarantees that previous writes that are available are also visible to subsequent commands.

Command buffer boundaries, both between primary command buffers of the same or different batches or submissions as well as between primary and secondary command buffers, do not introduce any additional ordering constraints. In other words, submitting the set of command buffers (which can include executing secondary command buffers) between any semaphore or fence operations execute the recorded commands as if they had all been recorded into a single primary command buffer, except that the current state is reset on each boundary. Explicit ordering constraints can be expressed with explicit synchronization primitives.

There are a few implicit ordering guarantees between commands within a command buffer, but only covering a subset of execution. Additional explicit ordering constraints can be expressed with the various explicit synchronization primitives.

Note
Implementations have significant freedom to overlap execution of work submitted to a queue, and this is common due to deep pipelining and parallelism in Vulkan devices.

Commands recorded in command buffers either perform actions (draw, dispatch, clear, copy, query/timestamp operations, begin/end subpass operations), set state (bind pipelines, descriptor sets, and buffers, set dynamic state, push constants, set render pass/subpass state), or perform synchronization (set/wait events, pipeline barrier, render pass/subpass dependencies). Some commands perform more than one of these tasks. State setting commands update the current state of the command buffer. Some commands that perform actions (e.g. draw/dispatch) do so based on the current state set cumulatively since the start of the command buffer. The work involved in performing action commands is often allowed to overlap or to be reordered, but doing so must not alter the state to be used by each action command. In general, action commands are those commands that alter framebuffer attachments, read/write buffer or image memory, or write to query pools.

Synchronization commands introduce explicit execution and memory dependencies between two sets of action commands, where the second set of commands depends on the first set of commands. These dependencies enforce that both the execution of certain pipeline stages in the later set occur after the execution of certain stages in the source set, and that the effects of memory accesses performed by certain pipeline stages occur in order and are visible to each other. When not enforced by an explicit dependency or implicit ordering guarantees, action commands may overlap execution or execute out of order, and may not see the side effects of each other’s memory accesses.

The device executes queue operations asynchronously with respect to the host. Control is returned to an application immediately following command buffer submission to a queue. The application must synchronize work between the host and device as needed.

2.3. Object Model

The devices, queues, and other entities in Vulkan are represented by Vulkan objects. At the API
level, all objects are referred to by handles. There are two classes of handles, dispatchable and non-
dispatchable. Dispatchable handle types are a pointer to an opaque type. This pointer may be used
by layers as part of intercepting API commands, and thus each API command takes a dispatchable
type as its first parameter. Each object of a dispatchable type must have a unique handle value
during its lifetime.

Non-dispatchable handle types are a 64-bit integer type whose meaning is implementation-
dependent, and may encode object information directly in the handle rather than acting as a reference to an underlying object. Objects of a non-dispatchable type may not have unique handle values within a type or across types. If handle values are not unique, then destroying one such handle must not cause identical handles of other types to become invalid, and must not cause identical handles of the same type to become invalid if that handle value has been created more times than it has been destroyed.

All objects created or allocated from a VkDevice (i.e. with a VkDevice as the first parameter) are
private to that device, and must not be used on other devices.

2.3.1. Object Lifetime

Objects are created or allocated by vkCreate* and vkAllocate* commands, respectively. Once an
object is created or allocated, its “structure” is considered to be immutable, though the contents of
certain object types is still free to change. Objects are destroyed or freed by vkDestroy* and vkFree*
commands, respectively.

Objects that are allocated (rather than created) take resources from an existing pool object or
memory heap, and when freed return resources to that pool or heap. While object creation and
destruction are generally expected to be low-frequency occurrences during runtime, allocating and
freeing objects can occur at high frequency. Pool objects help accommodate improved performance
of the allocations and frees.

It is an application’s responsibility to track the lifetime of Vulkan objects, and not to destroy them
while they are still in use.

The ownership of application-owned memory is immediately acquired by any Vulkan command it
is passed into. Ownership of such memory must be released back to the application at the end of
the duration of the command, so that the application can alter or free this memory as soon as all
the commands that acquired it have returned.

The following object types are consumed when they are passed into a Vulkan command and not
further accessed by the objects they are used to create. They must not be destroyed in the duration
of any API command they are passed into:

- VkShaderModule
- VkPipelineCache

A VkRenderPass object passed as a parameter to create another object is not further accessed by that
object after the duration of the command it is passed into. A VkRenderPass used in a command
buffer follows the rules described below.

A VkPipelineLayout object must not be destroyed while any command buffer that uses it is in the
**VkDescriptorSetLayout** objects may be accessed by commands that operate on descriptor sets allocated using that layout, and those descriptor sets must not be updated with **vkUpdateDescriptorSets** after the descriptor set layout has been destroyed. Otherwise, a **VkDescriptorSetLayout** object passed as a parameter to create another object is not further accessed by that object after the duration of the command it is passed into.

The application must not destroy any other type of Vulkan object until all uses of that object by the device (such as via command buffer execution) have completed.

The following Vulkan objects must not be destroyed while any command buffers using the object are in the **pending state**:

- VkEvent
- VkQueryPool
- VkBuffer
- VkBufferView
- VkImage
- VkImageView
- VkPipeline
- VkSampler
- VkSamplerYcbcrConversion
- VkDescriptorPool
- VkFramebuffer
- VkRenderPass
- VkCommandBuffer
- VkCommandPool
- VkDeviceMemory
- VkDescriptorSet

Destroying these objects will move any command buffers that are in the recording or executable state, and are using those objects, to the **invalid state**.

The following Vulkan objects must not be destroyed while any queue is executing commands that use the object:

- VkFence
- VkSemaphore
- VkCommandBuffer
- VkCommandPool

In general, objects can be destroyed or freed in any order, even if the object being freed is involved in the use of another object (e.g. use of a resource in a view, use of a view in a descriptor set, use of an object in a command buffer, binding of a memory allocation to a resource), as long as any object that uses the freed object is not further used in any way except to be destroyed or to be reset in such a way that it no longer uses the other object (such as resetting a command buffer). If the object
has been reset, then it can be used as if it never used the freed object. An exception to this is when there is a parent/child relationship between objects. In this case, the application must not destroy a parent object before its children, except when the parent is explicitly defined to free its children when it is destroyed (e.g. for pool objects, as defined below).

\( \text{VkCommandPool} \) objects are parents of \( \text{VkCommandBuffer} \) objects. \( \text{VkDescriptorPool} \) objects are parents of \( \text{VkDescriptorSet} \) objects. \( \text{VkDevice} \) objects are parents of many object types (all that take a \( \text{VkDevice} \) as a parameter to their creation).

The following Vulkan objects have specific restrictions for when they can be destroyed:

- \( \text{VkQueue} \) objects cannot be explicitly destroyed. Instead, they are implicitly destroyed when the \( \text{VkDevice} \) object they are retrieved from is destroyed.
- Destroying a pool object implicitly frees all objects allocated from that pool. Specifically, destroying \( \text{VkCommandPool} \) frees all \( \text{VkCommandBuffer} \) objects that were allocated from it, and destroying \( \text{VkDescriptorPool} \) frees all \( \text{VkDescriptorSet} \) objects that were allocated from it.
- \( \text{VkDevice} \) objects can be destroyed when all \( \text{VkQueue} \) objects retrieved from them are idle, and all objects created from them have been destroyed. This includes the following objects:
  - \( \text{VkFence} \)
  - \( \text{VkSemaphore} \)
  - \( \text{VkEvent} \)
  - \( \text{VkQueryPool} \)
  - \( \text{VkBuffer} \)
  - \( \text{VkBufferView} \)
  - \( \text{VkImage} \)
  - \( \text{VkImageView} \)
  - \( \text{VkShaderModule} \)
  - \( \text{VkPipelineCache} \)
  - \( \text{VkPipeline} \)
  - \( \text{VkPipelineLayout} \)
  - \( \text{VkSampler} \)
  - \( \text{VkSamplerYcbcrConversion} \)
  - \( \text{VkDescriptorSetLayout} \)
  - \( \text{VkDescriptorPool} \)
  - \( \text{VkFramebuffer} \)
  - \( \text{VkRenderPass} \)
  - \( \text{VkCommandPool} \)
  - \( \text{VkCommandBuffer} \)
  - \( \text{VkDeviceMemory} \)

- \( \text{VkPhysicalDevice} \) objects cannot be explicitly destroyed. Instead, they are implicitly destroyed when the \( \text{VkInstance} \) object they are retrieved from is destroyed.
- \( \text{VkInstance} \) objects can be destroyed once all \( \text{VkDevice} \) objects created from any of its \( \text{VkPhysicalDevice} \) objects have been destroyed.
• VkPipeline objects, that were created as pipeline library, can be destroyed once all VkPipeline objects that link with it have been destroyed.

2.3.2. External Object Handles

As defined above, the scope of object handles created or allocated from a VkDevice is limited to that logical device. Objects which are not in scope are said to be external. To bring an external object into scope, an external handle must be exported from the object in the source scope and imported into the destination scope.

Note

The scope of external handles and their associated resources may vary according to their type, but they can generally be shared across process and API boundaries.

2.4. Application Binary Interface

The mechanism by which Vulkan is made available to applications is platform- or implementation-defined. On many platforms the C interface described in this Specification is provided by a shared library. Since shared libraries can be changed independently of the applications that use them, they present particular compatibility challenges, and this Specification places some requirements on them.

Shared library implementations must use the default Application Binary Interface (ABI) of the standard C compiler for the platform, or provide customized API headers that cause application code to use the implementation’s non-default ABI. An ABI in this context means the size, alignment, and layout of C data types; the procedure calling convention; and the naming convention for shared library symbols corresponding to C functions. Customizing the calling convention for a platform is usually accomplished by defining calling convention macros appropriately in vk_platform.h.

On platforms where Vulkan is provided as a shared library, library symbols beginning with “vk” and followed by a digit or uppercase letter are reserved for use by the implementation. Applications which use Vulkan must not provide definitions of these symbols. This allows the Vulkan shared library to be updated with additional symbols for new API versions or extensions without causing symbol conflicts with existing applications.

Shared library implementations should provide library symbols for commands in the highest version of this Specification they support, and for Window System Integration extensions relevant to the platform. They may also provide library symbols for commands defined by additional extensions.
Note

These requirements and recommendations are intended to allow implementors to take advantage of platform-specific conventions for SDKs, ABIs, library versioning mechanisms, etc. while still minimizing the code changes necessary to port applications or libraries between platforms. Platform vendors, or providers of the de facto standard Vulkan shared library for a platform, are encouraged to document what symbols the shared library provides and how it will be versioned when new symbols are added.

Applications **should** only rely on shared library symbols for commands in the minimum core version required by the application. `vkGetInstanceProcAddr` and `vkGetDeviceProcAddr` **should** be used to obtain function pointers for commands in core versions beyond the application's minimum required version.

### 2.5. Command Syntax and Duration

The Specification describes Vulkan commands as functions or procedures using C99 syntax. Language bindings for other languages such as C++ and JavaScript **may** allow for stricter parameter passing, or object-oriented interfaces.

Vulkan uses the standard C types for the base type of scalar parameters (e.g. types from `<stdint.h>`), with exceptions described below, or elsewhere in the text when appropriate:

**VkBool32** represents boolean **True** and **False** values, since C does not have a sufficiently portable built-in boolean type:

```c
typedef uint32_t VkBool32;
```

**VK_TRUE** represents a boolean **True** (integer 1) value, and **VK_FALSE** a boolean **False** (integer 0) value. All values returned from a Vulkan implementation in a **VkBool32** will be either **VK_TRUE** or **VK_FALSE**. Applications **must** not pass any other values than **VK_TRUE** or **VK_FALSE** into a Vulkan implementation where a **VkBool32** is expected.

**VkDeviceSize** represents device memory size and offset values:

```c
typedef uint64_t VkDeviceSize;
```

**VkDeviceAddress** represents device buffer address values:

```c
typedef uint64_t VkDeviceAddress;
```

Commands that create Vulkan objects are of the form `vkCreate*` and take `Vk*CreateInfo` structures with the parameters needed to create the object. These Vulkan objects are destroyed with
commands of the form \texttt{vkDestroy*}.

The last in-parameter to each command that creates or destroys a Vulkan object is \texttt{pAllocator}. The \texttt{pAllocator} parameter \textbf{can} be set to a non-\texttt{NULL} value such that allocations for the given object are delegated to an application provided callback; refer to the Memory Allocation chapter for further details.

Commands that allocate Vulkan objects owned by pool objects are of the form \texttt{vkAllocate*}, and take \texttt{VkAllocateInfo} structures. These Vulkan objects are freed with commands of the form \texttt{vkFree*}. These objects do not take allocators; if host memory is needed, they will use the allocator that was specified when their parent pool was created.

Commands are recorded into a command buffer by calling API commands of the form \texttt{vkCmd*}. Each such command \textbf{may} have different restrictions on where it \textbf{can} be used: in a primary and/or secondary command buffer, inside and/or outside a render pass, and in one or more of the supported queue types. These restrictions are documented together with the definition of each such command.

The \textit{duration} of a Vulkan command refers to the interval between calling the command and its return to the caller.

\subsection*{2.5.1. Lifetime of Retrieved Results}

Information is retrieved from the implementation with commands of the form \texttt{vkGet*} and \texttt{vkEnumerate*}.

Unless otherwise specified for an individual command, the results are \textit{invariant}; that is, they will remain unchanged when retrieved again by calling the same command with the same parameters, so long as those parameters themselves all remain valid.

\subsection*{2.6. Threading Behavior}

Vulkan is intended to provide scalable performance when used on multiple host threads. All commands support being called concurrently from multiple threads, but certain parameters, or components of parameters are defined to be \textit{externally synchronized}. This means that the caller \textbf{must} guarantee that no more than one thread is using such a parameter at a given time.

More precisely, Vulkan commands use simple stores to update the state of Vulkan objects. A parameter declared as externally synchronized \textbf{may} have its contents updated at any time during the host execution of the command. If two commands operate on the same object and at least one of the commands declares the object to be externally synchronized, then the caller \textbf{must} guarantee not only that the commands do not execute simultaneously, but also that the two commands are separated by an appropriate memory barrier (if needed).
Note
Memory barriers are particularly relevant for hosts based on the ARM CPU architecture, which is more weakly ordered than many developers are accustomed to from x86/x64 programming. Fortunately, most higher-level synchronization primitives (like the pthread library) perform memory barriers as a part of mutual exclusion, so mutexing Vulkan objects via these primitives will have the desired effect.

Similarly the application must avoid any potential data hazard of application-owned memory that has its ownership temporarily acquired by a Vulkan command. While the ownership of application-owned memory remains acquired by a command the implementation may read the memory at any point, and it may write non-const qualified memory at any point. Parameters referring to non-const qualified application-owned memory are not marked explicitly as externally synchronized in the Specification.

If an application is using deferred host operations in a command, and that operation is successfully deferred, object parameters and application-owned memory passed to that command may be accessed at any time until the deferred operation is complete.

Many object types are immutable, meaning the objects cannot change once they have been created. These types of objects never need external synchronization, except that they must not be destroyed while they are in use on another thread. In certain special cases mutable object parameters are internally synchronized, making external synchronization unnecessary. Any command parameters that are not labeled as externally synchronized are either not mutated by the command or are internally synchronized. Additionally, certain objects related to a command’s parameters (e.g. command pools and descriptor pools) may be affected by a command, and must also be externally synchronized. These implicit parameters are documented as described below.

Parameters of commands that are externally synchronized are listed below.
Externally Synchronized Parameters

- The `instance` parameter in `vkDestroyInstance`
- The `device` parameter in `vkDestroyDevice`
- The `queue` parameter in `vkQueueSubmit`
- The `fence` parameter in `vkQueueSubmit`
- The `queue` parameter in `vkQueueWaitIdle`
- The `memory` parameter in `vkFreeMemory`
- The `memory` parameter in `vkMapMemory`
- The `memory` parameter in `vkUnmapMemory`
- The `buffer` parameter in `vkBindBufferMemory`
- The `image` parameter in `vkBindImageMemory`
- The `queue` parameter in `vkQueueBindSparse`
- The `fence` parameter in `vkQueueBindSparse`
- The `fence` parameter in `vkDestroyFence`
- The `semaphore` parameter in `vkDestroySemaphore`
- The `event` parameter in `vkDestroyEvent`
- The `event` parameter in `vkSetEvent`
- The `event` parameter in `vkResetEvent`
- The `queryPool` parameter in `vkDestroyQueryPool`
- The `buffer` parameter in `vkDestroyBuffer`
- The `bufferView` parameter in `vkDestroyBufferView`
- The `image` parameter in `vkDestroyImage`
- The `imageView` parameter in `vkDestroyImageView`
- The `shaderModule` parameter in `vkDestroyShaderModule`
- The `pipelineCache` parameter in `vkDestroyPipelineCache`
- The `dstCache` parameter in `vkMergePipelineCaches`
- The `pipeline` parameter in `vkDestroyPipeline`
- The `pipelineLayout` parameter in `vkDestroyPipelineLayout`
- The `sampler` parameter in `vkDestroySampler`
- The `descriptorSetLayout` parameter in `vkDestroyDescriptorSetLayout`
- The `descriptorPool` parameter in `vkDestroyDescriptorPool`
- The `descriptorPool` parameter in `vkResetDescriptorPool`
- The `descriptorPool` member of the `pAllocateInfo` parameter in `vkAllocateDescriptorSets`
- The `descriptorPool` parameter in `vkFreeDescriptorSets`
• The framebuffer parameter in vkDestroyFramebuffer
• The renderPass parameter in vkDestroyRenderPass
• The commandPool parameter in vkDestroyCommandPool
• The commandPool parameter in vkResetCommandPool
• The commandPool member of the pAllocateInfo parameter in vkAllocateCommandBuffers
• The commandPool parameter in vkFreeCommandBuffers
• The commandBuffer parameter in vkBeginCommandBuffer
• The commandBuffer parameter in vkEndCommandBuffer
• The commandBuffer parameter in vkResetCommandBuffer
• The commandBuffer parameter in vkCmdBindPipeline
• The commandBuffer parameter in vkCmdSetViewport
• The commandBuffer parameter in vkCmdSetScissor
• The commandBuffer parameter in vkCmdSetLineWidth
• The commandBuffer parameter in vkCmdSetDepthBias
• The commandBuffer parameter in vkCmdSetBlendConstants
• The commandBuffer parameter in vkCmdSetDepthBounds
• The commandBuffer parameter in vkCmdSetStencilCompareMask
• The commandBuffer parameter in vkCmdSetStencilWriteMask
• The commandBuffer parameter in vkCmdSetStencilReference
• The commandBuffer parameter in vkCmdBindDescriptorSets
• The commandBuffer parameter in vkCmdBindIndexBuffer
• The commandBuffer parameter in vkCmdBindVertexBuffers
• The commandBuffer parameter in vkCmdDraw
• The commandBuffer parameter in vkCmdDrawIndexed
• The commandBuffer parameter in vkCmdDrawIndirect
• The commandBuffer parameter in vkCmdDispatch
• The commandBuffer parameter in vkCmdDispatchIndirect
• The commandBuffer parameter in vkCmdCopyBuffer
• The commandBuffer parameter in vkCmdCopyImage
• The commandBuffer parameter in vkCmdBlitImage
• The commandBuffer parameter in vkCmdCopyBufferToImage
• The commandBuffer parameter in vkCmdCopyImageToBuffer
• The commandBuffer parameter in vkCmdUpdateBuffer
• The commandBuffer parameter in vkCmdFillBuffer
• The commandBuffer parameter in `vkCmdClearColorImage`
• The commandBuffer parameter in `vkCmdClearDepthStencilImage`
• The commandBuffer parameter in `vkCmdClearAttachments`
• The commandBuffer parameter in `vkCmdResolveImage`
• The commandBuffer parameter in `vkCmdSetEvent`
• The commandBuffer parameter in `vkCmdResetEvent`
• The commandBuffer parameter in `vkCmdWaitEvents`
• The commandBuffer parameter in `vkCmdPipelineBarrier`
• The commandBuffer parameter in `vkCmdBeginQuery`
• The commandBuffer parameter in `vkCmdEndQuery`
• The commandBuffer parameter in `vkCmdResetQueryPool`
• The commandBuffer parameter in `vkCmdWriteTimestamp`
• The commandBuffer parameter in `vkCmdCopyQueryPoolResults`
• The commandBuffer parameter in `vkCmdPushConstants`
• The commandBuffer parameter in `vkCmdBeginRenderPass`
• The commandBuffer parameter in `vkCmdNextSubpass`
• The commandBuffer parameter in `vkCmdEndRenderPass`
• The commandBuffer parameter in `vkCmdExecuteCommands`
• The commandBuffer parameter in `vkCmdSetDeviceMask`
• The commandPool parameter in `vkTrimCommandPool`
• The ycbcrConversion parameter in `vkDestroySamplerYcbcrConversion`
• The descriptorUpdateTemplate parameter in `vkDestroyDescriptorUpdateTemplate`
• The descriptorSet parameter in `vkUpdateDescriptorSetWithTemplate`
• The surface parameter in `vkUpdateDescriptorSetWithTemplate`
• The surface member of the pCreateInfo parameter in `vkCreateSwapchainKHR`
• The oldSwapchain member of the pCreateInfo parameter in `vkCreateSwapchainKHR`
• The swapchain parameter in `vkDestroySwapchainKHR`
• The swapchain parameter in `vkAcquireNextImageKHR`
• The semaphore parameter in `vkAcquireNextImageKHR`
• The fence parameter in `vkAcquireNextImageKHR`
• The queue parameter in `vkQueuePresentKHR`
• The surface parameter in `vkGetDeviceGroupSurfacePresentModesKHR`
• The surface parameter in `vkGetPhysicalDevicePresentRectanglesKHR`
• The display parameter in `vkCreateDisplayModeKHR`
• The `mode` parameter in `vkGetDisplayPlaneCapabilitiesKHR`
• The `commandBuffer` parameter in `vkCmdSetDeviceMaskKHR`
• The `commandBuffer` parameter in `vkCmdDispatchBaseKHR`
• The `commandPool` parameter in `vkTrimCommandPoolKHR`
• The `commandBuffer` parameter in `vkCmdPushDescriptorSetKHR`
• The `commandBuffer` parameter in `vkCmdPushDescriptorSetWithTemplateKHR`
• The `descriptorUpdateTemplate` parameter in `vkDestroyDescriptorUpdateTemplateKHR`
• The `descriptorSet` parameter in `vkUpdateDescriptorSetWithTemplateKHR`
• The `commandBuffer` parameter in `vkCmdBeginRenderPass2`
• The `commandBuffer` parameter in `vkCmdBeginRenderPass2KHR`
• The `commandBuffer` parameter in `vkCmdNextSubpass2`
• The `commandBuffer` parameter in `vkCmdNextSubpass2KHR`
• The `commandBuffer` parameter in `vkCmdEndRenderPass2`
• The `commandBuffer` parameter in `vkCmdEndRenderPass2KHR`
• The `swapchain` parameter in `vkGetSwapchainStatusKHR`
• The `ycbcrConversion` parameter in `vkDestroySamplerYcbcrConversionKHR`
• The `commandBuffer` parameter in `vkCmdDrawIndirectCount`
• The `commandBuffer` parameter in `vkCmdDrawIndirectCountKHR`
• The `commandBuffer` parameter in `vkCmdDrawIndexedIndirectCount`
• The `commandBuffer` parameter in `vkCmdDrawIndexedIndirectCountKHR`

There are also a few instances where a command can take in a user allocated list whose contents are externally synchronized parameters. In these cases, the caller must guarantee that at most one thread is using a given element within the list at a given time. These parameters are listed below.
Externally Synchronized Parameter Lists

• The buffer member of each element of the pBufferBinds member of each element of the pBindInfo parameter in vkQueueBindSparse
• The image member of each element of the pImageOpaqueBinds member of each element of the pBindInfo parameter in vkQueueBindSparse
• The image member of each element of the pImageBinds member of each element of the pBindInfo parameter in vkQueueBindSparse
• Each element of the pFences parameter in vkResetFences
• Each element of the pDescriptorSets parameter in vkFreeDescriptorSets
• The dstSet member of each element of the pDescriptorWrites parameter in vkUpdateDescriptorSets
• The dstSet member of each element of the pDescriptorCopies parameter in vkUpdateDescriptorSets
• Each element of the pCommandBuffers parameter in vkFreeCommandBuffers
• Each element of the pWaitSemaphores member of the pPresentInfo parameter in vkQueuePresentKHR
• Each element of the pSwapchains member of the pPresentInfo parameter in vkQueuePresentKHR
• The surface member of each element of the pCreateInfos parameter in vkCreateSharedSwapchainsKHR
• The oldSwapchain member of each element of the pCreateInfos parameter in vkCreateSharedSwapchainsKHR

In addition, there are some implicit parameters that need to be externally synchronized. For example, all commandBuffer parameters that need to be externally synchronized imply that the commandPool that was passed in when creating that command buffer also needs to be externally synchronized. The implicit parameters and their associated object are listed below.
Implicit Externally Synchronized Parameters

- All VkQueue objects created from device in vkDeviceWaitIdle
- Any VkDescriptorSet objects allocated from descriptorPool in vkResetDescriptorPool
- The VkCommandPool that commandBuffer was allocated from in vkBeginCommandBuffer
- The VkCommandPool that commandBuffer was allocated from in vkEndCommandBuffer
- The VkCommandPool that commandBuffer was allocated from, in vkCmdBindPipeline
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetViewport
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetScissor
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetLineWidth
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDepthBias
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetBlendConstants
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDepthBounds
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetStencilCompareMask
- The VkCommandPool that commandBuffer was allocated from, in vkCmdSetStencilWriteMask
- The VkCommandPool that commandBuffer was allocated from, in vkCmdBindDescriptorReference
- The VkCommandPool that commandBuffer was allocated from, in vkCmdBindIndexBuffer
- The VkCommandPool that commandBuffer was allocated from, in vkCmdBindVertexBuffer
- The VkCommandPool that commandBuffer was allocated from, in vkCmdDraw
- The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndexed
- The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndirect
- The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndexedIndirect
- The VkCommandPool that commandBuffer was allocated from, in vkCmdDispatch
- The VkCommandPool that commandBuffer was allocated from, in vkCmdDispatchIndirect
- The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyBuffer
- The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyImage
- The VkCommandPool that commandBuffer was allocated from, in vkCmdBlitImage
- The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyBufferToImage
- The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyImageToBuffer
- The VkCommandPool that commandBuffer was allocated from, in vkCmdUpdateBuffer
- The VkCommandPool that commandBuffer was allocated from, in vkCmdFillBuffer
- The VkCommandPool that commandBuffer was allocated from, in vkCmdClearColorImage
- The VkCommandPool that commandBuffer was allocated from, in vkCmdClearDepthStencilImage
vkCmdClearDepthStencilImage
• The VkCommandPool that commandBuffer was allocated from, in vkCmdClearAttachments
• The VkCommandPool that commandBuffer was allocated from, in vkCmdResolveImage
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetEvent
• The VkCommandPool that commandBuffer was allocated from, in vkCmdResetEvent
• The VkCommandPool that commandBuffer was allocated from, in vkCmdWaitEvents
• The VkCommandPool that commandBuffer was allocated from, in vkCmdPipelineBarrier
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginQuery
• The VkCommandPool that commandBuffer was allocated from, in vkCmdEndQuery
• The VkCommandPool that commandBuffer was allocated from, in vkCmdResetQueryPool
• The VkCommandPool that commandBuffer was allocated from, in vkCmdWriteTimestamp
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyQueryPoolResults
• The VkCommandPool that commandBuffer was allocated from, in vkCmdPushConstants
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginRenderPass
• The VkCommandPool that commandBuffer was allocated from, in vkCmdNextSubpass
• The VkCommandPool that commandBuffer was allocated from, in vkCmdEndRenderPass
• The VkCommandPool that commandBuffer was allocated from, in vkCmdExecuteCommands
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDeviceMask
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDispatchBase
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDispatchBaseKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdSetDeviceMaskKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdPushDescriptorSetKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdPushDescriptorSetWithTemplateKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginRenderPass2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBeginRenderPass2KHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdNextSubpass2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdNextSubpass2KHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdEndRenderPass2
• The VkCommandPool that commandBuffer was allocated from, in vkCmdEndRenderPass2KHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndirectCount
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndirectCountKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndexedIndirectCount
• The VkCommandPool that commandBuffer was allocated from, in vkCmdDrawIndexedIndirectCountKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBuildAccelerationStructureKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdBuildAccelerationStructureIndirectKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyAccelerationStructureKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyAccelerationStructureToMemoryKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdCopyMemoryToAccelerationStructureKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdTraceRaysKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdWriteAccelerationStructuresPropertiesKHR
• The VkCommandPool that commandBuffer was allocated from, in vkCmdTraceRaysIndirectKHR

2.7. Errors

Vulkan is a layered API. The lowest layer is the core Vulkan layer, as defined by this Specification. The application can use additional layers above the core for debugging, validation, and other purposes.

One of the core principles of Vulkan is that building and submitting command buffers should be highly efficient. Thus error checking and validation of state in the core layer is minimal, although more rigorous validation can be enabled through the use of layers.

The core layer assumes applications are using the API correctly. Except as documented elsewhere in the Specification, the behavior of the core layer to an application using the API incorrectly is undefined, and may include program termination. However, implementations must ensure that incorrect usage by an application does not affect the integrity of the operating system, the Vulkan implementation, or other Vulkan client applications in the system. In particular, any guarantees made by an operating system about whether memory from one process can be visible to another process or not must not be violated by a Vulkan implementation for any memory allocation. Vulkan implementations are not required to make additional security or integrity guarantees beyond those provided by the OS unless explicitly directed by the application's use of a particular feature or extension.
For instance, if an operating system guarantees that data in all its memory allocations are set to zero when newly allocated, the Vulkan implementation must make the same guarantees for any allocations it controls (e.g. VkDeviceMemory).

Similarly, if an operating system guarantees that use-after-free of host allocations will not result in values written by another process becoming visible, the same guarantees must be made by the Vulkan implementation for device memory.

If the protected memory feature is supported, the implementation provides additional guarantees when invalid usage occurs to prevent values in protected memory from being accessed or inferred outside of protected operations, as described in Protected Memory Access Rules.

Validation of correct API usage is left to validation layers. Applications should be developed with validation layers enabled, to help catch and eliminate errors. Once validated, released applications should not enable validation layers by default.

### 2.7.1. Valid Usage

Valid usage defines a set of conditions which must be met in order to achieve well-defined run-time behavior in an application. These conditions depend only on Vulkan state, and the parameters or objects whose usage is constrained by the condition.

Some valid usage conditions have dependencies on run-time limits or feature availability. It is possible to validate these conditions against Vulkan’s minimum supported values for these limits and features, or some subset of other known values.

Valid usage conditions do not cover conditions where well-defined behavior (including returning an error code) exists.

Valid usage conditions should apply to the command or structure where complete information about the condition would be known during execution of an application. This is such that a validation layer or linter can be written directly against these statements at the point they are specified.

This does lead to some non-obvious places for valid usage statements. For instance, the valid values for a structure might depend on a separate value in the calling command. In this case, the structure itself will not reference this valid usage as it is impossible to determine validity from the structure that it is invalid - instead this valid usage would be attached to the calling command.

Another example is draw state - the state setters are independent, and can cause a legitimately invalid state configuration between draw calls; so the valid usage statements are attached to the place where all state needs to be valid - at the draw command.

Valid usage conditions are described in a block labelled “Valid Usage” following each command or...
structure they apply to.

2.7.2. Implicit Valid Usage

Some valid usage conditions apply to all commands and structures in the API, unless explicitly denoted otherwise for a specific command or structure. These conditions are considered *implicit*, and are described in a block labelled “Valid Usage (Implicit)” following each command or structure they apply to. Implicit valid usage conditions are described in detail below.

**Valid Usage for Object Handles**

Any input parameter to a command that is an object handle **must** be a valid object handle, unless otherwise specified. An object handle is valid if:

- It has been created or allocated by a previous, successful call to the API. Such calls are noted in the Specification.
- It has not been deleted or freed by a previous call to the API. Such calls are noted in the Specification.
- Any objects used by that object, either as part of creation or execution, **must** also be valid.

The reserved values `VK_NULL_HANDLE` and `NULL` can be used in place of valid non-dispatchable handles and dispatchable handles, respectively, when *explicitly called out in the Specification*. Any command that creates an object successfully **must** not return these values. It is valid to pass these values to `vkDestroy*` or `vkFree*` commands, which will silently ignore these values.

**Valid Usage for Pointers**

Any parameter that is a pointer **must** be a *valid pointer* only if it is explicitly called out by a Valid Usage statement.

A pointer is “valid” if it points at memory containing values of the number and type(s) expected by the command, and all fundamental types accessed through the pointer (e.g. as elements of an array or as members of a structure) satisfy the alignment requirements of the host processor.

**Valid Usage for Strings**

Any parameter that is a pointer to `char` **must** be a finite sequence of values terminated by a null character, or if *explicitly called out in the Specification*, **can** be `NULL`.

**Valid Usage for Enumerated Types**

Any parameter of an enumerated type **must** be a valid enumerant for that type. A enumerant is valid if:

- The enumerant is defined as part of the enumerated type.
- The enumerant is not one of the special values defined for the enumerated type, which are suffixed with `_BEGIN_RANGE`, `_END_RANGE`, `_RANGE_SIZE` or `_MAX_ENUM`.

1
The meaning of these special tokens is not exposed in the Vulkan Specification. They are not part of the API, and they should not be used by applications. Their original intended use was for internal consumption by Vulkan implementations. Even that use will no longer be supported in the future, but they will be retained for backwards compatibility reasons.

Any enumerated type returned from a query command or otherwise output from Vulkan to the application must not have a reserved value. Reserved values are values not defined by any extension for that enumerated type.

Note
This language is intended to accommodate cases such as “hidden” extensions known only to driver internals, or layers enabling extensions without knowledge of the application, without allowing return of values not defined by any extension.

Valid Usage for Flags

A collection of flags is represented by a bitmask using the type VkFlags:

```c
typedef uint32_t VkFlags;
```

Bitmasks are passed to many commands and structures to compactly represent options, but VkFlags is not used directly in the API. Instead, a Vk*Flags type which is an alias of VkFlags, and whose name matches the corresponding Vk*FlagBits that are valid for that type, is used.

Any Vk*Flags member or parameter used in the API as an input must be a valid combination of bit flags. A valid combination is either zero or the bitwise OR of valid bit flags. A bit flag is valid if:

- The bit flag is defined as part of the Vk*FlagBits type, where the bits type is obtained by taking the flag type and replacing the trailing Flags with FlagBits. For example, a flag value of type VkColorComponentFlags must contain only bit flags defined by VkColorComponentFlagBits.
- The flag is allowed in the context in which it is being used. For example, in some cases, certain bit flags or combinations of bit flags are mutually exclusive.

Any Vk*Flags member or parameter returned from a query command or otherwise output from Vulkan to the application may contain bit flags undefined in its corresponding Vk*FlagBits type. An application cannot rely on the state of these unspecified bits.

Only the low-order 31 bits (bit positions zero through 30) are available for use as flag bits.

Note
This restriction is due to poorly defined behavior by C compilers given a C enumerant value of 0x80000000. In some cases adding this enumerant value may increase the size of the underlying Vk*FlagBits type, breaking the ABI.

Valid Usage for Structure Types

Any parameter that is a structure containing a sType member must have a value of sType which is a
A valid `VkStructureType` value matching the type of the structure.

Structure types supported by the Vulkan API include:

```c
typedef enum VkStructureType {
    VK_STRUCTURE_TYPE_APPLICATION_INFO = 0,
    VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO = 1,
    VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO = 2,
    VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO = 3,
    VK_STRUCTURE_TYPE_SUBMIT_INFO = 4,
    VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO = 5,
    VK_STRUCTURE_TYPE_MAPPED_MEMORY_RANGE = 6,
    VK_STRUCTURE_TYPE_BIND_SPARSE_INFO = 7,
    VK_STRUCTURE_TYPE_FENCE_CREATE_INFO = 8,
    VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO = 9,
    VK_STRUCTURE_TYPE_EVENT_CREATE_INFO = 10,
    VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO = 11,
    VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO = 12,
    VK_STRUCTURE_TYPE_BUFFER_VIEW_CREATE_INFO = 13,
    VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO = 14,
    VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO = 15,
    VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO = 16,
    VK_STRUCTURE_TYPE_PIPELINE_CACHE_CREATE_INFO = 17,
    VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO = 18,
    VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO = 19,
    VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO = 20,
    VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO = 21,
    VK_STRUCTURE_TYPE_PIPELINE_VIEWPORT_STATE_CREATE_INFO = 22,
    VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO = 23,
    VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO = 24,
    VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO = 25,
    VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO = 26,
    VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO = 27,
    VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO = 28,
    VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO = 29,
    VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO = 30,
    VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO = 31,
    VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO = 32,
    VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_CREATE_INFO = 33,
    VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO = 34,
    VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET = 35,
    VK_STRUCTURE_TYPE_COPY_DESCRIPTOR_SET = 36,
    VK_STRUCTURE_TYPE_FRAMEBUFFER_CREATE_INFO = 37,
    VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO = 38,
    VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO = 39,
    VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO = 40,
    VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_INFO = 41,
    VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO = 42,
    VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO = 43,
    VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER = 44,
    VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER = 45,
} VkStructureType;
```
VK_STRUCTURE_TYPE_MEMORY_BARRIER = 46,
VK_STRUCTURE_TYPE_LOADER_INSTANCE_CREATE_INFO = 47,
VK_STRUCTURE_TYPE_LOADER_DEVICE_CREATE_INFO = 48,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_PROPERTIES = 1000094000,
VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO = 1000157000,
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO = 1000157001,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES = 1000083000,
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS = 1000127000,
VK_STRUCTURE_TYPE_MEMORY_DEDICATE_ALLOCATE_INFO = 1000127001,
VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO = 1000060000,
VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO = 1000060003,
VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO = 1000060004,
VK_STRUCTURE_TYPE_DEVICE_GROUP_SUBMIT_INFO = 1000060005,
VK_STRUCTURE_TYPE_DEVICE_GROUP_BIND_SPARSE_INFO = 1000060006,
VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO = 1000060013,
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_DEVICE_GROUP_INFO = 1000060014,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_PROPERTIES = 1000070000,
VK_STRUCTURE_TYPE_DEVICE_GROUP_DEVICE_CREATE_INFO = 1000070001,
VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2 = 1000146000,
VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2 = 1000146001,
VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2 = 1000146002,
VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2 = 1000146003,
VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2 = 1000146004,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2 = 1000059000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROPERTIES_2 = 1000059001,
VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2 = 1000059002,
VK_STRUCTURE_TYPE_IMAGE_FORMAT_PROPERTIES_2 = 1000059003,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_FORMAT_INFO_2 = 1000059004,
VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2 = 1000059005,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MEMORY_PROPERTIES_2 = 1000059006,
VK_STRUCTURE_TYPE_SPARSE_IMAGE_FORMAT_PROPERTIES_2 = 1000059007,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SPARSE_IMAGE_FORMAT_INFO_2 = 1000059008,
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO = 1000156000,
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO = 1000156001,
VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO = 1000156002,
VK_STRUCTURE_TYPE_IMAGE_PLANE_MEMORY_REQUIREMENTS_INFO = 1000156003,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_YCBCR_CONVERSION_FEATURES = 1000156004,
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_IMAGE_FORMAT_PROPERTIES = 1000156005,
VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO = 100005000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_IMAGE_FORMAT_INFO = 1000071000,
VK_STRUCTURE_TYPE_EXTERNAL_IMAGE_FORMAT_PROPERTIES = 1000071001,
VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_INFO = 1000071002,
VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_PROPERTIES = 1000071003,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO = 1000072000,
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO = 1000072001,
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_IMAGE_CREATE_INFO = 1000072001,
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_PROPERTIES = 1000072002,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_FENCE_INFO = 1000112000,
VK_STRUCTURE_TYPE_EXTERNAL_FENCE_PROPERTIES = 1000112001,
VK_STRUCTURE_TYPE_EXPORT_FENCE_CREATE_INFO = 1000113000,
VK_STRUCTURE_TYPE_EXPORT_SEMAPHORE_CREATE_INFO = 1000114000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO = 1000114001,
VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES = 1000114002,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES = 1000114003,
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT = 1000114004,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DRAW_PARAMETERS_FEATURES = 1000114005,
VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO = 1000114006,
VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2 = 1000114007,
VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2 = 1000114008,
VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_2 = 1000114009,
VK_STRUCTURE_TYPE_SUBPASS_DEPENDENCY_2 = 1000114010,
VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO_2 = 1000114011,
VK_STRUCTURE_TYPE_SUBPASS_BEGIN_INFO = 1000114012,
VK_STRUCTURE_TYPE_SUBPASS_END_INFO = 1000114013,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES = 1000114014,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES = 1000114015,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES = 1000114016,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES = 1000114017,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_FLOAT_CONTROLS_PROPERTIES = 1000114018,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DEPTH_STENCIL_RESOLVE_PROPERTIES = 1000114019,
VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_DEPTH_STENCIL_RESOLVE = 1000114020,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_MEMORY_MODEL_FEATURES = 1000114021,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGELESS_FRAMEBUFFER_FEATURES = 1000114022,
VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENTS_CREATE_INFO = 1000114023,
VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENT_IMAGE_INFO = 1000114024,
VK_STRUCTURE_TYPE_RENDER_PASS_ATTACHMENT_BEGIN_INFO = 1000114025,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_UNIFORM_BUFFER_STANDARD_LAYOUT_FEATURES = 1000114026,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES = 1000114027,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SEPARATE_DEPTH_STENCIL_LAYOUTS_FEATURES = 1000114028,
VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_STENCIL_LAYOUT = 1000114029,
VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_STENCIL_LAYOUT = 1000114030,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_TIMELINE_SEMAPHORE_FEATURES = 1000114031,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_TIMELINE_SEMAPHORE_PROPERTIES = 1000114032,
VK_STRUCTURE_TYPE_SEMAPHORE_TYPE_CREATE_INFO = 1000114033,
VK_STRUCTURE_TYPE_TIMELINE_SEMAPHORE_SUBMIT_INFO = 1000114034,
VK_STRUCTURE_TYPE_SEMAPHORE_WAIT_INFO = 1000114035.
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_PROPERTIES,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROPERTIES_2_KHR =
VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2_KHR = VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2,
VK_STRUCTURE_TYPE_IMAGE_FORMAT_PROPERTIES_2_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_FORMAT_INFO_2_KHR =
VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MEMORY_PROPERTIES_2_KHR =
VK_STRUCTURE_TYPE_SPARSE_IMAGE_FORMAT_PROPERTIES_2_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SPARSE_IMAGE_FORMAT_INFO_2_KHR =
VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO_KHR =
VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO_KHR =
VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO_KHR =
VK_STRUCTURE_TYPE_DEVICE_GROUP_SUBMIT_INFO_KHR =
VK_STRUCTURE_TYPE_DEVICE_GROUP_BIND_SPARSE_INFO_KHR =
VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO_KHR =
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_DEVICE_GROUP_INFO_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_IMAGE_FORMAT_INFO_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_IMAGE_FORMAT_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_INFO_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_BUFFER_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_IMAGE_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_ALLOCATE_INFO_KHR =
VK_STRUCTURE_TYPE_EXPORT_MEMORY_ALLOCATE_INFO,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO,
    VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES,
    VK_STRUCTURE_TYPE_EXPORT_SEMAPHORE_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_EXPORT_SEMAPHORE_CREATE_INFO,
    VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES,
    VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT16_INT8_FEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES_KHR =
VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO,
    VK_STRUCTURE_TYPE_PHYSICALDEVICEIMAGELESSFRAMEBUFFERFEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICALDEVICEIMAGELESSFRAMEBUFFERFEATURES,
    VK_STRUCTUREFRAMEBUFFERATTACHMENTS_CREATE_INFO_KHR =
VK_STRUCTUREFRAMEBUFFERATTACHMENT_IMAGE_INFO_KHR =
VK_STRUCTUREFRAMEBUFFERATTACHMENT_IMAGE_INFO,
    VK_STRUCTURE_TYPE_RENDER_PASS_ATTACHMENT_BEGIN_INFO_KHR =
VK_STRUCTURE_TYPE_RENDER_PASS_ATTACHMENT_BEGIN_INFO,
    VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2_KHR =
VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2,
    VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2_KHR =
VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2,
    VK_STRUCTURE_SUBPASS_DESCRIPTION_2_KHR =
VK_STRUCTURE_SUBPASS_DESCRIPTION_2,
    VK_STRUCTURE_SUBPASS_DEPENDENCY_2_KHR =
VK_STRUCTURE_SUBPASS_DEPENDENCY_2,
    VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO_2_KHR =
VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO_2,
    VK_STRUCTURE_TYPE_SUBPASS_BEGIN_INFO_KHR = VK_STRUCTURE_TYPE_SUBPASS_BEGIN_INFO,
    VK_STRUCTURE_TYPE_SUBPASS_END_INFO_KHR = VK_STRUCTURE_TYPE_SUBPASS_END_INFO,
    VK_STRUCTURE_TYPE_PHYSICALDEVICEEXTERNALFENCEINFO_KHR =
VK_STRUCTURE_TYPE_PHYSICALDEVICEEXTERNALFENCEINFO,
    VK_STRUCTURE_TYPE_EXTERNALFENCE_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_EXTERNALFENCE_PROPERTIES,
    VK_STRUCTURE_TYPE_EXPORT_FENCE_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_EXPORT_FENCE_CREATE_INFO,
    VK_STRUCTURE_TYPE_PHYSICALDEVICEPOINTCLIPPINGPROPERTIES_KHR =
VK_STRUCTURE_TYPE_PHYSICALDEVICEPOINTCLIPPINGPROPERTIES,
    VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT_ASPECT_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT_ASPECT_CREATE_INFO,
    VK_STRUCTURE_TYPE_IMAGEVIEW_USAGE_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_IMAGEVIEW_USAGE_CREATE_INFO,
    VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_DOMAIN_ORIGIN_STATE_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_DOMAIN_ORIGIN_STATE_CREATE_INFO,
    VK_STRUCTURE_TYPE_PHYSICALDEVICE_VARIABLE_POINTER_FEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICALDEVICE_VARIABLE_POINTER_FEATURES,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTERS_FEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTER_FEATURES,
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS_KHR =
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS,
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO_KHR =
VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO,
VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2_KHR =
VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2,
VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2_KHR =
VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2,
VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2_KHR =
VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2,
VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2_KHR =
VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2,
VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2_KHR =
VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2,
VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO,
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO_KHR =
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO,
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO_KHR =
VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO,
VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO_KHR =
VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO,
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO_KHR =
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO,
VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO_KHR =
VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO,
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO_KHR =
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES,
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT_KHR =
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_SHADER_ATOMIC_INT64_FEATURES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DEPTH_STENCIL_RESOLVE_PROPERTIES_KHR =
VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_DEPTH_STENCIL_RESOLVE_KHR =
Each value corresponds to a particular structure with a sType member with a matching name. As a general rule, the name of each VkStructureType value is obtained by taking the name of the structure, stripping the leading Vk, prefixing each capital letter with _, converting the entire resulting string to upper case, and prefixing it with VK_STRUCTURE_TYPE_. For example, structures of type VkImageCreateInfo correspond to a VkStructureType of VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO, and thus its sType member must equal that when it is passed to the API.

The values VK_STRUCTURE_TYPE_LOADER_INSTANCE_CREATE_INFO and VK_STRUCTURE_TYPE_LOADER_DEVICE_CREATE_INFO are reserved for internal use by the loader, and do not have corresponding Vulkan structures in this Specification.

Valid Usage for Structure Pointer Chains

Any parameter that is a structure containing a void* pNext member must have a value of pNext that is either NULL, or is a pointer to a valid structure defined by an extension, containing sType and pNext
members as described in the Vulkan Documentation and Extensions document in the section “Extension Interactions”. The set of structures connected by pNext pointers is referred to as a pNext chain. If that extension is supported by the implementation, then it must be enabled.

Each type of valid structure must not appear more than once in a pNext chain, including any aliases.

Any component of the implementation (the loader, any enabled layers, and drivers) must skip over, without processing (other than reading the sType and pNext members) any structures in the chain with sType values not defined by extensions supported by that component.

Extension structures are not described in the base Vulkan Specification, but either in layered Specifications incorporating those extensions, or in separate vendor-provided documents.

As a convenience to implementations and layers needing to iterate through a structure pointer chain, the Vulkan API provides two base structures. These structures allow for some type safety, and can be used by Vulkan API functions that operate on generic inputs and outputs.

The VkBaseInStructure structure is defined as:

```c
typedef struct VkBaseInStructure {
    VkStructureType sType;
    const struct VkBaseInStructure* pNext;
} VkBaseInStructure;
```

- **sType** is the structure type of the structure being iterated through.
- **pNext** is NULL or a pointer to the next structure in a structure chain.

VkBaseInStructure can be used to facilitate iterating through a read-only structure pointer chain.

The VkBaseOutStructure structure is defined as:

```c
typedef struct VkBaseOutStructure {
    VkStructureType sType;
    struct VkBaseOutStructure* pNext;
} VkBaseOutStructure;
```

- **sType** is the structure type of the structure being iterated through.
- **pNext** is NULL or a pointer to the next structure in a structure chain.

VkBaseOutStructure can be used to facilitate iterating through a structure pointer chain that returns data back to the application.

**Valid Usage for Nested Structures**

The above conditions also apply recursively to members of structures provided as input to a command, either as a direct argument to the command, or themselves a member of another structure.
Specifics on valid usage of each command are covered in their individual sections.

**Valid Usage for Extensions**

Instance-level functionality or behavior added by an instance extension to the API must not be used unless that extension is supported by the instance as determined by `vkEnumerateInstanceExtensionProperties`, and that extension is enabled in `VkInstanceCreateInfo`.

Physical-device-level functionality or behavior added by an instance extension to the API must not be used unless that extension is supported by the instance as determined by `vkEnumerateInstanceExtensionProperties`, and that extension is enabled in `VkInstanceCreateInfo`.

Physical-device-level functionality or behavior added by a device extension to the API must not be used unless the conditions described in Extending Physical Device Core Functionality are met.

Device functionality or behavior added by a device extension to the API must not be used unless that extension is supported by the device as determined by `vkEnumerateDeviceExtensionProperties`, and that extension is enabled in `VkDeviceCreateInfo`.

**Valid Usage for Newer Core Versions**

Instance-level functionality or behavior added by a new core version of the API must not be used unless it is supported by the instance as determined by `vkEnumerateInstanceVersion` and the specified version of `VkApplicationInfo::apiVersion`.

Physical-device-level functionality or behavior added by a new core version of the API must not be used unless it is supported by the physical device as determined by `VkPhysicalDeviceProperties::apiVersion` and the specified version of `VkApplicationInfo::apiVersion`.

Device-level functionality or behavior added by a new core version of the API must not be used unless it is supported by the device as determined by `VkPhysicalDeviceProperties::apiVersion` and the specified version of `VkApplicationInfo::apiVersion`.

**2.7.3. Return Codes**

While the core Vulkan API is not designed to capture incorrect usage, some circumstances still require return codes. Commands in Vulkan return their status via return codes that are in one of two categories:

- Successful completion codes are returned when a command needs to communicate success or status information. All successful completion codes are non-negative values.

- Run time error codes are returned when a command needs to communicate a failure that could only be detected at run time. All run time error codes are negative values.

All return codes in Vulkan are reported via `VkResult` return values. The possible codes are:
typedef enum VkResult {
    VK_SUCCESS = 0,
    VK_NOT_READY = 1,
    VK_TIMEOUT = 2,
    VK_EVENT_SET = 3,
    VK_EVENT_RESET = 4,
    VK_INCOMPLETE = 5,
    VK_ERROR_OUT_OF_HOST_MEMORY = -1,
    VK_ERROR_OUT_OF_DEVICE_MEMORY = -2,
    VK_ERROR_INITIALIZATION_FAILED = -3,
    VK_ERROR_DEVICE_LOST = -4,
    VK_ERROR_MEMORY_MAP_FAILED = -5,
    VK_ERROR_LAYER_NOT_PRESENT = -6,
    VK_ERROR_EXTENSION_NOT_PRESENT = -7,
    VK_ERROR_FEATURE_NOT_PRESENT = -8,
    VK_ERROR_INCOMPATIBLE_DRIVER = -9,
    VK_ERROR_TOO_MANY_OBJECTS = -10,
    VK_ERROR_FORMAT_NOT_SUPPORTED = -11,
    VK_ERROR_FRAGMENTED_POOL = -12,
    VK_ERROR_UNKNOWN = -13,
    VK_ERROR_OUT_OF_POOL_MEMORY = -1000069000,
    VK_ERROR_INVALID_EXTERNAL_HANDLE = -1000072003,
    VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS = -1000257000,
    VK_ERROR_SURFACE_LOST_KHR = -1000000000,
    VK_ERROR_NATIVE_WINDOW_IN_USE_KHR = -1000000001,
    VK_SUBOPTIMAL_KHR = 1000001003,
    VK_ERROR_OUT_OF_DATE_KHR = -1000001004,
    VK_ERROR_INCOMPATIBLE_DISPLAY_KHR = -1000003001,
    VK_ERROR_INCOMPATIBLE_VERSION_KHR = -1000150000,
    VK_THREAD_IDLE_KHR = 1000268000,
    VK_THREAD DONE_KHR = 1000268001,
    VK_OPERATION_DEFERRED_KHR = 1000268002,
    VK_OPERATION_NOT_DEFERRED_KHR = 1000268003,
    VK_ERROR_OUT_OF_POOL_MEMORY_KHR = VK_ERROR_OUT_OF_POOL_MEMORY,
    VK_ERROR_INVALID_EXTERNAL_HANDLE_KHR = VK_ERROR_INVALID_EXTERNAL_HANDLE,
    VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR =
    VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS,
    VK_RESULT_MAX_ENUM = 0x7FFFFFFF
} VkResult;

Success Codes

- **VK_SUCCESS** Command successfully completed
- **VK_NOT_READY** A fence or query has not yet completed
- **VK_TIMEOUT** A wait operation has not completed in the specified time
- **VK_EVENT_SET** An event is signaled
- **VK_EVENT_RESET** An event is unsignaled
- **VK_INCOMPLETE** A return array was too small for the result
• **VK_SUBOPTIMAL_KHR** A swapchain no longer matches the surface properties exactly, but can still be used to present to the surface successfully.

• **VK_THREAD_IDLE_KHR** A deferred operation is not complete but there is currently no work for this thread to do at the time of this call.

• **VK_THREAD_DONE_KHR** A deferred operation is not complete but there is no work remaining to assign to additional threads.

• **VK_OPERATION_DEFERRED_KHR** A deferred operation was requested and at least some of the work was deferred.

• **VK_OPERATION_NOT_DEFERRED_KHR** A deferred operation was requested and no operations were deferred.

**Error codes**

• **VK_ERROR_OUT_OF_HOST_MEMORY** A host memory allocation has failed.

• **VK_ERROR_OUT_OF_DEVICE_MEMORY** A device memory allocation has failed.

• **VK_ERROR_INITIALIZATION_FAILED** Initialization of an object could not be completed for implementation-specific reasons.

• **VK_ERROR_DEVICE_LOST** The logical or physical device has been lost. See Lost Device.

• **VK_ERROR_MEMORY_MAP_FAILED** Mapping of a memory object has failed.

• **VK_ERROR_LAYER_NOT_PRESENT** A requested layer is not present or could not be loaded.

• **VK_ERROR_EXTENSION_NOT_PRESENT** A requested extension is not supported.

• **VK_ERROR_FEATURE_NOT_PRESENT** A requested feature is not supported.

• **VK_ERROR_INCOMPATIBLE_DRIVER** The requested version of Vulkan is not supported by the driver or is otherwise incompatible for implementation-specific reasons.

• **VK_ERROR_TOO_MANY_OBJECTS** Too many objects of the type have already been created.

• **VK_ERROR_FORMAT_NOT_SUPPORTED** A requested format is not supported on this device.

• **VK_ERROR_FRAGMENTED_POOL** A pool allocation has failed due to fragmentation of the pool’s memory. This must only be returned if no attempt to allocate host or device memory was made to accommodate the new allocation. This should be returned in preference to VK_ERROR_OUT_OF_POOL_MEMORY, but only if the implementation is certain that the pool allocation failure was due to fragmentation.

• **VK_ERROR_SURFACE_LOST_KHR** A surface is no longer available.

• **VK_ERROR_NATIVE_WINDOW_IN_USE_KHR** The requested window is already in use by Vulkan or another API in a manner which prevents it from being used again.

• **VK_ERROR_OUT_OF_DATE_KHR** A surface has changed in such a way that it is no longer compatible with the swapchain, and further presentation requests using the swapchain will fail. Applications must query the new surface properties and recreate their swapchain if they wish to continue presenting to the surface.

• **VK_ERROR_INCOMPATIBLE_DISPLAY_KHR** The display used by a swapchain does not use the same presentable image layout, or is incompatible in a way that prevents sharing an image.

• **VK_ERROR_OUT_OF_POOL_MEMORY** A pool memory allocation has failed. This must only be returned if
no attempt to allocate host or device memory was made to accommodate the new allocation. If the failure was definitely due to fragmentation of the pool, **VK_ERROR_FRAGMENTED_POOL** should be returned instead.

- **VK_ERROR_INVALID_EXTERNAL_HANDLE** An external handle is not a valid handle of the specified type.
- **VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS** A buffer creation or memory allocation failed because the requested address is not available. A shader group handle assignment failed because the requested shader group handle information is no longer valid.
- **VK_ERROR_UNKNOWN** An unknown error has occurred; either the application has provided invalid input, or an implementation failure has occurred.

If a command returns a run time error, unless otherwise specified any output parameters will have undefined contents, except that if the output parameter is a structure with **sType** and **pNext** fields, those fields will be unmodified. Any structures chained from **pNext** will also have undefined contents, except that **sType** and **pNext** will be unmodified.

Out of memory errors do not damage any currently existing Vulkan objects. Objects that have already been successfully created can still be used by the application.

**VK_ERROR_UNKNOWN** will be returned by an implementation when an unexpected error occurs that cannot be attributed to valid behavior of the application and implementation.

**Note**

If **VK_ERROR_UNKNOWN** is received, the application should be checked against the latest validation layers to verify correct behavior as much as possible. If no issues are identified it could be an implementation issue, and the implementor should be contacted for support.

This error should not be expected from any command if application behavior is valid, and if the implementation is bug-free, but it can be returned by *any* error returning command when that is not the case.

Performance-critical commands generally do not have return codes. If a run time error occurs in such commands, the implementation will defer reporting the error until a specified point. For commands that record into command buffers (**vkCmd***)) run time errors are reported by **vkEndCommandBuffer**.

### 2.8. Numeric Representation and Computation

Implementations normally perform computations in floating-point, and must meet the range and precision requirements defined under “Floating-Point Computation” below.

These requirements only apply to computations performed in Vulkan operations outside of shader execution, such as texture image specification and sampling, and per-fragment operations. Range and precision requirements during shader execution differ and are specified by the **Precision and Operation of SPIR-V Instructions** section.

In some cases, the representation and/or precision of operations is implicitly limited by the...
specified format of vertex or texel data consumed by Vulkan. Specific floating-point formats are described later in this section.

### 2.8.1. Floating-Point Computation

Most floating-point computation is performed in SPIR-V shader modules. The properties of computation within shaders are constrained as defined by the Precision and Operation of SPIR-V Instructions section.

Some floating-point computation is performed outside of shaders, such as viewport and depth range calculations. For these computations, we do not specify how floating-point numbers are to be represented, or the details of how operations on them are performed, but only place minimal requirements on representation and precision as described in the remainder of this section.

We require simply that numbers' floating-point parts contain enough bits and that their exponent fields are large enough so that individual results of floating-point operations are accurate to about 1 part in $10^5$. The maximum representable magnitude for all floating-point values must be at least $2^{32}$.

$$x \times 0 = 0 \times x = 0 \text{ for any non-infinite and non-NaN } x.$$  

$$1 \times x = x \times 1 = x.$$  

$$x + 0 = 0 + x = x.$$  

$$0^0 = 1.$$  

Occasionally, further requirements will be specified. Most single-precision floating-point formats meet these requirements.

The special values Inf and -Inf encode values with magnitudes too large to be represented; the special value NaN encodes “Not A Number” values resulting from undefined arithmetic operations such as $0 / 0$. Implementations may support Inf and NaN in their floating-point computations.

### 2.8.2. Floating-Point Format Conversions

When a value is converted to a defined floating-point representation, finite values falling between two representable finite values are rounded to one or the other. The rounding mode is not defined. Finite values whose magnitude is larger than that of any representable finite value may be rounded either to the closest representable finite value or to the appropriately signed infinity. For unsigned destination formats any negative values are converted to zero. Positive infinity is converted to positive infinity; negative infinity is converted to negative infinity in signed formats and to zero in unsigned formats; and any NaN is converted to a NaN.

### 2.8.3. 16-Bit Floating-Point Numbers

16-bit floating point numbers are defined in the “16-bit floating point numbers” section of the Khronos Data Format Specification.
2.8.4. Unsigned 11-Bit Floating-Point Numbers

Unsigned 11-bit floating point numbers are defined in the “Unsigned 11-bit floating point numbers” section of the Khronos Data Format Specification.

2.8.5. Unsigned 10-Bit Floating-Point Numbers

Unsigned 10-bit floating point numbers are defined in the “Unsigned 10-bit floating point numbers” section of the Khronos Data Format Specification.

2.8.6. General Requirements

Any representable floating-point value in the appropriate format is legal as input to a Vulkan command that requires floating-point data. The result of providing a value that is not a floating-point number to such a command is unspecified, but must not lead to Vulkan interruption or termination. For example, providing a negative zero (where applicable) or a denormalized number to a Vulkan command must yield deterministic results, while providing a NaN or Inf yields unspecified results.

Some calculations require division. In such cases (including implied divisions performed by vector normalization), division by zero produces an unspecified result but must not lead to Vulkan interruption or termination.

2.9. Fixed-Point Data Conversions

When generic vertex attributes and pixel color or depth components are represented as integers, they are often (but not always) considered to be normalized. Normalized integer values are treated specially when being converted to and from floating-point values, and are usually referred to as normalized fixed-point.

In the remainder of this section, b denotes the bit width of the fixed-point integer representation. When the integer is one of the types defined by the API, b is the bit width of that type. When the integer comes from an image containing color or depth component texels, b is the number of bits allocated to that component in its specified image format.

The signed and unsigned fixed-point representations are assumed to be b-bit binary two’s-complement integers and binary unsigned integers, respectively.

2.9.1. Conversion from Normalized Fixed-Point to Floating-Point

Unsigned normalized fixed-point integers represent numbers in the range [0,1]. The conversion from an unsigned normalized fixed-point value c to the corresponding floating-point value f is defined as

\[ f = \frac{c}{2^b - 1} \]

Signed normalized fixed-point integers represent numbers in the range [-1,1]. The conversion from a signed normalized fixed-point value c to the corresponding floating-point value f is performed using
Only the range \([-2^{b-1} + 1, 2^{b-1} - 1]\) is used to represent signed fixed-point values in the range \([-1,1]\). For example, if \(b = 8\), then the integer value -127 corresponds to -1.0 and the value 127 corresponds to 1.0. Note that while zero is exactly expressible in this representation, one value (-128 in the example) is outside the representable range, and must be clamped before use. This equation is used everywhere that signed normalized fixed-point values are converted to floating-point.

### 2.9.2. Conversion from Floating-Point to Normalized Fixed-Point

The conversion from a floating-point value \(f\) to the corresponding unsigned normalized fixed-point value \(c\) is defined by first clamping \(f\) to the range \([0,1]\), then computing

\[
c = \text{convertFloatToUint}(f \times (2^b - 1), b)
\]

where \(\text{convertFloatToUint}(r,b)\) returns one of the two unsigned binary integer values with exactly \(b\) bits which are closest to the floating-point value \(r\). Implementations should round to nearest. If \(r\) is equal to an integer, then that integer value must be returned. In particular, if \(f\) is equal to 0.0 or 1.0, then \(c\) must be assigned 0 or \(2^b - 1\), respectively.

The conversion from a floating-point value \(f\) to the corresponding signed normalized fixed-point value \(c\) is performed by clamping \(f\) to the range \([-1,1]\), then computing

\[
c = \text{convertFloatToInt}(f \times (2^{b-1} - 1), b)
\]

where \(\text{convertFloatToInt}(r,b)\) returns one of the two signed two’s-complement binary integer values with exactly \(b\) bits which are closest to the floating-point value \(r\). Implementations should round to nearest. If \(r\) is equal to an integer, then that integer value must be returned. In particular, if \(f\) is equal to -1.0, 0.0, or 1.0, then \(c\) must be assigned \(-(2^{b-1} - 1)\), 0, or \(2^{b-1} - 1\), respectively.

This equation is used everywhere that floating-point values are converted to signed normalized fixed-point.

### 2.10. Common Object Types

Some types of Vulkan objects are used in many different structures and command parameters, and are described here. These types include offsets, extents, and rectangles.

#### 2.10.1. Offsets

Offsets are used to describe a pixel location within an image or framebuffer, as an \((x,y)\) location for two-dimensional images, or an \((x,y,z)\) location for three-dimensional images.

A two-dimensional offset is defined by the structure:
typedef struct VkOffset2D {
    int32_t x;
    int32_t y;
} VkOffset2D;

- x is the x offset.
- y is the y offset.

A three-dimensional offset is defined by the structure:

typedef struct VkOffset3D {
    int32_t x;
    int32_t y;
    int32_t z;
} VkOffset3D;

- x is the x offset.
- y is the y offset.
- z is the z offset.

2.10.2. Extents

Extents are used to describe the size of a rectangular region of pixels within an image or framebuffer, as (width,height) for two-dimensional images, or as (width,height,depth) for three-dimensional images.

A two-dimensional extent is defined by the structure:

typedef struct VkExtent2D {
    uint32_t width;
    uint32_t height;
} VkExtent2D;

- width is the width of the extent.
- height is the height of the extent.

A three-dimensional extent is defined by the structure:

typedef struct VkExtent3D {
    uint32_t width;
    uint32_t height;
    uint32_t depth;
} VkExtent3D;
- **width** is the width of the extent.
- **height** is the height of the extent.
- **depth** is the depth of the extent.

### 2.10.3. Rectangles

Rectangles are used to describe a specified rectangular region of pixels within an image or framebuffer. Rectangles include both an offset and an extent of the same dimensionality, as described above. Two-dimensional rectangles are defined by the structure

```c
typedef struct VkRect2D {
    VkOffset2D   offset;
    VkExtent2D   extent;
} VkRect2D;
```

- **offset** is a `VkOffset2D` specifying the rectangle offset.
- **extent** is a `VkExtent2D` specifying the rectangle extent.
Chapter 3. Initialization

Before using Vulkan, an application must initialize it by loading the Vulkan commands, and creating a VkInstance object.

3.1. Command Function Pointers

Vulkan commands are not necessarily exposed by static linking on a platform. Commands to query function pointers for Vulkan commands are described below.

Note
When extensions are promoted or otherwise incorporated into another extension or Vulkan core version, command aliases may be included. Whilst the behavior of each command alias is identical, the behavior of retrieving each alias's function pointer is not. A function pointer for a given alias can only be retrieved if the extension or version that introduced that alias is supported and enabled, irrespective of whether any other alias is available.

Function pointers for all Vulkan commands can be obtained with the command:

```c
PFN_vkVoidFunction vkGetInstanceProcAddr(
    VkInstance instance, const char* pName);
```

- instance is the instance that the function pointer will be compatible with, or NULL for commands not dependent on any instance.
- pName is the name of the command to obtain.

vkGetInstanceProcAddr itself is obtained in a platform- and loader- specific manner. Typically, the loader library will export this command as a function symbol, so applications can link against the loader library, or load it dynamically and look up the symbol using platform-specific APIs.

The table below defines the various use cases for vkGetInstanceProcAddr and expected return value (“fp” is “function pointer”) for each case.

The returned function pointer is of type PFN_vkVoidFunction, and must be cast to the type of the command being queried.

<table>
<thead>
<tr>
<th>instance</th>
<th>pName</th>
<th>return value</th>
</tr>
</thead>
<tbody>
<tr>
<td>*(^1)</td>
<td>NULL</td>
<td>undefined</td>
</tr>
<tr>
<td>NULL</td>
<td>*(^1)</td>
<td>undefined</td>
</tr>
<tr>
<td>VkInstance</td>
<td>vkEnumerateInstanceVersion</td>
<td>fp</td>
</tr>
</tbody>
</table>

\(^1\) Indicates that the instance is non-NULL.
### Valid Usage (Implicit)

- If `instance` is not `NULL`, `instance` must be a valid `VkInstance` handle
- `pName` must be a null-terminated UTF-8 string

In order to support systems with multiple Vulkan implementations, the function pointers returned by `vkGetInstanceProcAddr` may point to dispatch code that calls a different real implementation for different `VkDevice` objects or their child objects. The overhead of the internal dispatch for `VkDevice` objects can be avoided by obtaining device-specific function pointers for any commands that use a device or device-child object as their dispatchable object. Such function pointers can be obtained with the command:

```c
PFN_vkVoidFunction vkGetDeviceProcAddr(
    VkDevice device,
    const char* pName);
```
The table below defines the various use cases for `vkGetDeviceProcAddr` and expected return value for each case.

The returned function pointer is of type `PFN_vkVoidFunction`, and must be cast to the type of the command being queried. The function pointer must only be called with a dispatchable object (the first parameter) that is `device` or a child of `device`.

Table 2. `vkGetDeviceProcAddr` behavior

<table>
<thead>
<tr>
<th>device</th>
<th>pName</th>
<th>return value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NULL</td>
<td>*¹</td>
<td>undefined</td>
</tr>
<tr>
<td>invalid device</td>
<td>*¹</td>
<td>undefined</td>
</tr>
<tr>
<td>device</td>
<td>NULL</td>
<td>undefined</td>
</tr>
<tr>
<td>device</td>
<td>core device-level Vulkan command</td>
<td>fp²</td>
</tr>
<tr>
<td>device</td>
<td>enabled extension device-level commands</td>
<td>fp²</td>
</tr>
<tr>
<td>any other case, not covered above</td>
<td>NULL</td>
<td></td>
</tr>
</tbody>
</table>

1

*¹ means any representable value for the parameter (including valid values, invalid values, and NULL).

2

The returned function pointer must only be called with a dispatchable object (the first parameter) that is `device` or a child of `device` e.g. `VkDevice, VkQueue, or VkCommandBuffer`.

Valid Usage (Implicit)

- device must be a valid `VkDevice` handle
- pName must be a null-terminated UTF-8 string

The definition of `PFN_vkVoidFunction` is:

```c
typedef void (VKAPI_PTR *PFN_vkVoidFunction)(void);
```

3.1.1. Extending Physical Device Core Functionality

New core physical-device-level functionality can be used when the physical-device version is greater than or equal to the version of Vulkan that added the new functionality. The Vulkan version supported by a physical device can be obtained by calling `vkGetPhysicalDeviceProperties`.

3.1.2. Extending Physical Device From Device Extensions

When the `VK_KHR_get_physical_device_properties2` extension is enabled, or when both the instance
and the physical-device versions are at least 1.1, physical-device-level functionality of a device extension can be used with a physical device if the corresponding extension is enumerated by `vkEnumerateDeviceExtensionProperties` for that physical device, even before a logical device has been created.

To obtain a function pointer for a physical-device-level command from a device extension, an application can use `vkGetInstanceProcAddr`. This function pointer may point to dispatch code, which calls a different real implementation for different `VkPhysicalDevice` objects. Applications must not use a `VkPhysicalDevice` in any command added by an extension or core version that is not supported by that physical device.

Device extensions may define structures that can be added to the `pNext` chain of physical-device-level commands.

### 3.2. Instances

There is no global state in Vulkan and all per-application state is stored in a `VkInstance` object. Creating a `VkInstance` object initializes the Vulkan library and allows the application to pass information about itself to the implementation.

Instances are represented by `VkInstance` handles:

```
VK_DEFINE_HANDLE(VkInstance)
```

To query the version of instance-level functionality supported by the implementation, call:

```
VkResult vkEnumerateInstanceVersion(
    uint32_t* pApiVersion);
```

- `pApiVersion` is a pointer to a `uint32_t`, which is the version of Vulkan supported by instance-level functionality, encoded as described in Version Numbers.

**Valid Usage (Implicit)**

- `pApiVersion` must be a valid pointer to a `uint32_t` value

**Return Codes**

- **Success**
  - `VK_SUCCESS`

To create an instance object, call:
VkResult vkCreateInstance(
    const VkInstanceCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkInstance* pInstance);

- **pCreateInfo** is a pointer to a `VkInstanceCreateInfo` structure controlling creation of the instance.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pInstance** points a `VkInstance` handle in which the resulting instance is returned.

`vkCreateInstance` verifies that the requested layers exist. If not, `vkCreateInstance` will return `VK_ERROR_LAYER_NOT_PRESENT`. Next `vkCreateInstance` verifies that the requested extensions are supported (e.g. in the implementation or in any enabled instance layer) and if any requested extension is not supported, `vkCreateInstance` **must** return `VK_ERROR_EXTENSION_NOT_PRESENT`. After verifying and enabling the instance layers and extensions the `VkInstance` object is created and returned to the application. If a requested extension is only supported by a layer, both the layer and the extension need to be specified at `vkCreateInstance` time for the creation to succeed.

### Valid Usage

- All **required extensions** for each extension in the `VkInstanceCreateInfo`::`ppEnabledExtensionNames` list **must** also be present in that list.

### Valid Usage (Implicit)

- **pCreateInfo** **must** be a valid pointer to a valid `VkInstanceCreateInfo` structure
- If **pAllocator** is not NULL, **pAllocator** **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pInstance** **must** be a valid pointer to a `VkInstance` handle

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INITIALIZATION_FAILED`
- `VK_ERROR_LAYER_NOT_PRESENT`
- `VK_ERROR_EXTENSION_NOT_PRESENT`
- `VK_ERROR_INCOMPATIBLE_DRIVER`
The `VkInstanceCreateInfo` structure is defined as:

```c
typedef struct VkInstanceCreateInfo {
    VkStructureType             sType;
    const void*                 pNext;
    VkInstanceCreateFlags       flags;
    const VkApplicationInfo*    pApplicationInfo;
    uint32_t                    enabledLayerCount;
    const char* const*          ppEnabledLayerNames;
    uint32_t                    enabledExtensionCount;
    const char* const*          ppEnabledExtensionNames;
} VkInstanceCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `pApplicationInfo` is `NULL` or a pointer to a `VkApplicationInfo` structure. If not `NULL`, this information helps implementations recognize behavior inherent to classes of applications. `VkApplicationInfo` is defined in detail below.
- `enabledLayerCount` is the number of global layers to enable.
- `ppEnabledLayerNames` is a pointer to an array of `enabledLayerCount` null-terminated UTF-8 strings containing the names of layers to enable for the created instance. The layers are loaded in the order they are listed in this array, with the first array element being the closest to the application, and the last array element being the closest to the driver. See the Layers section for further details.
- `enabledExtensionCount` is the number of global extensions to enable.
- `ppEnabledExtensionNames` is a pointer to an array of `enabledExtensionCount` null-terminated UTF-8 strings containing the names of extensions to enable.

### Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be `0`
- If `pApplicationInfo` is not `NULL`, `pApplicationInfo` **must** be a valid pointer to a valid `VkApplicationInfo` structure
- If `enabledLayerCount` is not `0`, `ppEnabledLayerNames` **must** be a valid pointer to an array of `enabledLayerCount` null-terminated UTF-8 strings
- If `enabledExtensionCount` is not `0`, `ppEnabledExtensionNames` **must** be a valid pointer to an array of `enabledExtensionCount` null-terminated UTF-8 strings
typedef VkFlags VkInstanceCreateFlags;

VkInstanceCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

The VkApplicationInfo structure is defined as:

typedef struct VkApplicationInfo {
    VkStructureType    sType;
    const void*        pNext;
    const char*        pApplicationName;
    uint32_t           applicationVersion;
    const char*        pEngineName;
    uint32_t           engineVersion;
    uint32_t           apiVersion;
} VkApplicationInfo;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **pApplicationName** is NULL or is a pointer to a null-terminated UTF-8 string containing the name of the application.
- **applicationVersion** is an unsigned integer variable containing the developer-supplied version number of the application.
- **pEngineName** is NULL or is a pointer to a null-terminated UTF-8 string containing the name of the engine (if any) used to create the application.
- **engineVersion** is an unsigned integer variable containing the developer-supplied version number of the engine used to create the application.
- **apiVersion** must be the highest version of Vulkan that the application is designed to use, encoded as described in Version Numbers. The patch version number specified in apiVersion is ignored when creating an instance object. Only the major and minor versions of the instance must match those requested in apiVersion.

Vulkan 1.0 implementations were required to return VK_ERROR_INCOMPATIBLE_DRIVER if apiVersion was larger than 1.0. Implementations that support Vulkan 1.1 or later must not return VK_ERROR_INCOMPATIBLE_DRIVER for any value of apiVersion.

**Note**

Because Vulkan 1.0 implementations may fail with VK_ERROR_INCOMPATIBLE_DRIVER, applications should determine the version of Vulkan available before calling vkCreateInstance. If the vkGetInstanceProcAddr returns NULL for vkEnumerateInstanceVersion, it is a Vulkan 1.0 implementation. Otherwise, the application can call vkEnumerateInstanceVersion to determine the version of Vulkan.

As long as the instance supports at least Vulkan 1.1, an application can use different versions of
Vulkan with an instance than it does with a device or physical device.

Note
The Khronos validation layers will treat `apiVersion` as the highest API version the application targets, and will validate API usage against the minimum of that version and the implementation version (instance or device, depending on context). If an application tries to use functionality from a greater version than this, a validation error will be triggered.

For example, if the instance supports Vulkan 1.1 and three physical devices support Vulkan 1.0, Vulkan 1.1, and Vulkan 1.2, respectively, and if the application sets `apiVersion` to 1.2, the application can use the following versions of Vulkan:

- Vulkan 1.0 can be used with the instance and with all physical devices.
- Vulkan 1.1 can be used with the instance and with the physical devices that support Vulkan 1.1 and Vulkan 1.2.
- Vulkan 1.2 can be used with the physical device that supports Vulkan 1.2.

If we modify the above example so that the application sets `apiVersion` to 1.1, then the application must not use Vulkan 1.2 functionality on the physical device that supports Vulkan 1.2.

Implicit layers must be disabled if they do not support a version at least as high as `apiVersion`. See the Vulkan Loader Specification and Architecture Overview document for additional information.

Note
Providing a `NULL VkInstanceCreateInfo::pApplicationInfo` or providing an `apiVersion` of 0 is equivalent to providing an `apiVersion` of `VK_MAKE_VERSION(1,0,0)`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_APPLICATION_INFO`
- `pNext` must be `NULL`
- If `pApplicationName` is not `NULL`, `pApplicationName` must be a null-terminated UTF-8 string
- If `pEngineName` is not `NULL`, `pEngineName` must be a null-terminated UTF-8 string

To destroy an instance, call:

```c
void vkDestroyInstance(
    VkInstance                                  instance,  
    const VkAllocationCallbacks*               pAllocator);
```

- `instance` is the handle of the instance to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
Valid Usage

- All child objects created using `instance` must have been destroyed prior to destroying `instance`
- If `VkAllocationCallbacks` were provided when `instance` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `instance` was created, `pAllocator` must be `NULL`

Valid Usage (Implicit)

- If `instance` is not `NULL`, `instance` must be a valid `VkInstance` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

Host Synchronization

- Host access to `instance` must be externally synchronized
Chapter 4. Devices and Queues

Once Vulkan is initialized, devices and queues are the primary objects used to interact with a Vulkan implementation.

Vulkan separates the concept of *physical* and *logical* devices. A physical device usually represents a single complete implementation of Vulkan (excluding instance-level functionality) available to the host, of which there are a finite number. A logical device represents an instance of that implementation with its own state and resources independent of other logical devices.

Physical devices are represented by *VkPhysicalDevice* handles:

```c
VK_DEFINE_HANDLE(VkPhysicalDevice)
```

### 4.1. Physical Devices

To retrieve a list of physical device objects representing the physical devices installed in the system, call:

```c
VkResult vkEnumeratePhysicalDevices(
    VkInstance instance, /* handle to Vulkan instance previously created with vkCreateInstance. */
    uint32_t* pPhysicalDeviceCount, /* pointer to an integer related to the number of physical devices available or queried, as described below. */
    VkPhysicalDevice* pPhysicalDevices); /* either NULL or a pointer to an array of VkPhysicalDevice handles. */
```

- *instance* is a handle to a Vulkan instance previously created with *vkCreateInstance*.
- *pPhysicalDeviceCount* is a pointer to an integer related to the number of physical devices available or queried, as described below.
- *pPhysicalDevices* is either NULL or a pointer to an array of *VkPhysicalDevice* handles.

If *pPhysicalDevices* is NULL, then the number of physical devices available is returned in *pPhysicalDeviceCount*. Otherwise, *pPhysicalDeviceCount* must point to a variable set by the user to the number of elements in the *pPhysicalDevices* array, and on return the variable is overwritten with the number of handles actually written to *pPhysicalDevices*. If *pPhysicalDeviceCount* is less than the number of physical devices available, *VK_INCOMPLETE* will be returned instead of *VK_SUCCESS*, to indicate that not all the available physical devices were returned.
Valid Usage (Implicit)

• instance must be a valid VkInstance handle
• pPhysicalDeviceCount must be a valid pointer to a uint32_t value
• If the value referenced by pPhysicalDeviceCount is not 0, and pPhysicalDevices is not NULL, pPhysicalDevices must be a valid pointer to an array of pPhysicalDeviceCount VkPhysicalDevice handles

Return Codes

Success
  • VK_SUCCESS
  • VK_INCOMPLETE

Failure
  • VK_ERROR_OUT_OF_HOST_MEMORY
  • VK_ERROR_OUT_OF_DEVICE_MEMORY
  • VK_ERROR_INITIALIZATION_FAILED

To query general properties of physical devices once enumerated, call:

```c
void vkGetPhysicalDeviceProperties(
    VkPhysicalDevice                            physicalDevice,
    VkPhysicalDeviceProperties*                 pProperties);
```

• physicalDevice is the handle to the physical device whose properties will be queried.
• pProperties is a pointer to a VkPhysicalDeviceProperties structure in which properties are returned.

Valid Usage (Implicit)

• physicalDevice must be a valid VkPhysicalDevice handle
• pProperties must be a valid pointer to a VkPhysicalDeviceProperties structure

The VkPhysicalDeviceProperties structure is defined as:
typedef struct VkPhysicalDeviceProperties {
    uint32_t apiVersion;
    uint32_t driverVersion;
    uint32_t vendorID;
    uint32_t deviceID;
    VkPhysicalDeviceType deviceType;
    char deviceName[VK_MAX_PHYSICAL_DEVICE_NAME_SIZE];
    uint8_t pipelineCacheUUID[VK_UUID_SIZE];
    VkPhysicalDeviceLimits limits;
    VkPhysicalDeviceSparseProperties sparseProperties;
} VkPhysicalDeviceProperties;

- **apiVersion** is the version of Vulkan supported by the device, encoded as described in Version Numbers.

- **driverVersion** is the vendor-specified version of the driver.

- **vendorID** is a unique identifier for the vendor (see below) of the physical device.

- **deviceID** is a unique identifier for the physical device among devices available from the vendor.

- **deviceType** is a VkPhysicalDeviceType specifying the type of device.

- **deviceName** is an array of VK_MAX_PHYSICAL_DEVICE_NAME_SIZE char containing a null-terminated UTF-8 string which is the name of the device.

- **pipelineCacheUUID** is an array of VK_UUID_SIZE uint8_t values representing a universally unique identifier for the device.

- **limits** is the VkPhysicalDeviceLimits structure specifying device-specific limits of the physical device. See Limits for details.

- **sparseProperties** is the VkPhysicalDeviceSparseProperties structure specifying various sparse related properties of the physical device. See Sparse Properties for details.

---

**Note**

The value of `apiVersion` may be different than the version returned by `vkEnumerateInstanceVersion`; either higher or lower. In such cases, the application must not use functionality that exceeds the version of Vulkan associated with a given object. The `pApiVersion` parameter returned by `vkEnumerateInstanceVersion` is the version associated with a `VkInstance` and its children, except for a `VkPhysicalDevice` and its children. `VkPhysicalDeviceProperties::apiVersion` is the version associated with a `VkPhysicalDevice` and its children.

---

The **vendorID** and **deviceID** fields are provided to allow applications to adapt to device characteristics that are not adequately exposed by other Vulkan queries.

---

**Note**

These may include performance profiles, hardware errata, or other characteristics.
The vendor identified by vendorID is the entity responsible for the most salient characteristics of the underlying implementation of the VkPhysicalDevice being queried.

Note
For example, in the case of a discrete GPU implementation, this should be the GPU chipset vendor. In the case of a hardware accelerator integrated into a system-on-chip (SoC), this should be the supplier of the silicon IP used to create the accelerator.

If the vendor has a PCI vendor ID, the low 16 bits of vendorID must contain that PCI vendor ID, and the remaining bits must be set to zero. Otherwise, the value returned must be a valid Khronos vendor ID, obtained as described in the Vulkan Documentation and Extensions: Procedures and Conventions document in the section “Registering a Vendor ID with Khronos”. Khronos vendor IDs are allocated starting at 0x10000, to distinguish them from the PCI vendor ID namespace. Khronos vendor IDs are symbolically defined in the VkVendorId type.

The vendor is also responsible for the value returned in deviceID. If the implementation is driven primarily by a PCI device with a PCI device ID, the low 16 bits of deviceID must contain that PCI device ID, and the remaining bits must be set to zero. Otherwise, the choice of what values to return may be dictated by operating system or platform policies - but should uniquely identify both the device version and any major configuration options (for example, core count in the case of multicore devices).

Note
The same device ID should be used for all physical implementations of that device version and configuration. For example, all uses of a specific silicon IP GPU version and configuration should use the same device ID, even if those uses occur in different SoCs.

Khronos vendor IDs which may be returned in VkPhysicalDeviceProperties::vendorID are:

typedef enum VkVendorId {
    VK_VENDOR_ID_VIV = 0x10001,
    VK_VENDOR_ID_VSI = 0x10002,
    VK_VENDOR_ID_KAZAN = 0x10003,
    VK_VENDOR_ID_CODEPLAY = 0x10004,
    VK_VENDOR_ID_MAX_ENUM = 0x7FFFFFFF
} VkVendorId;
Note

Khronos vendor IDs may be allocated by vendors at any time. Only the latest canonical versions of this Specification, of the corresponding `vk.xml` API Registry, and of the corresponding `vulkan_core.h` header file must contain all reserved Khronos vendor IDs.

Only Khronos vendor IDs are given symbolic names at present. PCI vendor IDs returned by the implementation can be looked up in the PCI-SIG database.

The physical device types which may be returned in `VkPhysicalDeviceProperties::deviceType` are:

```c
typedef enum VkPhysicalDeviceType {
    VK_PHYSICAL_DEVICE_TYPE_OTHER = 0,
    VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU = 1,
    VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU = 2,
    VK_PHYSICAL_DEVICE_TYPE_VIRTUAL_GPU = 3,
    VK_PHYSICAL_DEVICE_TYPE_CPU = 4,
    VK_PHYSICAL_DEVICE_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkPhysicalDeviceType;
```

- **VK_PHYSICAL_DEVICE_TYPE_OTHER** - the device does not match any other available types.
- **VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU** - the device is typically one embedded in or tightly coupled with the host.
- **VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU** - the device is typically a separate processor connected to the host via an interlink.
- **VK_PHYSICAL_DEVICE_TYPE_VIRTUAL_GPU** - the device is typically a virtual node in a virtualization environment.
- **VK_PHYSICAL_DEVICE_TYPE_CPU** - the device is typically running on the same processors as the host.

The physical device type is advertised for informational purposes only, and does not directly affect the operation of the system. However, the device type may correlate with other advertised properties or capabilities of the system, such as how many memory heaps there are.

To query general properties of physical devices once enumerated, call:

```c
void vkGetPhysicalDeviceProperties2(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceProperties2* pProperties);
```

or the equivalent command

```c
void vkGetPhysicalDeviceProperties2KHR(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceProperties2* pProperties);
```
• `physicalDevice` is the handle to the physical device whose properties will be queried.
• `pProperties` is a pointer to a `VkPhysicalDeviceProperties2` structure in which properties are returned.

Each structure in `pProperties` and its `pNext` chain contain members corresponding to properties or implementation-dependent limits. `vkGetPhysicalDeviceProperties2` writes each member to a value indicating the value of that property or limit.

**Valid Usage (Implicit)**

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pProperties` must be a valid pointer to a `VkPhysicalDeviceProperties2` structure

The `VkPhysicalDeviceProperties2` structure is defined as:

```c
typedef struct VkPhysicalDeviceProperties2 {
    VkStructureType sType;
    void* pNext;
    VkPhysicalDeviceProperties properties;
} VkPhysicalDeviceProperties2;
```

or the equivalent

```c
typedef VkPhysicalDeviceProperties2 VkPhysicalDeviceProperties2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `properties` is a `VkPhysicalDeviceProperties` structure describing properties of the physical device. This structure is written with the same values as if it were written by `vkGetPhysicalDeviceProperties`.

The `pNext` chain of this structure is used to extend the structure with properties defined by extensions.
Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROPERTIES_2**

- Each **pNext** member of any structure (including this one) in the **pNext** chain must be either NULL or a pointer to a valid instance of `VkPhysicalDeviceDepthStencilResolveProperties`, `VkPhysicalDeviceDriverProperties`, `VkPhysicalDeviceFloatControlsProperties`, `VkPhysicalDeviceIDProperties`, `VkPhysicalDeviceMaintenance3Properties`, `VkPhysicalDeviceMultiviewProperties`, `VkPhysicalDevicePerformanceQueryPropertiesKHR`, `VkPhysicalDevicePointClippingProperties`, `VkPhysicalDeviceProtectedMemoryProperties`, `VkPhysicalDevicePushDescriptorPropertiesKHR`, `VkPhysicalDeviceRayTracingPropertiesKHR`, `VkPhysicalDeviceSubgroupProperties`, or `VkPhysicalDeviceTimelineSemaphoreProperties`

- The **sType** value of each struct in the **pNext** chain must be unique

To query the UUID and LUID of a device, add a `VkPhysicalDeviceIDProperties` structure to the **pNext** chain of the `VkPhysicalDeviceProperties2` structure. The `VkPhysicalDeviceIDProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceIDProperties {
    VkStructureType    sType;
    void*              pNext;
    uint8_t            deviceUUID[VK_UUID_SIZE];
    uint8_t            driverUUID[VK_UUID_SIZE];
    uint8_t            deviceLUID[VK_LUID_SIZE];
    uint32_t           deviceNodeMask;
    VkBool32           deviceLUIDValid;
} VkPhysicalDeviceIDProperties;
```

or the equivalent

```c
typedef VkPhysicalDeviceIDProperties VkPhysicalDeviceIDPropertiesKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **deviceUUID** is an array of **VK_UUID_SIZE uint8_t** values representing a universally unique identifier for the device.
- **driverUUID** is an array of **VK_UUID_SIZE uint8_t** values representing a universally unique identifier for the driver build in use by the device.
- **deviceLUID** is an array of **VK_LUID_SIZE uint8_t** values representing a locally unique identifier for the device.
- **deviceNodeMask** is a **uint32_t** bitfield identifying the node within a linked device adapter.
deviceUUID must be immutable for a given device across instances, processes, driver APIs, driver versions, and system reboots.

Applications can compare the driverUUID value across instance and process boundaries, and can make similar queries in external APIs to determine whether they are capable of sharing memory objects and resources using them with the device.

deviceUUID and/or driverUUID must be used to determine whether a particular external object can be shared between driver components, where such a restriction exists as defined in the compatibility table for the particular object type:

- External memory handle types compatibility
- External semaphore handle types compatibility
- External fence handle types compatibility

If deviceLUIDValid is VK_FALSE, the values of deviceLUID and deviceNodeMask are undefined. If deviceLUIDValid is VK_TRUE and Vulkan is running on the Windows operating system, the contents of deviceLUID can be cast to an LUID object and must be equal to the locally unique identifier of a IDXGIAdapter1 object that corresponds to physicalDevice. If deviceLUIDValid is VK_TRUE, deviceNodeMask must contain exactly one bit. If Vulkan is running on an operating system that supports the Direct3D 12 API and physicalDevice corresponds to an individual device in a linked device adapter, deviceNodeMask identifies the Direct3D 12 node corresponding to physicalDevice. Otherwise, deviceNodeMask must be 1.

Note

Although they have identical descriptions, VkPhysicalDeviceIDProperties::deviceUUID may differ from VkPhysicalDeviceProperties2::pipelineCacheUUID. The former is intended to identify and correlate devices across API and driver boundaries, while the latter is used to identify a compatible device and driver combination to use when serializing and de-serializing pipeline state.

Note

While VkPhysicalDeviceIDProperties::deviceUUID is specified to remain consistent across driver versions and system reboots, it is not intended to be usable as a serializable persistent identifier for a device. It may change when a device is physically added to, removed from, or moved to a different connector in a system while that system is powered down. Further, there is no reasonable way to verify with conformance testing that a given device retains the same UUID in a given system across all driver versions supported in that system. While implementations should make every effort to report consistent device UUIDs across driver versions, applications should avoid relying on the persistence of this value for uses other than identifying compatible devices for external object sharing purposes.
To query the properties of the driver corresponding to a physical device, add a `VkPhysicalDeviceDriverProperties` structure to the `pNext` chain of the `VkPhysicalDeviceProperties2` structure. The `VkPhysicalDeviceDriverProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceDriverProperties {
    VkStructureType sType;
    void* pNext;
    VkDriverId driverID;
    char driverName[VK_MAX_DRIVER_NAME_SIZE];
    char driverInfo[VK_MAX_DRIVER_INFO_SIZE];
    VkConformanceVersion conformanceVersion;
} VkPhysicalDeviceDriverProperties;
```

or the equivalent

```c
typedef VkPhysicalDeviceDriverProperties VkPhysicalDeviceDriverPropertiesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension specific structure.
- `driverID` is a unique identifier for the driver of the physical device.
- `driverName` is an array of `VK_MAX_DRIVER_NAME_SIZE_KHR` containing a null-terminated UTF-8 string which is the name of the driver.
- `driverInfo` is an array of `VK_MAX_DRIVER_INFO_SIZE_KHR` containing a null-terminated UTF-8 string with additional information about the driver.
- `conformanceVersion` is the version of the Vulkan conformance test this driver is conformant against (see `VkConformanceVersion`).

`driverID` must be immutable for a given driver across instances, processes, driver versions, and system reboots.

Khronos driver IDs which may be returned in `VkPhysicalDeviceDriverProperties::driverID` are:
typedef enum VkDriverId {
    VK_DRIVER_ID_AMD_PROPRIETARY = 1,
    VK_DRIVER_ID_AMD_OPEN_SOURCE = 2,
    VK_DRIVER_ID_MESA_RADV = 3,
    VK_DRIVER_ID_NVIDIA_PROPRIETARY = 4,
    VK_DRIVER_ID_INTEL_PROPRIETARY_WINDOWS = 5,
    VK_DRIVER_ID_INTEL_OPEN_SOURCE_MESA = 6,
    VK_DRIVER_ID_IMAGINATION_PROPRIETARY = 7,
    VK_DRIVER_ID_QUALCOMM_PROPRIETARY = 8,
    VK_DRIVER_ID_ARM_PROPRIETARY = 9,
    VK_DRIVER_ID_GOOGLE_SWIFTSHADER = 10,
    VK_DRIVER_ID_GGP_PROPRIETARY = 11,
    VK_DRIVER_ID_BROADCOM_PROPRIETARY = 12,
    VK_DRIVER_ID_AMD_PROPRIETARY_KHR = VK_DRIVER_ID_AMD_PROPRIETARY,
    VK_DRIVER_ID_AMD_OPEN_SOURCE_KHR = VK_DRIVER_ID_AMD_OPEN_SOURCE,
    VK_DRIVER_ID_MESA_RADV_KHR = VK_DRIVER_ID_MESA_RADV,
    VK_DRIVER_ID_NVIDIA_PROPRIETARY_KHR = VK_DRIVER_ID_NVIDIA_PROPRIETARY,
    VK_DRIVER_ID_INTEL_PROPRIETARY_WINDOWS_KHR = VK_DRIVER_ID_INTEL_PROPRIETARY_WINDOWS,
    VK_DRIVER_ID_INTEL_OPEN_SOURCE_MESA_KHR = VK_DRIVER_ID_INTEL_OPEN_SOURCE_MESA,
    VK_DRIVER_ID_IMAGINATION_PROPRIETARY_KHR = VK_DRIVER_ID_IMAGINATION_PROPRIETARY,
    VK_DRIVER_ID_QUALCOMM_PROPRIETARY_KHR = VK_DRIVER_ID_QUALCOMM_PROPRIETARY,
    VK_DRIVER_ID_ARM_PROPRIETARY_KHR = VK_DRIVER_ID_ARM_PROPRIETARY,
    VK_DRIVER_ID_GOOGLE_SWIFTSHADER_KHR = VK_DRIVER_ID_GOOGLE_SWIFTSHADER,
    VK_DRIVER_ID_GGP_PROPRIETARY_KHR = VK_DRIVER_ID_GGP_PROPRIETARY,
    VK_DRIVER_ID_BROADCOM_PROPRIETARY_KHR = VK_DRIVER_ID_BROADCOM_PROPRIETARY,
    VK_DRIVER_ID_MAX_ENUM = 0x7FFFFFFF
} VkDriverId;

or the equivalent

typedef VkDriverId VkDriverIdKHR;

Note
Khronos driver IDs may be allocated by vendors at any time. There may be multiple driver IDs for the same vendor, representing different drivers (for e.g. different platforms, proprietary or open source, etc.). Only the latest canonical versions of this Specification, of the corresponding vk.xml API Registry, and of the corresponding vulkan_core.h header file must contain all reserved Khronos driver IDs.

Only driver IDs registered with Khronos are given symbolic names. There may be unregistered driver IDs returned.

The conformance test suite version an implementation is compliant with is described with the VkConformanceVersion structure:
typedef struct VkConformanceVersion {
    uint8_t    major;
    uint8_t    minor;
    uint8_t    subminor;
    uint8_t    patch;
} VkConformanceVersion;

or the equivalent

typedef VkConformanceVersion VkConformanceVersionKHR;

- **major** is the major version number of the conformance test suite.
- **minor** is the minor version number of the conformance test suite.
- **subminor** is the subminor version number of the conformance test suite.
- **patch** is the patch version number of the conformance test suite.

To query properties of queues available on a physical device, call:

```
void vkGetPhysicalDeviceQueueFamilyProperties(
    VkPhysicalDevice                            physicalDevice,
    uint32_t*                                   pQueueFamilyPropertyCount,
    VkQueueFamilyProperties*                    pQueueFamilyProperties);
```

- **physicalDevice** is the handle to the physical device whose properties will be queried.
- **pQueueFamilyPropertyCount** is a pointer to an integer related to the number of queue families available or queried, as described below.
- **pQueueFamilyProperties** is either **NULL** or a pointer to an array of **VkQueueFamilyProperties** structures.

If **pQueueFamilyProperties** is **NULL**, then the number of queue families available is returned in **pQueueFamilyPropertyCount**. Implementations **must** support at least one queue family. Otherwise, **pQueueFamilyPropertyCount** **must** point to a variable set by the user to the number of elements in the **pQueueFamilyProperties** array, and on return the variable is overwritten with the number of structures actually written to **pQueueFamilyProperties**. If **pQueueFamilyPropertyCount** is less than the number of queue families available, at most **pQueueFamilyPropertyCount** structures will be written.
**Valid Usage (Implicit)**

- physicalDevice must be a valid VkPhysicalDevice handle
- pQueueFamilyPropertyCount must be a valid pointer to a uint32_t value
- If the value referenced by pQueueFamilyPropertyCount is not 0, and pQueueFamilyProperties is not NULL, pQueueFamilyProperties must be a valid pointer to an array of pQueueFamilyPropertyCount VkQueueFamilyProperties structures

The VkQueueFamilyProperties structure is defined as:

```c
typedef struct VkQueueFamilyProperties {
    VkQueueFlags    queueFlags;
    uint32_t        queueCount;
    uint32_t        timestampValidBits;
    VkExtent3D      minImageTransferGranularity;
} VkQueueFamilyProperties;
```

- queueFlags is a bitmask of VkQueueFlagBits indicating capabilities of the queues in this queue family.
- queueCount is the unsigned integer count of queues in this queue family. Each queue family must support at least one queue.
- timestampValidBits is the unsigned integer count of meaningful bits in the timestamps written via vkCmdWriteTimestamp. The valid range for the count is 36..64 bits, or a value of 0, indicating no support for timestamps. Bits outside the valid range are guaranteed to be zeros.
- minImageTransferGranularity is the minimum granularity supported for image transfer operations on the queues in this queue family.

The value returned in minImageTransferGranularity has a unit of compressed texel blocks for images having a block-compressed format, and a unit of texels otherwise.

Possible values of minImageTransferGranularity are:

- (0,0,0) which indicates that only whole mip levels must be transferred using the image transfer operations on the corresponding queues. In this case, the following restrictions apply to all offset and extent parameters of image transfer operations:
  - The x, y, and z members of a VkOffset3D parameter must always be zero.
  - The width, height, and depth members of a VkExtent3D parameter must always match the width, height, and depth of the image subresource corresponding to the parameter, respectively.
- \((A_x, A_y, A_z)\) where \(A_x\), \(A_y\), and \(A_z\) are all integer powers of two. In this case the following restrictions apply to all image transfer operations:
  - x, y, and z of a VkOffset3D parameter must be integer multiples of \(A_x\), \(A_y\), and \(A_z\), respectively.
width of a VkExtent3D parameter must be an integer multiple of \( A_x \), or else \( x + \text{width} \) must equal the width of the image subresource corresponding to the parameter.

height of a VkExtent3D parameter must be an integer multiple of \( A_y \), or else \( y + \text{height} \) must equal the height of the image subresource corresponding to the parameter.

depth of a VkExtent3D parameter must be an integer multiple of \( A_z \), or else \( z + \text{depth} \) must equal the depth of the image subresource corresponding to the parameter.

If the format of the image corresponding to the parameters is one of the block-compressed formats then for the purposes of the above calculations the granularity must be scaled up by the compressed texel block dimensions.

Queues supporting graphics and/or compute operations must report (1,1,1) in minImageTransferGranularity, meaning that there are no additional restrictions on the granularity of image transfer operations for these queues. Other queues supporting image transfer operations are only required to support whole mip level transfers, thus minImageTransferGranularity for queues belonging to such queue families may be (0,0,0).

The Device Memory section describes memory properties queried from the physical device.

For physical device feature queries see the Features chapter.

Bits which may be set in VkQueueFamilyProperties::queueFlags indicating capabilities of queues in a queue family are:

```c
typedef enum VkQueueFlagBits {
    VK_QUEUE_GRAPHICS_BIT = 0x00000001,
    VK_QUEUE_COMPUTE_BIT = 0x00000002,
    VK_QUEUE_TRANSFER_BIT = 0x00000004,
    VK_QUEUE_SPARSE_BINDING_BIT = 0x00000008,
    VK_QUEUE_PROTECTED_BIT = 0x00000010,
    VK_QUEUE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkQueueFlagBits;
```

- **VK_QUEUE_GRAPHICS_BIT** specifies that queues in this queue family support graphics operations.
- **VK_QUEUE_COMPUTE_BIT** specifies that queues in this queue family support compute operations.
- **VK_QUEUE_TRANSFER_BIT** specifies that queues in this queue family support transfer operations.
- **VK_QUEUE_SPARSE_BINDING_BIT** specifies that queues in this queue family support sparse memory management operations (see Sparse Resources). If any of the sparse resource features are enabled, then at least one queue family must support this bit.
- if **VK_QUEUE_PROTECTED_BIT** is set, then the queues in this queue family support the VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT bit. (see Protected Memory). If the protected memory physical device feature is supported, then at least one queue family of at least one physical device exposed by the implementation must support this bit.

If an implementation exposes any queue family that supports graphics operations, at least one queue family of at least one physical device exposed by the implementation must support both graphics and compute operations.
Furthermore, if the protected memory physical device feature is supported, then at least one queue family of at least one physical device exposed by the implementation must support graphics operations, compute operations, and protected memory operations.

**Note**

All commands that are allowed on a queue that supports transfer operations are also allowed on a queue that supports either graphics or compute operations. Thus, if the capabilities of a queue family include `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`, then reporting the `VK_QUEUE_TRANSFER_BIT` capability separately for that queue family is optional.

For further details see Queues.

```c
typedef VkFlags VkQueueFlags;
```

`VkQueueFlags` is a bitmask type for setting a mask of zero or more `VkQueueFlagBits`.

To query properties of queues available on a physical device, call:

```c
void vkGetPhysicalDeviceQueueFamilyProperties2(
    VkPhysicalDevice physicalDevice,
    uint32_t* pQueueFamilyPropertyCount,
    VkQueueFamilyProperties2* pQueueFamilyProperties);
```

or the equivalent command

```c
void vkGetPhysicalDeviceQueueFamilyProperties2KHR(
    VkPhysicalDevice physicalDevice,
    uint32_t* pQueueFamilyPropertyCount,
    VkQueueFamilyProperties2* pQueueFamilyProperties);
```

- `physicalDevice` is the handle to the physical device whose properties will be queried.
- `pQueueFamilyPropertyCount` is a pointer to an integer related to the number of queue families available or queried, as described in `vkGetPhysicalDeviceQueueFamilyProperties`.
- `pQueueFamilyProperties` is either `NULL` or a pointer to an array of `VkQueueFamilyProperties2` structures.

`vkGetPhysicalDeviceQueueFamilyProperties2` behaves similarly to `vkGetPhysicalDeviceQueueFamilyProperties`, with the ability to return extended information in a `pNext` chain of output structures.
The `VkQueueFamilyProperties2` structure is defined as:

```c
typedef struct VkQueueFamilyProperties2 {
    VkStructureType sType;
    void* pNext;
    VkQueueFamilyProperties queueFamilyProperties;
} VkQueueFamilyProperties2;
```

or the equivalent

```c
typedef VkQueueFamilyProperties2 VkQueueFamilyProperties2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `queueFamilyProperties` is a `VkQueueFamilyProperties` structure which is populated with the same values as in `vkGetPhysicalDeviceQueueFamilyProperties`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2`
- `pNext` must be `NULL`

To enumerate the performance query counters available on a queue family of a physical device, call:

```c
VkResult vkEnumeratePhysicalDeviceQueueFamilyPerformanceQueryCountersKHR(
    VkPhysicalDevice physicalDevice,           // physicalDevice is the handle to the physical device whose queue family performance query counter properties will be queried.
    uint32_t queueFamilyIndex,                 // queue family index
    uint32_t* pCounterCount,                   // pointer to the count of performance query counters
    VkPerformanceCounterKHR* pCounters,        // pointer to the performance query counters
    VkPerformanceCounterDescriptionKHR* pCounterDescriptions
);
```
• `queueFamilyIndex` is the index into the queue family of the physical device we want to get properties for.

• `pCounterCount` is a pointer to an integer related to the number of counters available or queried, as described below.

• `pCounters` is either NULL or a pointer to an array of `VkPerformanceCounterKHR` structures.

• `pCounterDescriptions` is either NULL or a pointer to an array of `VkPerformanceCounterDescriptionKHR` structures.

If `pCounters` is NULL and `pCounterDescriptions` is NULL, then the number of counters available is returned in `pCounterCount`. Otherwise, `pCounterCount` must point to a variable set by the user to the number of elements in the `pCounters`, `pCounterDescriptions`, or both arrays and on return the variable is overwritten with the number of structures actually written out. If `pCounterCount` is less than the number of counters available, at most `pCounterCount` structures will be written and `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS`.

### Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pCounterCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pCounterCount` is not 0, and `pCounters` is not NULL, `pCounters` must be a valid pointer to an array of `pCounterCount` `VkPerformanceCounterKHR` structures
- If the value referenced by `pCounterCount` is not 0, and `pCounterDescriptions` is not NULL, `pCounterDescriptions` must be a valid pointer to an array of `pCounterCount` `VkPerformanceCounterDescriptionKHR` structures

### Return Codes

**Success**
- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INITIALIZATION_FAILED`

The `VkPerformanceCounterKHR` structure is defined as:
typedef struct VkPerformanceCounterKHR {
    VkStructureType                     sType;
    const void*                         pNext;
    VkPerformanceCounterUnitKHR         unit;
    VkPerformanceCounterScopeKHR        scope;
    VkPerformanceCounterStorageKHR      storage;
    uint8_t                             uuid[VK_UUID_SIZE];
} VkPerformanceCounterKHR;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• unit is a VkPerformanceCounterUnitKHR specifying the unit that the counter data will record.
• scope is a VkPerformanceCounterScopeKHR specifying the scope that the counter belongs to.
• storage is a VkPerformanceCounterStorageKHR specifying the storage type that the counter’s data uses.
• uuid is an array of size VK_UUID_SIZE, containing 8-bit values that represent a universally unique identifier for the counter of the physical device.

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_PERFORMANCE_COUNTER_KHR
• pNext must be NULL

Performance counters have an associated unit. This unit describes how to interpret the performance counter result.

The performance counter unit types which may be returned in VkPerformanceCounterKHR:unit are:

typedef enum VkPerformanceCounterUnitKHR {
    VK_PERFORMANCE_COUNTER_UNIT_GENERIC_KHR  = 0,
    VK_PERFORMANCE_COUNTER_UNIT_PERCENTAGE_KHR = 1,
    VK_PERFORMANCE_COUNTER_UNIT_NANOSECONDS_KHR = 2,
    VK_PERFORMANCE_COUNTER_UNIT_BYTES_KHR = 3,
    VK_PERFORMANCE_COUNTER_UNIT_BYTES_PER_SECOND_KHR = 4,
    VK_PERFORMANCE_COUNTER_UNIT_KELVIN_KHR = 5,
    VK_PERFORMANCE_COUNTER_UNIT_WATTS_KHR = 6,
    VK_PERFORMANCE_COUNTER_UNIT_VOLTS_KHR = 7,
    VK_PERFORMANCE_COUNTER_UNIT_AMPS_KHR = 8,
    VK_PERFORMANCE_COUNTER_UNIT_HERTZ_KHR = 9,
    VK_PERFORMANCE_COUNTER_UNIT_CYCLES_KHR = 10,
    VK_PERFORMANCE_COUNTER_UNIT_MAX_ENUM_KHR = 0x7FFFFFFF
} VkPerformanceCounterUnitKHR;
- VK_PERFORMANCE_COUNTER_UNIT_GENERIC_KHR - the performance counter unit is a generic data point.
- VK_PERFORMANCE_COUNTER_UNIT_PERCENTAGE_KHR - the performance counter unit is a percentage (%).
- VK_PERFORMANCE_COUNTER_UNIT_NANOSECONDS_KHR - the performance counter unit is a value of nanoseconds (ns).
- VK_PERFORMANCE_COUNTER_UNIT_BYTES_KHR - the performance counter unit is a value of bytes.
- VK_PERFORMANCE_COUNTER_UNIT_BYTES_PER_SECOND_KHR - the performance counter unit is a value of bytes/s.
- VK_PERFORMANCE_COUNTER_UNIT_KELVIN_KHR - the performance counter unit is a temperature reported in Kelvin.
- VK_PERFORMANCE_COUNTER_UNIT_WATTS_KHR - the performance counter unit is a value of watts (W).
- VK_PERFORMANCE_COUNTER_UNIT_VOLTS_KHR - the performance counter unit is a value of volts (V).
- VK_PERFORMANCE_COUNTER_UNIT_AMPS_KHR - the performance counter unit is a value of amps (A).
- VK_PERFORMANCE_COUNTER_UNIT_HERTZ_KHR - the performance counter unit is a value of hertz (Hz).
- VK_PERFORMANCE_COUNTER_UNIT_CYCLES_KHR - the performance counter unit is a value of cycles.

Performance counters have an associated scope. This scope describes the granularity of a performance counter.

The performance counter scope types which **may** be returned in `VkPerformanceCounterKHR::scope` are:

```c
typedef enum VkPerformanceCounterScopeKHR {
    VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_BUFFER_KHR = 0,
    VK_PERFORMANCE_COUNTER_SCOPE_RENDER_PASS_KHR = 1,
    VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_KHR = 2,
    __VK_QUERY_SCOPE_COMMAND_BUFFER_KHR = VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_BUFFER_KHR,
    __VK_QUERY_SCOPE_RENDER_PASS_KHR = VK_PERFORMANCE_COUNTER_SCOPE_RENDER_PASS_KHR,
    __VK_QUERY_SCOPE_COMMAND_KHR = VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_KHR,
    VK_PERFORMANCE_COUNTER_SCOPE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkPerformanceCounterScopeKHR;
```

- VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_BUFFER_KHR - the performance counter scope is a single complete command buffer.
- VK_PERFORMANCE_COUNTER_SCOPE_RENDER_PASS_KHR - the performance counter scope is zero or more complete render passes. The performance query containing the performance counter **must** begin and end outside a render pass instance.
- VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_KHR - the performance counter scope is zero or more commands.

Performance counters have an associated storage. This storage describes the payload of a counter result.

The performance counter storage types which **may** be returned in `VkPerformanceCounterKHR::storage` are:
typedef enum VkPerformanceCounterStorageKHR {
    VK_PERFORMANCE_COUNTER_STORAGE_INT32_KHR = 0,
    VK_PERFORMANCE_COUNTER_STORAGE_INT64_KHR = 1,
    VK_PERFORMANCE_COUNTER_STORAGE_UINT32_KHR = 2,
    VK_PERFORMANCE_COUNTER_STORAGE_UINT64_KHR = 3,
    VK_PERFORMANCE_COUNTER_STORAGE_FLOAT32_KHR = 4,
    VK_PERFORMANCE_COUNTER_STORAGE_FLOAT64_KHR = 5,
    VK_PERFORMANCE_COUNTER_STORAGE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkPerformanceCounterStorageKHR;

• VK_PERFORMANCE_COUNTER_STORAGE_INT32_KHR - the performance counter storage is a 32-bit signed integer.
• VK_PERFORMANCE_COUNTER_STORAGE_INT64_KHR - the performance counter storage is a 64-bit signed integer.
• VK_PERFORMANCE_COUNTER_STORAGE_UINT32_KHR - the performance counter storage is a 32-bit unsigned integer.
• VK_PERFORMANCE_COUNTER_STORAGE_UINT64_KHR - the performance counter storage is a 64-bit unsigned integer.
• VK_PERFORMANCE_COUNTER_STORAGE_FLOAT32_KHR - the performance counter storage is a 32-bit floating-point.
• VK_PERFORMANCE_COUNTER_STORAGE_FLOAT64_KHR - the performance counter storage is a 64-bit floating-point.

The VkPerformanceCounterDescriptionKHR structure is defined as:

typedef struct VkPerformanceCounterDescriptionKHR {
    VkStructureType sType;
    const void* pNext;
    VkPerformanceCounterDescriptionFlagsKHR flags;
    char name[VK_MAX_DESCRIPTION_SIZE];
    category[VK_MAX_DESCRIPTION_SIZE];
    description[VK_MAX_DESCRIPTION_SIZE];
} VkPerformanceCounterDescriptionKHR;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• flags is a bitmask of VkPerformanceCounterDescriptionFlagBitsKHR indicating the usage behavior for the counter.
• name is an array of size VK_MAX_DESCRIPTION_SIZE, containing a null-terminated UTF-8 string specifying the name of the counter.
• category is an array of size VK_MAX_DESCRIPTION_SIZE, containing a null-terminated UTF-8 string specifying the category of the counter.
- `description` is an array of size `VK_MAX_DESCRIPTION_SIZE`, containing a null-terminated UTF-8 string specifying the description of the counter.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PERFORMANCE_COUNTER_DESCRIPTION_KHR`
- `pNext` must be `NULL`

Bits which can be set in `VkPerformanceCounterDescriptionKHR::flags` to specify usage behavior for a command pool are:

```c
typedef enum VkPerformanceCounterDescriptionFlagBitsKHR {
    VK_PERFORMANCE_COUNTER_DESCRIPTION_PERFORMANCE_IMPACTING_KHR = 0x00000001,
    VK_PERFORMANCE_COUNTER_DESCRIPTION_CONCURRENTLY_IMPACTED_KHR = 0x00000002,
    VK_PERFORMANCE_COUNTER_DESCRIPTION_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkPerformanceCounterDescriptionFlagBitsKHR;
```

- `VK_PERFORMANCE_COUNTER_DESCRIPTION_PERFORMANCE_IMPACTING_KHR` specifies that recording the counter may have a noticeable performance impact.
- `VK_PERFORMANCE_COUNTER_DESCRIPTION_CONCURRENTLY_IMPACTED_KHR` specifies that concurrently recording the counter while other submitted command buffers are running may impact the accuracy of the recording.

```c
typedef VkFlags VkPerformanceCounterDescriptionFlagsKHR;
```

`VkPerformanceCounterDescriptionFlagsKHR` is a bitmask type for setting a mask of zero or more `VkPerformanceCounterDescriptionFlagBitsKHR`.

### 4.2. Devices

Device objects represent logical connections to physical devices. Each device exposes a number of `queue families` each having one or more `queues`. All queues in a queue family support the same operations.

As described in Physical Devices, a Vulkan application will first query for all physical devices in a system. Each physical device can then be queried for its capabilities, including its queue and queue family properties. Once an acceptable physical device is identified, an application will create a corresponding logical device. An application must create a separate logical device for each physical device it will use. The created logical device is then the primary interface to the physical device.

How to enumerate the physical devices in a system and query those physical devices for their queue family properties is described in the Physical Device Enumeration section above.

A single logical device can also be created from multiple physical devices, if those physical devices belong to the same device group. A `device group` is a set of physical devices that support accessing
each other’s memory and recording a single command buffer that can be executed on all the physical devices. Device groups are enumerated by calling vkEnumeratePhysicalDeviceGroups, and a logical device is created from a subset of the physical devices in a device group by passing the physical devices through VkDeviceGroupDeviceCreateInfo. For two physical devices to be in the same device group, they must support identical extensions, features, and properties.

**Note**

Physical devices in the same device group must be so similar because there are no rules for how different features/properties would interact. They must return the same values for nearly every invariant vkGetPhysicalDevice* feature, property, capability, etc., but could potentially differ for certain queries based on things like having a different display connected, or different compositor, etc. The specification does not attempt to enumerate which state is in each category, because such a list would quickly become out of date.

To retrieve a list of the device groups present in the system, call:

```c
VkResult vkEnumeratePhysicalDeviceGroups(
    VkInstance instance,
    uint32_t* pPhysicalDeviceGroupCount,
    VkPhysicalDeviceGroupProperties* pPhysicalDeviceGroupProperties);
```

or the equivalent command

```c
VkResult vkEnumeratePhysicalDeviceGroupsKHR(
    VkInstance instance,
    uint32_t* pPhysicalDeviceGroupCount,
    VkPhysicalDeviceGroupProperties* pPhysicalDeviceGroupProperties);
```

- instance is a handle to a Vulkan instance previously created with vkCreateInstance.
- pPhysicalDeviceGroupCount is a pointer to an integer related to the number of device groups available or queried, as described below.
- pPhysicalDeviceGroupProperties is either NULL or a pointer to an array of VkPhysicalDeviceGroupProperties structures.

If pPhysicalDeviceGroupProperties is NULL, then the number of device groups available is returned in pPhysicalDeviceGroupCount. Otherwise, pPhysicalDeviceGroupCount must point to a variable set by the user to the number of elements in the pPhysicalDeviceGroupProperties array, and on return the variable is overwritten with the number of structures actually written to pPhysicalDeviceGroupProperties. If pPhysicalDeviceGroupCount is less than the number of device groups available, at most pPhysicalDeviceGroupCount structures will be written. If pPhysicalDeviceGroupCount is smaller than the number of device groups available, VK_INCOMPLETE will be returned instead of VK_SUCCESS, to indicate that not all the available device groups were returned.

Every physical device must be in exactly one device group.
Valid Usage (Implicit)

- **instance** must be a valid `VkInstance` handle
- `pPhysicalDeviceGroupCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pPhysicalDeviceGroupCount` is not 0, and `pPhysicalDeviceGroupProperties` is not NULL, `pPhysicalDeviceGroupProperties` must be a valid pointer to an array of `pPhysicalDeviceGroupCount` `VkPhysicalDeviceGroupProperties` structures

Return Codes

**Success**
- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INITIALIZATION_FAILED`

The `VkPhysicalDeviceGroupProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceGroupProperties {
    VkStructureType sType;
    void* pNext;
    uint32_t physicalDeviceCount;
    VkPhysicalDevice physicalDevices[VK_MAX_DEVICE_GROUP_SIZE];
    VkBool32 subsetAllocation;
} VkPhysicalDeviceGroupProperties;
```

or the equivalent

```c
typedef VkPhysicalDeviceGroupProperties VkPhysicalDeviceGroupPropertiesKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `physicalDeviceCount` is the number of physical devices in the group.
- `physicalDevices` is an array of `VK_MAX_DEVICE_GROUP_SIZE` `VkPhysicalDevice` handles representing all physical devices in the group. The first `physicalDeviceCount` elements of the array will be valid.
- `subsetAllocation` specifies whether logical devices created from the group support allocating device memory on a subset of devices, via the `deviceMask` member of the
VkMemoryAllocateFlagsInfo. If this is VK_FALSE, then all device memory allocations are made across all physical devices in the group. If physicalDeviceCount is 1, then subsetAllocation must be VK_FALSE.

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_PROPERTIES
- **pNext** must be NULL

### 4.2.1. Device Creation

Logical devices are represented by **VkDevice** handles:

`VK_DEFINE_HANDLE(VkDevice)`

A logical device is created as a connection to a physical device. To create a logical device, call:

```cpp
VkResult vkCreateDevice(
    VkPhysicalDevice                            physicalDevice,
    const VkDeviceCreateInfo*                   pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkDevice*                                   pDevice);
```

- **physicalDevice** must be one of the device handles returned from a call to `vkEnumeratePhysicalDevices` (see Physical Device Enumeration).
- **pCreateInfo** is a pointer to a `VkDeviceCreateInfo` structure containing information about how to create the device.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pDevice** is a pointer to a handle in which the created `VkDevice` is returned.

`vkCreateDevice` verifies that extensions and features requested in the `ppEnabledExtensionNames` and `pEnabledFeatures` members of `pCreateInfo`, respectively, are supported by the implementation. If any requested extension is not supported, `vkCreateDevice` must return VK_ERROR_EXTENSION_NOT_PRESENT. If any requested feature is not supported, `vkCreateDevice` must return VK_ERROR_FEATURE_NOT_PRESENT. Support for extensions can be checked before creating a device by querying `vkEnumerateDeviceExtensionProperties`. Support for features can similarly be checked by querying `vkGetPhysicalDeviceFeatures`.

After verifying and enabling the extensions the `VkDevice` object is created and returned to the application. If a requested extension is only supported by a layer, both the layer and the extension need to be specified at `vkCreateInstance` time for the creation to succeed.

Multiple logical devices can be created from the same physical device. Logical device creation may fail due to lack of device-specific resources (in addition to the other errors). If that occurs,
vkCreateDevice will return VK_ERROR_TOO_MANY_OBJECTS.

**Valid Usage**

- All **required extensions** for each extension in the VkDeviceCreateInfo::ppEnabledExtensionNames list must also be present in that list.

**Valid Usage (Implicit)**

- `physicalDevice` must be a valid VkPhysicalDevice handle
- `pCreateInfo` must be a valid pointer to a valid VkDeviceCreateInfo structure
- If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid VkAllocationCallbacks structure
- `pDevice` must be a valid pointer to a VkDevice handle

**Return Codes**

**Success**

- VK_SUCCESS

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_INITIALIZATION_FAILED
- VK_ERROR_EXTENSION_NOT_PRESENT
- VK_ERROR_FEATURE_NOT_PRESENT
- VK_ERROR_TOO_MANY_OBJECTS
- VK_ERROR_DEVICE_LOST

The `VkDeviceCreateInfo` structure is defined as:

```c
typedef struct VkDeviceCreateInfo {
    VkStructureType           sType;
    const void*               pNext;
    VkDeviceCreateFlags       flags;
    uint32_t                   queueCreateInfoCount;
    const VkDeviceQueueCreateInfo* pQueueCreateInfos;
    uint32_t                   enabledLayerCount;
    const char* const*         ppEnabledLayerNames;
    uint32_t                   enabledExtensionCount;
    const char* const*         ppEnabledExtensionNames;
    const VkPhysicalDeviceFeatures* pEnabledFeatures;
} VkDeviceCreateInfo;
```
• sType is the type of this structure.

• pNext is NULL or a pointer to an extension-specific structure.

• flags is reserved for future use.

• queueCreateInfoCount is the unsigned integer size of the pQueueCreateInfos array. Refer to the Queue Creation section below for further details.

• pQueueCreateInfos is a pointer to an array of VkDeviceQueueCreateInfo structures describing the queues that are requested to be created along with the logical device. Refer to the Queue Creation section below for further details.

• enabledLayerCount is deprecated and ignored.

• ppEnabledLayerNames is deprecated and ignored. See Device Layer Deprecation.

• enabledExtensionCount is the number of device extensions to enable.

• ppEnabledExtensionNames is a pointer to an array of enabledExtensionCount null-terminated UTF-8 strings containing the names of extensions to enable for the created device. See the Extensions section for further details.

• pEnabledFeatures is NULL or a pointer to a VkPhysicalDeviceFeatures structure containing boolean indicators of all the features to be enabled. Refer to the Features section for further details.

Valid Usage

• The queueFamilyIndex member of each element of pQueueCreateInfos must be unique within pQueueCreateInfos, except that two members can share the same queueFamilyIndex if one is a protected-capable queue and one is not a protected-capable queue

• If the pNext chain includes a VkPhysicalDeviceFeatures2 structure, then pEnabledFeatures must be NULL
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO`

- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkDeviceGroupDeviceCreateInfo`, `VkPhysicalDevice16BitStorageFeatures`, `VkPhysicalDevice8BitStorageFeatures`, `VkPhysicalDeviceBufferDeviceAddressFeatures`, `VkPhysicalDeviceImagelessFramebufferFeatures`, `VkPhysicalDevicePerformanceQueryFeaturesKHR`, `VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR`, `VkPhysicalDeviceProtectedMemoryFeatures`, `VkPhysicalDeviceRayTracingFeaturesKHR`, `VkPhysicalDeviceSamplerYcbcrConversionFeatures`, `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures`, `VkPhysicalDeviceShaderAtomicInt64Features`, `VkPhysicalDeviceShaderClockFeaturesKHR`, `VkPhysicalDeviceShaderDrawParametersFeatures`, `VkPhysicalDeviceShaderFloat16Int8Features`, `VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures`, `VkPhysicalDeviceTimelineSemaphoreFeatures`, `VkPhysicalDeviceUniformBufferStandardLayoutFeatures`, `VkPhysicalDeviceVariablePointersFeatures`, or `VkPhysicalDeviceVulkanMemoryModelFeatures`

- The `sType` value of each struct in the `pNext` chain must be unique

- **flags** must be 0

- `pQueueCreateInfos` must be a valid pointer to an array of `queueCreateInfoCount` valid `VkDeviceQueueCreateInfo` structures

- If `enabledLayerCount` is not 0, `ppEnabledLayerNames` must be a valid pointer to an array of `enabledLayerCount` null-terminated UTF-8 strings

- If `enabledExtensionCount` is not 0, `ppEnabledExtensionNames` must be a valid pointer to an array of `enabledExtensionCount` null-terminated UTF-8 strings

- If `pEnabledFeatures` is not `NULL`, `pEnabledFeatures` must be a valid pointer to a valid `VkPhysicalDeviceFeatures` structure

- `queueCreateInfoCount` must be greater than 0

```c
typedef VkFlags VkDeviceCreateFlags;
```

`VkDeviceCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

A logical device can be created that connects to one or more physical devices by adding a `VkDeviceGroupDeviceCreateInfo` structure to the `pNext` chain of `VkDeviceCreateInfo`. The `VkDeviceGroupDeviceCreateInfo` structure is defined as:
typedef struct VkDeviceGroupDeviceCreateInfo {
    VkStructureType sType;
    const void*pNext;
    uint32_t physicalDeviceCount;
    const VkPhysicalDevice* pPhysicalDevices;
} VkDeviceGroupDeviceCreateInfo;

or the equivalent

typedef VkDeviceGroupDeviceCreateInfo VkDeviceGroupDeviceCreateInfoKHR;

• **sType** is the type of this structure.
• **pNext** is NULL or a pointer to an extension-specific structure.
• **physicalDeviceCount** is the number of elements in the **pPhysicalDevices** array.
• **pPhysicalDevices** is a pointer to an array of physical device handles belonging to the same device group.

The elements of the **pPhysicalDevices** array are an ordered list of the physical devices that the logical device represents. These **must** be a subset of a single device group, and need not be in the same order as they were enumerated. The order of the physical devices in the **pPhysicalDevices** array determines the **device index** of each physical device, with element i being assigned a device index of i. Certain commands and structures refer to one or more physical devices by using device indices or **device masks** formed using device indices.

A logical device created without using **VkDeviceGroupDeviceCreateInfo**, or with **physicalDeviceCount** equal to zero, is equivalent to a **physicalDeviceCount** of one and **pPhysicalDevices** pointing to the **physicalDevice** parameter to **vkCreateDevice**. In particular, the device index of that physical device is zero.

### Valid Usage

- Each element of **pPhysicalDevices** **must** be unique
- All elements of **pPhysicalDevices** **must** be in the same device group as enumerated by **vkEnumeratePhysicalDeviceGroups**
- If **physicalDeviceCount** is not 0, the **physicalDevice** parameter of **vkCreateDevice** **must** be an element of **pPhysicalDevices**.

### Valid Usage (Implicit)

- **sType** **must** be **VK_STRUCTURE_TYPE_DEVICE_GROUP_DEVICE_CREATE_INFO**
- If **physicalDeviceCount** is not 0, **pPhysicalDevices** **must** be a valid pointer to an array of **physicalDeviceCount** valid **VkPhysicalDevice** handles
4.2.2. Device Use

The following is a high-level list of VkDevice uses along with references on where to find more information:

• Creation of queues. See the Queues section below for further details.

• Creation and tracking of various synchronization constructs. See Synchronization and Cache Control for further details.

• Allocating, freeing, and managing memory. See Memory Allocation and Resource Creation for further details.

• Creation and destruction of command buffers and command buffer pools. See Command Buffers for further details.

• Creation, destruction, and management of graphics state. See Pipelines and Resource Descriptors, among others, for further details.

4.2.3. Lost Device

A logical device may become lost for a number of implementation-specific reasons, indicating that pending and future command execution may fail and cause resources and backing memory to become undefined.

**Note**

Typical reasons for device loss will include things like execution timing out (to prevent denial of service), power management events, platform resource management, implementation errors.

Applications not adhering to valid usage may also result in device loss being reported, however this is not guaranteed. Even if device loss is reported, the system may be in an unrecoverable state, and further usage of the API is still considered invalid.

When this happens, certain commands will return VK_ERROR_DEVICE_LOST. After any such event, the logical device is considered lost. It is not possible to reset the logical device to a non-lost state, however the lost state is specific to a logical device (VkDevice), and the corresponding physical device (VkPhysicalDevice) may be otherwise unaffected.

In some cases, the physical device may also be lost, and attempting to create a new logical device will fail, returning VK_ERROR_DEVICE_LOST. This is usually indicative of a problem with the underlying implementation, or its connection to the host. If the physical device has not been lost, and a new logical device is successfully created from that physical device, it must be in the non-lost state.
Whilst logical device loss may be recoverable, in the case of physical device loss, it is unlikely that an application will be able to recover unless additional, unaffected physical devices exist on the system. The error is largely informational and intended only to inform the user that a platform issue has occurred, and should be investigated further. For example, underlying hardware may have developed a fault or become physically disconnected from the rest of the system. In many cases, physical device loss may cause other more serious issues such as the operating system crashing; in which case it may not be reported via the Vulkan API.

When a device is lost, its child objects are not implicitly destroyed and their handles are still valid. Those objects must still be destroyed before their parents or the device can be destroyed (see the Object Lifetime section). The host address space corresponding to device memory mapped using vkMapMemory is still valid, and host memory accesses to these mapped regions are still valid, but the contents are undefined. It is still legal to call any API command on the device and child objects.

Once a device is lost, command execution may fail, and commands that return a VkResult may return VK_ERROR_DEVICE_LOST. Commands that do not allow run-time errors must still operate correctly for valid usage and, if applicable, return valid data.

Commands that wait indefinitely for device execution (namely vkDeviceWaitIdle, vkQueueWaitIdle, vkWaitForFences or vkAcquireNextImageKHR with a maximum timeout, and vkGetQueryPoolResults with the VK_QUERY_RESULT_WAIT_BIT bit set in flags) must return in finite time even in the case of a lost device, and return either VK_SUCCESS or VK_ERROR_DEVICE_LOST. For any command that may return VK_ERROR_DEVICE_LOST, for the purpose of determining whether a command buffer is in the pending state, or whether resources are considered in-use by the device, a return value of VK_ERROR_DEVICE_LOST is equivalent to VK_SUCCESS.

The content of any external memory objects that have been exported from or imported to a lost device become undefined. Objects on other logical devices or in other APIs which are associated with the same underlying memory resource as the external memory objects on the lost device are unaffected other than their content becoming undefined. The layout of subresources of images on other logical devices that are bound to VkDeviceMemory objects associated with the same underlying memory resources as external memory objects on the lost device becomes VK_IMAGE_LAYOUT_UNDEFINED.

The state of VkSemaphore objects on other logical devices created by importing a semaphore payload with temporary permanence which was exported from the lost device is undefined. The state of VkSemaphore objects on other logical devices that permanently share a semaphore payload with a VkSemaphore object on the lost device is undefined, and remains undefined following any subsequent signal operations. Implementations must ensure pending and subsequently submitted wait operations on such semaphores behave as defined in Semaphore State Requirements For Wait Operations for external semaphores not in a valid state for a wait operation.

### 4.2.4. Device Destruction

To destroy a device, call:
void vkDestroyDevice(
    VkDevice device,
    const VkAllocationCallbacks* pAllocator);

- `device` is the logical device to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

To ensure that no work is active on the device, `vkDeviceWaitIdle` can be used to gate the destruction of the device. Prior to destroying a device, an application is responsible for destroying/freeing any Vulkan objects that were created using that device as the first parameter of the corresponding `vkCreate*` or `vkAllocate*` command.

**Note**
The lifetime of each of these objects is bound by the lifetime of the `VkDevice` object. Therefore, to avoid resource leaks, it is critical that an application explicitly free all of these resources prior to calling `vkDestroyDevice`.

**Valid Usage**
- All child objects created on `device` must have been destroyed prior to destroying `device`
- If `VkAllocationCallbacks` were provided when `device` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `device` was created, `pAllocator` must be `NULL`

**Valid Usage (Implicit)**
- If `device` is not `NULL`, `device` must be a valid `VkDevice` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

**Host Synchronization**
- Host access to `device` must be externally synchronized

### 4.3. Queues

#### 4.3.1. Queue Family Properties
As discussed in the Physical Device Enumeration section above, the `vkGetPhysicalDeviceQueueFamilyProperties` command is used to retrieve details about the queue
families and queues supported by a device.

Each index in the `pQueueFamilyProperties` array returned by `vkGetPhysicalDeviceQueueFamilyProperties` describes a unique queue family on that physical device. These indices are used when creating queues, and they correspond directly with the `queueFamilyIndex` that is passed to the `vkCreateDevice` command via the `VkDeviceQueueCreateInfo` structure as described in the Queue Creation section below.

Grouping of queue families within a physical device is implementation-dependent.

Note
The general expectation is that a physical device groups all queues of matching capabilities into a single family. However, while implementations should do this, it is possible that a physical device may return two separate queue families with the same capabilities.

Once an application has identified a physical device with the queue(s) that it desires to use, it will create those queues in conjunction with a logical device. This is described in the following section.

### 4.3.2. Queue Creation

Creating a logical device also creates the queues associated with that device. The queues to create are described by a set of `VkDeviceQueueCreateInfo` structures that are passed to `vkCreateDevice` in `pQueueCreateInfos`.

Queues are represented by `VkQueue` handles:

```c
VK_DEFINE_HANDLE(VkQueue)
```

The `VkDeviceQueueCreateInfo` structure is defined as:

```c
typedef struct VkDeviceQueueCreateInfo {
    VkStructureType         sType;
    const void*              pNext;
    VkDeviceQueueCreateFlags flags;
    uint32_t                 queueFamilyIndex;
    uint32_t                 queueCount;
    const float*             pQueuePriorities;
} VkDeviceQueueCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is a bitmask indicating behavior of the queue.
- `queueFamilyIndex` is an unsigned integer indicating the index of the queue family to create on this device. This index corresponds to the index of an element of the `pQueueFamilyProperties` array that was returned by `vkGetPhysicalDeviceQueueFamilyProperties`.
• `queueCount` is an unsigned integer specifying the number of queues to create in the queue family indicated by `queueFamilyIndex`.

• `pQueuePriorities` is a pointer to an array of `queueCount` normalized floating point values, specifying priorities of work that will be submitted to each created queue. See Queue Priority for more information.

### Valid Usage

• `queueFamilyIndex` **must** be less than `pQueueFamilyPropertyCount` returned by `vkGetPhysicalDeviceQueueFamilyProperties`

• `queueCount` **must** be less than or equal to the `queueCount` member of the `VkQueueFamilyProperties` structure, as returned by `vkGetPhysicalDeviceQueueFamilyProperties` in the `pQueueFamilyProperties[queueFamilyIndex]`

• Each element of `pQueuePriorities` **must** be between 0.0 and 1.0 inclusive

• If the protected memory feature is not enabled, the `VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT` bit of `flags` **must** not be set.

### Valid Usage (Implicit)

• `sType` **must** be `VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO`

• `pNext` **must** be `NULL`

• `flags` **must** be a valid combination of `VkDeviceQueueCreateFlagBits` values

• `pQueuePriorities` **must** be a valid pointer to an array of `queueCount` `float` values

• `queueCount` **must** be greater than 0

Bits which **can** be set in `VkDeviceQueueCreateInfo::flags` to specify usage behavior of the queue are:

```c
typedef enum VkDeviceQueueCreateFlagBits {
    VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT = 0x00000001,
    VK_DEVICE_QUEUE_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkDeviceQueueCreateFlagBits;
```

• `VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT` specifies that the device queue is a protected-capable queue.

```c
typedef VkFlags VkDeviceQueueCreateFlags;
```

`VkDeviceQueueCreateFlags` is a bitmask type for setting a mask of zero or more `VkDeviceQueueCreateFlagBits`.

---

Chapter 4. Devices and Queues | 85
To retrieve a handle to a `VkQueue` object, call:

```c
void vkGetDeviceQueue(
    VkDevice device,                      
    uint32_t queueFamilyIndex,            
    uint32_t queueIndex,                  
    VkQueue* pQueue);
```

- `device` is the logical device that owns the queue.
- `queueFamilyIndex` is the index of the queue family to which the queue belongs.
- `queueIndex` is the index within this queue family of the queue to retrieve.
- `pQueue` is a pointer to a `VkQueue` object that will be filled with the handle for the requested queue.

`vkGetDeviceQueue` must only be used to get queues that were created with the `flags` parameter of `VkDeviceQueueCreateInfo` set to zero. To get queues that were created with a non-zero `flags` parameter use `vkGetDeviceQueue2`.

### Valid Usage

- `queueFamilyIndex` must be one of the queue family indices specified when `device` was created, via the `VkDeviceQueueCreateInfo` structure
- `queueIndex` must be less than the number of queues created for the specified queue family index when `device` was created, via the `queueCount` member of the `VkDeviceQueueCreateInfo` structure
- `VkDeviceQueueCreateInfo::flags` must have been set to zero when `device` was created

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pQueue` must be a valid pointer to a `VkQueue` handle

To retrieve a handle to a `VkQueue` object with specific `VkDeviceQueueCreateFlags` creation flags, call:

```c
void vkGetDeviceQueue2(
    VkDevice device,                  
    const VkDeviceQueueInfo2* pQueueInfo,  
    VkQueue* pQueue);
```

- `device` is the logical device that owns the queue.
- `pQueueInfo` is a pointer to a `VkDeviceQueueInfo2` structure, describing the parameters used to
create the device queue.

- *pQueue* is a pointer to a *VkQueue* object that will be filled with the handle for the requested queue.

### Valid Usage (Implicit)

- **device** must be a valid *VkDevice* handle
- **pQueueInfo** must be a valid pointer to a valid *VkDeviceQueueInfo2* structure
- **pQueue** must be a valid pointer to a *VkQueue* handle

The *VkDeviceQueueInfo2* structure is defined as:

```c
typedef struct VkDeviceQueueInfo2 {
    VkStructureType             sType;
    const void*                 pNext;
    VkDeviceQueueCreateFlags    flags;
    uint32_t                    queueFamilyIndex;
    uint32_t                    queueIndex;
} VkDeviceQueueInfo2;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure. The **pNext** chain of *VkDeviceQueueInfo2* is used to provide additional image parameters to *vkGetDeviceQueue2*.
- **flags** is a *VkDeviceQueueCreateFlags* value indicating the flags used to create the device queue.
- **queueFamilyIndex** is the index of the queue family to which the queue belongs.
- **queueIndex** is the index within this queue family of the queue to retrieve.

The queue returned by *vkGetDeviceQueue2* must have the same **flags** value from this structure as that used at device creation time in a *VkDeviceQueueCreateInfo* instance. If no matching **flags** were specified at device creation time then *pQueue* will return *VK_NULL_HANDLE*.

### Valid Usage

- **queueFamilyIndex** must be one of the queue family indices specified when **device** was created, via the *VkDeviceQueueCreateInfo* structure
- **queueIndex** must be less than the number of queues created for the specified queue family index and *VkDeviceQueueCreateInfo* member **flags** equal to this **flags** value when **device** was created, via the **queueCount** member of the *VkDeviceQueueCreateInfo* structure
4.3.3. Queue Family Index

The queue family index is used in multiple places in Vulkan in order to tie operations to a specific family of queues.

When retrieving a handle to the queue via `vkGetDeviceQueue`, the queue family index is used to select which queue family to retrieve the `VkQueue` handle from as described in the previous section.

When creating a `VkCommandPool` object (see Command Pools), a queue family index is specified in the `VkCommandPoolCreateInfo` structure. Command buffers from this pool can only be submitted on queues corresponding to this queue family.

When creating `VkImage` (see Images) and `VkBuffer` (see Buffers) resources, a set of queue families is included in the `VkImageCreateInfo` and `VkBufferCreateInfo` structures to specify the queue families that can access the resource.

When inserting a `VkBufferMemoryBarrier` or `VkImageMemoryBarrier` (see Pipeline Barriers), a source and destination queue family index is specified to allow the ownership of a buffer or image to be transferred from one queue family to another. See the Resource Sharing section for details.

4.3.4. Queue Priority

Each queue is assigned a priority, as set in the `VkDeviceQueueCreateInfo` structures when creating the device. The priority of each queue is a normalized floating point value between 0.0 and 1.0, which is then translated to a discrete priority level by the implementation. Higher values indicate a higher priority, with 0.0 being the lowest priority and 1.0 being the highest.

Within the same device, queues with higher priority may be allotted more processing time than queues with lower priority. The implementation makes no guarantees with regards to ordering or scheduling among queues with the same priority, other than the constraints defined by any explicit synchronization primitives. The implementation makes no guarantees with regards to queues across different devices.

An implementation may allow a higher-priority queue to starve a lower-priority queue on the same `VkDevice` until the higher-priority queue has no further commands to execute. The relationship of queue priorities must not cause queues on one `VkDevice` to starve queues on another `VkDevice`.

No specific guarantees are made about higher priority queues receiving more processing time or better quality of service than lower priority queues.
4.3.5. Queue Submission

Work is submitted to a queue via queue submission commands such as vkQueueSubmit. Queue submission commands define a set of queue operations to be executed by the underlying physical device, including synchronization with semaphores and fences.

Submission commands take as parameters a target queue, zero or more batches of work, and an optional fence to signal upon completion. Each batch consists of three distinct parts:

1. Zero or more semaphores to wait on before execution of the rest of the batch.
   - If present, these describe a semaphore wait operation.
2. Zero or more work items to execute.
   - If present, these describe a queue operation matching the work described.
3. Zero or more semaphores to signal upon completion of the work items.
   - If present, these describe a semaphore signal operation.

If a fence is present in a queue submission, it describes a fence signal operation.

All work described by a queue submission command must be submitted to the queue before the command returns.

Sparse Memory Binding

In Vulkan it is possible to sparsely bind memory to buffers and images as described in the Sparse Resource chapter. Sparse memory binding is a queue operation. A queue whose flags include the VK_QUEUE_SPARSE_BINDING_BIT must be able to support the mapping of a virtual address to a physical address on the device. This causes an update to the page table mappings on the device. This update must be synchronized on a queue to avoid corrupting page table mappings during execution of graphics commands. By binding the sparse memory resources on queues, all commands that are dependent on the updated bindings are synchronized to only execute after the binding is updated. See the Synchronization and Cache Control chapter for how this synchronization is accomplished.

4.3.6. Queue Destruction

Queues are created along with a logical device during vkCreateDevice. All queues associated with a logical device are destroyed when vkDestroyDevice is called on that device.
Chapter 5. Command Buffers

Command buffers are objects used to record commands which can be subsequently submitted to a device queue for execution. There are two levels of command buffers - primary command buffers, which can execute secondary command buffers, and which are submitted to queues, and secondary command buffers, which can be executed by primary command buffers, and which are not directly submitted to queues.

Command buffers are represented by VkCommandBuffer handles:

```cpp
VK_DEFINE_HANDLE(VkCommandBuffer)
```

Recorded commands include commands to bind pipelines and descriptor sets to the command buffer, commands to modify dynamic state, commands to draw (for graphics rendering), commands to dispatch (for compute), commands to execute secondary command buffers (for primary command buffers only), commands to copy buffers and images, and other commands.

Each command buffer manages state independently of other command buffers. There is no inheritance of state across primary and secondary command buffers, or between secondary command buffers. When a command buffer begins recording, all state in that command buffer is undefined. When secondary command buffer(s) are recorded to execute on a primary command buffer, the secondary command buffer inherits no state from the primary command buffer, and all state of the primary command buffer is undefined after an execute secondary command buffer command is recorded. There is one exception to this rule - if the primary command buffer is inside a render pass instance, then the render pass and subpass state is not disturbed by executing secondary command buffers. For state dependent commands (such as draws and dispatches), any state consumed by those commands must not be undefined.

Unless otherwise specified, and without explicit synchronization, the various commands submitted to a queue via command buffers may execute in arbitrary order relative to each other, and/or concurrently. Also, the memory side-effects of those commands may not be directly visible to other commands without explicit memory dependencies. This is true within a command buffer, and across command buffers submitted to a given queue. See the synchronization chapter for information on implicit and explicit synchronization between commands.

5.1. Command Buffer Lifecycle

Each command buffer is always in one of the following states:

**Initial**

When a command buffer is allocated, it is in the initial state. Some commands are able to reset a command buffer (or a set of command buffers) back to this state from any of the executable, recording or invalid state. Command buffers in the initial state can only be moved to the recording state, or freed.

**Recording**

vkBeginCommandBuffer changes the state of a command buffer from the initial state to the
Once a command buffer is in the recording state, \texttt{vkCmd*} commands can be used to record to the command buffer.

**Executable**

\texttt{vkEndCommandBuffer} ends the recording of a command buffer, and moves it from the recording state to the executable state. Executable command buffers can be submitted, reset, or recorded to another command buffer.

**Pending**

Queue submission of a command buffer changes the state of a command buffer from the executable state to the pending state. Whilst in the pending state, applications must not attempt to modify the command buffer in any way - as the device may be processing the commands recorded to it. Once execution of a command buffer completes, the command buffer either reverts back to the executable state, or if it was recorded with \texttt{VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT}, it moves to the invalid state. A synchronization command should be used to detect when this occurs.

**Invalid**

Some operations, such as modifying or deleting a resource that was used in a command recorded to a command buffer, will transition the state of that command buffer into the invalid state. Command buffers in the invalid state can only be reset or freed.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{command_buffer_lifecycle}
\caption{Lifecycle of a command buffer}
\end{figure}

Any given command that operates on a command buffer has its own requirements on what state a command buffer must be in, which are detailed in the valid usage constraints for that command.

Resetting a command buffer is an operation that discards any previously recorded commands and puts a command buffer in the initial state. Resetting occurs as a result of \texttt{vkResetCommandBuffer} or \texttt{vkResetCommandPool}, or as part of \texttt{vkBeginCommandBuffer} (which additionally puts the command buffer in the recording state).

Secondary command buffers can be recorded to a primary command buffer via \texttt{vkCmdExecuteCommands}. This partially ties the lifecycle of the two command buffers together - if the primary is submitted to a queue, both the primary and any secondaries recorded to it move to the pending state. Once execution of the primary completes, so it does for any secondary recorded
within it. After all executions of each command buffer complete, they each move to their appropriate completion state (either to the *execution state* or the *invalid state*, as specified above).

If a secondary moves to the *invalid state* or the *initial state*, then all primary buffers it is recorded in move to the *invalid state*. A primary moving to any other state does not affect the state of a secondary recorded in it.

**Note**
Resetting or freeing a primary command buffer removes the lifecycle linkage to all secondary command buffers that were recorded into it.

### 5.2. Command Pools

Command pools are opaque objects that command buffer memory is allocated from, and which allow the implementation to amortize the cost of resource creation across multiple command buffers. Command pools are externally synchronized, meaning that a command pool must not be used concurrently in multiple threads. That includes use via recording commands on any command buffers allocated from the pool, as well as operations that allocate, free, and reset command buffers or the pool itself.

Command pools are represented by *VkCommandPool* handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkCommandPool)
```

To create a command pool, call:

```
VkResult vkCreateCommandPool(
    VkDevice                                    device,
    const VkCommandPoolCreateInfo*              pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkCommandPool*                              pCommandPool);
```

- **device** is the logical device that creates the command pool.
- **pCreateInfo** is a pointer to a *VkCommandPoolCreateInfo* structure specifying the state of the command pool object.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pCommandPool** is a pointer to a *VkCommandPool* handle in which the created pool is returned.

**Valid Usage**

- **pCreateInfo->queueFamilyIndex** must be the index of a queue family available in the logical device **device**.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkCommandPoolCreateInfo` structure
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pCommandPool** must be a valid pointer to a `VkCommandPool` handle

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkCommandPoolCreateInfo` structure is defined as:

```c
typedef struct VkCommandPoolCreateInfo {
    VkStructureType             sType;
    const void*                 pNext;
    VkCommandPoolCreateFlags    flags;
    uint32_t                    queueFamilyIndex;
} VkCommandPoolCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is a bitmask of `VkCommandPoolCreateFlagBits` indicating usage behavior for the pool and command buffers allocated from it.
- **queueFamilyIndex** designates a queue family as described in section Queue Family Properties. All command buffers allocated from this command pool must be submitted on queues from the same queue family.

Valid Usage

- If the protected memory feature is not enabled, the `VK_COMMAND_POOL_CREATE_PROTECTED_BIT` bit of **flags** must not be set.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO`
- **pNext** must be `NULL`
- **flags** must be a valid combination of `VkCommandPoolCreateFlagBits` values

Bits which **can** be set in `VkCommandPoolCreateInfo::flags` to specify usage behavior for a command pool are:

```c
typedef enum VkCommandPoolCreateFlagBits {
    VK_COMMAND_POOL_CREATE_TRANSIENT_BIT = 0x00000001,
    VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT = 0x00000002,
    VK_COMMAND_POOL_CREATE_PROTECTED_BIT = 0x00000004,
    VK_COMMAND_POOL_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkCommandPoolCreateFlagBits;
```

- **VK_COMMAND_POOL_CREATE_TRANSIENT_BIT** specifies that command buffers allocated from the pool will be short-lived, meaning that they will be reset or freed in a relatively short timeframe. This flag **may** be used by the implementation to control memory allocation behavior within the pool.
- **VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT** allows any command buffer allocated from a pool to be individually reset to the initial state; either by calling `vkResetCommandBuffer`, or via the implicit reset when calling `vkBeginCommandBuffer`. If this flag is not set on a pool, then `vkResetCommandBuffer` must not be called for any command buffer allocated from that pool.
- **VK_COMMAND_POOL_CREATE_PROTECTED_BIT** specifies that command buffers allocated from the pool are protected command buffers.

```c
typedef VkFlags VkCommandPoolCreateFlags;
```

`VkCommandPoolCreateFlags` is a bitmask type for setting a mask of zero or more `VkCommandPoolCreateFlagBits`.

To trim a command pool, call:

```c
void vkTrimCommandPool(
    VkDevice device,
    VkCommandPool commandPool,
    VkCommandPoolTrimFlags flags);
```

or the equivalent command
```c
void vkTrimCommandPoolKHR(
    VkDevice                                    device,
    VkCommandPool                               commandPool,
    VkCommandPoolTrimFlags                      flags);
```

- `device` is the logical device that owns the command pool.
- `commandPool` is the command pool to trim.
- `flags` is reserved for future use.

Trimming a command pool recycles unused memory from the command pool back to the system. Command buffers allocated from the pool are not affected by the command.

**Note**

This command provides applications with some control over the internal memory allocations used by command pools.

Unused memory normally arises from command buffers that have been recorded and later reset, such that they are no longer using the memory. On reset, a command buffer can return memory to its command pool, but the only way to release memory from a command pool to the system requires calling `vkResetCommandPool`, which cannot be executed while any command buffers from that pool are still in use. Subsequent recording operations into command buffers will re-use this memory but since total memory requirements fluctuate over time, unused memory can accumulate.

In this situation, trimming a command pool may be useful to return unused memory back to the system, returning the total outstanding memory allocated by the pool back to a more “average” value.

Implementations utilize many internal allocation strategies that make it impossible to guarantee that all unused memory is released back to the system. For instance, an implementation of a command pool may involve allocating memory in bulk from the system and sub-allocating from that memory. In such an implementation any live command buffer that holds a reference to a bulk allocation would prevent that allocation from being freed, even if only a small proportion of the bulk allocation is in use.

In most cases trimming will result in a reduction in allocated but unused memory, but it does not guarantee the “ideal” behavior.

Trimming may be an expensive operation, and should not be called frequently. Trimming should be treated as a way to relieve memory pressure after application-known points when there exists enough unused memory that the cost of trimming is “worth” it.
Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `commandPool` must be a valid `VkCommandPool` handle
- `flags` must be 0
- `commandPool` must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `commandPool` must be externally synchronized

```plaintext
typedef VkFlags VkCommandPoolTrimFlags;
```
or the equivalent

```plaintext
typedef VkCommandPoolTrimFlags VkCommandPoolTrimFlagsKHR;
```

`VkCommandPoolTrimFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

To reset a command pool, call:

```plaintext
VkResult vkResetCommandPool(  
    VkDevice device,  
    VkCommandPool commandPool,  
    VkCommandPoolResetFlags flags);
```

- `device` is the logical device that owns the command pool.
- `commandPool` is the command pool to reset.
- `flags` is a bitmask of `VkCommandPoolResetFlagBits` controlling the reset operation.

Resetting a command pool recycles all of the resources from all of the command buffers allocated from the command pool back to the command pool. All command buffers that have been allocated from the command pool are put in the initial state.

Any primary command buffer allocated from another `VkCommandPool` that is in the recording or executable state and has a secondary command buffer allocated from `commandPool` recorded into it, becomes invalid.
Valid Usage

- All `VkCommandBuffer` objects allocated from `commandPool` must not be in the `pending state`.

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle.
- `commandPool` must be a valid `VkCommandPool` handle.
- `flags` must be a valid combination of `VkCommandPoolResetFlagBits` values.
- `commandPool` must have been created, allocated, or retrieved from `device`.

Host Synchronization

- Host access to `commandPool` must be externally synchronized.

Return Codes

Success

- `VK_SUCCESS`

Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

Bits which `can` be set in `vkResetCommandPool::flags` to control the reset operation are:

```c
typedef enum VkCommandPoolResetFlagBits {
    VK_COMMAND_POOL_RESET_RELEASE_RESOURCES_BIT = 0x00000001,
    VK_COMMAND_POOL_RESET_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkCommandPoolResetFlagBits;
```

- `VK_COMMAND_POOL_RESET_RELEASE_RESOURCES_BIT` specifies that resetting a command pool recycles all of the resources from the command pool back to the system.

```c
typedef VkFlags VkCommandPoolResetFlags;
```

`VkCommandPoolResetFlags` is a bitmask type for setting a mask of zero or more `VkCommandPoolResetFlagBits`.

To destroy a command pool, call:
void vkDestroyCommandPool(
    VkDevice device,
    VkCommandPool commandPool,
    const VkAllocationCallbacks* pAllocator);

- **device** is the logical device that destroys the command pool.
- **commandPool** is the handle of the command pool to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

When a pool is destroyed, all command buffers allocated from the pool are freed.

Any primary command buffer allocated from another VkCommandPool that is in the recording or executable state and has a secondary command buffer allocated from commandPool recorded into it, becomes invalid.

---

**Valid Usage**

- All VkCommandBuffer objects allocated from commandPool must not be in the pending state.
- If VkAllocationCallbacks were provided when commandPool was created, a compatible set of callbacks must be provided here.
- If no VkAllocationCallbacks were provided when commandPool was created, pAllocator must be NULL.

---

**Valid Usage (Implicit)**

- **device** must be a valid VkDevice handle.
- If commandPool is not VK_NULL_HANDLE, commandPool must be a valid VkCommandPool handle.
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure.
- If commandPool is a valid handle, it must have been created, allocated, or retrieved from device.

---

**Host Synchronization**

- Host access to commandPool must be externally synchronized.

---

**5.3. Command Buffer Allocation and Management**

To allocate command buffers, call:
VkResult vkAllocateCommandBuffers(
    VkDevice                                    device,
    const VkCommandBufferAllocateInfo*          pAllocateInfo,
    VkCommandBuffer*                            pCommandBuffers);

- **device** is the logical device that owns the command pool.
- **pAllocateInfo** is a pointer to a VkCommandBufferAllocateInfo structure describing parameters of the allocation.
- **pCommandBuffers** is a pointer to an array of VkCommandBuffer handles in which the resulting command buffer objects are returned. The array must be at least the length specified by the commandBufferCount member of pAllocateInfo. Each allocated command buffer begins in the initial state.

vkAllocateCommandBuffers can be used to create multiple command buffers. If the creation of any of those command buffers fails, the implementation must destroy all successfully created command buffer objects from this command, set all entries of the pCommandBuffers array to NULL and return the error.

When command buffers are first allocated, they are in the initial state.

### Valid Usage (Implicit)

- **device** must be a valid VkDevice handle
- **pAllocateInfo** must be a valid pointer to a valid VkCommandBufferAllocateInfo structure
- **pCommandBuffers** must be a valid pointer to an array of pAllocateInfo::commandBufferCount VkCommandBuffer handles
- The value referenced by pAllocateInfo::commandBufferCount must be greater than 0

### Host Synchronization

- Host access to pAllocateInfo::commandPool must be externally synchronized

### Return Codes

#### Success
- VK_SUCCESS

#### Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkCommandBufferAllocateInfo structure is defined as:
typedef struct VkCommandBufferAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkCommandPool commandPool;
    VkCommandBufferLevel level;
    uint32_t commandBufferCount;
} VkCommandBufferAllocateInfo;

• `sType` is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.
• `commandPool` is the command pool from which the command buffers are allocated.
• `level` is a `VkCommandBufferLevel` value specifying the command buffer level.
• `commandBufferCount` is the number of command buffers to allocate from the pool.

**Valid Usage**

• `commandBufferCount` must be greater than 0

**Valid Usage (Implicit)**

• `sType` must be `VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO`
• `pNext` must be `NULL`
• `commandPool` must be a valid `VkCommandPool` handle
• `level` must be a valid `VkCommandBufferLevel` value

Possible values of `VkCommandBufferAllocateInfo::level`, specifying the command buffer level, are:

typedef enum VkCommandBufferLevel {
    VK_COMMAND_BUFFER_LEVEL_PRIMARY = 0,
    VK_COMMAND_BUFFER_LEVEL_SECONDARY = 1,
    VK_COMMAND_BUFFER_LEVEL_MAX_ENUM = 0x7FFFFFFF
} VkCommandBufferLevel;

• `VK_COMMAND_BUFFER_LEVEL_PRIMARY` specifies a primary command buffer.
• `VK_COMMAND_BUFFER_LEVEL_SECONDARY` specifies a secondary command buffer.

To reset command buffers, call:

```c
VkResult vkResetCommandBuffer(
    VkCommandBuffer commandBuffer,
    VkCommandBufferResetFlags flags);
```
• `commandBuffer` is the command buffer to reset. The command buffer can be in any state other than `pending`, and is moved into the `initial state`.

• `flags` is a bitmask of `VkCommandBufferResetFlagBits` controlling the reset operation.

Any primary command buffer that is in the recording or executable state and has `commandBuffer` recorded into it, becomes invalid.

### Valid Usage

- `commandBuffer` must not be in the pending state
- `commandBuffer` must have been allocated from a pool that was created with the `VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT`

### Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `flags` must be a valid combination of `VkCommandBufferResetFlagBits` values

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

### Return Codes

**Success**

- `VK_SUCCESS`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

Bits which can be set in `vkResetCommandBuffer::flags` to control the reset operation are:

```c
typedef enum VkCommandBufferResetFlagBits {
    VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT = 0x00000001,
    VK_COMMAND_BUFFER_RESET_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkCommandBufferResetFlagBits;
```

- `VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT` specifies that most or all memory resources currently owned by the command buffer should be returned to the parent command pool. If this flag is not set, then the command buffer may hold onto memory resources and reuse them when recording commands. `commandBuffer` is moved to the `initial state`. 
typedef VkFlags VkCommandBufferResetFlags;

VkCommandBufferResetFlags is a bitmask type for setting a mask of zero or more VkCommandBufferResetFlagBits.

To free command buffers, call:

```c
void vkFreeCommandBuffers(
    VkDevice device,
    VkCommandPool commandPool,
    uint32_t commandBufferCount,
    const VkCommandBuffer* pCommandBuffers);
```

- **device** is the logical device that owns the command pool.
- **commandPool** is the command pool from which the command buffers were allocated.
- **commandBufferCount** is the length of the **pCommandBuffers** array.
- **pCommandBuffers** is a pointer to an array of handles of command buffers to free.

Any primary command buffer that is in the **recording** or **executable state** and has any element of **pCommandBuffers** recorded into it, becomes **invalid**.

### Valid Usage

- All elements of **pCommandBuffers** **must** not be in the **pending state**
- **pCommandBuffers** **must** be a valid pointer to an array of **commandBufferCount** VkCommandBuffer handles, each element of which **must** either be a valid handle or **NULL**

### Valid Usage (Implicit)

- **device** **must** be a valid VkDevice handle
- **commandPool** **must** be a valid VkCommandPool handle
- **commandBufferCount** **must** be greater than 0
- **commandPool** **must** have been created, allocated, or retrieved from **device**
- Each element of **pCommandBuffers** that is a valid handle **must** have been created, allocated, or retrieved from **commandPool**

### Host Synchronization

- Host access to **commandPool** **must** be externally synchronized
- Host access to each member of **pCommandBuffers** **must** be externally synchronized
5.4. Command Buffer Recording

To begin recording a command buffer, call:

```c
VkResult vkBeginCommandBuffer(
    VkCommandBuffer                             commandBuffer,
    const VkCommandBufferBeginInfo*             pBeginInfo);
```

- `commandBuffer` is the handle of the command buffer which is to be put in the recording state.
- `pBeginInfo` points to a `VkCommandBufferBeginInfo` structure defining additional information about how the command buffer begins recording.

### Valid Usage

- `commandBuffer` must not be in the recording or pending state
- If `commandBuffer` was allocated from a `VkCommandPool` which did not have the `VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT` flag set, `commandBuffer` must be in the initial state
- If `commandBuffer` is a secondary command buffer, the `pInheritanceInfo` member of `pBeginInfo` must be a valid `VkCommandBufferInheritanceInfo` structure
- If `commandBuffer` is a secondary command buffer and either the `occlusionQueryEnable` member of the `pInheritanceInfo` member of `pBeginInfo` is `VK_FALSE`, or the precise occlusion queries feature is not enabled, the `queryFlags` member of the `pInheritanceInfo` member `pBeginInfo` must not contain `VK_QUERY_CONTROL_PRECISE_BIT`
- If `commandBuffer` is a primary command buffer, then `pBeginInfo->flags` must not set both the `VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT` and the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flags

### Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `pBeginInfo` must be a valid pointer to a valid `VkCommandBufferBeginInfo` structure

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized
Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkCommandBufferBeginInfo` structure is defined as:

```c
typedef struct VkCommandBufferBeginInfo {
    VkStructureType sType;
    const void* pNext;
    VkCommandBufferUsageFlags flags;
    const VkCommandBufferInheritanceInfo* pInheritanceInfo;
} VkCommandBufferBeginInfo;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is a bitmask of `VkCommandBufferUsageFlagBits` specifying usage behavior for the command buffer.
- **pInheritanceInfo** is a pointer to a `VkCommandBufferInheritanceInfo` structure, used if `commandBuffer` is a secondary command buffer. If this is a primary command buffer, then this value is ignored.

Valid Usage

- If **flags** contains `VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT`, the `renderPass` member of `pInheritanceInfo` must be a valid `VkRenderPass`
- If **flags** contains `VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT`, the `subpass` member of `pInheritanceInfo` must be a valid subpass index within the `renderPass` member of `pInheritanceInfo`
- If **flags** contains `VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT`, the `framebuffer` member of `pInheritanceInfo` must be either `VK_NULL_HANDLE`, or a valid `VkFramebuffer` that is compatible with the `renderPass` member of `pInheritanceInfo`
Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO**
- **pNext** must be **NULL** or a pointer to a valid instance of **VkDeviceGroupCommandBufferBeginInfo**
- The **sType** value of each struct in the **pNext** chain must be unique
- **flags** must be a valid combination of **VkCommandBufferUsageFlagBits** values

Bits which can be set in **VkCommandBufferBeginInfo::flags** to specify usage behavior for a command buffer are:

```plaintext
typedef enum VkCommandBufferUsageFlagBits {
    VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT = 0x00000001,
    VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT = 0x00000002,
    VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT = 0x00000004,
    VK_COMMAND_BUFFER_USAGE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkCommandBufferUsageFlagBits;
```

- **VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT** specifies that each recording of the command buffer will only be submitted once, and the command buffer will be reset and recorded again between each submission.
- **VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT** specifies that a secondary command buffer is considered to be entirely inside a render pass. If this is a primary command buffer, then this bit is ignored.
- **VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT** specifies that a command buffer can be resubmitted to a queue while it is in the **pending state**, and recorded into multiple primary command buffers.

```plaintext
typedef VkFlags VkCommandBufferUsageFlags;
```

**VkCommandBufferUsageFlags** is a bitmask type for setting a mask of zero or more **VkCommandBufferUsageFlagBits**.

If the command buffer is a secondary command buffer, then the **VkCommandBufferInheritanceInfo** structure defines any state that will be inherited from the primary command buffer:
typedef struct VkCommandBufferInheritanceInfo {
    VkStructureType sType;
    const void* pNext;
    VkRenderPass renderPass;
    uint32_t subpass;
    VkFramebuffer framebuffer;
    VkBool32 occlusionQueryEnable;
    VkQueryControlFlags queryFlags;
    VkQueryPipelineStatisticFlags pipelineStatistics;
} VkCommandBufferInheritanceInfo;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **renderPass** is a `VkRenderPass` object defining which render passes the `VkCommandBuffer` will be compatible with and can be executed within. If the `VkCommandBuffer` will not be executed within a render pass instance, `renderPass` is ignored.
- **subpass** is the index of the subpass within the render pass instance that the `VkCommandBuffer` will be executed within. If the `VkCommandBuffer` will not be executed within a render pass instance, `subpass` is ignored.
- **framebuffer** optionally refers to the `VkFramebuffer` object that the `VkCommandBuffer` will be rendering to if it is executed within a render pass instance. It can be `VK_NULL_HANDLE` if the framebuffer is not known, or if the `VkCommandBuffer` will not be executed within a render pass instance.

  **Note**

  Specifying the exact framebuffer that the secondary command buffer will be executed with may result in better performance at command buffer execution time.

- **occlusionQueryEnable** specifies whether the command buffer can be executed while an occlusion query is active in the primary command buffer. If this is `VK_TRUE`, then this command buffer can be executed whether the primary command buffer has an occlusion query active or not. If this is `VK_FALSE`, then the primary command buffer must not have an occlusion query active.

- **queryFlags** specifies the query flags that can be used by an active occlusion query in the primary command buffer when this secondary command buffer is executed. If this value includes the `VK_QUERY_CONTROL_PRECISE_BIT` bit, then the active query can return boolean results or actual sample counts. If this bit is not set, then the active query must not use the `VK_QUERY_CONTROL_PRECISE_BIT` bit.

- **pipelineStatistics** is a bitmask of `VkQueryPipelineStatisticFlagBits` specifying the set of pipeline statistics that can be counted by an active query in the primary command buffer when this secondary command buffer is executed. If this value includes a given bit, then this command buffer can be executed whether the primary command buffer has a pipeline statistics query active that includes this bit or not. If this value excludes a given bit, then the active pipeline statistics query must not be from a query pool that counts that statistic.
Valid Usage

- If the inherited queries feature is not enabled, occlusionQueryEnable must be VK_FALSE
- If the inherited queries feature is enabled, queryFlags must be a valid combination of VkQueryControlFlagBits values
- If the inherited queries feature is not enabled, queryFlags must be 0
- If the pipeline statistics queries feature is enabled, pipelineStatistics must be a valid combination of VkQueryPipelineStatisticFlagBits values
- If the pipeline statistics queries feature is not enabled, pipelineStatistics must be 0

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_COMMAND_BUFFER_INHERITANCE_INFO
- pNext must be NULL
- Both of framebuffer, and renderPass that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkDevice

Note
On some implementations, not using the VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT bit enables command buffers to be patched in-place if needed, rather than creating a copy of the command buffer.

If a command buffer is in the invalid, or executable state, and the command buffer was allocated from a command pool with the VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT flag set, then vkBeginCommandBuffer implicitly resets the command buffer, behaving as if vkResetCommandBuffer had been called with VK_COMMAND_BUFFER_RESET_RELEASE_RESOURCES_BIT not set. After the implicit reset, commandBuffer is moved to the recording state.

Once recording starts, an application records a sequence of commands (vkCmd*) to set state in the command buffer, draw, dispatch, and other commands.

To complete recording of a command buffer, call:

```
VkResult vkEndCommandBuffer(
    VkCommandBuffer commandBuffer);
```

- commandBuffer is the command buffer to complete recording.

If there was an error during recording, the application will be notified by an unsuccessful return code returned by vkEndCommandBuffer. If the application wishes to further use the command buffer, the command buffer must be reset. The command buffer must have been in the recording state, and is moved to the executable state.
Valid Usage

- commandBuffer must be in the recording state.
- If commandBuffer is a primary command buffer, there must not be an active render pass instance.
- All queries made active during the recording of commandBuffer must have been made inactive.

Valid Usage (Implicit)

- commandBuffer must be a valid VkCommandBuffer handle.

Host Synchronization

- Host access to commandBuffer must be externally synchronized.
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized.

Return Codes

**Success**

- VK_SUCCESS

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

When a command buffer is in the executable state, it can be submitted to a queue for execution.

# 5.5. Command Buffer Submission

To submit command buffers to a queue, call:

```c
VkResult vkQueueSubmit(
    VkQueue                                     queue,
    uint32_t                                    submitCount,
    const VkSubmitInfo*                         pSubmits,
    VkFence                                     fence);
```

- queue is the queue that the command buffers will be submitted to.
- submitCount is the number of elements in the pSubmits array.
• **pSubmits** is a pointer to an array of *VkSubmitInfo* structures, each specifying a command buffer submission batch.

• **fence** is an **optional** handle to a fence to be signaled once all submitted command buffers have completed execution. If *fence* is not *VK_NULL_HANDLE*, it defines a fence signal operation.

**Note**
Submission can be a high overhead operation, and applications should attempt to batch work together into as few calls to *vkQueueSubmit* as possible.

*vkQueueSubmit* is a queue submission command, with each batch defined by an element of *pSubmits*. Batches begin execution in the order they appear in *pSubmits*, but may complete out of order.

Fence and semaphore operations submitted with *vkQueueSubmit* have additional ordering constraints compared to other submission commands, with dependencies involving previous and subsequent queue operations. Information about these additional constraints can be found in the *semaphore* and *fence* sections of the synchronization chapter.

Details on the interaction of *pWaitDstStageMask* with synchronization are described in the semaphore wait operation section of the synchronization chapter.

The order that batches appear in *pSubmits* is used to determine submission order, and thus all the implicit ordering guarantees that respect it. Other than these implicit ordering guarantees and any explicit synchronization primitives, these batches may overlap or otherwise execute out of order.

If any command buffer submitted to this queue is in the executable state, it is moved to the pending state. Once execution of all submissions of a command buffer complete, it moves from the pending state, back to the executable state. If a command buffer was recorded with the *VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT* flag, it instead moves to the invalid state.

If *vkQueueSubmit* fails, it may return *VK_ERROR_OUT_OF_HOST_MEMORY* or *VK_ERROR_OUT_OF_DEVICE_MEMORY*. If it does, the implementation must ensure that the state and contents of any resources or synchronization primitives referenced by the submitted command buffers and any semaphores referenced by *pSubmits* is unaffected by the call or its failure. If *vkQueueSubmit* fails in such a way that the implementation is unable to make that guarantee, the implementation must return *VK_ERROR_DEVICE_LOST*. See Lost Device.
Valid Usage

- If `fence` is not `VK_NULL_HANDLE`, `fence` must be unsignaled.

- If `fence` is not `VK_NULL_HANDLE`, `fence` must not be associated with any other queue command that has not yet completed execution on that queue.

- Any calls to `vkCmdSetEvent`, `vkCmdResetEvent` or `vkCmdWaitEvents` that have been recorded into any of the command buffer elements of the `pCommandBuffers` member of any element of `pSubmits`, must not reference any `VkEvent` that is referenced by any of those commands in a command buffer that has been submitted to another queue and is still in the pending state.

- Any stage flag included in any element of the `pWaitDstStageMask` member of any element of `pSubmits` must be a pipeline stage supported by one of the capabilities of `queue`, as specified in the table of supported pipeline stages.

- Each element of the `pSignalSemaphores` member of any element of `pSubmits` must be unsignaled when the semaphore signal operation it defines is executed on the device.

- When a semaphore wait operation referring to a binary semaphore defined by any element of the `pWaitSemaphores` member of any element of `pSubmits` executes on `queue`, there must be no other queues waiting on the same semaphore.

- All elements of the `pWaitSemaphores` member of all elements of `pSubmits` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY` must reference a semaphore signal operation that has been submitted for execution and any semaphore signal operations on which it depends (if any) must have also been submitted for execution.

- Each element of the `pCommandBuffers` member of each element of `pSubmits` must be in the pending or executable state.

- If any element of the `pCommandBuffers` member of any element of `pSubmits` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT`, it must not be in the pending state.

- Any secondary command buffers recorded into any element of the `pCommandBuffers` member of any element of `pSubmits` must be in the pending or executable state.

- If any secondary command buffers recorded into any element of the `pCommandBuffers` member of any element of `pSubmits` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT`, it must not be in the pending state.

- Each element of the `pCommandBuffers` member of each element of `pSubmits` must have been allocated from a `VkCommandPool` that was created for the same queue family `queue` belongs to.

- If any element of `pSubmits->pCommandBuffers` includes a Queue Family Transfer Acquire Operation, there must exist a previously submitted Queue Family Transfer Release Operation on a queue in the queue family identified by the acquire operation, with parameters matching the acquire operation as defined in the definition of such acquire operations, and which happens-before the acquire operation.

- If a command recorded into any element of `pCommandBuffers` was a `vkCmdBeginQuery` whose `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR`, the
profiling lock must have been held continuously on the VkDevice that queue was retrieved from, throughout recording of those command buffers

- Any resource created with VK_SHARING_MODE_EXCLUSIVE that is read by an operation specified by pSubmits must not be owned by any queue family other than the one which queue belongs to, at the time it is executed

Valid Usage (Implicit)

- queue must be a valid VkQueue handle
- If submitCount is not 0, pSubmits must be a valid pointer to an array of submitCount valid VkSubmitInfo structures
- If fence is not VK_NULL_HANDLE, fence must be a valid VkFence handle
- Both of fence, and queue that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to queue must be externally synchronized
- Host access to fence must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>Any</td>
<td>-</td>
</tr>
</tbody>
</table>

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

The VkSubmitInfo structure is defined as:
typedef struct VkSubmitInfo {
    VkStructureType                sType;
    const void*                    pNext;
    uint32_t                       waitSemaphoreCount;
    const VkSemaphore*             pWaitSemaphores;
    const VkPipelineStageFlags*    pWaitDstStageMask;
    uint32_t                       commandBufferCount;
    const VkCommandBuffer*         pCommandBuffers;
    uint32_t                       signalSemaphoreCount;
    const VkSemaphore*             pSignalSemaphores;
} VkSubmitInfo;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **waitSemaphoreCount** is the number of semaphores upon which to wait before executing the command buffers for the batch.
- **pWaitSemaphores** is a pointer to an array of **VkSemaphore** handles upon which to wait before the command buffers for this batch begin execution. If semaphores to wait on are provided, they define a semaphore wait operation.
- **pWaitDstStageMask** is a pointer to an array of pipeline stages at which each corresponding semaphore wait will occur.
- **commandBufferCount** is the number of command buffers to execute in the batch.
- **pCommandBuffers** is a pointer to an array of **VkCommandBuffer** handles to execute in the batch.
- **signalSemaphoreCount** is the number of semaphores to be signaled once the commands specified in **pCommandBuffers** have completed execution.
- **pSignalSemaphores** is a pointer to an array of **VkSemaphore** handles which will be signaled when the command buffers for this batch have completed execution. If semaphores to be signaled are provided, they define a semaphore signal operation.

The order that command buffers appear in **pCommandBuffers** is used to determine submission order, and thus all the implicit ordering guarantees that respect it. Other than these implicit ordering guarantees and any explicit synchronization primitives, these command buffers may overlap or otherwise execute out of order.
Valid Usage

• Each element of `pCommandBuffers` must not have been allocated with `VK_COMMAND_BUFFER_LEVEL_SECONDARY`.

• If the geometry shaders feature is not enabled, each element of `pWaitDstStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`.

• If the tessellation shaders feature is not enabled, each element of `pWaitDstStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`.

• Each element of `pWaitDstStageMask` must not include `VK_PIPELINE_STAGE_HOST_BIT`.

• If any element of `pWaitSemaphores` or `pSignalSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, then the `pNext` chain must include a `VkTimelineSemaphoreSubmitInfo` structure.

• If the `pNext` chain of this structure includes a `VkTimelineSemaphoreSubmitInfo` structure and any element of `pWaitSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, then its `waitSemaphoreValueCount` member must equal `waitSemaphoreCount`.

• If the `pNext` chain of this structure includes a `VkTimelineSemaphoreSubmitInfo` structure and any element of `pSignalSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, then its `signalSemaphoreValueCount` member must equal `signalSemaphoreCount`.

• For each element of `pSignalSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, the corresponding element of `VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues` must have a value greater than the current value of the semaphore when the semaphore signal operation is executed.

• For each element of `pWaitSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, the corresponding element of `VkTimelineSemaphoreSubmitInfo::pWaitSemaphoreValues` must have a value which does not differ from the current value of the semaphore or the value of any outstanding semaphore wait or signal operation on that semaphore by more than `maxTimelineSemaphoreValueDifference`.

• For each element of `pSignalSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, the corresponding element of `VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues` must have a value which does not differ from the current value of the semaphore or the value of any outstanding semaphore wait or signal operation on that semaphore by more than `maxTimelineSemaphoreValueDifference`.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_SUBMIT_INFO`
- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either NULL or a pointer to a valid instance of `VkD3D12FenceSubmitInfoKHR`, `VkDeviceGroupSubmitInfo`, `VkPerformanceQuerySubmitInfoKHR`, `VkProtectedSubmitInfo`, `VkTimelineSemaphoreSubmitInfo`, or `VkWin32KeyedMutexAcquireReleaseInfoKHR`
- The `sType` value of each struct in the `pNext` chain must be unique
- If `waitSemaphoreCount` is not 0, `pWaitSemaphores` must be a valid pointer to an array of `waitSemaphoreCount` valid `VkSemaphore` handles
- If `waitSemaphoreCount` is not 0, `pWaitDstStageMask` must be a valid pointer to an array of `waitSemaphoreCount` valid combinations of `VkPipelineStageFlagBits` values
- Each element of `pWaitDstStageMask` must not be 0
- If `commandBufferCount` is not 0, `pCommandBuffers` must be a valid pointer to an array of `commandBufferCount` valid `VkCommandBuffer` handles
- If `signalSemaphoreCount` is not 0, `pSignalSemaphores` must be a valid pointer to an array of `signalSemaphoreCount` valid `VkSemaphore` handles
- Each of the elements of `pCommandBuffers`, the elements of `pSignalSemaphores`, and the elements of `pWaitSemaphores` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

To specify the values to use when waiting for and signaling semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, add a `VkTimelineSemaphoreSubmitInfo` structure to the `pNext` chain of the `VkSubmitInfo` structure when using `vkQueueSubmit` or the `VkBindSparseInfo` structure when using `vkQueueBindSparse`. The `VkTimelineSemaphoreSubmitInfo` structure is defined as:

```c
typedef struct VkTimelineSemaphoreSubmitInfo {
    VkStructureType       sType;
    const void*            pNext;
    uint32_t               waitSemaphoreValueCount;
    const uint64_t*        pWaitSemaphoreValues;
    uint32_t               signalSemaphoreValueCount;
    const uint64_t*        pSignalSemaphoreValues;
} VkTimelineSemaphoreSubmitInfo;
```

or the equivalent

```c
typedef VkTimelineSemaphoreSubmitInfo VkTimelineSemaphoreSubmitInfoKHR;
```

- **sType** is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.

- `waitSemaphoreValueCount` is the number of semaphore wait values specified in `pWaitSemaphoreValues`.

- `pWaitSemaphoreValues` is an array of length `waitSemaphoreValueCount` containing values for the corresponding semaphores in `VkSubmitInfo::pWaitSemaphores` to wait for.

- `signalSemaphoreValueCount` is the number of semaphore signal values specified in `pSignalSemaphoreValues`.

- `pSignalSemaphoreValues` is an array of length `signalSemaphoreValueCount` containing values for the corresponding semaphores in `VkSubmitInfo::pSignalSemaphores` to set when signaled.

If the semaphore in `VkSubmitInfo::pWaitSemaphores` or `VkSubmitInfo::pSignalSemaphores` corresponding to an entry in `pWaitSemaphoreValues` or `pSignalSemaphoreValues` respectively was not created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, the implementation must ignore the value in the `pWaitSemaphoreValues` or `pSignalSemaphoreValues` entry.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_TIMELINE_SEMAPHORE_SUBMIT_INFO`

- If `waitSemaphoreValueCount` is not 0, and `pWaitSemaphoreValues` is not `NULL`, `pWaitSemaphoreValues` must be a valid pointer to an array of `waitSemaphoreValueCount` `uint64_t` values

- If `signalSemaphoreValueCount` is not 0, and `pSignalSemaphoreValues` is not `NULL`, `pSignalSemaphoreValues` must be a valid pointer to an array of `signalSemaphoreValueCount` `uint64_t` values

To specify the values to use when waiting for and signaling semaphores whose current payload refers to a Direct3D 12 fence, add a `VkD3D12FenceSubmitInfoKHR` structure to the `pNext` chain of the `VkSubmitInfo` structure. The `VkD3D12FenceSubmitInfoKHR` structure is defined as:

```c
typedef struct VkD3D12FenceSubmitInfoKHR {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           waitSemaphoreValuesCount;
    const uint64_t*    pWaitSemaphoreValues;
    uint32_t           signalSemaphoreValuesCount;
    const uint64_t*    pSignalSemaphoreValues;
} VkD3D12FenceSubmitInfoKHR;
```

- `sType` is the type of this structure.

- `pNext` is `NULL` or a pointer to an extension-specific structure.

- `waitSemaphoreValuesCount` is the number of semaphore wait values specified in `pWaitSemaphoreValues`.

- `pWaitSemaphoreValues` is a pointer to an array of `waitSemaphoreValuesCount` values for the
corresponding semaphores in VkSubmitInfo::pWaitSemaphores to wait for.

- signalSemaphoreValuesCount is the number of semaphore signal values specified in pSignalSemaphoreValues.
- pSignalSemaphoreValues is a pointer to an array of signalSemaphoreValuesCount values for the corresponding semaphores in VkSubmitInfo::pSignalSemaphores to set when signaled.

If the semaphore in VkSubmitInfo::pWaitSemaphores or VkSubmitInfo::pSignalSemaphores corresponding to an entry in pWaitSemaphoreValues or pSignalSemaphoreValues respectively does not currently have a payload referring to a Direct3D 12 fence, the implementation must ignore the value in the pWaitSemaphoreValues or pSignalSemaphoreValues entry.

Note
As the introduction of the external semaphore handle type VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT predates that of timeline semaphores, support for importing semaphore payloads from external handles of that type into semaphores created (implicitly or explicitly) with a VkSemaphoreType of VK_SEMAPHORE_TYPE_BINARY is preserved for backwards compatibility. However, applications should prefer importing such handle types into semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE, and use the VkTimelineSemaphoreSubmitInfo structure instead of the VkD3D12FenceSubmitInfoKHR structure to specify the values to use when waiting for and signaling such semaphores.

Valid Usage

- waitSemaphoreValuesCount must be the same value as VkSubmitInfo::waitSemaphoreCount, where VkSubmitInfo is in the pNext chain of this VkD3D12FenceSubmitInfoKHR structure.

- signalSemaphoreValuesCount must be the same value as VkSubmitInfo::signalSemaphoreCount, where VkSubmitInfo is in the pNext chain of this VkD3D12FenceSubmitInfoKHR structure.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_D3D12_FENCE_SUBMIT_INFO_KHR

- If waitSemaphoreValuesCount is not 0, and pWaitSemaphoreValues is not NULL, pWaitSemaphoreValues must be a valid pointer to an array of waitSemaphoreValuesCount uint64_t values.

- If signalSemaphoreValuesCount is not 0, and pSignalSemaphoreValues is not NULL, pSignalSemaphoreValues must be a valid pointer to an array of signalSemaphoreValuesCount uint64_t values.

When submitting work that operates on memory imported from a Direct3D 11 resource to a queue, the keyed mutex mechanism may be used in addition to Vulkan semaphores to synchronize the work. Keyed mutexes are a property of a properly created shareable Direct3D 11 resource.
can only be used if the imported resource was created with the
D3D11_RESOURCE_MISC_SHARED_KEYEDMUTEX flag.

To acquire keyed mutexes before submitted work and/or release them after, add a
VkWin32KeyedMutexAcquireReleaseInfoKHR structure to the pNext chain of the VkSubmitInfo
structure.

The VkWin32KeyedMutexAcquireReleaseInfoKHR structure is defined as:

```c
typedef struct VkWin32KeyedMutexAcquireReleaseInfoKHR {
    VkStructureType          sType;
    const void*              pNext;
    uint32_t                 acquireCount;
    const VkDeviceMemory*    pAcquireSyncs;
    const uint64_t*          pAcquireKeys;
    const uint32_t*          pAcquireTimeouts;
    uint32_t                 releaseCount;
    const VkDeviceMemory*    pReleaseSyncs;
    const uint64_t*          pReleaseKeys;
} VkWin32KeyedMutexAcquireReleaseInfoKHR;
```

- acquireCount is the number of entries in the pAcquireSyncs, pAcquireKeys, and
  pAcquireTimeoutMilliseconds arrays.

- pAcquireSyncs is a pointer to an array of VkDeviceMemory objects which were imported from
  Direct3D 11 resources.

- pAcquireKeys is a pointer to an array of mutex key values to wait for prior to beginning the
  submitted work. Entries refer to the keyed mutex associated with the corresponding entries in
  pAcquireSyncs.

- pAcquireTimeoutMilliseconds is a pointer to an array of timeout values, in millisecond units, for
  each acquire specified in pAcquireKeys.

- releaseCount is the number of entries in the pReleaseSyncs and pReleaseKeys arrays.

- pReleaseSyncs is a pointer to an array of VkDeviceMemory objects which were imported from
  Direct3D 11 resources.

- pReleaseKeys is a pointer to an array of mutex key values to set when the submitted work has
  completed. Entries refer to the keyed mutex associated with the corresponding entries in
  pReleaseSyncs.

Valid Usage

- Each member of pAcquireSyncs and pReleaseSyncs must be a device memory object
  imported by setting VkImportMemoryWin32HandleInfoKHR::handleType to
  VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT
  or
  VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT.
Valid Usage (Implicit)

- sType must be `VK_STRUCTURE_TYPE_WIN32_KEYED_MUTEX_ACQUIRE_RELEASE_INFO_KHR`
- If acquireCount is not 0, pAcquireSyncs must be a valid pointer to an array of acquireCount valid `VkDeviceMemory` handles
- If acquireCount is not 0, pAcquireKeys must be a valid pointer to an array of acquireCount `uint64_t` values
- If acquireCount is not 0, pAcquireTimeouts must be a valid pointer to an array of acquireCount `uint32_t` values
- If releaseCount is not 0, pReleaseSyncs must be a valid pointer to an array of releaseCount valid `VkDeviceMemory` handles
- If releaseCount is not 0, pReleaseKeys must be a valid pointer to an array of releaseCount `uint64_t` values
- Both of the elements of pAcquireSyncs, and the elements of pReleaseSyncs that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

If the `pNext` chain of `VkSubmitInfo` includes a `VkProtectedSubmitInfo` structure, then the structure indicates whether the batch is protected. The `VkProtectedSubmitInfo` structure is defined as:

```c
typedef struct VkProtectedSubmitInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkBool32           protectedSubmit;
} VkProtectedSubmitInfo;
```

- protectedSubmit specifies whether the batch is protected. If protectedSubmit is `VK_TRUE`, the batch is protected. If protectedSubmit is `VK_FALSE`, the batch is unprotected. If the `VkSubmitInfo::pNext` chain does not include this structure, the batch is unprotected.

Valid Usage

- If the protected memory feature is not enabled, protectedSubmit must not be `VK_TRUE`.
- If protectedSubmit is `VK_TRUE`, then each element of the pCommandBuffers array must be a protected command buffer.
- If protectedSubmit is `VK_FALSE`, then each element of the pCommandBuffers array must be an unprotected command buffer.
- If the `VkSubmitInfo::pNext` chain does not include a `VkProtectedSubmitInfo` structure, then each element of the command buffer of the pCommandBuffers array must be an unprotected command buffer.
Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_PROTECTED_SUBMIT_INFO**

If the **pNext** chain of **VkSubmitInfo** includes a **VkDeviceGroupSubmitInfo** structure, then that structure includes device indices and masks specifying which physical devices execute semaphore operations and command buffers.

The **VkDeviceGroupSubmitInfo** structure is defined as:

```c
typedef struct VkDeviceGroupSubmitInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           waitSemaphoreCount;
    const uint32_t*    pWaitSemaphoreDeviceIndices;
    uint32_t           commandBufferCount;
    const uint32_t*    pCommandBufferDeviceMasks;
    uint32_t           signalSemaphoreCount;
    const uint32_t*    pSignalSemaphoreDeviceIndices;
} VkDeviceGroupSubmitInfo;
```

or the equivalent

```c
typedef VkDeviceGroupSubmitInfo VkDeviceGroupSubmitInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **waitSemaphoreCount** is the number of elements in the **pWaitSemaphoreDeviceIndices** array.
- **pWaitSemaphoreDeviceIndices** is a pointer to an array of **waitSemaphoreCount** device indices indicating which physical device executes the semaphore wait operation in the corresponding element of **VkSubmitInfo::pWaitSemaphores**.
- **commandBufferCount** is the number of elements in the **pCommandBufferDeviceMasks** array.
- **pCommandBufferDeviceMasks** is a pointer to an array of **commandBufferCount** device masks indicating which physical devices execute the command buffer in the corresponding element of **VkSubmitInfo::pCommandBuffers**. A physical device executes the command buffer if the corresponding bit is set in the mask.
- **signalSemaphoreCount** is the number of elements in the **pSignalSemaphoreDeviceIndices** array.
- **pSignalSemaphoreDeviceIndices** is a pointer to an array of **signalSemaphoreCount** device indices indicating which physical device executes the semaphore signal operation in the corresponding element of **VkSubmitInfo::pSignalSemaphores**.

If this structure is not present, semaphore operations and command buffers execute on device index zero.
Valid Usage

- `waitSemaphoreCount` must equal `VkSubmitInfo::waitSemaphoreCount`
- `commandBufferCount` must equal `VkSubmitInfo::commandBufferCount`
- `signalSemaphoreCount` must equal `VkSubmitInfo::signalSemaphoreCount`
- All elements of `pWaitSemaphoreDeviceIndices` and `pSignalSemaphoreDeviceIndices` must be valid device indices
- All elements of `pCommandBufferDeviceMasks` must be valid device masks

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_DEVICE_GROUP_SUBMIT_INFO`
- If `waitSemaphoreCount` is not 0, `pWaitSemaphoreDeviceIndices` must be a valid pointer to an array of `waitSemaphoreCount uint32_t` values
- If `commandBufferCount` is not 0, `pCommandBufferDeviceMasks` must be a valid pointer to an array of `commandBufferCount uint32_t` values
- If `signalSemaphoreCount` is not 0, `pSignalSemaphoreDeviceIndices` must be a valid pointer to an array of `signalSemaphoreCount uint32_t` values

If the `pNext` chain of `VkSubmitInfo` includes a `VkPerformanceQuerySubmitInfoKHR` structure, then the structure indicates which counter pass is active for the batch in that submit.

The `VkPerformanceQuerySubmitInfoKHR` structure is defined as:

```c
typedef struct VkPerformanceQuerySubmitInfoKHR {
    VkStructureType sType;
    const void* pNext;
    uint32_t counterPassIndex;
} VkPerformanceQuerySubmitInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `counterPassIndex` specifies which counter pass index is active.

If the `VkSubmitInfo::pNext` chain does not include this structure, the batch defaults to use counter pass index 0.
Valid Usage

- `counterPassIndex` must be less than the number of counter passes required by any queries within the batch. The required number of counter passes for a performance query is obtained by calling `vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PERFORMANCE_QUERY_SUBMIT_INFO_KHR`.

5.6. Queue Forward Progress

When using binary semaphores, the application must ensure that command buffer submissions will be able to complete without any subsequent operations by the application on any queue. After any call to `vkQueueSubmit` (or other queue operation), for every queued wait on a semaphore created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY` there must be a prior signal of that semaphore that will not be consumed by a different wait on the semaphore.

When using timeline semaphores, wait-before-signal behavior is well-defined and applications can submit work via `vkQueueSubmit` which defines a timeline semaphore wait operation before submitting a corresponding semaphore signal operation. For each timeline semaphore wait operation defined by a call to `vkQueueSubmit`, the application must ensure that a corresponding semaphore signal operation is executed before forward progress can be made.

Command buffers in the submission can include `vkCmdWaitEvents` commands that wait on events that will not be signaled by earlier commands in the queue. Such events must be signaled by the application using `vkSetEvent`, and the `vkCmdWaitEvents` commands that wait upon them must not be inside a render pass instance. The event must be set before the `vkCmdWaitEvents` command is executed.

**Note**

Implementations may have some tolerance for waiting on events to be set, but this is defined outside of the scope of Vulkan.

5.7. Secondary Command Buffer Execution

A secondary command buffer must not be directly submitted to a queue. Instead, secondary command buffers are recorded to execute as part of a primary command buffer with the command:

```c
void vkCmdExecuteCommands(
    VkCommandBuffer                             commandBuffer,  
    uint32_t                                    commandBufferCount,  
    const VkCommandBuffer*                     pCommandBuffers);
```
• `commandBuffer` is a handle to a primary command buffer that the secondary command buffers are executed in.

• `commandBufferCount` is the length of the `pCommandBuffers` array.

• `pCommandBuffers` is a pointer to an array of `commandBufferCount` secondary command buffer handles, which are recorded to execute in the primary command buffer in the order they are listed in the array.

If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, and it was recorded into any other primary command buffer which is currently in the executable or recording state, that primary command buffer becomes invalid.
Valid Usage

- Each element of `pCommandBuffers` must have been allocated with a `level` of `VK_COMMAND_BUFFER_LEVEL_SECONDARY`.
- Each element of `pCommandBuffers` must be in the pending or executable state.
- If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, it must not be in the pending state.
- If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, it must not have already been recorded to `commandBuffer`.
- If any element of `pCommandBuffers` was not recorded with the `VK_COMMAND_BUFFER_USAGE_SIMULTANEOUS_USE_BIT` flag, it must not appear more than once in `pCommandBuffers`.
- Each element of `pCommandBuffers` must have been allocated from a `VkCommandPool` that was created for the same queue family as the `VkCommandPool` from which `commandBuffer` was allocated.
- If `vkCmdExecuteCommands` is being called within a render pass instance, that render pass instance must have been begun with the `contents` parameter of `vkCmdBeginRenderPass` set to `VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS`.
- If `vkCmdExecuteCommands` is being called within a render pass instance, each element of `pCommandBuffers` must have been recorded with the `VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT`.
- If `vkCmdExecuteCommands` is being called within a render pass instance, each element of `pCommandBuffers` must have been recorded with `VkCommandBufferInheritanceInfo::subpass` set to the index of the subpass which the given command buffer will be executed in.
- If `vkCmdExecuteCommands` is being called within a render pass instance, the render passes specified in the `pBeginInfo->pInheritanceInfo->renderPass` members of the `vkBeginCommandBuffer` commands used to begin recording each element of `pCommandBuffers` must be compatible with the current render pass.
- If `vkCmdExecuteCommands` is being called within a render pass instance, and any element of `pCommandBuffers` was recorded with `VkCommandBufferInheritanceInfo::framebuffer` not equal to `VK_NULL_HANDLE`, that `VkFramebuffer` must match the `VkFramebuffer` used in the current render pass instance.
- If `vkCmdExecuteCommands` is not being called within a render pass instance, each element of `pCommandBuffers` must not have been recorded with the `VK_COMMAND_BUFFER_USAGE_RENDER_PASS_CONTINUE_BIT`.
- If the inherited queries feature is not enabled, `commandBuffer` must not have any queries active.
- If `commandBuffer` has a `VK_QUERY_TYPE_OCCLUSION` query active, then each element of `pCommandBuffers` must have been recorded with `VkCommandBufferInheritanceInfo::occlusionQueryEnable` set to `VK_TRUE`.
- If `commandBuffer` has a `VK_QUERY_TYPE_OCCLUSION` query active, then each element of `pCommandBuffers` must have been recorded with `VkCommandBufferInheritanceInfo::occlusionQueryEnable` set to `VK_TRUE`. 

Chapter 5. Command Buffers | 123
::queryFlags having all bits set that are set for the query

- If `commandBuffer` has a `VK_QUERY_TYPE_PIPELINE_STATISTICS` query active, then each element of `pCommandBuffers` must have been recorded with `VkCommandBufferInheritanceInfo::pipelineStatistics` having all bits set that are set in the `VkQueryPool` the query uses

- Each element of `pCommandBuffers` must not begin any query types that are active in `commandBuffer`

- If `commandBuffer` is a protected command buffer, then each element of `pCommandBuffers` must be a protected command buffer

- If `commandBuffer` is an unprotected command buffer, then each element of `pCommandBuffers` must be an unprotected command buffer

### Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle

- `pCommandBuffers` must be a valid pointer to an array of `commandBufferCount` valid `VkCommandBuffer` handles

- `commandBuffer` must be in the `recording state`

- The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations

- `commandBuffer` must be a primary `VkCommandBuffer`

- `commandBufferCount` must be greater than 0

- Both of `commandBuffer`, and the elements of `pCommandBuffers` must have been created, allocated, or retrieved from the same `VkDevice`

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Transfer</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>
5.8. Command Buffer Device Mask

Each command buffer has a piece of state storing the current device mask of the command buffer. This mask controls which physical devices within the logical device all subsequent commands will execute on, including state-setting commands, action commands, and synchronization commands.

Scissor and viewport state can be set to different values on each physical device (only when set as dynamic state), and each physical device will render using its local copy of the state. Other state is shared between physical devices, such that all physical devices use the most recently set values for the state. However, when recording an action command that uses a piece of state, the most recent command that set that state must have included all physical devices that execute the action command in its current device mask.

The command buffer's device mask is orthogonal to the pCommandBufferDeviceMasks member of VkDeviceGroupSubmitInfo. Commands only execute on a physical device if the device index is set in both device masks.

If the pNext chain of VkCommandBufferBeginInfo includes a VkDeviceGroupCommandBufferBeginInfo structure, then that structure includes an initial device mask for the command buffer.

The VkDeviceGroupCommandBufferBeginInfo structure is defined as:

```c
typedef struct VkDeviceGroupCommandBufferBeginInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           deviceMask;
} VkDeviceGroupCommandBufferBeginInfo;
```

or the equivalent

```c
typedef VkDeviceGroupCommandBufferBeginInfo VkDeviceGroupCommandBufferBeginInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **deviceMask** is the initial value of the command buffer's device mask.

The initial device mask also acts as an upper bound on the set of devices that can ever be in the device mask in the command buffer.

If this structure is not present, the initial value of a command buffer's device mask is set to include all physical devices in the logical device when the command buffer begins recording.
Valid Usage

- `deviceMask` **must** be a valid device mask value
- `deviceMask` **must** not be zero

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO`

To update the current device mask of a command buffer, call:

```c
void vkCmdSetDeviceMask(
    VkCommandBuffer commandBuffer,  
    uint32_t deviceMask);
```

or the equivalent command

```c
void vkCmdSetDeviceMaskKHR(
    VkCommandBuffer commandBuffer,  
    uint32_t deviceMask);
```

- `commandBuffer` is command buffer whose current device mask is modified.
- `deviceMask` is the new value of the current device mask.

deviceMask is used to filter out subsequent commands from executing on all physical devices whose bit indices are not set in the mask, except commands beginning a render pass instance, commands transitioning to the next subpass in the render pass instance, and commands ending a render pass instance, which always execute on the set of physical devices whose bit indices are included in the `deviceMask` member of the `VkDeviceGroupRenderPassBeginInfo` structure passed to the command beginning the corresponding render pass instance.

Valid Usage

- `deviceMask` **must** be a valid device mask value
- `deviceMask` **must** not be zero
- `deviceMask` **must** not include any set bits that were not in the `VkDeviceGroupCommandBufferBeginInfo::deviceMask` value when the command buffer began recording.

If `vkCmdSetDeviceMask` is called inside a render pass instance, `deviceMask` **must** not include any set bits that were not in the `VkDeviceGroupRenderPassBeginInfo::deviceMask` value when the render pass instance began recording.
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, compute, or transfer operations

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transfer</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 6. Synchronization and Cache Control

Synchronization of access to resources is primarily the responsibility of the application in Vulkan. The order of execution of commands with respect to the host and other commands on the device has few implicit guarantees, and needs to be explicitly specified. Memory caches and other optimizations are also explicitly managed, requiring that the flow of data through the system is largely under application control.

Whilst some implicit guarantees exist between commands, five explicit synchronization mechanisms are exposed by Vulkan:

**Fences**

Fences **can** be used to communicate to the host that execution of some task on the device has completed.

**Semaphores**

Semaphores **can** be used to control resource access across multiple queues.

**Events**

Events provide a fine-grained synchronization primitive which **can** be signaled either within a command buffer or by the host, and **can** be waited upon within a command buffer or queried on the host.

**Pipeline Barriers**

Pipeline barriers also provide synchronization control within a command buffer, but at a single point, rather than with separate signal and wait operations.

**Render Passes**

Render passes provide a useful synchronization framework for most rendering tasks, built upon the concepts in this chapter. Many cases that would otherwise need an application to use other synchronization primitives **can** be expressed more efficiently as part of a render pass.

6.1. Execution and Memory Dependencies

An *operation* is an arbitrary amount of work to be executed on the host, a device, or an external entity such as a presentation engine. Synchronization commands introduce explicit *execution dependencies*, and *memory dependencies* between two sets of operations defined by the command’s two *synchronization scopes*.

The synchronization scopes define which other operations a synchronization command is able to create execution dependencies with. Any type of operation that is not in a synchronization command’s synchronization scopes will not be included in the resulting dependency. For example, for many synchronization commands, the synchronization scopes **can** be limited to just operations executing in specific *pipeline stages*, which allows other pipeline stages to be excluded from a dependency. Other scoping options are possible, depending on the particular command.
An execution dependency is a guarantee that for two sets of operations, the first set must happen-before the second set. If an operation happens-before another operation, then the first operation must complete before the second operation is initiated. More precisely:

- Let $A$ and $B$ be separate sets of operations.
- Let $S$ be a synchronization command.
- Let $A_S$ and $B_S$ be the synchronization scopes of $S$.
- Let $A'$ be the intersection of sets $A$ and $A_S$.
- Let $B'$ be the intersection of sets $B$ and $B_S$.
- Submitting $A$, $S$ and $B$ for execution, in that order, will result in execution dependency $E$ between $A'$ and $B'$.
- Execution dependency $E$ guarantees that $A'$ happens-before $B'$.

An execution dependency chain is a sequence of execution dependencies that form a happens-before relation between the first dependency's $A'$ and the final dependency's $B'$. For each consecutive pair of execution dependencies, a chain exists if the intersection of $B_S$ in the first dependency and $A_S$ in the second dependency is not an empty set. The formation of a single execution dependency from an execution dependency chain can be described by substituting the following in the description of execution dependencies:

- Let $S$ be a set of synchronization commands that generate an execution dependency chain.
- Let $A_S$ be the first synchronization scope of the first command in $S$.
- Let $B_S$ be the second synchronization scope scope of the last command in $S$.

Execution dependencies alone are not sufficient to guarantee that values resulting from writes in one set of operations can be read from another set of operations.

Three additional types of operation are used to control memory access. Availability operations cause the values generated by specified memory write accesses to become available to a memory domain for future access. Any available value remains available until a subsequent write to the same memory location occurs (whether it is made available or not) or the memory is freed. Memory domain operations cause writes that are available to a source memory domain to become available to a destination memory domain (an example of this is making writes available to the host domain available to the device domain). Visibility operations cause values available to a memory domain to become visible to specified memory accesses.

Availability, visibility, memory domains, and memory domain operations are formally defined in the Availability and Visibility section of the Memory Model chapter. Which API operations perform each of these operations is defined in Availability, Visibility, and Domain Operations.

A memory dependency is an execution dependency which includes availability and visibility operations such that:

- The first set of operations happens-before the availability operation.
- The availability operation happens-before the visibility operation.
- The visibility operation happens-before the second set of operations.
Once written values are made visible to a particular type of memory access, they can be read or written by that type of memory access. Most synchronization commands in Vulkan define a memory dependency.

The specific memory accesses that are made available and visible are defined by the access scopes of a memory dependency. Any type of access that is in a memory dependency's first access scope and occurs in \(A'\) is made available. Any type of access that is in a memory dependency's second access scope and occurs in \(B'\) has any available writes made visible to it. Any type of operation that is not in a synchronization command's access scopes will not be included in the resulting dependency.

A memory dependency enforces availability and visibility of memory accesses and execution order between two sets of operations. Adding to the description of execution dependency chains:

- Let \(a\) be the set of memory accesses performed by \(A'\).
- Let \(b\) be the set of memory accesses performed by \(B'\).
- Let \(a_s\) be the first access scope of the first command in \(S\).
- Let \(b_s\) be the second access scope of the last command in \(S\).
- Let \(a'\) be the intersection of sets \(a\) and \(a_s\).
- Let \(b'\) be the intersection of sets \(b\) and \(b_s\).
- Submitting \(A, S\) and \(B\) for execution, in that order, will result in a memory dependency \(m\) between \(A'\) and \(B'\).
- Memory dependency \(m\) guarantees that:
  - Memory writes in \(a'\) are made available.
  - Available memory writes, including those from \(a'\), are made visible to \(b'\).

**Note**

Execution and memory dependencies are used to solve data hazards, i.e. to ensure that read and write operations occur in a well-defined order. Write-after-read hazards can be solved with just an execution dependency, but read-after-write and write-after-write hazards need appropriate memory dependencies to be included between them. If an application does not include dependencies to solve these hazards, the results and execution orders of memory accesses are undefined.

### 6.1.1. Image Layout Transitions

Image subresources can be transitioned from one layout to another as part of a memory dependency (e.g. by using an image memory barrier). When a layout transition is specified in a memory dependency, it happens-after the availability operations in the memory dependency, and happens-before the visibility operations. Image layout transitions may perform read and write accesses on all memory bound to the image subresource range, so applications must ensure that all memory writes have been made available before a layout transition is executed. Available memory is automatically made visible to a layout transition, and writes performed by a layout transition are automatically made available.
Layout transitions always apply to a particular image subresource range, and specify both an old layout and new layout. If the old layout does not match the new layout, a transition occurs. The old layout must match the current layout of the image subresource range, with one exception. The old layout can always be specified as VK_IMAGE_LAYOUT_UNDEFINED, though doing so invalidates the contents of the image subresource range.

### Note
Setting the old layout to VK_IMAGE_LAYOUT_UNDEFINED implies that the contents of the image subresource need not be preserved. Implementations may use this information to avoid performing expensive data transition operations.

As image layout transitions may perform read and write accesses on the memory bound to the image, if the image subresource affected by the layout transition is bound to peer memory for any device in the current device mask then the memory heap the bound memory comes from must support the VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT and VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT capabilities as returned by vkGetDeviceGroupPeerMemoryFeatures.

### Note
Applications must ensure that layout transitions happen-after all operations accessing the image with the old layout, and happen-before any operations that will access the image with the new layout. Layout transitions are potentially read/write operations, so not defining appropriate memory dependencies to guarantee this will result in a data race.

Image layout transitions interact with memory aliasing.

### 6.1.2. Pipeline Stages

The work performed by an action or synchronization command consists of multiple operations, which are performed as a sequence of logically independent steps known as pipeline stages. The exact pipeline stages executed depend on the particular command that is used, and current command buffer state when the command was recorded. Drawing commands, dispatching commands, copy commands, clear commands, and synchronization commands all execute in different sets of pipeline stages. Synchronization commands do not execute in a defined pipeline, but do execute VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT and VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT.

### Note
Operations performed by synchronization commands (e.g. availability and visibility operations) are not executed by a defined pipeline stage. However other commands can still synchronize with them via the VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT and VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT pipeline stages.

Execution of operations across pipeline stages must adhere to implicit ordering guarantees, particularly including pipeline stage order. Otherwise, execution across pipeline stages may overlap or execute out of order with regards to other stages, unless otherwise enforced by an execution dependency.
Several of the synchronization commands include pipeline stage parameters, restricting the synchronization scopes for that command to just those stages. This allows fine grained control over the exact execution dependencies and accesses performed by action commands. Implementations should use these pipeline stages to avoid unnecessary stalls or cache flushing.

Bits which can be set, specifying pipeline stages, are:

```c
typedef enum VkPipelineStageFlagBits {
    VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT = 0x00000001,
    VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT = 0x00000002,
    VK_PIPELINE_STAGE_VERTEX_INPUT_BIT = 0x00000004,
    VK_PIPELINE_STAGE_VERTEX_SHADER_BIT = 0x00000008,
    VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT = 0x00000010,
    VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT = 0x00000020,
    VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT = 0x00000040,
    VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT = 0x00000080,
    VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT = 0x00000100,
    VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT = 0x00000200,
    VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT = 0x00000400,
    VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT = 0x00000800,
    VK_PIPELINE_STAGE_TRANSFER_BIT = 0x00001000,
    VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT = 0x00002000,
    VK_PIPELINE_STAGE_HOST_BIT = 0x00004000,
    VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT = 0x00008000,
    VK_PIPELINE_STAGE_ALL_COMMANDS_BIT = 0x00010000,
    VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR = 0x00200000,
    VK_PIPELINE_STAGE_ACCELERATION_STRUCTURE_BUILD_BIT_KHR = 0x02000000,
    VK_PIPELINE_STAGE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkPipelineStageFlagBits;
```

- **VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT** specifies the stage of the pipeline where any commands are initially received by the queue.
- **VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT** specifies the stage of the pipeline where Draw/DispatchIndirect data structures are consumed.
- **VK_PIPELINE_STAGE_VERTEX_INPUT_BIT** specifies the stage of the pipeline where vertex and index buffers are consumed.
- **VK_PIPELINE_STAGE_VERTEX_SHADER_BIT** specifies the vertex shader stage.
- **VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT** specifies the tessellation control shader stage.
- **VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT** specifies the tessellation evaluation shader stage.
- **VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT** specifies the geometry shader stage.
- **VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT** specifies the fragment shader stage.
- **VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT** specifies the stage of the pipeline where early fragment tests (depth and stencil tests before fragment shading) are performed. This stage also
includes subpass load operations for framebuffer attachments with a depth/stencil format.

- **VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT** specifies the stage of the pipeline where late fragment tests (depth and stencil tests after fragment shading) are performed. This stage also includes subpass store operations for framebuffer attachments with a depth/stencil format.

- **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT** specifies the stage of the pipeline after blending where the final color values are output from the pipeline. This stage also includes subpass load and store operations and multisample resolve operations for framebuffer attachments with a color or depth/stencil format.

- **VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT** specifies the execution of a compute shader.

- **VK_PIPELINE_STAGE_TRANSFER_BIT** specifies the following commands:
  - All copy commands, including `vkCmdCopyQueryPoolResults`
  - `vkCmdBlitImage`
  - `vkCmdResolveImage`
  - All clear commands, with the exception of `vkCmdClearAttachments`

- **VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT** specifies the final stage in the pipeline where operations generated by all commands complete execution.

- **VK_PIPELINE_STAGE_HOST_BIT** specifies a pseudo-stage indicating execution on the host of reads/writes of device memory. This stage is not invoked by any commands recorded in a command buffer.

- **VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR** specifies the execution of the ray tracing shader stages.

- **VK_PIPELINE_STAGE_ACCELERATION_STRUCTURE_BUILD_BIT_KHR** specifies the execution of `vkCmdBuildAccelerationStructureKHR`, `vkCmdCopyAccelerationStructureKHR`, and `vkCmdWriteAccelerationStructuresPropertiesKHR`.

- **VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT** specifies the execution of all graphics pipeline stages, and is equivalent to the logical OR of:
  - **VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT**
  - **VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT**
  - **VK_PIPELINE_STAGE_VERTEX_INPUT_BIT**
  - **VK_PIPELINE_STAGE_VERTEX_SHADER_BIT**
  - **VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT**
  - **VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT**
  - **VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT**
  - **VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT**
  - **VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT**
  - **VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT**
  - **VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT**
  - **VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT**

- **VK_PIPELINE_STAGE_ALL_COMMANDS_BIT** is equivalent to the logical OR of every other pipeline stage flag that is supported on the queue it is used with.
Note
An execution dependency with only `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT` in the destination stage mask will only prevent that stage from executing in subsequently submitted commands. As this stage does not perform any actual execution, this is not observable - in effect, it does not delay processing of subsequent commands. Similarly an execution dependency with only `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT` in the source stage mask will effectively not wait for any prior commands to complete.

When defining a memory dependency, using only `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT` or `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT` would never make any accesses available and/or visible because these stages do not access memory.

`VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT` and `VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT` are useful for accomplishing layout transitions and queue ownership operations when the required execution dependency is satisfied by other means - for example, semaphore operations between queues.

```
typedef VkFlags VkPipelineStageFlags;
```

`VkPipelineStageFlags` is a bitmask type for setting a mask of zero or more `VkPipelineStageFlagBits`.

If a synchronization command includes a source stage mask, its first synchronization scope only includes execution of the pipeline stages specified in that mask, and its first access scope only includes memory access performed by pipeline stages specified in that mask. If a synchronization command includes a destination stage mask, its second synchronization scope only includes execution of the pipeline stages specified in that mask, and its second access scope only includes memory access performed by pipeline stages specified in that mask.

Note
Including a particular pipeline stage in the first synchronization scope of a command implicitly includes logically earlier pipeline stages in the synchronization scope. Similarly, the second synchronization scope includes logically later pipeline stages.

However, note that access scopes are not affected in this way - only the precise stages specified are considered part of each access scope.

Certain pipeline stages are only available on queues that support a particular set of operations. The following table lists, for each pipeline stage flag, which queue capability flag must be supported by the queue. When multiple flags are enumerated in the second column of the table, it means that the pipeline stage is supported on the queue if it supports any of the listed capability flags. For further details on queue capabilities see Physical Device Enumeration and Queues.

```
<table>
<thead>
<tr>
<th>Pipeline Stage Flag</th>
<th>Queue Capability Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

Table 3. Supported pipeline stage flags
<table>
<thead>
<tr>
<th>Pipeline stage flag</th>
<th>Required queue capability flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_VERTEX_INPUT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_VERTEX_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT</td>
<td>VK_QUEUE_COMPUTE_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_TRANSFER_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT, VK_QUEUE_COMPUTE_BIT or VK_QUEUE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_HOST_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT</td>
<td>VK_QUEUE_GRAPHICS_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_ALL_COMMANDS_BIT</td>
<td>None required</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR</td>
<td>VK_QUEUE_COMPUTE_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_ACCELERATION_STRUCTURE_BUILD_BIT_KHR</td>
<td>VK_QUEUE_COMPUTE_BIT</td>
</tr>
</tbody>
</table>

Pipeline stages that execute as a result of a command logically complete execution in a specific order, such that completion of a logically later pipeline stage **must** not happen-before completion of a logically earlier stage. This means that including any stage in the source stage mask for a particular synchronization command also implies that any logically earlier stages are included in A, for that command.

Similarly, initiation of a logically earlier pipeline stage **must** not happen-after initiation of a logically later pipeline stage. Including any given stage in the destination stage mask for a particular synchronization command also implies that any logically later stages are included in B, for that command.
Note

Implementations may not support synchronization at every pipeline stage for every synchronization operation. If a pipeline stage that an implementation does not support synchronization for appears in a source stage mask, it may substitute any logically later stage in its place for the first synchronization scope. If a pipeline stage that an implementation does not support synchronization for appears in a destination stage mask, it may substitute any logically earlier stage in its place for the second synchronization scope.

For example, if an implementation is unable to signal an event immediately after vertex shader execution is complete, it may instead signal the event after color attachment output has completed.

If an implementation makes such a substitution, it must not affect the semantics of execution or memory dependencies or image and buffer memory barriers.

The order and set of pipeline stages executed by a given command is determined by the command’s pipeline type, as described below:

For the graphics pipeline, the following stages occur in this order:

- VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
- VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
- VK_PIPELINE_STAGE_VERTEX_INPUT_BIT
- VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
- VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT
- VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT
- VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT
- VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT
- VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT
- VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT

For the compute pipeline, the following stages occur in this order:

- VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
- VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT
- VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT
- VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT

For the transfer pipeline, the following stages occur in this order:

- VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT
- VK_PIPELINE_STAGE_TRANSFER_BIT
- VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT

For host operations, only one pipeline stage occurs, so no order is guaranteed:
For the ray tracing shader pipeline, only one pipeline stage occurs, so no order is guaranteed:

- **VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR**

For ray tracing acceleration structure operations, only one pipeline stage occurs, so no order is guaranteed:

- **VK_PIPELINE_STAGE_ACCELERATION_STRUCTURE_BUILD_BIT_KHR**

### 6.1.3. Access Types

Memory in Vulkan can be accessed from within shader invocations and via some fixed-function stages of the pipeline. The *access type* is a function of the *descriptor type* used, or how a fixed-function stage accesses memory. Each access type corresponds to a bit flag in `VkAccessFlagBits`.

Some synchronization commands take sets of access types as parameters to define the *access scopes* of a memory dependency. If a synchronization command includes a source access mask, its first *access scope* only includes accesses via the access types specified in that mask. Similarly, if a synchronization command includes a destination access mask, its second *access scope* only includes accesses via the access types specified in that mask.

Access types that can be set in an access mask include:

```c
typedef enum VkAccessFlagBits {
    VK_ACCESS_INDIRECT_COMMAND_READ_BIT = 0x00000001,
    VK_ACCESS_INDEX_READ_BIT = 0x00000002,
    VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT = 0x00000004,
    VK_ACCESS_UNIFORM_READ_BIT = 0x00000008,
    VK_ACCESS_INPUT_ATTACHMENT_READ_BIT = 0x00000010,
    VK_ACCESS_SHADER_READ_BIT = 0x00000020,
    VK_ACCESS_SHADER_WRITE_BIT = 0x00000040,
    VK_ACCESS_COLOR_ATTACHMENT_READ_BIT = 0x00000080,
    VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT = 0x00000100,
    VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT = 0x00000200,
    VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT = 0x00000400,
    VK_ACCESS_TRANSFER_READ_BIT = 0x00000800,
    VK_ACCESS_TRANSFER_WRITE_BIT = 0x00001000,
    VK_ACCESS_HOST_READ_BIT = 0x00002000,
    VK_ACCESS_HOST_WRITE_BIT = 0x00004000,
    VK_ACCESS_MEMORY_READ_BIT = 0x00008000,
    VK_ACCESS_MEMORY_WRITE_BIT = 0x00010000,
    VK_ACCESS_ACCELERATION_STRUCTURE_READ_BIT_KHR = 0x00200000,
    VK_ACCESS_ACCELERATION_STRUCTURE_WRITE_BIT_KHR = 0x00400000,
    VK_ACCESS_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkAccessFlagBits;
```

- **VK_ACCESS_INDIRECT_COMMAND_READ_BIT** specifies read access to indirect command data read as part of an indirect drawing or dispatch command.
• **VK_ACCESS_INDEX_READ_BIT** specifies read access to an index buffer as part of an indexed drawing command, bound by `vkCmdBindIndexBuffer`.

• **VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT** specifies read access to a vertex buffer as part of a drawing command, bound by `vkCmdBindVertexBuffers`.

• **VK_ACCESS_UNIFORM_READ_BIT** specifies read access to a uniform buffer.

• **VK_ACCESS_INPUT_ATTACHMENT_READ_BIT** specifies read access to an input attachment within a render pass during fragment shading.

• **VK_ACCESS_SHADER_READ_BIT** specifies read access to a storage buffer, physical storage buffer, uniform texel buffer, storage texel buffer, sampled image, or storage image.

• **VK_ACCESS_SHADER_WRITE_BIT** specifies write access to a storage buffer, physical storage buffer, storage texel buffer, or storage image.

• **VK_ACCESS_COLOR_ATTACHMENT_READ_BIT** specifies read access to a color attachment, such as via blending, logic operations, or via certain subpass load operations.

• **VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT** specifies write access to a color, resolve, or depth/stencil resolve attachment during a render pass or via certain subpass load and store operations.

• **VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT** specifies read access to a depth/stencil attachment, via depth or stencil operations or via certain subpass load operations.

• **VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT** specifies write access to a depth/stencil attachment, via depth or stencil operations or via certain subpass load and store operations.

• **VK_ACCESS_TRANSFER_READ_BIT** specifies read access to an image or buffer in a copy operation.

• **VK_ACCESS_TRANSFER_WRITE_BIT** specifies write access to an image or buffer in a clear or copy operation.

• **VK_ACCESS_HOST_READ_BIT** specifies read access by a host operation. Accesses of this type are not performed through a resource, but directly on memory.

• **VK_ACCESS_HOST_WRITE_BIT** specifies write access by a host operation. Accesses of this type are not performed through a resource, but directly on memory.

• **VK_ACCESS_MEMORY_READ_BIT** specifies all read accesses. It is always valid in any access mask, and is treated as equivalent to setting all READ access flags that are valid where it is used.

• **VK_ACCESS_MEMORY_WRITE_BIT** specifies all write accesses. It is always valid in any access mask, and is treated as equivalent to setting all WRITE access flags that are valid where it is used.

• **VK_ACCESS_ACCELERATION_STRUCTURE_READ_BIT_KHR** specifies read access to an acceleration structure as part of a trace or build command.

• **VK_ACCESS_ACCELERATION_STRUCTURE_WRITE_BIT_KHR** specifies write access to an acceleration structure as part of a build command.

Certain access types are only performed by a subset of pipeline stages. Any synchronization command that takes both stage masks and access masks uses both to define the access scopes - only the specified access types performed by the specified stages are included in the access scope. An application **must** not specify an access flag in a synchronization command if it does not include a pipeline stage in the corresponding stage mask that is able to perform accesses of that type. The following table lists, for each access flag, which pipeline stages **can** perform that type of access.
<table>
<thead>
<tr>
<th>Access flag</th>
<th>Supported pipeline stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_ACCESS_INDIRECT_COMMAND_READ_BIT</td>
<td>VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_INDEX_READ_BIT</td>
<td>VK_PIPELINE_STAGE_VERTEX_INPUT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT</td>
<td>VK_PIPELINE_STAGE_VERTEX_INPUT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_UNIFORM_READ_BIT</td>
<td>VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR, VK_PIPELINE_STAGE_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, or VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_SHADER_READ_BIT</td>
<td>VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR, VK_PIPELINE_STAGE_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, or VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_SHADER_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR, VK_PIPELINE_STAGE_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, or VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_INPUT_ATTACHMENT_READ_BIT</td>
<td>VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_COLOR_ATTACHMENT_READ_BIT</td>
<td>VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT</td>
<td>VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT, or VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT, or VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_TRANSFER_READ_BIT</td>
<td>VK_PIPELINE_STAGE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_TRANSFER_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_TRANSFER_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_HOST_READ_BIT</td>
<td>VK_PIPELINE_STAGE_HOST_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_HOST_WRITE_BIT</td>
<td>VK_PIPELINE_STAGE_HOST_BIT</td>
</tr>
<tr>
<td>VK_ACCESS_MEMORY_READ_BIT</td>
<td>Any</td>
</tr>
<tr>
<td>VK_ACCESS_MEMORY_WRITE_BIT</td>
<td>Any</td>
</tr>
<tr>
<td>VK_ACCESS_ACCELERATION_STRUCTURE_READ_BIT_KHR</td>
<td>VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR, or VK_PIPELINE_STAGE_ACCELERATION_STRUCTURE_BUILD_BIT_KHR</td>
</tr>
<tr>
<td>VK_ACCESS_ACCELERATION_STRUCTURE_WRITE_BIT_KHR</td>
<td>VK_PIPELINE_STAGE_ACCELERATION_STRUCTURE_BUILD_BIT_KHR</td>
</tr>
</tbody>
</table>

Chapter 6. Synchronization and Cache Control | 139
If a memory object does not have the `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` property, then `vkFlushMappedMemoryRanges` must be called in order to guarantee that writes to the memory object from the host are made available to the host domain, where they can be further made available to the device domain via a domain operation. Similarly, `vkInvalidateMappedMemoryRanges` must be called to guarantee that writes which are available to the host domain are made visible to host operations.

If the memory object does have the `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` property flag, writes to the memory object from the host are automatically made available to the host domain. Similarly, writes made available to the host domain are automatically made visible to the host.

**Note**
The `vkQueueSubmit` command automatically performs a domain operation from host to device for all writes performed before the command executes, so in most cases an explicit memory barrier is not needed for this case. In the few circumstances where a submit does not occur between the host write and the device read access, writes can be made available by using an explicit memory barrier.

```c
typedef VkFlags VkAccessFlags;
```

`VkAccessFlags` is a bitmask type for setting a mask of zero or more `VkAccessFlagBits`.

### 6.1.4. Framebuffer Region Dependencies

Pipeline stages that operate on, or with respect to, the framebuffer are collectively the *framebuffer-space* pipeline stages. These stages are:

- `VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT`
- `VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT`
- `VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT`
- `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT`

For these pipeline stages, an execution or memory dependency from the first set of operations to the second set can either be a single *framebuffer-global* dependency, or split into multiple *framebuffer-local* dependencies. A dependency with non-framebuffer-space pipeline stages is neither framebuffer-global nor framebuffer-local.

A *framebuffer region* is a set of sample (x, y, layer, sample) coordinates that is a subset of the entire framebuffer.

Both synchronization scopes of a framebuffer-local dependency include only the operations performed within corresponding framebuffer regions (as defined below). No ordering guarantees are made between different framebuffer regions for a framebuffer-local dependency.

Both synchronization scopes of a framebuffer-global dependency include operations on all framebuffer-regions.
If the first synchronization scope includes operations on pixels/fragments with N samples and the second synchronization scope includes operations on pixels/fragments with M samples, where N does not equal M, then a framebuffer region containing all samples at a given \((x, y, \text{layer})\) coordinate in the first synchronization scope corresponds to a region containing all samples at the same coordinate in the second synchronization scope. In other words, it is a pixel granularity dependency. If N equals M, then a framebuffer region containing a single \((x, y, \text{layer}, \text{sample})\) coordinate in the first synchronization scope corresponds to a region containing the same sample at the same coordinate in the second synchronization scope. In other words, it is a sample granularity dependency.

\[\text{Note}\]

Since fragment invocations are not specified to run in any particular groupings, the size of a framebuffer region is implementation-dependent, not known to the application, and **must** be assumed to be no larger than specified above.

\[\text{Note}\]

Practically, the pixel vs sample granularity dependency means that if an input attachment has a different number of samples than the pipeline's `rasterizationSamples`, then a fragment **can** access any sample in the input attachment's pixel even if it only uses framebuffer-local dependencies. If the input attachment has the same number of samples, then the fragment **can only access** the covered samples in its input `SampleMask` (i.e. the fragment operations happen-after a framebuffer-local dependency for each sample the fragment covers). To access samples that are not covered, a framebuffer-global dependency is required.

If a synchronization command includes a `dependencyFlags` parameter, and specifies the `VK_DEPENDENCY_BY_REGION_BIT` flag, then it defines framebuffer-local dependencies for the framebuffer-space pipeline stages in that synchronization command, for all framebuffer regions. If no `dependencyFlags` parameter is included, or the `VK_DEPENDENCY_BY_REGION_BIT` flag is not specified, then a framebuffer-global dependency is specified for those stages. The `VK_DEPENDENCY_BY_REGION_BIT` flag does not affect the dependencies between non-framebuffer-space pipeline stages, nor does it affect the dependencies between framebuffer-space and non-framebuffer-space pipeline stages.

\[\text{Note}\]

Framebuffer-local dependencies are more optimal for most architectures; particularly tile-based architectures - which can keep framebuffer-regions entirely in on-chip registers and thus avoid external bandwidth across such a dependency. Including a framebuffer-global dependency in your rendering will usually force all implementations to flush data to memory, or to a higher level cache, breaking any potential locality optimizations.

### 6.1.5. View-Local Dependencies

In a render pass instance that has `multiview` enabled, dependencies **can** be either view-local or view-global.
A view-local dependency only includes operations from a single source view from the source subpass in the first synchronization scope, and only includes operations from a single destination view from the destination subpass in the second synchronization scope. A view-global dependency includes all views in the view mask of the source and destination subpasses in the corresponding synchronization scopes.

If a synchronization command includes a dependencyFlags parameter and specifies the VK_DEPENDENCY_VIEW_LOCAL_BIT flag, then it defines view-local dependencies for that synchronization command, for all views. If no dependencyFlags parameter is included or the VK_DEPENDENCY_VIEW_LOCAL_BIT flag is not specified, then a view-global dependency is specified.

6.1.6. Device-Local Dependencies

Dependencies can be either device-local or non-device-local. A device-local dependency acts as multiple separate dependencies, one for each physical device that executes the synchronization command, where each dependency only includes operations from that physical device in both synchronization scopes. A non-device-local dependency is a single dependency where both synchronization scopes include operations from all physical devices that participate in the synchronization command. For subpass dependencies, all physical devices in the VkDeviceGroupRenderPassBeginInfo::deviceMask participate in the dependency, and for pipeline barriers all physical devices that are set in the command buffer's current device mask participate in the dependency.

If a synchronization command includes a dependencyFlags parameter and specifies the VK_DEPENDENCY_DEVICE_GROUP_BIT flag, then it defines a non-device-local dependency for that synchronization command. If no dependencyFlags parameter is included or the VK_DEPENDENCY_DEVICE_GROUP_BIT flag is not specified, then it defines device-local dependencies for that synchronization command, for all participating physical devices.

Semaphore and event dependencies are device-local and only execute on the one physical device that performs the dependency.

6.2. Implicit Synchronization Guarantees

A small number of implicit ordering guarantees are provided by Vulkan, ensuring that the order in which commands are submitted is meaningful, and avoiding unnecessary complexity in common operations.

Submission order is a fundamental ordering in Vulkan, giving meaning to the order in which action and synchronization commands are recorded and submitted to a single queue. Explicit and implicit ordering guarantees between commands in Vulkan all work on the premise that this ordering is meaningful. This order does not itself define any execution or memory dependencies; synchronization commands and other orderings within the API use this ordering to define their scopes.

Submission order for any given set of commands is based on the order in which they were recorded to command buffers and then submitted. This order is determined as follows:

1. The initial order is determined by the order in which vkQueueSubmit commands are executed
on the host, for a single queue, from first to last.

2. The order in which VkSubmitInfo structures are specified in the pSubmits parameter of vkQueueSubmit, from lowest index to highest.

3. The order in which command buffers are specified in the pCommandBuffers member of VkSubmitInfo, from lowest index to highest.

4. The order in which commands were recorded to a command buffer on the host, from first to last:
   - For commands recorded outside a render pass, this includes all other commands recorded outside a render pass, including vkCmdBeginRenderPass and vkCmdEndRenderPass commands; it does not directly include commands inside a render pass.
   - For commands recorded inside a render pass, this includes all other commands recorded inside the same subpass, including the vkCmdBeginRenderPass and vkCmdEndRenderPass commands that delimit the same render pass instance; it does not include commands recorded to other subpasses.

**Action and synchronization commands** recorded to a command buffer execute the VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT pipeline stage in submission order - forming an implicit execution dependency between this stage in each command.

**State commands** do not execute any operations on the device, instead they set the state of the command buffer when they execute on the host, in the order that they are recorded. **Action commands** consume the current state of the command buffer when they are recorded, and will execute state changes on the device as required to match the recorded state.

**Query commands**, the order of primitives passing through the graphics pipeline and image layout transitions as part of an image memory barrier provide additional guarantees based on submission order.

Execution of pipeline stages within a given command also has a loose ordering, dependent only on a single command.

**Signal operation order** is a fundamental ordering in Vulkan, giving meaning to the order in which semaphore and fence signal operations occur when submitted to a single queue. The signal operation order for queue operations is determined as follows:

1. The initial order is determined by the order in which vkQueueSubmit commands are executed on the host, for a single queue, from first to last.
2. The order in which VkSubmitInfo structures are specified in the pSubmits parameter of vkQueueSubmit, from lowest index to highest.
3. The fence signal operation defined by the fence parameter of a vkQueueSubmit or vkQueueBindSparse command is ordered after all semaphore signal operations defined by that command.

Semaphore signal operations defined by a single VkSubmitInfo or VkBindSparseInfo structure are unordered with respect to other semaphore signal operations defined within the same VkSubmitInfo or VkBindSparseInfo structure.
The `vkSignalSemaphore` command does not execute on a queue but instead performs the signal operation from the host. The semaphore signal operation defined by executing a `vkSignalSemaphore` command happens-after the `vkSignalSemaphore` command is invoked and happens-before the command returns.

**Note**

When signaling timeline semaphores, it is the responsibility of the client to ensure that they are ordered such that the semaphore value is strictly increasing. Because the first synchronization scope for a semaphore signal operation contains all semaphore signal operations which occur earlier in submission order, all semaphore signal operations contained in any given batch are guaranteed to happen-after all semaphore signal operations contained in any previous batches. However, no ordering guarantee is provided between the semaphore signal operations defined within a single batch. This, combined with the requirement that timeline semaphore values strictly increase, means that it is invalid to signal the same timeline semaphore twice within a single batch.

If a client wishes to ensure that some semaphore signal operation happens-after some other semaphore signal operation, it can submit a separate batch containing only semaphore signal operations, which will happen-after the semaphore signal operations in any earlier batches.

When signaling a semaphore from the host, the only ordering guarantee is that the signal operation happens-after when `vkSignalSemaphore` is called and happens-before it returns. Therefore, it is invalid to call `vkSignalSemaphore` while there are any outstanding signal operations on that semaphore from any queue submissions unless those queue submissions have some dependency which ensures that they happen-after the host signal operation. One example of this would be if the pending signal operation is, itself, waiting on the same semaphore at a lower value and the call to `vkSignalSemaphore` signals that lower value. Furthermore, if there are two or more processes or threads signaling the same timeline semaphore from the host, the client must ensure that the `vkSignalSemaphore` with the lower semaphore value returns before `vkSignalSemaphore` is called with the higher value.

### 6.3. Fences

Fences are a synchronization primitive that can be used to insert a dependency from a queue to the host. Fences have two states - signaled and unsignaled. A fence can be signaled as part of the execution of a `queue submission` command. Fences can be unsignaled on the host with `vkResetFences`. Fences can be waited on by the host with the `vkWaitForFences` command, and the current state can be queried with `vkGetFenceStatus`.

As with most objects in Vulkan, fences are an interface to internal data which is typically opaque to applications. This internal data is referred to as a fence’s *payload*.

However, in order to enable communication with agents outside of the current device, it is necessary to be able to export that payload to a commonly understood format, and subsequently import from that format as well.
The internal data of a fence may include a reference to any resources and pending work associated with signal or unsignal operations performed on that fence object. Mechanisms to import and export that internal data to and from fences are provided below. These mechanisms indirectly enable applications to share fence state between two or more fences and other synchronization primitives across process and API boundaries.

Fences are represented by VkFence handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFence)
```

To create a fence, call:

```
VkResult vkCreateFence(
    VkDevice                                    device,
    const VkFenceCreateInfo*                    pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkFence*                                    pFence);
```

- **device** is the logical device that creates the fence.
- **pCreateInfo** is a pointer to a VkFenceCreateInfo structure containing information about how the fence is to be created.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pFence** is a pointer to a handle in which the resulting fence object is returned.

### Valid Usage (Implicit)

- **device** must be a valid VkDevice handle
- **pCreateInfo** must be a valid pointer to a valid VkFenceCreateInfo structure
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid VkAllocationCallbacks structure
- **pFence** must be a valid pointer to a VkFence handle

### Return Codes

**Success**

- VK_SUCCESS

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkFenceCreateInfo structure is defined as:
typedef struct VkFenceCreateInfo {
    VkStructureType       sType;
    const void*           pNext;
    VkFenceCreateFlags    flags;
} VkFenceCreateInfo;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is a bitmask of VkFenceCreateFlagBits specifying the initial state and behavior of the fence.

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_FENCE_CREATE_INFO
- Each **pNext** member of any structure (including this one) in the **pNext** chain must be either NULL or a pointer to a valid instance of VkExportFenceCreateInfo or VkExportFenceWin32HandleInfoKHR
- The **sType** value of each struct in the **pNext** chain must be unique
- **flags** must be a valid combination of VkFenceCreateFlagBits values

typedef enum VkFenceCreateFlagBits {
    VK_FENCE_CREATE_SIGNALED_BIT = 0x00000001,
    VK_FENCE_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkFenceCreateFlagBits;

- **VK_FENCE_CREATE_SIGNALED_BIT** specifies that the fence object is created in the signaled state. Otherwise, it is created in the unsignaled state.

typedef VkFlags VkFenceCreateFlags;

**VkFenceCreateFlags** is a bitmask type for setting a mask of zero or more VkFenceCreateFlagBits.

To create a fence whose payload can be exported to external handles, add a VkExportFenceCreateInfo structure to the **pNext** chain of the VkFenceCreateInfo structure. The VkExportFenceCreateInfo structure is defined as:

typedef struct VkExportFenceCreateInfo {
    VkStructureType                   sType;
    const void*                       pNext;
    VkExternalFenceHandleTypeFlags    handleTypes;
} VkExportFenceCreateInfo;
typedef VkExportFenceCreateInfo VkExportFenceCreateInfoKHR;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **handleTypes** is a bitmask of **VkExternalFenceHandleTypeFlagBits** specifying one or more fence handle types the application can export from the resulting fence. The application can request multiple handle types for the same fence.

### Valid Usage

- The bits in **handleTypes** must be supported and compatible, as reported by **VkExternalFenceProperties**.

### Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_EXPORT_FENCE_CREATE_INFO**
- **handleTypes** must be a valid combination of **VkExternalFenceHandleTypeFlagBits** values

To specify additional attributes of NT handles exported from a fence, add a **VkExportFenceWin32HandleInfoKHR** structure to the **pNext** chain of the **VkFenceCreateInfo** structure. The **VkExportFenceWin32HandleInfoKHR** structure is defined as:

```c
typedef struct VkExportFenceWin32HandleInfoKHR {
    VkStructureType               sType;
    const void*                   pNext;
    const SECURITY_ATTRIBUTES*    pAttributes;
    DWORD                         dwAccess;
    LPCWSTR                       name;
} VkExportFenceWin32HandleInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **pAttributes** is a pointer to a Windows **SECURITY_ATTRIBUTES** structure specifying security attributes of the handle.
- **dwAccess** is a **DWORD** specifying access rights of the handle.
- **name** is a null-terminated UTF-16 string to associate with the underlying synchronization primitive referenced by NT handles exported from the created fence.

If **VkExportFenceCreateInfo** is not present in the same **pNext** chain, this structure is ignored.
If `VkExportFenceCreateInfo` is present in the `pNext` chain of `VkFenceCreateInfo` with a Windows `handleType`, but either `VkExportFenceWin32HandleInfoKHR` is not present in the `pNext` chain, or if it is but `pAttributes` is set to `NULL`, default security descriptor values will be used, and child processes created by the application will not inherit the handle, as described in the MSDN documentation for “Synchronization Object Security and Access Rights”. Further, if the structure is not present, the access rights will be

```
DXGI_SHARED_RESOURCE_READ | DXGI_SHARED_RESOURCE_WRITE
```

for handles of the following types:

```
VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT
```

1


Valid Usage

- If `VkExportFenceCreateInfo::handleTypes` does not include `VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT`, a `VkExportFenceWin32HandleInfoKHR` structure must not be included in the `pNext` chain of `VkFenceCreateInfo`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_EXPORT_FENCE_WIN32_HANDLE_INFO_KHR`
- If `pAttributes` is not `NULL`, `pAttributes` must be a valid pointer to a valid `SECURITY_ATTRIBUTES` value

To export a Windows handle representing the state of a fence, call:

```
VkResult vkGetFenceWin32HandleKHR(
    VkDevice                                    device,
    const VkFenceGetWin32HandleInfoKHR*         pGetWin32HandleInfo,
    HANDLE*                                     pHandle);
```

- `device` is the logical device that created the fence being exported.
- `pGetWin32HandleInfo` is a pointer to a `VkFenceGetWin32HandleInfoKHR` structure containing parameters of the export operation.
- `pHandle` will return the Windows handle representing the fence state.

For handle types defined as NT handles, the handles returned by `vkGetFenceWin32HandleKHR` are owned by the application. To avoid leaking resources, the application must release ownership of them using the `CloseHandle` system call when they are no longer needed.
Exporting a Windows handle from a fence may have side effects depending on the transference of the specified handle type, as described in Importing Fence Payloads.

Valid Usage (Implicit)

- **device must** be a valid VkDevice handle
- **pGetWin32HandleInfo must** be a valid pointer to a valid VkFenceGetWin32HandleInfoKHR structure
- **pHandle must** be a valid pointer to a HANDLE value

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_TOO_MANY_OBJECTS
- VK_ERROR_OUT_OF_HOST_MEMORY

The VkFenceGetWin32HandleInfoKHR structure is defined as:

```c
typedef struct VkFenceGetWin32HandleInfoKHR {
    VkStructureType                      sType;
    const void*                          pNext;
    VkFence                              fence;
    VkExternalFenceHandleTypeFlagBits    handleType;
} VkFenceGetWin32HandleInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **fence** is the fence from which state will be exported.
- **handleType** is the type of handle requested.

The properties of the handle returned depend on the value of **handleType**. See VkExternalFenceHandleTypeFlagBits for a description of the properties of the defined external fence handle types.
Valid Usage

- `handleType` must have been included in `VkExportFenceCreateInfo::handleTypes` when the fence’s current payload was created.

- If `handleType` is defined as an NT handle, `vkGetFenceWin32HandleKHR` must be called no more than once for each valid unique combination of fence and `handleType`.

- If `handleType` is defined as an NT handle, `vkGetFenceWin32HandleKHR` must be called no more than once for each valid unique combination of fence and `handleType`.

-`fence` must not currently have its payload replaced by an imported payload as described below in Importing Fence Payloads unless that imported payload’s handle type was included in `VkExternalFenceProperties::exportFromImportedHandleTypes` for `handleType`.

- If `handleType` refers to a handle type with copy payload transference semantics, `fence` must be signaled, or have an associated fence signal operation pending execution.

- `handleType` must be defined as an NT handle or a global share handle.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_FENCE_GET_WIN32_HANDLE_INFO_KHR`.
- `pNext` must be `NULL`.
- `fence` must be a valid `VkFence` handle.
- `handleType` must be a valid `VkExternalFenceHandleTypeFlagBits` value.

To export a POSIX file descriptor representing the payload of a fence, call:

```c
VkResult vkGetFenceFdKHR(
    VkDevice device,
    const VkFenceGetFdInfoKHR* pGetFdInfo,
    int* pFd);
```

- `device` is the logical device that created the fence being exported.
- `pGetFdInfo` is a pointer to a `VkFenceGetFdInfoKHR` structure containing parameters of the export operation.
- `pFd` will return the file descriptor representing the fence payload.

Each call to `vkGetFenceFdKHR` must create a new file descriptor and transfer ownership of it to the application. To avoid leaking resources, the application must release ownership of the file descriptor when it is no longer needed.

**Note**

Ownership can be released in many ways. For example, the application can call `close()` on the file descriptor, or transfer ownership back to Vulkan by using the file descriptor to import a fence payload.
If `pGetFdInfo->handleType` is `VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT` and the fence is signaled at the time `vkGetFenceFdKHR` is called, `pFd` may return the value -1 instead of a valid file descriptor.

Where supported by the operating system, the implementation must set the file descriptor to be closed automatically when an `execve` system call is made.

Exporting a file descriptor from a fence may have side effects depending on the transference of the specified handle type, as described in Importing Fence State.

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pGetFdInfo` must be a valid pointer to a valid `VkFenceGetFdInfoKHR` structure
- `pFd` must be a valid pointer to an `int` value

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_TOO_MANY_OBJECTS`
- `VK_ERROR_OUT_OF_HOST_MEMORY`

The `VkFenceGetFdInfoKHR` structure is defined as:

```c
typedef struct VkFenceGetFdInfoKHR {
    VkStructureType                      sType;                      
    const void*                          pNext;                      
    VkFence                              fence;                      
    VkExternalFenceHandleTypeFlagBits    handleType;                 
} VkFenceGetFdInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `fence` is the fence from which state will be exported.
- `handleType` is the type of handle requested.

The properties of the file descriptor returned depend on the value of `handleType`. See `VkExternalFenceHandleTypeFlagBits` for a description of the properties of the defined external fence handle types.
Valid Usage

- `handleType` **must** have been included in `VkExportFenceCreateInfo::handleTypes` when `fence`'s current payload was created.

- If `handleType` refers to a handle type with copy payload transference semantics, `fence` **must** be signaled, or have an associated `fence signal operation` pending execution.

- `fence` **must** not currently have its payload replaced by an imported payload as described below in *Importing Fence Payloads* unless that imported payload's handle type was included in `VkExternalFenceProperties::exportFromImportedHandleTypes` for `handleType`.

- `handleType` **must** be defined as a POSIX file descriptor handle.

Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_FENCE_GET_FD_INFO_KHR`
- `pNext` **must** be `NULL`
- `fence` **must** be a valid `VkFence` handle
- `handleType` **must** be a valid `VkExternalFenceHandleTypeFlagBits` value

To destroy a fence, call:

```c
void vkDestroyFence(  
    VkDevice device,  
    VkFence fence,  
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the fence.
- `fence` is the handle of the fence to destroy.
- `pAllocator` controls host memory allocation as described in the *Memory Allocation* chapter.

Valid Usage

- All queue submission commands that refer to `fence` **must** have completed execution

- If `VkAllocationCallbacks` were provided when `fence` was created, a compatible set of callbacks **must** be provided here

- If no `VkAllocationCallbacks` were provided when `fence` was created, `pAllocator` **must** be `NULL`
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- If `fence` is not `VK_NULL_HANDLE`, `fence` must be a valid `VkFence` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `fence` is a valid handle, it must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `fence` must be externally synchronized

To query the status of a fence from the host, call:

```c
VkResult vkGetFenceStatus(
    VkDevice device,
    VkFence fence);
```

- `device` is the logical device that owns the fence.
- `fence` is the handle of the fence to query.

Upon success, `vkGetFenceStatus` returns the status of the fence object, with the following return codes:

<table>
<thead>
<tr>
<th>Status</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_SUCCESS</td>
<td>The fence specified by <code>fence</code> is signaled.</td>
</tr>
<tr>
<td>VK_NOT_READY</td>
<td>The fence specified by <code>fence</code> is unsignaled.</td>
</tr>
<tr>
<td>VK_ERROR_DEVICE_LOST</td>
<td>The device has been lost. See Lost Device.</td>
</tr>
</tbody>
</table>

If a queue submission command is pending execution, then the value returned by this command may immediately be out of date.

If the device has been lost (see Lost Device), `vkGetFenceStatus` may return any of the above status codes. If the device has been lost and `vkGetFenceStatus` is called repeatedly, it will eventually return either `VK_SUCCESS` or `VK_ERROR_DEVICE_LOST`. 
Valid Usage (Implicit)

- **device** must be a valid VkDevice handle
- **fence** must be a valid VkFence handle
- **fence** must have been created, allocated, or retrieved from device

Return Codes

**Success**
- VK_SUCCESS
- VK_NOT_READY

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

To set the state of fences to unsignaled from the host, call:

```c
VkResult vkResetFences(
    VkDevice                                    device,
    uint32_t                                    fenceCount,
    const VkFence*                              pFences);
```

- **device** is the logical device that owns the fences.
- **fenceCount** is the number of fences to reset.
- **pFences** is a pointer to an array of fence handles to reset.

If any member of **pFences** currently has its payload imported with temporary permanence, that fence’s prior permanent payload is first restored. The remaining operations described therefore operate on the restored payload.

When **vkResetFences** is executed on the host, it defines a fence unsignal operation for each fence, which resets the fence to the unsignaled state.

If any member of **pFences** is already in the unsignaled state when **vkResetFences** is executed, then **vkResetFences** has no effect on that fence.

Valid Usage

- Each element of **pFences** must not be currently associated with any queue command that has not yet completed execution on that queue
Valid Usage (Implicit)

- **device must** be a valid `VkDevice` handle
- **pFences must** be a valid pointer to an array of `fenceCount` valid `VkFence` handles
- **fenceCount must** be greater than 0
- Each element of **pFences must** have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to each member of **pFences must** be externally synchronized

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

When a fence is submitted to a queue as part of a `queue submission` command, it defines a memory dependency on the batches that were submitted as part of that command, and defines a `fence signal operation` which sets the fence to the signaled state.

The first `synchronization scope` includes every batch submitted in the same `queue submission` command. Fence signal operations that are defined by `vkQueueSubmit` additionally include in the first synchronization scope all commands that occur earlier in `submission order`. Fence signal operations that are defined by `vkQueueSubmit` or `vkQueueBindSparse` additionally include in the first synchronization scope any semaphore and fence signal operations that occur earlier in `signal operation order`.

The second `synchronization scope` only includes the fence signal operation.

The first `access scope` includes all memory access performed by the device.

The second `access scope` is empty.

To wait for one or more fences to enter the signaled state on the host, call:
VkResult vkWaitForFences(
    VkDevice device,
    uint32_t fenceCount,
    const VkFence* pFences,
    VkBool32 waitAll,
    uint64_t timeout);  

- **device** is the logical device that owns the fences.
- **fenceCount** is the number of fences to wait on.
- **pFences** is a pointer to an array of **fenceCount** fence handles.
- **waitAll** is the condition that **must** be satisfied to successfully unblock the wait. If **waitAll** is **VK_TRUE**, then the condition is that all fences in **pFences** are signaled. Otherwise, the condition is that at least one fence in **pFences** is signaled.
- **timeout** is the timeout period in units of nanoseconds. **timeout** is adjusted to the closest value allowed by the implementation-dependent timeout accuracy, which **may** be substantially longer than one nanosecond, and **may** be longer than the requested period.

If the condition is satisfied when **vkWaitForFences** is called, then **vkWaitForFences** returns immediately. If the condition is not satisfied at the time **vkWaitForFences** is called, then **vkWaitForFences** will block and wait up to **timeout** nanoseconds for the condition to become satisfied.

If **timeout** is zero, then **vkWaitForFences** does not wait, but simply returns the current state of the fences. **VK_TIMEOUT** will be returned in this case if the condition is not satisfied, even though no actual wait was performed.

If the specified timeout period expires before the condition is satisfied, **vkWaitForFences** returns **VK_TIMEOUT**. If the condition is satisfied before **timeout** nanoseconds has expired, **vkWaitForFences** returns **VK_SUCCESS**.

If device loss occurs (see Lost Device) before the timeout has expired, **vkWaitForFences** **must** return in finite time with either **VK_SUCCESS** or **VK_ERROR_DEVICE_LOST**.

**Note**

While we guarantee that **vkWaitForFences** **must** return in finite time, no guarantees are made that it returns immediately upon device loss. However, the client can reasonably expect that the delay will be on the order of seconds and that calling **vkWaitForFences** will not result in a permanently (or seemingly permanently) dead process.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pFences** must be a valid pointer to an array of `fenceCount` valid `VkFence` handles
- **fenceCount** must be greater than 0
- Each element of **pFences** must have been created, allocated, or retrieved from **device**

Return Codes

**Success**
- VK_SUCCESS
- VK_TIMEOUT

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

An execution dependency is defined by waiting for a fence to become signaled, either via `vkWaitForFences` or by polling on `vkGetFenceStatus`.

The first *synchronization scope* includes only the fence signal operation.

The second *synchronization scope* includes the host operations of `vkWaitForFences` or `vkGetFenceStatus` indicating that the fence has become signaled.

**Note**

Signaling a fence and waiting on the host does not guarantee that the results of memory accesses will be visible to the host, as the access scope of a memory dependency defined by a fence only includes device access. A *memory barrier* or other memory dependency must be used to guarantee this. See the description of *host access types* for more information.

6.3.1. Importing Fence Payloads

Applications can import a fence payload into an existing fence using an external fence handle. The effects of the import operation will be either temporary or permanent, as specified by the application. If the import is temporary, the fence will be *restored* to its permanent state the next time that fence is passed to `vkResetFences`.

**Note**

Restoring a fence to its prior permanent payload is a distinct operation from resetting a fence payload. See `vkResetFences` for more detail.
Performing a subsequent temporary import on a fence before resetting it has no effect on this requirement; the next unsignal of the fence must still restore its last permanent state. A permanent payload import behaves as if the target fence was destroyed, and a new fence was created with the same handle but the imported payload. Because importing a fence payload temporarily or permanently detaches the existing payload from a fence, similar usage restrictions to those applied to \texttt{vkDestroyFence} are applied to any command that imports a fence payload. Which of these import types is used is referred to as the import operation’s \textit{permanence}. Each handle type supports either one or both types of permanence.

The implementation must perform the import operation by either referencing or copying the payload referred to by the specified external fence handle, depending on the handle’s type. The import method used is referred to as the handle type’s \textit{transference}. When using handle types with reference transference, importing a payload to a fence adds the fence to the set of all fences sharing that payload. This set includes the fence from which the payload was exported. Fence signaling, waiting, and resetting operations performed on any fence in the set must behave as if the set were a single fence. Importing a payload using handle types with copy transference creates a duplicate copy of the payload at the time of import, but makes no further reference to it. Fence signaling, waiting, and resetting operations performed on the target of copy imports must not affect any other fence or payload.

Export operations have the same transference as the specified handle type’s import operations. Additionally, exporting a fence payload to a handle with copy transference has the same side effects on the source fence’s payload as executing a fence reset operation. If the fence was using a temporarily imported payload, the fence’s prior permanent payload will be restored.

\begin{note}

The tables \texttt{Handle Types Supported by VkImportFenceWin32HandleInfoKHR} and \texttt{Handle Types Supported by VkImportFenceFdInfoKHR} define the permanence and transference of each handle type.

\end{note}

\textbf{External synchronization} allows implementations to modify an object’s internal state, i.e. payload, without internal synchronization. However, for fences sharing a payload across processes, satisfying the external synchronization requirements of \texttt{VkFence} parameters as if all fences in the set were the same object is sometimes infeasible. Satisfying valid usage constraints on the state of a fence would similarly require impractical coordination or levels of trust between processes. Therefore, these constraints only apply to a specific fence handle, not to its payload. For distinct fence objects which share a payload:

\begin{itemize}

\item If multiple commands which queue a signal operation, or which unsignal a fence, are called concurrently, behavior will be as if the commands were called in an arbitrary sequential order.

\item If a queue submission command is called with a fence that is sharing a payload, and the payload is already associated with another queue command that has not yet completed execution, either one or both of the commands will cause the fence to become signaled when they complete execution.

\item If a fence payload is reset while it is associated with a queue command that has not yet completed execution, the payload will become unsignaled, but may become signaled again when the command completes execution.

\end{itemize}
In the preceding cases, any of the devices associated with the fences sharing the payload may be lost, or any of the queue submission or fence reset commands may return VK_ERROR_INITIALIZATION_FAILED.

Other than these non-deterministic results, behavior is well defined. In particular:

- The implementation must not crash or enter an internally inconsistent state where future valid Vulkan commands might cause undefined results,
- Timeouts on future wait commands on fences sharing the payload must be effective.

**Note**

These rules allow processes to synchronize access to shared memory without trusting each other. However, such processes must still be cautious not to use the shared fence for more than synchronizing access to the shared memory. For example, a process should not use a fence with shared payload to tell when commands it submitted to a queue have completed and objects used by those commands may be destroyed, since the other process can accidentally or maliciously cause the fence to signal before the commands actually complete.

When a fence is using an imported payload, its VkExportFenceCreateInfo::handleTypes value is that specified when creating the fence from which the payload was exported, rather than that specified when creating the fence. Additionally, VkExternalFenceProperties::exportFromImportedHandleTypes restricts which handle types can be exported from such a fence based on the specific handle type used to import the current payload. Passing a fence to vkAcquireNextImageKHR is equivalent to temporarily importing a fence payload to that fence.

**Note**

Because the exportable handle types of an imported fence correspond to its current imported payload, and vkAcquireNextImageKHR behaves the same as a temporary import operation for which the source fence is opaque to the application, applications have no way of determining whether any external handle types can be exported from a fence in this state. Therefore, applications must not attempt to export handles from fences using a temporarily imported payload from vkAcquireNextImageKHR.

When importing a fence payload, it is the responsibility of the application to ensure the external handles meet all valid usage requirements. However, implementations must perform sufficient validation of external handles to ensure that the operation results in a valid fence which will not cause program termination, device loss, queue stalls, host thread stalls, or corruption of other resources when used as allowed according to its import parameters. If the external handle provided does not meet these requirements, the implementation must fail the fence payload import operation with the error code VK_ERROR_INVALID_EXTERNAL_HANDLE.

To import a fence payload from a Windows handle, call:
VkResult vkImportFenceWin32HandleKHR(
    VkDevice                                    device,
    const VkImportFenceWin32HandleInfoKHR*      pImportFenceWin32HandleInfo);

- **device** is the logical device that created the fence.
- **pImportFenceWin32HandleInfo** is a pointer to a `VkImportFenceWin32HandleInfoKHR` structure specifying the fence and import parameters.

Importing a fence payload from Windows handles does not transfer ownership of the handle to the Vulkan implementation. For handle types defined as NT handles, the application **must** release ownership using the `CloseHandle` system call when the handle is no longer needed.

Applications **can** import the same fence payload into multiple instances of Vulkan, into the same instance from which it was exported, and multiple times into a given Vulkan instance.

### Valid Usage (Implicit)

- **device** **must** be a valid `VkDevice` handle
- **pImportFenceWin32HandleInfo** **must** be a valid pointer to a valid `VkImportFenceWin32HandleInfoKHR` structure

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_INVALID_EXTERNAL_HANDLE`

The `VkImportFenceWin32HandleInfoKHR` structure is defined as:

```c
typedef struct VkImportFenceWin32HandleInfoKHR {
    VkStructureType                      sType;
    const void*                          pNext;
    VkFence                              fence;
    VkFenceImportFlags                   flags;
    VkExternalFenceHandleTypeFlagBits    handleType;
    HANDLE                               handle;
    LPCWSTR                              name;
} VkImportFenceWin32HandleInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
• fence is the fence into which the state will be imported.
• flags is a bitmask of VkFenceImportFlagBits specifying additional parameters for the fence payload import operation.
• handleType specifies the type of handle.
• handle is the external handle to import, or NULL.
• name is a null-terminated UTF-16 string naming the underlying synchronization primitive to import, or NULL.

The handle types supported by handleType are:

<table>
<thead>
<tr>
<th>Handle Type</th>
<th>Transference</th>
<th>Permanence Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Reference</td>
<td>Temporary, Permanent</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Reference</td>
<td>Temporary, Permanent</td>
</tr>
</tbody>
</table>

Valid Usage

• handleType must be a value included in the Handle Types Supported by VkImportFenceWin32HandleInfoKHR table.

• If handleType is not VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT, name must be NULL.

• If handleType is not 0 and handle is NULL, name must name a valid synchronization primitive of the type specified by handleType.

• If handleType is not 0 and name is NULL, handle must be a valid handle of the type specified by handleType.

• If handle is not NULL, name must be NULL.

• If handle is not NULL, it must obey any requirements listed for handleType in external fence handle types compatibility.

• If name is not NULL, it must obey any requirements listed for handleType in external fence handle types compatibility.

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_IMPORT_FENCE_WIN32_HANDLE_INFO_KHR
• pNext must be NULL
• fence must be a valid VkFence handle
• flags must be a valid combination of VkFenceImportFlagBits values
• If handleType is not 0, handleType must be a valid VkExternalFenceHandleTypeFlagBits value
Host Synchronization

- Host access to fence must be externally synchronized

To import a fence payload from a POSIX file descriptor, call:

```c
VkResult vkImportFenceFdKHR(
    VkDevice                                    device,
    const VkImportFenceFdInfoKHR*               pImportFenceFdInfo);
```

- device is the logical device that created the fence.
- pImportFenceFdInfo is a pointer to a VkImportFenceFdInfoKHR structure specifying the fence and import parameters.

Importing a fence payload from a file descriptor transfers ownership of the file descriptor from the application to the Vulkan implementation. The application must not perform any operations on the file descriptor after a successful import.

Applications can import the same fence payload into multiple instances of Vulkan, into the same instance from which it was exported, and multiple times into a given Vulkan instance.

Valid Usage

- fence must not be associated with any queue command that has not yet completed execution on that queue

Valid Usage (Implicit)

- device must be a valid VkDevice handle
- pImportFenceFdInfo must be a valid pointer to a valid VkImportFenceFdInfoKHR structure

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_INVALID_EXTERNAL_HANDLE

The VkImportFenceFdInfoKHR structure is defined as:
typedef struct VkImportFenceFdInfoKHR {
    VkStructureType                      sType;
    const void*                          pNext;
    VkFence                              fence;
    VkFenceImportFlags                   flags;
    VkExternalFenceHandleTypeFlagBits    handleType;
    int                                   fd;
} VkImportFenceFdInfoKHR;

• **sType** is the type of this structure.
• **pNext** is NULL or a pointer to an extension-specific structure.
• **fence** is the fence into which the payload will be imported.
• **flags** is a bitmask of VkFenceImportFlagBits specifying additional parameters for the fence payload import operation.
• **handleType** specifies the type of **fd**.
• **fd** is the external handle to import.

The handle types supported by **handleType** are:

Table 7. Handle Types Supported by `VkImportFenceFdInfoKHR`

<table>
<thead>
<tr>
<th>Handle Type</th>
<th>Transference</th>
<th>Permanence Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Reference</td>
<td>Temporary, Permanent</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT</td>
<td>Copy</td>
<td>Temporary</td>
</tr>
</tbody>
</table>

**Valid Usage**

- **handleType** must be a value included in the Handle Types Supported by `VkImportFenceFdInfoKHR` table.
- **fd** must obey any requirements listed for **handleType** in external fence handle types compatibility.

If **handleType** is VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT, the special value -1 for **fd** is treated like a valid sync file descriptor referring to an object that has already signaled. The import operation will succeed and the **VkFence** will have a temporarily imported payload as if a valid file descriptor had been provided.
Note
This special behavior for importing an invalid sync file descriptor allows easier interoperability with other system APIs which use the convention that an invalid sync file descriptor represents work that has already completed and does not need to be waited for. It is consistent with the option for implementations to return a -1 file descriptor when exporting a VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT from a VkFence which is signaled.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_IMPORT_FENCE_FD_INFO_KHR
- pNext must be NULL
- fence must be a valid VkFence handle
- flags must be a valid combination of VkFenceImportFlagBits values
- handleType must be a valid VkExternalFenceHandleTypeFlagBits value

Host Synchronization

- Host access to fence must be externally synchronized

Bits which can be set in VkImportFenceWin32HandleInfoKHR::flags and VkImportFenceFdInfoKHR::flags specifying additional parameters of a fence import operation are:

```c
typedef enum VkFenceImportFlagBits {
    VK_FENCE_IMPORT_TEMPORARY_BIT = 0x00000001,
    VK_FENCE_IMPORT_TEMPORARY_BIT_KHR = VK_FENCE_IMPORT_TEMPORARY_BIT,
    VK_FENCE_IMPORT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkFenceImportFlagBits;
```

or the equivalent

```c
typedef VkFenceImportFlagBits VkFenceImportFlagBitsKHR;
```

- VK_FENCE_IMPORT_TEMPORARY_BIT specifies that the fence payload will be imported only temporarily, as described in Importing Fence Payloads, regardless of the permanence of handleType.

```c
typedef VkFlags VkFenceImportFlags;
```

or the equivalent
typedef VkFenceImportFlags VkFenceImportFlagsKHR;

VkFenceImportFlags is a bitmask type for setting a mask of zero or more VkFenceImportFlagBits.

6.4. Semaphores

Semaphores are a synchronization primitive that can be used to insert a dependency between queue operations or between a queue operation and the host. Binary semaphores have two states - signaled and unsignaled. Timeline semaphores have a monotonically increasing 64-bit unsigned integer payload and are signaled with respect to a particular reference value. A semaphore can be signaled after execution of a queue operation is completed, and a queue operation can wait for a semaphore to become signaled before it begins execution. A timeline semaphore can additionally be signaled from the host with the vkSignalSemaphore command and waited on from the host with the vkWaitSemaphores command.

As with most objects in Vulkan, semaphores are an interface to internal data which is typically opaque to applications. This internal data is referred to as a semaphore's payload.

However, in order to enable communication with agents outside of the current device, it is necessary to be able to export that payload to a commonly understood format, and subsequently import from that format as well.

The internal data of a semaphore may include a reference to any resources and pending work associated with signal or unsignal operations performed on that semaphore object. Mechanisms to import and export that internal data to and from semaphores are provided below. These mechanisms indirectly enable applications to share semaphore state between two or more semaphores and other synchronization primitives across process and API boundaries.

Semaphores are represented by VkSemaphore handles:

VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSemaphore)

To create a semaphore, call:

```
VkResult vkCreateSemaphore(
    VkDevice                                    device,
    const VkSemaphoreCreateInfo*                pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkSemaphore*                                pSemaphore);
```

- **device** is the logical device that creates the semaphore.
- **pCreateInfo** is a pointer to a VkSemaphoreCreateInfo structure containing information about how the semaphore is to be created.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pSemaphore** is a pointer to a handle in which the resulting semaphore object is returned.
Valid Usage (Implicit)

- device must be a valid VkDevice handle
- pCreateInfo must be a valid pointer to a valid VkSemaphoreCreateInfo structure
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
- pSemaphore must be a valid pointer to a VkSemaphore handle

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkSemaphoreCreateInfo structure is defined as:

```c
typedef struct VkSemaphoreCreateInfo {
    VkStructureType           sType;
    const void*               pNext;
    VkSemaphoreCreateFlags    flags;
} VkSemaphoreCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO
- Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of VkExportSemaphoreCreateInfo, VkExportSemaphoreWin32HandleInfoKHR, or VkSemaphoreTypeCreateInfo
- The sType value of each struct in the pNext chain must be unique
- flags must be 0

```c
typedef VkFlags VkSemaphoreCreateFlags;
```
VkSemaphoreCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

To create a semaphore of a specific type, add a VkSemaphoreTypeCreateInfo structure to the pNext chain of the VkSemaphoreCreateInfo structure. The VkSemaphoreTypeCreateInfo structure is defined as:

```c
typedef struct VkSemaphoreTypeCreateInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkSemaphoreType    semaphoreType;
    uint64_t           initialValue;
} VkSemaphoreTypeCreateInfo;
```

or the equivalent

```c
typedef VkSemaphoreTypeCreateInfo VkSemaphoreTypeCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **semaphoreType** is a VkSemaphoreType value specifying the type of the semaphore.
- **initialValue** is the initial payload value if semaphoreType is VK_SEMAPHORE_TYPE_TIMELINE.

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_SEMAPHORE_TYPE_CREATE_INFO
- **semaphoreType** must be a valid VkSemaphoreType value

### Valid Usage

- If the timelineSemaphore feature is not enabled, **semaphoreType** must not equal VK_SEMAPHORE_TYPE_TIMELINE
- If semaphoreType is VK_SEMAPHORE_TYPE_BINARY, **initialValue** must be zero.

If no VkSemaphoreTypeCreateInfo structure is included in the pNext chain of VkSemaphoreCreateInfo, then the created semaphore will have a default VkSemaphoreType of VK_SEMAPHORE_TYPE_BINARY.

Possible values of VkSemaphoreTypeCreateInfo::semaphoreType, specifying the type of a semaphore, are:
typedef enum VkSemaphoreType {
    VK_SEMAPHORE_TYPE_BINARY = 0,
    VK_SEMAPHORE_TYPE_TIMELINE = 1,
    VK_SEMAPHORE_TYPE_BINARY_KHR = VK_SEMAPHORE_TYPE_BINARY,
    VK_SEMAPHORE_TYPE_TIMELINE_KHR = VK_SEMAPHORE_TYPE_TIMELINE,
    VK_SEMAPHORE_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkSemaphoreType;

or the equivalent

typedef VkSemaphoreType VkSemaphoreTypeKHR;

• VK_SEMAPHORE_TYPE_BINARY specifies a binary semaphore type that has a boolean payload indicating whether the semaphore is currently signaled or unsignaled. When created, the semaphore is in the unsignaled state.

• VK_SEMAPHORE_TYPE_TIMELINE specifies a timeline semaphore type that has a monotonically increasing 64-bit unsigned integer payload indicating whether the semaphore is signaled with respect to a particular reference value. When created, the semaphore payload has the value given by the initialValue field of VkSemaphoreTypeCreateInfo.

To create a semaphore whose payload can be exported to external handles, add a VkExportSemaphoreCreateInfo structure to the pNext chain of the VkSemaphoreCreateInfo structure. The VkExportSemaphoreCreateInfo structure is defined as:

typedef struct VkExportSemaphoreCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalSemaphoreHandleTypeFlags handleTypes;
} VkExportSemaphoreCreateInfo;

or the equivalent

typedef VkExportSemaphoreCreateInfo VkExportSemaphoreCreateInfoKHR;

• sType is the type of this structure.

• pNext is NULL or a pointer to an extension-specific structure.

• handleTypes is a bitmask of VkExternalSemaphoreHandleTypeFlagBits specifying one or more semaphore handle types the application can export from the resulting semaphore. The application can request multiple handle types for the same semaphore.
Valid Usage

- The bits in `handleTypes` must be supported and compatible, as reported by `VkExternalSemaphoreProperties`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE.ExportSemaphoreCreateInfo`
- `handleTypes` must be a valid combination of `VkExternalSemaphoreHandleTypeFlagBits` values

To specify additional attributes of NT handles exported from a semaphore, add a `VkExportSemaphoreWin32HandleInfoKHR` structure to the `pNext` chain of the `VkSemaphoreCreateInfo` structure. The `VkExportSemaphoreWin32HandleInfoKHR` structure is defined as:

```c
typedef struct VkExportSemaphoreWin32HandleInfoKHR {
    VkStructureType               sType;
    const void*                   pNext;
    const SECURITY_ATTRIBUTES*    pAttributes;
    DWORD                         dwAccess;
    LPCWSTR                       name;
} VkExportSemaphoreWin32HandleInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `pAttributes` is a pointer to a Windows `SECURITY_ATTRIBUTES` structure specifying security attributes of the handle.
- `dwAccess` is a `DWORD` specifying access rights of the handle.
- `name` is a null-terminated UTF-16 string to associate with the underlying synchronization primitive referenced by NT handles exported from the created semaphore.

If `VkExportSemaphoreCreateInfo` is not present in the same `pNext` chain, this structure is ignored.

If `VkExportSemaphoreCreateInfo` is present in the `pNext` chain of `VkSemaphoreCreateInfo` with a Windows `handleType`, but either `VkExportSemaphoreWin32HandleInfoKHR` is not present in the `pNext` chain, or if it is but `pAttributes` is set to NULL, default security descriptor values will be used, and child processes created by the application will not inherit the handle, as described in the MSDN documentation for “Synchronization Object Security and Access Rights”. Further, if the structure is not present, the access rights used depend on the handle type.

For handles of the following types:

`VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT`
The implementation **must** ensure the access rights allow both signal and wait operations on the semaphore.

For handles of the following types:

\texttt{VK\_EXTERNAL\_SEMAPHORE\_HANDLE\_TYPE\_D3D12\_FENCE\_BIT}

The access rights **must** be:

\texttt{GENERIC\_ALL}

1


---

**Valid Usage**

- If \texttt{VkExportSemaphoreCreateInfo::handleTypes} does not include \texttt{VK\_EXTERNAL\_SEMAPHORE\_HANDLE\_TYPE\_OPAQUE\_WIN32\_BIT} or \texttt{VK\_EXTERNAL\_SEMAPHORE\_HANDLE\_TYPE\_D3D12\_FENCE\_BIT}, \texttt{VkExportSemaphoreWin32HandleInfoKHR} **must** not be included in the \texttt{pNext} chain of \texttt{VkSemaphoreCreateInfo}.

---

**Valid Usage (Implicit)**

- \texttt{sType} **must** be \texttt{VK\_STRUCTURE\_TYPE\_EXPORT\_SEMAPHORE\_WIN32\_HANDLE\_INFO\_KHR}
- If \texttt{pAttributes} is not NULL, \texttt{pAttributes} **must** be a valid pointer to a valid \texttt{SECURITY\_ATTRIBUTES} value

To export a Windows handle representing the payload of a semaphore, call:

```c
VkResult vkGetSemaphoreWin32HandleKHR(
    VkDevice                                    device,
    const VkSemaphoreGetWin32HandleInfoKHR*     pGetWin32HandleInfo,
    HANDLE*                                     pHandle);
```

- \texttt{device} is the logical device that created the semaphore being exported.
- \texttt{pGetWin32HandleInfo} is a pointer to a \texttt{VkSemaphoreGetWin32HandleInfoKHR} structure containing parameters of the export operation.
- \texttt{pHandle} will return the Windows handle representing the semaphore state.

For handle types defined as NT handles, the handles returned by \texttt{vkGetSemaphoreWin32HandleKHR} are owned by the application. To avoid leaking resources, the application **must** release ownership of them using the \texttt{CloseHandle} system call when they are no longer needed.

Exporting a Windows handle from a semaphore **may** have side effects depending on the transference of the specified handle type, as described in Importing Semaphore Payloads.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pGetWin32HandleInfo** must be a valid pointer to a valid `VkSemaphoreGetWin32HandleInfoKHR` structure
- **pHandle** must be a valid pointer to a `HANDLE` value

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_TOO_MANY_OBJECTS`
- `VK_ERROR_OUT_OF_HOST_MEMORY`

The `VkSemaphoreGetWin32HandleInfoKHR` structure is defined as:

```c
typedef struct VkSemaphoreGetWin32HandleInfoKHR {
    VkStructureType sType;     // sType is the type of this structure.
    const void*      pNext;    // pNext is NULL or a pointer to an extension-specific structure.
    VkSemaphore semaphore;     // semaphore is the semaphore from which state will be exported.
    VkExternalSemaphoreHandleTypeFlagBits handleType;  // handleType is the type of handle requested.
} VkSemaphoreGetWin32HandleInfoKHR;
```

The properties of the handle returned depend on the value of **handleType**. See `VkExternalSemaphoreHandleTypeFlagBits` for a description of the properties of the defined external semaphore handle types.
Valid Usage

- **handleType must** have been included in `VkExportSemaphoreCreateInfo::handleTypes` when the semaphore's current payload was created.

- If **handleType** is defined as an NT handle, `vkGetSemaphoreWin32HandleKHR` **must** be called no more than once for each valid unique combination of semaphore and handleType.

- **semaphore must** not currently have its payload replaced by an imported payload as described below in Importing Semaphore Payloads unless that imported payload's handle type was included in `VkExternalSemaphoreProperties::exportFromImportedHandleTypes` for handleType.

- If **handleType** refers to a handle type with copy payload transference semantics, as defined below in Importing Semaphore Payloads, there **must** be no queue waiting on semaphore.

- If **handleType** refers to a handle type with copy payload transference semantics, semaphore **must** be signaled, or have an associated semaphore signal operation pending execution.

- **handleType must** be defined as an NT handle or a global share handle.

Valid Usage (Implicit)

- **sType must** be `VK_STRUCTURE_TYPE_SEMAPHORE_GET_WIN32_HANDLE_INFO_KHR`

- **pNext must** be `NULL`

- **semaphore must** be a valid `VkSemaphore` handle

- **handleType must** be a valid `VkExternalSemaphoreHandleTypeFlagBits` value

To export a POSIX file descriptor representing the payload of a semaphore, call:

```c
VkResult vkGetSemaphoreFdKHR(
    VkDevice                                    device,
    const VkSemaphoreGetFdInfoKHR*              pGetFdInfo,
    int*                                        pFd);
```

- **device** is the logical device that created the semaphore being exported.

- **pGetFdInfo** is a pointer to a `VkSemaphoreGetFdInfoKHR` structure containing parameters of the export operation.

- **pFd** will return the file descriptor representing the semaphore payload.

Each call to `vkGetSemaphoreFdKHR` **must** create a new file descriptor and transfer ownership of it to the application. To avoid leaking resources, the application **must** release ownership of the file descriptor when it is no longer needed.
Ownership can be released in many ways. For example, the application can call `close()` on the file descriptor, or transfer ownership back to Vulkan by using the file descriptor to import a semaphore payload.

Where supported by the operating system, the implementation must set the file descriptor to be closed automatically when an `execve` system call is made.

Exporting a file descriptor from a semaphore may have side effects depending on the transference of the specified handle type, as described in Importing Semaphore State.

Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pGetFdInfo** must be a valid pointer to a valid `VkSemaphoreGetFdInfoKHR` structure
- **pFd** must be a valid pointer to an `int` value

Return Codes

**Success**

- **VK_SUCCESS**

**Failure**

- **VK_ERROR_TOO_MANY_OBJECTS**
- **VK_ERROR_OUT_OF_HOST_MEMORY**

The `VkSemaphoreGetFdInfoKHR` structure is defined as:

```c
typedef struct VkSemaphoreGetFdInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkSemaphore semaphore;
    VkExternalSemaphoreHandleTypeFlagBits handleType;
} VkSemaphoreGetFdInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **semaphore** is the semaphore from which state will be exported.
- **handleType** is the type of handle requested.

The properties of the file descriptor returned depend on the value of **handleType**. See `VkExternalSemaphoreHandleTypeFlagBits` for a description of the properties of the defined external semaphore handle types.
Valid Usage

- `handleType must` have been included in `VkExportSemaphoreCreateInfo::handleTypes` when `semaphore`'s current payload was created.

- `semaphore must` not currently have its payload replaced by an imported payload as described below in Importing Semaphore Payloads unless that imported payload's handle type was included in `VkExternalSemaphoreProperties::exportFromImportedHandleTypes` for `handleType`.

- If `handleType` refers to a handle type with copy payload transference semantics, as defined below in Importing Semaphore Payloads, there `must be` no queue waiting on `semaphore`.

- If `handleType` refers to a handle type with copy payload transference semantics, `semaphore must` be signaled, or have an associated `semaphore signal operation` pending execution.

- `handleType must` be defined as a POSIX file descriptor handle.

- If `handleType` refers to a handle type with copy payload transference semantics, `semaphore must` have been created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY`.

- If `handleType` refers to a handle type with copy payload transference semantics, `semaphore must` have an associated semaphore signal operation that has been submitted for execution and any semaphore signal operations on which it depends (if any) `must have` also been submitted for execution.

Valid Usage (Implicit)

- `sType must` be `VK_STRUCTURE_TYPE_SEMAPHORE_GET_FD_INFO_KHR`
- `pNext must` be `NULL`
- `semaphore must` be a valid `VkSemaphore` handle
- `handleType must` be a valid `VkExternalSemaphoreHandleTypeFlagBits` value

To destroy a semaphore, call:

```c
void vkDestroySemaphore(
    VkDevice device,                  
    VkSemaphore semaphore,            
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the semaphore.
- `semaphore` is the handle of the semaphore to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
Valid Usage

- All submitted batches that refer to `semaphore` must have completed execution
- If `VkAllocationCallbacks` were provided when `semaphore` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `semaphore` was created, `pAllocator` must be `NULL`

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- If `semaphore` is not `VK_NULL_HANDLE`, `semaphore` must be a valid `VkSemaphore` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `semaphore` is a valid handle, it must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `semaphore` must be externally synchronized

6.4.1. Semaphore Signaling

When a batch is submitted to a queue via a `queue submission`, and it includes semaphores to be signaled, it defines a memory dependency on the batch, and defines `semaphore signal operations` which set the semaphores to the signaled state.

In case of semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` the semaphore is considered signaled with respect to the counter value set to be signaled as specified in `VkTimelineSemaphoreSubmitInfo` or `VkSemaphoreSignalInfo`.

The first `synchronization scope` includes every command submitted in the same batch. Semaphore signal operations that are defined by `vkQueueSubmit` additionally include all commands that occur earlier in `submission order`. Semaphore signal operations that are defined by `vkQueueSubmit` or `vkQueueBindSparse` additionally include in the first synchronization scope any semaphore and fence signal operations that occur earlier in `signal operation order`.

The second `synchronization scope` includes only the semaphore signal operation.

The first `access scope` includes all memory access performed by the device.

The second `access scope` is empty.
6.4.2. Semaphore Waiting

When a batch is submitted to a queue via a queue submission, and it includes semaphores to be waited on, it defines a memory dependency between prior semaphore signal operations and the batch, and defines semaphore wait operations.

Such semaphore wait operations set the semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_BINARY to the unsignaled state. In case of semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE a prior semaphore signal operation defines a memory dependency with a semaphore wait operation if the value the semaphore is signaled with is greater than or equal to the value the semaphore is waited with, thus the semaphore will continue to be considered signaled with respect to the counter value waited on as specified in VkTimelineSemaphoreSubmitInfo.

The first synchronization scope includes all semaphore signal operations that operate on semaphores waited on in the same batch, and that happen-before the wait completes.

The second synchronization scope includes every command submitted in the same batch. In the case of vkQueueSubmit, the second synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by the corresponding element of pWaitDstStageMask. Also, in the case of vkQueueSubmit, the second synchronization scope additionally includes all commands that occur later in submission order.

The first access scope is empty.

The second access scope includes all memory access performed by the device.

The semaphore wait operation happens-after the first set of operations in the execution dependency, and happens-before the second set of operations in the execution dependency.

Note

Unlike timeline semaphores, fences or events, the act of waiting for a binary semaphore also unsignals that semaphore. Applications must ensure that between two such wait operations, the semaphore is signaled again, with execution dependencies used to ensure these occur in order. Binary semaphore waits and signals should thus occur in discrete 1:1 pairs.
A common scenario for using `pWaitDstStageMask` with values other than `VK_PIPELINE_STAGE_ALL_COMMANDS_BIT` is when synchronizing a window system presentation operation against subsequent command buffers which render the next frame. In this case, a presentation image **must** not be overwritten until the presentation operation completes, but other pipeline stages **can** execute without waiting. A mask of `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT` prevents subsequent color attachment writes from executing until the semaphore signals. Some implementations **may** be able to execute transfer operations and/or vertex processing work before the semaphore is signaled.

If an image layout transition needs to be performed on a presentable image before it is used in a framebuffer, that **can** be performed as the first operation submitted to the queue after acquiring the image, and **should** not prevent other work from overlapping with the presentation operation. For example, a `VkImageMemoryBarrier` could use:

- `srcStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT`
- `srcAccessMask = 0`
- `dstStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT`
- `dstAccessMask = VK_ACCESS_COLOR_ATTACHMENT_READ_BIT | VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT`
- `oldLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR`
- `newLayout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`

Alternatively, `oldLayout` **can** be `VK_IMAGE_LAYOUT_UNDEFINED`, if the image's contents need not be preserved.

This barrier accomplishes a dependency chain between previous presentation operations and subsequent color attachment output operations, with the layout transition performed in between, and does not introduce a dependency between previous work and any vertex processing stages. More precisely, the semaphore signals after the presentation operation completes, the semaphore wait stalls the `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT` stage, and there is a dependency from that same stage to itself with the layout transition performed in between.

**6.4.3. Semaphore State Requirements For Wait Operations**

Before waiting on a semaphore, the application **must** ensure the semaphore is in a valid state for a wait operation. Specifically, when a **semaphore wait operation** is submitted to a queue:

- A binary semaphore **must** be signaled, or have an associated **semaphore signal operation** that is pending execution.
- Any **semaphore signal operations** on which the pending binary semaphore signal operation depends **must** also be completed or pending execution.
- There **must** be no other queue waiting on the same binary semaphore when the operation
6.4.4. Host Operations on Semaphores

In addition to semaphore signal operations and semaphore wait operations submitted to device queues, timeline semaphores support the following host operations:

- Query the current counter value of the semaphore using the `vkGetSemaphoreCounterValue` command.
- Wait for a set of semaphores to reach particular counter values using the `vkWaitSemaphores` command.
- Signal the semaphore with a particular counter value from the host using the `vkSignalSemaphore` command.

To query the current counter value of a semaphore created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` from the host, call:

```c
VkResult vkGetSemaphoreCounterValueKHR(
    VkDevice                                    device,
    VkSemaphore                                 semaphore,
    uint64_t*                                   pValue);
```

- `device` is the logical device that owns the semaphore.
- `semaphore` is the handle of the semaphore to query.
- `pValue` is a pointer to a 64-bit integer value in which the current counter value of the semaphore is returned.

**Note**

If a queue submission command is pending execution, then the value returned by this command may immediately be out of date.

**Valid Usage**

- `semaphore` must have been created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `semaphore` must be a valid `VkSemaphore` handle
- `pValue` must be a valid pointer to a `uint64_t` value
- `semaphore` must have been created, allocated, or retrieved from `device`
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY
• VK_ERROR_DEVICE_LOST

To wait for a set of semaphores created with a VkSemaphoreType of VK_SEMAPHORE_TYPE_TIMELINE to reach particular counter values on the host, call:

```c
VkResult vkWaitSemaphoresKHR(
    VkDevice                                    device,
    const VkSemaphoreWaitInfo*                  pWaitInfo,
    uint64_t                                    timeout);
```

• `device` is the logical device that owns the semaphore.

• `pWaitInfo` is a pointer to a VkSemaphoreWaitInfo structure containing information about the wait condition.

• `timeout` is the timeout period in units of nanoseconds. `timeout` is adjusted to the closest value allowed by the implementation-dependent timeout accuracy, which may be substantially longer than one nanosecond, and may be longer than the requested period.

If the condition is satisfied when `vkWaitSemaphores` is called, then `vkWaitSemaphores` returns immediately. If the condition is not satisfied at the time `vkWaitSemaphores` is called, then `vkWaitSemaphores` will block and wait up to `timeout` nanoseconds for the condition to become satisfied.

If `timeout` is zero, then `vkWaitSemaphores` does not wait, but simply returns information about the current state of the semaphore. VK_TIMEOUT will be returned in this case if the condition is not satisfied, even though no actual wait was performed.

If the specified timeout period expires before the condition is satisfied, `vkWaitSemaphores` returns VK_TIMEOUT. If the condition is satisfied before `timeout` nanoseconds has expired, `vkWaitSemaphores` returns VK_SUCCESS.

If device loss occurs (see Lost Device) before the timeout has expired, `vkWaitSemaphores` must return in finite time with either VK_SUCCESS or VK_ERROR_DEVICE_LOST.

Valid Usage (Implicit)

• `device` must be a valid VkDevice handle

• `pWaitInfo` must be a valid pointer to a valid VkSemaphoreWaitInfo structure
Return Codes

Success

• VK_SUCCESS
• VK_TIMEOUT

Failure

• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY
• VK_ERROR_DEVICE_LOST

The VkSemaphoreWaitInfo structure is defined as:

```c
typedef struct VkSemaphoreWaitInfo {
    VkStructureType sType;
    const void* pNext;
    VkSemaphoreWaitFlags flags;
    uint32_t semaphoreCount;
    const VkSemaphore* pSemaphores;
    const uint64_t* pValues;
} VkSemaphoreWaitInfo;
```

or the equivalent

```c
typedef VkSemaphoreWaitInfo VkSemaphoreWaitInfoKHR;
```

• `sType` is the type of this structure.
• `pNext` is NULL or a pointer to an extension-specific structure.
• `flags` is a bitmask of `VkSemaphoreWaitFlagBits` specifying additional parameters for the semaphore wait operation.
• `semaphoreCount` is the number of semaphores to wait on.
• `pSemaphores` is a pointer to an array of `semaphoreCount` semaphore handles to wait on.
• `pValues` is a pointer to an array of `semaphoreCount` timeline semaphore values.

Valid Usage

• All of the elements of `pSemaphores` must reference a semaphore that was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_SEMAPHORE_WAIT_INFO`
- **pNext** must be `NULL`
- **flags** must be a valid combination of `VkSemaphoreWaitFlagBits` values
- **pSemaphores** must be a valid pointer to an array of `semaphoreCount` valid `VkSemaphore` handles
- **pValues** must be a valid pointer to an array of `semaphoreCount` `uint64_t` values
- **semaphoreCount** must be greater than 0

Bits which **can** be set in `VkSemaphoreWaitInfo::flags`, specifying additional parameters of a semaphore wait operation, are:

```c
typedef enum VkSemaphoreWaitFlagBits {
    VK_SEMAPHORE_WAIT_ANY_BIT = 0x00000001,
    VK_SEMAPHORE_WAIT_ANY_BIT_KHR = VK_SEMAPHORE_WAIT_ANY_BIT,
    VK_SEMAPHORE_WAIT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSemaphoreWaitFlagBits;
```

or the equivalent

```c
typedef VkSemaphoreWaitFlagBits VkSemaphoreWaitFlagBitsKHR;
```

- **VK_SEMAPHORE_WAIT_ANY_BIT** specifies that the semaphore wait condition is that at least one of the semaphores in `VkSemaphoreWaitInfo::pSemaphores` has reached the value specified by the corresponding element of `VkSemaphoreWaitInfo::pValues`. If **VK_SEMAPHORE_WAIT_ANY_BIT** is not set, the semaphore wait condition is that all of the semaphores in `VkSemaphoreWaitInfo::pSemaphores` have reached the value specified by the corresponding element of `VkSemaphoreWaitInfo::pValues`.

```c
typedef VkFlags VkSemaphoreWaitFlags;
```

or the equivalent

```c
typedef VkSemaphoreWaitFlags VkSemaphoreWaitFlagsKHR;
```

`VkSemaphoreWaitFlags` is a bitmask type for setting a mask of zero or more `VkSemaphoreWaitFlagBits`.

To signal a semaphore created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` with a particular counter value, on the host, call:
VkResult vkSignalSemaphoreKHR(
    VkDevice device,
    const VkSemaphoreSignalInfo* pSignalInfo);

- `device` is the logical device that owns the semaphore.
- `pSignalInfo` is a pointer to a `VkSemaphoreSignalInfo` structure containing information about the signal operation.

When `vkSignalSemaphore` is executed on the host, it defines and immediately executes a semaphore signal operation which sets the timeline semaphore to the given value.

The first synchronization scope is defined by the host execution model, but includes execution of `vkSignalSemaphore` on the host and anything that happened-before it.

The second synchronization scope is empty.

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pSignalInfo` must be a valid pointer to a valid `VkSemaphoreSignalInfo` structure

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkSemaphoreSignalInfo` structure is defined as:

```c
typedef struct VkSemaphoreSignalInfo {
    VkStructureType sType;
    const void* pNext;
    VkSemaphore semaphore;
    uint64_t value;
} VkSemaphoreSignalInfo;
```

or the equivalent

```c
typedef VkSemaphoreSignalInfo VkSemaphoreSignalInfoKHR;
```
• `sType` is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.
• `semaphore` is the handle of the semaphore to signal.
• `value` is the value to signal.

### Valid Usage

- `semaphore` **must** have been created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`.
- `value` **must** have a value greater than the current value of the semaphore.
- `value` **must** be less than the value of any pending semaphore signal operations.
- `value` **must** have a value which does not differ from the current value of the semaphore or the value of any outstanding semaphore wait or signal operation on `semaphore` by more than `maxTimelineSemaphoreValueDifference`.

### Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_SEMAPHORE_SIGNAL_INFO`.
- `pNext` **must** be `NULL`.
- `semaphore` **must** be a valid `VkSemaphore` handle.

### 6.4.5. Importing Semaphore Payloads

Applications **can** import a semaphore payload into an existing semaphore using an external semaphore handle. The effects of the import operation will be either temporary or permanent, as specified by the application. If the import is temporary, the implementation **must** restore the semaphore to its prior permanent state after submitting the next semaphore wait operation. Performing a subsequent temporary import on a semaphore before performing a semaphore wait has no effect on this requirement; the next wait submitted on the semaphore **must** still restore its last permanent state. A permanent payload import behaves as if the target semaphore was destroyed, and a new semaphore was created with the same handle but the imported payload. Because importing a semaphore payload temporarily or permanently detaches the existing payload from a semaphore, similar usage restrictions to those applied to `vkDestroySemaphore` are applied to any command that imports a semaphore payload. Which of these import types is used is referred to as the import operation’s **permanence**. Each handle type supports either one or both types of permanence.

The implementation **must** perform the import operation by either referencing or copying the payload referred to by the specified external semaphore handle, depending on the handle’s type. The import method used is referred to as the handle type’s **transference**. When using handle types with reference transference, importing a payload to a semaphore adds the semaphore to the set of all semaphores sharing that payload. This set includes the semaphore from which the payload was exported. Semaphore signaling and waiting operations performed on any semaphore in the set
**must** behave as if the set were a single semaphore. Importing a payload using handle types with copy transference creates a duplicate copy of the payload at the time of import, but makes no further reference to it. Semaphore signaling and waiting operations performed on the target of copy imports **must** not affect any other semaphore or payload.

Export operations have the same transference as the specified handle type’s import operations. Additionally, exporting a semaphore payload to a handle with copy transference has the same side effects on the source semaphore’s payload as executing a semaphore wait operation. If the semaphore was using a temporarily imported payload, the semaphore’s prior permanent payload will be restored.

**Note**
The tables **Handle Types Supported by VkImportSemaphoreWin32HandleInfoKHR** and **Handle Types Supported by VkImportSemaphoreFdInfoKHR** define the permanence and transference of each handle type.

**External synchronization** allows implementations to modify an object’s internal state, i.e. payload, without internal synchronization. However, for semaphores sharing a payload across processes, satisfying the external synchronization requirements of **VkSemaphore** parameters as if all semaphores in the set were the same object is sometimes infeasible. Satisfying the wait operation state requirements would similarly require impractical coordination or levels of trust between processes. Therefore, these constraints only apply to a specific semaphore handle, not to its payload. For distinct semaphore objects which share a payload, if the semaphores are passed to separate queue submission commands concurrently, behavior will be as if the commands were called in an arbitrary sequential order. If the wait operation state requirements are violated for the shared payload by a queue submission command, or if a signal operation is queued for a shared payload that is already signaled or has a pending signal operation, effects **must** be limited to one or more of the following:

- Returning **VK_ERROR_INITIALIZATION_FAILED** from the command which resulted in the violation.
- Losing the logical device on which the violation occurred immediately or at a future time, resulting in a **VK_ERROR_DEVICE_LOST** error from subsequent commands, including the one causing the violation.
- Continuing execution of the violating command or operation as if the semaphore wait completed successfully after an implementation-dependent timeout. In this case, the state of the payload becomes undefined, and future operations on semaphores sharing the payload will be subject to these same rules. The semaphore **must** be destroyed or have its payload replaced by an import operation to again have a well-defined state.

**Note**
These rules allow processes to synchronize access to shared memory without trusting each other. However, such processes must still be cautious not to use the shared semaphore for more than synchronizing access to the shared memory. For example, a process should not use a shared semaphore as part of an execution dependency chain that, when complete, leads to objects being destroyed, if it does not trust other processes sharing the semaphore payload.
When a semaphore is using an imported payload, its `VkExportSemaphoreCreateInfo::handleTypes` value is that specified when creating the semaphore from which the payload was exported, rather than that specified when creating the semaphore. Additionally, `VkExternalSemaphoreProperties::exportFromImportedHandleTypes` restricts which handle types can be exported from such a semaphore based on the specific handle type used to import the current payload. Passing a semaphore to `vkAcquireNextImageKHR` is equivalent to temporarily importing a semaphore payload to that semaphore.

**Note**
Because the exportable handle types of an imported semaphore correspond to its current imported payload, and `vkAcquireNextImageKHR` behaves the same as a temporary import operation for which the source semaphore is opaque to the application, applications have no way of determining whether any external handle types can be exported from a semaphore in this state. Therefore, applications must not attempt to export external handles from semaphores using a temporarily imported payload from `vkAcquireNextImageKHR`.

When importing a semaphore payload, it is the responsibility of the application to ensure the external handles meet all valid usage requirements. However, implementations must perform sufficient validation of external handles to ensure that the operation results in a valid semaphore which will not cause program termination, device loss, queue stalls, or corruption of other resources when used as allowed according to its import parameters, and excepting those side effects allowed for violations of the valid semaphore state for wait operations rules. If the external handle provided does not meet these requirements, the implementation must fail the semaphore payload import operation with the error code `VK_ERROR_INVALID_EXTERNAL_HANDLE`.

In addition, when importing a semaphore payload that is not compatible with the payload type corresponding to the `VkSemaphoreType` the semaphore was created with, the implementation may fail the semaphore payload import operation with the error code `VK_ERROR_INVALID_EXTERNAL_HANDLE`.

**Note**
As the introduction of the external semaphore handle type `VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT` predates that of timeline semaphores, support for importing semaphore payloads from external handles of that type into semaphores created (implicitly or explicitly) with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY` is preserved for backwards compatibility. However, applications should prefer importing such handle types into semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`.

To import a semaphore payload from a Windows handle, call:

```c
VkResult vkImportSemaphoreWin32HandleKHR(
    VkDevice                                    device,
    const VkImportSemaphoreWin32HandleInfoKHR* pImportSemaphoreWin32HandleInfo);
```

- `device` is the logical device that created the semaphore.
• `pImportSemaphoreWin32HandleInfo` is a pointer to a `VkImportSemaphoreWin32HandleInfoKHR` structure specifying the semaphore and import parameters.

Importing a semaphore payload from Windows handles does not transfer ownership of the handle to the Vulkan implementation. For handle types defined as NT handles, the application must release ownership using the `CloseHandle` system call when the handle is no longer needed.

Applications can import the same semaphore payload into multiple instances of Vulkan, into the same instance from which it was exported, and multiple times into a given Vulkan instance.

### Valid Usage (Implicit)
- `device` must be a valid `VkDevice` handle
- `pImportSemaphoreWin32HandleInfo` must be a valid pointer to a valid `VkImportSemaphoreWin32HandleInfoKHR` structure

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_INVALID_EXTERNAL_HANDLE`

The `VkImportSemaphoreWin32HandleInfoKHR` structure is defined as:

```c
typedef struct VkImportSemaphoreWin32HandleInfoKHR {
    VkStructureType                          sType;            
    const void*                              pNext;            
    VkSemaphore                              semaphore;        
    VkSemaphoreImportFlags                   flags;            
    VkExternalSemaphoreHandleTypeFlagBits    handleType;       
    HANDLE                                   handle;           
    LPCWSTR                                  name;             
} VkImportSemaphoreWin32HandleInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `semaphore` is the semaphore into which the payload will be imported.
- `flags` is a bitmask of `VkSemaphoreImportFlagBits` specifying additional parameters for the semaphore payload import operation.
- `handleType` specifies the type of `handle`.
- `handle` is the external handle to import, or `NULL`.

---

186 | Chapter 6. Synchronization and Cache Control
• **name** is a null-terminated UTF-16 string naming the underlying synchronization primitive to import, or **NULL**.

The handle types supported by **handleType** are:

**Table 8. Handle Types Supported by VkImportSemaphoreWin32HandleInfoKHR**

<table>
<thead>
<tr>
<th>Handle Type</th>
<th>Transference</th>
<th>Permanence Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Reference</td>
<td>Temporary, Permanent</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Reference</td>
<td>Temporary, Permanent</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT</td>
<td>Reference</td>
<td>Temporary, Permanent</td>
</tr>
</tbody>
</table>

**Valid Usage**

- **handleType** must be a value included in the **Handle Types Supported by VkImportSemaphoreWin32HandleInfoKHR** table.

- If **handleType** is not **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT** or **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT**, **name** must be **NULL**.

- If **handleType** is not **0** and **handle** is **NULL**, **name** must name a valid synchronization primitive of the type specified by **handleType**.

- If **handleType** is not **0** and **name** is **NULL**, **handle** must be a valid handle of the type specified by **handleType**.

- If **handle** is not **NULL**, **name** must be **NULL**.

- If **handle** is not **NULL**, it must obey any requirements listed for **handleType** in external semaphore handle types compatibility.

- If **name** is not **NULL**, it must obey any requirements listed for **handleType** in external semaphore handle types compatibility.

- If **handleType** is **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT** or **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT**, the **VkSemaphoreCreateInfo**::**flags** field must match that of the semaphore from which **handle** or **name** was exported.

- If **handleType** is **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT** or **VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT**, the **VkSemaphoreTypeCreateInfo**::**semaphoreType** field must match that of the semaphore from which **handle** or **name** was exported.

- If **flags** contains **VK_SEMAPHORE_IMPORT_TEMPORARY_BIT**, the **VkSemaphoreTypeCreateInfo**::**semaphoreType** field of the semaphore from which **handle** or **name** was exported must not be **VK_SEMAPHORE_TYPE_TIMELINE**.
**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_IMPORT_SEMAPHORE_WIN32_HANDLE_INFO_KHR`
- `pNext` must be `NULL`
- `semaphore` must be a valid `VkSemaphore` handle
- `flags` must be a valid combination of `VkSemaphoreImportFlagBits` values
- If `handleType` is not `0`, `handleType` must be a valid `VkExternalSemaphoreHandleTypeFlagBits` value

**Host Synchronization**

- Host access to `semaphore` must be externally synchronized

To import a semaphore payload from a POSIX file descriptor, call:

```c
VkResult vkImportSemaphoreFdKHR(
    VkDevice                                    device,
    const VkImportSemaphoreFdInfoKHR*           pImportSemaphoreFdInfo);
```

- `device` is the logical device that created the semaphore.
- `pImportSemaphoreFdInfo` is a pointer to a `VkImportSemaphoreFdInfoKHR` structure specifying the semaphore and import parameters.

Importing a semaphore payload from a file descriptor transfers ownership of the file descriptor from the application to the Vulkan implementation. The application must not perform any operations on the file descriptor after a successful import.

Applications can import the same semaphore payload into multiple instances of Vulkan, into the same instance from which it was exported, and multiple times into a given Vulkan instance.

**Valid Usage**

- `semaphore` must not be associated with any queue command that has not yet completed execution on that queue

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `pImportSemaphoreFdInfo` must be a valid pointer to a valid `VkImportSemaphoreFdInfoKHR` structure
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_INVALID_EXTERNAL_HANDLE

The `VkImportSemaphoreFdInfoKHR` structure is defined as:

```c
typedef struct VkImportSemaphoreFdInfoKHR {
    VkStructureType                          sType;
    const void*                              pNext;
    VkSemaphore                              semaphore;
    VkSemaphoreImportFlags                   flags;
    VkExternalSemaphoreHandleTypeFlagBits    handleType;
    int                                      fd;
} VkImportSemaphoreFdInfoKHR;
```

• `sType` is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.
• `semaphore` is the semaphore into which the payload will be imported.
• `flags` is a bitmask of `VkSemaphoreImportFlagBits` specifying additional parameters for the semaphore payload import operation.
• `handleType` specifies the type of `fd`.
• `fd` is the external handle to import.

The handle types supported by `handleType` are:

<table>
<thead>
<tr>
<th>Handle Type</th>
<th>Transference</th>
<th>Permanence Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Reference</td>
<td>Temporary,Permanent</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT</td>
<td>Copy</td>
<td>Temporary</td>
</tr>
</tbody>
</table>
Valid Usage

- `handleType` must be a value included in the Handle Types Supported by `VkImportSemaphoreFdInfoKHR` table.
- `fd` must obey any requirements listed for `handleType` in external semaphore handle types compatibility.
- If `handleType` is `VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT`, the `VkSemaphoreCreateInfo::flags` field must match that of the semaphore from which `fd` was exported.
- If `handleType` is `VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT`, the `VkSemaphoreTypeCreateInfo::semaphoreType` field must match that of the semaphore from which `fd` was exported.
- If `flags` contains `VK_SEMAPHORE_IMPORT_TEMPORARY_BIT`, the `VkSemaphoreTypeCreateInfo::semaphoreType` field of the semaphore from which `fd` was exported must not be `VK_SEMAPHORE_TYPE_TIMELINE`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_IMPORT_SEMAPHORE_FD_INFO_KHR`.
- `pNext` must be `NULL`.
- `semaphore` must be a valid `VkSemaphore` handle.
- `flags` must be a valid combination of `VkSemaphoreImportFlagBits` values.
- `handleType` must be a valid `VkExternalSemaphoreHandleTypeFlagBits` value.

Host Synchronization

- Host access to `semaphore` must be externally synchronized.

Additional parameters of a semaphore import operation are specified by `VkImportSemaphoreWin32HandleInfoKHR::flags` or `VkImportSemaphoreFdInfoKHR::flags`. Bits which can be set include:

```c
typedef enum VkSemaphoreImportFlagBits {
    VK_SEMAPHORE_IMPORT_TEMPORARY_BIT = 0x00000001,
    VK_SEMAPHORE_IMPORT_TEMPORARY_BIT_KHR = VK_SEMAPHORE_IMPORT_TEMPORARY_BIT,
    VK_SEMAPHORE_IMPORT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSemaphoreImportFlagBits;
```

or the equivalent
These bits have the following meanings:

- **VK_SEMAPHORE_IMPORT_TEMPORARY_BIT** specifies that the semaphore payload will be imported only temporarily, as described in Importing Semaphore Payloads, regardless of the permanence of `handleType`.

### 6.5. Events

Events are a synchronization primitive that can be used to insert a fine-grained dependency between commands submitted to the same queue, or between the host and a queue. Events must not be used to insert a dependency between commands submitted to different queues. Events have two states - signaled and unsignaled. An application can signal or unsignal an event either on the host or on the device. A device can be made to wait for an event to become signaled before executing further operations. No command exists to wait for an event to become signaled on the host, but the current state of an event can be queried.

Events are represented by `VkEvent` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkEvent)
```

To create an event, call:

```c
VkResult vkCreateEvent(
    VkDevice device,    // device
    const VkEventCreateInfo* pCreateInfo, // pCreateInfo
    const VkAllocationCallbacks* pAllocator, // pAllocator
    VkEvent* pEvent); // pEvent
```

- **device** is the logical device that creates the event.
- **pCreateInfo** is a pointer to a `VkEventCreateInfo` structure containing information about how the event is to be created.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
• \texttt{pEvent} is a pointer to a handle in which the resulting event object is returned.

When created, the event object is in the unsignaled state.

\begin{itemize}
  \item \texttt{device} \textbf{must} be a valid \texttt{VkDevice} handle
  \item \texttt{pCreateInfo} \textbf{must} be a valid pointer to a valid \texttt{VkEventCreateInfo} structure
  \item If \texttt{pAllocator} is not \texttt{NULL}, \texttt{pAllocator} \textbf{must} be a valid pointer to a valid \texttt{VkAllocationCallbacks} structure
  \item \texttt{pEvent} \textbf{must} be a valid pointer to a \texttt{VkEvent} handle
\end{itemize}

\begin{mdframed}
\textbf{Valid Usage (Implicit)}
\begin{itemize}
  \item \texttt{device} \textbf{must} be a valid \texttt{VkDevice} handle
  \item \texttt{pCreateInfo} \textbf{must} be a valid pointer to a valid \texttt{VkEventCreateInfo} structure
  \item If \texttt{pAllocator} is not \texttt{NULL}, \texttt{pAllocator} \textbf{must} be a valid pointer to a valid \texttt{VkAllocationCallbacks} structure
  \item \texttt{pEvent} \textbf{must} be a valid pointer to a \texttt{VkEvent} handle
\end{itemize}
\end{mdframed}

\begin{itemize}
  \item \texttt{sType} \textbf{is} the type of this structure.
  \item \texttt{pNext} \textbf{is} \texttt{NULL} or a pointer to an extension-specific structure.
  \item \texttt{flags} \textbf{is} reserved for future use.
\end{itemize}

\begin{mdframed}
\textbf{Return Codes}
\begin{itemize}
  \item \textbf{Success}
    \begin{itemize}
      \item \texttt{VK_SUCCESS}
    \end{itemize}
  \item \textbf{Failure}
    \begin{itemize}
      \item \texttt{VK_ERROR_OUT_OF_HOST_MEMORY}
      \item \texttt{VK_ERROR_OUT_OF_DEVICE_MEMORY}
    \end{itemize}
\end{itemize}
\end{mdframed}

The \texttt{VkEventCreateInfo} structure is defined as:

\begin{verbatim}
typedef struct VkEventCreateInfo {
  VkStructureType       sType;
  const void*           pNext;
  VkEventCreateFlags    flags;
} VkEventCreateInfo;
\end{verbatim}

\begin{itemize}
  \item \texttt{sType} \textbf{is} the type of this structure.
  \item \texttt{pNext} \textbf{is} \texttt{NULL} or a pointer to an extension-specific structure.
  \item \texttt{flags} \textbf{is} reserved for future use.
\end{itemize}

\begin{mdframed}
\textbf{Valid Usage (Implicit)}
\begin{itemize}
  \item \texttt{sType} \textbf{must} be \texttt{VK_STRUCTURE_TYPE_EVENT_CREATE_INFO}
  \item \texttt{pNext} \textbf{must} be \texttt{NULL}
  \item \texttt{flags} \textbf{must} be 0
\end{itemize}
\end{mdframed}

\begin{verbatim}
typedef VkFlags VkEventCreateFlags;
\end{verbatim}
VkEventCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

To destroy an event, call:

```c
void vkDestroyEvent(
    VkDevice device,
    VkEvent event,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the event.
- `event` is the handle of the event to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

- All submitted commands that refer to `event` must have completed execution
- If `VkAllocationCallbacks` were provided when `event` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `event` was created, `pAllocator` must be `NULL`

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- If `event` is not `VK_NULL_HANDLE`, `event` must be a valid `VkEvent` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `event` is a valid handle, it must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `event` must be externally synchronized

To query the state of an event from the host, call:

```c
VkResult vkGetEventStatus(
    VkDevice device,
    VkEvent event);
```

- `device` is the logical device that owns the event.
- `event` is the handle of the event to query.
Upon success, `vkGetEventStatus` returns the state of the event object with the following return codes:

<table>
<thead>
<tr>
<th>Status</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EVENT_SET</td>
<td>The event specified by <code>event</code> is signaled.</td>
</tr>
<tr>
<td>VK_EVENT_RESET</td>
<td>The event specified by <code>event</code> is unsignaled.</td>
</tr>
</tbody>
</table>

If a `vkCmdSetEvent` or `vkCmdResetEvent` command is in a command buffer that is in the pending state, then the value returned by this command may immediately be out of date.

The state of an event can be updated by the host. The state of the event is immediately changed, and subsequent calls to `vkGetEventStatus` will return the new state. If an event is already in the requested state, then updating it to the same state has no effect.

### Valid Usage (Implicit)
- `device` must be a valid `VkDevice` handle
- `event` must be a valid `VkEvent` handle
- `event` must have been created, allocated, or retrieved from `device`

### Return Codes

**Success**
- VK_EVENT_SET
- VK_EVENT_RESET

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

To set the state of an event to signaled from the host, call:

```c
VkResult vkSetEvent(
    VkDevice device,
    VkEvent event);
```

- `device` is the logical device that owns the event.
- `event` is the event to set.

When `vkSetEvent` is executed on the host, it defines an event signal operation which sets the event to the signaled state.
If `event` is already in the signaled state when `vkSetEvent` is executed, then `vkSetEvent` has no effect, and no event signal operation occurs.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `event` must be a valid `VkEvent` handle
- `event` must have been created, allocated, or retrieved from `device`

**Host Synchronization**

- Host access to `event` must be externally synchronized

**Return Codes**

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

To set the state of an event to unsignaled from the host, call:

```c
VkResult vkResetEvent(
    VkDevice device,  // device is the logical device that owns the event.
    VkEvent event);   // event is the event to reset.
```

When `vkResetEvent` is executed on the host, it defines an `event unsignal operation` which resets the event to the unsignaled state.

If `event` is already in the unsignaled state when `vkResetEvent` is executed, then `vkResetEvent` has no effect, and no event unsignal operation occurs.

**Valid Usage**

- `event` must not be waited on by a `vkCmdWaitEvents` command that is currently executing
Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `event` must be a valid `VkEvent` handle
- `event` must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `event` must be externally synchronized

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The state of an event can also be updated on the device by commands inserted in command buffers.

To set the state of an event to signaled from a device, call:

```c
void vkCmdSetEvent(
    VkCommandBuffer                             commandBuffer,
    VkEvent                                     event,
    VkPipelineStageFlags                        stageMask);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `event` is the event that will be signaled.
- `stageMask` specifies the `source stage mask` used to determine when the `event` is signaled.

When `vkCmdSetEvent` is submitted to a queue, it defines an execution dependency on commands that were submitted before it, and defines an event signal operation which sets the event to the signaled state.

The first synchronization scope includes all commands that occur earlier in submission order. The synchronization scope is limited to operations on the pipeline stages determined by the `source stage mask` specified by `stageMask`.

The second synchronization scope includes only the event signal operation.

If `event` is already in the signaled state when `vkCmdSetEvent` is executed on the device, then
**Valid Usage**

- `stageMask must` not include `VK_PIPELINE_STAGE_HOST_BIT`
- If the *geometry shaders* feature is not enabled, `stageMask must` not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`
- If the *tessellation shaders* feature is not enabled, `stageMask must` not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`
- `commandBuffer’s current device mask must` include exactly one physical device.

**Valid Usage (Implicit)**

- `commandBuffer must` be a valid `VkCommandBuffer` handle
- `event must` be a valid `VkEvent` handle
- `stageMask must` be a valid combination of `VkPipelineStageFlagBits` values
- `stageMask must` not be 0
- `commandBuffer must` be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from *must* support graphics, or compute operations
- This command *must* only be called outside of a render pass instance
- Both of `commandBuffer`, and `event must` have been created, allocated, or retrieved from the same `VkDevice`

**Host Synchronization**

- Host access to `commandBuffer must` be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from *must* be externally synchronized

**Command Properties**

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

To set the state of an event to unsighaled from a device, call:
void vkCmdResetEvent(
    VkCommandBuffer commandBuffer,
    VkEvent event,
    VkPipelineStageFlags stageMask);

- **commandBuffer** is the command buffer into which the command is recorded.
- **event** is the event that will be unsignaled.
- **stageMask** is a bitmask of VkPipelineStageFlagBits specifying the source stage mask used to determine when the **event** is unsignaled.

When **vkCmdResetEvent** is submitted to a queue, it defines an execution dependency on commands that were submitted before it, and defines an event unsignal operation which resets the event to the unsignaled state.

The first synchronization scope includes all commands that occur earlier in submission order. The synchronization scope is limited to operations on the pipeline stages determined by the source stage mask specified by **stageMask**.

The second synchronization scope includes only the event unsignal operation.

If **event** is already in the unsignaled state when **vkCmdResetEvent** is executed on the device, then **vkCmdResetEvent** has no effect, no event unsignal operation occurs, and no execution dependency is generated.

---

### Valid Usage

- **stageMask** must not include **VK_PIPELINE_STAGE_HOST_BIT**
- If the **geometry shaders** feature is not enabled, **stageMask** must not contain **VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT**
- If the **tessellation shaders** feature is not enabled, **stageMask** must not contain **VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT** or **VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT**
- When this command executes, **event** must not be waited on by a **vkCmdWaitEvents** command that is currently executing
- **commandBuffer**’s current device mask must include exactly one physical device.
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `event` must be a valid `VkEvent` handle
- `stageMask` must be a valid combination of `VkPipelineStageFlagBits` values
- `stageMask` must not be 0
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, or compute operations
- This command must only be called outside of a render pass instance
- Both of `commandBuffer`, and `event` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td>Compute</td>
</tr>
</tbody>
</table>

To wait for one or more events to enter the signaled state on a device, call:

```c
void vkCmdWaitEvents(
    VkCommandBuffer commandBuffer,
    uint32_t eventCount,
    const VkEvent* pEvents,
    VkPipelineStageFlags srcStageMask,
    VkPipelineStageFlags dstStageMask,
    uint32_t memoryBarrierCount,
    const VkMemoryBarrier* pMemoryBarriers,
    uint32_t bufferMemoryBarrierCount,
    const VkBufferMemoryBarrier* pBufferMemoryBarriers,
    uint32_t imageMemoryBarrierCount,
    const VkImageMemoryBarrier* pImageMemoryBarriers);
```
• **commandBuffer** is the command buffer into which the command is recorded.

• **eventCount** is the length of the *pEvents* array.

• **pEvents** is a pointer to an array of event object handles to wait on.

• **srcStageMask** is a bitmask of `VkPipelineStageFlagBits` specifying the source stage mask.

• **dstStageMask** is a bitmask of `VkPipelineStageFlagBits` specifying the destination stage mask.

• **memoryBarrierCount** is the length of the *pMemoryBarriers* array.

• **pMemoryBarriers** is a pointer to an array of `VkMemoryBarrier` structures.

• **bufferMemoryBarrierCount** is the length of the *pBufferMemoryBarriers* array.

• **pBufferMemoryBarriers** is a pointer to an array of `VkBufferMemoryBarrier` structures.

• **imageMemoryBarrierCount** is the length of the *pImageMemoryBarriers* array.

• **pImageMemoryBarriers** is a pointer to an array of `VkImageMemoryBarrier` structures.

When *vkCmdWaitEvents* is submitted to a queue, it defines a memory dependency between prior event signal operations on the same queue or the host, and subsequent commands. *vkCmdWaitEvents* must not be used to wait on event signal operations occurring on other queues.

The first synchronization scope only includes event signal operations that operate on members of *pEvents*, and the operations that happened-before the event signal operations. Event signal operations performed by *vkCmdSetEvent* that occur earlier in submission order are included in the first synchronization scope, if the logically latest pipeline stage in their *stageMask* parameter is logically earlier than or equal to the logically latest pipeline stage in *srcStageMask*. Event signal operations performed by *vkSetEvent* are only included in the first synchronization scope if `VK_PIPELINE_STAGE_HOST_BIT` is included in *srcStageMask*.

The second synchronization scope includes all commands that occur later in submission order. The second synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by *dstStageMask*.

The first access scope is limited to access in the pipeline stages determined by the source stage mask specified by *srcStageMask*. Within that, the first access scope only includes the first access scopes defined by elements of the *pMemoryBarriers*, *pBufferMemoryBarriers* and *pImageMemoryBarriers* arrays, which each define a set of memory barriers. If no memory barriers are specified, then the first access scope includes no accesses.

The second access scope is limited to access in the pipeline stages determined by the destination stage mask specified by *dstStageMask*. Within that, the second access scope only includes the second access scopes defined by elements of the *pMemoryBarriers*, *pBufferMemoryBarriers* and *pImageMemoryBarriers* arrays, which each define a set of memory barriers. If no memory barriers are specified, then the second access scope includes no accesses.
Note

vkCmdWaitEvents is used with vkCmdSetEvent to define a memory dependency between two sets of action commands, roughly in the same way as pipeline barriers, but split into two commands such that work between the two may execute unhindered.

Unlike vkCmdPipelineBarrier, a queue family ownership transfer cannot be performed using vkCmdWaitEvents.

Note

Applications should be careful to avoid race conditions when using events. There is no direct ordering guarantee between a vkCmdResetEvent command and a vkCmdWaitEvents command submitted after it, so some other execution dependency must be included between these commands (e.g. a semaphore).
Valid Usage

- **srcStageMask** must be the bitwise OR of the **stageMask** parameter used in previous calls to **vkCmdSetEvent** with any of the members of **pEvents** and **VK_PIPELINE_STAGE_HOST_BIT** if any of the members of **pEvents** was set using **vkSetEvent**

- If the **geometry shaders** feature is not enabled, **srcStageMask** must not contain **VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT**

- If the **geometry shaders** feature is not enabled, **dstStageMask** must not contain **VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT**

- If the **tessellation shaders** feature is not enabled, **srcStageMask** must not contain **VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT** or **VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT**

- If the **tessellation shaders** feature is not enabled, **dstStageMask** must not contain **VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT** or **VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT**

- If **pEvents** includes one or more events that will be signaled by **vkSetEvent** after **commandBuffer** has been submitted to a queue, then **vkCmdWaitEvents** must not be called inside a render pass instance

- Any pipeline stage included in **srcStageMask** or **dstStageMask** must be supported by the capabilities of the queue family specified by the **queueFamilyIndex** member of the **VkCommandPoolCreateInfo** structure that was used to create the **VkCommandPool** that **commandBuffer** was allocated from, as specified in the table of supported pipeline stages.

- Each element of **pMemoryBarriers**, **pBufferMemoryBarriers** or **pImageMemoryBarriers** must not have any access flag included in its **srcAccessMask** member if that bit is not supported by any of the pipeline stages in **srcStageMask**, as specified in the table of supported access types.

- Each element of **pMemoryBarriers**, **pBufferMemoryBarriers** or **pImageMemoryBarriers** must not have any access flag included in its **dstAccessMask** member if that bit is not supported by any of the pipeline stages in **dstStageMask**, as specified in the table of supported access types.

- The **srcQueueFamilyIndex** and **dstQueueFamilyIndex** members of any element of **pBufferMemoryBarriers** or **pImageMemoryBarriers** must be equal.

- **commandBuffer**'s current device mask must include exactly one physical device.

- The **srcAccessMask** member of each element of **pMemoryBarriers** must only include access flags that are supported by one or more of the pipeline stages in **srcStageMask**, as specified in the table of supported access types

- The **dstAccessMask** member of each element of **pMemoryBarriers** must only include access flags that are supported by one or more of the pipeline stages in **dstStageMask**, as specified in the table of supported access types

- The **srcAccessMask** member of each element of **pBufferMemoryBarriers** must only include access flags that are supported by one or more of the pipeline stages in **srcStageMask**, as specified in the table of supported access types

- The **dstAccessMask** member of each element of **pBufferMemoryBarriers** must only include
access flags that are supported by one or more of the pipeline stages in \texttt{dstStageMask}, as specified in the table of supported access types

- The \texttt{srcAccessMask} member of each element of \texttt{pImageMemoryBarriers} must only include access flags that are supported by one or more of the pipeline stages in \texttt{srcStageMask}, as specified in the table of supported access types

- The \texttt{dstAccessMask} member of any element of \texttt{pImageMemoryBarriers} must only include access flags that are supported by one or more of the pipeline stages in \texttt{dstStageMask}, as specified in the table of supported access types

### Valid Usage (Implicit)

- \texttt{commandBuffer} must be a valid \texttt{VkCommandBuffer} handle
- \texttt{pEvents} must be a valid pointer to an array of \texttt{eventCount} valid \texttt{VkEvent} handles
- \texttt{srcStageMask} must be a valid combination of \texttt{VkPipelineStageFlagBits} values
- \texttt{srcStageMask} must not be 0
- \texttt{dstStageMask} must be a valid combination of \texttt{VkPipelineStageFlagBits} values
- \texttt{dstStageMask} must not be 0
- If \texttt{memoryBarrierCount} is not 0, \texttt{pMemoryBarriers} must be a valid pointer to an array of \texttt{memoryBarrierCount} valid \texttt{VkMemoryBarrier} structures
- If \texttt{bufferMemoryBarrierCount} is not 0, \texttt{pBufferMemoryBarriers} must be a valid pointer to an array of \texttt{bufferMemoryBarrierCount} valid \texttt{VkBufferMemoryBarrier} structures
- If \texttt{imageMemoryBarrierCount} is not 0, \texttt{pImageMemoryBarriers} must be a valid pointer to an array of \texttt{imageMemoryBarrierCount} valid \texttt{VkImageMemoryBarrier} structures
- \texttt{commandBuffer} must be in the recording state
- The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must support graphics, or compute operations
- \texttt{eventCount} must be greater than 0
- Both of \texttt{commandBuffer}, and the elements of \texttt{pEvents} must have been created, allocated, or retrieved from the same \texttt{VkDevice}

### Host Synchronization

- Host access to \texttt{commandBuffer} must be externally synchronized
- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must be externally synchronized
6.6. Pipeline Barriers

`vkCmdPipelineBarrier` is a synchronization command that inserts a dependency between commands submitted to the same queue, or between commands in the same subpass.

To record a pipeline barrier, call:

```c
void vkCmdPipelineBarrier(  
    VkCommandBuffer commandBuffer,  
    VkPipelineStageFlags srcStageMask,  
    VkPipelineStageFlags dstStageMask,  
    VkDependencyFlags dependencyFlags,  
    uint32_t memoryBarrierCount,  
    const VkMemoryBarrier* pMemoryBarriers,  
    uint32_t bufferMemoryBarrierCount,  
    const VkBufferMemoryBarrier* pBufferMemoryBarriers,  
    uint32_t imageMemoryBarrierCount,  
    const VkImageMemoryBarrier* pImageMemoryBarriers);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `srcStageMask` is a bitmask of `VkPipelineStageFlagBits` specifying the source stage mask.
- `dstStageMask` is a bitmask of `VkPipelineStageFlagBits` specifying the destination stage mask.
- `dependencyFlags` is a bitmask of `VkDependencyFlagBits` specifying how execution and memory dependencies are formed.
- `memoryBarrierCount` is the length of the `pMemoryBarriers` array.
- `pMemoryBarriers` is a pointer to an array of `VkMemoryBarrier` structures.
- `bufferMemoryBarrierCount` is the length of the `pBufferMemoryBarriers` array.
- `pBufferMemoryBarriers` is a pointer to an array of `VkBufferMemoryBarrier` structures.
- `imageMemoryBarrierCount` is the length of the `pImageMemoryBarriers` array.
- `pImageMemoryBarriers` is a pointer to an array of `VkImageMemoryBarrier` structures.

When `vkCmdPipelineBarrier` is submitted to a queue, it defines a memory dependency between commands that were submitted before it, and those submitted after it.

If `vkCmdPipelineBarrier` was recorded outside a render pass instance, the first synchronization scope includes all commands that occur earlier in submission order. If `vkCmdPipelineBarrier` was
recorded inside a render pass instance, the first synchronization scope includes only commands that occur earlier in submission order within the same subpass. In either case, the first synchronization scope is limited to operations on the pipeline stages determined by the source stage mask specified by srcStageMask.

If vkCmdPipelineBarrier was recorded outside a render pass instance, the second synchronization scope includes all commands that occur later in submission order. If vkCmdPipelineBarrier was recorded inside a render pass instance, the second synchronization scope includes only commands that occur later in submission order within the same subpass. In either case, the second synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by dstStageMask.

The first access scope is limited to access in the pipeline stages determined by the source stage mask specified by srcStageMask. Within that, the first access scope only includes the first access scopes defined by elements of the pMemoryBarriers, pBufferMemoryBarriers and pImageMemoryBarriers arrays, which each define a set of memory barriers. If no memory barriers are specified, then the first access scope includes no accesses.

The second access scope is limited to access in the pipeline stages determined by the destination stage mask specified by dstStageMask. Within that, the second access scope only includes the second access scopes defined by elements of the pMemoryBarriers, pBufferMemoryBarriers and pImageMemoryBarriers arrays, which each define a set of memory barriers. If no memory barriers are specified, then the second access scope includes no accesses.

If dependencyFlags includes VK_DEPENDENCY_BY_REGION_BIT, then any dependency between framebuffer-space pipeline stages is framebuffer-local - otherwise it is framebuffer-global.
Valid Usage

- If the geometry shaders feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`
- If the geometry shaders feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`
- If the tessellation shaders feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`
- If the tessellation shaders feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`

- If `vkCmdPipelineBarrier` is called within a render pass instance, the render pass must have been created with at least one `VkSubpassDependency` instance in `VkRenderPassCreateInfo::pDependencies` that expresses a dependency from the current subpass to itself, and for which `srcStageMask` contains a subset of the bit values in `VkSubpassDependency::srcStageMask`, `dstStageMask` contains a subset of the bit values in `VkSubpassDependency::dstStageMask`, `dependencyFlags` is equal to `VkSubpassDependency::dependencyFlags`, `srcAccessMask` member of each element of `pMemoryBarriers` and `pImageMemoryBarriers` contains a subset of the bit values in `VkSubpassDependency::srcAccessMask`, and `dstAccessMask` member of each element of `pMemoryBarriers` and `pImageMemoryBarriers` contains a subset of the bit values in `VkSubpassDependency::dstAccessMask`

- If `vkCmdPipelineBarrier` is called within a render pass instance, `bufferMemoryBarrierCount` must be 0

- If `vkCmdPipelineBarrier` is called within a render pass instance, the `image` member of any element of `pImageMemoryBarriers` must be equal to one of the elements of `pAttachments` that the current framebuffer was created with, that is also referred to by one of the elements of the `pColorAttachments`, `pResolveAttachments` or `pDepthStencilAttachment` members of the `VkSubpassDescription` instance or by the `pDepthStencilResolveAttachment` member of the `VkSubpassDescriptionDepthStencilResolve` structure that the current subpass was created with

- If `vkCmdPipelineBarrier` is called within a render pass instance, the `oldLayout` and `newLayout` members of any element of `pImageMemoryBarriers` must be equal to the `layout` member of an element of the `pColorAttachments`, `pResolveAttachments` or `pDepthStencilAttachment` members of the `VkSubpassDescription` instance or by the `pDepthStencilResolveAttachment` member of the `VkSubpassDescriptionDepthStencilResolve` structure that the current subpass was created with, that refers to the same `image`

- If `vkCmdPipelineBarrier` is called within a render pass instance, the `oldLayout` and `newLayout` members of an element of `pImageMemoryBarriers` must be equal

- If `vkCmdPipelineBarrier` is called within a render pass instance, the `srcQueueFamilyIndex` and `dstQueueFamilyIndex` members of any element of `pImageMemoryBarriers` must be `VK_QUEUE_FAMILY_IGNORED`

- Any pipeline stage included in `srcStageMask` or `dstStageMask` must be supported by the capabilities of the queue family specified by the `queueFamilyIndex` member of the `VkCommandPoolCreateInfo` structure that was used to create the `VkCommandPool` that
commandBuffer was allocated from, as specified in the table of supported pipeline stages

- If vkCmdPipelineBarrier is called outside of a render pass instance, dependencyFlags must not include VK_DEPENDENCY_VIEW_LOCAL_BIT

- The srcAccessMask member of each element of pMemoryBarriers must only include access flags that are supported by one or more of the pipeline stages in srcStageMask, as specified in the table of supported access types

- The dstAccessMask member of each element of pMemoryBarriers must only include access flags that are supported by one or more of the pipeline stages in dstStageMask, as specified in the table of supported access types

- For any element of pBufferMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its srcQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its srcAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in srcStageMask, as specified in the table of supported access types

- For any element of pBufferMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its dstQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its dstAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in dstStageMask, as specified in the table of supported access types

- For any element of pImageMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its srcQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its srcAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in srcStageMask, as specified in the table of supported access types

- For any element of pImageMemoryBarriers, if its srcQueueFamilyIndex and dstQueueFamilyIndex members are equal, or if its dstQueueFamilyIndex is the queue family index that was used to create the command pool that commandBuffer was allocated from, then its dstAccessMask member must only contain access flags that are supported by one or more of the pipeline stages in dstStageMask, as specified in the table of supported access types
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `srcStageMask` must be a valid combination of `VkPipelineStageFlagBits` values
- `srcStageMask` must not be 0
- `dstStageMask` must be a valid combination of `VkPipelineStageFlagBits` values
- `dstStageMask` must not be 0
- `dependencyFlags` must be a valid combination of `VkDependencyFlagBits` values
- If `memoryBarrierCount` is not 0, `pMemoryBarriers` must be a valid pointer to an array of `memoryBarrierCount` valid `VkMemoryBarrier` structures
- If `bufferMemoryBarrierCount` is not 0, `pBufferMemoryBarriers` must be a valid pointer to an array of `bufferMemoryBarrierCount` valid `VkBufferMemoryBarrier` structures
- If `imageMemoryBarrierCount` is not 0, `pImageMemoryBarriers` must be a valid pointer to an array of `imageMemoryBarrierCount` valid `VkImageMemoryBarrier` structures
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Transfer</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td>Compute</td>
</tr>
</tbody>
</table>

Bits which can be set in `vkCmdPipelineBarrier::dependencyFlags`, specifying how execution and memory dependencies are formed, are:
typedef enum VkDependencyFlagBits {
    VK_DEPENDENCY_BY_REGION_BIT = 0x00000001,
    VK_DEPENDENCY_DEVICE_GROUP_BIT = 0x00000004,
    VK_DEPENDENCY_VIEW_LOCAL_BIT = 0x00000002,
    VK_DEPENDENCY_VIEW_LOCAL_BIT_KHR = VK_DEPENDENCY_VIEW_LOCAL_BIT,
    VK_DEPENDENCY_DEVICE_GROUP_BIT_KHR = VK_DEPENDENCY_DEVICE_GROUP_BIT,
    VK_DEPENDENCY_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkDependencyFlagBits;

- **VK_DEPENDENCY_BY_REGION_BIT** specifies that dependencies will be framebuffer-local.
- **VK_DEPENDENCY_VIEW_LOCAL_BIT** specifies that a subpass has more than one view.
- **VK_DEPENDENCY_DEVICE_GROUP_BIT** specifies that dependencies are non-device-local dependency.

typedef VkFlags VkDependencyFlags;

*VkDependencyFlags* is a bitmask type for setting a mask of zero or more *VkDependencyFlagBits*.

### 6.6.1. Subpass Self-dependency

If `vkCmdPipelineBarrier` is called inside a render pass instance, the following restrictions apply. For a given subpass to allow a pipeline barrier, the render pass **must** declare a *self-dependency* from that subpass to itself. That is, there **must** exist a `VkSubpassDependency` in the subpass dependency list for the render pass with `srcSubpass` and `dstSubpass` equal to that subpass index. More than one self-dependency **can** be declared for each subpass.

Self-dependencies **must** only include pipeline stage bits that are graphics stages. If any of the stages in `srcStages` are framebuffer-space stages, `dstStages` **must** only contain framebuffer-space stages. Additionally, `srcStages` **must** not contain `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT` in a self-dependency.

If the source and destination stage masks both include framebuffer-space stages, then `dependencyFlags` **must** include `VK_DEPENDENCY_BY_REGION_BIT`. If the subpass has more than one view, then `dependencyFlags` **must** include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

A `vkCmdPipelineBarrier` command inside a render pass instance **must** be a subset of one of the self-dependencies of the subpass it is used in, meaning that the stage masks and access masks **must** each include only a subset of the bits of the corresponding mask in that self-dependency. If the self-dependency has `VK_DEPENDENCY_BY_REGION_BIT` or `VK_DEPENDENCY_VIEW_LOCAL_BIT` set, then so **must** the pipeline barrier. Pipeline barriers within a render pass instance **can** only be types `VkMemoryBarrier` or `VkImageMemoryBarrier`. If a `VkImageMemoryBarrier` is used, the image and image subresource range specified in the barrier **must** be a subset of one of the image views used by the framebuffer in the current subpass. Additionally, `oldLayout` **must** be equal to `newLayout`, and both the `srcQueueFamilyIndex` and `dstQueueFamilyIndex` **must** be `VK_QUEUE_FAMILY_IGNORED.`
6.7. Memory Barriers

Memory barriers are used to explicitly control access to buffer and image subresource ranges. Memory barriers are used to transfer ownership between queue families, change image layouts, and define availability and visibility operations. They explicitly define the access types and buffer and image subresource ranges that are included in the access scopes of a memory dependency that is created by a synchronization command that includes them.

6.7.1. Global Memory Barriers

Global memory barriers apply to memory accesses involving all memory objects that exist at the time of its execution.

The `VkMemoryBarrier` structure is defined as:

```c
typedef struct VkMemoryBarrier {
    VkStructureType    sType;
    const void*        pNext;
    VkAccessFlags      srcAccessMask;
    VkAccessFlags      dstAccessMask;
} VkMemoryBarrier;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `srcAccessMask` is a bitmask of `VkAccessFlagBits` specifying a source access mask.
- `dstAccessMask` is a bitmask of `VkAccessFlagBits` specifying a destination access mask.

The first access scope is limited to access types in the source access mask specified by `srcAccessMask`.

The second access scope is limited to access types in the destination access mask specified by `dstAccessMask`.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_MEMORY_BARRIER`
- `pNext` must be NULL
- `srcAccessMask` must be a valid combination of `VkAccessFlagBits` values
- `dstAccessMask` must be a valid combination of `VkAccessFlagBits` values

6.7.2. Buffer Memory Barriers

Buffer memory barriers only apply to memory accesses involving a specific buffer range. That is, a memory dependency formed from a buffer memory barrier is scoped to access via the specified buffer range. Buffer memory barriers can also be used to define a queue family ownership transfer
for the specified buffer range.

The `VkBufferMemoryBarrier` structure is defined as:

```c
typedef struct VkBufferMemoryBarrier {
    VkStructureType    sType;
    const void*        pNext;
    VkAccessFlags      srcAccessMask;
    VkAccessFlags      dstAccessMask;
    uint32_t           srcQueueFamilyIndex;
    uint32_t           dstQueueFamilyIndex;
    VkBuffer           buffer;
    VkDeviceSize       offset;
    VkDeviceSize       size;
} VkBufferMemoryBarrier;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `srcAccessMask` is a bitmask of `VkAccessFlagBits` specifying a source access mask.
- `dstAccessMask` is a bitmask of `VkAccessFlagBits` specifying a destination access mask.
- `srcQueueFamilyIndex` is the source queue family for a queue family ownership transfer.
- `dstQueueFamilyIndex` is the destination queue family for a queue family ownership transfer.
- `buffer` is a handle to the buffer whose backing memory is affected by the barrier.
- `offset` is an offset in bytes into the backing memory for `buffer`; this is relative to the base offset as bound to the buffer (see `vkBindBufferMemory`).
- `size` is a size in bytes of the affected area of backing memory for `buffer`, or `VK_WHOLE_SIZE` to use the range from `offset` to the end of the buffer.

The first access scope is limited to access to memory through the specified buffer range, via access types in the source access mask specified by `srcAccessMask`. If `srcAccessMask` includes `VK_ACCESS_HOST_WRITE_BIT`, memory writes performed by that access type are also made visible, as that access type is not performed through a resource.

The second access scope is limited to access to memory through the specified buffer range, via access types in the destination access mask specified by `dstAccessMask`. If `dstAccessMask` includes `VK_ACCESS_HOST_WRITE_BIT` or `VK_ACCESS_HOST_READ_BIT`, available memory writes are also made visible to accesses of those types, as those access types are not performed through a resource.

If `srcQueueFamilyIndex` is not equal to `dstQueueFamilyIndex`, and `srcQueueFamilyIndex` is equal to the current queue family, then the memory barrier defines a queue family release operation for the specified buffer range, and the second access scope includes no access, as if `dstAccessMask` was `0`.

If `dstQueueFamilyIndex` is not equal to `srcQueueFamilyIndex`, and `dstQueueFamilyIndex` is equal to the current queue family, then the memory barrier defines a queue family acquire operation for the specified buffer range, and the first access scope includes no access, as if `srcAccessMask` was `0`. 

Valid Usage

- **offset** must be less than the size of `buffer`
- If `size` is not equal to `VK_WHOLE_SIZE`, `size` must be greater than 0
- If `size` is not equal to `VK_WHOLE_SIZE`, `size` must be less than or equal to than the size of `buffer` minus `offset`
- If `buffer` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, at least one of `srcQueueFamilyIndex` and `dstQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED`
- If `buffer` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, and one of `srcQueueFamilyIndex` and `dstQueueFamilyIndex` is `VK_QUEUE_FAMILY_IGNORED`, the other must be `VK_QUEUE_FAMILY_IGNORED` or a special queue family reserved for external memory ownership transfers, as described in Queue Family Ownership Transfer.
- If `buffer` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE` and `srcQueueFamilyIndex` is `VK_QUEUE_FAMILY_IGNORED`, `dstQueueFamilyIndex` must also be `VK_QUEUE_FAMILY_IGNORED`
- If `buffer` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE` and `srcQueueFamilyIndex` is not `VK_QUEUE_FAMILY_IGNORED`, it must be a valid queue family or a special queue family reserved for external memory transfers, as described in Queue Family Ownership Transfer.
- If `buffer` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE` and `dstQueueFamilyIndex` is not `VK_QUEUE_FAMILY_IGNORED`, it must be a valid queue family or a special queue family reserved for external memory transfers, as described in Queue Family Ownership Transfer.
- If `buffer` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE`, and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are not `VK_QUEUE_FAMILY_IGNORED`, at least one of them must be the same as the family of the queue that will execute this barrier
- If `buffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_BUFFER_MEMORY_BARRIER`
- **pNext** must be `NULL`
- **buffer** must be a valid `VkBuffer` handle

6.7.3. Image Memory Barriers

Image memory barriers only apply to memory accesses involving a specific image subresource range. That is, a memory dependency formed from an image memory barrier is scoped to access via the specified image subresource range. Image memory barriers can also be used to define image layout transitions or a queue family ownership transfer for the specified image subresource
The `VkImageMemoryBarrier` structure is defined as:

```c
typedef struct VkImageMemoryBarrier {
    VkStructureType            sType;
    const void*                pNext;
    VkAccessFlags              srcAccessMask;
    VkAccessFlags              dstAccessMask;
    VkImageLayout              oldLayout;
    VkImageLayout              newLayout;
    uint32_t                   srcQueueFamilyIndex;
    uint32_t                   dstQueueFamilyIndex;
    VkImage                    image;
    VkImageSubresourceRange    subresourceRange;
} VkImageMemoryBarrier;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `srcAccessMask` is a bitmask of `VkAccessFlagBits` specifying a source access mask.
- `dstAccessMask` is a bitmask of `VkAccessFlagBits` specifying a destination access mask.
- `oldLayout` is the old layout in an image layout transition.
- `newLayout` is the new layout in an image layout transition.
- `srcQueueFamilyIndex` is the source queue family for a queue family ownership transfer.
- `dstQueueFamilyIndex` is the destination queue family for a queue family ownership transfer.
- `image` is a handle to the image affected by this barrier.
- `subresourceRange` describes the image subresource range within `image` that is affected by this barrier.

The first access scope is limited to access to memory through the specified image subresource range, via access types in the source access mask specified by `srcAccessMask`. If `srcAccessMask` includes `VK_ACCESS_HOST_WRITE_BIT`, memory writes performed by that access type are also made visible, as that access type is not performed through a resource.

The second access scope is limited to access to memory through the specified image subresource range, via access types in the destination access mask specified by `dstAccessMask`. If `dstAccessMask` includes `VK_ACCESS_HOST_WRITE_BIT` or `VK_ACCESS_HOST_READ_BIT`, available memory writes are also made visible to accesses of those types, as those access types are not performed through a resource.

If `srcQueueFamilyIndex` is not equal to `dstQueueFamilyIndex`, and `srcQueueFamilyIndex` is equal to the current queue family, then the memory barrier defines a queue family release operation for the specified image subresource range, and the second access scope includes no access, as if `dstAccessMask` was 0.

If `dstQueueFamilyIndex` is not equal to `srcQueueFamilyIndex`, and `dstQueueFamilyIndex` is equal to the
current queue family, then the memory barrier defines a *queue family acquire operation* for the specified image subresource range, and the first access scope includes no access, as if \text{srcAccessMask} was 0.

If \text{oldLayout} is not equal to \text{newLayout}, then the memory barrier defines an *image layout transition* for the specified image subresource range.

Layout transitions that are performed via image memory barriers execute in their entirety in *submission order*, relative to other image layout transitions submitted to the same queue, including those performed by *render passes*. In effect there is an implicit execution dependency from each such layout transition to all layout transitions previously submitted to the same queue.

If \text{image} has a multi-planar format and the image is *disjoint*, then including \text{VK_IMAGE_ASPECT_COLOR_BIT} in the \text{aspectMask} member of \text{subresourceRange} is equivalent to including \text{VK_IMAGE_ASPECT_PLANE_0_BIT}, \text{VK_IMAGE_ASPECT_PLANE_1_BIT}, and (for three-plane formats only) \text{VK_IMAGE_ASPECT_PLANE_2_BIT}.  


Valid Usage

• **oldLayout** must be `VK_IMAGE_LAYOUT_UNDEFINED` or the current layout of the image subresources affected by the barrier.

• **newLayout** must not be `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED`.

• If `image` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, at least one of `srcQueueFamilyIndex` and `dstQueueFamilyIndex` must be `VK_QUEUE_FAMILY_IGNORED`.

• If `image` was created with a sharing mode of `VK_SHARING_MODE_CONCURRENT`, and one of `srcQueueFamilyIndex` and `dstQueueFamilyIndex` is `VK_QUEUE_FAMILY_IGNORED`, the other must be `VK_QUEUE_FAMILY_IGNORED` or a special queue family reserved for external memory transfers, as described in Queue Family Ownership Transfer.

• If `image` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE` and `srcQueueFamilyIndex` is `VK_QUEUE_FAMILY_IGNORED`, `dstQueueFamilyIndex` must also be `VK_QUEUE_FAMILY_IGNORED`.

• If `image` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE` and `srcQueueFamilyIndex` is not `VK_QUEUE_FAMILY_IGNORED`, it must be a valid queue family or a special queue family reserved for external memory transfers, as described in Queue Family Ownership Transfer.

• If `image` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE` and `dstQueueFamilyIndex` is not `VK_QUEUE_FAMILY_IGNORED`, it must be a valid queue family or a special queue family reserved for external memory transfers, as described in Queue Family Ownership Transfer.

• If `image` was created with a sharing mode of `VK_SHARING_MODE_EXCLUSIVE`, and `srcQueueFamilyIndex` and `dstQueueFamilyIndex` are not `VK_QUEUE_FAMILY_IGNORED`, at least one of them must be the same as the family of the queue that will execute this barrier.

• **subresourceRange.baseMipLevel** must be less than the `mipLevels` specified in `VkImageCreateInfo` when `image` was created.

• If `subresourceRange.levelCount` is not `VK_REMAINING_MIP_LEVELS`, `subresourceRange.baseMipLevel + subresourceRange.levelCount` must be less than or equal to the `mipLevels` specified in `VkImageCreateInfo` when `image` was created.

• **subresourceRange.baseArrayLayer** must be less than the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.

• If `subresourceRange.layerCount` is not `VK_REMAINING_ARRAY_LAYERS`, `subresourceRange.baseArrayLayer + subresourceRange.layerCount` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.

• If `image` has a depth/stencil format with both depth and stencil and the `separateDepthStencilLayouts` feature is enabled, then the `aspectMask` member of `subresourceRange` must include either or both `VK_IMAGE_ASPECT_DEPTH_BIT` and `VK_IMAGE_ASPECT_STENCIL_BIT`.

• If `image` has a depth/stencil format with both depth and stencil and the `separateDepthStencilLayouts` feature is not enabled, then the `aspectMask` member of `subresourceRange` must include both `VK_IMAGE_ASPECT_DEPTH_BIT` and `VK_IMAGE_ASPECT_STENCIL_BIT`.
• If `image` has a color format and either the format is single-plane or the image is not disjoint then the `aspectMask` member of `subresourceRange` must only include `VK_IMAGE_ASPECT_COLOR_BIT`

• If `image` has a multi-planar format and the image is `disjoint`, then the `aspectMask` member of `subresourceRange` must include either at least one of `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, and `VK_IMAGE_ASPECT_PLANE_2_BIT`; or must include `VK_IMAGE_ASPECT_COLOR_BIT`

• If `image` has a multi-planar format with only two planes, then the `aspectMask` member of `subresourceRange` must not include `VK_IMAGE_ASPECT_PLANE_2_BIT`

• If either `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT` set

• If either `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT` set

• If either `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT` set

• If either `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT` set

• If either `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_SAMPLED_BIT` or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT` set

• If either `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` set

• If either `oldLayout` or `newLayout` is `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` then `image` must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` set

• If `image` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object

**Valid Usage (Implicit)**

• `sType` must be `VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER`

• `pNext` must be `NULL`

• `oldLayout` must be a valid `VkImageLayout` value

• `newLayout` must be a valid `VkImageLayout` value

• `image` must be a valid `VkImage` handle

• `subresourceRange` must be a valid `VkImageSubresourceRange` structure
6.7.4. Queue Family Ownership Transfer

Resources created with a VkSharingMode of VK_SHARING_MODE_EXCLUSIVE must have their ownership explicitly transferred from one queue family to another in order to access their content in a well-defined manner on a queue in a different queue family. Resources shared with external APIs or instances using external memory must also explicitly manage ownership transfers between local and external queues (or equivalent constructs in external APIs) regardless of the VkSharingMode specified when creating them. The special queue family index VK_QUEUE_FAMILY_EXTERNAL represents any queue external to the resource’s current Vulkan instance, as long as the queue uses the same underlying physical device or device group and uses the same driver version as the resource’s VkDevice, as indicated by VkPhysicalDeviceIDProperties::deviceUUID and VkPhysicalDeviceIDProperties::driverUUID. If memory dependencies are correctly expressed between uses of such a resource between two queues in different families, but no ownership transfer is defined, the contents of that resource are undefined for any read accesses performed by the second queue family.

**Note**

If an application does not need the contents of a resource to remain valid when transferring from one queue family to another, then the ownership transfer should be skipped.

A queue family ownership transfer consists of two distinct parts:

1. Release exclusive ownership from the source queue family
2. Acquire exclusive ownership for the destination queue family

An application must ensure that these operations occur in the correct order by defining an execution dependency between them, e.g. using a semaphore.

A release operation is used to release exclusive ownership of a range of a buffer or image subresource range. A release operation is defined by executing a buffer memory barrier (for a buffer range) or an image memory barrier (for an image subresource range) using vkCmdPipelineBarrier, on a queue from the source queue family. The srcQueueFamilyIndex parameter of the barrier must be set to the source queue family index, and the dstQueueFamilyIndex parameter to the destination queue family index. dstAccessMask is ignored for such a barrier, such that no visibility operation is executed - the value of this mask does not affect the validity of the barrier. The release operation happens-after the availability operation, and happens-before operations specified in the second synchronization scope of the calling command.

An acquire operation is used to acquire exclusive ownership of a range of a buffer or image subresource range. An acquire operation is defined by executing a buffer memory barrier (for a buffer range) or an image memory barrier (for an image subresource range) using vkCmdPipelineBarrier, on a queue from the destination queue family. The buffer range or image subresource range specified in an acquire operation must match exactly that of a previous release operation. The srcQueueFamilyIndex parameter of the barrier must be set to the source queue family index, and the dstQueueFamilyIndex parameter to the destination queue family index. srcAccessMask is ignored for such a barrier, such that no availability operation is executed - the value of this mask does not affect the validity of the barrier. The acquire operation happens-after operations in the
first synchronization scope of the calling command, and happens-before the visibility operation.

Note
Whilst it is not invalid to provide destination or source access masks for memory barriers used for release or acquire operations, respectively, they have no practical effect. Access after a release operation has undefined results, and so visibility for those accesses has no practical effect. Similarly, write access before an acquire operation will produce undefined results for future access, so availability of those writes has no practical use. In an earlier version of the specification, these were required to match on both sides - but this was subsequently relaxed. These masks should be set to 0.

If the transfer is via an image memory barrier, and an image layout transition is desired, then the values of oldLayout and newLayout in the release operation's memory barrier must be equal to values of oldLayout and newLayout in the acquire operation's memory barrier. Although the image layout transition is submitted twice, it will only be executed once. A layout transition specified in this way happens-after the release operation and happens-before the acquire operation.

If the values of srcQueueFamilyIndex and dstQueueFamilyIndex are equal, no ownership transfer is performed, and the barrier operates as if they were both set to VK_QUEUE_FAMILY_IGNORED.

Queue family ownership transfers may perform read and write accesses on all memory bound to the image subresource or buffer range, so applications must ensure that all memory writes have been made available before a queue family ownership transfer is executed. Available memory is automatically made visible to queue family release and acquire operations, and writes performed by those operations are automatically made available.

Once a queue family has acquired ownership of a buffer range or image subresource range of a VK_SHARING_MODE_EXCLUSIVE resource, its contents are undefined to other queue families unless ownership is transferred. The contents of any portion of another resource which aliases memory that is bound to the transferred buffer or image subresource range are undefined after a release or acquire operation.

Note
Because events cannot be used directly for inter-queue synchronization, and because vkCmdSetEvent does not have the queue family index or memory barrier parameters needed by a release operation, the release and acquire operations of a queue family ownership transfer can only be performed using vkCmdPipelineBarrier.

6.8. Wait Idle Operations
To wait on the host for the completion of outstanding queue operations for a given queue, call:

```c
VkResult vkQueueWaitIdle(VkQueue queue);
```
queue is the queue on which to wait.

vkQueueWaitIdle is equivalent to submitting a fence to a queue and waiting with an infinite timeout for that fence to signal.

### Valid Usage (Implicit)
- queue must be a valid VkQueue handle

### Host Synchronization
- Host access to queue must be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>Any</td>
<td>-</td>
</tr>
</tbody>
</table>

### Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

To wait on the host for the completion of outstanding queue operations for all queues on a given logical device, call:

```cpp
VkResult vkDeviceWaitIdle(
    VkDevice device);
```

- device is the logical device to idle.

vkDeviceWaitIdle is equivalent to calling vkQueueWaitIdle for all queues owned by device.

### Valid Usage (Implicit)
- device must be a valid VkDevice handle
6.9. Host Write Ordering Guarantees

When batches of command buffers are submitted to a queue via `vkQueueSubmit`, it defines a memory dependency with prior host operations, and execution of command buffers submitted to the queue.

The first synchronization scope is defined by the host execution model, but includes execution of `vkQueueSubmit` on the host and anything that happened-before it.

The second synchronization scope includes all commands submitted in the same queue submission, and all commands that occur later in submission order.

The first access scope includes all host writes to mappable device memory that are available to the host memory domain.

The second access scope includes all memory access performed by the device.

6.10. Synchronization and Multiple Physical Devices

If a logical device includes more than one physical device, then fences, semaphores, and events all still have a single instance of the signaled state.

A fence becomes signaled when all physical devices complete the necessary queue operations.

Semaphore wait and signal operations all include a device index that is the sole physical device that performs the operation. These indices are provided in the `VkDeviceGroupSubmitInfo` and `VkDeviceGroupBindSparseInfo` structures. Semaphores are not exclusively owned by any physical device. For example, a semaphore can be signaled by one physical device and then waited on by a different physical device.

An event can only be waited on by the same physical device that signaled it (or the host).
Chapter 7. Render Pass

A render pass represents a collection of attachments, subpasses, and dependencies between the subpasses, and describes how the attachments are used over the course of the subpasses. The use of a render pass in a command buffer is a render pass instance.

Render passes are represented by VkRenderPass handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkRenderPass)
```

An attachment description describes the properties of an attachment including its format, sample count, and how its contents are treated at the beginning and end of each render pass instance.

A subpass represents a phase of rendering that reads and writes a subset of the attachments in a render pass. Rendering commands are recorded into a particular subpass of a render pass instance.

A subpass description describes the subset of attachments that is involved in the execution of a subpass. Each subpass can read from some attachments as input attachments, write to some as color attachments or depth/stencil attachments, and perform multisample resolve operations to resolve attachments. A subpass description can also include a set of preserve attachments, which are attachments that are not read or written by the subpass but whose contents must be preserved throughout the subpass.

A subpass uses an attachment if the attachment is a color, depth/stencil, resolve, depth/stencil resolve, or input attachment for that subpass (as determined by the pColorAttachments, pDepthStencilAttachment, pResolveAttachments, VkSubpassDescriptionDepthStencilResolve::pDepthStencilResolveAttachment, and pInputAttachments members of VkSubpassDescription, respectively). A subpass does not use an attachment if that attachment is preserved by the subpass. The first use of an attachment is in the lowest numbered subpass that uses that attachment. Similarly, the last use of an attachment is in the highest numbered subpass that uses that attachment.

The subpasses in a render pass all render to the same dimensions, and fragments for pixel (x,y,layer) in one subpass can only read attachment contents written by previous subpasses at that same (x,y,layer) location.

Note

By describing a complete set of subpasses in advance, render passes provide the implementation an opportunity to optimize the storage and transfer of attachment data between subpasses.

In practice, this means that subpasses with a simple framebuffer-space dependency may be merged into a single tiled rendering pass, keeping the attachment data on-chip for the duration of a render pass instance. However, it is also quite common for a render pass to only contain a single subpass.

Subpass dependencies describe execution and memory dependencies between subpasses.
A subpass dependency chain is a sequence of subpass dependencies in a render pass, where the source subpass of each subpass dependency (after the first) equals the destination subpass of the previous dependency.

Execution of subpasses may overlap or execute out of order with regards to other subpasses, unless otherwise enforced by an execution dependency. Each subpass only respects submission order for commands recorded in the same subpass, and the vkCmdBeginRenderPass and vkCmdEndRenderPass commands that delimit the render pass - commands within other subpasses are not included. This affects most other implicit ordering guarantees.

A render pass describes the structure of subpasses and attachments independent of any specific image views for the attachments. The specific image views that will be used for the attachments, and their dimensions, are specified in VkFramebuffer objects. Framebuffers are created with respect to a specific render pass that the framebuffer is compatible with (see Render Pass Compatibility). Collectively, a render pass and a framebuffer define the complete render target state for one or more subpasses as well as the algorithmic dependencies between the subpasses.

The various pipeline stages of the drawing commands for a given subpass may execute concurrently and/or out of order, both within and across drawing commands, whilst still respecting pipeline order. However for a given (x,y,layer,sample) sample location, certain per-sample operations are performed in rasterization order.

7.1. Render Pass Creation

To create a render pass, call:

```c
VkResult vkCreateRenderPass(
    VkDevice device, 
    const VkRenderPassCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkRenderPass* pRenderPass);
```

- `device` is the logical device that creates the render pass.
- `pCreateInfo` is a pointer to a VkRenderPassCreateInfo structure describing the parameters of the render pass.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pRenderPass` is a pointer to a VkRenderPass handle in which the resulting render pass object is returned.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkRenderPassCreateInfo` structure
- If **pAllocator** is not `NULL`, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pRenderPass** must be a valid pointer to a `VkRenderPass` handle

Return Codes

**Success**
- **VK_SUCCESS**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

The `VkRenderPassCreateInfo` structure is defined as:

```c
typedef struct VkRenderPassCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkRenderPassCreateFlags flags;
    uint32_t attachmentCount;
    const VkAttachmentDescription* pAttachments;
    uint32_t subpassCount;
    const VkSubpassDescription* pSubpasses;
    uint32_t dependencyCount;
    const VkSubpassDependency* pDependencies;
} VkRenderPassCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **attachmentCount** is the number of attachments used by this render pass.
- **pAttachments** is a pointer to an array of `attachmentCount` `VkAttachmentDescription` structures describing the attachments used by the render pass.
- **subpassCount** is the number of subpasses to create.
- **pSubpasses** is a pointer to an array of `subpassCount` `VkSubpassDescription` structures describing each subpass.
- **dependencyCount** is the number of memory dependencies between pairs of subpasses.
• `pDependencies` is a pointer to an array of `dependencyCount` `VkSubpassDependency` structures describing dependencies between pairs of subpasses.

**Note**

Care should be taken to avoid a data race here; if any subpasses access attachments with overlapping memory locations, and one of those accesses is a write, a subpass dependency needs to be included between them.
Valid Usage

- If the attachment member of any element of pInputAttachments, pColorAttachments, pResolveAttachments or pDepthStencilAttachment, or any element of pPreserveAttachments in any element of pSubpasses is not VK_ATTACHMENT_UNUSED, it must be less than attachmentCount.

- For any member of pAttachments with a loadOp equal to VK_ATTACHMENT_LOAD_OP_CLEAR, the first use of that attachment must not specify a layout equal to VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL.

- For any member of pAttachments with a stencilLoadOp equal to VK_ATTACHMENT_LOAD_OP_CLEAR, the first use of that attachment must not specify a layout equal to VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL.

- If the pNext chain includes a VkRenderPassInputAttachmentAspectCreateInfo structure, the subpass member of each element of its pAspectReferences member must be less than subpassCount.

- If the pNext chain includes a VkRenderPassInputAttachmentAspectCreateInfo structure, the inputAttachmentIndex member of each element of its pAspectReferences member must be less than the value of inputAttachmentCount in the member of pSubpasses identified by its subpass member.

- If the pNext chain includes a VkRenderPassInputAttachmentAspectCreateInfo structure, for any element of the pInputAttachments member of any element of pSubpasses where the attachment member is not VK_ATTACHMENT_UNUSED, the aspectMask member of the corresponding element of VkRenderPassInputAttachmentAspectCreateInfo::pAspectReferences must only include aspects that are present in images of the format specified by the element of pAttachments at attachment.

- If the pNext chain includes a VkRenderPassMultiviewCreateInfo structure, and its subpassCount member is not zero, that member must be equal to the value of subpassCount.

- If the pNext chain includes a VkRenderPassMultiviewCreateInfo structure, if its dependencyCount member is not zero, it must be equal to dependencyCount.

- If the pNext chain includes a VkRenderPassMultiviewCreateInfo structure, for each non-zero element of pViewOffsets, the srcSubpass and dstSubpass members of pDependencies at the same index must not be equal.

- If the pNext chain includes a VkRenderPassMultiviewCreateInfo structure, for any element of pDependencies with a dependencyFlags member that does not include VK_DEPENDENCY_VIEW_LOCAL_BIT, the corresponding element of the pViewOffsets member of
that `VkRenderPassMultiviewCreateInfo` instance must be 0

- If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, elements of its `pViewMasks` member must either all be 0, or all not be 0
- If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, and each element of its `pViewMasks` member is 0, the `dependencyFlags` member of each element of `pDependencies` must not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`
- If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, and each element of its `pViewMasks` member is 0, `correlatedViewMaskCount` must be 0
- If the `pNext` chain includes a `VkRenderPassMultiviewCreateInfo` structure, each element of its `pViewMask` member must not have a bit set at an index greater than or equal to `VkPhysicalDeviceLimits::maxFramebufferLayers`

For any element of `pDependencies`, if the `srcSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `srcStageMask` member of that dependency must be a pipeline stage supported by the `pipeline` identified by the `pipelineBindPoint` member of the source subpass

- For any element of `pDependencies`, if the `dstSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `dstStageMask` member of that dependency must be a pipeline stage supported by the `pipeline` identified by the `pipelineBindPoint` member of the destination subpass
- The `srcSubpass` member of each element of `pDependencies` must be less than `subpassCount`
- The `dstSubpass` member of each element of `pDependencies` must be less than `subpassCount`

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO`
- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkRenderPassInputAttachmentAspectCreateInfo` or `VkRenderPassMultiviewCreateInfo`
- The `sType` value of each struct in the `pNext` chain must be unique
- **flags** must be 0
- If `attachmentCount` is not 0, `pAttachments` must be a valid pointer to an array of `attachmentCount` valid `VkAttachmentDescription` structures
- `pSubpasses` must be a valid pointer to an array of `subpassCount` valid `VkSubpassDescription` structures
- If `dependencyCount` is not 0, `pDependencies` must be a valid pointer to an array of `dependencyCount` valid `VkSubpassDependency` structures
- `subpassCount` must be greater than 0

```c
typedef VkFlags VkRenderPassCreateFlags;
```
**VkRenderPassCreateFlags** is a bitmask type for setting a mask, but is currently reserved for future use.

If the **VkRenderPassCreateInfo**:pNext chain includes a **VkRenderPassMultiviewCreateInfo** structure, then that structure includes an array of view masks, view offsets, and correlation masks for the render pass.

The **VkRenderPassMultiviewCreateInfo** structure is defined as:

```c
typedef struct VkRenderPassMultiviewCreateInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           subpassCount;
    const uint32_t*    pViewMasks;
    uint32_t           dependencyCount;
    const int32_t*     pViewOffsets;
    uint32_t           correlationMaskCount;
    const uint32_t*    pCorrelationMasks;
} VkRenderPassMultiviewCreateInfo;
```

or the equivalent

```c
typedef VkRenderPassMultiviewCreateInfo VkRenderPassMultiviewCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **subpassCount** is zero or the number of subpasses in the render pass.
- **pViewMasks** is a pointer to an array of **subpassCount** view masks, where each mask is a bitfield of view indices describing which views rendering is broadcast to in each subpass, when multiview is enabled. If **subpassCount** is zero, each view mask is treated as zero.
- **dependencyCount** is zero or the number of dependencies in the render pass.
- **pViewOffsets** is a pointer to an array of **dependencyCount** view offsets, one for each dependency. If **dependencyCount** is zero, each dependency’s view offset is treated as zero. Each view offset controls which views in the source subpass the views in the destination subpass depend on.
- **correlationMaskCount** is zero or the number of correlation masks.
- **pCorrelationMasks** is a pointer to an array of **correlationMaskCount** view masks indicating sets of views that **may** be more efficient to render concurrently.

When a subpass uses a non-zero view mask, **multiview** functionality is considered to be enabled. Multiview is all-or-nothing for a render pass - that is, either all subpasses **must** have a non-zero view mask (though some subpasses **may** have only one view) or all **must** be zero. Multiview causes all drawing and clear commands in the subpass to behave as if they were broadcast to each view, where a view is represented by one layer of the framebuffer attachments. All draws and clears are broadcast to each **view index** whose bit is set in the view mask. The view index is provided in the **ViewIndex** shader input variable, and color, depth/stencil, and input attachments all read/write the
layer of the framebuffer corresponding to the view index.

If the view mask is zero for all subpasses, multiview is considered to be disabled and all drawing commands execute normally, without this additional broadcasting.

Some implementations may not support multiview in conjunction with geometry shaders or tessellation shaders.

When multiview is enabled, the VK_DEPENDENCY_VIEW_LOCAL_BIT bit in a dependency can be used to express a view-local dependency, meaning that each view in the destination subpass depends on a single view in the source subpass. Unlike pipeline barriers, a subpass dependency can potentially have a different view mask in the source subpass and the destination subpass. If the dependency is view-local, then each view (dstView) in the destination subpass depends on the view dstView + pViewOffsets[dependency] in the source subpass. If there is not such a view in the source subpass, then this dependency does not affect that view in the destination subpass. If the dependency is not view-local, then all views in the destination subpass depend on all views in the source subpass, and the view offset is ignored. A non-zero view offset is not allowed in a self-dependency.

The elements of pCorrelationMasks are a set of masks of views indicating that views in the same mask may exhibit spatial coherency between the views, making it more efficient to render them concurrently. Correlation masks must not have a functional effect on the results of the multiview rendering.

When multiview is enabled, at the beginning of each subpass all non-render pass state is undefined. In particular, each time vkCmdBeginRenderPass or vkCmdNextSubpass is called the graphics pipeline must be bound, any relevant descriptor sets or vertex/index buffers must be bound, and any relevant dynamic state or push constants must be set before they are used.

Valid Usage

- Each view index must not be set in more than one element of pCorrelationMasks

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_RENDER_PASS_MULTIVIEW_CREATE_INFO
- If subpassCount is not 0, pViewMasks must be a valid pointer to an array of subpassCount uint32_t values
- If dependencyCount is not 0, pViewOffsets must be a valid pointer to an array of dependencyCount int32_t values
- If correlationMaskCount is not 0, pCorrelationMasks must be a valid pointer to an array of correlationMaskCount uint32_t values

The VkAttachmentDescription structure is defined as:
typedef struct VkAttachmentDescription {
    VkAttachmentDescriptionFlags flags;
    VkFormat format;
    VkSampleCountFlagBits samples;
    VkAttachmentLoadOp loadOp;
    VkAttachmentStoreOp storeOp;
    VkAttachmentLoadOp stencilLoadOp;
    VkAttachmentStoreOp stencilStoreOp;
    VkImageLayout initialLayout;
    VkImageLayout finalLayout;
} VkAttachmentDescription;

- **flags** is a bitmask of VkAttachmentDescriptionFlagBits specifying additional properties of the attachment.
- **format** is a VkFormat value specifying the format of the image view that will be used for the attachment.
- **samples** is the number of samples of the image as defined in VkSampleCountFlagBits.
- **loadOp** is a VkAttachmentLoadOp value specifying how the contents of color and depth components of the attachment are treated at the beginning of the subpass where it is first used.
- **storeOp** is a VkAttachmentStoreOp value specifying how the contents of color and depth components of the attachment are treated at the end of the subpass where it is last used.
- **stencilLoadOp** is a VkAttachmentLoadOp value specifying how the contents of stencil components of the attachment are treated at the beginning of the subpass where it is first used.
- **stencilStoreOp** is a VkAttachmentStoreOp value specifying how the contents of stencil components of the attachment are treated at the end of the last subpass where it is used.
- **initialLayout** is the layout the attachment image subresource will be in when a render pass instance begins.
- **finalLayout** is the layout the attachment image subresource will be transitioned to when a render pass instance ends.

If the attachment uses a color format, then loadOp and storeOp are used, and stencilLoadOp and stencilStoreOp are ignored. If the format has depth and/or stencil components, loadOp and storeOp apply only to the depth data, while stencilLoadOp and stencilStoreOp define how the stencil data is handled. loadOp and stencilLoadOp define the load operations that execute as part of the first subpass that uses the attachment. storeOp and stencilStoreOp define the store operations that execute as part of the last subpass that uses the attachment.

The load operation for each sample in an attachment happens-before any recorded command which accesses the sample in the first subpass where the attachment is used. Load operations for attachments with a depth/stencil format execute in the VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT pipeline stage. Load operations for attachments with a color format execute in the VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT pipeline stage.

The store operation for each sample in an attachment happens-after any recorded command which accesses the sample in the last subpass where the attachment is used. Store operations for
attachments with a depth/stencil format execute in the `VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT` pipeline stage. Store operations for attachments with a color format execute in the `VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT` pipeline stage.

If an attachment is not used by any subpass, then `loadOp`, `storeOp`, `stencilStoreOp`, and `stencilLoadOp` are ignored, and the attachment's memory contents will not be modified by execution of a render pass instance.

The load and store operations apply on the first and last use of each view in the render pass, respectively. If a view index of an attachment is not included in the view mask in any subpass that uses it, then the load and store operations are ignored, and the attachment's memory contents will not be modified by execution of a render pass instance.

During a render pass instance, input/color attachments with color formats that have a component size of 8, 16, or 32 bits must be represented in the attachment's format throughout the instance. Attachments with other floating- or fixed-point color formats, or with depth components may be represented in a format with a precision higher than the attachment format, but must be represented with the same range. When such a component is loaded via the `loadOp`, it will be converted into an implementation-dependent format used by the render pass. Such components must be converted from the render pass format, to the format of the attachment, before they are resolved or stored at the end of a render pass instance via `storeOp`. Conversions occur as described in *Numeric Representation and Computation* and *Fixed-Point Data Conversions*.

If `flags` includes `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT`, then the attachment is treated as if it shares physical memory with another attachment in the same render pass. This information limits the ability of the implementation to reorder certain operations (like layout transitions and the `loadOp`) such that it is not improperly reordered against other uses of the same physical memory via a different attachment. This is described in more detail below.

If a render pass uses multiple attachments that alias the same device memory, those attachments must each include the `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT` bit in their attachment description flags. Attachments aliasing the same memory occurs in multiple ways:

- Multiple attachments being assigned the same image view as part of framebuffer creation.
- Attachments using distinct image views that correspond to the same image subresource of an image.
- Attachments using views of distinct image subresources which are bound to overlapping memory ranges.

**Note**

Render passes must include subpass dependencies (either directly or via a subpass dependency chain) between any two subpasses that operate on the same attachment or aliasing attachments and those subpass dependencies must include execution and memory dependencies separating uses of the aliases, if at least one of those subpasses writes to one of the aliases. These dependencies must not include the `VK_DEPENDENCY_BY_REGION_BIT` if the aliases are views of distinct image subresources which overlap in memory.
Multiple attachments that alias the same memory must not be used in a single subpass. A given attachment index must not be used multiple times in a single subpass, with one exception: two subpass attachments can use the same attachment index if at least one use is as an input attachment and neither use is as a resolve or preserve attachment. In other words, the same view can be used simultaneously as an input and color or depth/stencil attachment, but must not be used as multiple color or depth/stencil attachments nor as resolve or preserve attachments. The precise set of valid scenarios is described in more detail below.

If a set of attachments alias each other, then all except the first to be used in the render pass must use an initialLayout of VK_IMAGE_LAYOUT_UNDEFINED, since the earlier uses of the other aliases make their contents undefined. Once an alias has been used and a different alias has been used after it, the first alias must not be used in any later subpasses. However, an application can assign the same image view to multiple aliasing attachment indices, which allows that image view to be used multiple times even if other aliases are used in between.

**Note**

Once an attachment needs the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT bit, there should be no additional cost of introducing additional aliases, and using these additional aliases may allow more efficient clearing of the attachments on multiple uses via VK_ATTACHMENT_LOAD_OP_CLEAR.
Valid Usage

- `finalLayout` must not be `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED`
- If `format` is a color format, `initialLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`
- If `format` is a depth/stencil format, `initialLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`
- If `format` is a color format, `finalLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`
- If `format` is a depth/stencil format, `finalLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`
- If the `separateDepthStencilLayouts` feature is not enabled, `initialLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`
- If the `separateDepthStencilLayouts` feature is not enabled, `finalLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`
- If `format` is a color format, `initialLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`
- If `format` is a color format, `finalLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`
- If `format` is a depth/stencil format which includes both depth and stencil aspects, `initialLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`
- If `format` is a depth/stencil format which includes both depth and stencil aspects, `finalLayout` must not be `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`
- If `format` is a depth/stencil format which includes only the depth aspect, `initialLayout` must not be `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`
- If `format` is a depth/stencil format which includes only the depth aspect, `finalLayout` must not be `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`
• If format is a depth/stencil format which includes only the stencil aspect, initialLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL.

• If format is a depth/stencil format which includes only the stencil aspect, finalLayout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL.

Valid Usage (Implicit)

• flags must be a valid combination of VkAttachmentDescriptionFlagBits values
• format must be a valid VkFormat value
• samples must be a valid VkSampleCountFlagBits value
• loadOp must be a valid VkAttachmentLoadOp value
• storeOp must be a valid VkAttachmentStoreOp value
• stencilLoadOp must be a valid VkAttachmentLoadOp value
• stencilStoreOp must be a valid VkAttachmentStoreOp value
• initialLayout must be a valid VkImageLayout value
• finalLayout must be a valid VkImageLayout value

Bits which can be set in VkAttachmentDescription::flags describing additional properties of the attachment are:

typedef enum VkAttachmentDescriptionFlagBits {
    VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT = 0x00000001,
    VK_ATTACHMENT_DESCRIPTION_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkAttachmentDescriptionFlagBits;

• VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT specifies that the attachment aliases the same device memory as other attachments.

typedef VkFlags VkAttachmentDescriptionFlags;

VkAttachmentDescriptionFlags is a bitmask type for setting a mask of zero or more VkAttachmentDescriptionFlagBits.

Possible values of VkAttachmentDescription::loadOp and stencilLoadOp, specifying how the contents of the attachment are treated, are:
```
typedef enum VkAttachmentLoadOp {
    VK_ATTACHMENT_LOAD_OP_LOAD = 0,
    VK_ATTACHMENT_LOAD_OP_CLEAR = 1,
    VK_ATTACHMENT_LOAD_OP_DONT_CARE = 2,
    VK_ATTACHMENT_LOAD_OP_MAX_ENUM = 0x7FFFFFFF
} VkAttachmentLoadOp;
```

- **VK_ATTACHMENT_LOAD_OP_LOAD** specifies that the previous contents of the image within the render area will be preserved. For attachments with a depth/stencil format, this uses the access type `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT`. For attachments with a color format, this uses the access type `VK_ACCESS_COLOR_ATTACHMENT_READ_BIT`.

- **VK_ATTACHMENT_LOAD_OP_CLEAR** specifies that the contents within the render area will be cleared to a uniform value, which is specified when a render pass instance is begun. For attachments with a depth/stencil format, this uses the access type `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`. For attachments with a color format, this uses the access type `VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT`.

- **VK_ATTACHMENT_LOAD_OP_DONT_CARE** specifies that the previous contents within the area need not be preserved; the contents of the attachment will be undefined inside the render area. For attachments with a depth/stencil format, this uses the access type `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`. For attachments with a color format, this uses the access type `VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT`.

Possible values of `VkAttachmentDescription::storeOp` and `stencilStoreOp`, specifying how the contents of the attachment are treated, are:

```
typedef enum VkAttachmentStoreOp {
    VK_ATTACHMENT_STORE_OP_STORE = 0,
    VK_ATTACHMENT_STORE_OP_DONT_CARE = 1,
    VK_ATTACHMENT_STORE_OP_MAX_ENUM = 0x7FFFFFFF
} VkAttachmentStoreOp;
```

- **VK_ATTACHMENT_STORE_OP_STORE** specifies the contents generated during the render pass and within the render area are written to memory. For attachments with a depth/stencil format, this uses the access type `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`. For attachments with a color format, this uses the access type `VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT`.

- **VK_ATTACHMENT_STORE_OP_DONT_CARE** specifies the contents within the render area are not needed after rendering, and may be discarded; the contents of the attachment will be undefined inside the render area. For attachments with a depth/stencil format, this uses the access type `VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT`. For attachments with a color format, this uses the access type `VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT`.

**Note**

`VK_ATTACHMENT_STORE_OP_DONT_CARE` can cause contents generated during previous render passes to be discarded before reaching memory, even if no write to the attachment occurs during the current render pass.
To specify which aspects of an input attachment can be read, add a `VkRenderPassInputAttachmentAspectCreateInfo` structure to the `pNext` chain of the `VkRenderPassCreateInfo` structure:

The `VkRenderPassInputAttachmentAspectCreateInfo` structure is defined as:

```c
typedef struct VkRenderPassInputAttachmentAspectCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t aspectReferenceCount;
    const VkInputAttachmentAspectReference* pAspectReferences;
} VkRenderPassInputAttachmentAspectCreateInfo;
```

or the equivalent

```c
typedef VkRenderPassInputAttachmentAspectCreateInfo
        VkRenderPassInputAttachmentAspectCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `aspectReferenceCount` is the number of elements in the `pAspectReferences` array.
- `pAspectReferences` is a pointer to an array of `aspectReferenceCount` `VkInputAttachmentAspectReference` structures containing a mask describing which aspect(s) can be accessed for a given input attachment within a given subpass.

An application can access any aspect of an input attachment that does not have a specified aspect mask in the `pAspectReferences` array. Otherwise, an application must not access aspect(s) of an input attachment other than those in its specified aspect mask.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT_ASPECT_CREATE_INFO`
- `pAspectReferences` must be a valid pointer to an array of `aspectReferenceCount` valid `VkInputAttachmentAspectReference` structures
- `aspectReferenceCount` must be greater than 0

The `VkInputAttachmentAspectReference` structure specifies an aspect mask for a specific input attachment of a specific subpass in the render pass.

`subpass` and `inputAttachmentIndex` index into the render pass as:

```c
pCreateInfo->pSubpasses[subpass].pInputAttachments[inputAttachmentIndex]
```
typedef struct VkInputAttachmentAspectReference {
    uint32_t subpass;
    uint32_t inputAttachmentIndex;
    VkImageAspectFlags aspectMask;
} VkInputAttachmentAspectReference;

or the equivalent

typedef VkInputAttachmentAspectReference VkInputAttachmentAspectReferenceKHR;

• **subpass** is an index into the pSubpasses array of the parent VkRenderPassCreateInfo structure.
• **inputAttachmentIndex** is an index into the pInputAttachments of the specified subpass.
• **aspectMask** is a mask of which aspect(s) can be accessed within the specified subpass.

**Valid Usage**

• **aspectMask** must not include VK_IMAGE_ASPECT_METADATA_BIT

**Valid Usage (Implicit)**

• **aspectMask** must be a valid combination of VkImageAspectFlagBits values
• **aspectMask** must not be 0

The **VkSubpassDescription** structure is defined as:

typedef struct VkSubpassDescription {
    VkSubpassDescriptionFlags flags;
    VkPipelineBindPoint pipelineBindPoint;
    uint32_t inputAttachmentCount;
    const VkAttachmentReference* pInputAttachments;
    const VkAttachmentReference* pColorAttachments;
    const VkAttachmentReference* pResolveAttachments;
    const VkAttachmentReference* pDepthStencilAttachment;
    const uint32_t* pPreserveAttachments;
    uint32_t preserveAttachmentCount;
} VkSubpassDescription;

• **flags** is a bitmask of VkSubpassDescriptionFlagBits specifying usage of the subpass.
• **pipelineBindPoint** is a VkPipelineBindPoint value specifying the pipeline type supported for this subpass.
• **inputAttachmentCount** is the number of input attachments.
• *pInputAttachments* is a pointer to an array of `VkAttachmentReference` structures defining the input attachments for this subpass and their layouts.

• `colorAttachmentCount` is the number of color attachments.

• *pColorAttachments* is a pointer to an array of `VkAttachmentReference` structures defining the color attachments for this subpass and their layouts.

• *pResolveAttachments* is an optional array of `colorAttachmentCount` `VkAttachmentReference` structures defining the resolve attachments for this subpass and their layouts.

• *pDepthStencilAttachment* is a pointer to a `VkAttachmentReference` structure specifying the depth/stencil attachment for this subpass and its layout.

• `preserveAttachmentCount` is the number of preserved attachments.

• *pPreserveAttachments* is a pointer to an array of `preserveAttachmentCount` render pass attachment indices identifying attachments that are not used by this subpass, but whose contents must be preserved throughout the subpass.

Each element of the *pInputAttachments* array corresponds to an input attachment index in a fragment shader, i.e. if a shader declares an image variable decorated with a `InputAttachmentIndex` value of *X*, then it uses the attachment provided in `pInputAttachments[X]`. Input attachments must also be bound to the pipeline in a descriptor set. If the `attachment` member of any element of *pInputAttachments* is `VK_ATTACHMENT_UNUSED`, the application must not read from the corresponding input attachment index. Fragment shaders can use subpass input variables to access the contents of an input attachment at the fragment's (x, y, layer) framebuffer coordinates.

Each element of the *pColorAttachments* array corresponds to an output location in the shader, i.e. if the shader declares an output variable decorated with a `Location` value of *X*, then it uses the attachment provided in `pColorAttachments[X]`. If the `attachment` member of any element of *pColorAttachments* is `VK_ATTACHMENT_UNUSED`, writes to the corresponding location by a fragment are discarded.

If *pResolveAttachments* is not NULL, each of its elements corresponds to a color attachment (the element in *pColorAttachments* at the same index), and a multisample resolve operation is defined for each attachment. At the end of each subpass, multisample resolve operations read the subpass’s color attachments, and resolve the samples for each pixel within the render area to the same pixel location in the corresponding resolve attachments, unless the resolve attachment index is `VK_ATTACHMENT_UNUSED`.

Similarly, if `VkSubpassDescriptionDepthStencilResolve::pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, it corresponds to the depth/stencil attachment in *pDepthStencilAttachment*, and multisample resolve operations for depth and stencil are defined by `VkSubpassDescriptionDepthStencilResolve::depthResolveMode` and `VkSubpassDescriptionDepthStencilResolve::stencilResolveMode`, respectively. At the end of each subpass, multisample resolve operations read the subpass’s depth/stencil attachment, and resolve the samples for each pixel to the same pixel location in the corresponding resolve attachment. If `VkSubpassDescriptionDepthStencilResolve::depthResolveMode` is `VK_RESOLVE_MODE_NONE`, then the depth component of the resolve attachment is not written to and its contents are preserved. Similarly, if `VkSubpassDescriptionDepthStencilResolve::stencilResolveMode` is `VK_RESOLVE_MODE_NONE`, then the stencil component of the resolve attachment is not written to and its contents are
preserved. `VkSubpassDescriptionDepthStencilResolve::depthResolveMode` is ignored if the `VkFormat` of the `pDepthStencilResolveAttachment` does not have a depth component. Similarly, `VkSubpassDescriptionDepthStencilResolve::stencilResolveMode` is ignored if the `VkFormat` of the `pDepthStencilResolveAttachment` does not have a stencil component.

If `pDepthStencilAttachment` is `NULL`, or if its attachment index is `VK_ATTACHMENT_UNUSED`, it indicates that no depth/stencil attachment will be used in the subpass.

The contents of an attachment within the render area become undefined at the start of a subpass `S` if all of the following conditions are true:

- The attachment is used as a color, depth/stencil, or resolve attachment in any subpass in the render pass.
- There is a subpass `S1` that uses or preserves the attachment, and a subpass dependency from `S1` to `S`.
- The attachment is not used or preserved in subpass `S`.

Once the contents of an attachment become undefined in subpass `S`, they remain undefined for subpasses in subpass dependency chains starting with subpass `S` until they are written again. However, they remain valid for subpasses in other subpass dependency chains starting with subpass `S1` if those subpasses use or preserve the attachment.
Valid Usage

- **pipelineBindPoint** must be **VK_PIPELINE_BIND_POINT_GRAPHICS**

- **colorAttachmentCount** must be less than or equal to **VkPhysicalDeviceLimits::maxColorAttachments**

- If the first use of an attachment in this render pass is as an input attachment, and the attachment is not also used as a color or depth/stencil attachment in the same subpass, then **loadOp** must not be **VK_ATTACHMENT_LOAD_OP_CLEAR**

- If **pResolveAttachments** is not **NULL**, for each resolve attachment that is not **VK_ATTACHMENT_UNUSED**, the corresponding color attachment must not be **VK_ATTACHMENT_UNUSED**

- If **pResolveAttachments** is not **NULL**, for each resolve attachment that is not **VK_ATTACHMENT_UNUSED**, the corresponding color attachment must not have a sample count of **VK_SAMPLE_COUNT_1_BIT**

- If **pResolveAttachments** is not **NULL**, each resolve attachment that is not **VK_ATTACHMENT_UNUSED** must have the same **VkFormat** as its corresponding color attachment

- All attachments in **pColorAttachments** that are not **VK_ATTACHMENT_UNUSED** must have the same sample count

- All attachments in **pInputAttachments** that are not **VK_ATTACHMENT_UNUSED** must have formats whose features contain at least one of **VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT** or **VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT**.

- All attachments in **pColorAttachments** that are not **VK_ATTACHMENT_UNUSED** must have formats whose features contain **VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT**

- All attachments in **pResolveAttachments** that are not **VK_ATTACHMENT_UNUSED** must have formats whose features contain **VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT**

- If **pDepthStencilAttachment** is not **NULL** and the attachment is not **VK_ATTACHMENT_UNUSED** then it must have a format whose features contain **VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT**

- If neither the **VK_AMD_mixed_attachment_samples** nor the **VK_NV_framebuffer_mixed_samples** extensions are enabled, and if **pDepthStencilAttachment** is not **VK_ATTACHMENT_UNUSED** and any attachments in **pColorAttachments** are not **VK_ATTACHMENT_UNUSED**, they must have the same sample count

- The **attachment** member of each element of **pPreserveAttachments** must not be **VK_ATTACHMENT_UNUSED**

- Each element of **pPreserveAttachments** must not also be an element of any other member of the subpass description

- If any attachment is used by more than one **VkAttachmentReference** member, then each use must use the same layout
Valid Usage (Implicit)

• flags must be 0

• pipelineBindPoint must be a valid VkPipelineBindPoint value

• If inputAttachmentCount is not 0, pInputAttachments must be a valid pointer to an array of
inputAttachmentCount valid VkAttachmentReference structures

• If colorAttachmentCount is not 0, pColorAttachments must be a valid pointer to an array of
colorAttachmentCount valid VkAttachmentReference structures

• If colorAttachmentCount is not 0, and pResolveAttachments is not NULL, pResolveAttachments
must be a valid pointer to an array of colorAttachmentCount valid VkAttachmentReference structures

• If pDepthStencilAttachment is not NULL, pDepthStencilAttachment must be a valid pointer to
a valid VkAttachmentReference structure

• If preserveAttachmentCount is not 0, pPreserveAttachments must be a valid pointer to an
array of preserveAttachmentCount uint32_t values

Bits which can be set in VkSubpassDescription::flags, specifying usage of the subpass, are:

```c
typedef enum VkSubpassDescriptionFlagBits {
    VK_SUBPASS_DESCRIPTION_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSubpassDescriptionFlagBits;
```

Note
All bits for this type are defined by extensions, and none of those extensions are
enabled in this build of the specification.

```c
typedef VkFlags VkSubpassDescriptionFlags;
```

VkSubpassDescriptionFlags is a bitmask type for setting a mask of zero or more
VkSubpassDescriptionFlagBits.

The VkAttachmentReference structure is defined as:

```c
typedef struct VkAttachmentReference {
    uint32_t attachment;
    VkImageLayout layout;
} VkAttachmentReference;
```

• attachment is either an integer value identifying an attachment at the corresponding index in
VkRenderPassCreateInfo::pAttachments, or VK_ATTACHMENT_UNUSED to signify that this attachment is
not used.
• **layout** is a *VkImageLayout* value specifying the layout the attachment uses during the subpass.

**Valid Usage**

- If attachment is not VK_ATTACHMENT_UNUSED, layout **must** not be VK_IMAGE_LAYOUT_UNDEFINED, VK_IMAGE_LAYOUT_PREINITIALIZED, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL_KHR, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL_KHR, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL_KHR, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL_KHR.

**Valid Usage (Implicit)**

- layout **must** be a valid *VkImageLayout* value

The *VkSubpassDependency* structure is defined as:

```c
typedef struct VkSubpassDependency {
    uint32_t srcSubpass;
    uint32_t dstSubpass;
    VkPipelineStageFlags srcStageMask;
    VkPipelineStageFlags dstStageMask;
    VkAccessFlags srcAccessMask;
    VkAccessFlags dstAccessMask;
    VkDependencyFlags dependencyFlags;
} VkSubpassDependency;
```

- **srcSubpass** is the subpass index of the first subpass in the dependency, or VK_SUBPASS_EXTERNAL.
- **dstSubpass** is the subpass index of the second subpass in the dependency, or VK_SUBPASS_EXTERNAL.
- **srcStageMask** is a bitmask of *VkPipelineStageFlagBits* specifying the source stage mask.
- **dstStageMask** is a bitmask of *VkPipelineStageFlagBits* specifying the destination stage mask.
- **srcAccessMask** is a bitmask of *VkAccessFlagBits* specifying a source access mask.
- **dstAccessMask** is a bitmask of *VkAccessFlagBits* specifying a destination access mask.
- **dependencyFlags** is a bitmask of *VkDependencyFlagBits* specifying.

If **srcSubpass** is equal to **dstSubpass** then the *VkSubpassDependency* describes a subpass self-dependency, and only constrains the pipeline barriers allowed within a subpass instance. Otherwise, when a render pass instance which includes a subpass dependency is submitted to a queue, it defines a memory dependency between the subpasses identified by **srcSubpass** and **dstSubpass**.

If **srcSubpass** is equal to VK_SUBPASS_EXTERNAL, the first synchronization scope includes commands that occur earlier in submission order than the vkCmdBeginRenderPass used to begin the render...
pass instance. Otherwise, the first set of commands includes all commands submitted as part of the subpass instance identified by `srcSubpass` and any load, store or multisample resolve operations on attachments used in `srcSubpass`. In either case, the first synchronization scope is limited to operations on the pipeline stages determined by the source stage mask specified by `srcStageMask`.

If `dstSubpass` is equal to `VK_SUBPASS_EXTERNAL`, the second synchronization scope includes commands that occur later in submission order than the `vkCmdEndRenderPass` used to end the render pass instance. Otherwise, the second set of commands includes all commands submitted as part of the subpass instance identified by `dstSubpass` and any load, store or multisample resolve operations on attachments used in `dstSubpass`. In either case, the second synchronization scope is limited to operations on the pipeline stages determined by the destination stage mask specified by `dstStageMask`.

The first access scope is limited to access in the pipeline stages determined by the source stage mask specified by `srcStageMask`. It is also limited to access types in the source access mask specified by `srcAccessMask`.

The second access scope is limited to access in the pipeline stages determined by the destination stage mask specified by `dstStageMask`. It is also limited to access types in the destination access mask specified by `dstAccessMask`.

The availability and visibility operations defined by a subpass dependency affect the execution of image layout transitions within the render pass.

---

**Note**

For non-attachment resources, the memory dependency expressed by subpass dependency is nearly identical to that of a `VkMemoryBarrier` (with matching `srcAccessMask` and `dstAccessMask` parameters) submitted as a part of a `vkCmdPipelineBarrier` (with matching `srcStageMask` and `dstStageMask` parameters). The only difference being that its scopes are limited to the identified subpasses rather than potentially affecting everything before and after.

For attachments however, subpass dependencies work more like a `VkImageMemoryBarrier` defined similarly to the `VkMemoryBarrier` above, the queue family indices set to `VK_QUEUE_FAMILY_IGNORED`, and layouts as follows:

- The equivalent to `oldLayout` is the attachment's layout according to the subpass description for `srcSubpass`.
- The equivalent to `newLayout` is the attachment's layout according to the subpass description for `dstSubpass`.

---
Valid Usage

- If the geometry shaders feature is not enabled, srcStageMask must not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the geometry shaders feature is not enabled, dstStageMask must not contain VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT
- If the tessellation shaders feature is not enabled, srcStageMask must not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- If the tessellation shaders feature is not enabled, dstStageMask must not contain VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT or VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT
- srcSubpass must be less than or equal to dstSubpass, unless one of them is VK_SUBPASS_EXTERNAL, to avoid cyclic dependencies and ensure a valid execution order
- srcSubpass and dstSubpass must not both be equal to VK_SUBPASS_EXTERNAL
- If srcSubpass is equal to dstSubpass and not all of the stages in srcStageMask and dstStageMask are framebuffer-space stages, the logically latest pipeline stage in srcStageMask must be logically earlier than or equal to the logically earliest pipeline stage in dstStageMask
- Any access flag included in srcAccessMask must be supported by one of the pipeline stages in srcStageMask, as specified in the table of supported access types
- Any access flag included in dstAccessMask must be supported by one of the pipeline stages in dstStageMask, as specified in the table of supported access types
- If srcSubpass equals dstSubpass, and srcStageMask and dstStageMask both include a framebuffer-space stage, then dependencyFlags must include VK_DEPENDENCY_BY_REGION_BIT
- If dependencyFlags includes VK_DEPENDENCY_VIEW_LOCAL_BIT, srcSubpass must not be equal to VK_SUBPASS_EXTERNAL
- If dependencyFlags includes VK_DEPENDENCY_VIEW_LOCAL_BIT, dstSubpass must not be equal to VK_SUBPASS_EXTERNAL
- If srcSubpass equals dstSubpass and that subpass has more than one bit set in the view mask, then dependencyFlags must include VK_DEPENDENCY_VIEW_LOCAL_BIT
Valid Usage (Implicit)

- `srcStageMask` must be a valid combination of `VkPipelineStageFlagBits` values
- `srcStageMask` must not be 0
- `dstStageMask` must be a valid combination of `VkPipelineStageFlagBits` values
- `dstStageMask` must not be 0
- `srcAccessMask` must be a valid combination of `VkAccessFlagBits` values
- `dstAccessMask` must be a valid combination of `VkAccessFlagBits` values
- `dependencyFlags` must be a valid combination of `VkDependencyFlagBits` values

When multiview is enabled, the execution of the multiple views of one subpass may not occur simultaneously or even back-to-back, and rather may be interleaved with the execution of other subpasses. The load and store operations apply to attachments on a per-view basis. For example, an attachment using `VK_ATTACHMENT_LOAD_OP_CLEAR` will have each view cleared on first use, but the first use of one view may be temporally distant from the first use of another view.

**Note**

A good mental model for multiview is to think of a multiview subpass as if it were a collection of individual (per-view) subpasses that are logically grouped together and described as a single multiview subpass in the API. Similarly, a multiview attachment can be thought of like several individual attachments that happen to be layers in a single image. A view-local dependency between two multiview subpasses acts like a set of one-to-one dependencies between corresponding pairs of per-view subpasses. A view-global dependency between two multiview subpasses acts like a set of \( N \times M \) dependencies between all pairs of per-view subpasses in the source and destination. Thus, it is a more compact representation which also makes clear the commonality and reuse that is present between views in a subpass. This interpretation motivates the answers to questions like “when does the load op apply” - it is on the first use of each view of an attachment, as if each view were a separate attachment.

If there is no subpass dependency from `VK_SUBPASS_EXTERNAL` to the first subpass that uses an attachment, then an implicit subpass dependency exists from `VK_SUBPASS_EXTERNAL` to the first subpass it is used in. The implicit subpass dependency only exists if there exists an automatic layout transition away from `initialLayout`. The subpass dependency operates as if defined with the following parameters:
Similarly, if there is no subpass dependency from the last subpass that uses an attachment to `VK_SUBPASS_EXTERNAL`, then an implicit subpass dependency exists from the last subpass it is used in to `VK_SUBPASS_EXTERNAL`. The implicit subpass dependency only exists if there exists an automatic layout transition into `finalLayout`. The subpass dependency operates as if defined with the following parameters:

```cpp
VkSubpassDependency implicitDependency = {
    .srcSubpass = lastSubpass; // Last subpass attachment is used in
    .dstSubpass = VK_SUBPASS_EXTERNAL;
    .srcStageMask = VK_PIPELINE_STAGE_ALL_COMMANDS_BIT;
    .dstStageMask = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;
    .srcAccessMask = VK_ACCESS_INPUT_ATTACHMENT_READ_BIT |
                     VK_ACCESS_COLOR_ATTACHMENT_READ_BIT |
                    VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT |
                     VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT |
                     VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT;
    .dstAccessMask = 0;
    .dependencyFlags = 0;
};
```

As subpasses may overlap or execute out of order with regards to other subpasses unless a subpass dependency chain describes otherwise, the layout transitions required between subpasses cannot be known to an application. Instead, an application provides the layout that each attachment must be in at the start and end of a render pass, and the layout it must be in during each subpass it is used in. The implementation then must execute layout transitions between subpasses in order to guarantee that the images are in the layouts required by each subpass, and in the final layout at the end of the render pass.

Automatic layout transitions apply to the entire image subresource attached to the framebuffer. If the attachment view is a 2D or 2D array view of a 3D image, even if the attachment view only refers to a subset of the slices of the selected mip level of the 3D image, automatic layout transitions apply to the entire subresource referenced which is the entire mip level in this case.

Automatic layout transitions away from the layout used in a subpass happen-after the availability
operations for all dependencies with that subpass as the srcSubpass.

Automatic layout transitions into the layout used in a subpass happen-before the visibility operations for all dependencies with that subpass as the dstSubpass.

Automatic layout transitions away from initialLayout happens-after the availability operations for all dependencies with a srcSubpass equal to VK_SUBPASS_EXTERNAL, where dstSubpass uses the attachment that will be transitioned. For attachments created with VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT, automatic layout transitions away from initialLayout happen-after the availability operations for all dependencies with a srcSubpass equal to VK_SUBPASS_EXTERNAL, where dstSubpass uses any aliased attachment.

Automatic layout transitions into finalLayout happens-before the visibility operations for all dependencies with a dstSubpass equal to VK_SUBPASS_EXTERNAL, where srcSubpass uses the attachment that will be transitioned. For attachments created with VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT, automatic layout transitions into finalLayout happen-before the visibility operations for all dependencies with a dstSubpass equal to VK_SUBPASS_EXTERNAL, where srcSubpass uses any aliased attachment.

If two subpasses use the same attachment, and both subpasses use the attachment in a read-only layout, no subpass dependency needs to be specified between those subpasses. If an implementation treats those layouts separately, it must insert an implicit subpass dependency between those subpasses to separate the uses in each layout. The subpass dependency operates as if defined with the following parameters:

```c
// Used for input attachments
VkPipelineStageFlags inputAttachmentStages = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
VkAccessFlags inputAttachmentAccess = VK_ACCESS_INPUT_ATTACHMENT_READ_BIT;

// Used for depth/stencil attachments
VkPipelineStageFlags depthStencilAttachmentStages =
    VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT |
    VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT;
VkAccessFlags depthStencilAttachmentAccess =
    VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT;

VkSubpassDependency implicitDependency = {
    .srcSubpass = firstSubpass;
    .dstSubpass = secondSubpass;
    .srcStageMask = inputAttachmentStages | depthStencilAttachmentStages;
    .dstStageMask = inputAttachmentStages | depthStencilAttachmentStages;
    .srcAccessMask = inputAttachmentAccess | depthStencilAttachmentAccess;
    .dstAccessMask = inputAttachmentAccess | depthStencilAttachmentAccess;
    .dependencyFlags = 0;
};
```

If a subpass uses the same attachment as both an input attachment and either a color attachment or a depth/stencil attachment, writes via the color or depth/stencil attachment are not automatically made visible to reads via the input attachment, causing a feedback loop, except in any of the
following conditions:

- If the color components or depth/stencil components read by the input attachment are mutually exclusive with the components written by the color or depth/stencil attachments, then there is no feedback loop. This requires the graphics pipelines used by the subpass to disable writes to color components that are read as inputs via the `colorWriteMask`, and to disable writes to depth/stencil components that are read as inputs via `depthWriteEnable` or `stencilTestEnable`.

- If the attachment is used as an input attachment and depth/stencil attachment only, and the depth/stencil attachment is not written to.

- If a memory dependency is inserted between when the attachment is written and when it is subsequently read by later fragments. **Pipeline barriers** expressing a **subpass self-dependency** are the only way to achieve this, and one **must** be inserted every time a fragment will read values at a particular sample (x, y, layer, sample) coordinate, if those values have been written since the most recent pipeline barrier; or the since start of the subpass if there have been no pipeline barriers since the start of the subpass.

An attachment used as both an input attachment and a color attachment **must** be in the `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR` or `VK_IMAGE_LAYOUT_GENERAL` layout. An attachment used as an input attachment and depth/stencil attachment **must** be in the `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR`, `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_GENERAL` layout. An attachment **must** not be used as both a depth/stencil attachment and a color attachment.

A more extensible version of render pass creation is also defined below.

To create a render pass, call:

```c
VkResult vkCreateRenderPass2KHR(
    VkDevice                                    device,
    const VkRenderPassCreateInfo2*              pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkRenderPass*                               pRenderPass);
```

- **device** is the logical device that creates the render pass.
- **pCreateInfo** is a pointer to a `VkRenderPassCreateInfo2` structure describing the parameters of the render pass.
- **pAllocator** controls host memory allocation as described in the **Memory Allocation** chapter.
- **pRenderPass** is a pointer to a `VkRenderPass` handle in which the resulting render pass object is returned.

This command is functionally identical to `vkCreateRenderPass`, but includes extensible substructures that include `sType` and `pNext` parameters, allowing them to be more easily extended.
Valid Usage (Implicit)

- device must be a valid VkDevice handle
- pCreateInfo must be a valid pointer to a valid VkRenderPassCreateInfo2 structure
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
- pRenderPass must be a valid pointer to a VkRenderPass handle

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkRenderPassCreateInfo2 structure is defined as:

```c
typedef struct VkRenderPassCreateInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkRenderPassCreateFlags flags;
    uint32_t attachmentCount;
    const VkAttachmentDescription2* pAttachments;
    uint32_t subpassCount;
    const VkSubpassDescription2* pSubpasses;
    uint32_t dependencyCount;
    const VkSubpassDependency2* pDependencies;
    uint32_t correlatedViewMaskCount;
    const uint32_t* pCorrelatedViewMasks;
} VkRenderPassCreateInfo2;
```

or the equivalent

```c
typedef VkRenderPassCreateInfo2 VkRenderPassCreateInfo2KHR;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- attachmentCount is the number of attachments used by this render pass.
- pAttachments is a pointer to an array of attachmentCount VkAttachmentDescription2 structures
describing the attachments used by the render pass.

- **subpassCount** is the number of subpasses to create.
- **pSubpasses** is a pointer to an array of **subpassCount** VkSubpassDescription2 structures describing each subpass.

- **dependencyCount** is the number of dependencies between pairs of subpasses.
- **pDependencies** is a pointer to an array of **dependencyCount** VkSubpassDependency structures describing dependencies between pairs of subpasses.

- **correlatedViewMaskCount** is the number of correlation masks.
- **pCorrelatedViewMasks** is a pointer to an array of view masks indicating sets of views that may be more efficient to render concurrently.

Parameters defined by this structure with the same name as those in VkRenderPassCreateInfo have the identical effect to those parameters; the child structures are variants of those used in VkRenderPassCreateInfo which add **sType** and **pNext** parameters, allowing them to be extended.

If the VkSubpassDescription2::viewMask member of any element of **pSubpasses** is not zero, multiview functionality is considered to be enabled for this render pass.

**correlatedViewMaskCount** and **pCorrelatedViewMasks** have the same effect as VkRenderPassMultiviewCreateInfo::correlationMaskCount and VkRenderPassMultiviewCreateInfo::pCorrelationMasks, respectively.
Valid Usage

- If any two subpasses operate on attachments with overlapping ranges of the same `VkDeviceMemory` object, and at least one subpass writes to that area of `VkDeviceMemory`, a subpass dependency must be included (either directly or via some intermediate subpasses) between them.

- If the attachment member of any element of `pInputAttachments`, `pColorAttachments`, `pResolveAttachments` or `pDepthStencilAttachment`, or the attachment indexed by any element of `pPreserveAttachments` in any given element of `pSubpasses` is bound to a range of a `VkDeviceMemory` object that overlaps with any other attachment in any subpass (including the same subpass), the `VkAttachmentDescription2` structures describing them must include `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT` in flags.

- If the attachment member of any element of `pInputAttachments`, `pColorAttachments`, `pResolveAttachments` or `pDepthStencilAttachment`, or any element of `pPreserveAttachments` in any given element of `pSubpasses` is not `VK_ATTACHMENT_UNUSED`, it must be less than `attachmentCount`.

- For any member of `pAttachments` with a `loadOp` equal to `VK_ATTACHMENT_LOAD_OP_CLEAR`, the first use of that attachment must not specify a layout equal to `VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`.

- For any member of `pAttachments` with a `stencilLoadOp` equal to `VK_ATTACHMENT_LOAD_OP_CLEAR`, the first use of that attachment must not specify a layout equal to `VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`.

- For any element of `pDependencies`, if the `srcSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `srcStageMask` member of that dependency must be a pipeline stage supported by the pipeline identified by the `pipelineBindPoint` member of the source subpass.

- For any element of `pDependencies`, if the `dstSubpass` is not `VK_SUBPASS_EXTERNAL`, all stage flags included in the `dstStageMask` member of that dependency must be a pipeline stage supported by the pipeline identified by the `pipelineBindPoint` member of the destination subpass.

- The set of bits included in any element of `pCorrelatedViewMasks` must not overlap with the set of bits included in any other element of `pCorrelatedViewMasks`.

- If the `VkSubpassDescription2::viewMask` member of all elements of `pSubpasses` is θ, `correlatedViewMaskCount` must be θ.

- The `VkSubpassDescription2::viewMask` member of all elements of `pSubpasses` must either all be θ, or all not be θ.

- If the `VkSubpassDescription2::viewMask` member of all elements of `pSubpasses` is θ, the `dependencyFlags` member of any element of `pDependencies` must not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`.

- For any element of `pDependencies` where its `srcSubpass` member equals its `dstSubpass`
member, if the `viewMask` member of the corresponding element of `pSubpasses` includes more than one bit, its `dependencyFlags` member **must** include `VK_DEPENDENCY_VIEW_LOCAL_BIT

- The `viewMask` member **must** not have a bit set at an index greater than or equal to `VkPhysicalDeviceLimits::maxFramebufferLayers`

- If the `attachment` member of any element of the `pInputAttachments` member of any element of `pSubpasses` is not `VK_ATTACHMENT_UNUSED`, the `aspectMask` member of that element of `pInputAttachments` **must** only include aspects that are present in images of the format specified by the element of `pAttachments` specified by `attachment`

- The `srcSubpass` member of each element of `pDependencies` **must** be less than `subpassCount`

- The `dstSubpass` member of each element of `pDependencies` **must** be less than `subpassCount`

### Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO_2`

- `pNext` **must** be `NULL`

- `flags` **must** be `0`

- If `attachmentCount` is not `0`, `pAttachments` **must** be a valid pointer to an array of `attachmentCount` valid `VkAttachmentDescription2` structures

- `pSubpasses` **must** be a valid pointer to an array of `subpassCount` valid `VkSubpassDescription2` structures

- If `dependencyCount` is not `0`, `pDependencies` **must** be a valid pointer to an array of `dependencyCount` valid `VkSubpassDependency2` structures

- If `correlatedViewMaskCount` is not `0`, `pCorrelatedViewMasks` **must** be a valid pointer to an array of `correlatedViewMaskCount` `uint32_t` values

- `subpassCount` **must** be greater than `0`

The `VkAttachmentDescription2` structure is defined as:

```plaintext
typedef struct VkAttachmentDescription2 {
    VkStructureType sType;
    const void* pNext;
    VkAttachmentDescriptionFlags flags;
    VkFormat format;
    VkSampleCountFlagBits samples;
    VkAttachmentLoadOp loadOp;
    VkAttachmentStoreOp storeOp;
    VkAttachmentLoadOp stencilLoadOp;
    VkAttachmentStoreOp stencilStoreOp;
    VkImageLayout initialLayout;
    VkImageLayout finalLayout;
} VkAttachmentDescription2;
```
or the equivalent

typedef VkAttachmentDescription2 VkAttachmentDescription2KHR;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is a bitmask of VkAttachmentDescriptionFlagBits specifying additional properties of the attachment.
- **format** is a VkFormat value specifying the format of the image that will be used for the attachment.
- **samples** is the number of samples of the image as defined in VkSampleCountFlagBits.
- **loadOp** is a VkAttachmentLoadOp value specifying how the contents of color and depth components of the attachment are treated at the beginning of the subpass where it is first used.
- **storeOp** is a VkAttachmentStoreOp value specifying how the contents of color and depth components of the attachment are treated at the end of the subpass where it is last used.
- **stencilLoadOp** is a VkAttachmentLoadOp value specifying how the contents of stencil components of the attachment are treated at the beginning of the subpass where it is first used.
- **stencilStoreOp** is a VkAttachmentStoreOp value specifying how the contents of stencil components of the attachment are treated at the end of the last subpass where it is used.
- **initialLayout** is the layout the attachment image subresource will be in when a render pass instance begins.
- **finalLayout** is the layout the attachment image subresource will be transitioned to when a render pass instance ends.

Parameters defined by this structure with the same name as those in VkAttachmentDescription have the identical effect to those parameters.

If the separateDepthStencilLayouts feature is enabled, and format is a depth/stencil format, initialLayout and finalLayout can be set to a layout that only specifies the layout of the depth aspect.

If format is a depth/stencil format, and initialLayout only specifies the initial layout of the depth aspect of the attachment, the initial layout of the stencil aspect is specified by the stencilInitialLayout member of a VkAttachmentDescriptionStencilLayout structure included in the pNext chain. Otherwise, initialLayout describes the initial layout for all relevant image aspects.

If format is a depth/stencil format, and finalLayout only specifies the final layout of the depth aspect of the attachment, the final layout of the stencil aspect is specified by the stencilFinalLayout member of a VkAttachmentDescriptionStencilLayout structure included in the pNext chain. Otherwise, finalLayout describes the final layout for all relevant image aspects.
Valid Usage

- **finalLayout** must not be `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED`

- If `format` is a color format, `initialLayout` must not be:
  - `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`

- If `format` is a depth/stencil format, `initialLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`

- If `format` is a color format, `finalLayout` must not be:
  - `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`

- If `format` is a depth/stencil format, `finalLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`

- If the `separateDepthStencilLayouts` feature is not enabled, `initialLayout` must not be:
  - `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`
  - `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`

- If the `separateDepthStencilLayouts` feature is not enabled, `finalLayout` must not be:
  - `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`
  - `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`

- If `format` is a color format, `initialLayout` must not be:
  - `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`
  - `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`
  - `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`

- If `format` is a depth/stencil format which includes both depth and stencil aspects, and `initialLayout` is `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, the `pNext` chain must include a `VkAttachmentDescriptionStencilLayout` structure.

- If `format` is a depth/stencil format which includes both depth and stencil aspects, and `finalLayout` is `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, the `pNext` chain must include a `VkAttachmentDescriptionStencilLayout` structure.

- If `format` is a depth/stencil format which includes only the depth aspect, `initialLayout` must not be `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL` or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`

- If `format` is a depth/stencil format which includes only the depth aspect, `finalLayout` must...
not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL or
VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL

• If format is a depth/stencil format which includes only the stencil aspect, initialLayout must
  not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or
  VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL

• If format is a depth/stencil format which includes only the stencil aspect, finalLayout must
  not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or
  VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2

• flags must be a valid combination of VkAttachmentDescriptionFlagBits values

• format must be a valid VkFormat value

• samples must be a valid VkSampleCountFlagBits value

• loadOp must be a valid VkAttachmentLoadOp value

• storeOp must be a valid VkAttachmentStoreOp value

• stencilLoadOp must be a valid VkAttachmentLoadOp value

• stencilStoreOp must be a valid VkAttachmentStoreOp value

• initialLayout must be a valid VkImageLayout value

• finalLayout must be a valid VkImageLayout value

The VkAttachmentDescriptionStencilLayout structure is defined as:

typedef struct VkAttachmentDescriptionStencilLayout {
    VkStructureType sType;
    void* pNext;
    VkImageLayout stencilInitialLayout;
    VkImageLayout stencilFinalLayout;
} VkAttachmentDescriptionStencilLayout;

or the equivalent

typedef VkAttachmentDescriptionStencilLayout VkAttachmentDescriptionStencilLayoutKHR;

• sType is the type of this structure.

• pNext is NULL or a pointer to an extension-specific structure.

• stencilInitialLayout is the layout the stencil aspect of the attachment image subresource will
  be in when a render pass instance begins.

• stencilFinalLayout is the layout the stencil aspect of the attachment image subresource will be
transitioned to when a render pass instance ends.

Valid Usage

- `stencilInitialLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`

- `stencilFinalLayout` must not be `VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`

- `stencilFinalLayout` must not be `VK_IMAGE_LAYOUT_UNDEFINED` or `VK_IMAGE_LAYOUT_PREINITIALIZED`

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_STENCIL_LAYOUT`
- `stencilInitialLayout` must be a valid `VkImageLayout` value
- `stencilFinalLayout` must be a valid `VkImageLayout` value

The `VkSubpassDescription2` structure is defined as:

```c
typedef struct VkSubpassDescription2 {
    VkStructureType                      sType;
    const void*                           pNext;
    VkSubpassDescriptionFlags            flags;
    VkPipelineBindPoint                  pipelineBindPoint;
    uint32_t                              viewMask;
    uint32_t                              inputAttachmentCount;
    const VkAttachmentReference2*        pInputAttachments;
    uint32_t                              colorAttachmentCount;
    const VkAttachmentReference2*        pColorAttachments;
    const VkAttachmentReference2*        pResolveAttachments;
    const VkAttachmentReference2*        pDepthStencilAttachment;
    uint32_t                              preserveAttachmentCount;
    const uint32_t*                       pPreserveAttachments;
} VkSubpassDescription2;
```

or the equivalent
typedef VkSubpassDescription2 VkSubpassDescription2KHR;

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **flags** is a bitmask of `VkSubpassDescriptionFlagBits` specifying usage of the subpass.
- **pipelineBindPoint** is a `VkPipelineBindPoint` value specifying the pipeline type supported for this subpass.
- **viewMask** is a bitfield of view indices describing which views rendering is broadcast to in this subpass, when multiview is enabled.
- **inputAttachmentCount** is the number of input attachments.
- **pInputAttachments** is a pointer to an array of `VkAttachmentReference2` structures defining the input attachments for this subpass and their layouts.
- **colorAttachmentCount** is the number of color attachments.
- **pColorAttachments** is a pointer to an array of `VkAttachmentReference2` structures defining the color attachments for this subpass and their layouts.
- **pResolveAttachments** is an optional array of `colorAttachmentCount` `VkAttachmentReference2` structures defining the resolve attachments for this subpass and their layouts.
- **pDepthStencilAttachment** is a pointer to a `VkAttachmentReference2` structure specifying the depth/stencil attachment for this subpass and its layout.
- **preserveAttachmentCount** is the number of preserved attachments.
- **pPreserveAttachments** is a pointer to an array of `preserveAttachmentCount` render pass attachment indices identifying attachments that are not used by this subpass, but whose contents must be preserved throughout the subpass.

Parameters defined by this structure with the same name as those in `VkSubpassDescription` have the identical effect to those parameters.

**viewMask** has the same effect for the described subpass as `VkRenderPassMultiviewCreateInfo::pViewMasks` has on each corresponding subpass.
Valid Usage

- **pipelineBindPoint must** be `VK_PIPELINE_BIND_POINT_GRAPHICS`
- **colorAttachmentCount must** be less than or equal to `VkPhysicalDeviceLimits::maxColorAttachments`
  - If the first use of an attachment in this render pass is as an input attachment, and the attachment is not also used as a color or depth/stencil attachment in the same subpass, then **loadOp must not** be `VK_ATTACHMENT_LOAD_OP_CLEAR`
  - If `pResolveAttachments` is not `NULL`, for each resolve attachment that does not have the value `VK_ATTACHMENT_UNUSED`, the corresponding color attachment **must** not have the value `VK_ATTACHMENT_UNUSED`
  - If `pResolveAttachments` is not `NULL`, for each resolve attachment that is not `VK_ATTACHMENT_UNUSED`, the corresponding color attachment **must** not have a sample count of `VK_SAMPLE_COUNT_1_BIT`
  - If `pResolveAttachments` is not `NULL`, each resolve attachment that is not `VK_ATTACHMENT_UNUSED** must** have a sample count of `VK_SAMPLE_COUNT_1_BIT`
  - Any given element of `pResolveAttachments must` have the same `VkFormat` as its corresponding color attachment
  - All attachments in `pColorAttachments` that are not `VK_ATTACHMENT_UNUSED must` have the same sample count
  - All attachments in `pInputAttachments` that are not `VK_ATTACHMENT_UNUSED must` have formats whose features contain at least one of `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT` or `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`
  - All attachments in `pColorAttachments` that are not `VK_ATTACHMENT_UNUSED must` have formats whose features contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`
  - All attachments in `pResolveAttachments` that are not `VK_ATTACHMENT_UNUSED must` have formats whose features contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`
  - If `pDepthStencilAttachment` is not `NULL` and the attachment is not `VK_ATTACHMENT_UNUSED` then it **must** have a format whose features contain `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`
  - If neither the `VK_AMD_mixed_attachment_samples` nor the `VK_NV_framebuffer_mixed_samples` extensions are enabled, and if `pDepthStencilAttachment` is not `VK_ATTACHMENT_UNUSED` and any attachments in `pColorAttachments` are not `VK_ATTACHMENT_UNUSED`, they must have the same sample count
  - The **attachment** member of any element of `pPreserveAttachments must not** be `VK_ATTACHMENT_UNUSED`
  - Any given element of `pPreserveAttachments must not also` be an element of any other member of the subpass description
  - If any attachment is used by more than one `VkAttachmentReference` member, then each use **must use** the same layout
  - If the **attachment** member of any element of `pInputAttachments` is not `VK_ATTACHMENT_UNUSED`, then the **aspectMask** member **must be** a valid combination of `VkImageAspectFlagBits`
• If the attachment member of any element of pInputAttachments is not VK_ATTACHMENT_UNUSED, then the aspectMask member must not be 0

• If the attachment member of any element of pInputAttachments is not VK_ATTACHMENT_UNUSED, then the aspectMask member must not include VK_IMAGE_ASPECT_METADATA_BIT

### Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_2

• flags must be 0

• pipelineBindPoint must be a valid VkPipelineBindPoint value

• If inputAttachmentCount is not 0, pInputAttachments must be a valid pointer to an array of inputAttachmentCount valid VkAttachmentReference2 structures

• If colorAttachmentCount is not 0, pColorAttachments must be a valid pointer to an array of colorAttachmentCount valid VkAttachmentReference2 structures

• If colorAttachmentCount is not 0, and pResolveAttachments is not NULL, pResolveAttachments must be a valid pointer to an array of colorAttachmentCount valid VkAttachmentReference2 structures

• If pDepthStencilAttachment is not NULL, pDepthStencilAttachment must be a valid pointer to a valid VkAttachmentReference2 structure

• If preserveAttachmentCount is not 0, pPreserveAttachments must be a valid pointer to an array of preserveAttachmentCount uint32_t values

If the pNext list of VkSubpassDescription2 includes a VkSubpassDescriptionDepthStencilResolve structure, then that structure describes multisample resolve operations for the depth/stencil attachment in a subpass.

The VkSubpassDescriptionDepthStencilResolve structure is defined as:

```c
typedef struct VkSubpassDescriptionDepthStencilResolve {
    VkStructureType sType;
    const void* pNext;
    VkResolveModeFlagBits depthResolveMode;
    VkResolveModeFlagBits stencilResolveMode;
    const VkAttachmentReference2* pDepthStencilResolveAttachment;
} VkSubpassDescriptionDepthStencilResolve;
```

or the equivalent

```c
typedef VkSubpassDescriptionDepthStencilResolve
VkSubpassDescriptionDepthStencilResolveKHR;
```

- sType is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.
• `depthResolveMode` is a bitmask of `VkResolveModeFlagBits` describing the depth resolve mode.
• `stencilResolveMode` is a bitmask of `VkResolveModeFlagBits` describing the stencil resolve mode.
• `pDepthStencilResolveAttachment` is an optional `VkAttachmentReference` structure defining the depth/stencil resolve attachment for this subpass and its layout.
Valid Usage

- If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, `pDepthStencilAttachment` must not have the value `VK_ATTACHMENT_UNUSED`.

- If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, `depthResolveMode` and `stencilResolveMode` must not both be `VK_RESOLVE_MODE_NONE`.

- If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, `pDepthStencilAttachment` must not have a sample count of `VK_SAMPLE_COUNT_1_BIT`.

- If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED`, `pDepthStencilResolveAttachment` must have a sample count of `VK_SAMPLE_COUNT_1_BIT`.

- If `pDepthStencilResolveAttachment` is not NULL and does not have the value `VK_ATTACHMENT_UNUSED` then it must have a format whose features contain `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`.

- If the `VkFormat` of `pDepthStencilResolveAttachment` has a depth component, then the `VkFormat` of `pDepthStencilAttachment` must have a depth component with the same number of bits and numerical type.

- If the `VkFormat` of `pDepthStencilResolveAttachment` has a stencil component, then the `VkFormat` of `pDepthStencilAttachment` must have a stencil component with the same number of bits and numerical type.

- The value of `depthResolveMode` must be one of the bits set in `VkPhysicalDeviceDepthStencilResolveProperties::supportedDepthResolveModes` or `VK_RESOLVE_MODE_NONE`.

- The value of `stencilResolveMode` must be one of the bits set in `VkPhysicalDeviceDepthStencilResolveProperties::supportedStencilResolveModes` or `VK_RESOLVE_MODE_NONE`.

- If the `VkFormat` of `pDepthStencilResolveAttachment` has both depth and stencil components, `VkPhysicalDeviceDepthStencilResolveProperties::independentResolve` is `VK_FALSE`, and `VkPhysicalDeviceDepthStencilResolveProperties::independentResolveNone` is `VK_FALSE`, then the values of `depthResolveMode` and `stencilResolveMode` must be identical.

- If the `VkFormat` of `pDepthStencilResolveAttachment` has both depth and stencil components, `VkPhysicalDeviceDepthStencilResolveProperties::independentResolve` is `VK_FALSE` and `VkPhysicalDeviceDepthStencilResolveProperties::independentResolveNone` is `VK_TRUE`, then the values of `depthResolveMode` and `stencilResolveMode` must be identical or one of them must be `VK_RESOLVE_MODE_NONE`. 

260 | Chapter 7. Render Pass
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_DEPTH_STENCIL_RESOLVE`
- **depthResolveMode** must be a valid `VkResolveModeFlagBits` value
- **stencilResolveMode** must be a valid `VkResolveModeFlagBits` value
- If `pDepthStencilResolveAttachment` is not NULL, `pDepthStencilResolveAttachment` must be a valid pointer to a valid `VkAttachmentReference2` structure

Possible values of `VkSubpassDescriptionDepthStencilResolve::depthResolveMode` and `stencilResolveMode`, specifying the depth and stencil resolve modes, are:

```cpp
typedef enum VkResolveModeFlagBits {
    VK_RESOLVE_MODE_NONE = 0,
    VK_RESOLVE_MODE_SAMPLE_ZERO_BIT = 0x00000001,
    VK_RESOLVE_MODE_AVERAGE_BIT = 0x00000002,
    VK_RESOLVE_MODE_MIN_BIT = 0x00000004,
    VK_RESOLVE_MODE_MAX_BIT = 0x00000008,
    VK_RESOLVE_MODE_NONE_KHR = VK_RESOLVE_MODE_NONE,
    VK_RESOLVE_MODE_SAMPLE_ZERO_BIT_KHR = VK_RESOLVE_MODE_SAMPLE_ZERO_BIT,
    VK_RESOLVE_MODE_AVERAGE_BIT_KHR = VK_RESOLVE_MODE_AVERAGE_BIT,
    VK_RESOLVE_MODE_MIN_BIT_KHR = VK_RESOLVE_MODE_MIN_BIT,
    VK_RESOLVE_MODE_MAX_BIT_KHR = VK_RESOLVE_MODE_MAX_BIT,
    VK_RESOLVE_MODE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkResolveModeFlagBits;
```

or the equivalent

```cpp
typedef VkResolveModeFlagBits VkResolveModeFlagBitsKHR;
```

- **VK_RESOLVE_MODE_NONE** indicates that no resolve operation is done.
- **VK_RESOLVE_MODE_SAMPLE_ZERO_BIT** indicates that result of the resolve operation is equal to the value of sample 0.
- **VK_RESOLVE_MODE_AVERAGE_BIT** indicates that result of the resolve operation is the average of the sample values.
- **VK_RESOLVE_MODE_MIN_BIT** indicates that result of the resolve operation is the minimum of the sample values.
- **VK_RESOLVE_MODE_MAX_BIT** indicates that result of the resolve operation is the maximum of the sample values.

```cpp
typedef VkFlags VkResolveModeFlags;
```

or the equivalent
typedef VkResolveModeFlags VkResolveModeFlagsKHR;

VkResolveModeFlags is a bitmask type for setting a mask of zero or more VkResolveModeFlagBits.

The VkAttachmentReference2 structure is defined as:

typedef struct VkAttachmentReference2 {
    VkStructureType       sType;
    const void*           pNext;
    uint32_t              attachment;
    VkImageLayout         layout;
    VkImageAspectFlags    aspectMask;
} VkAttachmentReference2;

or the equivalent

typedef VkAttachmentReference2 VkAttachmentReference2KHR;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **attachment** is either an integer value identifying an attachment at the corresponding index in VkRenderPassCreateInfo::pAttachments, or VK_ATTACHMENT_UNUSED to signify that this attachment is not used.
- **layout** is a VkImageLayout value specifying the layout the attachment uses during the subpass.
- **aspectMask** is a mask of which aspect(s) **can** be accessed within the specified subpass as an input attachment.

Parameters defined by this structure with the same name as those in VkAttachmentReference have the identical effect to those parameters.

**aspectMask** has the same effect for the described attachment as VkInputAttachmentAspectReference::aspectMask has on each corresponding attachment. It is ignored when this structure is used to describe anything other than an input attachment reference.

If the separateDepthStencilLayouts feature is enabled, and **attachment** has a depth/stencil format, **layout** **can** be set to a layout that only specifies the layout of the depth aspect.

If **layout** only specifies the layout of the depth aspect of the attachment, the layout of the stencil aspect is specified by the stencillayout member of a VkAttachmentReferenceStencilLayout structure included in the pNext chain. Otherwise, **layout** describes the layout for all relevant image aspects.
Valid Usage

- If attachment is not VK_ATTACHMENT_UNUSED, layout must not be VK_IMAGE_LAYOUT_UNDEFINED, VK_IMAGE_LAYOUT_PREINITIALIZED, or VK_IMAGE_LAYOUT_PRESENT_SRC_KHR.

- If attachment is not VK_ATTACHMENT_UNUSED, and aspectMask does not include VK_IMAGE_ASPECT_STENCIL_BIT or VK_IMAGE_ASPECT_DEPTH_BIT, layout must not be VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL.

- If attachment is not VK_ATTACHMENT_UNUSED, and aspectMask does not include VK_IMAGE_ASPECT_COLOR_BIT, layout must not be VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL.

- If the separateDepthStencilLayouts feature is not enabled, and attachment is not VK_ATTACHMENT_UNUSED, layout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL.

- If attachment is not VK_ATTACHMENT_UNUSED, and aspectMask includes both VK_IMAGE_ASPECT_DEPTH_BIT and VK_IMAGE_ASPECT_STENCIL_BIT, and layout is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, the pNext chain must include a VkAttachmentReferenceStencilLayout structure.

- If attachment is not VK_ATTACHMENT_UNUSED, and aspectMask includes only VK_IMAGE_ASPECT_STENCIL_BIT, then layout must not be VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL.

- If attachment is not VK_ATTACHMENT_UNUSED, and aspectMask includes only VK_IMAGE_ASPECT_DEPTH_BIT, then layout must not be VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2.
- layout must be a valid VkImageLayout value.

The VkAttachmentReferenceStencilLayout structure is defined as:
typedef struct VkAttachmentReferenceStencilLayout {
    VkStructureType    sType;
    void*              pNext;
    VkImageLayout      stencilLayout;
} VkAttachmentReferenceStencilLayout;

or the equivalent

typedef VkAttachmentReferenceStencilLayout VkAttachmentReferenceStencilLayoutKHR;

• *sType* is the type of this structure.
• *pNext* is NULL or a pointer to an extension-specific structure.
• *stencilLayout* is a VkImageLayout value specifying the layout the stencil aspect of the attachment uses during the subpass.

### Valid Usage

• *stencilLayout* must not be VK_IMAGE_LAYOUT_UNDEFINED, VK_IMAGE_LAYOUT_PREINITIALIZED, VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_PRESENT_SRC_KHR

### Valid Usage (Implicit)

• *sType* must be VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_STENCIL_LAYOUT
• *stencilLayout* must be a valid VkImageLayout value

The VkSubpassDependency2 structure is defined as:
typedef struct VkSubpassDependency2 {
    VkStructureType         sType;
    const void*             pNext;
    uint32_t                srcSubpass;
    uint32_t                dstSubpass;
    VkPipelineStageFlags    srcStageMask;
    VkPipelineStageFlags    dstStageMask;
    VkAccessFlags           srcAccessMask;
    VkAccessFlags           dstAccessMask;
    VkDependencyFlags       dependencyFlags;
    int32_t                 viewOffset;
} VkSubpassDependency2;

or the equivalent

typedef VkSubpassDependency2 VkSubpassDependency2KHR;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **srcSubpass** is the subpass index of the first subpass in the dependency, or **VK_SUBPASS_EXTERNAL**.
- **dstSubpass** is the subpass index of the second subpass in the dependency, or **VK_SUBPASS_EXTERNAL**.
- **srcStageMask** is a bitmask of **VkPipelineStageFlagBits** specifying the source stage mask.
- **dstStageMask** is a bitmask of **VkPipelineStageFlagBits** specifying the destination stage mask.
- **srcAccessMask** is a bitmask of **VkAccessFlagBits** specifying a source access mask.
- **dstAccessMask** is a bitmask of **VkAccessFlagBits** specifying a destination access mask.
- **dependencyFlags** is a bitmask of **VkDependencyFlagBits**.
- **viewOffset** controls which views in the source subpass the views in the destination subpass depend on.

Parameters defined by this structure with the same name as those in **VkSubpassDependency** have the identical effect to those parameters.

**viewOffset** has the same effect for the described subpass dependency as **VkRenderPassMultiviewCreateInfo::pViewOffsets** has on each corresponding subpass dependency.
Valid Usage

- If the **geometry shaders** feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`.
- If the **geometry shaders** feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT`.
- If the **tessellation shaders** feature is not enabled, `srcStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`.
- If the **tessellation shaders** feature is not enabled, `dstStageMask` must not contain `VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT` or `VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT`.
- `srcSubpass` must be less than or equal to `dstSubpass`, unless one of them is `VK_SUBPASS_EXTERNAL`, to avoid cyclic dependencies and ensure a valid execution order.
- `srcSubpass` and `dstSubpass` must not both be equal to `VK_SUBPASS_EXTERNAL`.
- If `srcSubpass` is equal to `dstSubpass` and not all of the stages in `srcStageMask` and `dstStageMask` are framebuffer-space stages, the logically latest pipeline stage in `srcStageMask` must be logically earlier than or equal to the logically earliest pipeline stage in `dstStageMask`.
- Any access flag included in `srcAccessMask` must be supported by one of the pipeline stages in `srcStageMask`, as specified in the table of supported access types.
- Any access flag included in `dstAccessMask` must be supported by one of the pipeline stages in `dstStageMask`, as specified in the table of supported access types.
- If `dependencyFlags` includes `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `srcSubpass` must not be equal to `VK_SUBPASS_EXTERNAL`.
- If `dependencyFlags` includes `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `dstSubpass` must not be equal to `VK_SUBPASS_EXTERNAL`.
- If `srcSubpass` equals `dstSubpass`, and `srcStageMask` and `dstStageMask` both include a framebuffer-space stage, then `dependencyFlags` must include `VK_DEPENDENCY_BY_REGION_BIT`.
- If `viewOffset` is not equal to 0, `srcSubpass` must not be equal to `dstSubpass`.
- If `dependencyFlags` does not include `VK_DEPENDENCY_VIEW_LOCAL_BIT`, `viewOffset` must be 0.
- If `viewOffset` is not 0, `srcSubpass` must not be equal to `dstSubpass`. 
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_SUBPASS_DEPENDENCY_2`
- `srcStageMask` must be a valid combination of `VkPipelineStageFlagBits` values
- `srcStageMask` must not be `0`
- `dstStageMask` must be a valid combination of `VkPipelineStageFlagBits` values
- `dstStageMask` must not be `0`
- `srcAccessMask` must be a valid combination of `VkAccessFlagBits` values
- `dstAccessMask` must be a valid combination of `VkAccessFlagBits` values
- `dependencyFlags` must be a valid combination of `VkDependencyFlagBits` values

To destroy a render pass, call:

```c
void vkDestroyRenderPass(
    VkDevice device, 
    VkRenderPass renderPass, 
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the render pass.
- `renderPass` is the handle of the render pass to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

- All submitted commands that refer to `renderPass` must have completed execution
- If `VkAllocationCallbacks` were provided when `renderPass` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `renderPass` was created, `pAllocator` must be `NULL`

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- If `renderPass` is not `VK_NULL_HANDLE`, `renderPass` must be a valid `VkRenderPass` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `renderPass` is a valid handle, it must have been created, allocated, or retrieved from `device`
7.2. Render Pass Compatibility

Framebuffers and graphics pipelines are created based on a specific render pass object. They **must** only be used with that render pass object, or one compatible with it.

Two attachment references are compatible if they have matching format and sample count, or are both `VK_ATTACHMENT_UNUSED` or the pointer that would contain the reference is `NULL`.

Two arrays of attachment references are compatible if all corresponding pairs of attachments are compatible. If the arrays are of different lengths, attachment references not present in the smaller array are treated as `VK_ATTACHMENT_UNUSED`.

Two render passes are compatible if their corresponding color, input, resolve, and depth/stencil attachment references are compatible and if they are otherwise identical except for:

- Initial and final image layout in attachment descriptions
- Load and store operations in attachment descriptions
- Image layout in attachment references

As an additional special case, if two render passes have a single subpass, the resolve attachment reference and depth/stencil resolve mode compatibility requirements are ignored.

A framebuffer is compatible with a render pass if it was created using the same render pass or a compatible render pass.

7.3. Framebuffers

Render passes operate in conjunction with **framebuffers**. Framebuffers represent a collection of specific memory attachments that a render pass instance uses.

Framebuffers are represented by `VkFramebuffer` handles:

```cpp
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFramebuffer)
```

To create a framebuffer, call:

```cpp
VkResult vkCreateFramebuffer(
    VkDevice                                    device,
    const VkFramebufferCreateInfo*              pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkFramebuffer*                              pFramebuffer);
```
• `device` is the logical device that creates the framebuffer.

• `pCreateInfo` is a pointer to a `VkFramebufferCreateInfo` structure describing additional information about framebuffer creation.

• `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

• `pFramebuffer` is a pointer to a `VkFramebuffer` handle in which the resulting framebuffer object is returned.

### Valid Usage

If `pCreateInfo->flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, and `attachmentCount` is not 0, each element of `pCreateInfo->pAttachments` must have been created on `device`.

### Valid Usage (Implicit)

• `device` must be a valid `VkDevice` handle

• `pCreateInfo` must be a valid pointer to a valid `VkFramebufferCreateInfo` structure

• If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

• `pFramebuffer` must be a valid pointer to a `VkFramebuffer` handle

### Return Codes

**Success**

• `VK_SUCCESS`

**Failure**

• `VK_ERROR_OUT_OF_HOST_MEMORY`

• `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkFramebufferCreateInfo` structure is defined as:
typedef struct VkFramebufferCreateInfo {
    VkStructureType             sType;
    const void*                 pNext;
    VkFramebufferCreateFlags    flags;
    VkRenderPass                renderPass;
    uint32_t                    attachmentCount;
    const VkImageView*          pAttachments;
    uint32_t                    width;
    uint32_t                    height;
    uint32_t                    layers;
} VkFramebufferCreateInfo;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is a bitmask of VkFramebufferCreateFlagBits
- **renderPass** is a render pass defining what render passes the framebuffer will be compatible with. See Render Pass Compatibility for details.
- **attachmentCount** is the number of attachments.
- **pAttachments** is a pointer to an array of VkImageView handles, each of which will be used as the corresponding attachment in a render pass instance. If **flags** includes VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT, this parameter is ignored.
- **width**, **height** and **layers** define the dimensions of the framebuffer. If the render pass uses multiview, then **layers** must be one and each attachment requires a number of layers that is greater than the maximum bit index set in the view mask in the subpasses in which it is used.

Applications **must** ensure that all accesses to memory that backs image subresources used as attachments in a given renderpass instance either happen-before the load operations for those attachments, or happen-after the store operations for those attachments.

For depth/stencil attachments, each aspect can be used separately as attachments and non-attachments as long as the non-attachment accesses are also via an image subresource in either the VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL layout or the VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL layout, and the attachment resource uses whichever of those two layouts the image accesses do not. Use of non-attachment aspects in this case is only well defined if the attachment is used in the subpass where the non-attachment access is being made, or the layout of the image subresource is constant throughout the entire render pass instance, including the initialLayout and finalLayout.

**Note**
These restrictions mean that the render pass has full knowledge of all uses of all of the attachments, so that the implementation is able to make correct decisions about when and how to perform layout transitions, when to overlap execution of subpasses, etc.

It is legal for a subpass to use no color or depth/stencil attachments, and rather use shader side
effects such as image stores and atomics to produce an output. In this case, the subpass continues to use the width, height, and layers of the framebuffer to define the dimensions of the rendering area, and the rasterizationSamples from each pipeline’s VkPipelineMultisampleStateCreateInfo to define the number of samples used in rasterization; however, if VkPhysicalDeviceFeatures ::variableMultisampleRate is VK_FALSE, then all pipelines to be bound with a given zero-attachment subpass must have the same value for VkPipelineMultisampleStateCreateInfo ::rasterizationSamples.
Valid Usage

- **attachmentCount** must be equal to the attachment count specified in `renderPass`.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, and `attachmentCount` is not 0, `pAttachments` must be a valid pointer to an array of `attachmentCount` valid `VkImageView` handles.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as a color attachment or resolve attachment by `renderPass` must have been created with a `usage` value including `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as a depth/stencil attachment by `renderPass` must have been created with a `usage` value including `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is used as a depth/stencil resolve attachment by `renderPass` must have been created with a `usage` value including `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have been created with a `VkFormat` value that matches the `VkFormat` specified by the corresponding `VkAttachmentDescription` in `renderPass`.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have been created with a `samples` value that matches the `samples` value specified by the corresponding `VkAttachmentDescription` in `renderPass`.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have dimensions at least as large as the corresponding framebuffer dimension.

- If `renderPass` was specified with non-zero view masks, each element of `pAttachments` must have a `layerCount` greater than the index of the most significant bit set in any of those view masks.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must only specify a single mip level.

- If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` must have been created with the identity swizzle.

- **width** must be greater than 0.

- **width** must be less than or equal to `VkPhysicalDeviceLimits::maxFramebufferWidth`.

- **height** must be greater than 0.

- **height** must be less than or equal to `VkPhysicalDeviceLimits::maxFramebufferHeight`.

- **layers** must be greater than 0.

- **layers** must be less than or equal to `VkPhysicalDeviceLimits::maxFramebufferLayers`.
• If `renderPass` was specified with non-zero view masks, `layers` must be 1.

• If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of `pAttachments` that is a 2D or 2D array image view taken from a 3D image must not be a depth/stencil format.

• If `flags` does not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, and `attachmentCount` is not 0, `pAttachments` must be a valid pointer to an array of `attachmentCount` valid `VkImageView` handles.

• If the imageless framebuffer feature is not enabled, `flags` must not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `pNext` chain must include a `VkFramebufferAttachmentsCreateInfo` structure.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `attachmentImageInfoCount` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain must be equal to either zero or `attachmentCount`.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `width` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain must be greater than or equal to `width`.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `height` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain must be greater than or equal to `height`.

• If multiview is enabled for `renderPass`, and `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `layerCount` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain must be greater than the maximum bit index set in the view mask in the subpasses in which it is used in `renderPass`.

• If multiview is not enabled for `renderPass`, and `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `layerCount` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain must be greater than or equal to `layers`.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `usage` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain that refers to an attachment used as a color attachment or resolve attachment by `renderPass` must include `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `usage` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain that refers to an attachment used as a depth/stencil attachment by `renderPass` must include `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `usage` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain that refers to an attachment used as a depth/stencil resolve attachment by `renderPass` must include `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`.
• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `usage` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain that refers to an attachment used as an input attachment by `renderPass` must include `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`.

• If `flags` includes `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, at least one element of the `pViewFormats` member of any element of the `pAttachmentImageInfos` member of a `VkFramebufferAttachmentsCreateInfo` structure included in the `pNext` chain must be equal to the corresponding value of `VkAttachmentDescription::format` used to create `renderPass`.

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_FRAMEBUFFER_CREATE_INFO`.
- **pNext** must be `NULL` or a pointer to a valid instance of `VkFramebufferAttachmentsCreateInfo`.
- The `sType` value of each struct in the `pNext` chain must be unique.
- **flags** must be a valid combination of `VkFramebufferCreateFlagBits` values.
- **renderPass** must be a valid `VkRenderPass` handle.
- Both of `renderPass`, and the elements of `pAttachments` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`.

The `VkFramebufferAttachmentsCreateInfo` structure is defined as:

```c
typedef struct VkFramebufferAttachmentsCreateInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t attachmentImageInfoCount;
    const VkFramebufferAttachmentImageInfo* pAttachmentImageInfos;
} VkFramebufferAttachmentsCreateInfo;
```

or the equivalent

```c
typedef VkFramebufferAttachmentsCreateInfo VkFramebufferAttachmentsCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **attachmentImageInfoCount** is the number of attachments being described.
- **pAttachmentImageInfos** is a pointer to an array of `VkFramebufferAttachmentImageInfo` instances, each of which describes a number of parameters of the corresponding attachment in a render pass instance.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENTS_CREATE_INFO`

- If `attachmentImageInfoCount` is not 0, `pAttachmentImageInfos` must be a valid pointer to an array of `attachmentImageInfoCount` valid `VkFramebufferAttachmentImageInfo` structures

The `VkFramebufferAttachmentImageInfo` structure is defined as:

```c
typedef struct VkFramebufferAttachmentImageInfo {
    VkStructureType       sType;
    const void*           pNext;
    VkImageCreateFlags    flags;
    VkImageUsageFlags     usage;
    uint32_t              width;
    uint32_t              height;
    uint32_t              layerCount;
    uint32_t              viewFormatCount;
    const VkFormat*       pViewFormats;
} VkFramebufferAttachmentImageInfo;
```

or the equivalent

```c
typedef VkFramebufferAttachmentImageInfo VkFramebufferAttachmentImageInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **flags** is a bitmask of `VkImageCreateFlagBits`, matching the value of `VkImageCreateInfo::flags` used to create an image that will be used with this framebuffer.
- **usage** is a bitmask of `VkImageUsageFlagBits`, matching the value of `VkImageCreateInfo::usage` used to create an image used with this framebuffer.
- **width** is the width of the image view used for rendering.
- **height** is the height of the image view used for rendering.
- **viewFormatCount** is the number of entries in the `pViewFormats` array, matching the value of `VkImageFormatListCreateInfo::viewFormatCount` used to create an image used with this framebuffer.
- **pViewFormats** is an array which lists of all formats which **can** be used when creating views of the image, matching the value of `VkImageFormatListCreateInfo::pViewFormats` used to create an image used with this framebuffer.

Images that **can** be used with the framebuffer when beginning a render pass, as specified by `VkRenderPassAttachmentBeginInfo`, **must** be created with parameters that are identical to those specified here.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENT_IMAGE_INFO`
- **pNext** must be `NULL`
- **flags** must be a valid combination of `VkImageCreateFlagBits` values
- **usage** must be a valid combination of `VkImageUsageFlagBits` values
- **usage** must not be `0`
- If `viewFormatCount` is not `0`, `pViewFormats` must be a valid pointer to an array of `viewFormatCount` valid `VkFormat` values

Bits which **can** be set in `VkFramebufferCreateInfo::flags` to specify options for framebuffers are:

```c
typedef enum VkFramebufferCreateFlagBits {
    VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT = 0x00000001,
    VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT_KHR = VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT,
    VK_FRAMEBUFFER_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkFramebufferCreateFlagBits;
```

- **VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT** specifies that image views are not specified, and only attachment compatibility information will be provided via a `VkFramebufferAttachmentImageInfo` structure.

```c
typedef VkFlags VkFramebufferCreateFlags;
```

`VkFramebufferCreateFlags` is a bitmask type for setting a mask of zero or more `VkFramebufferCreateFlagBits`.

To destroy a framebuffer, call:

```c
void vkDestroyFramebuffer(
    VkDevice device,                     // device
    VkFramebuffer framebuffer,          // framebuffer
    const VkAllocationCallbacks* pAllocator);  // pAllocator
```

- **device** is the logical device that destroys the framebuffer.
- **framebuffer** is the handle of the framebuffer to destroy.
- **pAllocator** controls host memory allocation as described in the [Memory Allocation](#) chapter.
Valid Usage

- All submitted commands that refer to framebuffer must have completed execution
- If VkAllocationCallbacks were provided when framebuffer was created, a compatible set of callbacks must be provided here
- If no VkAllocationCallbacks were provided when framebuffer was created, pAllocator must be NULL

Valid Usage (Implicit)

- device must be a valid VkDevice handle
- If framebuffer is not VK_NULL_HANDLE, framebuffer must be a valid VkFramebuffer handle
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
- If framebuffer is a valid handle, it must have been created, allocated, or retrieved from device

Host Synchronization

- Host access to framebuffer must be externally synchronized

7.4. Render Pass Commands

An application records the commands for a render pass instance one subpass at a time, by beginning a render pass instance, iterating over the subpasses to record commands for that subpass, and then ending the render pass instance.

To begin a render pass instance, call:

```c
void vkCmdBeginRenderPass(
    VkCommandBuffer                             commandBuffer,
    const VkRenderPassBeginInfo*                pRenderPassBegin,
    VkSubpassContents                           contents);
```

- commandBuffer is the command buffer in which to record the command.
- pRenderPassBegin is a pointer to a VkRenderPassBeginInfo structure specifying the render pass to begin an instance of, and the framebuffer the instance uses.
- contents is a VkSubpassContents value specifying how the commands in the first subpass will be provided.
After beginning a render pass instance, the command buffer is ready to record the commands for the first subpass of that render pass.
Valid Usage

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

- If any of the stencilInitialLayout or stencilFinalLayout member of the VkAttachmentDescriptionStencilLayout structures or the stencilLayout member of the VkAttachmentReferenceStencilLayout structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT
then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_SRC_BIT

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_DST_BIT

- If any of the initialLayout members of the VkAttachmentDescription structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is not VK_IMAGE_LAYOUT_UNDEFINED, then each such initialLayout must be equal to the current layout of the corresponding attachment image subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin

- The srcStageMask and dstStageMask members of any element of the pDependencies member of VkRenderPassCreateInfo used to create renderPass must be supported by the capabilities of the queue family identified by the queueFamilyIndex member of the VkCommandPoolCreateInfo used to create the command pool which commandBuffer was allocated from

- For any attachment in framebuffer that is used by renderPass and is bound to memory locations that are also bound to another attachment used by renderPass, and if at least one of those uses causes either attachment to be written to, both attachments must have had the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT set

### Valid Usage (Implicit)

- commandBuffer must be a valid VkCommandBuffer handle
- pRenderPassBegin must be a valid pointer to a valid VkRenderPassBeginInfo structure
- contents must be a valid VkSubpassContents value
- commandBuffer must be in the recording state
- The VkCommandPool that commandBuffer was allocated from must support graphics operations
- This command must only be called outside of a render pass instance
- commandBuffer must be a primary VkCommandBuffer

### Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized
Alternatively to begin a render pass, call:

```c
void vkCmdBeginRenderPass2(
    VkCommandBuffer commandBuffer,
    const VkRenderPassBeginInfo* pRenderPassBegin,
    const VkSubpassBeginInfo* pSubpassBeginInfo);
```

```c
void vkCmdBeginRenderPass2KHR(
    VkCommandBuffer commandBuffer,
    const VkRenderPassBeginInfo* pRenderPassBegin,
    const VkSubpassBeginInfo* pSubpassBeginInfo);
```

- `commandBuffer` is the command buffer in which to record the command.
- `pRenderPassBegin` is a pointer to a `VkRenderPassBeginInfo` structure specifying the render pass to begin an instance of, and the framebuffer the instance uses.
- `pSubpassBeginInfo` is a pointer to a `VkSubpassBeginInfo` structure containing information about the subpass which is about to begin rendering.

After beginning a render pass instance, the command buffer is ready to record the commands for the first subpass of that render pass.
Valid Usage

- Both the framebuffer and renderPass members of pRenderPassBegin must have been created on the same VkDevice that commandBuffer was allocated on.

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT.

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT.

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT.

- If any of the stencilInitialLayout or stencilFinalLayout member of the VkAttachmentDescriptionStencilLayout structures or the stencilLayout member of the VkAttachmentReferenceStencilLayout structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL, or VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT.

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT.

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT.

- If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_SAMPLED_BIT or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT.
structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_SRC_BIT

• If any of the initialLayout or finalLayout member of the VkAttachmentDescription structures or the layout member of the VkAttachmentReference structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL then the corresponding attachment image view of the framebuffer specified in the framebuffer member of pRenderPassBegin must have been created with a usage value including VK_IMAGE_USAGE_TRANSFER_DST_BIT

• If any of the initialLayout members of the VkAttachmentDescription structures specified when creating the render pass specified in the renderPass member of pRenderPassBegin is not VK_IMAGE_LAYOUT_UNDEFINED, then each such initialLayout must be equal to the current layout of the corresponding attachment image subresource of the framebuffer specified in the framebuffer member of pRenderPassBegin

• The srcStageMask and dstStageMask members of any element of the pDependencies member of VkRenderPassCreateInfo used to create renderPass must be supported by the capabilities of the queue family identified by the queueFamilyIndex member of the VkCommandPoolCreateInfo used to create the command pool which commandBuffer was allocated from

• For any attachment in framebuffer that is used by renderPass and is bound to memory locations that are also bound to another attachment used by renderPass, and if at least one of those uses causes either attachment to be written to, both attachments must have had the VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT set

---

**Valid Usage (Implicit)**

• commandBuffer must be a valid VkCommandBuffer handle

• pRenderPassBegin must be a valid pointer to a valid VkRenderPassBeginInfo structure

• pSubpassBeginInfo must be a valid pointer to a valid VkSubpassBeginInfo structure

• commandBuffer must be in the recording state

• The VkCommandPool that commandBuffer was allocated from must support graphics operations

• This command must only be called outside of a render pass instance

• commandBuffer must be a primary VkCommandBuffer
Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
</tbody>
</table>

The VkRenderPassBeginInfo structure is defined as:

```c
typedef struct VkRenderPassBeginInfo {
    VkStructureType        sType;
    const void*            pNext;
    VkRenderPass           renderPass;
    VkFramebuffer          framebuffer;
    VkRect2D               renderArea;
    uint32_t               clearValueCount;
    const VkClearColor*    pClearValues;
} VkRenderPassBeginInfo;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `renderPass` is the render pass to begin an instance of.
- `framebuffer` is the framebuffer containing the attachments that are used with the render pass.
- `renderArea` is the render area that is affected by the render pass instance, and is described in more detail below.
- `clearValueCount` is the number of elements in `pClearValues`.
- `pClearValues` is a pointer to an array of `clearValueCount` `VkClearColor` structures that contains clear values for each attachment, if the attachment uses a `loadOp` value of `VK_ATTACHMENT_LOAD_OP_CLEAR` or if the attachment has a depth/stencil format and uses a `stencilLoadOp` value of `VK_ATTACHMENT_LOAD_OP_CLEAR`. The array is indexed by attachment number. Only elements corresponding to cleared attachments are used. Other elements of `pClearValues` are ignored.

`renderArea` is the render area that is affected by the render pass instance. The effects of attachment load, store and multisample resolve operations are restricted to the pixels whose x and y coordinates fall within the render area on all attachments. The render area extends to all layers of framebuffer. The application must ensure (using scissor if necessary) that all rendering is contained in the render area.
within the render area. The render area **must** be contained within the framebuffer dimensions.

When multiview is enabled, the resolve operation at the end of a subpass applies to all views in the view mask.

**Note**

There **may** be a performance cost for using a render area smaller than the framebuffer, unless it matches the render area granularity for the render pass.
Valid Usage

- **clearValueCount must** be greater than the largest attachment index in `renderPass` that specifies a `loadOp` (or `stencilLoadOp`, if the attachment has a depth/stencil format) of `VK_ATTACHMENT_LOAD_OP_CLEAR`

- `renderPass must` be **compatible** with the `renderPass` member of the `VkFramebufferCreateInfo` structure specified when creating `framebuffer`

- If the `pNext` chain does not contain `VkDeviceGroupRenderPassBeginInfo` or its `deviceRenderAreaCount` member is equal to 0, `renderArea.offset.x must` be greater than or equal to 0

- If the `pNext` chain does not contain `VkDeviceGroupRenderPassBeginInfo` or its `deviceRenderAreaCount` member is equal to 0, `renderArea.offset.y must` be greater than or equal to 0

- If the `pNext` chain does not contain `VkDeviceGroupRenderPassBeginInfo` or its `deviceRenderAreaCount` member is equal to 0, `renderArea.offset.x + renderArea.offset.width must` be less than or equal to `VkFramebufferCreateInfo::width` the `framebuffer` was created with

- If the `pNext` chain does not contain `VkDeviceGroupRenderPassBeginInfo` or its `deviceRenderAreaCount` member is equal to 0, `renderArea.offset.y + renderArea.offset.height must` be less than or equal to `VkFramebufferCreateInfo::height` the `framebuffer` was created with

- If the `pNext` chain contains `VkDeviceGroupRenderPassBeginInfo`, the `offset.x` member of each element of `pDeviceRenderAreas must` be greater than or equal to 0

- If the `pNext` chain contains `VkDeviceGroupRenderPassBeginInfo`, the `offset.y` member of each element of `pDeviceRenderAreas must` be greater than or equal to 0

- If the `pNext` chain contains `VkDeviceGroupRenderPassBeginInfo`, `offset.x + offset.width of each element of pDeviceRenderAreas must` be less than or equal to `VkFramebufferCreateInfo::width` the `framebuffer` was created with

- If the `pNext` chain contains `VkDeviceGroupRenderPassBeginInfo`, `offset.y + offset.height of each element of pDeviceRenderAreas must` be less than or equal to `VkFramebufferCreateInfo::height` the `framebuffer` was created with

- If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that did not include `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, and the `pNext` chain includes a `VkRenderPassAttachmentBeginInfo` structure, its `attachmentCount must` be zero

- If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, the `attachmentCount of a VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must be equal to the value of `VkFramebufferAttachmentsCreateInfo::attachmentImageInfoCount` used to create `framebuffer`

- If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT_KHR`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain must have been created on the same `VkDevice` as `framebuffer` and `renderPass`
• If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain **must** be a `VkImageView` of an image created with a value of `VkImageCreateInfo::flags` equal to the `flags` member of the corresponding element of `VkFramebufferAttachmentsCreateInfoKHR::pAttachments` used to create `framebuffer`.

• If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain **must** be a `VkImageView` of an image created with a value of `VkImageCreateInfo::usage` equal to the `usage` member of the corresponding element of `VkFramebufferAttachmentsCreateInfoKHR::pAttachments` used to create `framebuffer`.

• If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain **must** be a `VkImageView` of an image created with a value of `VkImageCreateInfo::subresourceRange.layerCount` equal to the `layerCount` member of the corresponding element of `VkFramebufferAttachmentsCreateInfoKHR::pAttachments` used to create `framebuffer`.

• If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain **must** be a `VkImageView` of an image created with a value of `VkImageFormatListCreateInfo::viewFormatCount` equal to the `viewFormatCount` member of the corresponding element of `VkFramebufferAttachmentsCreateInfoKHR::pAttachments` used to create `framebuffer`.

• If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain **must** be a `VkImageView` of an image created with a value of `VkImageFormatListCreateInfo::pViewFormats` equal to the set of elements in the `pViewFormats` member of the corresponding element of `VkFramebufferAttachmentsCreateInfoKHR::pAttachments` used to create `framebuffer`.
to the corresponding value of `VkAttachmentDescription::format` in `renderPass`.

- If `framebuffer` was created with a `VkFramebufferCreateInfo::flags` value that included `VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT`, each element of the `pAttachments` member of a `VkRenderPassAttachmentBeginInfo` structure included in the `pNext` chain **must** be a `VkImageView` of an image created with a value of `VkImageCreateInfo::samples` equal to the corresponding value of `VkAttachmentDescription::samples` in `renderPass`.

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO`
- Each `pNext` member of any structure (including this one) in the `pNext` chain **must** be either `NULL` or a pointer to a valid instance of `VkDeviceGroupRenderPassBeginInfo` or `VkRenderPassAttachmentBeginInfo`.
- The `sType` value of each struct in the `pNext` chain **must** be unique.
- `renderPass` **must** be a valid `VkRenderPass` handle.
- `framebuffer` **must** be a valid `VkFramebuffer` handle.
- If `clearValueCount` is not `0`, `pClearValues` **must** be a valid pointer to an array of `clearValueCount` `VkClearValue` unions.
- Both of `framebuffer`, and `renderPass` **must** have been created, allocated, or retrieved from the same `VkDevice`.

The `VkSubpassBeginInfo` structure is defined as:

```c
typedef struct VkSubpassBeginInfo {
    VkStructureType      sType;
    const void*          pNext;
    VkSubpassContents    contents;
} VkSubpassBeginInfo;
```

or the equivalent:

```c
typedef VkSubpassBeginInfo VkSubpassBeginInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **contents** is a `VkSubpassContents` value specifying how the commands in the next subpass will be provided.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_SUBPASS_BEGIN_INFO`
- **pNext** must be `NULL`
- **contents** must be a valid `VkSubpassContents` value

Possible values of `vkCmdBeginRenderPass::contents`, specifying how the commands in the first subpass will be provided, are:

```c
typedef enum VkSubpassContents {
    VK_SUBPASS_CONTENTS_INLINE = 0,
    VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS = 1,
    VK_SUBPASS_CONTENTS_MAX_ENUM = 0x7FFFFFFF
} VkSubpassContents;
```

- `VK_SUBPASS_CONTENTS_INLINE` specifies that the contents of the subpass will be recorded inline in the primary command buffer, and secondary command buffers must not be executed within the subpass.

- `VK_SUBPASS_CONTENTS_SECONDARY_COMMAND_BUFFERS` specifies that the contents are recorded in secondary command buffers that will be called from the primary command buffer, and `vkCmdExecuteCommands` is the only valid command on the command buffer until `vkCmdNextSubpass` or `vkCmdEndRenderPass`.

If the `pNext` chain of `VkRenderPassBeginInfo` includes a `VkDeviceGroupRenderPassBeginInfo` structure, then that structure includes a device mask and set of render areas for the render pass instance.

The `VkDeviceGroupRenderPassBeginInfo` structure is defined as:

```c
typedef struct VkDeviceGroupRenderPassBeginInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t deviceMask;
    uint32_t deviceRenderAreaCount;
    const VkRect2D* pDeviceRenderAreas;
} VkDeviceGroupRenderPassBeginInfo;
```

or the equivalent

```c
typedef VkDeviceGroupRenderPassBeginInfo VkDeviceGroupRenderPassBeginInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **deviceMask** is the device mask for the render pass instance.
• `deviceRenderAreaCount` is the number of elements in the `pDeviceRenderAreas` array.

• `pDeviceRenderAreas` is a pointer to an array of `VkRect2D` structures defining the render area for each physical device.

The `deviceMask` serves several purposes. It is an upper bound on the set of physical devices that can be used during the render pass instance, and the initial device mask when the render pass instance begins. In addition, commands transitioning to the next subpass in the render pass instance and commands ending the render pass instance, and, accordingly render pass attachment load, store, and resolve operations and subpass dependencies corresponding to the render pass instance, are executed on the physical devices included in the device mask provided here.

If `deviceRenderAreaCount` is not zero, then the elements of `pDeviceRenderAreas` override the value of `VkRenderPassBeginInfo::renderArea`, and provide a render area specific to each physical device. These render areas serve the same purpose as `VkRenderPassBeginInfo::renderArea`, including controlling the region of attachments that are cleared by `VK_ATTACHMENT_LOAD_OP_CLEAR` and that are resolved into resolve attachments.

If this structure is not present, the render pass instance's device mask is the value of `VkDeviceGroupCommandBufferBeginInfo::deviceMask`. If this structure is not present or if `deviceRenderAreaCount` is zero, `VkRenderPassBeginInfo::renderArea` is used for all physical devices.

### Valid Usage

- `deviceMask` must be a valid device mask value
- `deviceMask` must not be zero
- `deviceMask` must be a subset of the command buffer's initial device mask
- `deviceRenderAreaCount` must either be zero or equal to the number of physical devices in the logical device.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO`
- If `deviceRenderAreaCount` is not 0, `pDeviceRenderAreas` must be a valid pointer to an array of `deviceRenderAreaCount` `VkRect2D` structures

The `VkRenderPassAttachmentBeginInfo` structure is defined as:

```c
typedef struct VkRenderPassAttachmentBeginInfo {
    VkStructureType       sType;
    const void*           pNext;
    uint32_t              attachmentCount;
    const VkImageView*    pAttachments;
} VkRenderPassAttachmentBeginInfo;
```
or the equivalent

typedef VkRenderPassAttachmentBeginInfo VkRenderPassAttachmentBeginInfoKHR;

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `attachmentCount` is the number of attachments.
- `pAttachments` is a pointer to an array of `VkImageView` handles, each of which will be used as the corresponding attachment in the render pass instance.

Valid Usage

- Each element of `pAttachments` must only specify a single mip level
- Each element of `pAttachments` must have been created with the identity swizzle

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_RENDER_PASS_ATTACHMENT_BEGIN_INFO`
- If `attachmentCount` is not 0, `pAttachments` must be a valid pointer to an array of `attachmentCount` valid `VkImageView` handles

To query the render area granularity, call:

```c
void vkGetRenderAreaGranularity(
    VkDevice device,        // device
    VkRenderPass renderPass,  // render pass
    VkExtent2D* pGranularity); // pointer to a VkExtent2D structure in which the granularity is returned
```

- `device` is the logical device that owns the render pass.
- `renderPass` is a handle to a render pass.
- `pGranularity` is a pointer to a `VkExtent2D` structure in which the granularity is returned.

The conditions leading to an optimal `renderArea` are:

- the `offset.x` member in `renderArea` is a multiple of the `width` member of the returned `VkExtent2D` (the horizontal granularity).
- the `offset.y` member in `renderArea` is a multiple of the `height` of the returned `VkExtent2D` (the vertical granularity).
- either the `offset.width` member in `renderArea` is a multiple of the horizontal granularity or `offset.x + offset.width` is equal to the `width` of the framebuffer in the `VkRenderPassBeginInfo`.
- either the `offset.height` member in `renderArea` is a multiple of the vertical granularity or
offset.y + offset.height is equal to the height of the framebuffer in the VkRenderPassBeginInfo.

Subpass dependencies are not affected by the render area, and apply to the entire image subresources attached to the framebuffer as specified in the description of automatic layout transitions. Similarly, pipeline barriers are valid even if their effect extends outside the render area.

Valid Usage (Implicit)

- device must be a valid VkDevice handle
- renderPass must be a valid VkRenderPass handle
- pGranularity must be a valid pointer to a VkExtent2D structure
- renderPass must have been created, allocated, or retrieved from device

To transition to the next subpass in the render pass instance after recording the commands for a subpass, call:

```c
void vkCmdNextSubpass(
    VkCommandBuffer commandBuffer,
    VkSubpassContents contents);
```

- commandBuffer is the command buffer in which to record the command.
- contents specifies how the commands in the next subpass will be provided, in the same fashion as the corresponding parameter of vkCmdBeginRenderPass.

The subpass index for a render pass begins at zero when vkCmdBeginRenderPass is recorded, and increments each time vkCmdNextSubpass is recorded.

Moving to the next subpass automatically performs any multisample resolve operations in the subpass being ended. End-of-subpass multisample resolves are treated as color attachment writes for the purposes of synchronization. This applies to resolve operations for both color and depth/stencil attachments. That is, they are considered to execute in the VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT pipeline stage and their writes are synchronized with VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT. Synchronization between rendering within a subpass and any resolve operations at the end of the subpass occurs automatically, without need for explicit dependencies or pipeline barriers. However, if the resolve attachment is also used in a different subpass, an explicit dependency is needed.

After transitioning to the next subpass, the application can record the commands for that subpass.

Valid Usage

- The current subpass index must be less than the number of subpasses in the render pass minus one
Valid Usage (Implicit)

- **commandBuffer** must be a valid `VkCommandBuffer` handle
- **contents** must be a valid `VkSubpassContents` value
- **commandBuffer** must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- This command must only be called inside of a render pass instance
- **commandBuffer** must be a primary `VkCommandBuffer`

Host Synchronization

- Host access to **commandBuffer** must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
</tbody>
</table>

To transition to the next subpass in the render pass instance after recording the commands for a subpass, call:

```c
void vkCmdNextSubpass2(
    VkCommandBuffer                             commandBuffer,
    const VkSubpassBeginInfo*                   pSubpassBeginInfo,
    const VkSubpassEndInfo*                     pSubpassEndInfo);
```

```c
void vkCmdNextSubpass2KHR(
    VkCommandBuffer                             commandBuffer,
    const VkSubpassBeginInfo*                   pSubpassBeginInfo,
    const VkSubpassEndInfo*                     pSubpassEndInfo);
```

- **commandBuffer** is the command buffer in which to record the command.
- **pSubpassBeginInfo** is a pointer to a `VkSubpassBeginInfo` structure containing information about the subpass which is about to begin rendering.
- **pSubpassEndInfo** is a pointer to a `VkSubpassEndInfo` structure containing information about how
the previous subpass will be ended.

\texttt{vkCmdNextSubpass2} is semantically identical to \texttt{vkCmdNextSubpass}, except that it is extensible, and that \texttt{contents} is provided as part of an extensible structure instead of as a flat parameter.

### Valid Usage

- The current subpass index \textbf{must} be less than the number of subpasses in the render pass minus one

### Valid Usage (Implicit)

- \texttt{commandBuffer} \textbf{must} be a valid \texttt{VkCommandBuffer} handle
- \texttt{pSubpassBeginInfo} \textbf{must} be a valid pointer to a valid \texttt{VkSubpassBeginInfo} structure
- \texttt{pSubpassEndInfo} \textbf{must} be a valid pointer to a valid \texttt{VkSubpassEndInfo} structure
- \texttt{commandBuffer} \textbf{must} be in the \textit{recording state}
- The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} support graphics operations
- This command \textbf{must} only be called inside of a render pass instance
- \texttt{commandBuffer} \textbf{must} be a primary \texttt{VkCommandBuffer}

### Host Synchronization

- Host access to \texttt{commandBuffer} \textbf{must} be externally synchronized
- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
</tbody>
</table>

To record a command to end a render pass instance after recording the commands for the last subpass, call:

```c
void vkCmdEndRenderPass(
    VkCommandBuffer commandBuffer);
```

- \texttt{commandBuffer} is the command buffer in which to end the current render pass instance.
Ending a render pass instance performs any multisample resolve operations on the final subpass.

**Valid Usage**

- The current subpass index **must** be equal to the number of subpasses in the render pass minus one

**Valid Usage (Implicit)**

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations
- This command **must** only be called inside of a render pass instance
- `commandBuffer` **must** be a primary `VkCommandBuffer`

**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

**Command Properties**

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
</tbody>
</table>

To record a command to end a render pass instance after recording the commands for the last subpass, call:

```c
void vkCmdEndRenderPass2(
    VkCommandBuffer                             commandBuffer,
    const VkSubpassEndInfo*                     pSubpassEndInfo);
```

```c
void vkCmdEndRenderPass2KHR(
    VkCommandBuffer                             commandBuffer,
    const VkSubpassEndInfo*                     pSubpassEndInfo);
```
• `commandBuffer` is the command buffer in which to end the current render pass instance.

• `pSubpassEndInfo` is a pointer to a `VkSubpassEndInfo` structure containing information about how the previous subpass will be ended.

`vkCmdEndRenderPass2` is semantically identical to `vkCmdEndRenderPass`, except that it is extensible.

### Valid Usage

- The current subpass index **must** be equal to the number of subpasses in the render pass minus one

### Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle

- `pSubpassEndInfo` **must** be a valid pointer to a valid `VkSubpassEndInfo` structure

- `commandBuffer` **must** be in the recording state

- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations

- This command **must** only be called inside of a render pass instance

- `commandBuffer` **must** be a primary `VkCommandBuffer`

### Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
</tbody>
</table>

The `VkSubpassEndInfo` structure is defined as:

```c
typedef struct VkSubpassEndInfo {
    VkStructureType    sType;
    const void*        pNext;
} VkSubpassEndInfo;
```
or the equivalent

```c
typedef VkSubpassEndInfo VkSubpassEndInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.

**Valid Usage (Implicit)**

- `sType` **must** be `VK_STRUCTURE_TYPE_SUBPASS_END_INFO`
- `pNext` **must** be `NULL`
Chapter 8. Shaders

A shader specifies programmable operations that execute for each vertex, control point, tessellated vertex, primitive, fragment, or workgroup in the corresponding stage(s) of the graphics and compute pipelines.

Graphics pipelines include vertex shader execution as a result of primitive assembly, followed, if enabled, by tessellation control and evaluation shaders operating on patches, geometry shaders, if enabled, operating on primitives, and fragment shaders, if present, operating on fragments generated by Rasterization. In this specification, vertex, tessellation control, tessellation evaluation and geometry shaders are collectively referred to as vertex processing stages and occur in the logical pipeline before rasterization. The fragment shader occurs logically after rasterization.

Only the compute shader stage is included in a compute pipeline. Compute shaders operate on compute invocations in a workgroup.

Shaders can read from input variables, and read from and write to output variables. Input and output variables can be used to transfer data between shader stages, or to allow the shader to interact with values that exist in the execution environment. Similarly, the execution environment provides constants that describe capabilities.

Shader variables are associated with execution environment-provided inputs and outputs using built-in decorations in the shader. The available decorations for each stage are documented in the following subsections.

8.1. Shader Modules

Shader modules contain shader code and one or more entry points. Shaders are selected from a shader module by specifying an entry point as part of pipeline creation. The stages of a pipeline can use shaders that come from different modules. The shader code defining a shader module must be in the SPIR-V format, as described by the Vulkan Environment for SPIR-V appendix.

Shader modules are represented by VkShaderModule handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkShaderModule)
```

To create a shader module, call:

```
VkResult vkCreateShaderModule(
    VkDevice device,
    const VkShaderModuleCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkShaderModule* pShaderModule);
```

- `device` is the logical device that creates the shader module.
- `pCreateInfo` is a pointer to a VkShaderModuleCreateInfo structure.
• **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

• **pShaderModule** is a pointer to a VkShaderModule handle in which the resulting shader module object is returned.

Once a shader module has been created, any entry points it contains can be used in pipeline shader stages as described in Compute Pipelines and Graphics Pipelines.

### Valid Usage (Implicit)

- **device** must be a valid VkDevice handle
- **pCreateInfo** must be a valid pointer to a valid VkShaderModuleCreateInfo structure
- If **pAllocator** is not **NULL**, **pAllocator** must be a valid pointer to a valid VkAllocationCallbacks structure
- **pShaderModule** must be a valid pointer to a VkShaderModule handle

### Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkShaderModuleCreateInfo structure is defined as:

```c
typedef struct VkShaderModuleCreateInfo {
    VkStructureType              sType;
    const void*                  pNext;
    VkShaderModuleCreateFlags    flags;
    size_t                       codeSize;
    const uint32_t*              pCode;
} VkShaderModuleCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **codeSize** is the size, in bytes, of the code pointed to by **pCode**.
- **pCode** is a pointer to code that is used to create the shader module. The type and format of the code is determined from the content of the memory addressed by **pCode**.
Valid Usage

- **codeSize** must be greater than 0
- **codeSize** must be a multiple of 4
- **pCode** must point to valid SPIR-V code, formatted and packed as described by the Khronos SPIR-V Specification
- **pCode** must adhere to the validation rules described by the Validation Rules within a Module section of the SPIR-V Environment appendix
- **pCode** must declare the Shader capability for SPIR-V code
- **pCode** must not declare any capability that is not supported by the API, as described by the Capabilities section of the SPIR-V Environment appendix
- If **pCode** declares any of the capabilities listed as **optional** in the SPIR-V Environment appendix, the corresponding feature(s) must be enabled.

Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO
- **pNext** must be NULL
- **flags** must be 0
- **pCode** must be a valid pointer to an array of \( \frac{\text{codeSize}}{4} \) uint32_t values

```c
typedef VkFlags VkShaderModuleCreateFlags;
```

`VkShaderModuleCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

To destroy a shader module, call:

```c
void vkDestroyShaderModule(
    VkDevice device,
    VkShaderModule shaderModule,
    const VkAllocationCallbacks* pAllocator);
```

- **device** is the logical device that destroys the shader module.
- **shaderModule** is the handle of the shader module to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

A shader module can be destroyed while pipelines created using its shaders are still in use.
Valid Usage

- If VkAllocationCallbacks were provided when shaderModule was created, a compatible set of callbacks must be provided here.
- If no VkAllocationCallbacks were provided when shaderModule was created, pAllocator must be NULL.

Valid Usage (Implicit)

- device must be a valid VkDevice handle.
- If shaderModule is not VK_NULL_HANDLE, shaderModule must be a valid VkShaderModule handle.
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure.
- If shaderModule is a valid handle, it must have been created, allocated, or retrieved from device.

Host Synchronization

- Host access to shaderModule must be externally synchronized.

8.2. Shader Execution

At each stage of the pipeline, multiple invocations of a shader may execute simultaneously. Further, invocations of a single shader produced as the result of different commands may execute simultaneously. The relative execution order of invocations of the same shader type is undefined. Shader invocations may complete in a different order than that in which the primitives they originated from were drawn or dispatched by the application. However, fragment shader outputs are written to attachments in rasterization order.

The relative execution order of invocations of different shader types is largely undefined. However, when invoking a shader whose inputs are generated from a previous pipeline stage, the shader invocations from the previous stage are guaranteed to have executed far enough to generate input values for all required inputs.

8.3. Shader Memory Access Ordering

The order in which image or buffer memory is read or written by shaders is largely undefined. For some shader types (vertex, tessellation evaluation, and in some cases, fragment), even the number of shader invocations that may perform loads and stores is undefined.

In particular, the following rules apply:
• **Vertex** and **tessellation evaluation** shaders will be invoked at least once for each unique vertex, as defined in those sections.

• **Fragment** shaders will be invoked zero or more times, as defined in that section.

• The relative execution order of invocations of the same shader type is undefined. A store issued by a shader when working on primitive B might complete prior to a store for primitive A, even if primitive A is specified prior to primitive B. This applies even to fragment shaders; while fragment shader outputs are always written to the framebuffer in **rasterization order**, stores executed by fragment shader invocations are not.

• The relative execution order of invocations of different shader types is largely undefined.

**Note**

The above limitations on shader invocation order make some forms of synchronization between shader invocations within a single set of primitives unimplementable. For example, having one invocation poll memory written by another invocation assumes that the other invocation has been launched and will complete its writes in finite time.

The **Memory Model** appendix defines the terminology and rules for how to correctly communicate between shader invocations, such as when a write is **Visible-To** a read, and what constitutes a **Data Race**.

Applications **must** not cause a data race.

### 8.4. Shader Inputs and Outputs

Data is passed into and out of shaders using variables with input or output storage class, respectively. User-defined inputs and outputs are connected between stages by matching their **Location** decorations. Additionally, data **can** be provided by or communicated to special functions provided by the execution environment using **BuiltIn** decorations.

In many cases, the same **BuiltIn** decoration **can** be used in multiple shader stages with similar meaning. The specific behavior of variables decorated as **BuiltIn** is documented in the following sections.

### 8.5. Vertex Shaders

Each vertex shader invocation operates on one vertex and its associated **vertex attribute** data, and outputs one vertex and associated data. Graphics pipelines **must** include a vertex shader, and the vertex shader stage is always the first shader stage in the graphics pipeline.

#### 8.5.1. Vertex Shader Execution

A vertex shader **must** be executed at least once for each vertex specified by a draw command. If the subpass includes multiple views in its view mask, the shader **may** be invoked separately for each view. During execution, the shader is presented with the index of the vertex and instance for which it has been invoked. Input variables declared in the vertex shader are filled by the implementation...
with the values of vertex attributes associated with the invocation being executed.

If the same vertex is specified multiple times in a draw command (e.g. by including the same index value multiple times in an index buffer) the implementation may reuse the results of vertex shading if it can statically determine that the vertex shader invocations will produce identical results.

Note

It is implementation-dependent when and if results of vertex shading are reused, and thus how many times the vertex shader will be executed. This is true also if the vertex shader contains stores or atomic operations (see vertexPipelineStoresAndAtomics).

8.6. Tessellation Control Shaders

The tessellation control shader is used to read an input patch provided by the application and to produce an output patch. Each tessellation control shader invocation operates on an input patch (after all control points in the patch are processed by a vertex shader) and its associated data, and outputs a single control point of the output patch and its associated data, and can also output additional per-patch data. The input patch is sized according to the patchControlPoints member of VkPipelineTessellationStateCreateInfo, as part of input assembly. The size of the output patch is controlled by the OpExecutionMode OutputVertices specified in the tessellation control or tessellation evaluation shaders, which must be specified in at least one of the shaders. The size of the input and output patches must each be greater than zero and less than or equal to VkPhysicalDeviceLimits::maxTessellationPatchSize.

8.6.1. Tessellation Control Shader Execution

A tessellation control shader is invoked at least once for each output vertex in a patch. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view.

Inputs to the tessellation control shader are generated by the vertex shader. Each invocation of the tessellation control shader can read the attributes of any incoming vertices and their associated data. The invocations corresponding to a given patch execute logically in parallel, with undefined relative execution order. However, the OpControlBarrier instruction can be used to provide limited control of the execution order by synchronizing invocations within a patch, effectively dividing tessellation control shader execution into a set of phases. Tessellation control shaders will read undefined values if one invocation reads a per-vertex or per-patch attribute written by another invocation at any point during the same phase, or if two invocations attempt to write different values to the same per-patch output in a single phase.

8.7. Tessellation Evaluation Shaders

The Tessellation Evaluation Shader operates on an input patch of control points and their associated data, and a single input barycentric coordinate indicating the invocation’s relative position within the subdivided patch, and outputs a single vertex and its associated data.
8.7.1. Tessellation Evaluation Shader Execution

A tessellation evaluation shader is invoked at least once for each unique vertex generated by the tessellator. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view.

8.8. Geometry Shaders

The geometry shader operates on a group of vertices and their associated data assembled from a single input primitive, and emits zero or more output primitives and the group of vertices and their associated data required for each output primitive.

8.8.1. Geometry Shader Execution

A geometry shader is invoked at least once for each primitive produced by the tessellation stages, or at least once for each primitive generated by primitive assembly when tessellation is not in use. A shader can request that the geometry shader runs multiple instances. A geometry shader is invoked at least once for each instance. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view.

8.9. Fragment Shaders

Fragment shaders are invoked as the result of rasterization in a graphics pipeline. Each fragment shader invocation operates on a single fragment and its associated data. With few exceptions, fragment shaders do not have access to any data associated with other fragments and are considered to execute in isolation of fragment shader invocations associated with other fragments.

8.9.1. Fragment Shader Execution

For each fragment generated by rasterization, a fragment shader may be invoked. A fragment shader must not be invoked if the Early Per-Fragment Tests cause it to have no coverage. If the subpass includes multiple views in its view mask, the shader may be invoked separately for each view.

Furthermore, if it is determined that a fragment generated as the result of rasterizing a first primitive will have its outputs entirely overwritten by a fragment generated as the result of rasterizing a second primitive in the same subpass, and the fragment shader used for the fragment has no other side effects, then the fragment shader may not be executed for the fragment from the first primitive.

Relative ordering of execution of different fragment shader invocations is not defined.

For each fragment generated by a primitive, the number of times the fragment shader is invoked is implementation-dependent, but must obey the following constraints:

- Each covered sample is included in a single fragment shader invocation.
- When sample shading is not enabled, there is at least one fragment shader invocation.
- When sample shading is enabled, the minimum number of fragment shader invocations is as
When there is more than one fragment shader invocation per fragment, the association of samples to invocations is implementation-dependent.

In addition to the conditions outlined above for the invocation of a fragment shader, a fragment shader invocation may be produced as a helper invocation. A helper invocation is a fragment shader invocation that is created solely for the purposes of evaluating derivatives for use in non-helper fragment shader invocations. Stores and atomics performed by helper invocations must not have any effect on memory, and values returned by atomic instructions in helper invocations are undefined.

### 8.9.2. Early Fragment Tests

An explicit control is provided to allow fragment shaders to enable early fragment tests. If the fragment shader specifies the `EarlyFragmentTests OpExecutionMode`, the per-fragment tests described in Early Fragment Test Mode are performed prior to fragment shader execution. Otherwise, they are performed after fragment shader execution.

### 8.10. Compute Shaders

Compute shaders are invoked via `vkCmdDispatch` and `vkCmdDispatchIndirect` commands. In general, they have access to similar resources as shader stages executing as part of a graphics pipeline.

Compute workloads are formed from groups of work items called workgroups and processed by the compute shader in the current compute pipeline. A workgroup is a collection of shader invocations that execute the same shader, potentially in parallel. Compute shaders execute in global workgroups which are divided into a number of local workgroups with a size that can be set by assigning a value to the `LocalSize` execution mode or via an object decorated by the `WorkgroupSize` decoration. An invocation within a local workgroup can share data with other members of the local workgroup through shared variables and issue memory and control flow barriers to synchronize with other members of the local workgroup.

### 8.11. Interpolation Decorations

Interpolation decorations control the behavior of attribute interpolation in the fragment shader stage. Interpolation decorations can be applied to Input storage class variables in the fragment shader stage’s interface, and control the interpolation behavior of those variables.

Inputs that could be interpolated can be decorated by at most one of the following decorations:

- **Flat**: no interpolation
- **NoPerspective**: linear interpolation (for lines and polygons)

Fragment input variables decorated with neither Flat nor NoPerspective use perspective-correct interpolation (for lines and polygons).
The presence of and type of interpolation is controlled by the above interpolation decorations as well as the auxiliary decorations Centroid and Sample.

A variable decorated with Flat will not be interpolated. Instead, it will have the same value for every fragment within a triangle. This value will come from a single provoking vertex. A variable decorated with Flat can also be decorated with Centroid or Sample, which will mean the same thing as decorating it only as Flat.

For fragment shader input variables decorated with neither Centroid nor Sample, the assigned variable may be interpolated anywhere within the fragment and a single value may be assigned to each sample within the fragment.

If a fragment shader input is decorated with Centroid, a single value may be assigned to that variable for all samples in the fragment, but that value must be interpolated to a location that lies in both the fragment and in the primitive being rendered, including any of the fragment's samples covered by the primitive. Because the location at which the variable is interpolated may be different in neighboring fragments, and derivatives may be computed by computing differences between neighboring fragments, derivatives of centroid-sampled inputs may be less accurate than those for non-centroid interpolated variables.

If a fragment shader input is decorated with Sample, a separate value must be assigned to that variable for each covered sample in the fragment, and that value must be sampled at the location of the individual sample. When rasterizationSamples is VK_SAMPLE_COUNT_1_BIT, the fragment center must be used for Centroid, Sample, and undecorated attribute interpolation.

Fragment shader inputs that are signed or unsigned integers, integer vectors, or any double-precision floating-point type must be decorated with Flat.

### 8.12. Ray Generation Shaders

A ray generation shader is similar to a compute shader. Its main purpose is to execute ray tracing queries using OpTraceRayKHR instructions and process the results.

#### 8.12.1. Ray Generation Shader Execution

One ray generation shader is executed per ray tracing dispatch. Its location in the shader binding table (see Shader Binding Table for details) is passed directly into vkCmdTraceRaysKHR using the raygenShaderBindingTableBuffer and raygenShaderBindingOffset parameters.

### 8.13. Intersection Shaders

Intersection shaders enable the implementation of arbitrary, application defined geometric primitives. An intersection shader for a primitive is executed whenever its axis-aligned bounding box is hit by a ray.

Like other ray tracing shader domains, an intersection shader operates on a single ray at a time. It also operates on a single primitive at a time. It is therefore the purpose of an intersection shader to compute the ray-primitive intersections and report them. To report an intersection, the shader calls the OpReportIntersectionKHR instruction.
An intersection shader communicates with any-hit and closest shaders by generating attribute values that they can read. Intersection shaders cannot read or modify the ray payload.

### 8.13.1. Intersection Shader Execution

The order in which intersections are found along a ray, and therefore the order in which intersection shaders are executed, is unspecified.

The intersection shader of the closest AABB which intersects the ray is guaranteed to be executed at some point during traversal, unless the ray is forcibly terminated.

### 8.14. Any-Hit Shaders

The any-hit shader is executed after the intersection shader reports an intersection that lies within the current $[t_{\text{min}}, t_{\text{max}}]$ of the ray. The main use of any-hit shaders is to programmatically decide whether or not an intersection will be accepted. The intersection will be accepted unless the shader calls the `OpIgnoreIntersectionKHR` instruction. Any-hit shaders have read-only access to the attributes generated by the corresponding intersection shader, and can read or modify the ray payload.

#### 8.14.1. Any-Hit Shader Execution

The order in which intersections are found along a ray, and therefore the order in which any-hit shaders are executed, is unspecified.

The any-hit shader of the closest hit is guaranteed to be executed at some point during traversal, unless the ray is forcibly terminated.

### 8.15. Closest Hit Shaders

Closest hit shaders have read-only access to the attributes generated by the corresponding intersection shader, and can read or modify the ray payload. They also have access to a number of system-generated values. Closest hit shaders can call `OpTraceRayKHR` to recursively trace rays.

#### 8.15.1. Closest Hit Shader Execution

Exactly one closest hit shader is executed when traversal is finished and an intersection has been found and accepted.

### 8.16. Miss Shaders

Miss shaders can access the ray payload and can trace new rays through the `OpTraceRayKHR` instruction, but cannot access attributes since they are not associated with an intersection.

#### 8.16.1. Miss Shader Execution

A miss shader is executed instead of a closest hit shader if no intersection was found during traversal.
8.17. Callable Shaders

Callable shaders can access a callable payload that works similarly to ray payloads to do subroutine work.

8.17.1. Callable Shader Execution

A callable shader is executed by calling OpExecuteCallableKHR from an allowed shader stage.

8.18. Static Use

A SPIR-V module declares a global object in memory using the OpVariable instruction, which results in a pointer \( x \) to that object. A specific entry point in a SPIR-V module is said to statically use that object if that entry point's call tree contains a function containing a memory instruction or image instruction with \( x \) as an id operand. See the “Memory Instructions” and “Image Instructions” subsections of section 3 “Binary Form” of the SPIR-V specification for the complete list of SPIR-V memory instructions.

Static use is not used to control the behavior of variables with Input and Output storage. The effects of those variables are applied based only on whether they are present in a shader entry point’s interface.

8.19. Scope

A scope describes a set of shader invocations, where each such set is a scope instance. Each invocation belongs to one or more scope instances, but belongs to no more than one scope instance for each scope.

The operations available between invocations in a given scope instance vary, with smaller scopes generally able to perform more operations, and with greater efficiency.

8.19.1. Cross Device

All invocations executed in a Vulkan instance fall into a single cross device scope instance.

Whilst the CrossDevice scope is defined in SPIR-V, it is disallowed in Vulkan. API synchronization commands can be used to communicate between devices.

8.19.2. Device

All invocations executed on a single device form a device scope instance.

If the vulkanMemoryModel and vulkanMemoryModelDeviceScope features are enabled, this scope is represented in SPIR-V by the Device Scope, which can be used as a Memory Scope for barrier and atomic operations.

There is no method to synchronize the execution of these invocations within SPIR-V, and this can only be done with API synchronization primitives.
Invocations executing on different devices in a device group operate in separate device scope instances.

### 8.19.3. Queue Family

Invocations executed by queues in a given queue family form a *queue family scope instance*.

This scope is identified in SPIR-V as the *QueueFamily Scope* if the *vulkanMemoryModel* feature is enabled, or if not, the *Device Scope*, which can be used as a *Memory Scope* for barrier and atomic operations.

There is no method to synchronize the execution of these invocations within SPIR-V, and this can only be done with API synchronization primitives.

Each invocation in a queue family scope instance **must** be in the same *device scope instance*.

### 8.19.4. Command

Any shader invocations executed as the result of a single command such as *vkCmdDispatch* or *vkCmdDraw* form a *command scope instance*. For indirect drawing commands with *drawCount* greater than one, invocations from separate draws are in separate command scope instances. For ray tracing shaders, an invocation group is an implementation-dependent subset of the set of shader invocations of a given shader stage which are produced by a single trace rays command.

There is no specific Scope for communication across invocations in a command scope instance. As this has a clear boundary at the API level, coordination here can be performed in the API, rather than in SPIR-V.

Each invocation in a command scope instance **must** be in the same *queue-family scope instance*.

For shaders without defined *workgroups*, this set of invocations forms an *invocation group* as defined in the SPIR-V specification (see the subsection “Control Flow” of section 2 of the SPIR-V 1.00 Revision 4 specification).

### 8.19.5. Primitive

Any fragment shader invocations executed as the result of rasterization of a single primitive form a *primitive scope instance*.

There is no specific Scope for communication across invocations in a primitive scope instance.

Any generated *helper invocations* are included in this scope instance.

Each invocation in a primitive scope instance **must** be in the same *command scope instance*.

Any input variables decorated with *Flat* are uniform within a primitive scope instance.

### 8.19.6. Shader Call

Any *shader-call-related* invocations that are executed in one or more ray tracing execution models form a *shader call scope instance*.
The ShaderCallKHR Scope can be used as Memory Scope for barrier and atomic operations.

Each invocation in a shader call scope instance must be in the same queue family scope instance.

### 8.19.7. Workgroup

A local workgroup is a set of invocations that can synchronize and share data with each other using memory in the Workgroup storage class.

The Workgroup Scope can be used as both an Execution Scope and Memory Scope for barrier and atomic operations.

Each invocation in a local workgroup must be in the same command scope instance.

Only compute shaders have defined workgroups - other shader types cannot use workgroup functionality. For shaders that have defined workgroups, this set of invocations forms an invocation group as defined in the SPIR-V specification (see the subsection “Control Flow” of section 2 of the SPIR-V 1.00 Revision 4 specification).

### 8.19.8. Subgroup

A subgroup (see the subsection “Control Flow” of section 2 of the SPIR-V 1.3 Revision 1 specification) is a set of invocations that can synchronize and share data with each other efficiently.

The Subgroup Scope can be used as both an Execution Scope and Memory Scope for barrier and atomic operations. Other subgroup features allow the use of group operations with subgroup scope.

For shaders that have defined workgroups, each invocation in a subgroup must be in the same local workgroup.

In other shader stages, each invocation in a subgroup must be in the same device scope instance.

Only shader stages that support subgroup operations have defined subgroups.

### 8.19.9. Quad

A quad scope instance is formed of four shader invocations.

In a fragment shader, each invocation in a quad scope instance is formed of invocations in neighboring framebuffer locations \((x_i, y_i)\), where:

- \(i\) is the index of the invocation within the scope instance.
- \(x_0 = x_1 - 1 = x_2 = x_3 - 1\)
- \(y_0 = y_1 = y_2 - 1 = y_3 - 1\)
- Each invocation has the same layer and sample indices.

In all shaders, each invocation in a quad scope instance is formed of invocations in adjacent subgroup invocation indices \((s_i)\), where:

- \(i\) is the index of the invocation within the quad scope instance.
\[ s_0 = s_1 - 1 = s_2 - 2 = s_3 - 3 \]

- \( s_0 \) is an integer multiple of 4.

Each invocation in a quad scope instance **must** be in the same **subgroup**.

Fragment and compute shaders have defined quad scope instances. If the \texttt{quadOperationsInAllStages} limit is supported, any shader stages that support subgroup operations also have defined quad scope instances.

### 8.19.10. Invocation

The smallest **scope** is a single invocation; this is represented by the **Invocation Scope** in SPIR-V.

Fragment shader invocations **must** be in a [shaders-scope-primitive primitive scope instance].

Invocations in shaders that have defined workgroups **must** be in a **local workgroup**.

Invocations in shaders that have a defined subgroup scope **must** be in a **subgroup**.

Invocations in shaders that have a defined quad scope **must** be in a **quad scope instance**.

All invocations in all stages **must** be in a **command scope instance**.

### 8.20. Group Operations

**Group operations** are executed by multiple invocations within a **scope instance**; with each invocation involved in calculating the result. This provides a mechanism for efficient communication between invocations in a particular scope instance.

Group operations all take a **Scope** defining the desired **scope instance** to operate within. Only the **Subgroup** scope **can** be used for these operations; the **subgroupSupportedOperations** limit defines which types of operation **can** be used.

#### 8.20.1. Basic Group Operations

Basic group operations include the use of **OpGroupNonUniformElect**, **OpControlBarrier**, **OpMemoryBarrier**, and atomic operations.

**OpGroupNonUniformElect** **can** be used to choose a single invocation to perform a task for the whole group. Only the invocation with the lowest id in the group will return **true**.

The **Memory Model** appendix defines the operation of barriers and atomics.

#### 8.20.2. Vote Group Operations

The vote group operations allow invocations within a group to compare values across a group. The types of votes enabled are:

- Do all active group invocations agree that an expression is true?
- Do any active group invocations evaluate an expression to true?
• Do all active group invocations have the same value of an expression?

**Note**
These operations are useful in combination with control flow in that they allow for developers to check whether conditions match across the group and choose potentially faster code-paths in these cases.

### 8.20.3. Arithmetic Group Operations

The arithmetic group operations allow invocations to perform scans and reductions across a group. The operators supported are add, mul, min, max, and, or, xor.

For reductions, every invocation in a group will obtain the cumulative result of these operators applied to all values in the group. For exclusive scans, each invocation in a group will obtain the cumulative result of these operators applied to all values in invocations with a lower index in the group. Inclusive scans are identical to exclusive scans, except the cumulative result includes the operator applied to the value in the current invocation.

The order in which these operators are applied is implementation-dependent.

### 8.20.4. Ballot Group Operations

The ballot group operations allow invocations to perform more complex votes across the group. The ballot functionality allows all invocations within a group to provide a boolean value and get as a result what each invocation provided as their boolean value. The broadcast functionality allows values to be broadcast from an invocation to all other invocations within the group.

### 8.20.5. Shuffle Group Operations

The shuffle group operations allow invocations to read values from other invocations within a group.

### 8.20.6. Shuffle Relative Group Operations

The shuffle relative group operations allow invocations to read values from other invocations within the group relative to the current invocation in the group. The relative operations supported allow data to be shifted up and down through the invocations within a group.

### 8.20.7. Clustered Group Operations

The clustered group operations allow invocations to perform an operation among partitions of a group, such that the operation is only performed within the group invocations within a partition. The partitions for clustered group operations are consecutive power-of-two size groups of invocations and the cluster size must be known at pipeline creation time. The operations supported are add, mul, min, max, and, or, xor.
8.21. Quad Group Operations

Quad group operations (*OpGroupNonUniformQuad*) are a specialized type of group operations that only operate on quad scope instances. Whilst these instructions do include a Scope parameter, this scope is always overridden; only the quad scope instance is included in its execution scope.

Fragment shaders that statically execute quad group operations must launch sufficient invocations to ensure their correct operation; additional helper invocations are launched for framebuffer locations not covered by rasterized fragments if necessary.

The index used to select participating invocations is i, as described for a quad scope instance. For *OpGroupNonUniformQuadBroadcast* this value is equal to Index. For *OpGroupNonUniformQuadSwap*, it’s equal to the implicit Index used by each participating invocation.

8.22. Derivative Operations

Derivative operations calculate the partial derivative for an expression P as a function of an invocation’s x and y coordinates.

Derivative operations operate on a set of invocations known as a derivative group as defined in the SPIR-V specification (see the subsection “Control Flow” of section 2 of the SPIR-V 1.00 Revision 4 specification). A derivative group is equivalent to the primitive scope instance for a fragment shader invocation.

Derivatives are calculated assuming that P is piecewise linear and continuous within the derivative group. All dynamic instances of explicit derivative instructions (*OpDPdx*, *OpDPdy*, and *OpFwidth*) must be executed in control flow that is uniform within a derivative group. For other derivative operations, results are undefined if a dynamic instance is executed in control flow is not uniform within the derivative group.

Fragment shaders that statically execute derivative operations must launch sufficient invocations to ensure their correct operation; additional helper invocations are launched for framebuffer locations not covered by rasterized fragments if necessary.

Derivative operations calculate their results as the difference between the result of P across invocations in the quad. For fine derivative operations (*OpDPdxFine* and *OpDPdyFine*), the values of DPdx(P_i) are calculated as

\[ DPdx(P_0) = DPdx(P_1) = P_1 - P_0 \]
\[ DPdx(P_2) = DPdx(P_3) = P_3 - P_2 \]

and the values of DPdy(P_i) are calculated as

\[ DPdy(P_0) = DPdy(P_2) = P_2 - P_0 \]
\[ DPdy(P_1) = DPdy(P_3) = P_3 - P_1 \]

where i is the index of each invocation as described in Quad.
Coarse derivative operations (\texttt{OpDPdxCoarse} and \texttt{OpDPdyCoarse}), calculate their results in roughly the same manner, but \textbf{may} only calculate two values instead of four (one for each of DPdx and DPdy), reusing the same result no matter the originating invocation. If an implementation does this, it \textbf{should} use the fine derivative calculations described for \texttt{P}_{\circ}.

The results for \texttt{OpDPdx} and \texttt{OpDPdy} \textbf{may} be calculated as either fine or coarse derivatives, with implementations favouring the most efficient approach. Implementations \textbf{must} choose coarse or fine consistently between the two.

Executing \texttt{OpFwidthFine}, \texttt{OpFwidthCoarse}, or \texttt{OpFwidth} is equivalent to executing the corresponding \texttt{OpDPdx*} and \texttt{OpDPdy*} instructions, taking the absolute value of the results, and summing them.

Executing a \texttt{OpImage*Sample*ImplicitLod} instruction is equivalent to executing \texttt{OpDPdx(Coordinate)} and \texttt{OpDPdy(Coordinate)}, and passing the results as the \texttt{Grad} operands \texttt{dx} and \texttt{dy}.

\begin{quote}
\textbf{Note}

It is expected that using the \texttt{ImplicitLod} variants of sampling functions will be substantially more efficient than using the \texttt{ExplicitLod} variants with explicitly generated derivatives.
\end{quote}

\section*{8.23. Helper Invocations}

When performing \texttt{derivative} or \texttt{quad group} operations in a fragment shader, additional invocations \textbf{may} be spawned in order to ensure correct results. These additional invocations are known as \textit{helper invocations} and \textbf{can} be identified by a non-zero value in the \texttt{HelperInvocation} built-in. Stores and atomics performed by helper invocations \textbf{must} not have any effect on memory, and values returned by atomic instructions in helper invocations are undefined.

Helper invocations \textbf{may} become inactive at any time for any reason, with one exception. If a helper invocation would be active if it were not a helper invocation, it \textbf{must} be active for \texttt{derivative} and \texttt{quad group} operations.
Chapter 9. Pipelines

The following figure shows a block diagram of the Vulkan pipelines. Some Vulkan commands specify geometric objects to be drawn or computational work to be performed, while others specify state controlling how objects are handled by the various pipeline stages, or control data transfer between memory organized as images and buffers. Commands are effectively sent through a processing pipeline, either a graphics pipeline, a ray tracing pipeline, or a compute pipeline.

The first stage of the graphics pipeline (Input Assembler) assembles vertices to form geometric primitives such as points, lines, and triangles, based on a requested primitive topology. In the next stage (Vertex Shader) vertices can be transformed, computing positions and attributes for each vertex. If tessellation and/or geometry shaders are supported, they can then generate multiple primitives from a single input primitive, possibly changing the primitive topology or generating additional attribute data in the process.

The final resulting primitives are clipped to a clip volume in preparation for the next stage, Rasterization. The rasterizer produces a series of framebuffer addresses and values using a two-dimensional description of a point, line segment, or triangle. Each fragment so produced is fed to the next stage (Fragment Shader) that performs operations on individual fragments before they finally alter the framebuffer. These operations include conditional updates into the framebuffer based on incoming and previously stored depth values (to effect depth buffering), blending of incoming fragment colors with stored colors, as well as masking, stenciling, and other logical operations on fragment values.

Framebuffer operations read and write the color and depth/stencil attachments of the framebuffer for a given subpass of a render pass instance. The attachments can be used as input attachments in the fragment shader in a later subpass of the same render pass.

The compute pipeline is a separate pipeline from the graphics pipeline, which operates on one-, two-, or three-dimensional workgroups which can read from and write to buffer and image memory.

This ordering is meant only as a tool for describing Vulkan, not as a strict rule of how Vulkan is implemented, and we present it only as a means to organize the various operations of the pipelines. Actual ordering guarantees between pipeline stages are explained in detail in the synchronization chapter.
Each pipeline is controlled by a monolithic object created from a description of all of the shader stages and any relevant fixed-function stages. Linking the whole pipeline together allows the optimization of shaders based on their input/outputs and eliminates expensive draw time state validation.

A pipeline object is bound to the current state using `vkCmdBindPipeline`. Any pipeline object state that is specified as dynamic is not applied to the current state when the pipeline object is bound, but is instead set by dynamic state setting commands.

No state, including dynamic state, is inherited from one command buffer to another.

Compute, ray tracing, and graphics pipelines are each represented by `VkPipeline` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipeline)
```

### 9.1. Compute Pipelines

Compute pipelines consist of a single static compute shader stage and the pipeline layout.

The compute pipeline represents a compute shader and is created by calling `vkCreateComputePipelines` with `module` and `pName` selecting an entry point from a shader module, where that entry point defines a valid compute shader, in the `VkPipelineShaderStageCreateInfo` structure contained within the `VkComputePipelineCreateInfo` structure.

To create compute pipelines, call:
VkResult vkCreateComputePipelines(
    VkDevice device,
    VkPipelineCache pipelineCache,
    uint32_t createInfoCount,
    const VkComputePipelineCreateInfo* pCreateInfos,
    const VkAllocationCallbacks* pAllocator,
    VkPipeline* pPipelines);

- **device** is the logical device that creates the compute pipelines.
- **pipelineCache** is either `VK_NULL_HANDLE`, indicating that pipeline caching is disabled; or the handle of a valid pipeline cache object, in which case use of that cache is enabled for the duration of the command.
- **createInfoCount** is the length of the `pCreateInfos` and `pPipelines` arrays.
- **pCreateInfos** is a pointer to an array of `VkComputePipelineCreateInfo` structures.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pPipelines** is a pointer to an array of `VkPipeline` handles in which the resulting compute pipeline objects are returned.

**Valid Usage**

- If the **flags** member of any element of `pCreateInfos` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and the **basePipelineIndex** member of that same element is not -1, **basePipelineIndex** must be less than the index into `pCreateInfos` that corresponds to that element.

- If the **flags** member of any element of `pCreateInfos` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, the base pipeline **must** have been created with the `VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT` flag set.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- If `pipelineCache` is not `VK_NULL_HANDLE`, `pipelineCache` must be a valid `VkPipelineCache` handle
- `pCreateInfos` must be a valid pointer to an array of `createInfoCount` valid `VkComputePipelineCreateInfo` structures
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- `pPipelines` must be a valid pointer to an array of `createInfoCount` `VkPipeline` handles
- `createInfoCount` must be greater than 0
- If `pipelineCache` is a valid handle, it must have been created, allocated, or retrieved from `device`

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkComputePipelineCreateInfo` structure is defined as:

```c
typedef struct VkComputePipelineCreateInfo {
    VkStructureType sType;
    const void*     pNext;
    VkPipelineCreateFlags flags;
    VkPipelineShaderStageCreateInfo stage;
    VkPipelineLayout layout;
    VkPipeline basePipelineHandle;
    int32_t         basePipelineIndex;
} VkComputePipelineCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is a bitmask of `VkPipelineCreateFlagBits` specifying how the pipeline will be generated.
- `stage` is a `VkPipelineShaderStageCreateInfo` structure describing the compute shader.
- `layout` is the description of binding locations used by both the pipeline and descriptor sets used with the pipeline.
• **basePipelineHandle** is a pipeline to derive from

• **basePipelineIndex** is an index into the **pCreateInfos** parameter to use as a pipeline to derive from

The parameters **basePipelineHandle** and **basePipelineIndex** are described in more detail in the [Pipeline Derivatives](#).

---

**Valid Usage**

- If **flags** contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and **basePipelineIndex** is -1, **basePipelineHandle** must be a valid handle to a compute **VkPipeline**

- If **flags** contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and **basePipelineHandle** is **VK_NULL_HANDLE**, **basePipelineIndex** must be a valid index into the calling command's **pCreateInfos** parameter

- If **flags** contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and **basePipelineIndex** is not -1, **basePipelineHandle** must be **VK_NULL_HANDLE**

- If **flags** contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and **basePipelineHandle** is not **VK_NULL_HANDLE**, **basePipelineIndex** must be -1

- The **stage** member of **stage** must be `VK_SHADER_STAGE_COMPUTE_BIT`

- The shader code for the entry point identified by **stage** and the rest of the state identified by this structure must adhere to the pipeline linking rules described in the [Shader Interfaces](#) chapter

- **layout** must be consistent with the layout of the compute shader specified in **stage**

- The number of resources in **layout** accessible to the compute shader stage must be less than or equal to **VkPhysicalDeviceLimits::maxPerStageResources**

- **flags** must not include `VK_PIPELINE_CREATE_LIBRARY_BIT_KHR`

- **flags** must not include `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_ANY_HIT_SHADERS_BIT_KHR`

- **flags** must not include `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_CLOSEST_HIT_SHADERS_BIT_KHR`

- **flags** must not include `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_MISS_SHADERS_BIT_KHR`

- **flags** must not include `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_INTERSECTION_SHADERS_BIT_KHR`

- **flags** must not include `VK_PIPELINE_CREATE_RAY_TRACING_SKIP_TRIANGLES_BIT_KHR`

- **flags** must not include `VK_PIPELINE_CREATE_RAY_TRACING_SKIP_AABBS_BIT_KHR`
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO`
- **pNext** must be `NULL`
- **flags** must be a valid combination of `VkPipelineCreateFlagBits` values
- **stage** must be a valid `VkPipelineShaderStageCreateInfo` structure
- **layout** must be a valid `VkPipelineLayout` handle
- Both of `basePipelineHandle`, and **layout** that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

The `VkPipelineShaderStageCreateInfo` structure is defined as:

```c
typedef struct VkPipelineShaderStageCreateInfo {
    VkStructureType         sType;
    const void*             pNext;
    VkPipelineShaderStageCreateFlags flags;
    VkShaderStageFlagBits   stage;
    VkShaderModule          module;
    const char*             pName;
    const VkSpecializationInfo* pSpecializationInfo;
} VkPipelineShaderStageCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **flags** is a bitmask of `VkPipelineShaderStageCreateFlagBits` specifying how the pipeline shader stage will be generated.
- **stage** is a `VkShaderStageFlagBits` value specifying a single pipeline stage.
- **module** is a `VkShaderModule` object containing the shader for this stage.
- **pName** is a pointer to a null-terminated UTF-8 string specifying the entry point name of the shader for this stage.
- **pSpecializationInfo** is a pointer to a `VkSpecializationInfo` structure, as described in `Specialization Constants`, or `NULL`. 
Valid Usage

• If the geometry shaders feature is not enabled, stage must not be VK_SHADER_STAGE_GEOMETRY_BIT

• If the tessellation shaders feature is not enabled, stage must not be VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT or VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT

• stage must not be VK_SHADER_STAGE_ALL_GRAPHICS, or VK_SHADER_STAGE_ALL

• pName must be the name of an OpEntryPoint in module with an execution model that matches stage

• If the identified entry point includes any variable in its interface that is declared with the ClipDistance BuiltIn decoration, that variable must not have an array size greater than VkPhysicalDeviceLimits::maxClipDistances

• If the identified entry point includes any variable in its interface that is declared with the CullDistance BuiltIn decoration, that variable must not have an array size greater than VkPhysicalDeviceLimits::maxCullDistances

• If the identified entry point includes any variables in its interface that are declared with the ClipDistance or CullDistance BuiltIn decoration, those variables must not have array sizes which sum to more than VkPhysicalDeviceLimits::maxCombinedClipAndCullDistances

• If the identified entry point includes any variable in its interface that is declared with the SampleMask BuiltIn decoration, that variable must not have an array size greater than VkPhysicalDeviceLimits::maxSampleMaskWords

• If stage is VK_SHADER_STAGE_VERTEX_BIT, the identified entry point must not include any input variable in its interface that is decorated with CullDistance

• If stage is VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT or VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT, and the identified entry point has an OpExecutionMode instruction that specifies a patch size with OutputVertices, the patch size must be greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxTessellationPatchSize

• If stage is VK_SHADER_STAGE_GEOMETRY_BIT, the identified entry point must have an OpExecutionMode instruction that specifies a maximum output vertex count that is greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxGeometryOutputVertices

• If stage is VK_SHADER_STAGE_GEOMETRY_BIT, the identified entry point must have an OpExecutionMode instruction that specifies an invocation count that is greater than 0 and less than or equal to VkPhysicalDeviceLimits::maxGeometryShaderInvocations

• If stage is a vertex processing stage, and the identified entry point writes to Layer for any primitive, it must write the same value to Layer for all vertices of a given primitive

• If stage is a vertex processing stage, and the identified entry point writes to ViewportIndex for any primitive, it must write the same value to ViewportIndex for all vertices of a given primitive

• If stage is VK_SHADER_STAGE_FRAGMENT_BIT, the identified entry point must not include any output variables in its interface decorated with CullDistance
• If stage is VK_SHADER_STAGE_FRAGMENT_BIT, and the identified entry point writes to FragDepth in any execution path, it must write to FragDepth in all execution paths

**Valid Usage (Implicit)**

• sType must be VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO
• pNext must be NULL
• flags must be 0
• stage must be a valid VkShaderStageFlagBits value
• module must be a valid VkShaderModule handle
• pName must be a null-terminated UTF-8 string
• If pSpecializationInfo is not NULL, pSpecializationInfo must be a valid pointer to a valid VkSpecializationInfo structure

**typedef** VkFlags VkPipelineShaderStageCreateFlags;

VkPipelineShaderStageCreateFlags is a bitmask type for setting a mask of zero or more VkPipelineShaderStageCreateFlagBits.

Possible values of the flags member of VkPipelineShaderStageCreateInfo specifying how a pipeline shader stage is created, are:

**typedef enum** VkPipelineShaderStageCreateFlagBits {
    VK_PIPELINE_SHADER_STAGE_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkPipelineShaderStageCreateFlagBits;

Commands and structures which need to specify one or more shader stages do so using a bitmask whose bits correspond to stages. Bits which can be set to specify shader stages are:
typedef enum VkShaderStageFlagBits {
    VK_SHADER_STAGE_VERTEX_BIT = 0x00000001,
    VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT = 0x00000002,
    VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT = 0x00000004,
    VK_SHADER_STAGE_GEOMETRY_BIT = 0x00000008,
    VK_SHADER_STAGE_FRAGMENT_BIT = 0x00000010,
    VK_SHADER_STAGE_COMPUTE_BIT = 0x00000020,
    VK_SHADER_STAGE_ALL_GRAPHICS = 0x0000001F,
    VK_SHADER_STAGE_ALL = 0x7FFFFFFF,
    VK_SHADER_STAGE_RAYGEN_BIT_KHR = 0x00000100,
    VK_SHADER_STAGE_ANY_HIT_BIT_KHR = 0x00000200,
    VK_SHADER_STAGE_CLOSEST_HIT_BIT_KHR = 0x00000400,
    VK_SHADER_STAGE_MISS_BIT_KHR = 0x00000800,
    VK_SHADER_STAGE_INTERSECTION_BIT_KHR = 0x00001000,
    VK_SHADER_STAGE_CALLABLE_BIT_KHR = 0x00002000,
    VK_SHADER_STAGE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkShaderStageFlagBits;

- **VK_SHADER_STAGE_VERTEX_BIT** specifies the vertex stage.
- **VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT** specifies the tessellation control stage.
- **VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT** specifies the tessellation evaluation stage.
- **VK_SHADER_STAGE_GEOMETRY_BIT** specifies the geometry stage.
- **VK_SHADER_STAGE_FRAGMENT_BIT** specifies the fragment stage.
- **VK_SHADER_STAGE_COMPUTE_BIT** specifies the compute stage.
- **VK_SHADER_STAGE_ALL_GRAPHICS** is a combination of bits used as shorthand to specify all graphics stages defined above (excluding the compute stage).
- **VK_SHADER_STAGE_ALL** is a combination of bits used as shorthand to specify all shader stages supported by the device, including all additional stages which are introduced by extensions.
- **VK_SHADER_STAGE_RAYGEN_BIT_KHR** specifies the ray generation stage.
- **VK_SHADER_STAGE_ANY_HIT_BIT_KHR** specifies the any-hit stage.
- **VK_SHADER_STAGE_CLOSEST_HIT_BIT_KHR** specifies the closest hit stage.
- **VK_SHADER_STAGE_MISS_BIT_KHR** specifies the miss stage.
- **VK_SHADER_STAGE_INTERSECTION_BIT_KHR** specifies the intersection stage.
- **VK_SHADER_STAGE_CALLABLE_BIT_KHR** specifies the callable stage.

**Note**

**VK_SHADER_STAGE_ALL_GRAPHICS** only includes the original five graphics stages included in Vulkan 1.0, and not any stages added by extensions. Thus, it may not have the desired effect in all cases.

typedef VkFlags VkShaderStageFlags;
**VkShaderStageFlags** is a bitmask type for setting a mask of zero or more **VkShaderStageFlagBits**.

## 9.2. Graphics Pipelines

Graphics pipelines consist of multiple shader stages, multiple fixed-function pipeline stages, and a pipeline layout.

To create graphics pipelines, call:

```c
VkResult vkCreateGraphicsPipelines(
    VkDevice device,     // The logical device that creates the graphics pipelines.
    VkPipelineCache pipelineCache, // Either VK_NULL_HANDLE, indicating that pipeline caching is disabled; or the handle of a valid pipeline cache object, in which case use of that cache is enabled for the duration of the command.
    uint32_t createInfoCount, // The length of the pCreateInfos and pPipelines arrays.
    const VkGraphicsPipelineCreateInfo* pCreateInfos, // A pointer to an array of VkGraphicsPipelineCreateInfo structures.
    const VkAllocationCallbacks* pAllocator, // Controls host memory allocation as described in the Memory Allocation chapter.
    VkPipeline* pPipelines); // A pointer to an array of VkPipeline handles in which the resulting graphics pipeline objects are returned.
```

- **device** is the logical device that creates the graphics pipelines.
- **pipelineCache** is either **VK_NULL_HANDLE**, indicating that pipeline caching is disabled; or the handle of a valid pipeline cache object, in which case use of that cache is enabled for the duration of the command.
- **createInfoCount** is the length of the **pCreateInfos** and **pPipelines** arrays.
- **pCreateInfos** is a pointer to an array of **VkGraphicsPipelineCreateInfo** structures.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pPipelines** is a pointer to an array of **VkPipeline** handles in which the resulting graphics pipeline objects are returned.

The **VkGraphicsPipelineCreateInfo** structure includes an array of shader create info structures containing all the desired active shader stages, as well as creation info to define all relevant fixed-function stages, and a pipeline layout.

### Valid Usage

- If the **flags** member of any element of **pCreateInfos** contains the **VK_PIPELINE_CREATE_DERIVATIVE_BIT** flag, and the **basePipelineIndex** member of that same element is not -1, **basePipelineIndex** must be less than the index into **pCreateInfos** that corresponds to that element.
- If the **flags** member of any element of **pCreateInfos** contains the **VK_PIPELINE_CREATE_DERIVATIVE_BIT** flag, the base pipeline **must** have been created with the **VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT** flag set.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle

- If `pipelineCache` is not `VK_NULL_HANDLE`, `pipelineCache` must be a valid `VkPipelineCache` handle

- `pCreateInfos` must be a valid pointer to an array of `createInfoCount` valid `VkGraphicsPipelineCreateInfo` structures

- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure

- `pPipelines` must be a valid pointer to an array of `createInfoCount` `VkPipeline` handles

- `createInfoCount` must be greater than 0

- If `pipelineCache` is a valid handle, it must have been created, allocated, or retrieved from `device`

---

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkGraphicsPipelineCreateInfo` structure is defined as:
typedef struct VkGraphicsPipelineCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineCreateFlags flags;
    uint32_t stageCount;
    const VkPipelineShaderStageCreateInfo* pStages;
    const VkPipelineVertexInputStateCreateInfo* pVertexInputState;
    const VkPipelineInputAssemblyStateCreateInfo* pInputAssemblyState;
    const VkPipelineTessellationStateCreateInfo* pTessellationState;
    const VkPipelineViewportStateCreateInfo* pViewportState;
    const VkPipelineRasterizationStateCreateInfo* pRasterizationState;
    const VkPipelineMultisampleStateCreateInfo* pMultisampleState;
    const VkPipelineColorBlendStateCreateInfo* pColorBlendState;
    const VkPipelineDynamicStateCreateInfo* pDynamicState;
    VkPipelineLayout layout;
    VkRenderPass renderPass;
    uint32_t subpass;
    VkPipeline basePipelineHandle;
    int32_t basePipelineIndex;
} VkGraphicsPipelineCreateInfo;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is a bitmask of VkPipelineCreateFlagBits specifying how the pipeline will be generated.
- **stageCount** is the number of entries in the **pStages** array.
- **pStages** is a pointer to an array of **stageCount** VkPipelineShaderStageCreateInfo structures describing the set of the shader stages to be included in the graphics pipeline.
- **pVertexInputState** is a pointer to a VkPipelineVertexInputStateCreateInfo structure.
- **pInputAssemblyState** is a pointer to a VkPipelineInputAssemblyStateCreateInfo structure which determines input assembly behavior, as described in Drawing Commands.
- **pTessellationState** is a pointer to a VkPipelineTessellationStateCreateInfo structure, and is ignored if the pipeline does not include a tessellation control shader stage and tessellation evaluation shader stage.
- **pViewportState** is a pointer to a VkPipelineViewportStateCreateInfo structure, and is ignored if the pipeline has rasterization disabled.
- **pRasterizationState** is a pointer to a VkPipelineRasterizationStateCreateInfo structure.
- **pMultisampleState** is a pointer to a VkPipelineMultisampleStateCreateInfo structure, and is ignored if the pipeline has rasterization disabled.
- **pDepthStencilState** is a pointer to a VkPipelineDepthStencilStateCreateInfo structure, and is ignored if the pipeline has rasterization disabled or if the subpass of the render pass the pipeline is created against does not use a depth/stencil attachment.
- **pColorBlendState** is a pointer to a VkPipelineColorBlendStateCreateInfo structure, and is ignored
if the pipeline has rasterization disabled or if the subpass of the render pass the pipeline is created against does not use any color attachments.

- **pDynamicState** is a pointer to a `VkPipelineDynamicStateCreateInfo` structure, and is used to indicate which properties of the pipeline state object are dynamic and can be changed independently of the pipeline state. This can be **NULL**, which means no state in the pipeline is considered dynamic.

- **layout** is the description of binding locations used by both the pipeline and descriptor sets used with the pipeline.

- **renderPass** is a handle to a render pass object describing the environment in which the pipeline will be used; the pipeline **must** only be used with an instance of any render pass compatible with the one provided. See **Render Pass Compatibility** for more information.

- **subpass** is the index of the subpass in the render pass where this pipeline will be used.

- **basePipelineHandle** is a pipeline to derive from.

- **basePipelineIndex** is an index into the **pCreateInfos** parameter to use as a pipeline to derive from.

The parameters **basePipelineHandle** and **basePipelineIndex** are described in more detail in **Pipeline Derivatives**.
Valid Usage

- If flags contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and basePipelineIndex is -1, basePipelineHandle must be a valid handle to a graphics VkPipeline.

- If flags contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and basePipelineHandle is VK_NULL_HANDLE, basePipelineIndex must be a valid index into the calling command's pCreateInfos parameter.

- If flags contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and basePipelineIndex is not -1, basePipelineHandle must be VK_NULL_HANDLE.

- If flags contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and basePipelineHandle is not VK_NULL_HANDLE, basePipelineIndex must be -1.

- The stage member of each element of pStages must be unique.

- The stage member of one element of pStages must be VK_SHADER_STAGE_VERTEX_BIT.

- The stage member of each element of pStages must not be VK_SHADER_STAGE_COMPUTE_BIT.

- If pStages includes a tessellation control shader stage, it must include a tessellation evaluation shader stage.

- If pStages includes a tessellation evaluation shader stage, it must include a tessellation control shader stage.

- If pStages includes a tessellation control shader stage and a tessellation evaluation shader stage, pTessellationState must be a valid pointer to a valid VkPipelineTessellationStateCreateInfo structure.

- If pStages includes tessellation shader stages, the shader code of at least one stage must contain an OpExecutionMode instruction that specifies the type of subdivision in the pipeline.

- If pStages includes tessellation shader stages, and the shader code of both stages contain an OpExecutionMode instruction that specifies the type of subdivision in the pipeline, they must both specify the same subdivision mode.

- If pStages includes tessellation shader stages, the shader code of at least one stage must contain an OpExecutionMode instruction that specifies the output patch size in the pipeline.

- If pStages includes tessellation shader stages, and the shader code of both contain an OpExecutionMode instruction that specifies the output patch size in the pipeline, they must both specify the same patch size.

- If pStages includes tessellation shader stages, the topology member of pInputAssembly must be VK_PRIMITIVE_TOPOLOGY_PATCH_LIST.

- If the topology member of pInputAssembly is VK_PRIMITIVE_TOPOLOGY_PATCH_LIST, pStages must include tessellation shader stages.

- If pStages includes a geometry shader stage, and does not include any tessellation shader stages, its shader code must contain an OpExecutionMode instruction that specifies an input primitive type that is compatible with the primitive topology specified in pInputAssembly.

- If pStages includes a geometry shader stage, and also includes tessellation shader stages, its shader code must contain an OpExecutionMode instruction that specifies an input primitive type that is compatible with the primitive topology specified in pInputAssembly.
primitive type that is compatible with the primitive topology that is output by the tessellation stages

- If `pStages` includes a fragment shader stage and a geometry shader stage, and the fragment shader code reads from an input variable that is decorated with `PrimitiveID`, then the geometry shader code must write to a matching output variable, decorated with `PrimitiveID`, in all execution paths

- If `pStages` includes a fragment shader stage, its shader code must not read from any input attachment that is defined as `VK_ATTACHMENT_UNUSED` in `subpass`

- The shader code for the entry points identified by `pStages`, and the rest of the state identified by this structure must adhere to the pipeline linking rules described in the Shader Interfaces chapter

- If rastorization is not disabled and `subpass` uses a depth/stencil attachment in `renderPass` that has a layout of `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL` in the `VkAttachmentReference` defined by `subpass`, the `depthWriteEnable` member of `pDepthStencilState` must be `VK_FALSE`

- If rastorization is not disabled and `subpass` uses a depth/stencil attachment in `renderPass` that has a layout of `VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL` or `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL` in the `VkAttachmentReference` defined by `subpass`, the `failOp`, `passOp` and `depthFailOp` members of each of the front and back members of `pDepthStencilState` must be `VK_STENCIL_OP_KEEP`

- If rastorization is not disabled and the subpass uses color attachments, then for each color attachment in the subpass the `blendEnable` member of the corresponding element of the `pAttachment` member of `pColorBlendState` must be `VK_FALSE` if the attached image's format features does not contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT`.

- If rastorization is not disabled and the subpass uses color attachments, the `attachmentCount` member of `pColorBlendState` must be equal to the `colorAttachmentCount` used to create `subpass`

- If no element of the `pDynamicStates` member of `pDynamicState` is `VK_DYNAMIC_STATE_VIEWPORT`, the `pViewports` member of `pViewportState` must be a valid pointer to an array of `pViewportState->viewportCount` valid `VkViewport` structures

- If no element of the `pDynamicStates` member of `pDynamicState` is `VK_DYNAMIC_STATE_SCISSOR`, the `pScissors` member of `pViewportState` must be a valid pointer to an array of `pViewportState->scissorCount` `VkRect2D` structures

- If the wide lines feature is not enabled, and no element of the `pDynamicStates` member of `pRasterizationState` is `VK_DYNAMIC_STATE_LINE_WIDTH`, the `lineWidth` member of `pRasterizationState` must be `1.0`

- If the `rasterizerDiscardEnable` member of `pRasterizationState` is `VK_FALSE`, `pViewportState` must be a valid pointer to a valid `VkPipelineViewportStateCreateInfo` structure

- If the `rasterizerDiscardEnable` member of `pRasterizationState` is `VK_FALSE`, `pMultisampleState` must be a valid pointer to a valid `VkPipelineMultisampleStateCreateInfo` structure

- If the `rasterizerDiscardEnable` member of `pRasterizationState` is `VK_FALSE`, and `subpass` uses a depth/stencil attachment, `pDepthStencilState` must be a valid pointer to a valid
VkPipelineDepthStencilStateCreateInfo structure

- If the `rasterizerDiscardEnable` member of `pRasterizationState` is `VK_FALSE`, and `subpass` uses color attachments, `pColorBlendState` must be a valid pointer to a valid `VkPipelineColorBlendStateCreateInfo` structure.

- If the depth bias clamping feature is not enabled, no element of the `pDynamicStates` member of `pDynamicState` is `VK_DYNAMIC_STATE_DEPTH_BIAS`, and the `depthBiasEnable` member of `pRasterizationState` is `VK_TRUE`, the `depthBiasClamp` member of `pRasterizationState` must be `0.0`.

- If no element of the `pDynamicStates` member of `pDynamicState` is `VK_DYNAMIC_STATE_DEPTH_BOUNDS`, and the `depthBoundsTestEnable` member of `pDepthStencilState` is `VK_TRUE`, the `minDepthBounds` and `maxDepthBounds` members of `pDepthStencilState` must be between `0.0` and `1.0`, inclusive.

- `layout` must be consistent with all shaders specified in `pStages`.

- If neither the `VK_AMD_mixed_attachment_samples` nor the `VK_NV_framebuffer_mixed_samples` extensions are enabled, and if `subpass` uses color and/or depth/stencil attachments, then the `rasterizationSamples` member of `pMultisampleState` must be the same as the sample count for those `subpass` attachments.

- If `subpass` does not use any color and/or depth/stencil attachments, then the `rasterizationSamples` member of `pMultisampleState` must follow the rules for a zero-attachment `subpass`.

- `subpass` must be a valid `subpass` within `renderPass`.

- If the `renderPass` has multiview enabled and `subpass` has more than one bit set in the view mask and `multiviewTessellationShader` is not enabled, then `pStages` must not include tessellation shaders.

- If the `renderPass` has multiview enabled and `subpass` has more than one bit set in the view mask and `multiviewGeometryShader` is not enabled, then `pStages` must not include a geometry shader.

- If the `renderPass` has multiview enabled and `subpass` has more than one bit set in the view mask, shaders in the pipeline must not write to the `Layer` built-in output.

- If the `renderPass` has multiview enabled, then all shaders must not include variables decorated with the `Layer` built-in decoration in their interfaces.

- `flags` must not contain the `VK_PIPELINE_CREATE_DISPATCH_BASE` flag.

- If `pStages` includes a fragment shader stage and an input attachment was referenced by the `VkRenderPassInputAttachmentAspectCreateInfo` at `renderPass` create time, its shader code must not read from any aspect that was not specified in the `aspectMask` of the corresponding `VkInputAttachmentAspectReference` structure.

- The number of resources in `layout` accessible to each shader stage that is used by the pipeline must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageResources`.

- If `pStages` includes a vertex shader stage, `pVertexInputState` must be a valid pointer to a valid `VkPipelineVertexInputStateCreateInfo` structure.

- If `pStages` includes a vertex shader stage, `pInputAssemblyState` must be a valid pointer to a valid `VkPipelineInputAssemblyStateCreateInfo` structure.
• **flags** must not include **VK_PIPELINE_CREATE_LIBRARY_BIT_KHR**

• **flags** must not include **VK_PIPELINE_CREATERAY TRACING_NO_NULL_ANY_HIT_SHADERS_BIT_KHR**

• **flags** must not include **VK_PIPELINECREATERAY TRACING_NO_NULLCLOSEST_HIT_SHADERS_BIT_KHR**

• **flags** must not include **VK_PIPELINECREATERAY TRACING_NO_NULL_MISS_SHADERS_BIT_KHR**

• **flags** must not include **VK_PIPELINECREATERAY TRACING_NO_NULL_INTERSECTION_SHADERS_BIT_KHR**

• **flags** must not include **VK_PIPELINECREATERAY TRACING_SKIP_TRIANGLES_BIT_KHR**

• **flags** must not include **VK_PIPELINECREATERAY TRACING_SKIP_AABBS_BIT_KHR**

Valid Usage (Implicit)

• **sType** must be **VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO**

• **pNext** must be **NULL**

• **flags** must be a valid combination of **VkPipelineCreateFlagBits** values

• **pStages** must be a valid pointer to an array of **stageCount** valid **VkPipelineShaderStageCreateInfo** structures

• **pRasterizationState** must be a valid pointer to a valid **VkPipelineRasterizationStateCreateInfo** structure

• If **pDynamicState** is not **NULL**, **pDynamicState** must be a valid pointer to a valid **VkPipelineDynamicStateCreateInfo** structure

• **layout** must be a valid **VkPipelineLayout** handle

• **renderPass** must be a valid **VkRenderPass** handle

• **stageCount** must be greater than **0**

• Each of **basePipelineHandle**, **layout**, and **renderPass** that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same **VkDevice**

Possible values of the **flags** member of **VkGraphicsPipelineCreateInfo**, **VkRayTracingPipelineCreateInfoKHR**, and **VkComputePipelineCreateInfo**, specifying how a pipeline is created, are:
typedef enum VkPipelineCreateFlagBits {
    VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT = 0x00000001,
    VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT = 0x00000002,
    VK_PIPELINE_CREATE_DERIVATIVE_BIT = 0x00000004,
    VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT = 0x00000008,
    VK_PIPELINE_CREATE_DISPATCH_BASE_BIT = 0x00000010,
    VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_ANY_HIT_SHADERS_BIT_KHR = 0x00004000,
    VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_CLOSEST_HIT_SHADERS_BIT_KHR = 0x00008000,
    VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_MISS_SHADERS_BIT_KHR = 0x00010000,
    VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_INTERSECTION_SHADERS_BIT_KHR = 0x00020000,
    VK_PIPELINE_CREATE_RAY_TRACING_SKIP_TRIANGLES_BIT_KHR = 0x00001000,
    VK_PIPELINE_CREATE_RAY_TRACING_SKIP_AABBS_BIT_KHR = 0x00002000,
    VK_PIPELINE_CREATE_CAPTURE_STATISTICS_BIT_KHR = 0x00000040,
    VK_PIPELINE_CREATE_CAPTURE_INTERNAL_REPRESENTATIONS_BIT_KHR = 0x00000080,
    VK_PIPELINE_CREATE_LIBRARY_BIT_KHR = 0x00000800,
    VK_PIPELINE_CREATE_CAPTURE_INTERNAL_REPRESENTATIONS_BIT_KHR = 0x00000080,
    VK_PIPELINE_CREATE_LIBRARY_BIT_KHR = 0x00000080,
    VK_PIPELINE_CREATE_DISPATCH_BASE = VK_PIPELINE_CREATE_DISPATCH_BASE_BIT,
    VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT_KHR =
    VK_PIPELINE_CREATE_DISPATCH_BASE_KHR = VK_PIPELINE_CREATE_DISPATCH_BASE,
    VK_PIPELINE_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkPipelineCreateFlagBits;

- **VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT** specifies that the created pipeline will not be optimized. Using this flag may reduce the time taken to create the pipeline.

- **VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT** specifies that the pipeline to be created is allowed to be the parent of a pipeline that will be created in a subsequent call to `vkCreateGraphicsPipelines` or `vkCreateComputePipelines`.

- **VK_PIPELINE_CREATE_DERIVATIVE_BIT** specifies that the pipeline to be created will be a child of a previously created parent pipeline.

- **VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT** specifies that any shader input variables decorated as `ViewIndex` will be assigned values as if they were decorated as `DeviceIndex`.

- **VK_PIPELINE_CREATE_DISPATCH_BASE** specifies that a compute pipeline can be used with `vkCmdDispatchBase` with a non-zero base workgroup.

- **VK_PIPELINE_CREATE_CAPTURE_STATISTICS_BIT_KHR** specifies that the shader compiler should capture statistics for the executables produced by the compile process which can later be retrieved by calling `vkGetPipelineExecutableStatisticsKHR`. Enabling this flag must not affect the final compiled pipeline but may disable pipeline caching or otherwise affect pipeline creation time.

- **VK_PIPELINE_CREATE_CAPTURE_INTERNAL_REPRESENTATIONS_BIT_KHR** specifies that the shader compiler should capture the internal representations of executables produced by the compile process which can later be retrieved by calling `vkGetPipelineExecutableInternalRepresentationsKHR`. Enabling this flag must not affect the final compiled pipeline but may disable pipeline caching or otherwise affect pipeline creation time.

- **VK_PIPELINE_CREATE_LIBRARY_BIT_KHR** specifies that the pipeline cannot be used directly, and
instead defines a **pipeline library** that can be combined with other pipelines using the `VkPipelineLibraryCreateInfoKHR` structure. This is available in raytracing pipelines.

- `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_ANY_HIT_SHADERS_BIT_KHR` specifies that an any hit shader will always be present when an any hit shader would be executed.
- `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_CLOSEST_HIT_SHADERS_BIT_KHR` specifies that a closest hit shader will always be present when a closest hit shader would be executed.
- `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_MISS_SHADERS_BIT_KHR` specifies that a miss shader will always be present when a miss shader would be executed.
- `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_INTERSECTION_SHADERS_BIT_KHR` specifies that an intersection shader will always be present when an intersection shader would be executed.
- `VK_PIPELINE_CREATE_RAY_TRACING_SKIP_TRIANGLES_BIT_KHR` specifies that triangle primitives will be skipped during traversal using `OpTraceKHR`.
- `VK_PIPELINE_CREATE_RAY_TRACING_SKIP_AABBS_BIT_KHR` specifies that AABB primitives will be skipped during traversal using `OpTraceKHR`.

It is valid to set both `VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT` and `VK_PIPELINE_CREATE_DERIVATIVE_BIT`. This allows a pipeline to be both a parent and possibly a child in a pipeline hierarchy. See **Pipeline Derivatives** for more information.

```c
typedef VkFlags VkPipelineCreateFlags;
```

`VkPipelineCreateFlags` is a bitmask type for setting a mask of zero or more `VkPipelineCreateFlagBits`.

The `VkPipelineDynamicStateCreateInfo` structure is defined as:

```c
typedef struct VkPipelineDynamicStateCreateInfo {
    VkStructureType                      sType;
    const void*                          pNext;
    VkPipelineDynamicStateCreateFlags    flags;
    uint32_t                             dynamicStateCount;
    const VkDynamicState*                pDynamicStates;
} VkPipelineDynamicStateCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `dynamicStateCount` is the number of elements in the `pDynamicStates` array.
- `pDynamicStates` is a pointer to an array of `VkDynamicState` values specifying which pieces of pipeline state will use the values from dynamic state commands rather than from pipeline state creation info.
Valid Usage

• Each element of \texttt{pDynamicStates} must be unique

Valid Usage (Implicit)

• \texttt{sType} must be $\texttt{VK\_STRUCTURE\_TYPE\_PIPELINE\_DYNAMIC\_STATE\_CREATE\_INFO}$
• \texttt{pNext} must be \texttt{NULL}
• \texttt{flags} must be 0
• If \texttt{dynamicStateCount} is not 0, \texttt{pDynamicStates} must be a valid pointer to an array of \texttt{dynamicStateCount} valid \texttt{VkDynamicState} values

\begin{verbatim}
typedef VkFlags VkPipelineDynamicStateCreateFlags;
\end{verbatim}

\texttt{VkPipelineDynamicStateCreateFlags} is a bitmask type for setting a mask, but is currently reserved for future use.

The source of different pieces of dynamic state is specified by the \texttt{VkPipelineDynamicStateCreateInfo::pDynamicStates} property of the currently active pipeline, each of whose elements must be one of the values:

\begin{verbatim}
typedef enum VkDynamicState {
    VK_DYNAMIC_STATE_VIEWPORT = 0,
    VK_DYNAMIC_STATE_SCISSOR = 1,
    VK_DYNAMIC_STATE_LINE_WIDTH = 2,
    VK_DYNAMIC_STATE_DEPTH_BIAS = 3,
    VK_DYNAMIC_STATE_BLEND_CONSTANTS = 4,
    VK_DYNAMIC_STATE_DEPTH_BOUNDS = 5,
    VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK = 6,
    VK_DYNAMIC_STATE_STENCIL_WRITE_MASK = 7,
    VK_DYNAMIC_STATE_STENCIL_REFERENCE = 8,
    VK_DYNAMIC_STATE_MAX_ENUM = 0x7FFFFFFF
} VkDynamicState;
\end{verbatim}

• \texttt{VK\_DYNAMIC\_STATE\_VIEWPORT} specifies that the \texttt{pViewports} state in \texttt{VkPipelineViewportStateCreateInfo} will be ignored and must be set dynamically with \texttt{vkCmdSetViewport} before any draw commands. The number of viewports used by a pipeline is still specified by the \texttt{viewportCount} member of \texttt{VkPipelineViewportStateCreateInfo}.
• \texttt{VK\_DYNAMIC\_STATE\_SCISSOR} specifies that the \texttt{pScissors} state in \texttt{VkPipelineViewportStateCreateInfo} will be ignored and must be set dynamically with \texttt{vkCmdSetScissor} before any draw commands. The number of scissor rectangles used by a pipeline is still specified by the \texttt{scissorCount} member of \texttt{VkPipelineViewportStateCreateInfo}.
• \texttt{VK\_DYNAMIC\_STATE\_LINE\_WIDTH} specifies that the \texttt{lineWidth} state in
*VkPipelineRasterizationStateCreateInfo* will be ignored and **must** be set dynamically with

*vkCmdSetLineWidth* before any draw commands that generate line primitives for the rasterizer.

- **VK_DYNAMIC_STATE_DEPTH_BIAS** specifies that the `depthBiasConstantFactor`, `depthBiasClamp` and `depthBiasSlopeFactor` states in *VkPipelineRasterizationStateCreateInfo* will be ignored and **must** be set dynamically with `vkCmdSetDepthBias` before any draws are performed with `depthBiasEnable` in *VkPipelineRasterizationStateCreateInfo* set to `VK_TRUE`.

- **VK_DYNAMIC_STATE_BLEND_CONSTANTS** specifies that the `blendConstants` state in *VkPipelineColorBlendStateCreateInfo* will be ignored and **must** be set dynamically with `vkCmdSetBlendConstants` before any draws are performed with a pipeline state with *VkPipelineColorBlendAttachmentState* member `blendEnable` set to `VK_TRUE` and any of the blend functions using a constant blend color.

- **VK_DYNAMIC_STATE_DEPTH_BOUNDS** specifies that the `minDepthBounds` and `maxDepthBounds` states of *VkPipelineDepthStencilStateCreateInfo* will be ignored and **must** be set dynamically with `vkCmdSetDepthBounds` before any draws are performed with a pipeline state with *VkPipelineDepthStencilStateCreateInfo* member `depthBoundsTestEnable` set to `VK_TRUE`.

- **VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK** specifies that the `compareMask` state in *VkPipelineDepthStencilStateCreateInfo* for both `front` and `back` will be ignored and **must** be set dynamically with `vkCmdSetStencilCompareMask` before any draws are performed with a pipeline state with *VkPipelineDepthStencilStateCreateInfo* member `stencilTestEnable` set to `VK_TRUE`.

- **VK_DYNAMIC_STATE_STENCIL_WRITE_MASK** specifies that the `writeMask` state in *VkPipelineDepthStencilStateCreateInfo* for both `front` and `back` will be ignored and **must** be set dynamically with `vkCmdSetStencilWriteMask` before any draws are performed with a pipeline state with *VkPipelineDepthStencilStateCreateInfo* member `stencilTestEnable` set to `VK_TRUE`.

- **VK_DYNAMIC_STATE_STENCIL_REFERENCE** specifies that the `reference` state in *VkPipelineDepthStencilStateCreateInfo* for both `front` and `back` will be ignored and **must** be set dynamically with `vkCmdSetStencilReference` before any draws are performed with a pipeline state with *VkPipelineDepthStencilStateCreateInfo* member `stencilTestEnable` set to `VK_TRUE`.

### 9.2.1. Valid Combinations of Stages for Graphics Pipelines

If tessellation shader stages are omitted, the tessellation shading and fixed-function stages of the pipeline are skipped.

If a geometry shader is omitted, the geometry shading stage is skipped.

If a fragment shader is omitted, fragment color outputs have undefined values, and the fragment depth value is unmodified. This can be useful for depth-only rendering.

Presence of a shader stage in a pipeline is indicated by including a valid *VkPipelineShaderStageCreateInfo* with `module` and `pName` selecting an entry point from a shader module, where that entry point is valid for the stage specified by `stage`.

Presence of some of the fixed-function stages in the pipeline is implicitly derived from enabled shaders and provided state. For example, the fixed-function tessellator is always present when the pipeline has valid Tessellation Control and Tessellation Evaluation shaders.
For example:

- Depth/stencil-only rendering in a subpass with no color attachments
  - Active Pipeline Shader Stages
    - Vertex Shader
  - Required: Fixed-Function Pipeline Stages
    - VkPipelineVertexInputStateCreateInfo
    - VkPipelineInputAssemblyStateCreateInfo
    - VkPipelineViewportStateCreateInfo
    - VkPipelineRasterizationStateCreateInfo
    - VkPipelineMultisampleStateCreateInfo
    - VkPipelineDepthStencilStateCreateInfo

- Color-only rendering in a subpass with no depth/stencil attachment
  - Active Pipeline Shader Stages
    - Vertex Shader
    - Fragment Shader
  - Required: Fixed-Function Pipeline Stages
    - VkPipelineVertexInputStateCreateInfo
    - VkPipelineInputAssemblyStateCreateInfo
    - VkPipelineViewportStateCreateInfo
    - VkPipelineRasterizationStateCreateInfo
    - VkPipelineMultisampleStateCreateInfo
    - VkPipelineColorBlendStateCreateInfo

- Rendering pipeline with tessellation and geometry shaders
  - Active Pipeline Shader Stages
    - Vertex Shader
    - Tessellation Control Shader
    - Tessellation Evaluation Shader
    - Geometry Shader
    - Fragment Shader
  - Required: Fixed-Function Pipeline Stages
    - VkPipelineVertexInputStateCreateInfo
    - VkPipelineInputAssemblyStateCreateInfo
    - VkPipelineTessellationStateCreateInfo
    - VkPipelineViewportStateCreateInfo
    - VkPipelineRasterizationStateCreateInfo
9.3. Pipeline destruction

To destroy a graphics or compute pipeline, call:

```c
void vkDestroyPipeline(
    VkDevice device,  // logical device
    VkPipeline pipeline, // pipeline to destroy
    const VkAllocationCallbacks* pAllocator); // host memory allocation
```

- `device` is the logical device that destroys the pipeline.
- `pipeline` is the handle of the pipeline to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

**Valid Usage**

- All submitted commands that refer to `pipeline` must have completed execution.
- If `VkAllocationCallbacks` were provided when `pipeline` was created, a compatible set of callbacks must be provided here.
- If no `VkAllocationCallbacks` were provided when `pipeline` was created, `pAllocator` must be `NULL`.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle.
- If `pipeline` is not `VK_NULL_HANDLE`, `pipeline` must be a valid `VkPipeline` handle.
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.
- If `pipeline` is a valid handle, it must have been created, allocated, or retrieved from `device`.

**Host Synchronization**

- Host access to `pipeline` must be externally synchronized.
9.4. Multiple Pipeline Creation

Multiple pipelines can be created simultaneously by passing an array of `VkGraphicsPipelineCreateInfo` or `VkComputePipelineCreateInfo` structures into the `vkCreateGraphicsPipelines` and `vkCreateComputePipelines` commands, respectively. Applications can group together similar pipelines to be created in a single call, and implementations are encouraged to look for reuse opportunities within a group-create.

When an application attempts to create many pipelines in a single command, it is possible that some subset may fail creation. In that case, the corresponding entries in the `pPipelines` output array will be filled with `VK_NULL_HANDLE` values. If any pipeline fails creation despite valid arguments (for example, due to out of memory errors), the `VkResult` code returned by `vkCreate*Pipelines` will indicate why. The implementation will attempt to create all pipelines, and only return `VK_NULL_HANDLE` values for those that actually failed.

9.5. Pipeline Derivatives

A pipeline derivative is a child pipeline created from a parent pipeline, where the child and parent are expected to have much commonality. The goal of derivative pipelines is that they be cheaper to create using the parent as a starting point, and that it be more efficient (on either host or device) to switch/bind between children of the same parent.

A derivative pipeline is created by setting the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag in the `Vk*PipelineCreateInfo` structure. If this is set, then exactly one of `basePipelineHandle` or `basePipelineIndex` members of the structure must have a valid handle/index, and specifies the parent pipeline. If `basePipelineHandle` is used, the parent pipeline must have already been created. If `basePipelineIndex` is used, then the parent is being created in the same command. `VK_NULL_HANDLE` acts as the invalid handle for `basePipelineHandle` and -1 is the invalid index for `basePipelineIndex`. If `basePipelineIndex` is used, the base pipeline must appear earlier in the array. The base pipeline must have been created with the `VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT` flag set.

9.6. Pipeline Cache

Pipeline cache objects allow the result of pipeline construction to be reused between pipelines and between runs of an application. Reuse between pipelines is achieved by passing the same pipeline cache object when creating multiple related pipelines. Reuse across runs of an application is achieved by retrieving pipeline cache contents in one run of an application, saving the contents, and using them to preinitialize a pipeline cache on a subsequent run. The contents of the pipeline cache objects are managed by the implementation. Applications can manage the host memory consumed by a pipeline cache object and control the amount of data retrieved from a pipeline cache object.

Pipeline cache objects are represented by `VkPipelineCache` handles:
To create pipeline cache objects, call:

```c
VkResult vkCreatePipelineCache(
    VkDevice                                    device,
    const VkPipelineCacheCreateInfo*            pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkPipelineCache*                            pPipelineCache);
```

- **device** is the logical device that creates the pipeline cache object.
- **pCreateInfo** is a pointer to a `VkPipelineCacheCreateInfo` structure containing initial parameters for the pipeline cache object.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pPipelineCache** is a pointer to a `VkPipelineCache` handle in which the resulting pipeline cache object is returned.

**Note**
Applications can track and manage the total host memory size of a pipeline cache object using the `pAllocator`. Applications can limit the amount of data retrieved from a pipeline cache object in `vkGetPipelineCacheData`. Implementations should not internally limit the total number of entries added to a pipeline cache object or the total host memory consumed.

Once created, a pipeline cache can be passed to the `vkCreateGraphicsPipelines` and `vkCreateComputePipelines` commands. If the pipeline cache passed into these commands is not `VK_NULL_HANDLE`, the implementation will query it for possible reuse opportunities and update it with new content. The use of the pipeline cache object in these commands is internally synchronized, and the same pipeline cache object can be used in multiple threads simultaneously.

**Note**
Implementations should make every effort to limit any critical sections to the actual accesses to the cache, which is expected to be significantly shorter than the duration of the `vkCreateGraphicsPipelines` and `vkCreateComputePipelines` commands.

---

**Valid Usage (Implicit)**

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkPipelineCacheCreateInfo` structure
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pPipelineCache** must be a valid pointer to a `VkPipelineCache` handle
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkPipelineCacheCreateInfo` structure is defined as:

```c
typedef struct VkPipelineCacheCreateInfo {
    VkStructureType           sType;
    const void*               pNext;
    VkPipelineCacheCreateFlags flags;
    size_t                     initialDataSize;
    const void*               pInitialData;
} VkPipelineCacheCreateInfo;
```

• `sType` is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.
• `flags` is reserved for future use.
• `initialDataSize` is the number of bytes in `pInitialData`. If `initialDataSize` is zero, the pipeline cache will initially be empty.
• `pInitialData` is a pointer to previously retrieved pipeline cache data. If the pipeline cache data is incompatible (as defined below) with the device, the pipeline cache will be initially empty. If `initialDataSize` is zero, `pInitialData` is ignored.

Valid Usage

• If `initialDataSize` is not 0, it must be equal to the size of `pInitialData`, as returned by `vkGetPipelineCacheData` when `pInitialData` was originally retrieved.
• If `initialDataSize` is not 0, `pInitialData` must have been retrieved from a previous call to `vkGetPipelineCacheData`.
Valid Usage (Implicit)

• **sType** must be `VK_STRUCTURE_TYPE_PIPELINE_CACHE_CREATE_INFO`
• **pNext** must be `NULL`
• **flags** must be 0
• If `initialDataSize` is not 0, **pInitialData** must be a valid pointer to an array of `initialDataSize` bytes

```
typedef VkFlags VkPipelineCacheCreateFlags;
```

`VkPipelineCacheCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

Pipeline cache objects can be merged using the command:

```
VkResult vkMergePipelineCaches(
    VkDevice device,                
    VkPipelineCache dstCache,      
    uint32_t srcCacheCount,         
    const VkPipelineCache* pSrcCaches);
```

• **device** is the logical device that owns the pipeline cache objects.
• **dstCache** is the handle of the pipeline cache to merge results into.
• **srcCacheCount** is the length of the **pSrcCaches** array.
• **pSrcCaches** is a pointer to an array of pipeline cache handles, which will be merged into **dstCache**. The previous contents of **dstCache** are included after the merge.

*Note*

The details of the merge operation are implementation dependent, but implementations should merge the contents of the specified pipelines and prune duplicate entries.

Valid Usage

• **dstCache** must not appear in the list of source caches
Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `dstCache` must be a valid `VkPipelineCache` handle
- `pSrcCaches` must be a valid pointer to an array of `srcCacheCount` valid `VkPipelineCache` handles
- `srcCacheCount` must be greater than 0
- `dstCache` must have been created, allocated, or retrieved from `device`
- Each element of `pSrcCaches` must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `dstCache` must be externally synchronized

Return Codes

Success
- `VK_SUCCESS`

Failure
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

Data can be retrieved from a pipeline cache object using the command:

```c
VkResult vkGetPipelineCacheData(
    VkDevice device,                              
    VkPipelineCache pipelineCache,               
    size_t* pDataSize,                           
    void* pData);                                
```

- `device` is the logical device that owns the pipeline cache.
- `pipelineCache` is the pipeline cache to retrieve data from.
- `pDataSize` is a pointer to a `size_t` value related to the amount of data in the pipeline cache, as described below.
- `pData` is either `NULL` or a pointer to a buffer.

If `pData` is `NULL`, then the maximum size of the data that can be retrieved from the pipeline cache, in bytes, is returned in `pDataSize`. Otherwise, `pDataSize` must point to a variable set by the user to the size of the buffer, in bytes, pointed to by `pData`, and on return the variable is overwritten with the amount of data actually written to `pData`. 
If pDataSize is less than the maximum size that can be retrieved by the pipeline cache, at most pDataSize bytes will be written to pData, and vkGetPipelineCacheData will return VK_INCOMPLETE. Any data written to pData is valid and can be provided as the pInitialData member of the VkPipelineCacheCreateInfo structure passed to vkCreatePipelineCache.

Two calls to vkGetPipelineCacheData with the same parameters must retrieve the same data unless a command that modifies the contents of the cache is called between them.

Applications can store the data retrieved from the pipeline cache, and use these data, possibly in a future run of the application, to populate new pipeline cache objects. The results of pipeline compiles, however, may depend on the vendor ID, device ID, driver version, and other details of the device. To enable applications to detect when previously retrieved data is incompatible with the device, the initial bytes written to pData must be a header consisting of the following members:

<table>
<thead>
<tr>
<th>Offset</th>
<th>Size</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>length in bytes of the entire pipeline cache header written as a stream of bytes, with the least significant byte first</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>a VkPipelineCacheHeaderVersion value written as a stream of bytes, with the least significant byte first</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>a vendor ID equal to VkPhysicalDeviceProperties::vendorID written as a stream of bytes, with the least significant byte first</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>a device ID equal to VkPhysicalDeviceProperties::deviceID written as a stream of bytes, with the least significant byte first</td>
</tr>
<tr>
<td>16</td>
<td>VK_UUID_SIZE</td>
<td>a pipeline cache ID equal to VkPhysicalDeviceProperties::pipelineCacheUUID</td>
</tr>
</tbody>
</table>

The first four bytes encode the length of the entire pipeline cache header, in bytes. This value includes all fields in the header including the pipeline cache version field and the size of the length field.

The next four bytes encode the pipeline cache version, as described for VkPipelineCacheHeaderVersion. A consumer of the pipeline cache should use the cache version to interpret the remainder of the cache header.

If pDataSize is less than what is necessary to store this header, nothing will be written to pData and zero will be written to pDataSize.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pipelineCache** must be a valid `VkPipelineCache` handle
- **pDataSize** must be a valid pointer to a `size_t` value
- If the value referenced by **pDataSize** is not 0, and **pData** is not NULL, **pData** must be a valid pointer to an array of **pDataSize** bytes
- **pipelineCache** must have been created, allocated, or retrieved from **device**

Return Codes

**Success**
- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

Possible values of the second group of four bytes in the header returned by `vkGetPipelineCacheData`, encoding the pipeline cache version, are:

```c
typedef enum VkPipelineCacheHeaderVersion {
    VK_PIPELINE_CACHE_HEADER_VERSION_ONE = 1,
    VK_PIPELINE_CACHE_HEADER_VERSION_MAX_ENUM = 0x7FFFFFFF
} VkPipelineCacheHeaderVersion;
```

- `VK_PIPELINE_CACHE_HEADER_VERSION_ONE` specifies version one of the pipeline cache.

To destroy a pipeline cache, call:

```c
void vkDestroyPipelineCache(
    VkDevice device, VkPipelineCache pipelineCache,
    const VkAllocationCallbacks* pAllocator);
```

- **device** is the logical device that destroys the pipeline cache object.
- **pipelineCache** is the handle of the pipeline cache to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
Valid Usage

- If `VkAllocationCallbacks` were provided when `pipelineCache` was created, a compatible set of callbacks **must** be provided here.

- If no `VkAllocationCallbacks` were provided when `pipelineCache` was created, `pAllocator` **must** be `NULL`.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle.

- If `pipelineCache` is not `VK_NULL_HANDLE`, `pipelineCache` **must** be a valid `VkPipelineCache` handle.

- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure.

- If `pipelineCache` is a valid handle, it **must** have been created, allocated, or retrieved from `device`.

Host Synchronization

- Host access to `pipelineCache` **must** be externally synchronized.

9.7. Specialization Constants

Specialization constants are a mechanism whereby constants in a SPIR-V module **can** have their constant value specified at the time the `VkPipeline` is created. This allows a SPIR-V module to have constants that **can** be modified while executing an application that uses the Vulkan API.

**Note**

Specialization constants are useful to allow a compute shader to have its local workgroup size changed at runtime by the user, for example.

Each `VkPipelineShaderStageCreateInfo` structure contains a `pSpecializationInfo` member, which **can** be `NULL` to indicate no specialization constants, or point to a `VkSpecializationInfo` structure.

The `VkSpecializationInfo` structure is defined as:

```c
typedef struct VkSpecializationInfo {
    uint32_t                               mapEntryCount;
    const VkSpecializationMapEntry*        pMapEntries;
    size_t                                 dataSize;
    const void*                            pData;
} VkSpecializationInfo;
```
mapEntryCount is the number of entries in the pMapEntries array.

pMapEntries is a pointer to an array of VkSpecializationMapEntry structures which map constant IDs to offsets in pData.

dataSize is the byte size of the pData buffer.

pData contains the actual constant values to specialize with.

pMapEntries is a pointer to a VkSpecializationMapEntry structure.

Valid Usage

• The offset member of each element of pMapEntries must be less than dataSize
• The size member of each element of pMapEntries must be less than or equal to dataSize minus offset

Valid Usage (Implicit)

• If mapEntryCount is not 0, pMapEntries must be a valid pointer to an array of mapEntryCount valid VkSpecializationMapEntry structures
• If dataSize is not 0, pData must be a valid pointer to an array of dataSize bytes

The VkSpecializationMapEntry structure is defined as:

```c
typedef struct VkSpecializationMapEntry {
    uint32_t    constantID;
    uint32_t    offset;
    size_t      size;
} VkSpecializationMapEntry;
```

• constantID is the ID of the specialization constant in SPIR-V.
• offset is the byte offset of the specialization constant value within the supplied data buffer.
• size is the byte size of the specialization constant value within the supplied data buffer.

If a constantID value is not a specialization constant ID used in the shader, that map entry does not affect the behavior of the pipeline.

Valid Usage

• For a constantID specialization constant declared in a shader, size must match the byte size of the constantID. If the specialization constant is of type boolean, size must be the byte size of VkBool32

In human readable SPIR-V:
From the above we have three specialization constants, one for each of the x, y & z elements of the WorkgroupSize vector.

Now to specialize the above via the specialization constants mechanism:

```cpp
const VkSpecializationMapEntry entries[] = {
  { 13, 0 * sizeof(uint32_t), sizeof(uint32_t) },
  { 42, 1 * sizeof(uint32_t), sizeof(uint32_t) },
  { 3, 2 * sizeof(uint32_t), sizeof(uint32_t) }
};

const uint32_t data[] = { 16, 8, 4 }; // our workgroup size is 16x8x4

const VkSpecializationInfo info = {
  3, // mapEntryCount
  entries, // pMapEntries
  3 * sizeof(uint32_t), // dataSize
  data, // pData
};
```

Then when calling `vkCreateComputePipelines`, and passing the `VkSpecializationInfo` we defined as the `pSpecializationInfo` parameter of `VkPipelineShaderStageCreateInfo`, we will create a compute pipeline with the runtime specified local workgroup size.
Another example would be that an application has a SPIR-V module that has some platform-dependent constants they wish to use.

In human readable SPIR-V:

```
OpDecorate %1 SpecId 0  ; decorate our signed 32-bit integer constant
OpDecorate %2 SpecId 12 ; decorate our 32-bit floating-point constant
%i32 = OpTypeInt 32 1   ; declare a signed 32-bit type
%float = OpTypeFloat 32 ; declare a 32-bit floating-point type
%1 = OpSpecConstant %i32 -1 ; some signed 32-bit integer constant
%2 = OpSpecConstant %float 0.5 ; some 32-bit floating-point constant
```

From the above we have two specialization constants, one is a signed 32-bit integer and the second is a 32-bit floating-point.

Now to specialize the above via the specialization constants mechanism:

```
struct SpecializationData {
    int32_t data0;
    float data1;
};

const VkSpecializationMapEntry entries[] =
{
    { 0,           // constantID
       offsetof(SpecializationData, data0), // offset
       sizeof(SpecializationData::data0)   // size
    },
    { 12,          // constantID
       offsetof(SpecializationData, data1), // offset
       sizeof(SpecializationData::data1)   // size
    }
};

SpecializationData data;
data.data0 = -42;    // set the data for the 32-bit integer
data.data1 = 42.0f; // set the data for the 32-bit floating-point

const VkSpecializationInfo info =
{
    2,               // mapEntryCount
    entries,         // pMapEntries
    sizeof(data),    // dataSize
    &data             // pData
};
```

It is legal for a SPIR-V module with specializations to be compiled into a pipeline where no
specialization info was provided. SPIR-V specialization constants contain default values such that if 
a specialization is not provided, the default value will be used. In the examples above, it would be 
valid for an application to only specialize some of the specialization constants within the SPIR-V 
module, and let the other constants use their default values encoded within the OpSpecConstant 
declarations.

9.8. Pipeline Libraries

A pipeline library is a special pipeline that was created using the 
VK_PIPELINE_CREATE_LIBRARY_BIT_KHR and cannot be bound, instead it defines a set of pipeline state 
which can be linked into other pipelines. For ray tracing pipelines this includes shaders and shader 
groups. The application must maintain the lifetime of pipeline libraries based on the pipelines that 
link with it. A pipeline library is considered in-use, as long as one of the linking pipelines is in-use.

This linkage is achieved by using the following structure within the appropriate creation 
mechanisms:

The VkPipelineLibraryCreateInfoKHR structure is defined as:

```c
typedef struct VkPipelineLibraryCreateInfoKHR {
    VkStructureType sType;
    const void* pNext;
    uint32_t libraryCount;
    const VkPipeline* pLibraries;
} VkPipelineLibraryCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **libraryCount** is the number of pipeline libraries in **pLibraries**.
- **pLibraries** is an array of pipeline libraries to use when creating a pipeline.

### Valid Usage

- Each element of **pLibraries** must have been created with 
  VK_PIPELINE_CREATE_LIBRARY_BIT_KHR

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_PIPELINE_LIBRARY_CREATE_INFO_KHR
- **pNext** must be NULL
- If **libraryCount** is not 0, **pLibraries** must be a valid pointer to an array of **libraryCount** 
  valid VkPipeline handles
9.9. Pipeline Binding

Once a pipeline has been created, it can be bound to the command buffer using the command:

```c
void vkCmdBindPipeline(
    VkCommandBuffer                             commandBuffer,
    VkPipelineBindPoint                         pipelineBindPoint,
    VkPipeline                                  pipeline);
```

- `commandBuffer` is the command buffer that the pipeline will be bound to.
- `pipelineBindPoint` is a `VkPipelineBindPoint` value specifying whether to bind to the compute or graphics bind point. Binding one does not disturb the other.
- `pipeline` is the pipeline to be bound.

Once bound, a pipeline binding affects subsequent graphics or compute commands in the command buffer until a different pipeline is bound to the bind point. The pipeline bound to `VK_PIPELINE_BIND_POINT_COMPUTE` controls the behavior of `vkCmdDispatch` and `vkCmdDispatchIndirect`. The pipeline bound to `VK_PIPELINE_BIND_POINT_GRAPHICS` controls the behavior of all drawing commands. The pipeline bound to `VK_PIPELINE_BIND_POINT_RAY_TRACING_KHR` controls the behavior of `vkCmdTraceRaysKHR`. No other commands are affected by the pipeline state.

**Valid Usage**

- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_COMPUTE`, the `VkCommandPool` that `commandBuffer` was allocated from must support compute operations.
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_GRAPHICS`, the `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations.
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_COMPUTE`, `pipeline` must be a compute pipeline.
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_GRAPHICS`, `pipeline` must be a graphics pipeline.
- If the variable multisample rate feature is not supported, `pipeline` is a graphics pipeline, the current subpass has no attachments, and this is not the first call to this function with a graphics pipeline after transitioning to the current subpass, then the sample count specified by this pipeline must match that set in the previous pipeline.
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_RAY_TRACING_KHR`, the `VkCommandPool` that `commandBuffer` was allocated from must support compute operations.
- If `pipelineBindPoint` is `VK_PIPELINE_BIND_POINT_RAY_TRACING_KHR`, the `pipeline` must be a ray tracing pipeline.
- The `pipeline` must not have been created with `VK_PIPELINE_CREATE_LIBRARY_BIT_KHR` set.
Valid Usage (Implicit)

- **commandBuffer** must be a valid *VkCommandBuffer* handle
- **pipelineBindPoint** must be a valid *VkPipelineBindPoint* value
- **pipeline** must be a valid *VkPipeline* handle
- **commandBuffer** must be in the recording state
- The *VkCommandPool* that **commandBuffer** was allocated from must support graphics, or compute operations
- Both of **commandBuffer**, and **pipeline** must have been created, allocated, or retrieved from the same *VkDevice*

Host Synchronization

- Host access to **commandBuffer** must be externally synchronized
- Host access to the *VkCommandPool* that **commandBuffer** was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

Possible values of *vkCmdBindPipeline::pipelineBindPoint*, specifying the bind point of a pipeline object, are:

```c
typedef enum VkPipelineBindPoint {
    VK_PIPELINE_BIND_POINT_GRAPHICS = 0,
    VK_PIPELINE_BIND_POINT_COMPUTE = 1,
    VK_PIPELINE_BIND_POINT_RAY_TRACING_KHR = 1000165000,
    VK_PIPELINE_BIND_POINT_MAX_ENUM = 0x7FFFFFFF
} VkPipelineBindPoint;
```

- **VK_PIPELINE_BIND_POINT_COMPUTE** specifies binding as a compute pipeline.
- **VK_PIPELINE_BIND_POINT_GRAPHICS** specifies binding as a graphics pipeline.
- **VK_PIPELINE_BIND_POINT_RAY_TRACING_KHR** specifies binding as a ray tracing pipeline.
9.10. Dynamic State

When a pipeline object is bound, any pipeline object state that is not specified as dynamic is applied to the command buffer state. Pipeline object state that is specified as dynamic is not applied to the command buffer state at this time. Instead, dynamic state can be modified at any time and persists for the lifetime of the command buffer, or until modified by another dynamic state setting command or another pipeline bind.

When a pipeline object is bound, the following applies to each state parameter:

- If the state is not specified as dynamic in the new pipeline object, then that command buffer state is overwritten by the state in the new pipeline object. Before any draw or dispatch call with this pipeline there must not have been any call to any of the corresponding dynamic state setting commands after this pipeline was bound.

- If the state is specified as dynamic in the new pipeline object, then that command buffer state is not disturbed. Before any draw or dispatch call with this pipeline there must have been at least one call to each of the corresponding dynamic state setting commands since the command buffer recording was begun, or the last bound pipeline object with that state specified as static, whichever was the latter.

Dynamic state that does not affect the result of operations can be left undefined.

Note

For example, if blending is disabled by the pipeline object state then the dynamic color blend constants do not need to be specified in the command buffer, even if this state is specified as dynamic in the pipeline object.

9.11. Pipeline Shader Information

When a pipeline is created, its state and shaders are compiled into zero or more device-specific executables, which are used when executing commands against that pipeline. To query the properties of these executables, call:

```c
VkResult vkGetPipelineExecutablePropertiesKHR(
    VkDevice device, const VkPipelineInfoKHR* pPipelineInfo,
    uint32_t* pExecutableCount, VkPipelineExecutablePropertiesKHR* pProperties);
```

- `device` is the device that created the pipeline.
- `pPipelineInfo` describes the pipeline being queried.
- `pExecutableCount` is a pointer to an integer related to the number of pipeline executables available or queried, as described below.
- `pProperties` is either `NULL` or a pointer to an array of `VkPipelineExecutablePropertiesKHR` structures.
If \( p\text{Properties} \) is null, then the number of executables associated with the pipeline is returned in \( p\text{ExecutableCount} \). Otherwise, \( p\text{ExecutableCount} \) must point to a variable set by the user to the number of elements in the \( p\text{Properties} \) array, and on return the variable is overwritten with the number of structures actually written to \( p\text{Properties} \). If \( p\text{ExecutableCount} \) is less than the number of executables associated with the pipeline, at most \( p\text{ExecutableCount} \) structures will be written and \( \text{vkGetPipelineExecutablePropertiesKHR} \) will return \( \text{VK_INCOMPLETE} \).

### Valid Usage

- \( \text{pipelineExecutableInfo} \) must be enabled.
- \( \text{pipeline} \) member of \( p\text{PipelineInfo} \) must have been created with \( \text{device} \).

### Valid Usage (Implicit)

- \( \text{device} \) must be a valid \( \text{VkDevice} \) handle
- \( p\text{PipelineInfo} \) must be a valid pointer to a valid \( \text{VkPipelineInfoKHR} \) structure
- \( p\text{ExecutableCount} \) must be a valid pointer to a \( \text{uint32_t} \) value
- If the value referenced by \( p\text{ExecutableCount} \) is not 0, and \( p\text{Properties} \) is not null, \( p\text{Properties} \) must be a valid pointer to an array of \( p\text{ExecutableCount} \) \( \text{VkPipelineExecutablePropertiesKHR} \) structures

### Return Codes

**Success**

- \( \text{VK_SUCCESS} \)
- \( \text{VK_INCOMPLETE} \)

**Failure**

- \( \text{VK_ERROR_OUT_OF_HOST_MEMORY} \)
- \( \text{VK_ERROR_OUT_OF_DEVICE_MEMORY} \)

The \( \text{VkPipelineInfoKHR} \) structure is defined as:

```c
typedef struct VkPipelineInfoKHR {
    VkStructureType    sType;
    const void*        pNext;
    VkPipeline         pipeline;
} VkPipelineInfoKHR;
```

- \( \text{sType} \) is the type of this structure.
- \( \text{pNext} \) is null or a pointer to an extension-specific structure.
- \( \text{pipeline} \) is a \( \text{VkPipeline} \) handle.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PIPELINE_INFO_KHR`
- **pNext** must be `NULL`
- **pipeline** must be a valid `VkPipeline` handle

The `VkPipelineExecutablePropertiesKHR` structure is defined as:

```c
typedef struct VkPipelineExecutablePropertiesKHR {
    VkStructureType sType;
    void* pNext;
    VkShaderStageFlags stages;
    char name[VK_MAX_DESCRIPTION_SIZE];
    char description[VK_MAX_DESCRIPTION_SIZE];
    uint32_t subgroupSize;
} VkPipelineExecutablePropertiesKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **stages** is a bitmask of `VkShaderStageFlagBits` indicating which shader stages (if any) were principally used as inputs to compile this pipeline executable.
- **name** is an array of `VK_MAX_DESCRIPTION_SIZE` `char` containing a null-terminated UTF-8 string which is a short human readable name for this executable.
- **description** is an array of `VK_MAX_DESCRIPTION_SIZE` `char` containing a null-terminated UTF-8 string which is a human readable description for this executable.
- **subgroupSize** is the subgroup size with which this executable is dispatched.

The **stages** field may be zero or it may contain one or more bits describing the stages principally used to compile this pipeline. Not all implementations have a 1:1 mapping between shader stages and pipeline executables and some implementations may reduce a given shader stage to fixed function hardware programming such that no executable is available. No guarantees are provided about the mapping between shader stages and pipeline executables and **stages should** be considered a best effort hint. Because the application cannot rely on the **stages** field to provide an exact description, **name** and **description** provide a human readable name and description which more accurately describes the given pipeline executable.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_PROPERTIES_KHR`
- **pNext** must be `NULL`

Each pipeline executable may have a set of statistics associated with it that are generated by the
pipeline compilation process. These statistics may include things such as instruction counts, amount of spilling (if any), maximum number of simultaneous threads, or anything else which may aid developers in evaluating the expected performance of a shader. To query the compile-time statistics associated with a pipeline executable, call:

```c
VkResult vkGetPipelineExecutableStatisticsKHR(
    VkDevice                                    device,
    const VkPipelineExecutableInfoKHR*          pExecutableInfo,
    uint32_t*                                   pStatisticCount,
    VkPipelineExecutableStatisticKHR*           pStatistics);
```

- `device` is the device that created the pipeline.
- `pExecutableInfo` describes the pipeline executable being queried.
- `pStatisticCount` is a pointer to an integer related to the number of statistics available or queried, as described below.
- `pStatistics` is either NULL or a pointer to an array of `VkPipelineExecutableStatisticKHR` structures.

If `pStatistics` is NULL, then the number of statistics associated with the pipeline executable is returned in `pStatisticCount`. Otherwise, `pStatisticCount` must point to a variable set by the user to the number of elements in the `pStatistics` array, and on return the variable is overwritten with the number of structures actually written to `pStatistics`. If `pStatisticCount` is less than the number of statistics associated with the pipeline executable, at most `pStatisticCount` structures will be written and `vkGetPipelineExecutableStatisticsKHR` will return `VK_INCOMPLETE`.

### Valid Usage

- `pipelineExecutableInfo` must be enabled.
- `pipeline` member of `pExecutableInfo` must have been created with `device`.
- `pipeline` member of `pExecutableInfo` must have been created with `VK_PIPELINE_CREATE_CAPTURE_STATISTICS_BIT_KHR` set in the `flags` field of `VkGraphicsPipelineCreateInfo` or `VkComputePipelineCreateInfo`.

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pExecutableInfo` must be a valid pointer to a valid `VkPipelineExecutableInfoKHR` structure
- `pStatisticCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pStatisticCount` is not 0, and `pStatistics` is not NULL, `pStatistics` must be a valid pointer to an array of `pStatisticCount` `VkPipelineExecutableStatisticKHR` structures
Return Codes

Success
- VK_SUCCESS
- VK_INCOMPLETE

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkPipelineExecutableInfoKHR structure is defined as:

```c
typedef struct VkPipelineExecutableInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkPipeline pipeline;
    uint32_t executableIndex;
} VkPipelineExecutableInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `pipeline` is the pipeline to query.
- `executableIndex` is the index of the executable to query in the array of executable properties returned by `vkGetPipelineExecutablePropertiesKHR`.

Valid Usage

- `executableIndex` must be less than the number of executables associated with `pipeline` as returned in the `pExecutableCount` parameter of `vkGetPipelineExecutablePropertiesKHR`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_INFO_KHR`
- `pNext` must be `NULL`
- `pipeline` must be a valid `VkPipeline` handle

The VkPipelineExecutableStatisticKHR structure is defined as:
typedef struct VkPipelineExecutableStatisticKHR {
    VkStructureType sType;
    void* pNext;
    char name[VK_MAX_DESCRIPTION_SIZE];
    char description[VK_MAX_DESCRIPTION_SIZE];
    VkPipelineExecutableStatisticFormatKHR format;
    VkPipelineExecutableStatisticValueKHR value;
} VkPipelineExecutableStatisticKHR;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **name** is an array of VK_MAX_DESCRIPTION_SIZE char containing a null-terminated UTF-8 string which is a short human readable name for this statistic.
- **description** is an array of VK_MAX_DESCRIPTION_SIZE char containing a null-terminated UTF-8 string which is a human readable description for this statistic.
- **format** is a VkPipelineExecutableStatisticFormatKHR value specifying the format of the data found in **value**.
- **value** is the value of this statistic.

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_STATISTIC_KHR
- **pNext** must be NULL

The VkPipelineExecutableStatisticFormatKHR enum is defined as:

typedef enum VkPipelineExecutableStatisticFormatKHR {
    VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_BOOL32_KHR = 0,
    VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_INT64_KHR = 1,
    VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_UINT64_KHR = 2,
    VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_FLOAT64_KHR = 3,
    VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_MAX_ENUM_KHR = 0x7FFFFFFF
} VkPipelineExecutableStatisticFormatKHR;

- **VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_BOOL32_KHR** specifies that the statistic is returned as a 32-bit boolean value which must be either VK_TRUE or VK_FALSE and should be read from the b32 field of VkPipelineExecutableStatisticValueKHR.
- **VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_INT64_KHR** specifies that the statistic is returned as a signed 64-bit integer and should be read from the i64 field of VkPipelineExecutableStatisticValueKHR.
- **VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_UINT64_KHR** specifies that the statistic is returned as an unsigned 64-bit integer and should be read from the u64 field of VkPipelineExecutableStatisticValueKHR.
VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_FLOAT64_KHR specifies that the statistic is returned as a 64-bit floating-point value and should be read from the f64 field of VkPipelineExecutableStatisticValueKHR.

The VkPipelineExecutableStatisticValueKHR union is defined as:

```c
typedef union VkPipelineExecutableStatisticValueKHR {
    VkBool32 b32;
    int64_t i64;
    uint64_t u64;
    double f64;
} VkPipelineExecutableStatisticValueKHR;
```

- b32 is the 32-bit boolean value if the VkPipelineExecutableStatisticFormatKHR is VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_BOOL32_KHR.
- i64 is the signed 64-bit integer value if the VkPipelineExecutableStatisticFormatKHR is VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_INT64_KHR.
- u64 is the unsigned 64-bit integer value if the VkPipelineExecutableStatisticFormatKHR is VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_UINT64_KHR.
- f64 is the 64-bit floating-point value if the VkPipelineExecutableStatisticFormatKHR is VK_PIPELINE_EXECUTABLE_STATISTIC_FORMAT_FLOAT64_KHR.

Each pipeline executable may have one or more text or binary internal representations associated with it which are generated as part of the compile process. These may include the final shader assembly, a binary form of the compiled shader, or the shader compiler's internal representation at any number of intermediate compile steps. To query the internal representations associated with a pipeline executable, call:

```c
VkResult vkGetPipelineExecutableInternalRepresentationsKHR(
    VkDevice                      device,  
    const VkPipelineExecutableInfoKHR* pExecutableInfo,  
    uint32_t*                      pInternalRepresentationCount,  
    VkPipelineExecutableInternalRepresentationKHR* pInternalRepresentations);
```

- device is the device that created the pipeline.
- pExecutableInfo describes the pipeline executable being queried.
- pInternalRepresentationCount is a pointer to an integer related to the number of internal representations available or queried, as described below.
- pInternalRepresentations is either NULL or a pointer to an array of VkPipelineExecutableInternalRepresentationKHR structures.

If pInternalRepresentations is NULL, then the number of internal representations associated with the pipeline executable is returned in pInternalRepresentationCount. Otherwise, pInternalRepresentationCount must point to a variable set by the user to the number of elements in the pInternalRepresentations array, and on return the variable is overwritten with the number of
structures actually written to `pInternalRepresentations`. If `pInternalRepresentationCount` is less than the number of internal representations associated with the pipeline executable, at most `pInternalRepresentationCount` structures will be written and `vkGetPipelineExecutableInternalRepresentationsKHR` will return `VK_INCOMPLETE`.

While the details of the internal representations remain implementation dependent, the implementation should order the internal representations in the order in which they occur in the compile pipeline with the final shader assembly (if any) last.

**Valid Usage**

- `pipelineExecutableInfo` must be enabled.
- `pipeline` member of `pExecutableInfo` must have been created with `device`.
- `pipeline` member of `pExecutableInfo` must have been created with `VK_PIPELINE_CREATE_CAPTURE_INTERNAL_REPRESENTATIONS_BIT_KHR` set in the `flags` field of `VkGraphicsPipelineCreateInfo` or `VkComputePipelineCreateInfo`.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `pExecutableInfo` must be a valid pointer to a valid `VkPipelineExecutableInfoKHR` structure
- `pInternalRepresentationCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pInternalRepresentationCount` is not 0, and `pInternalRepresentations` is not NULL, `pInternalRepresentations` must be a valid pointer to an array of `pInternalRepresentationCount` `VkPipelineExecutableInternalRepresentationKHR` structures

**Return Codes**

**Success**

- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkPipelineExecutableInternalRepresentationKHR` structure is defined as:
typedef struct VkPipelineExecutableInternalRepresentationKHR {
  VkStructureType       sType;
  void*                  pNext;
  char                   name[VK_MAX_DESCRIPTION_SIZE];
  char                   description[VK_MAX_DESCRIPTION_SIZE];
  VkBool32               isText;
  size_t                 dataSize;
  void*                  pData;
} VkPipelineExecutableInternalRepresentationKHR;

• sType is the type of this structure.
•pNext is NULL or a pointer to an extension-specific structure.
•name is an array of VK_MAX_DESCRIPTION_SIZE char containing a null-terminated UTF-8 string which is a short human readable name for this internal representation.
•description is an array of VK_MAX_DESCRIPTION_SIZE char containing a null-terminated UTF-8 string which is a human readable description for this internal representation.
•isText specifies whether the returned data is text or opaque data. If isText is VK_TRUE then the data returned in pData is text and is guaranteed to be a null-terminated UTF-8 string.
•dataSize is an integer related to the size, in bytes, of the internal representation data, as described below.
•pData is either NULL or a pointer to an block of data into which the implementation will write the textual form of the internal representation.

If pData is NULL, then the size, in bytes, of the internal representation data is returned in dataSize. Otherwise, dataSize must be the size of the buffer, in bytes, pointed to by pData and on return dataSize is overwritten with the number of bytes of data actually written to pData including any trailing null character. If dataSize is less than the size, in bytes, of the internal representation data, at most dataSize bytes of data will be written to pData and vkGetPipelineExecutableInternalRepresentationsKHR will return VK_INCOMPLETE. If isText is VK_TRUE and pData is not NULL and dataSize is not zero, the last byte written to pData will be a null character.

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_INTERNAL_REPRESENTATION_KHR
• pNext must be NULL

9.12. Ray Tracing Pipeline

Ray tracing pipelines consist of multiple shader stages, fixed-function traversal stages, and a pipeline layout.

To create ray tracing pipelines, call:
VkResult vkCreateRayTracingPipelinesKHR(
    VkDevice                                    device,
    VkPipelineCache                             pipelineCache,
    uint32_t                                    createInfoCount,
    const VkRayTracingPipelineCreateInfoKHR*    pCreateInfos,
    const VkAllocationCallbacks*                pAllocator,
    VkPipeline*                                 pPipelines);

- **device** is the logical device that creates the ray tracing pipelines.
- **pipelineCache** is either VK_NULL_HANDLE, indicating that pipeline caching is disabled, or the handle of a valid pipeline cache object, in which case use of that cache is enabled for the duration of the command.
- **createInfoCount** is the length of the pCreateInfos and pPipelines arrays.
- **pCreateInfos** is a pointer to an array of VkRayTracingPipelineCreateInfoKHR structures.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pPipelines** is a pointer to an array in which the resulting ray tracing pipeline objects are returned.

The VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS error is returned if the implementation is unable to re-use the shader group handles provided in VkRayTracingShaderGroupCreateInfoKHR → pShaderGroupCaptureReplayHandle when VkPhysicalDeviceRayTracingFeaturesKHR → rayTracingShaderGroupHandleCaptureReplay is enabled.

### Valid Usage

- If the **flags** member of any element of pCreateInfos contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, and the **basePipelineIndex** member of that same element is not -1, **basePipelineIndex must be** less than the index into pCreateInfos that corresponds to that element

- If the **flags** member of any element of pCreateInfos contains the VK_PIPELINE_CREATE_DERIVATIVE_BIT flag, the base pipeline **must have** been created with the VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT flag set

- The **rayTracing** feature **must be** enabled
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- If `pipelineCache` is not `VK_NULL_HANDLE`, `pipelineCache` must be a valid `VkPipelineCache` handle
- `pCreateInfos` must be a valid pointer to an array of `createInfoCount` valid `VkRayTracingPipelineCreateInfoKHR` structures
- If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- `pPipelines` must be a valid pointer to an array of `createInfoCount` `VkPipeline` handles
- `createInfoCount` must be greater than 0
- If `pipelineCache` is a valid handle, it must have been created, allocated, or retrieved from `device`

Return Codes

**Success**
- `VK_SUCCESS`
- `VK_OPERATION_DEFERRED_KHR`
- `VK_OPERATION_NOT_DEFERRED_KHR`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS`

The `VkRayTracingPipelineCreateInfoKHR` structure is defined as:

```c
typedef struct VkRayTracingPipelineCreateInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkPipelineCreateFlags flags;
    uint32_t stageCount;
    const VkPipelineShaderStageCreateInfo* pStages;
    uint32_t groupCount;
    const VkRayTracingShaderGroupCreateInfoKHR* pGroups;
    uint32_t maxRecursionDepth;
    VkPipelineLibraryCreateInfoKHR libraries;
    const VkRayTracingPipelineInterfaceCreateInfoKHR* pLibraryInterface;
    VkPipelineLayout layout;
    VkPipeline basePipelineHandle;
    int32_t basePipelineIndex;
} VkRayTracingPipelineCreateInfoKHR;
```
• **sType** is the type of this structure.

• **pNext** is NULL or a pointer to an extension-specific structure.

• **flags** is a bitmask of VkPipelineCreateFlagBits specifying how the pipeline will be generated.

• **stageCount** is the number of entries in the **pStages** array.

• **pStages** is a pointer to an array of stageCount VkPipelineShaderStageCreateInfo structures describing the set of the shader stages to be included in the ray tracing pipeline.

• **groupCount** is the number of entries in the **pGroups** array.

• **pGroups** is a pointer to an array of groupCount VkRayTracingShaderGroupCreateInfoKHR structures describing the set of the shader stages to be included in each shader group in the ray tracing pipeline.

• **maxRecursionDepth** is the maximum recursion depth of shaders executed by this pipeline.

• **libraries** is a VkPipelineLibraryCreateInfoKHR structure defining pipeline libraries to include.

• **pLibraryInterface** is a pointer to a VkRayTracingPipelineInterfaceCreateInfoKHR structure defining additional information when using pipeline libraries.

• **layout** is the description of binding locations used by both the pipeline and descriptor sets used with the pipeline.

• **basePipelineHandle** is a pipeline to derive from.

• **basePipelineIndex** is an index into the **pCreateInfos** parameter to use as a pipeline to derive from.

The parameters basePipelineHandle and basePipelineIndex are described in more detail in Pipeline Derivatives.

When VK_PIPELINE_CREATE_LIBRARY_BIT_KHR is specified, this pipeline defines a pipeline library which cannot be bound as a ray tracing pipeline directly. Instead, pipeline libraries define common shaders and shader groups which can be included in future pipeline creation.

If pipeline libraries are included in **libraries**, shaders defined in those libraries are treated as if they were defined as additional entries in **pStages**, appended in the order they appear in the **pLibraries** array and in the **pStages** array when those libraries were defined.

When referencing shader groups in order to obtain a shader group handle, groups defined in those libraries are treated as if they were defined as additional entries in **pGroups**, appended in the order they appear in the **pLibraries** array and in the **pGroups** array when those libraries were defined. The shaders these groups reference are set when the pipeline library is created, referencing those specified in the pipeline library, not in the pipeline that includes it.

If the VkDeferredOperationInfoKHR structure is included in the **pNext** chain of VkRayTracingPipelineCreateInfoKHR, the operation of this pipeline creation is deferred, as defined in the Deferred Host Operations chapter.
Valid Usage

- If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineIndex` is `-1`, `basePipelineHandle` must be a valid handle to a ray tracing `VkPipeline`.
- If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineHandle` is `VK_NULL_HANDLE`, `basePipelineIndex` must be a valid index into the calling command's `pCreateInfos` parameter.
- If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineIndex` is not `-1`, `basePipelineHandle` must be `VK_NULL_HANDLE`.
- If `flags` contains the `VK_PIPELINE_CREATE_DERIVATIVE_BIT` flag, and `basePipelineHandle` is not `VK_NULL_HANDLE`, `basePipelineIndex` must be `-1`.
- The `stage` member of at least one element of `pStages` must be `VK_SHADER_STAGE_RAYGEN_BIT_KHR`.
- The shader code for the entry points identified by `pStages`, and the rest of the state identified by this structure must adhere to the pipeline linking rules described in the Shader Interfaces chapter.
- `layout` must be consistent with all shaders specified in `pStages`.
- The number of resources in `layout` accessible to each shader stage that is used by the pipeline must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageResources`.
- `maxRecursionDepth` must be less than or equal to `VkPhysicalDeviceRayTracingPropertiesKHR::maxRecursionDepth`.
- If `flags` includes `VK_PIPELINE_CREATE_LIBRARY_BIT_KHR`, `pLibraryInterface` must not be NULL.
- If the `libraryCount` member of `libraries` is greater than 0, `pLibraryInterface` must not be NULL.
- Each element of the `pLibraries` member of `libraries` must have been created with the value of `maxRecursionDepth` equal to that in this pipeline.
- Each element of the `pLibraries` member of `libraries` must have been created with a `layout` that is compatible with the `layout` in this pipeline.
- Each element of the `pLibraries` member of `libraries` must have been created with values of the `maxPayloadSize`, `maxAttributeSize`, and `maxCallableSize` members of `pLibraryInterface` equal to those in this pipeline.
- If `flags` includes `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_ANY_HIT_SHADERS_BIT_KHR`, for any element of `pGroups` with a type of `VK_RAY_TRACING_SHADER_GROUP_TYPE_TRIANGLES_HIT_GROUP_KHR` or `VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR`, the anyHitShader of that element must not be `VK_SHADER_UNUSED_KHR`.
- If `flags` includes `VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_CLOSEST_HIT_SHADERS_BIT_KHR`, for any element of `pGroups` with a type of `VK_RAY_TRACING_SHADER_GROUP_TYPE_TRIANGLES_HIT_GROUP_KHR` or `VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR`, the closestHitShader of that element must not be `VK_SHADER_UNUSED_KHR`. 

364 | Chapter 9. Pipelines
• If the `rayTracingPrimitiveCulling` feature is not enabled, `flags` **must** not include `VK_PIPELINE_CREATE_RAY_TRACING_SKIP_AABBS_BIT_KHR`

• If the `rayTracingPrimitiveCulling` feature is not enabled, `flags` **must** not include `VK_PIPELINE_CREATE_RAY_TRACING_SKIP_TRIANGLES_BIT_KHR`

• If `libraries.pname.libraryCount` is zero, then `stageCount` **must** not be zero

• If `libraries.pname.libraryCount` is zero, then `groupCount` **must** not be zero

---

**Valid Usage (Implicit)**

• **sType** **must** be `VK_STRUCTURE_TYPE_RAY_TRACING_PIPELINE_CREATE_INFO_KHR`

• **pNext** **must** be `NULL` or a pointer to a valid instance of `VkDeferredOperationInfoKHR`

• The `sType` value of each struct in the `pNext` chain **must** be unique

• **flags** **must** be a valid combination of `VkPipelineCreateFlagBits` values

• If `stageCount` is not 0, `pStages` **must** be a valid pointer to an array of `stageCount` valid `VkPipelineShaderStageCreateInfo` structures

• If `groupCount` is not 0, `pGroups` **must** be a valid pointer to an array of `groupCount` valid `VkRayTracingShaderGroupCreateInfoKHR` structures

• **libraries** **must** be a valid `VkPipelineLibraryCreateInfoKHR` structure

• If `pLibraryInterface` is not `NULL`, `pLibraryInterface` **must** be a valid pointer to a valid `VkRayTracingPipelineInterfaceCreateInfoKHR` structure

• **layout** **must** be a valid `VkPipelineLayout` handle

• Both of `basePipelineHandle`, and `layout` that are valid handles of non-ignored parameters **must** have been created, allocated, or retrieved from the same `VkDevice`

The `VkRayTracingShaderGroupCreateInfoKHR` structure is defined as:

```c
typedef struct VkRayTracingShaderGroupCreateInfoKHR {
    VkStructureType                   sType;
    const void*                       pNext;
    VkRayTracingShaderGroupTypeKHR    type;
    uint32_t                          generalShader;
    uint32_t                          closestHitShader;
    uint32_t                          anyHitShader;
    uint32_t                          intersectionShader;
    const void*                       pShaderGroupCaptureReplayHandle;
} VkRayTracingShaderGroupCreateInfoKHR;
```

• **sType** is the type of this structure.

• **pNext** is `NULL` or a pointer to an extension-specific structure.

• **type** is the type of hit group specified in this structure.

• **generalShader** is the index of the ray generation, miss, or callable shader from
**VkRayTracingPipelineCreateInfoKHR::pStages** in the group if the shader group has *type* of
**VK_RAY_TRACING_SHADER_GROUP_TYPE_GENERAL_KHR**, and **VK_SHADER_UNUSED_KHR** otherwise.

- **closestHitShader** is the optional index of the closest hit shader from
**VkRayTracingPipelineCreateInfoKHR::pStages** in the group if the shader group has *type* of
**VK_RAY_TRACING_SHADER_GROUP_TYPE_TRIANGLES_HIT_GROUP_KHR** or
**VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR**, and **VK_SHADER_UNUSED_KHR** otherwise.

- **anyHitShader** is the optional index of the any-hit shader from
**VkRayTracingPipelineCreateInfoKHR::pStages** in the group if the shader group has *type* of
**VK_RAY_TRACING_SHADER_GROUP_TYPE_TRIANGLES_HIT_GROUP_KHR** or
**VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR**, and **VK_SHADER_UNUSED_KHR** otherwise.

- **intersectionShader** is the index of the intersection shader from
**VkRayTracingPipelineCreateInfoKHR::pStages** in the group if the shader group has *type* of
**VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR**, and **VK_SHADER_UNUSED_KHR** otherwise.

- **pShaderGroupCaptureReplayHandle** is an optional pointer to replay information for this shader group. Ignored if **VkPhysicalDeviceRayTracingFeaturesKHR::rayTracingShaderGroupHandleCaptureReplay** is **VK_FALSE**.
Valid Usage

- If `type` is `VK_RAY_TRACING_SHADER_GROUP_TYPE_GENERAL_KHR` then `generalShader` must be a valid index into `VkRayTracingPipelineCreateInfoKHR::pStages` referring to a shader of `VK_SHADER_STAGE_RAYGEN_BIT_KHR`, `VK_SHADER_STAGE_MISS_BIT_KHR`, or `VK_SHADER_STAGE_CALLABLE_BIT_KHR`.

- If `type` is `VK_RAY_TRACING_SHADER_GROUP_TYPE_GENERAL_KHR` then `closestHitShader`, `anyHitShader`, and `intersectionShader` must be `VK_SHADER_UNUSED_KHR`.

- If `type` is `VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR` then `intersectionShader` must be a valid index into `VkRayTracingPipelineCreateInfoKHR::pStages` referring to a shader of `VK_SHADER_STAGE_INTERSECTION_BIT_KHR`.

- If `type` is `VK_RAY_TRACING_SHADER_GROUP_TYPE_TRIANGLES_HIT_GROUP_KHR` then `intersectionShader` must be `VK_SHADER_UNUSED_KHR`.

- If `closestHitShader` must be either `VK_SHADER_UNUSED_KHR` or a valid index into `VkRayTracingPipelineCreateInfoKHR::pStages` referring to a shader of `VK_SHADER_STAGE_CLOSEST_HIT_BIT_KHR`.

- If `anyHitShader` must be either `VK_SHADER_UNUSED_KHR` or a valid index into `VkRayTracingPipelineCreateInfoKHR::pStages` referring to a shader of `VK_SHADER_STAGE_ANY_HIT_BIT_KHR`.

- If `VkPhysicalDeviceRayTracingFeaturesKHR::rayTracingShaderGroupHandleCaptureReplayMixed` is `VK_FALSE` then `pShaderGroupCaptureReplayHandle` must not be provided if it has not been provided on a previous call to ray tracing pipeline creation.

- If `VkPhysicalDeviceRayTracingFeaturesKHR::rayTracingShaderGroupHandleCaptureReplayMixed` is `VK_FALSE` then the caller must guarantee that no ray tracing pipeline creation commands with `pShaderGroupCaptureReplayHandle` provided execute simultaneously with ray tracing pipeline creation commands without `pShaderGroupCaptureReplayHandle` provided.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_RAY_TRACING_SHADER_GROUP_CREATE_INFO_KHR`.

- `pNext` must be `NULL`.

- `type` must be a valid `VkRayTracingShaderGroupTypeKHR` value.

Possible values of `type` in `VkRayTracingShaderGroupCreateInfoKHR` are:
typedef enum VkRayTracingShaderGroupTypeKHR {
    VK_RAY_TRACING_SHADER_GROUP_TYPE_GENERAL_KHR = 0,
    VK_RAY_TRACING_SHADER_GROUP_TYPE_TRIANGLES_HIT_GROUP_KHR = 1,
    VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR = 2,
    VK_RAY_TRACING_SHADER_GROUP_TYPE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkRayTracingShaderGroupTypeKHR;

- **VK_RAY_TRACING_SHADER_GROUP_TYPE_GENERAL_KHR** indicates a shader group with a single
  VK_SHADER_STAGE_RAYGEN_BIT_KHR, VK_SHADER_STAGE_MISS_BIT_KHR, or
  VK_SHADER_STAGE_CALLABLE_BIT_KHR shader in it.
- **VK_RAY_TRACING_SHADER_GROUP_TYPE_TRIANGLES_HIT_GROUP_KHR** specifies a shader group that only
  hits triangles and **must** not contain an intersection shader, only closest hit and any-hit shaders.
- **VK_RAY_TRACING_SHADER_GROUP_TYPE_PROCEDURAL_HIT_GROUP_KHR** specifies a shader group that only
  intersects with custom geometry and **must** contain an intersection shader and **may** contain
  closest hit and any-hit shaders.

**Note**

For current group types, the hit group type could be inferred from the presence or
absence of the intersection shader, but we provide the type explicitly for future hit
groups that do not have that property.

The **VkRayTracingPipelineInterfaceCreateInfoKHR** structure is defined as:

```c
typedef struct VkRayTracingPipelineInterfaceCreateInfoKHR {
    VkStructureType          sType;
    const void*              pNext;
    uint32_t                 maxPayloadSize;
    uint32_t                 maxAttributeSize;
    uint32_t                 maxCallableSize;
} VkRayTracingPipelineInterfaceCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **maxPayloadSize** is the maximum payload size in bytes used by any shader in the pipeline.
- **maxAttributeSize** is the maximum attribute structure size in bytes used by any shader in the
  pipeline.
- **maxCallableSize** is the maximum callable data size in bytes used by any shader in the pipeline.

**maxPayloadSize** is calculated as the maximum number of bytes used by any block declared in the
RayPayloadKHR or IncomingRayPayloadKHR storage classes. **maxAttributeSize** is calculated as the
maximum number of bytes used by any block declared in the HitAttributeKHR storage class.
**maxCallableSize** is calculated as the maximum number of bytes used by any block declared in the
CallableDataKHR or IncomingCallableDataKHR. As variables in these storage classes do not have
explicit offsets, the size should be calculated as if each variable has a **scalar alignment** equal to the
largest scalar alignment of any of the block’s members.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_RAY_TRACING_PIPELINE_INTERFACE_CREATE_INFO_KHR`
- **pNext** must be `NULL`

To query the opaque handles of shaders in the ray tracing pipeline, call:

```c
VkResult vkGetRayTracingShaderGroupHandlesKHR(
    VkDevice                                    device,
    VkPipeline                                  pipeline,
    uint32_t                                    firstGroup,
    uint32_t                                    groupCount,
    size_t                                      dataSize,
    void*                                       pData);
```

- **device** is the logical device containing the ray tracing pipeline.
- **pipeline** is the ray tracing pipeline object containing the shaders.
- **firstGroup** is the index of the first group to retrieve a handle for from the `VkRayTracingPipelineCreateInfoKHR::pGroups` array.
- **groupCount** is the number of shader handles to retrieve.
- **dataSize** is the size in bytes of the buffer pointed to by **pData**.
- **pData** is a pointer to a user-allocated buffer where the results will be written.

Valid Usage

- The sum of **firstGroup** and **groupCount** must be less than the number of shader groups in **pipeline**.
- **dataSize** must be at least `VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupHandleSize × groupCount`
- **pipeline** must have not been created with `VK_PIPELINE_CREATE_LIBRARY_BIT_KHR`

Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pipeline** must be a valid `VkPipeline` handle
- **pData** must be a valid pointer to an array of **dataSize** bytes
- **dataSize** must be greater than 0
- **pipeline** must have been created, allocated, or retrieved from **device**
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY

To query the optional capture handle information of shaders in the ray tracing pipeline, call:

```c
VkResult vkGetRayTracingCaptureReplayShaderGroupHandlesKHR(
    VkDevice device,
    VkPipeline pipeline,
    uint32_t firstGroup,
    uint32_t groupCount,
    size_t dataSize,
    void* pData);
```

- **device** is the logical device containing the ray tracing pipeline.
- **pipeline** is the ray tracing pipeline object containing the shaders.
- **firstGroup** is the index of the first group to retrieve a handle for from the
  `VkRayTracingPipelineCreateInfoKHR::pGroups` array.
- **groupCount** is the number of shader handles to retrieve.
- **dataSize** is the size in bytes of the buffer pointed to by **pData**.
- **pData** is a pointer to a user-allocated buffer where the results will be written.

Valid Usage

- The sum of **firstGroup** and **groupCount** must be less than the number of shader groups in **pipeline**.
- **dataSize** must be at least `VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupHandleCaptureReplaySize × groupCount`
- `VkPhysicalDeviceRayTracingFeaturesKHR::rayTracingShaderGroupHandleCaptureReplay` must be enabled to call this function.
Valid Usage (Implicit)

- **device must** be a valid `VkDevice` handle
- **pipeline must** be a valid `VkPipeline` handle
- **pData must** be a valid pointer to an array of `dataSize` bytes
- **dataSize must** be greater than 0
- **pipeline must** have been created, allocated, or retrieved from `device`

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
Chapter 10. Memory Allocation

Vulkan memory is broken up into two categories, host memory and device memory.

10.1. Host Memory

Host memory is memory needed by the Vulkan implementation for non-device-visible storage.

Note

This memory may be used to store the implementation's representation and state of Vulkan objects.

Vulkan provides applications the opportunity to perform host memory allocations on behalf of the Vulkan implementation. If this feature is not used, the implementation will perform its own memory allocations. Since most memory allocations are off the critical path, this is not meant as a performance feature. Rather, this can be useful for certain embedded systems, for debugging purposes (e.g. putting a guard page after all host allocations), or for memory allocation logging.

Allocators are provided by the application as a pointer to a VkAllocationCallbacks structure:

```c
typedef struct VkAllocationCallbacks {
    void* pUserData;
    PFN_vkAllocationFunction pfnAllocation;
    PFN_vkReallocationFunction pfnReallocation;
    PFN_vkFreeFunction pfnFree;
    PFN_vkInternalAllocationNotification pfnInternalAllocation;
    PFN_vkInternalFreeNotification pfnInternalFree;
} VkAllocationCallbacks;
```

- **pUserData** is a value to be interpreted by the implementation of the callbacks. When any of the callbacks in VkAllocationCallbacks are called, the Vulkan implementation will pass this value as the first parameter to the callback. This value can vary each time an allocator is passed into a command, even when the same object takes an allocator in multiple commands.

- **pfnAllocation** is a PFN_vkAllocationFunction pointer to an application-defined memory allocation function.

- **pfnReallocation** is a PFN_vkReallocationFunction pointer to an application-defined memory reallocation function.

- **pfnFree** is a PFN_vkFreeFunction pointer to an application-defined memory free function.

- **pfnInternalAllocation** is a PFN_vkInternalAllocationNotification pointer to an application-defined function that is called by the implementation when the implementation makes internal allocations.

- **pfnInternalFree** is a PFN_vkInternalFreeNotification pointer to an application-defined function that is called by the implementation when the implementation frees internal allocations.
Valid Usage

- **pfnAllocation** must be a valid pointer to a valid user-defined `PFN_vkAllocationFunction`
- **pfnReallocation** must be a valid pointer to a valid user-defined `PFN_vkReallocationFunction`
- **pfnFree** must be a valid pointer to a valid user-defined `PFN_vkFreeFunction`
- If either of **pfnInternalAllocation** or **pfnInternalFree** is not NULL, both must be valid callbacks

The type of **pfnAllocation** is:

```c
typedef void* (VKAPI_PTR *PFN_vkAllocationFunction)(
    void* pUserData,
    size_t size,
    size_t alignment,
    VkSystemAllocationScope allocationScope);
```

- **pUserData** is the value specified for `VkAllocationCallbacks::pUserData` in the allocator specified by the application.
- **size** is the size in bytes of the requested allocation.
- **alignment** is the requested alignment of the allocation in bytes and must be a power of two.
- **allocationScope** is a `VkSystemAllocationScope` value specifying the allocation scope of the lifetime of the allocation, as described here.

If **pfnAllocation** is unable to allocate the requested memory, it must return NULL. If the allocation was successful, it must return a valid pointer to memory allocation containing at least **size** bytes, and with the pointer value being a multiple of **alignment**.

**Note**
Correct Vulkan operation cannot be assumed if the application does not follow these rules.

For example, **pfnAllocation** (or **pfnReallocation**) could cause termination of running Vulkan instance(s) on a failed allocation for debugging purposes, either directly or indirectly. In these circumstances, it cannot be assumed that any part of any affected `VkInstance` objects are going to operate correctly (even `vkDestroyInstance`), and the application must ensure it cleans up properly via other means (e.g. process termination).

If **pfnAllocation** returns NULL, and if the implementation is unable to continue correct processing of the current command without the requested allocation, it must treat this as a run-time error, and generate `VK_ERROR_OUT_OF_HOST_MEMORY` at the appropriate time for the command in which the condition was detected, as described in Return Codes.
If the implementation is able to continue correct processing of the current command without the requested allocation, then it may do so, and must not generate VK_ERROR_OUT_OF_HOST_MEMORY as a result of this failed allocation.

The type of pfnReallocation is:

```c
typedef void* (VKAPI_PTR *PFN_vkReallocationFunction)(
    void* pUserData,
    void* pOriginal,
    size_t size,
    size_t alignment,
    VkSystemAllocationScope allocationScope);
```

- pUserData is the value specified for VkAllocationCallbacks::pUserData in the allocator specified by the application.
- pOriginal must be either NULL or a pointer previously returned by pfnReallocation or pfnAllocation of a compatible allocator.
- size is the size in bytes of the requested allocation.
- alignment is the requested alignment of the allocation in bytes and must be a power of two.
- allocationScope is a VkSystemAllocationScope value specifying the allocation scope of the lifetime of the allocation, as described here.

pfnReallocation must return an allocation with enough space for size bytes, and the contents of the original allocation from bytes zero to min(original size, new size) - 1 must be preserved in the returned allocation. If size is larger than the old size, the contents of the additional space are undefined. If satisfying these requirements involves creating a new allocation, then the old allocation should be freed.

If pOriginal is NULL, then pfnReallocation must behave equivalently to a call to PFN_vkAllocationFunction with the same parameter values (without pOriginal).

If size is zero, then pfnReallocation must behave equivalently to a call to PFN_vkFreeFunction with the same pUserData parameter value, and pMemory equal to pOriginal.

If pOriginal is non-NULL, the implementation must ensure that alignment is equal to the alignment used to originally allocate pOriginal.

If this function fails and pOriginal is non-NULL the application must not free the old allocation.

pfnReallocation must follow the same rules for return values as PFN_vkAllocationFunction.

The type of pfnFree is:

```c
typedef void (VKAPI_PTR *PFN_vkFreeFunction)(
    void* pUserData,
    void* pMemory);
```
• **pUserData** is the value specified for **VkAllocationCallbacks::pUserData** in the allocator specified by the application.

• **pMemory** is the allocation to be freed.

**pMemory** may be **NULL**, which the callback **must** handle safely. If **pMemory** is non-**NULL**, it **must** be a pointer previously allocated by **PFNAllocation** or **PFNReallocation**. The application **should** free this memory.

The type of **PFNInternalAllocation** is:

```c
typedef void (VKAPI_PTR *PFN_vkInternalAllocationNotification)(
    void* pUserData,
    size_t size,
    VkInternalAllocationType allocationType,
    VkSystemAllocationScope allocationScope);
```

• **pUserData** is the value specified for **VkAllocationCallbacks::pUserData** in the allocator specified by the application.

• **size** is the requested size of an allocation.

• **allocationType** is a **VkInternalAllocationType** value specifying the requested type of an allocation.

• **allocationScope** is a **VkSystemAllocationScope** value specifying the allocation scope of the lifetime of the allocation, as described [here](#).

This is a purely informational callback.

The type of **PFNInternalFree** is:

```c
typedef void (VKAPI_PTR *PFN_vkInternalFreeNotification)(
    void* pUserData,
    size_t size,
    VkInternalAllocationType allocationType,
    VkSystemAllocationScope allocationScope);
```

• **pUserData** is the value specified for **VkAllocationCallbacks::pUserData** in the allocator specified by the application.

• **size** is the requested size of an allocation.

• **allocationType** is a **VkInternalAllocationType** value specifying the requested type of an allocation.

• **allocationScope** is a **VkSystemAllocationScope** value specifying the allocation scope of the lifetime of the allocation, as described [here](#).

Each allocation has an **allocation scope** defining its lifetime and which object it is associated with. Possible values passed to the **allocationScope** parameter of the callback functions specified by **VkAllocationCallbacks**, indicating the allocation scope, are:
typedef enum VkSystemAllocationScope {
    VK_SYSTEM_ALLOCATION_SCOPE_COMMAND = 0,
    VK_SYSTEM_ALLOCATION_SCOPE_OBJECT = 1,
    VK_SYSTEM_ALLOCATION_SCOPE_CACHE = 2,
    VK_SYSTEM_ALLOCATION_SCOPE_DEVICE = 3,
    VK_SYSTEM_ALLOCATION_SCOPE_INSTANCE = 4,
    VK_SYSTEM_ALLOCATION_SCOPE_MAX_ENUM = 0x7FFFFFFF
} VkSystemAllocationScope;

- **VK_SYSTEM_ALLOCATION_SCOPE_COMMAND** specifies that the allocation is scoped to the duration of the Vulkan command.
- **VK_SYSTEM_ALLOCATION_SCOPE_OBJECT** specifies that the allocation is scoped to the lifetime of the Vulkan object that is being created or used.
- **VK_SYSTEM_ALLOCATION_SCOPE_CACHE** specifies that the allocation is scoped to the lifetime of a VkPipelineCache object.
- **VK_SYSTEM_ALLOCATION_SCOPE_DEVICE** specifies that the allocation is scoped to the lifetime of the Vulkan device.
- **VK_SYSTEM_ALLOCATION_SCOPE_INSTANCE** specifies that the allocation is scoped to the lifetime of the Vulkan instance.

Most Vulkan commands operate on a single object, or there is a sole object that is being created or manipulated. When an allocation uses an allocation scope of **VK_SYSTEM_ALLOCATION_SCOPE_OBJECT** or **VK_SYSTEM_ALLOCATION_SCOPE_CACHE**, the allocation is scoped to the object being created or manipulated.

When an implementation requires host memory, it will make callbacks to the application using the most specific allocator and allocation scope available:

- If an allocation is scoped to the duration of a command, the allocator will use the **VK_SYSTEM_ALLOCATION_SCOPE_COMMAND** allocation scope. The most specific allocator available is used: if the object being created or manipulated has an allocator, that object's allocator will be used, else if the parent VkDevice has an allocator it will be used, else if the parent VkInstance has an allocator it will be used. Else,

- If an allocation is associated with a VkPipelineCache object, the allocator will use the **VK_SYSTEM_ALLOCATION_SCOPE_CACHE** allocation scope. The most specific allocator available is used (cache, else device, else instance). Else,

- If an allocation is scoped to the lifetime of an object, that object is being created or manipulated by the command, and that object's type is not VkDevice or VkInstance, the allocator will use an allocation scope of **VK_SYSTEM_ALLOCATION_SCOPE_OBJECT**. The most specific allocator available is used (object, else device, else instance). Else,

- If an allocation is scoped to the lifetime of a device, the allocator will use an allocation scope of **VK_SYSTEM_ALLOCATION_SCOPE_DEVICE**. The most specific allocator available is used (device, else instance). Else,

- If the allocation is scoped to the lifetime of an instance and the instance has an allocator, its allocator will be used with an allocation scope of **VK_SYSTEM_ALLOCATION_SCOPE_INSTANCE**.
• Otherwise an implementation will allocate memory through an alternative mechanism that is unspecified.

Objects that are allocated from pools do not specify their own allocator. When an implementation requires host memory for such an object, that memory is sourced from the object’s parent pool’s allocator.

The application is not expected to handle allocating memory that is intended for execution by the host due to the complexities of differing security implementations across multiple platforms. The implementation will allocate such memory internally and invoke an application provided informational callback when these internal allocations are allocated and freed. Upon allocation of executable memory, pfnInternalAllocation will be called. Upon freeing executable memory, pfnInternalFree will be called. An implementation will only call an informational callback for executable memory allocations and frees.

The allocationType parameter to the pfnInternalAllocation and pfnInternalFree functions may be one of the following values:

```c
typedef enum VkInternalAllocationType {
    VK_INTERNAL_ALLOCATION_TYPE_EXECUTABLE = 0,
    VK_INTERNAL_ALLOCATION_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkInternalAllocationType;
```

• VK_INTERNAL_ALLOCATION_TYPE_EXECUTABLE specifies that the allocation is intended for execution by the host.

An implementation must only make calls into an application-provided allocator during the execution of an API command. An implementation must only make calls into an application-provided allocator from the same thread that called the provoking API command. The implementation should not synchronize calls to any of the callbacks. If synchronization is needed, the callbacks must provide it themselves. The informational callbacks are subject to the same restrictions as the allocation callbacks.

If an implementation intends to make calls through a VkAllocationCallbacks structure between the time a vkCreate* command returns and the time a corresponding vkDestroy* command begins, that implementation must save a copy of the allocator before the vkCreate* command returns. The callback functions and any data structures they rely upon must remain valid for the lifetime of the object they are associated with.

If an allocator is provided to a vkCreate* command, a compatible allocator must be provided to the corresponding vkDestroy* command. Two VkAllocationCallbacks structures are compatible if memory allocated with pfnAllocation or pfnReallocation in each can be freed with pfnReallocation or pfnFree in the other. An allocator must not be provided to a vkDestroy* command if an allocator was not provided to the corresponding vkCreate* command.

If a non-NULL allocator is used, the pfnAllocation, pfnReallocation and pfnFree members must be non-NULL and point to valid implementations of the callbacks. An application can choose to not provide informational callbacks by setting both pfnInternalAllocation and pfnInternalFree to NULL. pfnInternalAllocation and pfnInternalFree must either both be NULL or both be non-NULL.
If `pfnAllocation` or `pfnReallocation` fail, the implementation **may** fail object creation and/or generate a `VK_ERROR_OUT_OF_HOST_MEMORY` error, as appropriate.

Allocation callbacks **must** not call any Vulkan commands.

The following sets of rules define when an implementation is permitted to call the allocator callbacks.

`pfnAllocation` or `pfnReallocation` **may** be called in the following situations:

- Allocations scoped to a `VkDevice` or `VkInstance` **may** be allocated from any API command.
- Allocations scoped to a command **may** be allocated from any API command.
- Allocations scoped to a `VkPipelineCache` **may** only be allocated from:
  - `vkCreatePipelineCache`
  - `vkMergePipelineCaches` for `dstCache`
  - `vkCreateGraphicsPipelines` for `pipelineCache`
  - `vkCreateComputePipelines` for `pipelineCache`
- Allocations scoped to a `VkDescriptorPool` **may** only be allocated from:
  - any command that takes the pool as a direct argument
  - `vkAllocateDescriptorSets` for the `descriptorPool` member of its `pAllocateInfo` parameter
  - `vkCreateDescriptorPool`
- Allocations scoped to a `VkCommandPool` **may** only be allocated from:
  - any command that takes the pool as a direct argument
  - `vkCreateCommandPool`
  - `vkAllocateCommandBuffers` for the `commandPool` member of its `pAllocateInfo` parameter
  - any `vkCmd*` command whose `commandBuffer` was allocated from that `VkCommandPool`
- Allocations scoped to any other object **may** only be allocated in that object’s `vkCreate*` command.

`pfnFree`, or `pfnReallocation` with zero size, **may** be called in the following situations:

- Allocations scoped to a `VkDevice` or `VkInstance` **may** be freed from any API command.
- Allocations scoped to a command **must** be freed by any API command which allocates such memory.
- Allocations scoped to a `VkPipelineCache` **may** be freed from `vkDestroyPipelineCache`.
- Allocations scoped to a `VkDescriptorPool` **may** be freed from:
  - any command that takes the pool as a direct argument
- Allocations scoped to a `VkCommandPool` **may** be freed from:
  - any command that takes the pool as a direct argument
  - `vkResetCommandBuffer` whose `commandBuffer` was allocated from that `VkCommandPool`
- Allocations scoped to any other object **may** be freed in that object’s `vkDestroy*` command.
• Any command that allocates host memory may also free host memory of the same scope.

10.2. Device Memory

Device memory is memory that is visible to the device — for example the contents of the image or buffer objects, which can be natively used by the device.

Memory properties of a physical device describe the memory heaps and memory types available.

To query memory properties, call:

```c
void vkGetPhysicalDeviceMemoryProperties(
    VkPhysicalDevice                            physicalDevice,
    VkPhysicalDeviceMemoryProperties*           pMemoryProperties);
```

• physicalDevice is the handle to the device to query.

• pMemoryProperties is a pointer to a VkPhysicalDeviceMemoryProperties structure in which the properties are returned.

Valid Usage (Implicit)

• physicalDevice must be a valid VkPhysicalDevice handle

• pMemoryProperties must be a valid pointer to a VkPhysicalDeviceMemoryProperties structure

The VkPhysicalDeviceMemoryProperties structure is defined as:

```c
typedef struct VkPhysicalDeviceMemoryProperties {
    uint32_t memoryTypeCount;
    VkMemoryType memoryTypes[VK_MAX_MEMORY_TYPES];
    uint32_t memoryHeapCount;
    VkMemoryHeap memoryHeaps[VK_MAX_MEMORY_HEAPS];
} VkPhysicalDeviceMemoryProperties;
```

• memoryTypeCount is the number of valid elements in the memoryTypes array.

• memoryTypes is an array of VK_MAX_MEMORY_TYPES VkMemoryType structures describing the memory types that can be used to access memory allocated from the heaps specified by memoryHeaps.

• memoryHeapCount is the number of valid elements in the memoryHeaps array.

• memoryHeaps is an array of VK_MAX_MEMORY_HEAPS VkMemoryHeap structures describing the memory heaps from which memory can be allocated.

The VkPhysicalDeviceMemoryProperties structure describes a number of memory heaps as well as a number of memory types that can be used to access memory allocated in those heaps. Each heap
describes a memory resource of a particular size, and each memory type describes a set of memory properties (e.g. host cached vs uncached) that can be used with a given memory heap. Allocations using a particular memory type will consume resources from the heap indicated by that memory type’s heap index. More than one memory type may share each heap, and the heaps and memory types provide a mechanism to advertise an accurate size of the physical memory resources while allowing the memory to be used with a variety of different properties.

The number of memory heaps is given by `memoryHeapCount` and is less than or equal to `VK_MAX_MEMORY_HEAPS`. Each heap is described by an element of the `memoryHeaps` array as a `VkMemoryHeap` structure. The number of memory types available across all memory heaps is given by `memoryTypeCount` and is less than or equal to `VK_MAX_MEMORY_TYPES`. Each memory type is described by an element of the `memoryTypes` array as a `VkMemoryType` structure.

At least one heap must include `VK_MEMORY_HEAP_DEVICE_LOCAL_BIT` in `VkMemoryHeap::flags`. If there are multiple heaps that all have similar performance characteristics, they may all include `VK_MEMORY_HEAP_DEVICE_LOCAL_BIT`. In a unified memory architecture (UMA) system there is often only a single memory heap which is considered to be equally “local” to the host and to the device, and such an implementation must advertise the heap as device-local.

Each memory type returned by `vkGetPhysicalDeviceMemoryProperties` must have its `propertyFlags` set to one of the following values:

- 0
- `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT`
- `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT`
- `VK_MEMORY_PROPERTYDEVICE_LOCAL_BIT | VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORY_PROPERTYDEVICE_LOCAL_BIT | VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORYPROPERTY_DEVICE_LOCAL_BIT | VK_MEMORYPROPERTY_HOST_VISIBLE_BIT | VK_MEMORYPROPERTY_HOST_CACHED_BIT | VK_MEMORYPROPERTY_DEVICE_LOCAL_BIT | VK_MEMORYPROPERTY_HOST_COHERENT_BIT`
- `VK_MEMORYPROPERTY_DEVICE_LOCAL_BIT | VK_MEMORYPROPERTY_HOST_VISIBLE_BIT | VK_MEMORYPROPERTY_HOST_CACHED_BIT | VK_MEMORYPROPERTY_HOST_COHERENT_BIT | VK_MEMORYPROPERTY_LAZILY_ALLOCATED_BIT`
- `VK_MEMORYPROPERTY_PROTECTED_BIT`
- `VK_MEMORYPROPERTY_PROTECTED_BIT | VK_MEMORYPROPERTY_DEVICE_LOCAL_BIT`
There **must** be at least one memory type with both the `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` and `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` bits set in its `propertyFlags`. There **must** be at least one memory type with the `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` bit set in its `propertyFlags`.

For each pair of elements \(X\) and \(Y\) returned in `memoryTypes`, \(X\) **must** be placed at a lower index position than \(Y\) if:

- either the set of bit flags returned in the `propertyFlags` member of \(X\) is a strict subset of the set of bit flags returned in the `propertyFlags` member of \(Y\); or
- the `propertyFlags` members of \(X\) and \(Y\) are equal, and \(X\) belongs to a memory heap with greater performance (as determined in an implementation-specific manner)

**Note**

There is no ordering requirement between \(X\) and \(Y\) elements for the case their `propertyFlags` members are not in a subset relation. That potentially allows more than one possible way to order the same set of memory types. Notice that the list of all allowed memory property flag combinations is written in a valid order. But if instead `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT` was before `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT`, the list would still be in a valid order.

This ordering requirement enables applications to use a simple search loop to select the desired memory type along the lines of:
Find a memory in `memoryTypeBitsRequirement` that includes all of `requiredProperties`:

```c
int32_t findProperties(const VkPhysicalDeviceMemoryProperties* pMemoryProperties, int32_t memoryTypeBitsRequirement, VkMemoryPropertyFlags requiredProperties) {
    const uint32_t memoryCount = pMemoryProperties->memoryTypeCount;
    for (uint32_t memoryIndex = 0; memoryIndex < memoryCount; ++memoryIndex) {
        const uint32_t memoryTypeBits = (1 << memoryIndex);
        const bool isRequiredMemoryType = memoryTypeBitsRequirement & memoryTypeBits;
        const VkMemoryPropertyFlags properties = pMemoryProperties->memoryTypes[memoryIndex].propertyFlags;
        const bool hasRequiredProperties = (properties & requiredProperties) == requiredProperties;
        if (isRequiredMemoryType && hasRequiredProperties)
            return static_cast<int32_t>(memoryIndex);
    }
    // failed to find memory type
    return -1;
}
```

Try to find an optimal memory type, or if it does not exist try fallback memory type:

```c
// Try to find an optimal memory type, or if it does not exist try fallback memory type
// `device` is the VkDevice
// `image` is the VkImage that requires memory to be bound
// `memoryProperties` properties as returned by vkGetPhysicalDeviceMemoryProperties
// `requiredProperties` are the property flags that must be present
// `optimalProperties` are the property flags that are preferred by the application
VkMemoryRequirements memoryRequirements;
vkGetImageMemoryRequirements(device, image, &memoryRequirements);
int32_t memoryType = findProperties(&memoryProperties, memoryRequirements.memoryTypeBits, optimalProperties);
if (memoryType == -1) // not found; try fallback properties
    memoryType = findProperties(&memoryProperties, memoryRequirements.memoryTypeBits, requiredProperties);
```

To query memory properties, call:

```c
void vkGetPhysicalDeviceMemoryProperties2(
    VkPhysicalDevice physicalDevice, VkPhysicalDeviceMemoryProperties2* pMemoryProperties);
```

or the equivalent command
void vkGetPhysicalDeviceMemoryProperties2KHR(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceMemoryProperties2* pMemoryProperties);

- `physicalDevice` is the handle to the device to query.
- `pMemoryProperties` is a pointer to a `VkPhysicalDeviceMemoryProperties2` structure in which the properties are returned.

`vkGetPhysicalDeviceMemoryProperties2KHR` behaves similarly to `vkGetPhysicalDeviceMemoryProperties`, with the ability to return extended information in a `pNext` chain of output structures.

**Valid Usage (Implicit)**

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pMemoryProperties` must be a valid pointer to a `VkPhysicalDeviceMemoryProperties2` structure

The `VkPhysicalDeviceMemoryProperties2` structure is defined as:

```c
typedef struct VkPhysicalDeviceMemoryProperties2 {
    VkStructureType sType;
    void* pNext;
    VkPhysicalDeviceMemoryProperties memoryProperties;
} VkPhysicalDeviceMemoryProperties2;
```

or the equivalent

```c
typedef VkPhysicalDeviceMemoryProperties2 VkPhysicalDeviceMemoryProperties2KHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `memoryProperties` is a `VkPhysicalDeviceMemoryProperties` structure which is populated with the same values as in `vkGetPhysicalDeviceMemoryProperties`.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MEMORY_PROPERTIES_2`
- `pNext` must be NULL

The `VkMemoryHeap` structure is defined as:
typedef struct VkMemoryHeap {
    VkDeviceSize size;
    VkMemoryHeapFlags flags;
} VkMemoryHeap;

- **size** is the total memory size in bytes in the heap.
- **flags** is a bitmask of VkMemoryHeapFlagBits specifying attribute flags for the heap.

Bits which **may** be set in VkMemoryHeap::flags, indicating attribute flags for the heap, are:

typedef enum VkMemoryHeapFlagBits {
    VK_MEMORY_HEAP_DEVICE_LOCAL_BIT = 0x00000001,
    VK_MEMORY_HEAP_MULTI_INSTANCE_BIT = 0x00000002,
    VK_MEMORY_HEAP_MULTI_INSTANCE_BIT_KHR = VK_MEMORY_HEAP_MULTI_INSTANCE_BIT,
    VK_MEMORY_HEAP_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkMemoryHeapFlagBits;

- **VK_MEMORY_HEAP_DEVICE_LOCAL_BIT** specifies that the heap corresponds to device local memory. Device local memory **may** have different performance characteristics than host local memory, and **may** support different memory property flags.
- **VK_MEMORY_HEAP_MULTI_INSTANCE_BIT** specifies that in a logical device representing more than one physical device, there is a per-physical device instance of the heap memory. By default, an allocation from such a heap will be replicated to each physical device's instance of the heap.

typedef VkFlags VkMemoryHeapFlags;

VkMemoryHeapFlags is a bitmask type for setting a mask of zero or more VkMemoryHeapFlagBits.

The **VkMemoryType** structure is defined as:

typedef struct VkMemoryType {
    VkMemoryPropertyFlags propertyFlags;
    uint32_t heapIndex;
} VkMemoryType;

- **heapIndex** describes which memory heap this memory type corresponds to, and **must** be less than memoryHeapCount from the VkPhysicalDeviceMemoryProperties structure.
- **propertyFlags** is a bitmask of VkMemoryPropertyFlagBits of properties for this memory type.

Bits which **may** be set in VkMemoryType::propertyFlags, indicating properties of a memory heap, are:
typedef enum VkMemoryPropertyFlagBits {
    VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT = 0x00000001,
    VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT = 0x00000002,
    VK_MEMORY_PROPERTY_HOST_COHERENT_BIT = 0x00000004,
    VK_MEMORY_PROPERTY_HOST_CACHED_BIT = 0x00000008,
    VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT = 0x00000010,
    VK_MEMORY_PROPERTY_PROTECTED_BIT = 0x00000020,
    VK_MEMORY_PROPERTY_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkMemoryPropertyFlagBits;

- VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT bit specifies that memory allocated with this type is the most efficient for device access. This property will be set if and only if the memory type belongs to a heap with the VK_MEMORY_HEAP_DEVICE_LOCAL_BIT set.

- VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT bit specifies that memory allocated with this type can be mapped for host access using vkMapMemory.

- VK_MEMORY_PROPERTY_HOST_COHERENT_BIT bit specifies that the host cache management commands vkFlushMappedMemoryRanges and vkInvalidateMappedMemoryRanges are not needed to flush host writes to the device or make device writes visible to the host, respectively.

- VK_MEMORY_PROPERTY_HOST_CACHED_BIT bit specifies that memory allocated with this type is cached on the host. Host memory accesses to uncached memory are slower than to cached memory, however uncached memory is always host coherent.

- VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT bit specifies that the memory type only allows device access to the memory. Memory types must not have both VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT and VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT set. Additionally, the object's backing memory may be provided by the implementation lazily as specified in Lazily Allocated Memory.

- VK_MEMORY_PROPERTY_PROTECTED_BIT bit specifies that the memory type only allows device access to the memory, and allows protected queue operations to access the memory. Memory types must not have VK_MEMORY_PROPERTY_PROTECTED_BIT set and any of VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT set, or VK_MEMORY_PROPERTY_HOST_COHERENT_BIT set, or VK_MEMORY_PROPERTY_HOST_CACHED_BIT set.

typedef VkFlags VkMemoryPropertyFlags;

VkMemoryPropertyFlags is a bitmask type for setting a mask of zero or more VkMemoryPropertyFlagBits.

A Vulkan device operates on data in device memory via memory objects that are represented in the API by a VkDeviceMemory handle:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDeviceMemory)
```

To allocate memory objects, call:
VkResult vkAllocateMemory(
    VkDevice                                    device,
    const VkMemoryAllocateInfo*                 pAllocateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkDeviceMemory*                             pMemory);

• device is the logical device that owns the memory.

• pAllocateInfo is a pointer to a VkMemoryAllocateInfo structure describing parameters of the allocation. A successful returned allocation must use the requested parameters—no substitution is permitted by the implementation.

• pAllocator controls host memory allocation as described in the Memory Allocation chapter.

• pMemory is a pointer to a VkDeviceMemory handle in which information about the allocated memory is returned.

Allocations returned by vkAllocateMemory are guaranteed to meet any alignment requirement of the implementation. For example, if an implementation requires 128 byte alignment for images and 64 byte alignment for buffers, the device memory returned through this mechanism would be 128-byte aligned. This ensures that applications can correctly suballocate objects of different types (with potentially different alignment requirements) in the same memory object.

When memory is allocated, its contents are undefined with the following constraint:

• The contents of unprotected memory must not be a function of data protected memory objects, even if those memory objects were previously freed.

```
Note
The contents of memory allocated by one application should not be a function of data from protected memory objects of another application, even if those memory objects were previously freed.
```

The maximum number of valid memory allocations that can exist simultaneously within a VkDevice may be restricted by implementation- or platform-dependent limits. If a call to vkAllocateMemory would cause the total number of allocations to exceed these limits, such a call will fail and must return VK_ERROR_TOO_MANY_OBJECTS. The maxMemoryAllocationCount feature describes the number of allocations that can exist simultaneously before encountering these internal limits.

Some platforms may have a limit on the maximum size of a single allocation. For example, certain systems may fail to create allocations with a size greater than or equal to 4GB. Such a limit is implementation-dependent, and if such a failure occurs then the error VK_ERROR_OUT_OF_DEVICE_MEMORY must be returned. This limit is advertised in VkPhysicalDeviceMaintenance3Properties::maxMemoryAllocationSize.
Valid Usage

- `pAllocateInfo->allocationSize` **must** be less than or equal to `VkPhysicalDeviceMemoryProperties::memoryHeaps[memindex].size` where `memindex = VkPhysicalDeviceMemoryProperties::memoryTypes[pAllocateInfo->memoryTypeIndex].heapIndex` as returned by `vkGetPhysicalDeviceMemoryProperties` for the `VkPhysicalDevice` that `device` was created from.

- `pAllocateInfo->memoryTypeIndex` **must** be less than `VkPhysicalDeviceMemoryProperties::memoryTypeCount` as returned by `vkGetPhysicalDeviceMemoryProperties` for the `VkPhysicalDevice` that `device` was created from.

Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle

- `pAllocateInfo` **must** be a valid pointer to a valid `VkMemoryAllocateInfo` structure

- If `pAllocator` is not `NULL`, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure

- `pMemory` **must** be a valid pointer to a `VkDeviceMemory` handle

Return Codes

Success

- `VK_SUCCESS`

Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_TOO_MANY_OBJECTS`
- `VK_ERROR_INVALID_EXTERNAL_HANDLE`
- `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR`

The `VkMemoryAllocateInfo` structure is defined as:

```c
typedef struct VkMemoryAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDeviceSize allocationSize;
    uint32_t memoryTypeIndex;
} VkMemoryAllocateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
• allocationSize is the size of the allocation in bytes
• memoryTypeIndex is an index identifying a memory type from the memoryTypes array of the VkPhysicalDeviceMemoryProperties structure

A VkMemoryAllocateInfo structure defines a memory import operation if its pNext chain includes one of the following structures:

• VkImportMemoryWin32HandleInfoKHR with non-zero handleType value
• VkImportMemoryFdInfoKHR with a non-zero handleType value

Importing memory must not modify the content of the memory. Implementations must ensure that importing memory does not enable the importing Vulkan instance to access any memory or resources in other Vulkan instances other than that corresponding to the memory object imported. Implementations must also ensure accessing imported memory which has not been initialized does not allow the importing Vulkan instance to obtain data from the exporting Vulkan instance or vice-versa.

**Note**

How exported and imported memory is isolated is left to the implementation, but applications should be aware that such isolation may prevent implementations from placing multiple exportable memory objects in the same physical or virtual page. Hence, applications should avoid creating many small external memory objects whenever possible.

When performing a memory import operation, it is the responsibility of the application to ensure the external handles meet all valid usage requirements. However, implementations must perform sufficient validation of external handles to ensure that the operation results in a valid memory object which will not cause program termination, device loss, queue stalls, or corruption of other resources when used as allowed according to its allocation parameters. If the external handle provided does not meet these requirements, the implementation must fail the memory import operation with the error code VK_ERROR_INVALID_EXTERNAL_HANDLE.
Valid Usage

- \textbf{allocationSize} must be greater than 0

- If the \texttt{pNext} chain includes a \texttt{VkExportMemoryAllocateInfo} structure, and any of the handle types specified in \texttt{VkExportMemoryAllocateInfo::handleTypes} require a dedicated allocation, as reported by \texttt{vkGetPhysicalDeviceImageFormatProperties2} in \texttt{VkExternalImageFormatProperties::externalMemoryProperties.externalMemoryFeatures} or \texttt{VkExternalBufferProperties::externalMemoryProperties.externalMemoryFeatures}, the \texttt{pNext} chain must include a \texttt{VkMemoryDedicatedAllocateInfo} structure with either its \texttt{image} or \texttt{buffer} member set to a value other than \texttt{VK_NULL_HANDLE}.

- If the parameters define an import operation, the external handle specified was created by the Vulkan API, and the external handle type is \texttt{VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_KHR}, then the values of \texttt{allocationSize} and \texttt{memoryTypeIndex} must match those specified when the memory object being imported was created.

- If the parameters define an import operation and the external handle specified was created by the Vulkan API, the device mask specified by \texttt{VkMemoryAllocateFlagsInfo} must match that specified when the memory object being imported was allocated.

- If the parameters define an import operation and the external handle specified was created by the Vulkan API, the list of physical devices that comprise the logical device passed to \texttt{vkAllocateMemory} must match the list of physical devices that comprise the logical device on which the memory was originally allocated.

- If the parameters define an import operation and the external handle is an NT handle or a global share handle created outside of the Vulkan API, the value of \texttt{memoryTypeIndex} must be one of those returned by \texttt{vkGetMemoryWin32HandlePropertiesKHR}.

- If the parameters define an import operation and the external handle type is \texttt{VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT}, \texttt{VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT}, or \texttt{VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT}, \texttt{allocationSize} must match the size reported in the memory requirements of the \texttt{image} or \texttt{buffer} member of the \texttt{VkDedicatedAllocationMemoryAllocateInfoNV} structure included in the \texttt{pNext} chain.

- If the parameters define an import operation and the external handle is a POSIX file descriptor created outside of the Vulkan API, the value of \texttt{memoryTypeIndex} must be one of those returned by \texttt{vkGetMemoryFdPropertiesKHR}. 
• If the protected memory feature is not enabled, the `VkMemoryAllocateInfo::memoryTypeIndex` must not indicate a memory type that reports `VK_MEMORY_PROPERTY_PROTECTED_BIT`.

• If `VkMemoryOpaqueCaptureAddressAllocateInfo::opaqueCaptureAddress` is not zero, `VkMemoryAllocateFlagsInfo::flags` must include `VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`.

• If `VkMemoryAllocateFlagsInfo::flags` includes `VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`, the `bufferDeviceAddressCaptureReplay` feature must be enabled.

• If `VkMemoryAllocateFlagsInfo::flags` includes `VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT`, the `bufferDeviceAddress` feature must be enabled.

• If the parameters define an import operation, `VkMemoryOpaqueCaptureAddressAllocateInfo::opaqueCaptureAddress` must be zero.

Valid Usage (Implicit)

• `sType` must be `VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO`.

• Each `pNext` member of any structure (including this one) in the `pNext` chain must be either NULL or a pointer to a valid instance of `VkExportMemoryAllocateInfo`, `VkExportMemoryWin32HandleInfoKHR`, `VkImportMemoryFdInfoKHR`, `VkImportMemoryWin32HandleInfoKHR`, `VkMemoryAllocateFlagsInfo`, `VkMemoryDedicatedAllocateInfo`, or `VkMemoryOpaqueCaptureAddressAllocateInfo`.

• The `sType` value of each struct in the `pNext` chain must be unique.

If the `pNext` chain includes a `VkMemoryDedicatedAllocateInfo` structure, then that structure includes a handle of the sole buffer or image resource that the memory can be bound to.

The `VkMemoryDedicatedAllocateInfo` structure is defined as:

```c
typedef struct VkMemoryDedicatedAllocateInfo {
    VkStructureType sType;
    const void*     pNext;
    VkImage         image;
    VkBuffer        buffer;
} VkMemoryDedicatedAllocateInfo;
```

or the equivalent

```c
typedef VkMemoryDedicatedAllocateInfo VkMemoryDedicatedAllocateInfoKHR;
```

• `sType` is the type of this structure.

• `pNext` is NULL or a pointer to an extension-specific structure.

• `image` is `VK_NULL_HANDLE` or a handle of an image which this memory will be bound to.
Valid Usage

- At least one of `image` and `buffer` must be `VK_NULL_HANDLE`.
- If `image` is not `VK_NULL_HANDLE`, `VkMemoryAllocateInfo::allocationSize` must equal the `VkMemoryRequirements::size` of the image.
- If `image` is not `VK_NULL_HANDLE`, `image` must have been created without `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` set in `VkImageCreateInfo::flags`.
- If `buffer` is not `VK_NULL_HANDLE`, `VkMemoryAllocateInfo::allocationSize` must equal the `VkMemoryRequirements::size` of the buffer.
- If `buffer` is not `VK_NULL_HANDLE`, `buffer` must have been created without `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` set in `VkBufferCreateInfo::flags`.
- If `image` is not `VK_NULL_HANDLE` and `VkMemoryAllocateInfo` defines a memory import operation with handle type `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT`, or `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_Resource_BIT`, and the external handle was created by the Vulkan API, then the memory being imported must also be a dedicated image allocation and `image` must be identical to the image associated with the imported memory.
- If `buffer` is not `VK_NULL_HANDLE` and `VkMemoryAllocateInfo` defines a memory import operation with handle type `VK_EXTERNAL_MEMORY.Handle_TYPE_OPAQUE_WIN32_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT`, or `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_Resource_BIT`, and the external handle was created by the Vulkan API, then the memory being imported must also be a dedicated buffer allocation and `buffer` must be identical to the buffer associated with the imported memory.
- If `image` is not `VK_NULL_HANDLE` and `VkMemoryAllocateInfo` defines a memory import operation with handle type `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT`, the memory being imported must also be a dedicated image allocation and `image` must be identical to the image associated with the imported memory.
- If `buffer` is not `VK_NULL_HANDLE` and `VkMemoryAllocateInfo` defines a memory import operation with handle type `VK_EXTERNAL_MEMORY.Handle_TYPE_OPAQUE_FD_BIT`, the memory being imported must also be a dedicated buffer allocation and `buffer` must be identical to the buffer associated with the imported memory.
- If `image` is not `VK_NULL_HANDLE`, `image` must not have been created with `VK_IMAGE_CREATE_DISJOINT_BIT` set in `VkImageCreateInfo::flags`.
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_MEMORY_DEPRECATED_ALLOCATE_INFO`
- If `image` is not `VK_NULL_HANDLE`, `image` must be a valid `VkImage` handle
- If `buffer` is not `VK_NULL_HANDLE`, `buffer` must be a valid `VkBuffer` handle
- Both of `buffer`, and `image` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

When allocating memory that may be exported to another process or Vulkan instance, add a `VkExportMemoryAllocateInfo` structure to the `pNext` chain of the `VkMemoryAllocateInfo` structure, specifying the handle types that may be exported.

The `VkExportMemoryAllocateInfo` structure is defined as:

```c
typedef struct VkExportMemoryAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlags handleTypes;
} VkExportMemoryAllocateInfo;
```

or the equivalent

```c
typedef VkExportMemoryAllocateInfo VkExportMemoryAllocateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `handleTypes` is a bitmask of `VkExternalMemoryHandleTypeFlagBits` specifying one or more memory handle types the application can export from the resulting allocation. The application can request multiple handle types for the same allocation.

Valid Usage

- The bits in `handleTypes` must be supported and compatible, as reported by `VkExternalImageFormatProperties` or `VkExternalBufferProperties`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_EXPORT_MEMORY_ALLOCATE_INFO`
- `handleTypes` must be a valid combination of `VkExternalMemoryHandleTypeFlagBits` values
To specify additional attributes of NT handles exported from a memory object, add a `VkExportMemoryWin32HandleInfoKHR` structure to the `pNext` chain of the `VkMemoryAllocateInfo` structure. The `VkExportMemoryWin32HandleInfoKHR` structure is defined as:

```c
typedef struct VkExportMemoryWin32HandleInfoKHR {
    VkStructureType               sType;
    const void*                   pNext;
    const SECURITY_ATTRIBUTES*    pAttributes;
    DWORD                         dwAccess;
    LPCWSTR                       name;
} VkExportMemoryWin32HandleInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **pAttributes** is a pointer to a Windows `SECURITY_ATTRIBUTES` structure specifying security attributes of the handle.
- **dwAccess** is a `DWORD` specifying access rights of the handle.
- **name** is a null-terminated UTF-16 string to associate with the underlying resource referenced by NT handles exported from the created memory.

If `VkExportMemoryAllocateInfo` is not present in the same `pNext` chain, this structure is ignored.

If `VkExportMemoryAllocateInfo` is present in the `pNext` chain of `VkMemoryAllocateInfo` with a Windows `handleType`, but either `VkExportMemoryWin32HandleInfoKHR` is not present in the `pNext` chain, or if it is but `pAttributes` is set to NULL, default security descriptor values will be used, and child processes created by the application will not inherit the handle, as described in the MSDN documentation for “Synchronization Object Security and Access Rights”¹. Further, if the structure is not present, the access rights used depend on the handle type.

For handles of the following types:

- `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT`
- `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT`

The implementation **must** ensure the access rights allow read and write access to the memory.

For handles of the following types:

- `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT`  `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT`

The access rights **must be**:

- `GENERIC_ALL`

Valid Usage

- If `VkExportMemoryAllocateInfo::handleTypes` does not include `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT`, `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT`, or `VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT`, a `VkExportMemoryWin32HandleInfoKHR` structure must not be included in the `pNext` chain of `VkMemoryAllocateInfo`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_EXPORT_MEMORY_WIN32_HANDLE_INFO_KHR`
- If `pAttributes` is not `NULL`, `pAttributes` must be a valid pointer to a valid `SECURITY_ATTRIBUTES` value

To import memory from a Windows handle, add a `VkImportMemoryWin32HandleInfoKHR` structure to the `pNext` chain of the `VkMemoryAllocateInfo` structure.

The `VkImportMemoryWin32HandleInfoKHR` structure is defined as:

```c
typedef struct VkImportMemoryWin32HandleInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlagBits handleType;
    HANDLE handle;
    LPCWSTR name;
} VkImportMemoryWin32HandleInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `handleType` specifies the type of `handle` or `name`.
- `handle` is the external handle to import, or `NULL`.
- `name` is a null-terminated UTF-16 string naming the underlying memory resource to import, or `NULL`.

Importing memory objects from Windows handles does not transfer ownership of the handle to the Vulkan implementation. For handle types defined as NT handles, the application must release ownership using the `CloseHandle` system call when the handle is no longer needed.

Applications can import the same underlying memory into multiple instances of Vulkan, into the same instance from which it was exported, and multiple times into a given Vulkan instance. In all cases, each import operation must create a distinct `VkDeviceMemory` object.
Valid Usage

- If `handleType` is not 0, it must be supported for import, as reported by `VkExternalImageFormatProperties` or `VkExternalBufferProperties`.

- The memory from which `handle` was exported, or the memory named by `name` must have been created on the same underlying physical device as `device`.

- If `handleType` is not 0, it must be defined as an NT handle or a global share handle.

- If `handleType` is not 0, and `handle` is NULL, `name` must name a valid memory resource of the type specified by `handleType`.

- If `handleType` is not 0 and `name` is NULL, `handle` must be a valid handle of the type specified by `handleType`.

- If `handle` is not NULL, `name` must be NULL.

- If `handle` is not NULL, it must obey any requirements listed for `handleType` in external memory handle types compatibility.

- If `name` is not NULL, it must obey any requirements listed for `handleType` in external memory handle types compatibility.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_IMPORT_MEMORY_WIN32_HANDLE_INFO_KHR`.

- If `handleType` is not 0, `handleType` must be a valid `VkExternalMemoryHandleTypeFlagBits` value.

To export a Windows handle representing the underlying resources of a Vulkan device memory object, call:

```c
VkResult vkGetMemoryWin32HandleKHR(
    VkDevice                device,
    const VkMemoryGetWin32HandleInfoKHR* pGetWin32HandleInfo,
    HANDLE*                 pHandle);
```

- `device` is the logical device that created the device memory being exported.

- `pGetWin32HandleInfo` is a pointer to a `VkMemoryGetWin32HandleInfoKHR` structure containing parameters of the export operation.

- `pHandle` will return the Windows handle representing the underlying resources of the device memory object.
For handle types defined as NT handles, the handles returned by `vkGetMemoryWin32HandleKHR` are owned by the application. To avoid leaking resources, the application **must** release ownership of them using the `CloseHandle` system call when they are no longer needed.

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- `pGetWin32HandleInfo` must be a valid pointer to a valid `VkMemoryGetWin32HandleInfoKHR` structure
- `pHandle` must be a valid pointer to a `HANDLE` value

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_TOO_MANY_OBJECTS`
- `VK_ERROR_OUT_OF_HOST_MEMORY`

The `VkMemoryGetWin32HandleInfoKHR` structure is defined as:

```c
typedef struct VkMemoryGetWin32HandleInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkDeviceMemory memory;
    VkExternalMemoryHandleTypeFlagBits handleType;
} VkMemoryGetWin32HandleInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `memory` is the memory object from which the handle will be exported.
- `handleType` is the type of handle requested.

The properties of the handle returned depend on the value of `handleType`. See `VkExternalMemoryHandleTypeFlagBits` for a description of the properties of the defined external memory handle types.
Valid Usage

- `handleType` must have been included in `VkExportMemoryAllocateInfo::handleTypes` when memory was created.
- If `handleType` is defined as an NT handle, `vkGetMemoryWin32HandleKHR` must be called no more than once for each valid unique combination of memory and `handleType`.
- `handleType` must be defined as an NT handle or a global share handle.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_MEMORY_GET_WIN32_HANDLE_INFO_KHR`
- `pNext` must be `NULL`
- `memory` must be a valid `VkDeviceMemory` handle
- `handleType` must be a valid `VkExternalMemoryHandleTypeFlagBits` value

Windows memory handles compatible with Vulkan may also be created by non-Vulkan APIs using methods beyond the scope of this specification. To determine the correct parameters to use when importing such handles, call:

```c
VkResult vkGetMemoryWin32HandlePropertiesKHR(
    VkDevice device,
    VkExternalMemoryHandleTypeFlagBits handleType,
    HANDLE handle,
    VkMemoryWin32HandlePropertiesKHR* pMemoryWin32HandleProperties);
```

- `device` is the logical device that will be importing `handle`.
- `handleType` is the type of the handle `handle`.
- `handle` is the handle which will be imported.
- `pMemoryWin32HandleProperties` will return properties of `handle`.

Valid Usage

- `handle` must be an external memory handle created outside of the Vulkan API.
- `handleType` must not be one of the handle types defined as opaque.
Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `handleType` must be a valid `VkExternalMemoryHandleTypeFlagBits` value
- `pMemoryWin32HandleProperties` must be a valid pointer to a `VkMemoryWin32HandlePropertiesKHR` structure

Return Codes

Success
- `VK_SUCCESS`

Failure
- `VK_ERROR_INVALID_EXTERNAL_HANDLE`

The `VkMemoryWin32HandlePropertiesKHR` structure returned is defined as:

```c
typedef struct VkMemoryWin32HandlePropertiesKHR {
    VkStructureType    sType;
    void*              pNext;
    uint32_t           memoryTypeBits;
} VkMemoryWin32HandlePropertiesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `memoryTypeBits` is a bitmask containing one bit set for every memory type which the specified windows handle can be imported as.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_MEMORY_WIN32_HANDLE_PROPERTIES_KHR`
- `pNext` must be `NULL`

To import memory from a POSIX file descriptor handle, add a `VkImportMemoryFdInfoKHR` structure to the `pNext` chain of the `VkMemoryAllocateInfo` structure. The `VkImportMemoryFdInfoKHR` structure is defined as:
typedef struct VkImportMemoryFdInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlagBits handleType;
    int fd;
} VkImportMemoryFdInfoKHR;

• *sType* is the type of this structure.
• *pNext* is NULL or a pointer to an extension-specific structure.
• *handleType* specifies the handle type of *fd*.
• *fd* is the external handle to import.

Importing memory from a file descriptor transfers ownership of the file descriptor from the application to the Vulkan implementation. The application must not perform any operations on the file descriptor after a successful import.

Applications can import the same underlying memory into multiple instances of Vulkan, into the same instance from which it was exported, and multiple times into a given Vulkan instance. In all cases, each import operation must create a distinct *VkDeviceMemory* object.

**Valid Usage**

- If *handleType* is not 0, it must be supported for import, as reported by *VkExternalImageFormatProperties* or *VkExternalBufferProperties*.
- The memory from which *fd* was exported must have been created on the same underlying physical device as *device*.
- If *handleType* is not 0, it must be defined as a POSIX file descriptor handle.
- If *handleType* is not 0, *fd* must be a valid handle of the type specified by *handleType*.
- The memory represented by *fd* must have been created from a physical device and driver that is compatible with *device* and *handleType*, as described in External memory handle types compatibility.
- *fd* must obey any requirements listed for *handleType* in external memory handle types compatibility.

**Valid Usage (Implicit)**

- *sType* must be VK_STRUCTURE_TYPE_IMPORT_MEMORY_FD_INFO_KHR
- If *handleType* is not 0, *handleType* must be a valid *VkExternalMemoryHandleTypeFlagBits* value

To export a POSIX file descriptor representing the underlying resources of a Vulkan device memory object, call:
VkResult vkGetMemoryFdKHR(
    VkDevice device,
    const VkMemoryGetFdInfoKHR* pGetFdInfo,
    int* pFd);

- **device** is the logical device that created the device memory being exported.
- **pGetFdInfo** is a pointer to a `VkMemoryGetFdInfoKHR` structure containing parameters of the export operation.
- **pFd** will return a file descriptor representing the underlying resources of the device memory object.

Each call to `vkGetMemoryFdKHR` must create a new file descriptor and transfer ownership of it to the application. To avoid leaking resources, the application must release ownership of the file descriptor using the `close` system call when it is no longer needed, or by importing a Vulkan memory object from it. Where supported by the operating system, the implementation must set the file descriptor to be closed automatically when an `execve` system call is made.

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pGetFdInfo** must be a valid pointer to a valid `VkMemoryGetFdInfoKHR` structure
- **pFd** must be a valid pointer to an `int` value

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_TOO_MANY_OBJECTS`
- `VK_ERROR_OUT_OF_HOST_MEMORY`

The `VkMemoryGetFdInfoKHR` structure is defined as:

```c
typedef struct VkMemoryGetFdInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkDeviceMemory memory;
    VkExternalMemoryHandleTypeFlagBits handleType;
} VkMemoryGetFdInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- `memory` is the memory object from which the handle will be exported.
- `handleType` is the type of handle requested.

The properties of the file descriptor exported depend on the value of `handleType`. See `VkExternalMemoryHandleTypeFlagBits` for a description of the properties of the defined external memory handle types.

### Valid Usage

- `handleType must` have been included in `VkExportMemoryAllocateInfo::handleTypes` when `memory` was created.
- `handleType must` be defined as a POSIX file descriptor handle.

### Valid Usage (Implicit)

- `sType must` be `VK_STRUCTURE_TYPE_MEMORY_GET_FD_INFO_KHR`
- `pNext must` be `NULL`
- `memory must` be a valid `VkDeviceMemory` handle
- `handleType must` be a valid `VkExternalMemoryHandleTypeFlagBits` value

POSIX file descriptor memory handles compatible with Vulkan may also be created by non-Vulkan APIs using methods beyond the scope of this specification. To determine the correct parameters to use when importing such handles, call:

```c
VkResult vkGetMemoryFdPropertiesKHR(
    VkDevice                                    device,
    VkExternalMemoryHandleTypeFlagBits          handleType,
    int                                        fd,
    VkMemoryFdPropertiesKHR*                    pMemoryFdProperties);
```

- `device` is the logical device that will be importing `fd`.
- `handleType` is the type of the handle `fd`.
- `fd` is the handle which will be imported.
- `pMemoryFdProperties` is a pointer to a `VkMemoryFdPropertiesKHR` structure in which the properties of the handle `fd` are returned.

### Valid Usage

- `fd must` be an external memory handle created outside of the Vulkan API.
- `handleType must` not be `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT_KHR`.

---

Chapter 10. Memory Allocation | 401
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **handleType** must be a valid `VkExternalMemoryHandleTypeFlagBits` value
- **pMemoryFdProperties** must be a valid pointer to a `VkMemoryFdPropertiesKHR` structure

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_INVALID_EXTERNAL_HANDLE

The `VkMemoryFdPropertiesKHR` structure returned is defined as:

```c
typedef struct VkMemoryFdPropertiesKHR {
    VkStructureType    sType;
    void*              pNext;
    uint32_t           memoryTypeBits;
} VkMemoryFdPropertiesKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **memoryTypeBits** is a bitmask containing one bit set for every memory type which the specified file descriptor can be imported as.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_MEMORY_FD_PROPERTIES_KHR`
- **pNext** must be NULL

If the **pNext** chain of `VkMemoryAllocateInfo` includes a `VkMemoryAllocateFlagsInfo` structure, then that structure includes flags and a device mask controlling how many instances of the memory will be allocated.

The `VkMemoryAllocateFlagsInfo` structure is defined as:
typedef struct VkMemoryAllocateFlagsInfo {
    VkStructureType sType;
    const void* pNext;
    VkMemoryAllocateFlags flags;
    uint32_t deviceMask;
} VkMemoryAllocateFlagsInfo;

or the equivalent

typedef VkMemoryAllocateFlagsInfo VkMemoryAllocateFlagsInfoKHR;

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is a bitmask of `VkMemoryAllocateFlagBits` controlling the allocation.
- `deviceMask` is a mask of physical devices in the logical device, indicating that memory must be allocated on each device in the mask, if `VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT` is set in `flags`.

If `VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT` is not set, the number of instances allocated depends on whether `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` is set in the memory heap. If `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` is set, then memory is allocated for every physical device in the logical device (as if `deviceMask` has bits set for all device indices). If `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` is not set, then a single instance of memory is allocated (as if `deviceMask` is set to one).

On some implementations, allocations from a multi-instance heap may consume memory on all physical devices even if the `deviceMask` excludes some devices. If `VkPhysicalDeviceGroupProperties::subsetAllocation` is `VK_TRUE`, then memory is only consumed for the devices in the device mask.

**Note**

In practice, most allocations on a multi-instance heap will be allocated across all physical devices. Unicast allocation support is an optional optimization for a minority of allocations.

**Valid Usage**

- If `VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT` is set, `deviceMask` must be a valid device mask.
- If `VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT` is set, `deviceMask` must not be zero.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO`
- **flags** must be a valid combination of `VkMemoryAllocateFlagBits` values

Bits which **can** be set in `VkMemoryAllocateFlagsInfo::flags`, controlling device memory allocation, are:

```c
typedef enum VkMemoryAllocateFlagBits {
    VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT = 0x00000001,
    VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT = 0x00000002,
    VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT = 0x00000004,
    VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT_KHR = VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT,
    VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT_KHR = VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT,
    VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT_KHR =
        VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT,
    VK_MEMORY_ALLOCATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkMemoryAllocateFlagBits;
```

or the equivalent

```c
typedef VkMemoryAllocateFlagBits VkMemoryAllocateFlagBitsKHR;
```

- **VK_MEMORY_ALLOCATE_DEVICE_MASK_BIT** specifies that memory will be allocated for the devices in `VkMemoryAllocateFlagsInfo::deviceMask`.
- **VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT** specifies that the memory **can** be attached to a buffer object created with the `VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT` bit set in `usage`, and that the memory handle **can** be used to retrieve an opaque address via `vkGetDeviceMemoryOpaqueCaptureAddress`.
- **VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT** specifies that the memory's address **can** be saved and reused on a subsequent run (e.g. for trace capture and replay), see `VkBufferOpaqueCaptureAddressCreateInfo` for more detail.

```c
typedef VkFlags VkMemoryAllocateFlags;
```

or the equivalent

```c
typedef VkMemoryAllocateFlags VkMemoryAllocateFlagsKHR;
```

`VkMemoryAllocateFlags` is a bitmask type for setting a mask of zero or more `VkMemoryAllocateFlagBits`.

To request a specific device address for a memory allocation, add a
The `VkMemoryOpaqueCaptureAddressAllocateInfo` structure is used to allocate memory with an opaque capture address. This structure is appended to the `pNext` chain of the `VkMemoryAllocateInfo` structure. The `VkMemoryOpaqueCaptureAddressAllocateInfo` structure is defined as:

```c
typedef struct VkMemoryOpaqueCaptureAddressAllocateInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint64_t           opaqueCaptureAddress;
} VkMemoryOpaqueCaptureAddressAllocateInfo;
```

or the equivalent

```c
typedef VkMemoryOpaqueCaptureAddressAllocateInfo
VkMemoryOpaqueCaptureAddressAllocateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `opaqueCaptureAddress` is the opaque capture address requested for the memory allocation.

If `opaqueCaptureAddress` is zero, no specific address is requested.

If `opaqueCaptureAddress` is not zero, it should be an address retrieved from `vkGetDeviceMemoryOpaqueCaptureAddress` on an identically created memory allocation on the same implementation.

**Note**

In most cases, it is expected that a non-zero `opaqueAddress` is an address retrieved from `vkGetDeviceMemoryOpaqueCaptureAddress` on an identically created memory allocation. If this is not the case, it likely that `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS` errors will occur.

This is, however, not a strict requirement because trace capture/replay tools may need to adjust memory allocation parameters for imported memory.

If this structure is not present, it is as if `opaqueCaptureAddress` is zero.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_MEMORY_OPAQUE_CAPTURE_ADDRESS_ALLOCATE_INFO`

To free a memory object, call:
void vkFreeMemory(
    VkDevice                                    device,
    VkDeviceMemory                              memory,
    const VkAllocationCallbacks*                pAllocator);

- **device** is the logical device that owns the memory.
- **memory** is the VkDeviceMemory object to be freed.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

Before freeing a memory object, an application must ensure the memory object is no longer in use by the device—for example by command buffers in the pending state. Memory can be freed whilst still bound to resources, but those resources must not be used afterwards. If there are still any bound images or buffers, the memory may not be immediately released by the implementation, but must be released by the time all bound images and buffers have been destroyed. Once memory is released, it is returned to the heap from which it was allocated.

How memory objects are bound to Images and Buffers is described in detail in the Resource Memory Association section.

If a memory object is mapped at the time it is freed, it is implicitly unmapped.

**Note**
As described below, host writes are not implicitly flushed when the memory object is unmapped, but the implementation must guarantee that writes that have not been flushed do not affect any other memory.

### Valid Usage

- All submitted commands that refer to memory (via images or buffers) must have completed execution

### Valid Usage (Implicit)

- **device** must be a valid VkDevice handle
- If memory is not VK_NULL_HANDLE, **memory** must be a valid VkDeviceMemory handle
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
- If memory is a valid handle, it must have been created, allocated, or retrieved from device

### Host Synchronization

- Host access to memory must be externally synchronized
10.2.1. Host Access to Device Memory Objects

Memory objects created with **vkAllocateMemory** are not directly host accessible.

Memory objects created with the memory property **VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT** are considered *mappable*. Memory objects **must** be mappable in order to be successfully mapped on the host.

To retrieve a host virtual address pointer to a region of a mappable memory object, call:

```c
vkResult vkMapMemory(
    VkDevice                                    device,  
    VkDeviceMemory                              memory,  
    VkDeviceSize                                offset,  
    VkDeviceSize                                size,  
    VkMemoryMapFlags                            flags,  
    void**                                      ppData);
```

- **device** is the logical device that owns the memory.
- **memory** is the **VkDeviceMemory** object to be mapped.
- **offset** is a zero-based byte offset from the beginning of the memory object.
- **size** is the size of the memory range to map, or **VK_WHOLE_SIZE** to map from **offset** to the end of the allocation.
- **flags** is reserved for future use.
- **pData** is a pointer to a **void** * variable in which is returned a host-accessible pointer to the beginning of the mapped range. This pointer minus **offset** **must** be aligned to at least **VkPhysicalDeviceLimits::minMemoryMapAlignment**.

After a successful call to **vkMapMemory** the memory object **memory** is considered to be currently *host mapped*.

**Note**

It is an application error to call **vkMapMemory** on a memory object that is already *host mapped*.

**Note**

**vkMapMemory** will fail if the implementation is unable to allocate an appropriately sized contiguous virtual address range, e.g. due to virtual address space fragmentation or platform limits. In such cases, **vkMapMemory** **must** return **VK_ERROR_MEMORY_MAP_FAILED**. The application can improve the likelihood of success by reducing the size of the mapped range and/or removing unneeded mappings using **vkUnmapMemory**.

**vkMapMemory** does not check whether the device memory is currently in use before returning the host-accessible pointer. The application **must** guarantee that any previously submitted command
that writes to this range has completed before the host reads from or writes to that range, and that any previously submitted command that reads from that range has completed before the host writes to that region (see here for details on fulfilling such a guarantee). If the device memory was allocated without the `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` set, these guarantees must be made for an extended range: the application must round down the start of the range to the nearest multiple of `VkPhysicalDeviceLimits::nonCoherentAtomSize`, and round the end of the range up to the nearest multiple of `VkPhysicalDeviceLimits::nonCoherentAtomSize`.

While a range of device memory is host mapped, the application is responsible for synchronizing both device and host access to that memory range.

Note

It is important for the application developer to become meticulously familiar with all of the mechanisms described in the chapter on Synchronization and Cache Control as they are crucial to maintaining memory access ordering.

Valid Usage

- memory must not be currently host mapped
- offset must be less than the size of memory
- If size is not equal to `VK_WHOLE_SIZE`, size must be greater than 0
- If size is not equal to `VK_WHOLE_SIZE`, size must be less than or equal to the size of the memory minus offset
- memory must have been created with a memory type that reports `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT`
- memory must not have been allocated with multiple instances.

Valid Usage (Implicit)

- device must be a valid `VkDevice` handle
- memory must be a valid `VkDeviceMemory` handle
- flags must be 0
- ppData must be a valid pointer to a pointer value
- memory must have been created, allocated, or retrieved from device

Host Synchronization

- Host access to memory must be externally synchronized
**Return Codes**

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_MEMORY_MAP_FAILED

```c
typedef VkFlags VkMemoryMapFlags;
```

VkMemoryMapFlags is a bitmask type for setting a mask, but is currently reserved for future use.

Two commands are provided to enable applications to work with non-coherent memory allocations: `vkFlushMappedMemoryRanges` and `vkInvalidateMappedMemoryRanges`.

**Note**
If the memory object was created with the `VK_MEMORY_PROPERTY_HOST_COHERENT_BIT` set, `vkFlushMappedMemoryRanges` and `vkInvalidateMappedMemoryRanges` are unnecessary and may have a performance cost. However, availability and visibility operations still need to be managed on the device. See the description of host access types for more information.

To flush ranges of non-coherent memory from the host caches, call:

```c
VkResult vkFlushMappedMemoryRanges(
    VkDevice device,
    uint32_t memoryRangeCount,
    const VkMappedMemoryRange* pMemoryRanges);
```

- **device** is the logical device that owns the memory ranges.
- **memoryRangeCount** is the length of the `pMemoryRanges` array.
- **pMemoryRanges** is a pointer to an array of `VkMappedMemoryRange` structures describing the memory ranges to flush.

`vkFlushMappedMemoryRanges` guarantees that host writes to the memory ranges described by `pMemoryRanges` are made available to the host memory domain, such that they can be made available to the device memory domain via memory domain operations using the `VK_ACCESS_HOST_WRITE_BIT` access type.

Within each range described by `pMemoryRanges`, each set of `nonCoherentAtomSize` bytes in that range is flushed if any byte in that set has been written by the host since it was first host mapped, or the last time it was flushed. If `pMemoryRanges` includes sets of `nonCoherentAtomSize` bytes where no bytes have been written by the host, those bytes **must** not be flushed.
Unmapping non-coherent memory does not implicitly flush the host mapped memory, and host writes that have not been flushed may not ever be visible to the device. However, implementations must ensure that writes that have not been flushed do not become visible to any other memory.

**Note**
The above guarantee avoids a potential memory corruption in scenarios where host writes to a mapped memory object have not been flushed before the memory is unmapped (or freed), and the virtual address range is subsequently reused for a different mapping (or memory allocation).

### Valid Usage (Implicit)
- **device** must be a valid `VkDevice` handle
- **pMemoryRanges** must be a valid pointer to an array of `memoryRangeCount` valid `VkMappedMemoryRange` structures
- **memoryRangeCount** must be greater than 0

### Return Codes
**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

To invalidate ranges of non-coherent memory from the host caches, call:

```c
VkResult vkInvalidateMappedMemoryRanges(
    VkDevice                                    device,
    uint32_t                                    memoryRangeCount,
    const            VkMappedMemoryRange*                  pMemoryRanges);
```

- **device** is the logical device that owns the memory ranges.
- **memoryRangeCount** is the length of the **pMemoryRanges** array.
- **pMemoryRanges** is a pointer to an array of `VkMappedMemoryRange` structures describing the memory ranges to invalidate.

`vkInvalidateMappedMemoryRanges` guarantees that device writes to the memory ranges described by **pMemoryRanges**, which have been made available to the host memory domain using the **VK_ACCESS_HOST_WRITE_BIT** and **VK_ACCESS_HOST_READ_BIT** access types, are made visible to the host. If a range of non-coherent memory is written by the host and then invalidated without first being flushed, its contents are undefined.
Within each range described by `pMemoryRanges`, each set of `nonCoherentAtomSize` bytes in that range is invalidated if any byte in that set has been written by the device since it was first host mapped, or the last time it was invalidated.

**Note**

Mapping non-coherent memory does not implicitly invalidate that memory.

---

**Valid Usage (Implicit)**

- `device` **must** be a valid `VkDevice` handle
- `pMemoryRanges` **must** be a valid pointer to an array of `memoryRangeCount` valid `VkMappedMemoryRange` structures
- `memoryRangeCount` **must** be greater than 0

---

**Return Codes**

**Success**

- `VK_SUCCESS`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

---

The `VkMappedMemoryRange` structure is defined as:

```c
typedef struct VkMappedMemoryRange {
    VkStructureType    sType;
    const void*        pNext;
    VkDeviceMemory     memory;
    VkDeviceSize       offset;
    VkDeviceSize       size;
} VkMappedMemoryRange;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `memory` is the memory object to which this range belongs.
- `offset` is the zero-based byte offset from the beginning of the memory object.
- `size` is either the size of range, or `VK_WHOLE_SIZE` to affect the range from `offset` to the end of the current mapping of the allocation.
Valid Usage

- **memory** must be currently host mapped
- If `size` is not equal to `VK_WHOLE_SIZE`, `offset` and `size` must specify a range contained within the currently mapped range of `memory`
- If `size` is equal to `VK_WHOLE_SIZE`, `offset` must be within the currently mapped range of `memory`
- If `size` is equal to `VK_WHOLE_SIZE`, the end of the current mapping of `memory` must be a multiple of `VkPhysicalDeviceLimits::nonCoherentAtomSize` bytes from the beginning of the memory object.
- `offset` must be a multiple of `VkPhysicalDeviceLimits::nonCoherentAtomSize`
- If `size` is not equal to `VK_WHOLE_SIZE`, `size` must either be a multiple of `VkPhysicalDeviceLimits::nonCoherentAtomSize`, or `offset` plus `size` must equal the size of `memory`.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_MAPPED_MEMORY_RANGE`
- **pNext** must be `NULL`
- **memory** must be a valid `VkDeviceMemory` handle

To unmap a memory object once host access to it is no longer needed by the application, call:

```c
void vkUnmapMemory(
    VkDevice device,
    VkDeviceMemory memory);
```

- **device** is the logical device that owns the memory.
- **memory** is the memory object to be unmapped.

Valid Usage

- **memory** must be currently host mapped

Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **memory** must be a valid `VkDeviceMemory` handle
- **memory** must have been created, allocated, or retrieved from `device`
10.2.2. Lazily Allocated Memory

If the memory object is allocated from a heap with the `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` bit set, that object's backing memory may be provided by the implementation lazily. The actual committed size of the memory may initially be as small as zero (or as large as the requested size), and monotonically increases as additional memory is needed.

A memory type with this flag set is only allowed to be bound to a `VkImage` whose usage flags include `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`.

**Note**

Using lazily allocated memory objects for framebuffer attachments that are not needed once a render pass instance has completed may allow some implementations to never allocate memory for such attachments.

To determine the amount of lazily-allocated memory that is currently committed for a memory object, call:

```c
void vkGetDeviceMemoryCommitment(
    VkDevice device,           
    VkDeviceMemory memory,    
    VkDeviceSize* pCommittedMemoryInBytes);
```

- `device` is the logical device that owns the memory.
- `memory` is the memory object being queried.
- `pCommittedMemoryInBytes` is a pointer to a `VkDeviceSize` value in which the number of bytes currently committed is returned, on success.

The implementation may update the commitment at any time, and the value returned by this query may be out of date.

The implementation guarantees to allocate any committed memory from the `heapIndex` indicated by the memory type that the memory object was created with.

**Valid Usage**

- `memory` must have been created with a memory type that reports `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT`
Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `memory` must be a valid `VkDeviceMemory` handle
- `pCommittedMemoryInBytes` must be a valid pointer to a `VkDeviceSize` value
- `memory` must have been created, allocated, or retrieved from `device`

10.2.3. Protected Memory

`Protected memory` divides device memory into protected device memory and unprotected device memory.

Protected memory adds the following concepts:

- **Memory:**
  - Unprotected device memory, which **can** be visible to the device and **can** be visible to the host
  - Protected device memory, which **can** be visible to the device but **must** not be visible to the host

- **Resources:**
  - Unprotected images and unprotected buffers, to which unprotected memory **can** be bound
  - Protected images and protected buffers, to which protected memory **can** be bound

- **Command buffers:**
  - Unprotected command buffers, which **can** be submitted to a device queue to execute unprotected queue operations
  - Protected command buffers, which **can** be submitted to a protected-capable device queue to execute protected queue operations

- **Device queues:**
  - Unprotected device queues, to which unprotected command buffers **can** be submitted
  - Protected-capable device queues, to which unprotected command buffers or protected command buffers **can** be submitted

- **Queue submissions**
  - Unprotected queue submissions, through which unprotected command buffers **can** be submitted
  - Protected queue submissions, through which protected command buffers **can** be submitted

- **Queue operations**
  - Unprotected queue operations
  - Protected queue operations
**Protected Memory Access Rules**

If `VkPhysicalDeviceProtectedMemoryProperties::protectedNoFault` is `VK_FALSE`, applications **must** not perform any of the following operations:

- Write to unprotected memory within protected queue operations.
- Access protected memory within protected queue operations other than in framebuffer-space pipeline stages, the compute shader stage, or the transfer stage.
- Perform a query within protected queue operations.
- Execute an indirect command within protected queue operations.

If `VkPhysicalDeviceProtectedMemoryProperties::protectedNoFault` is `VK_TRUE`, these operations are valid, but reads will return undefined values, and writes will either be dropped or store undefined values.

Whether these operations are valid or not, or if any other invalid usage is performed, the implementation **must** guarantee that:

- Protected device memory **must** never be visible to the host.
- Values written to unprotected device memory **must** not be a function of values from protected memory.

### 10.2.4. Peer Memory Features

*Peer memory* is memory that is allocated for a given physical device and then bound to a resource and accessed by a different physical device, in a logical device that represents multiple physical devices. Some ways of reading and writing peer memory **may** not be supported by a device.

To determine how peer memory **can** be accessed, call:

```c
void vkGetDeviceGroupPeerMemoryFeatures(
    VkDevice                                    device,
    uint32_t                                    heapIndex,
    uint32_t                                    localDeviceIndex,
    uint32_t                                    remoteDeviceIndex,
    VkPeerMemoryFeatureFlags*                   pPeerMemoryFeatures);
```

or the equivalent command

```c
void vkGetDeviceGroupPeerMemoryFeaturesKHR(
    VkDevice                                    device,
    uint32_t                                    heapIndex,
    uint32_t                                    localDeviceIndex,
    uint32_t                                    remoteDeviceIndex,
    VkPeerMemoryFeatureFlags*                   pPeerMemoryFeatures);
```

- **device** is the logical device that owns the memory.
• heapIndex is the index of the memory heap from which the memory is allocated.
• localDeviceIndex is the device index of the physical device that performs the memory access.
• remoteDeviceIndex is the device index of the physical device that the memory is allocated for.
• pPeerMemoryFeatures is a pointer to a VkPeerMemoryFeatureFlags bitmask indicating which types of memory accesses are supported for the combination of heap, local, and remote devices.

### Valid Usage

- heapIndex must be less than memoryHeapCount
- localDeviceIndex must be a valid device index
- remoteDeviceIndex must be a valid device index
- localDeviceIndex must not equal remoteDeviceIndex

### Valid Usage (Implicit)

- device must be a valid VkDevice handle
- pPeerMemoryFeatures must be a valid pointer to a VkPeerMemoryFeatureFlags value

Bits which may be set in the value returned for vkGetDeviceGroupPeerMemoryFeatures::pPeerMemoryFeatures, indicating the supported peer memory features, are:

```cpp
typedef enum VkPeerMemoryFeatureFlagBits {
    VK_PEER_MEMORY_FEATURE_COPY_SRC_BIT = 0x00000001,
    VK_PEER_MEMORY_FEATURE_COPY_DST_BIT = 0x00000002,
    VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT = 0x00000004,
    VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT = 0x00000008,
    VK_PEER_MEMORY_FEATURE_COPY_SRC_BIT_KHR = VK_PEER_MEMORY_FEATURE_COPY_SRC_BIT,
    VK_PEER_MEMORY_FEATURE_COPY_DST_BIT_KHR = VK_PEER_MEMORY_FEATURE_COPY_DST_BIT,
    VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT_KHR = VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT,
    VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT_KHR = VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT,
    VK_PEER_MEMORY_FEATURE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkPeerMemoryFeatureFlagBits;
```

or the equivalent

```cpp
typedef VkPeerMemoryFeatureFlagBits VkPeerMemoryFeatureFlagBitsKHR;
```

- VK_PEER_MEMORY_FEATURE_COPY_SRC_BIT specifies that the memory can be accessed as the source of a vkCmdCopyBuffer, vkCmdCopyImage, vkCmdCopyBufferToImage, or vkCmdCopyImageToBuffer command.
• **VK_PEER_MEMORY_FEATURE_COPY_DST_BIT** specifies that the memory **can** be accessed as the destination of a *vkCmdCopyBuffer*, *vkCmdCopyImage*, *vkCmdCopyBufferToImage*, or *vkCmdCopyImageToBuffer* command.

• **VK_PEER_MEMORY_FEATURE_GENERIC_SRC_BIT** specifies that the memory **can** be read as any memory access type.

• **VK_PEER_MEMORY_FEATURE_GENERIC_DST_BIT** specifies that the memory **can** be written as any memory access type. Shader atomics are considered to be writes.

  **Note**
  
  The peer memory features of a memory heap also apply to any accesses that **may** be performed during *image layout transitions*.

**VK_PEER_MEMORY_FEATURE_COPY_DST_BIT** **must** be supported for all host local heaps and for at least one device local heap.

If a device does not support a peer memory feature, it is still valid to use a resource that includes both local and peer memory bindings with the corresponding access type as long as only the local bindings are actually accessed. For example, an application doing split-frame rendering would use framebuffer attachments that include both local and peer memory bindings, but would scissor the rendering to only update local memory.

```c
typedef VkFlags VkPeerMemoryFeatureFlags;
```

or the equivalent

```c
typedef VkPeerMemoryFeatureFlags VkPeerMemoryFeatureFlagsKHR;
```

**VkPeerMemoryFeatureFlags** is a bitmask type for setting a mask of zero or more **VkPeerMemoryFeatureFlagBits**.

To query a 64-bit opaque capture address value from a memory object, call:

```c
uint64_t vkGetDeviceMemoryOpaqueCaptureAddressKHR(
    VkDevice device,
    const VkDeviceMemoryOpaqueCaptureAddressInfo* pInfo);
```

• **device** is the logical device that the memory object was allocated on.

• **pInfo** is a pointer to a **VkDeviceMemoryOpaqueCaptureAddressInfo** structure specifying the memory object to retrieve an address for.

The 64-bit return value is an opaque address representing the start of **pInfo->memory**.

If the memory object was allocated with a non-zero value of **VkMemoryOpaqueCaptureAddressAllocateInfo::opaqueCaptureAddress**, the return value **must** be the same address.
Note
The expected usage for these opaque addresses is only for trace capture/replay tools to store these addresses in a trace and subsequently specify them during replay.

Valid Usage
- The bufferDeviceAddress feature must be enabled
- If device was created with multiple physical devices, then the bufferDeviceAddressMultiDevice feature must be enabled

Valid Usage (Implicit)
- device must be a valid VkDevice handle
- pInfo must be a valid pointer to a valid VkDeviceMemoryOpaqueCaptureAddressInfo structure

The VkDeviceMemoryOpaqueCaptureAddressInfo structure is defined as:

```c
typedef struct VkDeviceMemoryOpaqueCaptureAddressInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkDeviceMemory     memory;
} VkDeviceMemoryOpaqueCaptureAddressInfo;
```

or the equivalent

```c
typedef VkDeviceMemoryOpaqueCaptureAddressInfo
    VkDeviceMemoryOpaqueCaptureAddressInfoKHR;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- memory specifies the memory whose address is being queried.

Valid Usage
- memory must have been allocated with VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_DEVICE_MEMORY_OPAQUE_CAPTURE_ADDRESS_INFO`
- **pNext** must be `NULL`
- **memory** must be a valid `VkDeviceMemory` handle
Chapter 11. Resource Creation

Vulkan supports two primary resource types: *buffers* and *images*. Resources are views of memory with associated formatting and dimensionality. Buffers are essentially unformatted arrays of bytes whereas images contain format information, *can* be multidimensional and *may* have associated metadata.

### 11.1. Buffers

Buffers represent linear arrays of data which are used for various purposes by binding them to a graphics or compute pipeline via descriptor sets or via certain commands, or by directly specifying them as parameters to certain commands.

Buffers are represented by `VkBuffer` handles:

```cpp
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkBuffer)
```

To create buffers, call:

```cpp
VkResult vkCreateBuffer(
    VkDevice device,  // Logical device that creates the buffer object.
    const VkBufferCreateInfo* pCreateInfo,  // Pointer to a VkBufferCreateInfo structure containing parameters affecting creation of the buffer.
    const VkAllocationCallbacks* pAllocator,  // Controls host memory allocation as described in the Memory Allocation chapter.
    VkBuffer* pBuffer)  // Pointer to a VkBuffer handle in which the resulting buffer object is returned.
```

- `device` is the logical device that creates the buffer object.
- `pCreateInfo` is a pointer to a `VkBufferCreateInfo` structure containing parameters affecting creation of the buffer.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pBuffer` is a pointer to a `VkBuffer` handle in which the resulting buffer object is returned.

#### Valid Usage

- If the `flags` member of `pCreateInfo` includes `VK_BUFFER_CREATE_SPARSE_BINDING_BIT`, creating this `VkBuffer` must not cause the total required sparse memory for all currently valid sparse resources on the device to exceed `VkPhysicalDeviceLimits::sparseAddressSpaceSize`
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkBufferCreateInfo` structure
- If **pAllocator** is not `NULL`, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pBuffer** must be a valid pointer to a `VkBuffer` handle

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR`

The `VkBufferCreateInfo` structure is defined as:

```c
typedef struct VkBufferCreateInfo {
    VkStructureType        sType;
    const void*            pNext;
    VkBufferCreateFlags    flags;
    VkDeviceSize           size;
    VkBufferUsageFlags     usage;
    VkSharingMode          sharingMode;
    uint32_t               queueFamilyIndexCount;
    const uint32_t*        pQueueFamilyIndices;
} VkBufferCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **flags** is a bitmask of `VkBufferCreateFlagBits` specifying additional parameters of the buffer.
- **size** is the size in bytes of the buffer to be created.
- **usage** is a bitmask of `VkBufferUsageFlagBits` specifying allowed usages of the buffer.
- **sharingMode** is a `VkSharingMode` value specifying the sharing mode of the buffer when it will be accessed by multiple queue families.
- **queueFamilyIndexCount** is the number of entries in the `pQueueFamilyIndices` array.
- **pQueueFamilyIndices** is a list of queue families that will access this buffer (ignored if **sharingMode** is not `VK_SHARING_MODE_CONCURRENT`).
Valid Usage

- **size must** be greater than 0

- If `sharingMode` is `VK_SHARING_MODE_CONCURRENT`, `pQueueFamilyIndices` **must** be a valid pointer to an array of `queueFamilyIndexCount uint32_t` values

- If `sharingMode` is `VK_SHARING_MODE_CONCURRENT`, `queueFamilyIndexCount` **must** be greater than 1

- If `sharingMode` is `VK_SHARING_MODE_CONCURRENT`, each element of `pQueueFamilyIndices` **must** be unique and **must** be less than `pQueueFamilyPropertyCount` returned by either `vkGetPhysicalDeviceQueueFamilyProperties` or `vkGetPhysicalDeviceQueueFamilyProperties2` for the `physicalDevice` that was used to create device

- If the **sparse bindings** feature is not enabled, **flags** **must** not contain `VK_BUFFER_CREATE_SPARSE_BINDING_BIT`

- If the **sparse buffer residency** feature is not enabled, **flags** **must** not contain `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT`

- If the **sparse aliased residency** feature is not enabled, **flags** **must** not contain `VK_BUFFER_CREATE_SPARSE_ALIASED_BIT`

- If **flags** contains `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` or `VK_BUFFER_CREATE_SPARSE_ALIASED_BIT`, it **must** also contain `VK_BUFFER_CREATE_SPARSE_BINDING_BIT`

- If the `pNext` chain includes a `VkExternalMemoryBufferCreateInfo` structure, its `handleTypes` member **must** only contain bits that are also in `VkExternalBufferProperties::externalMemoryProperties.compatibleHandleTypes`, as returned by `vkGetPhysicalDeviceExternalBufferProperties` with `pExternalBufferInfo->handleType` equal to any one of the handle types specified in `VkExternalMemoryBufferCreateInfo::handleTypes`

- If the protected memory feature is not enabled, **flags** **must** not contain `VK_BUFFER_CREATE_PROTECTED_BIT`

- If any of the bits `VK_BUFFER_CREATE_SPARSE_BINDING_BIT`, `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT`, or `VK_BUFFER_CREATE_SPARSE_ALIASED_BIT` are set, `VK_BUFFER_CREATE_PROTECTED_BIT` **must** not also be set

- If `VkBufferOpaqueCaptureAddressCreateInfo::opaqueCaptureAddress` is not zero, **flags** **must** include `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`

- If **flags** includes `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`, the `bufferDeviceAddressCaptureReplay` or `VkPhysicalDeviceBufferDeviceAddressFeaturesEXT::bufferDeviceAddressCaptureReplay` feature **must** be enabled
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO`
- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkBufferOpaqueCaptureAddressCreateInfo` or `VkExternalMemoryBufferCreateInfo`
- The `sType` value of each struct in the `pNext` chain must be unique
- `flags` must be a valid combination of `VkBufferCreateFlagBits` values
- `usage` must be a valid combination of `VkBufferUsageFlagBits` values
- `usage` must not be 0
- `sharingMode` must be a valid `VkSharingMode` value

Bits which can be set in `VkBufferCreateInfo::usage`, specifying usage behavior of a buffer, are:

```c
typedef enum VkBufferUsageFlagBits {
    VK_BUFFER_USAGE_TRANSFER_SRC_BIT = 0x00000001,
    VK_BUFFER_USAGE_TRANSFER_DST_BIT = 0x00000002,
    VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT = 0x00000004,
    VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT = 0x00000008,
    VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT = 0x00000010,
    VK_BUFFER_USAGE_STORAGE_BUFFER_BIT = 0x00000020,
    VK_BUFFER_USAGE_INDEX_BUFFER_BIT = 0x00000040,
    VK_BUFFER_USAGE_VERTEX_BUFFER_BIT = 0x00000080,
    VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT = 0x00000100,
    VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT = 0x00020000,
    VK_BUFFER_USAGE_RAY_TRACING_BIT_KHR = 0x00000400,
    VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT_KHR = VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT,
    VK_BUFFER_USAGE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkBufferUsageFlagBits;
```

- `VK_BUFFER_USAGE_TRANSFER_SRC_BIT` specifies that the buffer can be used as the source of a transfer command (see the definition of `VK_PIPELINE_STAGE_TRANSFER_BIT`).
- `VK_BUFFER_USAGE_TRANSFER_DST_BIT` specifies that the buffer can be used as the destination of a transfer command.
- `VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT` specifies that the buffer can be used to create a `VkBufferView` suitable for occupying a `VkDescriptorSet` slot of type `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER`.
- `VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT` specifies that the buffer can be used to create a `VkBufferView` suitable for occupying a `VkDescriptorSet` slot of type `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`.
- `VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT` specifies that the buffer can be used in a `VkDescriptorBufferInfo` suitable for occupying a `VkDescriptorSet` slot either of type
VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC.

- VK_BUFFER_USAGE_STORAGE_BUFFER_BIT specifies that the buffer can be used in a VkDescriptorBufferInfo suitable for occupying a VkDescriptorSet slot either of type VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC.

- VK_BUFFER_USAGE_INDEX_BUFFER_BIT specifies that the buffer is suitable for passing as the buffer parameter to vkCmdBindIndexBuffer.

- VK_BUFFER_USAGE_VERTEX_BUFFER_BIT specifies that the buffer is suitable for passing as an element of the pBuffers array to vkCmdBindVertexBuffers.

- VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT specifies that the buffer is suitable for passing as the buffer parameter to vkCmdDrawIndirect, vkCmdDrawIndexedIndirect, or vkCmdDispatchIndirect.

- VK_BUFFER_USAGE_RAY_TRACING_BIT_KHR specifies that the buffer is suitable for use in vkCmdTraceRaysKHR and vkCmdBuildAccelerationStructureKHR.

- VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT specifies that the buffer can be used to retrieve a buffer device address via vkGetBufferDeviceAddress and use that address to access the buffer’s memory from a shader.

```c
typedef VkFlags VkBufferUsageFlags;
```

VkBufferUsageFlags is a bitmask type for setting a mask of zero or more VkBufferUsageFlagBits.

Bits which can be set in VkBufferCreateInfo::flags, specifying additional parameters of a buffer, are:

```c
typedef enum VkBufferCreateFlagBits {
    VK_BUFFER_CREATE_SPARSE_BINDING_BIT = 0x00000001,
    VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT = 0x00000002,
    VK_BUFFER_CREATE_SPARSE_ALIASED_BIT = 0x00000004,
    VK_BUFFER_CREATE_PROTECTED_BIT = 0x00000008,
    VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT = 0x00000010,
    VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT_KHR =
    VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT,
    VK_BUFFER_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkBufferCreateFlagBits;
```

- VK_BUFFER_CREATE_SPARSE_BINDING_BIT specifies that the buffer will be backed using sparse memory binding.

- VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT specifies that the buffer can be partially backed using sparse memory binding. Buffers created with this flag must also be created with the VK_BUFFER_CREATE_SPARSE_BINDING_BIT flag.

- VK_BUFFER_CREATE_SPARSE_ALIASED_BIT specifies that the buffer will be backed using sparse memory binding with memory ranges that might also simultaneously be backing another buffer (or another portion of the same buffer). Buffers created with this flag must also be created with the VK_BUFFER_CREATE_SPARSE_BINDING_BIT flag.
• `VK_BUFFER_CREATE_PROTECTED_BIT` specifies that the buffer is a protected buffer.

• `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT` specifies that the buffer’s address can be saved and reused on a subsequent run (e.g. for trace capture and replay), see `VkBufferOpaqueCaptureAddressCreateInfo` for more detail.

See Sparse Resource Features and Physical Device Features for details of the sparse memory features supported on a device.

```c
typedef VkFlags VkBufferCreateFlags;
```

`VkBufferCreateFlags` is a bitmask type for setting a mask of zero or more `VkBufferCreateFlagBits`.

To define a set of external memory handle types that may be used as backing store for a buffer, add a `VkExternalMemoryBufferCreateInfo` structure to the `pNext` chain of the `VkBufferCreateInfo` structure. The `VkExternalMemoryBufferCreateInfo` structure is defined as:

```c
typedef struct VkExternalMemoryBufferCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlags handleTypes;
} VkExternalMemoryBufferCreateInfo;
```

or the equivalent

```c
typedef VkExternalMemoryBufferCreateInfo VkExternalMemoryBufferCreateInfoKHR;
```

**Note**

A `VkExternalMemoryBufferCreateInfo` structure must be included in the creation parameters for a buffer that will be bound to memory that is either exported or imported.

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `handleTypes` is a bitmask of `VkExternalMemoryHandleTypeFlagBits` specifying one or more external memory handle types.

**Valid Usage (Implicit)**

- `sType` **must** be `VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO`
- `handleTypes` **must** be a valid combination of `VkExternalMemoryHandleTypeFlagBits` values

To request a specific device address for a buffer, add a `VkBufferOpaqueCaptureAddressCreateInfo`
structure to the `pNext` chain of the `VkBufferCreateInfo` structure. The `VkBufferOpaqueCaptureAddressCreateInfo` structure is defined as:

```c
typedef struct VkBufferOpaqueCaptureAddressCreateInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint64_t           opaqueCaptureAddress;
} VkBufferOpaqueCaptureAddressCreateInfo;
```

or the equivalent

```c
typedef VkBufferOpaqueCaptureAddressCreateInfo
VkBufferOpaqueCaptureAddressCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `opaqueCaptureAddress` is the opaque capture address requested for the buffer.

If `opaqueCaptureAddress` is zero, no specific address is requested.

If `opaqueCaptureAddress` is not zero, then it should be an address retrieved from `vkGetBufferOpaqueCaptureAddress` for an identically created buffer on the same implementation.

If this structure is not present, it is as if `opaqueCaptureAddress` is zero.

Apps should avoid creating buffers with app-provided addresses and implementation-provided addresses in the same process, to reduce the likelihood of `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS` errors.

**Note**

The expected usage for this is that a trace capture/replay tool will add the `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT` flag to all buffers that use `VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT`, and during capture will save the queried opaque device addresses in the trace. During replay, the buffers will be created specifying the original address so any address values stored in the trace data will remain valid.

Implementations are expected to separate such buffers in the GPU address space so normal allocations will avoid using these addresses. Apps/tools should avoid mixing app-provided and implementation-provided addresses for buffers created with `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT`, to avoid address space allocation conflicts.
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_BUFFER_OPAQUE_CAPTURE_ADDRESS_CREATE_INFO`

To destroy a buffer, call:

```c
void vkDestroyBuffer(
    VkDevice device,
    VkBuffer buffer,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the buffer.
- `buffer` is the buffer to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

- All submitted commands that refer to `buffer`, either directly or via a `VkBufferView`, must have completed execution
- If `VkAllocationCallbacks` were provided when `buffer` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `buffer` was created, `pAllocator` must be `NULL`

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- If `buffer` is not `VK_NULL_HANDLE`, `buffer` must be a valid `VkBuffer` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `buffer` is a valid handle, it must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `buffer` must be externally synchronized

11.2. Buffer Views

A `buffer view` represents a contiguous range of a buffer and a specific format to be used to interpret the data. Buffer views are used to enable shaders to access buffer contents interpreted as formatted
data. In order to create a valid buffer view, the buffer **must** have been created with at least one of the following usage flags:

- VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT
- VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT

Buffer views are represented by `VkBufferView` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkBufferView)
```

To create a buffer view, call:

```c
VkResult vkCreateBufferView(
    VkDevice                                    device,
    const VkBufferViewCreateInfo*               pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkBufferView*                               pView);
```

- *device* is the logical device that creates the buffer view.
- *pCreateInfo* is a pointer to a `VkBufferViewCreateInfo` structure containing parameters to be used to create the buffer.
- *pAllocator* controls host memory allocation as described in the [Memory Allocation](#) chapter.
- *pView* is a pointer to a `VkBufferView` handle in which the resulting buffer view object is returned.

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkBufferViewCreateInfo` structure
- If *pAllocator* is not NULL, *pAllocator* must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pView** must be a valid pointer to a `VkBufferView` handle

### Return Codes

**Success**

- **VK_SUCCESS**

**Failure**

- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

The `VkBufferViewCreateInfo` structure is defined as:
typedef struct VkBufferViewCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkBufferViewCreateFlags flags;
    VkBuffer buffer;
    VkFormat format;
    VkDeviceSize offset;
    VkDeviceSize range;
} VkBufferViewCreateInfo;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **buffer** is a **VkBuffer** on which the view will be created.
- **format** is a **VkFormat** describing the format of the data elements in the buffer.
- **offset** is an offset in bytes from the base address of the buffer. Accesses to the buffer view from shaders use addressing that is relative to this starting offset.
- **range** is a size in bytes of the buffer view. If **range** is equal to **VK_WHOLE_SIZE**, the range from **offset** to the end of the buffer is used. If **VK_WHOLE_SIZE** is used and the remaining size of the buffer is not a multiple of the texel block size of **format**, the nearest smaller multiple is used.
Valid Usage

- **offset** must be less than the size of **buffer**
- **offset** must be a multiple of **VkPhysicalDeviceLimits.minTexelBufferOffsetAlignment**
- If **range** is not equal to **VK_WHOLE_SIZE**, **range** must be greater than 0
- If **range** is not equal to **VK_WHOLE_SIZE**, **range** must be an integer multiple of the texel block size of **format**
- If **range** is not equal to **VK_WHOLE_SIZE**, **range** divided by the texel block size of **format**, multiplied by the number of texels per texel block for that format (as defined in the Compatible Formats table), **must** be less than or equal to **VkPhysicalDeviceLimits.maxTexelBufferElements**
- If **range** is not equal to **VK_WHOLE_SIZE**, the sum of **offset** and **range** must be less than or equal to the size of **buffer**
- **buffer** must have been created with a **usage** value containing at least one of **VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT** or **VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT**
- If **buffer** was created with **usage** containing **VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT**, **format** must be supported for uniform texel buffers, as specified by the **VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT** flag in **VkFormatProperties::bufferFeatures** returned by **vkGetPhysicalDeviceFormatProperties**
- If **buffer** was created with **usage** containing **VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT**, **format** must be supported for storage texel buffers, as specified by the **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT** flag in **VkFormatProperties::bufferFeatures** returned by **vkGetPhysicalDeviceFormatProperties**
- If **buffer** is non-sparse then it must be bound completely and contiguously to a single **VkDeviceMemory** object

Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_BUFFER_VIEW_CREATE_INFO**
- **pNext** must be **NULL**
- **flags** must be 0
- **buffer** must be a valid **VkBuffer** handle
- **format** must be a valid **VkFormat** value

```cpp
typedef VkFlags VkBufferViewCreateFlags;
```

**VkBufferViewCreateFlags** is a bitmask type for setting a mask, but is currently reserved for future use.

To destroy a buffer view, call:
```c
void vkDestroyBufferView(
    VkDevice device,           // Logical device that destroys the buffer view.
    VkBufferView bufferView,  // Buffer view to destroy.
    const VkAllocationCallbacks* pAllocator); // Controls host memory allocation as described in the Memory Allocation chapter.
```

- `device` is the logical device that destroys the buffer view.
- `bufferView` is the buffer view to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- All submitted commands that refer to `bufferView` must have completed execution.
- If `VkAllocationCallbacks` were provided when `bufferView` was created, a compatible set of callbacks must be provided here.
- If no `VkAllocationCallbacks` were provided when `bufferView` was created, `pAllocator` must be `NULL`.

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle.
- If `bufferView` is not `VK_NULL_HANDLE`, `bufferView` must be a valid `VkBufferView` handle.
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.
- If `bufferView` is a valid handle, it must have been created, allocated, or retrieved from `device`.

### Host Synchronization

- Host access to `bufferView` must be externally synchronized.

### 11.3. Images

Images represent multidimensional - up to 3 - arrays of data which can be used for various purposes (e.g. attachments, textures), by binding them to a graphics or compute pipeline via descriptor sets, or by directly specifying them as parameters to certain commands.

Images are represented by `VkImage` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImage)
```
To create images, call:

```c
VkResult vkCreateImage(
    VkDevice                                    device,
    const
    VkImageCreateInfo*                    pCreateInfo,
    const
    VkAllocationCallbacks*                pAllocator,
    VkImage*                                    pImage);
```

- **device** is the logical device that creates the image.
- **pCreateInfo** is a pointer to a `VkImageCreateInfo` structure containing parameters to be used to create the image.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pImage** is a pointer to a `VkImage` handle in which the resulting image object is returned.

### Valid Usage

- If the **flags** member of **pCreateInfo** includes `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`, creating this `VkImage` **must** not cause the total required sparse memory for all currently valid sparse resources on the device to exceed `VkPhysicalDeviceLimits::sparseAddressSpaceSize`

### Valid Usage (Implicit)

- **device** **must** be a valid `VkDevice` handle
- **pCreateInfo** **must** be a valid pointer to a valid `VkImageCreateInfo` structure
- If **pAllocator** is not **NULL**, **pAllocator** **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pImage** **must** be a valid pointer to a `VkImage` handle

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkImageCreateInfo` structure is defined as:
typedef struct VkImageCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkImageCreateFlags flags;
    VkImageType imageType;
    VkFormat format;
    VkExtent3D extent;
    uint32_t mipLevels;
    uint32_t arrayLayers;
    VkSampleCountFlagBits samples;
    VkImageTiling tiling;
    VkImageUsageFlags usage;
    VkSharingMode sharingMode;
    uint32_t queueFamilyIndexCount;
    const uint32_t* pQueueFamilyIndices;
    VkImageLayout initialLayout;
} VkImageCreateInfo;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• flags is a bitmask of VkImageCreateFlagBits describing additional parameters of the image.
• imageType is a VkImageType value specifying the basic dimensionality of the image. Layers in array textures do not count as a dimension for the purposes of the image type.
• format is a VkFormat describing the format and type of the texel blocks that will be contained in the image.
• extent is a VkExtent3D describing the number of data elements in each dimension of the base level.
• mipLevels describes the number of layers of detail available for minified sampling of the image.
• arrayLayers is the number of layers in the image.
• samples is a VkSampleCountFlagBits specifying the number of samples per texel.
• tiling is a VkImageTiling value specifying the tiling arrangement of the texel blocks in memory.
• usage is a bitmask of VkImageUsageFlagBits describing the intended usage of the image.
• sharingMode is a VkSharingMode value specifying the sharing mode of the image when it will be accessed by multiple queue families.
• queueFamilyIndexCount is the number of entries in the pQueueFamilyIndices array.
• pQueueFamilyIndices is a list of queue families that will access this image (ignored if sharingMode is not VK_SHARING_MODE_CONCURRENT).
• initialLayout is a VkImageLayout value specifying the initial VkImageLayout of all image subresources of the image. See Image Layouts.

Images created with tiling equal to VK_IMAGE_TILING_LINEAR have further restrictions on their limits and capabilities compared to images created with tiling equal to VK_IMAGE_TILING_OPTIMAL. Creation
of images with tiling `VK_IMAGE_TILING_LINEAR` may not be supported unless other parameters meet all of the constraints:

- `imageType` is `VK_IMAGE_TYPE_2D`
- `format` is not a depth/stencil format
- `mipLevels` is 1
- `arrayLayers` is 1
- `samples` is `VK_SAMPLE_COUNT_1_BIT`
- `usage` only includes `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` and/or `VK_IMAGE_USAGE_TRANSFER_DST_BIT`

Images created with a `format` from one of those listed in Formats requiring sampler $Y'CbCr$ conversion for `VK_IMAGE_ASPECT_COLOR_BIT` image views have further restrictions on their limits and capabilities compared to images created with other formats. Creation of images with a format requiring $Y'CbCr$ conversion may not be supported unless other parameters meet all of the constraints:

- `imageType` is `VK_IMAGE_TYPE_2D`
- `mipLevels` is 1
- `arrayLayers` is 1
- `samples` is `VK_SAMPLE_COUNT_1_BIT`

Implementations may support additional limits and capabilities beyond those listed above.

To determine the set of valid `usage` bits for a given format, call `vkGetPhysicalDeviceFormatProperties`.

If the size of the resultant image would exceed `maxResourceSize`, then `vkCreateImage` must fail and return `VK_ERROR_OUT_OF_DEVICE_MEMORY`. This failure may occur even when all image creation parameters satisfy their valid usage requirements.

---

**Note**

For images created without `VK_IMAGE_CREATE_EXTENDED_USAGE_BIT` a `usage` bit is valid if it is supported for the format the image is created with.

For images created with `VK_IMAGE_CREATE_EXTENDED_USAGE_BIT` a `usage` bit is valid if it is supported for at least one of the formats a `VkImageView` created from the image can have (see Image Views for more detail).
Image Creation Limits

Valid values for some image creation parameters are limited by a numerical upper bound or by inclusion in a bitset. For example, `VkImageCreateInfo::arrayLayers` is limited by `imageCreateMaxArrayLayers`, defined below; and `VkImageCreateInfo::samples` is limited by `imageCreateSampleCounts`, also defined below.

Several limiting values are defined below, as well as assisting values from which the limiting values are derived. The limiting values are referenced by the relevant valid usage statements of `VkImageCreateInfo`.

- Let `VkBool32 imageCreateMaybeLinear` indicate if the resultant image may be linear. (The definition below is trivial because certain extensions are disabled in this build of the specification).
  - If `tiling` is `VK_IMAGE_TILING_LINEAR`, then `imageCreateMaybeLinear` is true.
  - If `tiling` is `VK_IMAGE_TILING_OPTIMAL`, then `imageCreateMaybeLinear` is false.

- Let `VkFormatFeatureFlags imageCreateFormatFeatures` be the set of format features available during image creation.
  - If `tiling` is `VK_IMAGE_TILING_LINEAR`, then `imageCreateFormatFeatures` is the value of `VkImageFormatProperties::linearTilingFeatures` found by calling `vkGetPhysicalDeviceFormatProperties` with parameter `format` equal to `VkImageCreateInfo::format`.
  - If `tiling` is `VK_IMAGE_TILING_OPTIMAL`, then `imageCreateFormatFeatures` is value of `VkImageFormatProperties::optimalTilingFeatures` found by calling `vkGetPhysicalDeviceFormatProperties` with parameter `format` equal to `VkImageCreateInfo::format`.

- Let `VkImageFormatProperties2 imageCreateImageFormatPropertiesList[]` be the list of structures obtained by calling `vkGetPhysicalDeviceImageFormatProperties2`, possibly multiple times, as follows:
  - The parameters `VkPhysicalDeviceImageFormatInfo2::format`, `imageType`, `tiling`, `usage`, and `flags` must be equal to those in `VkImageCreateInfo`.
  - If `VkImageCreateInfo::pNext` contains a `VkExternalMemoryImageCreateInfo` structure whose `handleTypes` is not 0, then `VkPhysicalDeviceImageFormatInfo2::pNext` must contain a `VkPhysicalDeviceExternalImageFormatInfo` structure whose `handleType` is not 0; and `vkGetPhysicalDeviceDeviceImageFormatProperties2` must be called for each handle type in `VkExternalMemoryImageCreateInfo::handleTypes`, successively setting `VkPhysicalDeviceExternalImageFormatInfo::handleType` on each call.
  - If `VkImageCreateInfo::pNext` contains no `VkExternalMemoryImageCreateInfo` structure, or contains a structure whose `handleTypes` is 0, then `VkPhysicalDeviceImageFormatInfo2::pNext` must either contain no `VkPhysicalDeviceExternalImageFormatInfo` structure, or contain a structure whose `handleType` is 0.
  - If any call to `vkGetPhysicalDeviceImageFormatProperties2` returns an error, then `imageCreateImageFormatPropertiesList` is defined to be the empty list.
• Let `uint32_t imageCreateMaxMipLevels` be the minimum value of `VkImageFormatProperties::maxMipLevels` in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.

• Let `uint32_t imageCreateMaxArrayLayers` be the minimum value of `VkImageFormatProperties::maxArrayLayers` in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.

• Let `VkExtent3D imageCreateMaxExtent` be the component-wise minimum over all `VkImageFormatProperties::maxExtent` values in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.

• Let `VkSampleCountFlags imageCreateSampleCounts` be the intersection of each `VkImageFormatProperties::sampleCounts` in `imageCreateImageFormatPropertiesList`. The value is undefined if `imageCreateImageFormatPropertiesList` is empty.
Valid Usage

- Each of the following values (as described in Image Creation Limits) must not be undefined: imageCreateMaxMipLevels, imageCreateMaxArrayLayers, imageCreateMaxExtent, and imageCreateSampleCounts.

- If sharingMode is VK_SHARING_MODE_CONCURRENT, pQueueFamilyIndices must be a valid pointer to an array of queueFamilyIndexCount uint32_t values.

- If sharingMode is VK_SHARING_MODE_CONCURRENT, queueFamilyIndexCount must be greater than 1.

- If sharingMode is VK_SHARING_MODE_CONCURRENT, each element of pQueueFamilyIndices must be unique and must be less than pQueueFamilyPropertyCount returned by either vkGetPhysicalDeviceQueueFamilyProperties or vkGetPhysicalDeviceQueueFamilyProperties2 for the physicalDevice that was used to create device.

- format must not be VK_FORMAT_UNDEFINED.

- extent.width must be greater than 0.

- extent.height must be greater than 0.

- extent.depth must be greater than 0.

- mipLevels must be greater than 0.

- arrayLayers must be greater than 0.

- If flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, imageType must be VK_IMAGE_TYPE_2D.

- If flags contains VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT, imageType must be VK_IMAGE_TYPE_3D.

- extent.width must be less than or equal to imageCreateMaxExtent.width (as defined in Image Creation Limits).

- extent.height must be less than or equal to imageCreateMaxExtent.height (as defined in Image Creation Limits).

- extent.depth must be less than or equal to imageCreateMaxExtent.depth (as defined in Image Creation Limits).

- If imageType is VK_IMAGE_TYPE_2D and flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT, extent.width and extent.height must be equal and arrayLayers must be greater than or equal to 6.

- If imageType is VK_IMAGE_TYPE_1D, both extent.height and extent.depth must be 1.

- If imageType is VK_IMAGE_TYPE_2D, extent.depth must be 1.

- mipLevels must be less than or equal to the number of levels in the complete mipmap chain based on extent.width, extent.height, and extent.depth.

- mipLevels must be less than or equal to imageCreateMaxMipLevels (as defined in Image Creation Limits).

- arrayLayers must be less than or equal to imageCreateMaxArrayLayers (as defined in Image Creation Limits).
Creation Limits).

- If `imageType` is `VK_IMAGE_TYPE_3D`, `arrayLayers` must be 1.

- If `samples` is not `VK_SAMPLE_COUNT_1_BIT`, then `imageType` must be `VK_IMAGE_TYPE_2D`, `flags` must not contain `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT`, `mipLevels` must be equal to 1, and `imageCreateMaybeLinear` (as defined in Image Creation Limits) must be false.

- If `usage` includes `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`, then bits other than `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, and `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT` must not be set.

- If `usage` includes `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`, `extent.width` must be less than or equal to `VkPhysicalDeviceLimits::maxFramebufferWidth`.

- If `usage` includes `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`, `extent.height` must be less than or equal to `VkPhysicalDeviceLimits::maxFramebufferHeight`.

- If `usage` includes `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT`, `usage` must also contain at least one of `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT`, `VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT`, or `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT`.

- `samples` must be a bit value that is set in `imageCreateSampleCounts` (as defined in Image Creation Limits).

- If the multisampled storage images feature is not enabled, and `usage` contains `VK_IMAGE_USAGE_STORAGE_BIT`, `samples` must be `VK_SAMPLE_COUNT_1_BIT`.

- If the sparse bindings feature is not enabled, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`.

- If the sparse aliased residency feature is not enabled, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT`.

- If `imageType` is `VK_IMAGE_TYPE_1D`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the sparse residency for 2D images feature is not enabled, and `imageType` is `VK_IMAGE_TYPE_2D`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the sparse residency for 3D images feature is not enabled, and `imageType` is `VK_IMAGE_TYPE_3D`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the sparse residency for images with 2 samples feature is not enabled, `imageType` is `VK_IMAGE_TYPE_2D`, and `samples` is `VK_SAMPLE_COUNT_2_BIT`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the sparse residency for images with 4 samples feature is not enabled, `imageType` is `VK_IMAGE_TYPE_2D`, and `samples` is `VK_SAMPLE_COUNT_4_BIT`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the sparse residency for images with 8 samples feature is not enabled, `imageType` is `VK_IMAGE_TYPE_2D`, and `samples` is `VK_SAMPLE_COUNT_8_BIT`, `flags` must not contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the sparse residency for images with 16 samples feature is not enabled, `imageType` is
VK_IMAGE_TYPE_2D, and samples is VK_SAMPLE_COUNT_16_BIT, flags must not contain VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT.

- If flags contains VK_IMAGE_CREATE_SPARSE_ALIASED_BIT, VK_IMAGE_CREATE_SPARSE_BINDING_BIT it must also contain VK_IMAGE_CREATE_SPARSE_BINDING_BIT.

- If any of the bits VK_IMAGE_CREATE_SPARSE_BINDING_BIT, VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT, or VK_IMAGE_CREATE_SPARSE_ALIASED_BIT are set, VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT must not also be set.

- If the protected memory feature is not enabled, flags must not contain VK_IMAGE_CREATE_PROTECTED_BIT.

- If any of the bits VK_IMAGE_CREATE_SPARSE_BINDING_BIT, VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT, or VK_IMAGE_CREATE_SPARSE_ALIASED_BIT are set, VK_IMAGE_CREATE_PROTECTED_BIT must not also be set.

- If the pNext chain includes a VkExternalMemoryImageCreateInfo structure, its handleTypes member must only contain bits that are also in VkExternalImageFormatProperties::externalMemoryProperties.compatibleHandleTypes, as returned by vkGetPhysicalDeviceImageFormatProperties2 with format, imageType, tiling, usage, and flags equal to those in this structure, and with a VkPhysicalDeviceExternalImageFormatInfo structure included in the pNext chain, with a handleType equal to any one of the handle types specified in VkExternalMemoryImageCreateInfo::handleTypes.

- If the logical device was created with VkDeviceGroupDeviceCreateInfo::physicalDeviceCount equal to 1, flags must not contain VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT.

- If flags contains VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT, then mipLevels must be one, arrayLayers must be one, imageType must be VK_IMAGE_TYPE_2D, and imageCreateMaybeLinear (as defined in Image Creation Limits) must be false.

- If flags contains VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT, then format must be a block-compressed image format, an ETC compressed image format, or an ASTC compressed image format.

- If flags contains VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT, then flags must also contain VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT.

- initialLayout must be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED.

- If the pNext chain includes a VkExternalMemoryImageCreateInfo structure whose handleTypes member is not 0, initialLayout must be VK_IMAGE_LAYOUT_UNDEFINED.

- If the image format is one of those listed in Formats requiring sampler YCbCr conversion for VK_IMAGE_ASPECT_COLOR_BIT image views, then mipLevels must be 1.

- If the image format is one of those listed in Formats requiring sampler YCbCr conversion for VK_IMAGE_ASPECT_COLOR_BIT image views, samples must be VK_SAMPLE_COUNT_1_BIT.

- If the image format is one of those listed in Formats requiring sampler YCbCr conversion for VK_IMAGE_ASPECT_COLOR_BIT image views, imageType must be VK_IMAGE_TYPE_2D.

- If the image format is one of those listed in Formats requiring sampler YCbCr conversion for VK_IMAGE_ASPECT_COLOR_BIT image views, arrayLayers must be 1.
• If `format` is a *multi-planar* format, and if `imageCreateFormatFeatures` (as defined in *Image Creation Limits*) does not contain `VK_FORMAT_FEATURE_DISJOINT_BIT`, then `flags` **must** not contain `VK_IMAGE_CREATE_DISJOINT_BIT`.

• If `format` is not a *multi-planar* format, and `flags` does not include `VK_IMAGE_CREATE_ALIAS_BIT`, `flags` **must** not contain `VK_IMAGE_CREATE_DISJOINT_BIT`.

### Valid Usage (Implicit)

- **sType** **must** be `VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO`.
- Each `pNext` member of any structure (including this one) in the `pNext` chain **must** be either `NULL` or a pointer to a valid instance of `VkExternalMemoryImageCreateInfo`, `VkImageFormatListCreateInfo`, or `VkImageSwapchainCreateInfoKHR`.
- The `sType` value of each struct in the `pNext` chain **must** be unique.
- `flags` **must** be a valid combination of `VkImageCreateFlagBits` values.
- `imageType` **must** be a valid `VkImageType` value.
- `format` **must** be a valid `VkFormat` value.
- `samples` **must** be a valid `VkSampleCountFlagBits` value.
- `tiling` **must** be a valid `VkImageTiling` value.
- `usage` **must** be a valid combination of `VkImageUsageFlagBits` values.
- `usage` **must** not be `0`.
- `sharingMode` **must** be a valid `VkSharingMode` value.
- `initialLayout` **must** be a valid `VkImageLayout` value.

To define a set of external memory handle types that **may** be used as backing store for an image, add a `VkExternalMemoryImageCreateInfo` structure to the `pNext` chain of the `VkImageCreateInfo` structure. The `VkExternalMemoryImageCreateInfo` structure is defined as:

```c
typedef struct VkExternalMemoryImageCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalMemoryHandleTypeFlags handleTypes;
} VkExternalMemoryImageCreateInfo;
```

or the equivalent:

```c
typedef VkExternalMemoryImageCreateInfo VkExternalMemoryImageCreateInfoKHR;
```
Note

A `VkExternalMemoryImageCreateInfo` structure must be included in the creation parameters for an image that will be bound to memory that is either exported or imported.

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `handleTypes` is a bitmask of `VkExternalMemoryHandleTypeFlagBits` specifying one or more external memory handle types.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_IMAGE_CREATE_INFO`
- `handleTypes` must be a valid combination of `VkExternalMemoryHandleTypeFlagBits` values
- `handleTypes` must not be `0`

If the `pNext` chain of `VkImageCreateInfo` includes a `VkImageSwapchainCreateInfoKHR` structure, then that structure includes a swapchain handle indicating that the image will be bound to memory from that swapchain.

The `VkImageSwapchainCreateInfoKHR` structure is defined as:

```c
typedef struct VkImageSwapchainCreateInfoKHR {
    VkStructureType    sType;
    const void*        pNext;
    VkSwapchainKHR     swapchain;
} VkImageSwapchainCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `swapchain` is `VK_NULL_HANDLE` or a handle of a swapchain that the image will be bound to.

### Valid Usage

- If `swapchain` is not `VK_NULL_HANDLE`, the fields of `VkImageCreateInfo` must match the implied image creation parameters of the swapchain
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_IMAGE_SWAPCHAIN_CREATE_INFO_KHR`
- If `swapchain` is not `VK_NULL_HANDLE`, `swapchain` must be a valid `VkSwapchainKHR` handle

If the `pNext` list of `VkImageCreateInfo` includes a `VkImageFormatListCreateInfo` structure, then that structure contains a list of all formats that *can* be used when creating views of this image.

The `VkImageFormatListCreateInfo` structure is defined as:

```c
typedef struct VkImageFormatListCreateInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           viewFormatCount;
    const VkFormat*    pViewFormats;
} VkImageFormatListCreateInfo;
```

or the equivalent

```c
typedef VkImageFormatListCreateInfo VkImageFormatListCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **viewFormatCount** is the number of entries in the `pViewFormats` array.
- **pViewFormats** is an array which lists all formats which *can* be used when creating views of this image.

If `viewFormatCount` is zero, `pViewFormats` is ignored and the image is created as if the `VkImageFormatListCreateInfo` structure were not included in the `pNext` list of `VkImageCreateInfo`.

Valid Usage

- If `viewFormatCount` is not 0, all of the formats in the `pViewFormats` array must be compatible with the format specified in the `format` field of `VkImageCreateInfo`, as described in the compatibility table.
- If `VkImageCreateInfo::flags` does not contain `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT`, `viewFormatCount` must be 0 or 1.
- If `viewFormatCount` is not 0, `VkImageCreateInfo::format` must be in `pViewFormats`.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO`
- If `viewFormatCount` is not 0, **pViewFormats** must be a valid pointer to an array of `viewFormatCount` valid `VkFormat` values

Bits which **can** be set in `VkImageCreateInfo::usage`, specifying intended usage of an image, are:

```c
typedef enum VkImageUsageFlagBits {
    VK_IMAGE_USAGE_TRANSFER_SRC_BIT = 0x00000001,
    VK_IMAGE_USAGE_TRANSFER_DST_BIT = 0x00000002,
    VK_IMAGE_USAGE_SAMPLED_BIT = 0x00000004,
    VK_IMAGE_USAGE_STORAGE_BIT = 0x00000008,
    VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT = 0x00000010,
    VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT = 0x00000020,
    VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT = 0x00000040,
    VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT = 0x00000080,
    VK_IMAGE_USAGE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkImageUsageFlagBits;
```

- **VK_IMAGE_USAGE_TRANSFER_SRC_BIT** specifies that the image **can** be used as the source of a transfer command.
- **VK_IMAGE_USAGE_TRANSFER_DST_BIT** specifies that the image **can** be used as the destination of a transfer command.
- **VK_IMAGE_USAGE_SAMPLED_BIT** specifies that the image **can** be used to create a `VkImageView` suitable for occupying a `VkDescriptorSet` slot either of type `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, and be sampled by a shader.
- **VK_IMAGE_USAGE_STORAGE_BIT** specifies that the image **can** be used to create a `VkImageView` suitable for occupying a `VkDescriptorSet` slot of type `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`.
- **VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT** specifies that the image **can** be used to create a `VkImageView` suitable for use as a color or resolve attachment in a `VkFramebuffer`.
- **VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT** specifies that the image **can** be used to create a `VkImageView` suitable for use as a depth/stencil or depth/stencil resolve attachment in a `VkFramebuffer`.
- **VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT** specifies that the memory bound to this image will have been allocated with the `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` (see Memory Allocation for more detail). This bit **can** be set for any image that **can** be used to create a `VkImageView` suitable for use as a color, resolve, depth/stencil, or input attachment.
- **VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT** specifies that the image **can** be used to create a `VkImageView` suitable for occupying `VkDescriptorSet` slot of type `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT`; be read from a shader as an input attachment; and be used as an input attachment in a framebuffer.
typedef VkFlags VkImageUsageFlags;

VkImageUsageFlags is a bitmask type for setting a mask of zero or more VkImageUsageFlagBits.

Bits which can be set in VkImageCreateInfo::flags, specifying additional parameters of an image, are:

typedef enum VkImageCreateFlagBits {
    VK_IMAGE_CREATE_SPARSE_BINDING_BIT = 0x00000001,
    VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT = 0x00000002,
    VK_IMAGE_CREATE_SPARSE_ALIASED_BIT = 0x00000004,
    VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT = 0x00000008,
    VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT = 0x00000010,
    VK_IMAGE_CREATE_ALIAS_BIT = 0x00000400,
    VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT = 0x00000040,
    VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT = 0x00000020,
    VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT = 0x00000080,
    VK_IMAGE_CREATE_EXTENDED_USAGE_BIT = 0x00000100,
    VK_IMAGE_CREATE_PROTECTED_BIT = 0x00000800,
    VK_IMAGE_CREATE_DISJOINT_BIT = 0x00000200,
    VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR = VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT,
    VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT_KHR = VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT,
    VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT_KHR = VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT,
    VK_IMAGE_CREATE_EXTENDED_USAGE_BIT_KHR = VK_IMAGE_CREATE_EXTENDED_USAGE_BIT,
    VK_IMAGE_CREATE_DISJOINT_BIT_KHR = VK_IMAGE_CREATE_DISJOINT_BIT,
    VK_IMAGE_CREATE_ALIAS_BIT_KHR = VK_IMAGE_CREATE_ALIAS_BIT,
    VK_IMAGE_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkImageCreateFlagBits;

- **VK_IMAGE_CREATE_SPARSE_BINDING_BIT** specifies that the image will be backed using sparse memory binding.
- **VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT** specifies that the image can be partially backed using sparse memory binding. Images created with this flag must also be created with the **VK_IMAGE_CREATE_SPARSE_BINDING_BIT** flag.
- **VK_IMAGE_CREATE_SPARSE_ALIASED_BIT** specifies that the image will be backed using sparse memory binding with memory ranges that might also simultaneously be backing another image (or another portion of the same image). Images created with this flag must also be created with the **VK_IMAGE_CREATE_SPARSE_BINDING_BIT** flag.
- **VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT** specifies that the image can be used to create a VkImageView with a different format from the image. For multi-planar formats, **VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT** specifies that a VkImageView can be created of a plane of the image.
- **VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT** specifies that the image can be used to create a
VkImageView of type VK_IMAGE_VIEW_TYPE_CUBE or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY.

- **VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT** specifies that the image can be used to create a VkImageView of type VK_IMAGE_VIEW_TYPE_2D or VK_IMAGE_VIEW_TYPE_2D_ARRAY.

- **VK_IMAGE_CREATE_PROTECTED_BIT** specifies that the image is a protected image.

- **VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT** specifies that the image can be used with a non-zero value of the splitInstanceBindRegionCount member of a VkBindImageMemoryDeviceGroupInfo structure passed into vkBindImageMemory2. This flag also has the effect of making the image use the standard sparse image block dimensions.

- **VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT** specifies that the image having a compressed format can be used to create a VkImageView with an uncompressed format where each texel in the image view corresponds to a compressed texel block of the image.

- **VK_IMAGE_CREATE_EXTENDED_USAGE_BIT** specifies that the image can be created with usage flags that are not supported for the format the image is created with but are supported for at least one format a VkImageView created from the image can have.

- **VK_IMAGE_CREATE_DISJOINT_BIT** specifies that an image with a multi-planar format must have each plane separately bound to memory, rather than having a single memory binding for the whole image; the presence of this bit distinguishes a disjoint image from an image without this bit set.

- **VK_IMAGE_CREATE_ALIAS_BIT** specifies that two images created with the same creation parameters and aliased to the same memory can interpret the contents of the memory consistently with each other, subject to the rules described in the Memory Aliasing section. This flag further specifies that each plane of a disjoint image can share an in-memory non-linear representation with single-plane images, and that a single-plane image can share an in-memory non-linear representation with a plane of a multi-planar disjoint image, according to the rules in Compatible formats of planes of multi-planar formats. If the pNext chain includes a VkExternalMemoryImageCreateInfo structure whose handleTypes member is not 0, it is as if VK_IMAGE_CREATE_ALIAS_BIT is set.

See Sparse Resource Features and Sparse Physical Device Features for more details.

```typedef VkFlags VkImageCreateFlags;
```

**VkImageCreateFlags** is a bitmask type for setting a mask of zero or more **VkImageCreateFlagBits**.

Possible values of **VkImageCreateInfo::imageType**, specifying the basic dimensionality of an image, are:

```typedef enum VkImageType {
    VK_IMAGE_TYPE_1D = 0,
    VK_IMAGE_TYPE_2D = 1,
    VK_IMAGE_TYPE_3D = 2,
    VK_IMAGE_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkImageType;
```
• **VK_IMAGE_TYPE_1D** specifies a one-dimensional image.

• **VK_IMAGE_TYPE_2D** specifies a two-dimensional image.

• **VK_IMAGE_TYPE_3D** specifies a three-dimensional image.

Possible values of `VkImageCreateInfo::tiling`, specifying the tiling arrangement of texel blocks in an image, are:

```c
typedef enum VkImageTiling {
    VK_IMAGE_TILING_OPTIMAL = 0,
    VK_IMAGE_TILING_LINEAR = 1,
    VK_IMAGE_TILING_MAX_ENUM = 0x7FFFFFFF
} VkImageTiling;
```

• **VK_IMAGE_TILING_OPTIMAL** specifies optimal tiling (texels are laid out in an implementation-dependent arrangement, for more optimal memory access).

• **VK_IMAGE_TILING_LINEAR** specifies linear tiling (texels are laid out in memory in row-major order, possibly with some padding on each row).

To query the memory layout of an image subresource, call:

```c
void vkGetImageSubresourceLayout(
    VkDevice device,                  // device
    VkImage image,                    // image
    const VkImageSubresource* pSubresource, // pSubresource
    VkSubresourceLayout* pLayout);    // pLayout
```

• **device** is the logical device that owns the image.

• **image** is the image whose layout is being queried.

• **pSubresource** is a pointer to a `VkImageSubresource` structure selecting a specific image for the image subresource.

• **pLayout** is a pointer to a `VkSubresourceLayout` structure in which the layout is returned.

The image **must** be **linear**. The returned layout is valid for host access.

If the image’s format is a multi-planar format, then `vkGetImageSubresourceLayout` describes one plane of the image.

`vkGetImageSubresourceLayout` is invariant for the lifetime of a single image.
Valid Usage

- **image** must have been created with **tiling** equal to **VK_IMAGE_TILING_LINEAR**
- The **aspectMask** member of **pSubresource** must only have a single bit set
- The **mipLevel** member of **pSubresource** must be less than the **mipLevels** specified in **VkImageCreateInfo** when **image** was created
- The **arrayLayer** member of **pSubresource** must be less than the **arrayLayers** specified in **VkImageCreateInfo** when **image** was created
- If the **tiling** of the **image** is **VK_IMAGE_TILING_LINEAR** and its **format** is a **multi-planar format** with two planes, the **aspectMask** member of **pSubresource** must be **VK_IMAGE_ASPECT_PLANE_0_BIT** or **VK_IMAGE_ASPECT_PLANE_1_BIT**
- If the **tiling** of the **image** is **VK_IMAGE_TILING_LINEAR** and its **format** is a **multi-planar format** with three planes, the **aspectMask** member of **pSubresource** must be **VK_IMAGE_ASPECT_PLANE_0_BIT**, **VK_IMAGE_ASPECT_PLANE_1_BIT** or **VK_IMAGE_ASPECT_PLANE_2_BIT**

Valid Usage (Implicit)

- **device** must be a valid **VkDevice** handle
- **image** must be a valid **VkImage** handle
- **pSubresource** must be a valid pointer to a valid **VkImageSubresource** structure
- **pLayout** must be a valid pointer to a **VkSubresourceLayout** structure
- **image** must have been created, allocated, or retrieved from **device**

The **VkImageSubresource** structure is defined as:

```c
typedef struct VkImageSubresource {
    VkImageAspectFlags aspectMask;
    uint32_t mipLevel;
    uint32_t arrayLayer;
} VkImageSubresource;
```

- **aspectMask** is a **VkImageAspectFlags** selecting the image **aspect**.
- **mipLevel** selects the mipmap level.
- **arrayLayer** selects the array layer.

Valid Usage (Implicit)

- **aspectMask** must be a valid combination of **VkImageAspectFlagBits** values
- **aspectMask** must not be 0
Information about the layout of the image subresource is returned in a `VkSubresourceLayout` structure:

```c
typedef struct VkSubresourceLayout {
    VkDeviceSize    offset;
    VkDeviceSize    size;
    VkDeviceSize    rowPitch;
    VkDeviceSize    arrayPitch;
    VkDeviceSize    depthPitch;
} VkSubresourceLayout;
```

- `offset` is the byte offset from the start of the image or the plane where the image subresource begins.
- `size` is the size in bytes of the image subresource. `size` includes any extra memory that is required based on `rowPitch`.
- `rowPitch` describes the number of bytes between each row of texels in an image.
- `arrayPitch` describes the number of bytes between each array layer of an image.
- `depthPitch` describes the number of bytes between each slice of 3D image.

If the image is `linear`, then `rowPitch`, `arrayPitch` and `depthPitch` describe the layout of the image subresource in linear memory. For uncompressed formats, `rowPitch` is the number of bytes between texels with the same x coordinate in adjacent rows (y coordinates differ by one). `arrayPitch` is the number of bytes between texels with the same x and y coordinate in adjacent array layers of the image (array layer values differ by one). `depthPitch` is the number of bytes between texels with the same x and y coordinate in adjacent slices of a 3D image (z coordinates differ by one). Expressed as an addressing formula, the starting byte of a texel in the image subresource has address:

```c
// (x,y,z,layer) are in texel coordinates
address(x,y,z,layer) = layer*arrayPitch + z*depthPitch + y*rowPitch + x*elementSize + offset
```

For compressed formats, the `rowPitch` is the number of bytes between compressed texel blocks in adjacent rows. `arrayPitch` is the number of bytes between compressed texel blocks in adjacent array layers. `depthPitch` is the number of bytes between compressed texel blocks in adjacent slices of a 3D image.

```c
// (x,y,z,layer) are in compressed texel block coordinates
address(x,y,z,layer) = layer*arrayPitch + z*depthPitch + y*rowPitch + x *compressedTexelBlockByteSize + offset;
```

The value of `arrayPitch` is undefined for images that were not created as arrays. `depthPitch` is defined only for 3D images.

If the image has a `single-plane` color format, then the `aspectMask` member of `VkImageSubresource` must be `VK_IMAGE_ASPECT_COLOR_BIT`.  

448 | Chapter 11. Resource Creation
If the image has a depth/stencil format, then `aspectMask` must be either `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT`. On implementations that store depth and stencil aspects separately, querying each of these image subresource layouts will return a different offset and size representing the region of memory used for that aspect. On implementations that store depth and stencil aspects interleaved, the same offset and size are returned and represent the interleaved memory allocation.

If the image has a multi-planar format, then the `aspectMask` member of `VkImageSubresource` must be `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, or (for 3-plane formats only) `VK_IMAGE_ASPECT_PLANE_2_BIT`. Querying each of these image subresource layouts will return a different offset and size representing the region of memory used for that plane. If the image is disjoint, then the offset is relative to the base address of the plane. If the image is non-disjoint, then the offset is relative to the base address of the image.

To destroy an image, call:

```c
void vkDestroyImage(
    VkDevice device,        // Logical device that destroys the image.
    VkImage image,             // Image to destroy.
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the image.
- `image` is the image to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- All submitted commands that refer to `image`, either directly or via a `VkImageView`, must have completed execution.
- If `VkAllocationCallbacks` were provided when `image` was created, a compatible set of callbacks must be provided here.
- If no `VkAllocationCallbacks` were provided when `image` was created, `pAllocator` must be `NULL`.

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle.
- If `image` is not `VK_NULL_HANDLE`, `image` must be a valid `VkImage` handle.
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.
- If `image` is a valid handle, it must have been created, allocated, or retrieved from `device`.
11.3.1. Image Format Features

Valid usage of a VkImage may be constrained by the image’s format features, defined below. Such constraints are documented in the affected valid usage statement.

- If the image was created with VK_IMAGE_TILING_LINEAR, then its set of format features is the value of VkFormatProperties::linearTilingFeatures found by calling vkGetPhysicalDeviceFormatProperties on the same format as VkImageCreateInfo::format.
- If the image was created with VK_IMAGE_TILING_OPTIMAL, then its set of format features is the value of VkFormatProperties::optimalTilingFeatures found by calling vkGetPhysicalDeviceFormatProperties on the same format as VkImageCreateInfo::format.

11.3.2. Image Miplevel Sizing

A complete mipmap chain is the full set of mipmap levels, from the largest mipmap level provided, down to the minimum mipmap size.

Conventional Images

For conventional images, the dimensions of each successive mipmap level, n+1, are:

\[
\begin{align*}
width_{n+1} & = \max\left( \frac{width_n}{2}, 1 \right) \\
height_{n+1} & = \max\left( \frac{height_n}{2}, 1 \right) \\
depth_{n+1} & = \max\left( \frac{depth_n}{2}, 1 \right)
\end{align*}
\]

where \( width_n, height_n, \) and \( depth_n \) are the dimensions of the next larger mipmap level, \( n \).

The minimum mipmap size is:

- 1 for one-dimensional images,
- 1x1 for two-dimensional images, and
- 1x1x1 for three-dimensional images.

The number of levels in a complete mipmap chain is:

\[
\log_2(\max(width_0, height_0, depth_0)) + 1
\]

where \( width_0, height_0, \) and \( depth_0 \) are the dimensions of the largest (most detailed) mipmap level, \( 0 \).
11.4. Image Layouts

Images are stored in implementation-dependent opaque layouts in memory. Each layout has limitations on what kinds of operations are supported for image subresources using the layout. At any given time, the data representing an image subresource in memory exists in a particular layout which is determined by the most recent layout transition that was performed on that image subresource. Applications have control over which layout each image subresource uses, and can transition an image subresource from one layout to another. Transitions can happen with an image memory barrier, included as part of a vkCmdPipelineBarrier or a vkCmdWaitEvents command buffer command (see Image Memory Barriers), or as part of a subpass dependency within a render pass (see VkSubpassDependency). The image layout is per-image subresource, and separate image subresources of the same image can be in different layouts at the same time with one exception - depth and stencil aspects of a given image subresource must always be in the same layout.

Note

Each layout may offer optimal performance for a specific usage of image memory. For example, an image with a layout of VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL may provide optimal performance for use as a color attachment, but be unsupported for use in transfer commands. Applications can transition an image subresource from one layout to another in order to achieve optimal performance when the image subresource is used for multiple kinds of operations. After initialization, applications need not use any layout other than the general layout, though this may produce suboptimal performance on some implementations.

Upon creation, all image subresources of an image are initially in the same layout, where that layout is selected by the VkImageCreateInfo::initialLayout member. The initialLayout must be either VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED. If it is VK_IMAGE_LAYOUT_PREINITIALIZED, then the image data can be preinitialized by the host while using this layout, and the transition away from this layout will preserve that data. If it is VK_IMAGE_LAYOUT_UNDEFINED, then the contents of the data are considered to be undefined, and the transition away from this layout is not guaranteed to preserve that data. For either of these initial layouts, any image subresources must be transitioned to another layout before they are accessed by the device.

Host access to image memory is only well-defined for linear images and for image subresources of those images which are currently in either the VK_IMAGE_LAYOUT_PREINITIALIZED or VK_IMAGE_LAYOUT_GENERAL layout. Calling vkGetImageSubresourceLayout for a linear image returns a subresource layout mapping that is valid for either of those image layouts.

The set of image layouts consists of:
typedef enum VkImageLayout {
    VK_IMAGE_LAYOUT_UNDEFINED = 0,
    VK_IMAGE_LAYOUT_GENERAL = 1,
    VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL = 2,
    VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL = 3,
    VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL = 4,
    VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL = 5,
    VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL = 6,
    VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL = 7,
    VK_IMAGE_LAYOUT_PREINITIALIZED = 8,
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_ATTACHMENT_OPTIMAL = 1000117000,
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL = 1000117001,
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL = 1000241000,
    VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL = 1000241001,
    VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL = 1000241002,
    VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL = 1000241003,
    VK_IMAGE_LAYOUT_PRESENT_SRC_KHR = 1000001002,
    VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR = 1000111000,
    VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL_KHR =
    VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL,
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL_KHR =
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL,
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL_KHR =
    VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL,
    VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL_KHR =
    VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL,
    VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL_KHR =
    VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL,
    VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL_KHR =
    VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL,
    VK_IMAGE_LAYOUT_MAX_ENUM = 0x7FFFFFFF
} VkImageLayout;

The type(s) of device access supported by each layout are:

- **VK_IMAGE_LAYOUT_UNDEFINED** does not support device access. This layout **must** only be used as the *initialLayout* member of *VkImageCreateInfo* or *VkAttachmentDescription*, or as the *oldLayout* in an image transition. When transitioning out of this layout, the contents of the memory are not guaranteed to be preserved.

- **VK_IMAGE_LAYOUT_PREINITIALIZED** does not support device access. This layout **must** only be used as the *initialLayout* member of *VkImageCreateInfo* or *VkAttachmentDescription*, or as the *oldLayout* in an image transition. When transitioning out of this layout, the contents of the memory are preserved. This layout is intended to be used as the initial layout for an image whose contents are written by the host, and hence the data **can** be written to memory immediately, without first executing a layout transition. Currently, **VK_IMAGE_LAYOUT_PREINITIALIZED** is only useful with linear images because there is not a standard layout defined for **VK_IMAGE_TILING_OPTIMAL** images.

- **VK_IMAGE_LAYOUT_GENERAL** supports all types of device access.
• **VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL** must only be used as a color or resolve attachment in a VkFramebuffer. This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT** usage bit enabled.

• **VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL** specifies a layout for both the depth and stencil aspects of a depth/stencil format image allowing read and write access as a depth/stencil attachment. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL** and **VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL**.

• **VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL** specifies a layout for both the depth and stencil aspects of a depth/stencil format image allowing read only access as a depth/stencil attachment or in shaders. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL** and **VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL**.

• **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL** specifies a layout for depth/stencil format images allowing read and write access to the stencil aspect as a stencil attachment, and read only access to the depth aspect as a depth attachment or in shaders. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL** and **VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL**.

• **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL** specifies a layout for depth/stencil format images allowing read and write access to the stencil aspect as a stencil attachment, and read only access to the depth aspect as a depth attachment or in shaders. It is equivalent to **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL** and **VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL**.

• **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL** specifies a layout for the depth aspect of a depth/stencil format image allowing read and write access as a depth attachment.

• **VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL** specifies a layout for the depth aspect of a depth/stencil format image allowing read-only access as a depth attachment or in shaders.

• **VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL** specifies a layout for the stencil aspect of a depth/stencil format image allowing read and write access as a stencil attachment.

• **VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL** specifies a layout for the stencil aspect of a depth/stencil format image allowing read-only access as a stencil attachment or in shaders.

• **VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL** must only be used as a read-only image in a shader (which can be read as a sampled image, combined image/sampler and/or input attachment). This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_SAMPLED_BIT** or **VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT** usage bit enabled.

• **VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL** must only be used as a source image of a transfer command (see the definition of **VK_PIPELINE_STAGE_TRANSFER_BIT**). This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_TRANSFER_SRC_BIT** usage bit enabled.

• **VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL** must only be used as a destination image of a transfer command. This layout is valid only for image subresources of images created with the **VK_IMAGE_USAGE_TRANSFER_DST_BIT** usage bit enabled.

• **VK_IMAGE_LAYOUT_PRESENT_SRC_KHR** must only be used for presenting a presentable image for display. A swapchain’s image must be transitioned to this layout before calling **vkQueuePresentKHR**, and must be transitioned away from this layout after calling **vkAcquireNextImageKHR**.

• **VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR** is valid only for shared presentable images, and must be
used for any usage the image supports.

The layout of each image subresource is not a state of the image subresource itself, but is rather a property of how the data in memory is organized, and thus for each mechanism of accessing an image in the API the application must specify a parameter or structure member that indicates which image layout the image subresource(s) are considered to be in when the image will be accessed. For transfer commands, this is a parameter to the command (see Clear Commands and Copy Commands). For use as a framebuffer attachment, this is a member in the substructures of the VkRenderPassCreateInfo (see Render Pass). For use in a descriptor set, this is a member in the VkDescriptorImageInfo structure (see Descriptor Set Updates).

11.4.1. Image Layout Matching Rules

At the time that any command buffer command accessing an image executes on any queue, the layouts of the image subresources that are accessed must all match exactly the layout specified via the API controlling those accesses, except in case of accesses to an image with a depth/stencil format performed through descriptors referring to only a single aspect of the image, where the following relaxed matching rules apply:

- Descriptors referring just to the depth aspect of a depth/stencil image only need to match in the image layout of the depth aspect, thus VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL and VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL are considered to match.

- Descriptors referring just to the stencil aspect of a depth/stencil image only need to match in the image layout of the stencil aspect, thus VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL and VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL are considered to match.

When performing a layout transition on an image subresource, the old layout value must either equal the current layout of the image subresource (at the time the transition executes), or else be VK_IMAGE_LAYOUT_UNDEFINED (implying that the contents of the image subresource need not be preserved). The new layout used in a transition must not be VK_IMAGE_LAYOUT_UNDEFINED or VK_IMAGE_LAYOUT_PREINITIALIZED.

11.5. Image Views

Image objects are not directly accessed by pipeline shaders for reading or writing image data. Instead, image views representing contiguous ranges of the image subresources and containing additional metadata are used for that purpose. Views must be created on images of compatible types, and must represent a valid subset of image subresources.

Image views are represented by VkImageView handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImageView)
```

The types of image views that can be created are:
typedef enum VkImageViewType {
    VK_IMAGE_VIEW_TYPE_1D = 0,
    VK_IMAGE_VIEW_TYPE_2D = 1,
    VK_IMAGE_VIEW_TYPE_3D = 2,
    VK_IMAGE_VIEW_TYPE_CUBE = 3,
    VK_IMAGE_VIEW_TYPE_1D_ARRAY = 4,
    VK_IMAGE_VIEW_TYPE_2D_ARRAY = 5,
    VK_IMAGE_VIEW_TYPE_CUBE_ARRAY = 6,
    VK_IMAGE_VIEW_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkImageViewType;

The exact image view type is partially implicit, based on the image’s type and sample count, as well as the view creation parameters as described in the image view compatibility table for `vkCreateImageView`. This table also shows which SPIR-V `OpTypeImage Dim` and `Arrayed` parameters correspond to each image view type.

To create an image view, call:

```
VkResult vkCreateImageView(
    VkDevice                                    device,
    const VkImageViewCreateInfo*                pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkImageView*                                pView);
```

- **device** is the logical device that creates the image view.
- **pCreateInfo** is a pointer to a `VkImageViewCreateInfo` structure containing parameters to be used to create the image view.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pView** is a pointer to a `VkImageView` handle in which the resulting image view object is returned.

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkImageViewCreateInfo` structure
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pView** must be a valid pointer to a `VkImageView` handle
Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkImageViewCreateInfo` structure is defined as:

```c
typedef struct VkImageViewCreateInfo {
    VkStructureType           sType;
    const void*               pNext;
    VkImageViewCreateFlags    flags;
    VkImage                   image;
    VkImageViewType           viewType;
    VkFormat                  format;
    VkComponentMapping        components;
    VkImageSubresourceRange   subresourceRange;
} VkImageViewCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `flags` is a bitmask of `VkImageViewCreateFlagBits` describing additional parameters of the image view.
- `image` is a `VkImage` on which the view will be created.
- `viewType` is a `VkImageViewType` value specifying the type of the image view.
- `format` is a `VkFormat` describing the format and type used to interpret texel blocks in the image.
- `components` is a `VkComponentMapping` specifies a remapping of color components (or of depth or stencil components after they have been converted into color components).
- `subresourceRange` is a `VkImageSubresourceRange` selecting the set of mipmap levels and array layers to be accessible to the view.

Some of the `image` creation parameters are inherited by the view. In particular, image view creation inherits the implicit parameter `usage` specifying the allowed usages of the image view that, by default, takes the value of the corresponding `usage` parameter specified in `VkImageCreateInfo` at image creation time.

The implicit `usage` can be overridden by adding a `VkImageViewUsageCreateInfo` structure to the `pNext` chain.

If `image` was created with the `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT` flag, and if the `format` of the image is not multi-planar, `format` can be different from the image’s format, but if `image` was created
without the VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT flag and they are not equal they must be compatible. Image format compatibility is defined in the Format Compatibility Classes section. Views of compatible formats will have the same mapping between texel coordinates and memory locations irrespective of the format, with only the interpretation of the bit pattern changing.

**Note**

Values intended to be used with one view format may not be exactly preserved when written or read through a different format. For example, an integer value that happens to have the bit pattern of a floating point denorm or NaN may be flushed or canonicalized when written or read through a view with a floating point format. Similarly, a value written through a signed normalized format that has a bit pattern exactly equal to \(-2^b\) may be changed to \(-2^b + 1\) as described in Conversion from Normalized Fixed-Point to Floating-Point.

If image was created with the VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT flag, format must be compatible with the image’s format as described above, or must be an uncompressed format in which case it must be size-compatible with the image’s format, as defined for copying data between images. In this case the resulting image view’s texel dimensions equal the dimensions of the selected mip level divided by the compressed texel block size and rounded up.

If the image view is to be used with a sampler which supports sampler Y’CbCr conversion, an identically defined object of type VkSamplerYcbcrConversion to that used to create the sampler must be passed to vkCreateImageView in a VkSamplerYcbcrConversionInfo included in the pNext chain of VkImageViewCreateInfo. Conversely, if a VkSamplerYcbcrConversion object is passed to vkCreateImageView, an identically defined VkSamplerYcbcrConversion object must be used when sampling the image.

If the image has a multi-planar format and subresourceRange.aspectMask is VK_IMAGE_ASPECT_COLOR_BIT, format must be identical to the image format, and the sampler to be used with the image view must enable sampler Y’CbCr conversion.

If image was created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT and the image has a multi-planar format, and if subresourceRange.aspectMask is VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT, format must be compatible with the corresponding plane of the image, and the sampler to be used with the image view must not enable sampler Y’CbCr conversion. The width and height of the single-plane image view must be derived from the multi-planar image’s dimensions in the manner listed for plane compatibility for the plane.

Any view of an image plane will have the same mapping between texel coordinates and memory locations as used by the channels of the color aspect, subject to the formulae relating texel coordinates to lower-resolution planes as described in Chroma Reconstruction. That is, if an R or B plane has a reduced resolution relative to the G plane of the multi-planar image, the image view operates using the \((u_{\text{plane}}, v_{\text{plane}})\) unnormalized coordinates of the reduced-resolution plane, and these coordinates access the same memory locations as the \((u_{\text{color}}, v_{\text{color}})\) unnormalized coordinates of the color aspect for which chroma reconstruction operations operate on the same \((u_{\text{plane}}, v_{\text{plane}})\) or \((i_{\text{plane}}, j_{\text{plane}})\) coordinates.

**Table 12. Image and image view parameter compatibility requirements**
<table>
<thead>
<tr>
<th>Dim, Arrayed, MS</th>
<th>Image parameters</th>
<th>View parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><code>imageType = ci.imageType</code></td>
<td><code>baseArrayLayer, layerCount, and levelCount</code> are members of the <code>subresourceRange</code> member.</td>
</tr>
<tr>
<td></td>
<td><code>width = ci.extent.width</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>height = ci.extent.height</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>depth = ci.extent.depth</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>arrayLayers = ci.arrayLayers</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>samples = ci.samples</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>flags = ci.flags</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>where ci is the </code>VkImageCreateInfo<code> used to create image.</code></td>
<td></td>
</tr>
<tr>
<td>1D, 0, 0</td>
<td><code>imageType = VK_IMAGE_TYPE_1D</code></td>
<td><code>viewType = VK_IMAGE_VIEW_TYPE_1D</code></td>
</tr>
<tr>
<td></td>
<td><code>width ≥ 1</code></td>
<td><code>baseArrayLayer ≥ 0</code></td>
</tr>
<tr>
<td></td>
<td><code>height = 1</code></td>
<td><code>layerCount = 1</code></td>
</tr>
<tr>
<td></td>
<td><code>depth = 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>arrayLayers ≥ 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>samples = 1</code></td>
<td></td>
</tr>
<tr>
<td>1D, 1, 0</td>
<td><code>imageType = VK_IMAGE_TYPE_1D</code></td>
<td><code>viewType = VK_IMAGE_VIEW_TYPE_1D_ARRAY</code></td>
</tr>
<tr>
<td></td>
<td><code>width ≥ 1</code></td>
<td><code>baseArrayLayer ≥ 0</code></td>
</tr>
<tr>
<td></td>
<td><code>height = 1</code></td>
<td><code>layerCount ≥ 1</code></td>
</tr>
<tr>
<td></td>
<td><code>depth = 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>arrayLayers ≥ 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>samples = 1</code></td>
<td></td>
</tr>
<tr>
<td>2D, 0, 0</td>
<td><code>imageType = VK_IMAGE_TYPE_2D</code></td>
<td><code>viewType = VK_IMAGE_VIEW_TYPE_2D</code></td>
</tr>
<tr>
<td></td>
<td><code>width ≥ 1</code></td>
<td><code>baseArrayLayer ≥ 0</code></td>
</tr>
<tr>
<td></td>
<td><code>height ≥ 1</code></td>
<td><code>layerCount = 1</code></td>
</tr>
<tr>
<td></td>
<td><code>depth = 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>arrayLayers ≥ 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>samples = 1</code></td>
<td></td>
</tr>
<tr>
<td>2D, 1, 0</td>
<td><code>imageType = VK_IMAGE_TYPE_2D</code></td>
<td><code>viewType = VK_IMAGE_VIEW_TYPE_2D_ARRAY</code></td>
</tr>
<tr>
<td></td>
<td><code>width ≥ 1</code></td>
<td><code>baseArrayLayer ≥ 0</code></td>
</tr>
<tr>
<td></td>
<td><code>height ≥ 1</code></td>
<td><code>layerCount ≥ 1</code></td>
</tr>
<tr>
<td></td>
<td><code>depth = 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>arrayLayers ≥ 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>samples = 1</code></td>
<td></td>
</tr>
<tr>
<td>2D, 0, 1</td>
<td><code>imageType = VK_IMAGE_TYPE_2D</code></td>
<td><code>viewType = VK_IMAGE_VIEW_TYPE_2D</code></td>
</tr>
<tr>
<td></td>
<td><code>width ≥ 1</code></td>
<td><code>baseArrayLayer ≥ 0</code></td>
</tr>
<tr>
<td></td>
<td><code>height ≥ 1</code></td>
<td><code>layerCount = 1</code></td>
</tr>
<tr>
<td></td>
<td><code>depth = 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>arrayLayers ≥ 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>samples &gt; 1</code></td>
<td></td>
</tr>
<tr>
<td>2D, 1, 1</td>
<td><code>imageType = VK_IMAGE_TYPE_2D</code></td>
<td><code>viewType = VK_IMAGE_VIEW_TYPE_2D_ARRAY</code></td>
</tr>
<tr>
<td></td>
<td><code>width ≥ 1</code></td>
<td><code>baseArrayLayer ≥ 0</code></td>
</tr>
<tr>
<td></td>
<td><code>height ≥ 1</code></td>
<td><code>layerCount ≥ 1</code></td>
</tr>
<tr>
<td></td>
<td><code>depth = 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>arrayLayers ≥ 1</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>samples &gt; 1</code></td>
<td></td>
</tr>
<tr>
<td>Dim, Arrayed, MS</td>
<td>Image parameters</td>
<td>View parameters</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------</td>
<td>-----------------</td>
</tr>
</tbody>
</table>
| **CUBE, 0, 0**   | imageType = VK_IMAGE_TYPE_2D  
width ≥ 1  
height = width  
depth = 1  
arrayLayers ≥ 6  
samples = 1  
flags includes VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT | viewType = VK_IMAGE_VIEW_TYPE_CUBE  
baseArrayLayer ≥ 0  
layerCount = 6 |
|                  | CUBE, 1, 0       | VK_IMAGE_CREATE_CUBE_ARRAY  
baseArrayLayer ≥ 0  
layerCount = 6 × N, N ≥ 1 |
| **CUBE, 1, 0**   | imageType = VK_IMAGE_TYPE_2D  
width ≥ 1  
height = width  
depth = 1  
N ≥ 1  
arrayLayers ≥ 6 × N  
samples = 1  
flags includes VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT | viewType = VK_IMAGE_VIEW_TYPE_CUBE_ARRAY  
baseArrayLayer ≥ 0  
layerCount = 6 × N, N ≥ 1 |
| **3D, 0, 0**     | imageType = VK_IMAGE_TYPE_3D  
width ≥ 1  
height ≥ 1  
depth ≥ 1  
arrayLayers = 1  
samples = 1 | viewType = VK_IMAGE_VIEW_TYPE_3D  
baseArrayLayer = 0  
layerCount = 1 |
| **3D, 0, 0**     | imageType = VK_IMAGE_TYPE_3D  
width ≥ 1  
height ≥ 1  
depth ≥ 1  
arrayLayers = 1  
samples = 1  
flags includes VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT  
flags does not include VK_IMAGE_CREATE_SPARSE_BINDING_BIT, VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT, and VK_IMAGE_CREATE_SPARSE_ALIASED_BIT | viewType = VK_IMAGE_VIEW_TYPE_2D  
levelCount = 1  
baseArrayLayer ≥ 0  
layerCount = 1 |
<table>
<thead>
<tr>
<th>Dim, Arrayed, MS</th>
<th>Image parameters</th>
<th>View parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D, 0, 0</td>
<td>$\text{imageType} = \text{VK_IMAGE_TYPE_3D}$&lt;br&gt;$\text{width} \geq 1$&lt;br&gt;$\text{height} \geq 1$&lt;br&gt;$\text{depth} \geq 1$&lt;br&gt;$\text{arrayLayers} = 1$&lt;br&gt;$\text{samples} = 1$&lt;br&gt;$\text{flags includes}$&lt;br&gt;$\text{VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT}$&lt;br&gt;$\text{flags does not include}$&lt;br&gt;$\text{VK_IMAGE_CREATE_SPARSE_BINDING_BIT}$,&lt;br&gt;$\text{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT}$, and&lt;br&gt;$\text{VK_IMAGE_CREATE_SPARSE_ALIASED_BIT}$</td>
<td>$\text{viewType} = \text{VK_IMAGE_VIEW_TYPE_2D_ARRAY}$&lt;br&gt;$\text{levelCount} = 1$&lt;br&gt;$\text{baseArrayLayer} \geq 0$&lt;br&gt;$\text{layerCount} \geq 1$</td>
</tr>
</tbody>
</table>
Valid Usage

• If image was not created with VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT then viewType must not be VK_IMAGE_VIEW_TYPE_CUBE or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY

• If the image cubemap arrays feature is not enabled, viewType must not be VK_IMAGE_VIEW_TYPE_CUBE_ARRAY

• If image was created with VK_IMAGE_TYPE_3D but without VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT set then viewType must not be VK_IMAGE_VIEW_TYPE_2D or VK_IMAGE_VIEW_TYPE_2D_ARRAY

• image must have been created with a usage value containing at least one of VK_IMAGE_USAGE_SAMPLED_BIT, VK_IMAGE_USAGE_STORAGE_BIT, VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, or VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT

• The format features of the resultant image view must contain at least one bit.

• If usage contains VK_IMAGE_USAGE_SAMPLED_BIT, then the format features of the resultant image view must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT.

• If usage contains VK_IMAGE_USAGE_STORAGE_BIT, then the image view’s format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT.

• If usage contains VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT, then the image view’s format features must contain VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT.

• If usage contains VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, then the image view’s format features must contain VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT.

• If usage contains VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT, then the image view’s format features must contain at least one of VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT or VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT.

• subresourceRange.baseMipLevel must be less than the mipLevels specified in VkImageCreateInfo when image was created

• If subresourceRange.levelCount is not VK_REMAINING_MIP_LEVELS, subresourceRange.baseMipLevel + subresourceRange.levelCount must be less than or equal to the mipLevels specified in VkImageCreateInfo when image was created

• If image is not a 3D image created with VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT set, or viewType is not VK_IMAGE_VIEW_TYPE_2D or VK_IMAGE_VIEW_TYPE_2D_ARRAY, subresourceRange.baseArrayLayer must be less than the arrayLayers specified in VkImageCreateInfo when image was created

• If subresourceRange.layerCount is not VK_REMAINING_ARRAY_LAYERS, image is not a 3D image created with VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT set, or viewType is not VK_IMAGE_VIEW_TYPE_2D or VK_IMAGE_VIEW_TYPE_2D_ARRAY, subresourceRange.layerCount must be non-zero and subresourceRange.baseArrayLayer + subresourceRange.layerCount must be less than or equal to the arrayLayers specified in VkImageCreateInfo when image was created

• If image is a 3D image created with VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT set, and viewType is VK_IMAGE_VIEW_TYPE_2D or VK_IMAGE_VIEW_TYPE_2D_ARRAY,
subresourceRange.baseArrayLayer must be less than the depth computed from baseMipLevel and extent.depth specified in VkImageCreateInfo when image was created, according to the formula defined in Image Miplevel Sizing.

- If subresourceRange.layerCount is not VK_REMAINING_ARRAY_LAYERS, image is a 3D image created with VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT set, and viewType is VK_IMAGE_VIEW_TYPE_2D or VK_IMAGE_VIEW_TYPE_2D_ARRAY, subresourceRange.layerCount must be non-zero and subresourceRange.baseArrayLayer + subresourceRange.layerCount must be less than or equal to the depth computed from baseMipLevel and extent.depth specified in VkImageCreateInfo when image was created, according to the formula defined in Image Miplevel Sizing.

- If image was created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT flag, but without the VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT flag, and if the format of the image is not a multi-planar format, format must be compatible with the format used to create image, as defined in Format Compatibility Classes

- If image was created with the VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT flag, format must be compatible with, or must be an uncompressed format that is size-compatible with, the format used to create image.

- If image was created with the VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT flag, levelCount and layerCount members of subresourceRange must both be 1.

- If a VkImageFormatListCreateInfo structure was included in the pNext chain of the VkImageCreateInfo structure used when creating image and the viewFormatCount field of VkImageFormatListCreateInfo is not zero then format must be one of the formats in VkImageFormatListCreateInfo::pViewFormats.

- If image was created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT flag, if the format of the image is a multi-planar format, and if subresourceRange.aspectMask is one of VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT, then format must be compatible with the VkFormat for the plane of the image format indicated by subresourceRange.aspectMask, as defined in Compatible formats of planes of multi-planar formats.

- If image was not created with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT flag, or if the format of the image is a multi-planar format and if subresourceRange.aspectMask is VK_IMAGE_ASPECT_COLOR_BIT, format must be identical to the format used to create image.

- If the pNext chain includes a VkSamplerYcbcrConversionInfo structure with a conversion value other than VK_NULL_HANDLE, all members of components must have the value VK_COMPONENT_SWIZZLE_IDENTITY.

- If image is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

- subresourceRange and viewType must be compatible with the image, as described in the compatibility table.

- If the pNext chain includes a VkImageViewUsageCreateInfo structure, its usage member must not include any bits that were not set in the usage member of the VkImageCreateInfo structure used to create image.

- If viewType is VK_IMAGE_VIEW_TYPE_CUBE and subresourceRange.layerCount is not
VK_REMAINING_ARRAY_LAYERS, subresourceRange.layerCount must be 6

- If viewType is VK_IMAGE_VIEW_TYPE_CUBE_ARRAY and subresourceRange.layerCount is not VK_REMAINING_ARRAY_LAYERS, subresourceRange.layerCount must be a multiple of 6
- If viewType is VK_IMAGE_VIEW_TYPE_CUBE and subresourceRange.layerCount is VK_REMAINING_ARRAY_LAYERS, the remaining number of layers must be 6
- If viewType is VK_IMAGE_VIEW_TYPE_CUBE_ARRAY and subresourceRange.layerCount is VK_REMAINING_ARRAY_LAYERS, the remaining number of layers must be a multiple of 6

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO
- Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of VkImageViewUsageCreateInfo or VkSamplerYcbcrConversionInfo
- The sType value of each struct in the pNext chain must be unique
- flags must be 0
- image must be a valid VkImage handle
- viewType must be a valid VkImageViewType value
- format must be a valid VkFormat value
- components must be a valid VkComponentMapping structure
- subresourceRange must be a valid VkImageSubresourceRange structure

Bits which can be set in VkImageViewCreateInfo::flags, specifying additional parameters of an image, are:

typedef enum VkImageViewCreateFlagBits {
    VK_IMAGE_VIEW_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkImageViewCreateFlagBits;

typedef VkFlags VkImageViewCreateFlags;

VkImageViewCreateFlags is a bitmask type for setting a mask of zero or more VkImageViewCreateFlagBits.

The set of usages for the created image view can be restricted compared to the parent image's usage flags by adding a VkImageViewUsageCreateInfo structure to the pNext chain of VkImageViewCreateInfo.

The VkImageViewUsageCreateInfo structure is defined as:
```c
typedef struct VkImageViewUsageCreateInfo {
    VkStructureType      sType;
    const void*          pNext;
    VkImageUsageFlags    usage;
} VkImageViewUsageCreateInfo;
```

or the equivalent

```c
typedef VkImageViewUsageCreateInfo VkImageViewUsageCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `usage` is a bitmask describing the allowed usages of the image view. See `VkImageUsageFlagBits` for a description of the supported bits.

When this structure is chained to `VkImageViewCreateInfo` the `usage` field overrides the implicit `usage` parameter inherited from image creation time and its value is used instead for the purposes of determining the valid usage conditions of `VkImageViewCreateInfo`.

### Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_IMAGE_VIEW_USAGE_CREATE_INFO`
- `usage` **must** be a valid combination of `VkImageUsageFlagBits` values
- `usage` **must** not be 0

The `VkImageSubresourceRange` structure is defined as:

```c
typedef struct VkImageSubresourceRange {
    VkImageAspectFlags    aspectMask;
    uint32_t              baseMipLevel;
    uint32_t              levelCount;
    uint32_t              baseArrayLayer;
    uint32_t              layerCount;
} VkImageSubresourceRange;
```

- `aspectMask` is a bitmask of `VkImageAspectFlagBits` specifying which aspect(s) of the image are included in the view.
- `baseMipLevel` is the first mipmap level accessible to the view.
- `levelCount` is the number of mipmap levels (starting from `baseMipLevel`) accessible to the view.
- `baseArrayLayer` is the first array layer accessible to the view.
- `layerCount` is the number of array layers (starting from `baseArrayLayer`) accessible to the view.
The number of mipmap levels and array layers **must** be a subset of the image subresources in the image. If an application wants to use all mip levels or layers in an image after the `baseMipLevel` or `baseArrayLayer`, it **can** set `levelCount` and `layerCount` to the special values `VK_REMAINING_MIP_LEVELS` and `VK_REMAINING_ARRAY_LAYERS` without knowing the exact number of mip levels or layers.

For cube and cube array image views, the layers of the image view starting at `baseArrayLayer` correspond to faces in the order +X, -X, +Y, -Y, +Z, -Z. For cube arrays, each set of six sequential layers is a single cube, so the number of cube maps in a cube map array view is `layerCount / 6`, and image array layer \((baseArrayLayer + i)\) is face index \((i \mod 6)\) of cube \(i / 6\). If the number of layers in the view, whether set explicitly in `layerCount` or implied by `VK_REMAINING_ARRAY_LAYERS`, is not a multiple of 6, the last cube map in the array **must** not be accessed.

**aspectMask** **must** be only `VK_IMAGE_ASPECT_COLOR_BIT`, `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT` if `format` is a color, depth-only or stencil-only format, respectively, except if `format` is a multi-planar format. If using a depth/stencil format with both depth and stencil components, **aspectMask** **must** include at least one of `VK_IMAGE_ASPECTDEPTH_BIT` and `VK_IMAGE_ASPECT_STENCIL_BIT`, and **can** include both.

When the `VkImageSubresourceRange` structure is used to select a subset of the slices of a 3D image's mip level in order to create a 2D or 2D array image view of a 3D image created with `VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT`, `baseArrayLayer` and `layerCount` specify the first slice index and the number of slices to include in the created image view. Such an image view **can** be used as a framebuffer attachment that refers only to the specified range of slices of the selected mip level. However, any layout transitions performed on such an attachment view during a render pass instance still apply to the entire subresource referenced which includes all the slices of the selected mip level.

When using an image view of a depth/stencil image to populate a descriptor set (e.g. for sampling in the shader, or for use as an input attachment), the **aspectMask** **must** only include one bit and selects whether the image view is used for depth reads (i.e. using a floating-point sampler or input attachment in the shader) or stencil reads (i.e. using an unsigned integer sampler or input attachment in the shader). When an image view of a depth/stencil image is used as a depth/stencil framebuffer attachment, the **aspectMask** is ignored and both depth and stencil image subresources are used.

The **VkComponentMapping** **components** member describes a remapping from components of the image to components of the vector returned by shader image instructions. This remapping **must** be identity for storage image descriptors, input attachment descriptors, framebuffer attachments, and any `VkImageView` used with a combined image sampler that enables sampler Y’CbCr conversion.

When creating a `VkImageView`, if sampler Y’CbCr conversion is enabled in the sampler, the **aspectMask** of a `subresourceRange` used by the `VkImageView` **must** be `VK_IMAGE_ASPECT_COLOR_BIT`.

When creating a `VkImageView`, if sampler Y’CbCr conversion is not enabled in the sampler and the image `format` is multi-planar, the image **must** have been created with `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT`, and the **aspectMask** of the `VkImageView`'s `subresourceRange` **must** be `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT` or `VK_IMAGE_ASPECT_PLANE_2_BIT`. 
Valid Usage

- If `levelCount` is not `VK_REMAINING_MIP_LEVELS`, it **must** be greater than 0
- If `layerCount` is not `VK_REMAINING_ARRAY_LAYERS`, it **must** be greater than 0
- If `aspectMask` includes `VK_IMAGE_ASPECT_COLOR_BIT`, then it **must** not include any of `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, or `VK_IMAGE_ASPECT_PLANE_2_BIT`

Valid Usage (Implicit)

- `aspectMask` **must** be a valid combination of `VkImageAspectFlagBits` values
- `aspectMask` **must** not be 0

Bits which **can** be set in an aspect mask to specify aspects of an image for purposes such as identifying a subresource, are:

```c
typedef enum VkImageAspectFlagBits {
    VK_IMAGE_ASPECT_COLOR_BIT = 0x00000001,
    VK_IMAGE_ASPECT_DEPTH_BIT = 0x00000002,
    VK_IMAGE_ASPECT_STENCIL_BIT = 0x00000004,
    VK_IMAGE_ASPECT_METADATA_BIT = 0x00000008,
    VK_IMAGE_ASPECT_PLANE_0_BIT = 0x00000010,
    VK_IMAGE_ASPECT_PLANE_1_BIT = 0x00000020,
    VK_IMAGE_ASPECT_PLANE_2_BIT = 0x00000040,
    VK_IMAGE_ASPECT_PLANE_0_BIT_KHR = VK_IMAGE_ASPECT_PLANE_0_BIT,
    VK_IMAGE_ASPECT_PLANE_1_BIT_KHR = VK_IMAGE_ASPECT_PLANE_1_BIT,
    VK_IMAGE_ASPECT_PLANE_2_BIT_KHR = VK_IMAGE_ASPECT_PLANE_2_BIT,
    VK_IMAGE_ASPECT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkImageAspectFlagBits;
```

- `VK_IMAGE_ASPECT_COLOR_BIT` specifies the color aspect.
- `VK_IMAGE_ASPECT_DEPTH_BIT` specifies the depth aspect.
- `VK_IMAGE_ASPECT_STENCIL_BIT` specifies the stencil aspect.
- `VK_IMAGE_ASPECT_METADATA_BIT` specifies the metadata aspect, used for sparse resource operations.
- `VK_IMAGE_ASPECT_PLANE_0_BIT` specifies plane 0 of a *multi-planar* image format.
- `VK_IMAGE_ASPECT_PLANE_1_BIT` specifies plane 1 of a *multi-planar* image format.
- `VK_IMAGE_ASPECT_PLANE_2_BIT` specifies plane 2 of a *multi-planar* image format.

```c
typedef VkFlags VkImageAspectFlags;
```

`VkImageAspectFlags` is a bitmask type for setting a mask of zero or more `VkImageAspectFlagBits`. 
The *VkComponentMapping* structure is defined as:

```c
typedef struct VkComponentMapping {
    VkComponentSwizzle r;
    VkComponentSwizzle g;
    VkComponentSwizzle b;
    VkComponentSwizzle a;
} VkComponentMapping;
```

- `r` is a *VkComponentSwizzle* specifying the component value placed in the R component of the output vector.
- `g` is a *VkComponentSwizzle* specifying the component value placed in the G component of the output vector.
- `b` is a *VkComponentSwizzle* specifying the component value placed in the B component of the output vector.
- `a` is a *VkComponentSwizzle* specifying the component value placed in the A component of the output vector.

**Valid Usage (Implicit)**

- `r` must be a valid *VkComponentSwizzle* value
- `g` must be a valid *VkComponentSwizzle* value
- `b` must be a valid *VkComponentSwizzle* value
- `a` must be a valid *VkComponentSwizzle* value

Possible values of the members of *VkComponentMapping*, specifying the component values placed in each component of the output vector, are:

```c
typedef enum VkComponentSwizzle {
    VK_COMPONENT_SWIZZLE_IDENTITY = 0,
    VK_COMPONENT_SWIZZLE_ZERO = 1,
    VK_COMPONENT_SWIZZLE_ONE = 2,
    VK_COMPONENT_SWIZZLE_R = 3,
    VK_COMPONENT_SWIZZLE_G = 4,
    VK_COMPONENT_SWIZZLE_B = 5,
    VK_COMPONENT_SWIZZLE_A = 6,
    VK_COMPONENT_SWIZZLE_MAX_ENUM = 0x7FFFFFFF
} VkComponentSwizzle;
```

- `VK_COMPONENT_SWIZZLE_IDENTITY` specifies that the component is set to the identity swizzle.
- `VK_COMPONENT_SWIZZLE_ZERO` specifies that the component is set to zero.
- `VK_COMPONENT_SWIZZLE_ONE` specifies that the component is set to either 1 or 1.0, depending on whether the type of the image view format is integer or floating-point respectively, as
determined by the Format Definition section for each VkFormat.

- **VK_COMPONENT_SWIZZLE_R** specifies that the component is set to the value of the R component of the image.
- **VK_COMPONENT_SWIZZLE_G** specifies that the component is set to the value of the G component of the image.
- **VK_COMPONENT_SWIZZLE_B** specifies that the component is set to the value of the B component of the image.
- **VK_COMPONENT_SWIZZLE_A** specifies that the component is set to the value of the A component of the image.

Setting the identity swizzle on a component is equivalent to setting the identity mapping on that component. That is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Identity Mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>components.r</td>
<td>VK_COMPONENT_SWIZZLE_R</td>
</tr>
<tr>
<td>components.g</td>
<td>VK_COMPONENT_SWIZZLE_G</td>
</tr>
<tr>
<td>components.b</td>
<td>VK_COMPONENT_SWIZZLE_B</td>
</tr>
<tr>
<td>components.a</td>
<td>VK_COMPONENT_SWIZZLE_A</td>
</tr>
</tbody>
</table>

To destroy an image view, call:

```c
void vkDestroyImageView(
    VkDevice device,
    VkImageView imageView,
    const VkAllocationCallbacks* pAllocator);
```

- **device** is the logical device that destroys the image view.
- **imageView** is the image view to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- All submitted commands that refer to **imageView** must have completed execution
- If **VkAllocationCallbacks** were provided when **imageView** was created, a compatible set of callbacks must be provided here
- If no **VkAllocationCallbacks** were provided when **imageView** was created, **pAllocator** must be **NULL**
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- If `imageView` is not `VK_NULL_HANDLE`, `imageView` must be a valid `VkImageView` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `imageView` is a valid handle, it must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `imageView` must be externally synchronized

11.5.1. Image View Format Features

Valid usage of a `VkImageView` may be constrained by the image view’s format features, defined below. Such constraints are documented in the affected valid usage statement.

- If the view’s image was created with `VK_IMAGE_TILING_LINEAR`, then the image view’s set of format features is the value of `VkFormatProperties::linearTilingFeatures` found by calling `vkGetPhysicalDeviceFormatProperties` on the same format as `VkImageViewCreateInfo::format`.

- If the view’s image was created with `VK_IMAGE_TILING_OPTIMAL`, then the image view’s set of format features is the value of `VkFormatProperties::optimalTilingFeatures` found by calling `vkGetPhysicalDeviceFormatProperties` on the same format as `VkImageViewCreateInfo::format`.

11.6. Resource Memory Association

Resources are initially created as virtual allocations with no backing memory. Device memory is allocated separately (see Device Memory) and then associated with the resource. This association is done differently for sparse and non-sparse resources.

Resources created with any of the sparse creation flags are considered sparse resources. Resources created without these flags are non-sparse. The details on resource memory association for sparse resources is described in Sparse Resources.

Non-sparse resources must be bound completely and contiguously to a single `VkDeviceMemory` object before the resource is passed as a parameter to any of the following operations:

- creating image or buffer views
- updating descriptor sets
- recording commands in a command buffer

Once bound, the memory binding is immutable for the lifetime of the resource.
In a logical device representing more than one physical device, buffer and image resources exist on all physical devices but can be bound to memory differently on each. Each such replicated resource is an instance of the resource. For sparse resources, each instance can be bound to memory arbitrarily differently. For non-sparse resources, each instance can either be bound to the local or a peer instance of the memory, or for images can be bound to rectangular regions from the local and/or peer instances. When a resource is used in a descriptor set, each physical device interprets the descriptor according to its own instance’s binding to memory.

\(\text{Note}\)

There are no new copy commands to transfer data between physical devices. Instead, an application can create a resource with a peer mapping and use it as the source or destination of a transfer command executed by a single physical device to copy the data from one physical device to another.

To determine the memory requirements for a buffer resource, call:

```c
void vkGetBufferMemoryRequirements(
    VkDevice                                    device,
    VkBuffer                                    buffer,
    VkMemoryRequirements*                       pMemoryRequirements);
```

- `device` is the logical device that owns the buffer.
- `buffer` is the buffer to query.
- `pMemoryRequirements` is a pointer to a `VkMemoryRequirements` structure in which the memory requirements of the buffer object are returned.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `buffer` must be a valid `VkBuffer` handle
- `pMemoryRequirements` must be a valid pointer to a `VkMemoryRequirements` structure
- `buffer` must have been created, allocated, or retrieved from `device`

To determine the memory requirements for an image resource which is not created with the `VK_IMAGE_CREATE_DISJOINT_BIT` flag set, call:

```c
void vkGetImageMemoryRequirements(
    VkDevice                                    device,
    VkImage                                     image,
    VkMemoryRequirements*                       pMemoryRequirements);
```

- `device` is the logical device that owns the image.
- `image` is the image to query.
MemoryRequirements is a pointer to a VkMemoryRequirements structure in which the memory requirements of the image object are returned.

### Valid Usage

- image **must** not have been created with the VK_IMAGE_CREATE_DISJOINT_BIT flag set

### Valid Usage (Implicit)

- device **must** be a valid VkDevice handle
- image **must** be a valid VkImage handle
- pMemoryRequirements **must** be a valid pointer to a VkMemoryRequirements structure
- image **must** have been created, allocated, or retrieved from device

The VkMemoryRequirements structure is defined as:

```c
typedef struct VkMemoryRequirements {
    VkDeviceSize    size;
    VkDeviceSize    alignment;
    uint32_t        memoryTypeBits;
} VkMemoryRequirements;
```

- size is the size, in bytes, of the memory allocation required for the resource.
- alignment is the alignment, in bytes, of the offset within the allocation required for the resource.
- memoryTypeBits is a bitmask and contains one bit set for every supported memory type for the resource. Bit $i$ is set if and only if the memory type $i$ in the VkPhysicalDeviceMemoryProperties structure for the physical device is supported for the resource.

The implementation guarantees certain properties about the memory requirements returned by vkGetBufferMemoryRequirements and vkGetImageMemoryRequirements:

- The memoryTypeBits member always contains at least one bit set.
- If buffer is a VkBuffer not created with the VK_BUFFER_CREATE_SPARSE_BINDING_BIT bit set, or if image is linear image, then the memoryTypeBits member always contains at least one bit set corresponding to a VkMemoryType with a propertyFlags that has both the VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT and the VK_MEMORY_PROPERTY_HOST_COHERENT_BIT bit set. In other words, mappable coherent memory can always be attached to these objects.
- If buffer was created with VkExternalMemoryBufferCreateInfo::handleTypes set to 0 or image was created with VkExternalMemoryImageCreateInfo::handleTypes set to 0, the memoryTypeBits member always contains at least one bit set corresponding to a VkMemoryType with a propertyFlags that has the VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT bit set.
The `memoryTypeBits` member is identical for all `VkBuffer` objects created with the same value for the `flags` and `usage` members in the `VkBufferCreateInfo` structure and the `handleTypes` member of the `VkExternalMemoryBufferCreateInfo` structure passed to `vkCreateBuffer`. Further, if `usage1` and `usage2` of type `VkBufferUsageFlags` are such that the bits set in `usage2` are a subset of the bits set in `usage1`, and they have the same `flags` and `VkExternalMemoryBufferCreateInfo`::`handleTypes`, then the bits set in `memoryTypeBits` returned for `usage1` must be a subset of the bits set in `memoryTypeBits` returned for `usage2`, for all values of `flags`.

- The `alignment` member is identical for all `VkBuffer` objects created with the same combination of values for the `usage` and `flags` members in the `VkBufferCreateInfo` structure passed to `vkCreateBuffer`.

- The `alignment` member is identical for all `VkBuffer` objects created with the same combination of values for the `flags` and `usage` members in the `VkBufferCreateInfo` structure passed to `vkCreateBuffer`.

- The `alignment` member satisfies the buffer descriptor offset alignment requirements associated with the `VkBuffer`'s `usage`:
  - If `usage` included `VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT` or `VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT`, `alignment` must be an integer multiple of `VkPhysicalDeviceLimits::minTexelBufferOffsetAlignment`.
  - If `usage` included `VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT`, `alignment` must be an integer multiple of `VkPhysicalDeviceLimits::minUniformBufferOffsetAlignment`.
  - If `usage` included `VK_BUFFER_USAGE_STORAGE_BUFFER_BIT`, `alignment` must be an integer multiple of `VkPhysicalDeviceLimits::minStorageBufferOffsetAlignment`.

- For images created with a color format, the `memoryTypeBits` member is identical for all `VkImage` objects created with the same combination of values for the `tiling` member, the `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` bit of the `flags` member, the `VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT` bit of the `flags` member, `handleTypes` member of `VkExternalMemoryImageCreateInfo`, and the `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT` of the `usage` member in the `VkImageCreateInfo` structure passed to `vkCreateImage`.

- For images created with a depth/stencil format, the `memoryTypeBits` member is identical for all `VkImage` objects created with the same combination of values for the `format` member, the `tiling` member, the `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` bit of the `flags` member, the `VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT` bit of the `flags` member, `handleTypes` member of `VkExternalMemoryImageCreateInfo`, and the `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT` of the `usage` member in the `VkImageCreateInfo` structure passed to `vkCreateImage`.

- If the memory requirements are for a `VkImage`, the `memoryTypeBits` member must not refer to a `VkMemoryType` with a `propertyFlags` that has the `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` bit set if the image did not have `VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT` bit set in the `usage` member of the `VkImageCreateInfo` structure passed to `vkCreateImage`.

- If the memory requirements are for a `VkBuffer`, the `memoryTypeBits` member must not refer to a `VkMemoryType` with a `propertyFlags` that has the `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` bit set.

**Note**

The implication of this requirement is that lazily allocated memory is disallowed for buffers in all cases.

- The `size` member is identical for all `VkBuffer` objects created with the same combination of
creation parameters specified in ` VkBufferCreateInfo` and its `pNext` chain.

- The `size` member is identical for all ` VkImage` objects created with the same combination of creation parameters specified in ` VkImageCreateInfo` and its `pNext` chain.

**Note**

This, however, does not imply that they interpret the contents of the bound memory identically with each other. That additional guarantee, however, can be explicitly requested using `VK_IMAGE_CREATE_ALIAS_BIT`.

To determine the memory requirements for a buffer resource, call:

```c
void vkGetBufferMemoryRequirements2(
    VkDevice                                    device,
    const VkBufferMemoryRequirementsInfo2*      pInfo,
    VkMemoryRequirements2*                      pMemoryRequirements);
```

or the equivalent command

```c
void vkGetBufferMemoryRequirements2KHR(
    VkDevice                                    device,
    const VkBufferMemoryRequirementsInfo2*      pInfo,
    VkMemoryRequirements2*                      pMemoryRequirements);
```

- `device` is the logical device that owns the buffer.
- `pInfo` is a pointer to a `VkBufferMemoryRequirementsInfo2` structure containing parameters required for the memory requirements query.
- `pMemoryRequirements` is a pointer to a `VkMemoryRequirements2` structure in which the memory requirements of the buffer object are returned.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `pInfo` must be a valid pointer to a valid `VkBufferMemoryRequirementsInfo2` structure
- `pMemoryRequirements` must be a valid pointer to a `VkMemoryRequirements2` structure

The `VkBufferMemoryRequirementsInfo2` structure is defined as:

```c
typdef struct VkBufferMemoryRequirementsInfo2 {
    VkStructureType    sType;
    const void*        pNext;
    VkBuffer           buffer;
} VkBufferMemoryRequirementsInfo2;
```
or the equivalent

```c
typedef VkBufferMemoryRequirementsInfo2 VkBufferMemoryRequirementsInfo2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `buffer` is the buffer to query.

### Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2`
- `pNext` **must** be `NULL`
- `buffer` **must** be a valid `VkBuffer` handle

To determine the memory requirements for an image resource, call:

```c
void vkGetImageMemoryRequirements2(
    VkDevice device,
    const VkImageMemoryRequirementsInfo2* pInfo,
    VkMemoryRequirements2* pMemoryRequirements);
```

or the equivalent command

```c
void vkGetImageMemoryRequirements2KHR(
    VkDevice device,
    const VkImageMemoryRequirementsInfo2* pInfo,
    VkMemoryRequirements2* pMemoryRequirements);
```

- `device` is the logical device that owns the image.
- `pInfo` is a pointer to a `VkImageMemoryRequirementsInfo2` structure containing parameters required for the memory requirements query.
- `pMemoryRequirements` is a pointer to a `VkMemoryRequirements2` structure in which the memory requirements of the image object are returned.

### Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pInfo` **must** be a valid pointer to a `VkImageMemoryRequirementsInfo2` structure
- `pMemoryRequirements` **must** be a valid pointer to a `VkMemoryRequirements2` structure

The `VkImageMemoryRequirementsInfo2` structure is defined as:
typedef struct VkImageMemoryRequirementsInfo2 {
    VkStructureType    sType;
    const void*        pNext;
    VkImage            image;
} VkImageMemoryRequirementsInfo2;

or the equivalent

typedef VkImageMemoryRequirementsInfo2 VkImageMemoryRequirementsInfo2KHR;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• image is the image to query.

Valid Usage

• If image was created with a multi-planar format and the VK_IMAGE_CREATE_DISJOINT_BIT flag, there must be a VkImagePlaneMemoryRequirementsInfo included in the pNext chain of the VkImageMemoryRequirementsInfo2 structure

• If image was not created with the VK_IMAGE_CREATE_DISJOINT_BIT flag, there must not be a VkImagePlaneMemoryRequirementsInfo included in the pNext chain of the VkImageMemoryRequirementsInfo2 structure

• If image was created with a single-plane format, there must not be a VkImagePlaneMemoryRequirementsInfo included in the pNext chain of the VkImageMemoryRequirementsInfo2 structure

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2
• pNext must be NULL or a pointer to a valid instance of VkImagePlaneMemoryRequirementsInfo
• The sType value of each struct in the pNext chain must be unique
• image must be a valid VkImage handle

To determine the memory requirements for a plane of a disjoint image, add a VkImagePlaneMemoryRequirementsInfo structure to the pNext chain of the VkImageMemoryRequirementsInfo2 structure.

The VkImagePlaneMemoryRequirementsInfo structure is defined as:
typedef struct VkImagePlaneMemoryRequirementsInfo {
    VkStructureType          sType;
    const void*              pNext;
    VkImageAspectFlagBits    planeAspect;
} VkImagePlaneMemoryRequirementsInfo;

or the equivalent

typedef VkImagePlaneMemoryRequirementsInfo VkImagePlaneMemoryRequirementsInfoKHR;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• planeAspect is the aspect corresponding to the image plane to query.

Valid Usage

• If the image's tiling is VK_IMAGE_TILING_LINEAR or VK_IMAGE_TILING_OPTIMAL, then planeAspect must be a single valid format plane for the image. (That is, for a two-plane image planeAspect must be VK_IMAGE_ASPECT_PLANE_0_BIT or VK_IMAGE_ASPECT_PLANE_1_BIT, and for a three-plane image planeAspect must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT or VK_IMAGE_ASPECT_PLANE_2_BIT).

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_IMAGE_PLANE_MEMORY_REQUIREMENTS_INFO
• planeAspect must be a valid VkImageAspectFlagBits value

The VkMemoryRequirements2 structure is defined as:

typedef struct VkMemoryRequirements2 {
    VkStructureType         sType;
    void*                   pNext;
    VkMemoryRequirements    memoryRequirements;
} VkMemoryRequirements2;

or the equivalent

typedef VkMemoryRequirements2 VkMemoryRequirements2KHR;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
memoryRequirements is a VkMemoryRequirements structure describing the memory requirements of the resource.

Valid Usage (Implicit)

- `sType` must be VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2
- `pNext` must be NULL or a pointer to a valid instance of VkMemoryDedicatedRequirements
- The `sType` value of each struct in the `pNext` chain must be unique

To determine the dedicated allocation requirements of a buffer or image resource, add aVkMemoryDedicatedRequirements structure to the `pNext` chain of the `VkMemoryRequirements2` structure passed as the `pMemoryRequirements` parameter of `vkGetBufferMemoryRequirements2` or `vkGetImageMemoryRequirements2`.

The `VkMemoryDedicatedRequirements` structure is defined as:

```
typedef struct VkMemoryDedicatedRequirements {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           prefersDedicatedAllocation;
    VkBool32           requiresDedicatedAllocation;
} VkMemoryDedicatedRequirements;
```

or the equivalent

```
typedef VkMemoryDedicatedRequirements VkMemoryDedicatedRequirementsKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `prefersDedicatedAllocation` specifies that the implementation would prefer a dedicated allocation for this resource. The application is still free to suballocate the resource but it may get better performance if a dedicated allocation is used.
- `requiresDedicatedAllocation` specifies that a dedicated allocation is required for this resource.

When the implementation sets `requiresDedicatedAllocation` to VK_TRUE, it must also set `prefersDedicatedAllocation` to VK_TRUE.

If the `VkMemoryDedicatedRequirements` structure is included in the `pNext` chain of the `VkMemoryRequirements2` structure passed as the `pMemoryRequirements` parameter of a `vkGetBufferMemoryRequirements2` call, `requiresDedicatedAllocation` may be VK_TRUE under one of the following conditions:

- The `pNext` chain of `VkBufferCreateInfo` for the call to `vkCreateBuffer` used to create the buffer being queried included a `VkExternalMemoryBufferCreateInfo` structure, and any of the handle
types specified in `VkExternalMemoryBufferCreateInfo::handleTypes` requires dedicated allocation, as reported by `vkGetPhysicalDeviceExternalBufferProperties` in `VkExternalBufferProperties::externalMemoryProperties.externalMemoryFeatures`, the `requiresDedicatedAllocation` field will be set to `VK_TRUE`.

In all other cases, `requiresDedicatedAllocation` must be set to `VK_FALSE` by the implementation whenever a `VkMemoryDedicatedRequirements` structure is included in the `pNext` chain of the `VkMemoryRequirements2` structure passed to a call to `vkGetBufferMemoryRequirements2`.

If the `VkMemoryDedicatedRequirements` structure is included in the `pNext` chain of the `VkMemoryRequirements2` structure passed as the `pMemoryRequirements` parameter of a `vkGetBufferMemoryRequirements2` call and `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` was set in `VkBufferCreateInfo::flags` when buffer was created then the implementation must set both `prefersDedicatedAllocation` and `requiresDedicatedAllocation` to `VK_FALSE`.

If the `VkMemoryDedicatedRequirements` structure is included in the `pNext` chain of the `VkMemoryRequirements2` structure passed as the `pMemoryRequirements` parameter of a `vkGetImageMemoryRequirements2` call, `requiresDedicatedAllocation` may be `VK_TRUE` under one of the following conditions:

- The `pNext` chain of `VkImageCreateInfo` for the call to `vkCreateImage` used to create the image being queried included a `VkExternalMemoryImageCreateInfo` structure, and any of the handle types specified in `VkExternalMemoryImageCreateInfo::handleTypes` requires dedicated allocation, as reported by `vkGetPhysicalDeviceImageFormatProperties2` in `VkExternalImageFormatProperties::externalMemoryProperties.externalMemoryFeatures`, the `requiresDedicatedAllocation` field will be set to `VK_TRUE`.

In all other cases, `requiresDedicatedAllocation` must be set to `VK_FALSE` by the implementation whenever a `VkMemoryDedicatedRequirements` structure is included in the `pNext` chain of the `VkMemoryRequirements2` structure passed to a call to `vkGetImageMemoryRequirements2`.

If the `VkMemoryDedicatedRequirements` structure is included in the `pNext` chain of the `VkMemoryRequirements2` structure passed as the `pMemoryRequirements` parameter of a `vkGetImageMemoryRequirements2` call and `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` was set in `VkImageCreateInfo::flags` when image was created then the implementation must set both `prefersDedicatedAllocation` and `requiresDedicatedAllocation` to `VK_FALSE`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS`

To attach memory to a buffer object, call:
VkResult vkBindBufferMemory(
    VkDevice device,  
    VkBuffer buffer,  
    VkDeviceMemory memory,  
    VkDeviceSize memoryOffset);

• device is the logical device that owns the buffer and memory.
• buffer is the buffer to be attached to memory.
• memory is a VkDeviceMemory object describing the device memory to attach.
• memoryOffset is the start offset of the region of memory which is to be bound to the buffer. The number of bytes returned in the VkMemoryRequirements::size member in memory, starting from memoryOffset bytes, will be bound to the specified buffer.

vkBindBufferMemory is equivalent to passing the same parameters through VkBindBufferMemoryInfo to vkBindBufferMemory2.
Valid Usage

- **buffer** must not already be backed by a memory object
- **buffer** must not have been created with any sparse memory binding flags
- **memoryOffset** must be less than the size of **memory**
- **memory** must have been allocated using one of the memory types allowed in the **memoryTypeBits** member of the **VkMemoryRequirements** structure returned from a call to **vkGetBufferMemoryRequirements** with **buffer**
- **memoryOffset** must be an integer multiple of the **alignment** member of the **VkMemoryRequirements** structure returned from a call to **vkGetBufferMemoryRequirements** with **buffer**
- The **size** member of the **VkMemoryRequirements** structure returned from a call to **vkGetBufferMemoryRequirements** with **buffer** must be less than or equal to the size of **memory** minus **memoryOffset**
- If **buffer** requires a dedicated allocation (as reported by **vkGetBufferMemoryRequirements2** in **VkMemoryDedicatedRequirements**::requiresDedicatedAllocation for **buffer**), **memory** must have been created with **VkMemoryDedicatedAllocateInfo**::buffer equal to **buffer**
- If the **VkMemoryAllocateInfo** provided when **memory** was allocated included a **VkMemoryDedicatedAllocateInfo** structure in its **pNext** chain, and **VkMemoryDedicatedAllocateInfo**::buffer was not **VK_NULL_HANDLE**, then **buffer** must equal **VkMemoryDedicatedAllocateInfo**::buffer, and **memoryOffset** must be zero.
- If **buffer** was created with the **VK_BUFFER_CREATE_PROTECTED_BIT** bit set, the **buffer** must be bound to a memory object allocated with a memory type that reports **VK_MEMORY_PROPERTY_PROTECTED_BIT**
- If **buffer** was created with the **VK_BUFFER_CREATE_PROTECTED_BIT** bit not set, the **buffer** must not be bound to a memory object created with a memory type that reports **VK_MEMORY_PROPERTY_PROTECTED_BIT**
- If the value of **VkExportMemoryAllocateInfo**::handleTypes used to allocate **memory** is not **0**, it must include at least one of the handles set in **VkExternalMemoryBufferCreateInfo**::handleTypes when **buffer** was created
- If **memory** was created by a memory import operation, the external handle type of the imported memory must also have been set in **VkExternalMemoryBufferCreateInfo**::handleTypes when **buffer** was created
- If the **VkPhysicalDeviceBufferDeviceAddressFeatures**::bufferDeviceAddress feature is enabled and **buffer** was created with the **VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT** bit set, **memory** must have been allocated with the **VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT** bit set
Valid Usage (Implicit)

- **device** **must** be a valid `VkDevice` handle
- **buffer** **must** be a valid `VkBuffer` handle
- **memory** **must** be a valid `VkDeviceMemory` handle
- **buffer** **must** have been created, allocated, or retrieved from **device**
- **memory** **must** have been created, allocated, or retrieved from **device**

Host Synchronization

- Host access to **buffer** **must** be externally synchronized

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR`

To attach memory to buffer objects for one or more buffers at a time, call:

```c
VkResult vkBindBufferMemory2(
    VkDevice                                    device,
    uint32_t                                    bindInfoCount,
    const VkBindBufferMemoryInfo*               pBindInfos);
```

or the equivalent command

```c
VkResult vkBindBufferMemory2KHR(
    VkDevice                                    device,
    uint32_t                                    bindInfoCount,
    const VkBindBufferMemoryInfo*               pBindInfos);
```

- **device** is the logical device that owns the buffers and memory.
- **bindInfoCount** is the number of elements in **pBindInfos**.
- **pBindInfos** is a pointer to an array of **bindInfoCount** `VkBindBufferMemoryInfo` structures describing buffers and memory to bind.
On some implementations, it may be more efficient to batch memory bindings into a single command.

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pBindInfos** must be a valid pointer to an array of `bindInfoCount` valid `VkBindBufferMemoryInfo` structures
- **bindInfoCount** must be greater than 0

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR`

`VkBindBufferMemoryInfo` contains members corresponding to the parameters of `vkBindBufferMemory`.

The `VkBindBufferMemoryInfo` structure is defined as:

```c
typedef struct VkBindBufferMemoryInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkBuffer           buffer;
    VkDeviceMemory     memory;
    VkDeviceSize       memoryOffset;
} VkBindBufferMemoryInfo;
```

or the equivalent

```c
typedef VkBindBufferMemoryInfo   VkBindBufferMemoryInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **buffer** is the buffer to be attached to memory.
- **memory** is a `VkDeviceMemory` object describing the device memory to attach.
- **memoryOffset** is the start offset of the region of **memory** which is to be bound to the buffer. The
number of bytes returned in the `VkMemoryRequirements::size` member in `memory`, starting from `memoryOffset` bytes, will be bound to the specified buffer.

**Valid Usage**

- **buffer** must not already be backed by a memory object
- **buffer** must not have been created with any sparse memory binding flags
- **memoryOffset** must be less than the size of `memory`
- **memory** must have been allocated using one of the memory types allowed in the `memoryTypeBits` member of the `VkMemoryRequirements` structure returned from a call to `vkGetBufferMemoryRequirements` with `buffer`
- **memoryOffset** must be an integer multiple of the `alignment` member of the `VkMemoryRequirements` structure returned from a call to `vkGetBufferMemoryRequirements` with `buffer`
- The `size` member of the `VkMemoryRequirements` structure returned from a call to `vkGetBufferMemoryRequirements` with `buffer` must be less than or equal to the size of `memory` minus `memoryOffset`
- If `buffer` requires a dedicated allocation (as reported by `vkGetBufferMemoryRequirements2` in `VkMemoryDedicatedRequirements::requiresDedicatedAllocation` for `buffer`), **memory** must have been created with `VkMemoryDedicatedAllocateInfo::buffer` equal to `buffer` and **memoryOffset** must be zero
- If the `VkMemoryAllocateInfo` provided when `memory` was allocated included a `VkMemoryDedicatedAllocateInfo` structure in its `pNext` chain, and `VkMemoryDedicatedAllocateInfo::buffer` was not `VK_NULL_HANDLE`, then **buffer** must equal `VkMemoryDedicatedAllocateInfo::buffer` and **memoryOffset** must be zero
- If the `pNext` chain includes a `VkBindBufferMemoryDeviceGroupInfo` structure, all instances of `memory` specified by `VkBindBufferMemoryDeviceGroupInfo::pDeviceIndices` must have been allocated
- If the value of `VkExportMemoryAllocateInfo::handleTypes` used to allocate `memory` is not 0, it must include at least one of the handles set in `VkExternalMemoryBufferCreateInfo::handleTypes` when `buffer` was created
- If `memory` was created by a memory import operation, the external handle type of the imported memory must also have been set in `VkExternalMemoryBufferCreateInfo::handleTypes` when `buffer` was created
- If the `VkPhysicalDeviceBufferDeviceAddressFeaturesKHR::bufferDeviceAddress` feature is enabled and `buffer` was created with the `VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT_KHR` bit set, **memory** must have been allocated with the `VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT_KHR` bit set
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO`
- **pNext** must be `NULL` or a pointer to a valid instance of `VkBindBufferMemoryDeviceGroupInfo`
- The **sType** value of each struct in the **pNext** chain must be unique
- **buffer** must be a valid `VkBuffer` handle
- **memory** must be a valid `VkDeviceMemory` handle
- Both of **buffer**, and **memory** must have been created, allocated, or retrieved from the same `VkDevice`

```c
typedef struct VkBindBufferMemoryDeviceGroupInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           deviceIndexCount;
    const uint32_t*    pDeviceIndices;
} VkBindBufferMemoryDeviceGroupInfo;
```

or the equivalent

```c
typedef VkBindBufferMemoryDeviceGroupInfo VkBindBufferMemoryDeviceGroupInfoKHR;
```

If the **pNext** list of `VkBindBufferMemoryInfo` includes a `VkBindBufferMemoryDeviceGroupInfo` structure, then that structure determines how memory is bound to buffers across multiple devices in a device group.

The `VkBindBufferMemoryDeviceGroupInfo` structure is defined as:

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **deviceIndexCount** is the number of elements in **pDeviceIndices**.
- **pDeviceIndices** is a pointer to an array of device indices.

If **deviceIndexCount** is greater than zero, then on device index `i` the buffer is attached to the instance of **memory** on the physical device with device index `pDeviceIndices[i]`.

If **deviceIndexCount** is zero and **memory** comes from a memory heap with the `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` bit set, then it is as if **pDeviceIndices** contains consecutive indices from zero to the number of physical devices in the logical device, minus one. In other words, by default each physical device attaches to its own instance of **memory**.

If **deviceIndexCount** is zero and **memory** comes from a memory heap without the `VK_MEMORY_HEAP_MULTI_INSTANCE_BIT` bit set, then it is as if **pDeviceIndices** contains an array of zeros.
In other words, by default each physical device attaches to instance zero.

**Valid Usage**

- `deviceIndexCount` **must** either be zero or equal to the number of physical devices in the logical device
- All elements of `pDeviceIndices` **must** be valid device indices

**Valid Usage (Implicit)**

- `sType` **must** be `VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO`
- If `deviceIndexCount` is not 0, `pDeviceIndices` **must** be a valid pointer to an array of `deviceIndexCount uint32_t` values

To attach memory to a `VkImage` object created without the `VK_IMAGE_CREATE_DISJOINT_BIT` set, call:

```c
VkResult vkBindImageMemory(
    VkDevice                                    device,
    VkImage                                     image,
    VkDeviceMemory                              memory,
    VkDeviceSize                                memoryOffset);
```

- **device** is the logical device that owns the image and memory.
- **image** is the image.
- **memory** is the `VkDeviceMemory` object describing the device memory to attach.
- **memoryOffset** is the start offset of the region of `memory` which is to be bound to the image. The number of bytes returned in the `VkMemoryRequirements::size` member in `memory`, starting from `memoryOffset` bytes, will be bound to the specified image.

`vkBindImageMemory` is equivalent to passing the same parameters through `VkBindImageMemoryInfo` to `vkBindImageMemory2`. 
Valid Usage

- **image** must not have been created with the `VK_IMAGE_CREATE_DISJOINT_BIT` set.
- **image** must not already be backed by a memory object
- **image** must not have been created with any sparse memory binding flags
- **memoryOffset** must be less than the size of **memory**
- **memory** must have been allocated using one of the memory types allowed in the **memoryTypeBits** member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements` with **image**
- **memoryOffset** must be an integer multiple of the **alignment** member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements` with **image**
- The difference of the size of **memory** and **memoryOffset** must be greater than or equal to the **size** member of the `VkMemoryRequirements` structure returned from a call to `vkGetImageMemoryRequirements` with the same **image**
- If **image** requires a dedicated allocation (as reported by `vkGetImageMemoryRequirements2` in `VkMemoryDedicatedRequirements::requiresDedicatedAllocation` for **image**), **memory** must have been created with `VkMemoryDedicatedAllocateInfo::image` equal to **image**
- If the `VkMemoryAllocateInfo` provided when **memory** was allocated included a `VkMemoryDedicatedAllocateInfo::image` structure in its `pNext` chain, and `VkMemoryDedicatedAllocateInfo::image` was not `VK_NULL_HANDLE`, then **image** must equal `VkMemoryDedicatedAllocateInfo::image` and **memoryOffset** must be zero
- If **image** was created with the `VK_IMAGE_CREATE_PROTECTED_BIT` bit set, the **image** must be bound to a memory object allocated with a memory type that reports `VK_MEMORY_PROPERTY_PROTECTED_BIT`
- If **image** was created with the `VK_IMAGE_CREATE_PROTECTED_BIT` bit not set, the **image** must not be bound to a memory object created with a memory type that reports `VK_MEMORY_PROPERTY_PROTECTED_BIT`
- If the value of `VkExportMemoryAllocateInfo::handleTypes` used to allocate **memory** is not 0, **it must** include at least one of the handles set in `VkExternalMemoryImageCreateInfo::handleTypes` when **image** was created
- If **memory** was created by a memory import operation, the external handle type of the imported memory **must** also have been set in `VkExternalMemoryImageCreateInfo::handleTypes` when **image** was created
Valid Usage (Implicit)

- **device** must be a valid VkDevice handle
- **image** must be a valid VkImage handle
- **memory** must be a valid VkDeviceMemory handle
- **image** must have been created, allocated, or retrieved from **device**
- **memory** must have been created, allocated, or retrieved from **device**

Host Synchronization

- Host access to **image** must be externally synchronized

Return Codes

**Success**
- Vk_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

To attach memory to image objects for one or more images at a time, call:

```c
VkResult vkBindImageMemory2(
    VkDevice device,
    uint32_t bindInfoCount,
    const VkBindImageMemoryInfo* pBindInfos);
```

or the equivalent command

```c
VkResult vkBindImageMemory2KHR(
    VkDevice device,
    uint32_t bindInfoCount,
    const VkBindImageMemoryInfo* pBindInfos);
```

- **device** is the logical device that owns the images and memory.
- **bindInfoCount** is the number of elements in **pBindInfos**.
- **pBindInfos** is a pointer to an array of VkBindImageMemoryInfo structures, describing images and memory to bind.

On some implementations, it **may** be more efficient to batch memory bindings into a single
Valid Usage

• If any `VkBindImageMemoryInfo::image` was created with `VK_IMAGE_CREATE_DISJOINT_BIT` then all planes of `VkBindImageMemoryInfo::image` **must** be bound individually in separate `pBindInfos`

Valid Usage (Implicit)

• `device` **must** be a valid `VkDevice` handle
• `pBindInfos` **must** be a valid pointer to an array of `bindInfoCount` valid `VkBindImageMemoryInfo` structures
• `bindInfoCount` **must** be greater than 0

Return Codes

**Success**
• `VK_SUCCESS`

**Failure**
• `VK_ERROR_OUT_OF_HOST_MEMORY`
• `VK_ERROR_OUT_OF_DEVICE_MEMORY`

`VkBindImageMemoryInfo` contains members corresponding to the parameters of `vkBindImageMemory`.

The `VkBindImageMemoryInfo` structure is defined as:

```c
typedef struct VkBindImageMemoryInfo {
    VkStructureType sType;
    const void* pNext;
    VkImage image;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
} VkBindImageMemoryInfo;
```

or the equivalent

```c
typedef VkBindImageMemoryInfo VkBindImageMemoryInfoKHR;
```

• `sType` is the type of this structure.
• `pNext` is NULL or a pointer to an extension-specific structure.
• **image** is the image to be attached to memory.

• **memory** is a `VkDeviceMemory` object describing the device memory to attach.

• **memoryOffset** is the start offset of the region of memory which is to be bound to the image. The number of bytes returned in the `VkMemoryRequirements::size` member in `memory`, starting from `memoryOffset` bytes, will be bound to the specified image.
Valid Usage

- **image must** not already be backed by a memory object
- **image must** not have been created with any sparse memory binding flags
- **memoryOffset must** be less than the size of **memory**
- If the **pNext** chain does not include a **VkBindImagePlaneMemoryInfo** structure, **memory must** have been allocated using one of the memory types allowed in the **memoryTypeBits** member of the **VkMemoryRequirements** structure returned from a call to **vkGetImageMemoryRequirements2** with **image**
- If the **pNext** chain does not include a **VkBindImagePlaneMemoryInfo** structure, **memoryOffset must** be an integer multiple of the **alignment** member of the **VkMemoryRequirements** structure returned from a call to **vkGetImageMemoryRequirements2** with **image**
- If the **pNext** chain does not include a **VkBindImagePlaneMemoryInfo** structure, the difference of the size of **memory** and **memoryOffset must** be greater than or equal to the size member of the **VkMemoryRequirements** structure returned from a call to **vkGetImageMemoryRequirements2** with the same **image**
- If the **pNext** chain includes a **VkBindImagePlaneMemoryInfo** structure, **image must** have been created with the **VK_IMAGE_CREATE_DISJOINT_BIT** bit set.
- If the **pNext** chain includes a **VkBindImagePlaneMemoryInfo** structure, **memory must** have been allocated using one of the memory types allowed in the **memoryTypeBits** member of the **VkMemoryRequirements** structure returned from a call to **vkGetImageMemoryRequirements2** with **image** and where **VkBindImagePlaneMemoryInfo::planeAspect** corresponds to the **VkImagePlaneMemoryRequirementsInfo::planeAspect** in the **VkImageMemoryRequirementsInfo2** structure's **pNext** chain
- If the **pNext** chain includes a **VkBindImagePlaneMemoryInfo** structure, **memoryOffset must** be an integer multiple of the **alignment** member of the **VkMemoryRequirements** structure returned from a call to **vkGetImageMemoryRequirements2** with **image** and where **VkBindImagePlaneMemoryInfo::planeAspect** corresponds to the **VkImagePlaneMemoryRequirementsInfo::planeAspect** in the **VkImageMemoryRequirementsInfo2** structure's **pNext** chain
- If the **pNext** chain includes a **VkBindImagePlaneMemoryInfo** structure, the difference of the size of **memory** and **memoryOffset must** be greater than or equal to the size member of the **VkMemoryRequirements** structure returned from a call to **vkGetImageMemoryRequirements2** with the same **image** and where **VkBindImagePlaneMemoryInfo::planeAspect** corresponds to the **VkImagePlaneMemoryRequirementsInfo::planeAspect** in the **VkImageMemoryRequirementsInfo2** structure's **pNext** chain
- If **image** requires a dedicated allocation (as reported by **vkGetImageMemoryRequirements2** in **VkMemoryDedicatedRequirements::requiresDedicatedAllocation** for **image**), **memory must** have been created with **VkMemoryDedicatedAllocateInfo::image** equal to **image** and...
memoryOffset must be zero

- If the VkMemoryAllocateInfo provided when memory was allocated included a VkMemoryDedicatedAllocateInfo structure in its pNext chain, and VkMemoryDedicatedAllocateInfo::image was not VK_NULL_HANDLE, then image must equal VkMemoryDedicatedAllocateInfo::image and memoryOffset must be zero.
- If the pNext chain includes a VkBindImageMemoryDeviceGroupInfo structure, all instances of memory specified by VkBindImageMemoryDeviceGroupInfo::pDeviceIndices must have been allocated.
- If the pNext chain includes a VkBindImageMemoryDeviceGroupInfo structure, and VkBindImageMemoryDeviceGroupInfo::splitInstanceBindRegionCount is not zero, then image must have been created with the VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT bit set.
- If the pNext chain includes a VkBindImageMemoryDeviceGroupInfo structure, all elements of VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions must be valid rectangles contained within the dimensions of image.
- If the pNext chain includes a VkBindImageMemoryDeviceGroupInfo structure, the union of the areas of all elements of VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions that correspond to the same instance of image must cover the entire image.
- If image was created with a valid swapchain handle in VkImageSwapchainCreateInfoKHR::swapchain, then the pNext chain must include a VkBindImageMemorySwapchainInfoKHR structure containing the same swapchain handle.
- If the pNext chain includes a VkBindImageMemorySwapchainInfoKHR structure, memory must be VK_NULL_HANDLE.
- If the pNext chain does not include a VkBindImageMemorySwapchainInfoKHR structure, memory must be a valid VkDeviceMemory handle.
- If the value of VkExportMemoryAllocateInfo::handleTypes used to allocate memory is not 0, it must include at least one of the handles set in VkExternalMemoryImageCreateInfo::handleTypes when image was created.
- If memory was created by a memory import operation, the external handle type of the imported memory must also have been set in VkExternalMemoryImageCreateInfo::handleTypes when image was created.
Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO

- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either NULL or a pointer to a valid instance of `VkBindImageMemoryDeviceGroupInfo`, `VkBindImageMemorySwapchainInfoKHR`, or `VkBindImagePlaneMemoryInfo`

- The `sType` value of each struct in the `pNext` chain must be unique

- `image` must be a valid `VkImage` handle

- Both of `image` and `memory` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

```c
typedef struct VkBindImageMemoryDeviceGroupInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           deviceIndexCount;
    const uint32_t*    pDeviceIndices;
    uint32_t           splitInstanceBindRegionCount;
    const VkRect2D*    pSplitInstanceBindRegions;
} VkBindImageMemoryDeviceGroupInfo;
```

or the equivalent

```c
typedef VkBindImageMemoryDeviceGroupInfo VkBindImageMemoryDeviceGroupInfoKHR;
```

If the `pNext` list of `VkBindImageMemoryInfo` includes a `VkBindImageMemoryDeviceGroupInfo` structure, then that structure determines how memory is bound to images across multiple devices in a device group.

The `VkBindImageMemoryDeviceGroupInfo` structure is defined as:

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `deviceIndexCount` is the number of elements in `pDeviceIndices`.
- `pDeviceIndices` is a pointer to an array of device indices.
- `splitInstanceBindRegionCount` is the number of elements in `pSplitInstanceBindRegions`.
- `pSplitInstanceBindRegions` is a pointer to an array of `VkRect2D` structures describing which regions of the image are attached to each instance of memory.

If `deviceIndexCount` is greater than zero, then on device index `i` `image` is attached to the instance of the memory on the physical device with device index `pDeviceIndices[i]`.

Let `N` be the number of physical devices in the logical device. If `splitInstanceBindRegionCount` is greater than zero, then `pSplitInstanceBindRegions` is an array of `N^2` rectangles, where the image
region specified by the rectangle at element i*N+j in resource instance i is bound to the memory instance j. The blocks of the memory that are bound to each sparse image block region use an offset in memory, relative to $\text{memoryOffset}$, computed as if the whole image were being bound to a contiguous range of memory. In other words, horizontally adjacent image blocks use consecutive blocks of memory, vertically adjacent image blocks are separated by the number of bytes per block multiplied by the width in blocks of $\text{image}$, and the block at (0,0) corresponds to memory starting at $\text{memoryOffset}$.

If $\text{splitInstanceBindRegionCount}$ and $\text{deviceIndexCount}$ are zero and the memory comes from a memory heap with the VK_MEMORY_HEAP_MULTI_INSTANCE_BIT bit set, then it is as if $\text{pDeviceIndices}$ contains consecutive indices from zero to the number of physical devices in the logical device, minus one. In other words, by default each physical device attaches to its own instance of the memory.

If $\text{splitInstanceBindRegionCount}$ and $\text{deviceIndexCount}$ are zero and the memory comes from a memory heap without the VK_MEMORY_HEAP_MULTI_INSTANCE_BIT bit set, then it is as if $\text{pDeviceIndices}$ contains an array of zeros. In other words, by default each physical device attaches to instance zero.

**Valid Usage**

- At least one of $\text{deviceIndexCount}$ and $\text{splitInstanceBindRegionCount}$ must be zero.
- $\text{deviceIndexCount}$ must either be zero or equal to the number of physical devices in the logical device.
- All elements of $\text{pDeviceIndices}$ must be valid device indices.
- $\text{splitInstanceBindRegionCount}$ must either be zero or equal to the number of physical devices in the logical device squared.
- Elements of $\text{pSplitInstanceBindRegions}$ that correspond to the same instance of an image must not overlap.
- The offset.x member of any element of $\text{pSplitInstanceBindRegions}$ must be a multiple of the sparse image block width (VkSparseImageFormatProperties::imageGranularity.width) of all non-metadata aspects of the image.
- The offset.y member of any element of $\text{pSplitInstanceBindRegions}$ must be a multiple of the sparse image block height (VkSparseImageFormatProperties::imageGranularity.height) of all non-metadata aspects of the image.
- The extent.width member of any element of $\text{pSplitInstanceBindRegions}$ must either be a multiple of the sparse image block width of all non-metadata aspects of the image, or else extent.width + offset.x must equal the width of the image subresource.
- The extent.height member of any element of $\text{pSplitInstanceBindRegions}$ must either be a multiple of the sparse image block height of all non-metadata aspects of the image, or else extent.height + offset.y must equal the width of the image subresource.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_DEVICE_GROUP_INFO`
- If `deviceIndexCount` is not 0, `pDeviceIndices` must be a valid pointer to an array of `deviceIndexCount` `uint32_t` values
- If `splitInstanceBindRegionCount` is not 0, `pSplitInstanceBindRegions` must be a valid pointer to an array of `splitInstanceBindRegionCount` `VkRect2D` structures

If the `pNext` chain of `VkBindImageMemoryInfo` includes a `VkBindImageMemorySwapchainInfoKHR` structure, then that structure includes a swapchain handle and image index indicating that the image will be bound to memory from that swapchain.

The `VkBindImageMemorySwapchainInfoKHR` structure is defined as:

```c
typedef struct VkBindImageMemorySwapchainInfoKHR {
    VkStructureType    sType;
    const void*        pNext;
    VkSwapchainKHR     swapchain;
    uint32_t           imageIndex;
} VkBindImageMemorySwapchainInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **swapchain** is `VK_NULL_HANDLE` or a swapchain handle.
- **imageIndex** is an image index within `swapchain`.

If `swapchain` is not `NULL`, the `swapchain` and `imageIndex` are used to determine the memory that the image is bound to, instead of `memory` and `memoryOffset`.

Memory can be bound to a swapchain and use the `pDeviceIndices` or `pSplitInstanceBindRegions` members of `VkBindImageMemoryDeviceGroupInfo`.

Valid Usage

- **imageIndex** must be less than the number of images in `swapchain`

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_SWAPCHAIN_INFO_KHR`
- **swapchain** must be a valid `VkSwapchainKHR` handle
Host Synchronization

- Host access to swapchain must be externally synchronized

In order to bind planes of a disjoint image, add a VkBindImagePlaneMemoryInfo structure to the pNext chain of VkBindImageMemoryInfo.

The VkBindImagePlaneMemoryInfo structure is defined as:

```c
typedef struct VkBindImagePlaneMemoryInfo {
    VkStructureType          sType;
    const void*              pNext;
    VkImageAspectFlagBits    planeAspect;
} VkBindImagePlaneMemoryInfo;
```

or the equivalent

```c
typedef VkBindImagePlaneMemoryInfo VkBindImagePlaneMemoryInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `planeAspect` is the aspect of the disjoint image plane to bind.

Valid Usage

- If the image’s tiling is VK_IMAGE_TILING_LINEAR or VK_IMAGE_TILING_OPTIMAL, then `planeAspect` must be a single valid format plane for the image. (That is, `planeAspect` must be VK_IMAGE_ASPECT_PLANE_0_BIT or VK_IMAGE_ASPECT_PLANE_1_BIT for “2PLANE” formats and `planeAspect` must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT for “3PLANE” formats.)

Valid Usage (Implicit)

- `sType` must be VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO
- `planeAspect` must be a valid VkImageAspectFlagBits value

Buffer-Image Granularity

There is an implementation-dependent limit, bufferImageGranularity, which specifies a page-like granularity at which linear and non-linear resources must be placed in adjacent memory locations to avoid aliasing. Two resources which do not satisfy this granularity requirement are said to alias. bufferImageGranularity is specified in bytes, and must be a power of two. Implementations which do not impose a granularity restriction may report a bufferImageGranularity value of one.
**Note**

Despite its name, `bufferImageGranularity` is really a granularity between “linear” and “non-linear” resources.

Given resourceA at the lower memory offset and resourceB at the higher memory offset in the same `VkDeviceMemory` object, where one resource is linear and the other is non-linear (as defined in the Glossary), and the following:

```c
resourceA.end = resourceA.memoryOffset + resourceA.size - 1
resourceA.endPage = resourceA.end & ~(bufferImageGranularity-1)
resourceB.start = resourceB.memoryOffset
resourceB.startPage = resourceB.start & ~(bufferImageGranularity-1)
```

The following property must hold:

```c
resourceA.endPage < resourceB.startPage
```

That is, the end of the first resource (A) and the beginning of the second resource (B) must be on separate “pages” of size `bufferImageGranularity`. `bufferImageGranularity` may be different than the physical page size of the memory heap. This restriction is only needed when a linear resource and a non-linear resource are adjacent in memory and will be used simultaneously. The memory ranges of adjacent resources can be closer than `bufferImageGranularity`, provided they meet the alignment requirement for the objects in question.

Sparse block size in bytes and sparse image and buffer memory alignments must all be multiples of the `bufferImageGranularity`. Therefore, memory bound to sparse resources naturally satisfies the `bufferImageGranularity`.

### 11.7. Resource Sharing Mode

Buffer and image objects are created with a *sharing mode* controlling how they can be accessed from queues. The supported sharing modes are:

```c
typedef enum VkSharingMode {
    VK_SHARING_MODE_EXCLUSIVE = 0,
    VK_SHARING_MODE_CONCURRENT = 1,
    VK_SHARING_MODE_MAX_ENUM = 0x7FFFFFFF
} VkSharingMode;
```

- **VK_SHARING_MODE_EXCLUSIVE** specifies that access to any range or image subresource of the object will be exclusive to a single queue family at a time.
- **VK_SHARING_MODE_CONCURRENT** specifies that concurrent access to any range or image subresource of the object from multiple queue families is supported.
Note

**VK_SHARING_MODE_CONCURRENT** may result in lower performance access to the buffer or image than **VK_SHARING_MODE_EXCLUSIVE**.

Ranges of buffers and image subresources of image objects created using **VK_SHARING_MODE_EXCLUSIVE** must only be accessed by queues in the queue family that has **ownership** of the resource. Upon creation, such resources are not owned by any queue family; ownership is implicitly acquired upon first use within a queue. Once a resource using **VK_SHARING_MODE_EXCLUSIVE** is owned by some queue family, the application must perform a **queue family ownership transfer** to make the memory contents of a range or image subresource accessible to a different queue family.

Note

Images still require a **layout transition** from **VK_IMAGE_LAYOUT_UNDEFINED** or **VK_IMAGE_LAYOUT_PREINITIALIZED** before being used on the first queue.

A queue family can take ownership of an image subresource or buffer range of a resource created with **VK_SHARING_MODE_EXCLUSIVE**, without an ownership transfer, in the same way as for a resource that was just created; however, taking ownership in this way has the effect that the contents of the image subresource or buffer range are undefined.

Ranges of buffers and image subresources of image objects created using **VK_SHARING_MODE_CONCURRENT** must only be accessed by queues from the queue families specified through the **queueFamilyIndexCount** and **pQueueFamilyIndices** members of the corresponding create info structures.

### 11.7.1. External Resource Sharing

Resources should only be accessed in the Vulkan instance that has exclusive ownership of their underlying memory. Only one Vulkan instance has exclusive ownership of a resource’s underlying memory at a given time, regardless of whether the resource was created using **VK_SHARING_MODE_EXCLUSIVE** or **VK_SHARING_MODE_CONCURRENT**. Applications can transfer ownership of a resource's underlying memory only if the memory has been imported from or exported to another instance or external API using external memory handles. The semantics for transferring ownership outside of the instance are similar to those used for transferring ownership of **VK_SHARING_MODE_EXCLUSIVE** resources between queues, and is also accomplished using **VkBufferMemoryBarrier** or **VkImageMemoryBarrier** operations. Applications must

1. Release exclusive ownership from the source instance or API.
2. Ensure the release operation has completed using semaphores or fences.
3. Acquire exclusive ownership in the destination instance or API

Unlike queue ownership transfers, the destination instance or API is not specified explicitly when releasing ownership, nor is the source instance or API specified when acquiring ownership. Instead, the image or memory barrier's **dstQueueFamilyIndex** or **srcQueueFamilyIndex** parameters are set to the reserved queue family index **VK_QUEUE_FAMILY_EXTERNAL** to represent the external destination or source respectively.
Binding a resource to a memory object shared between multiple Vulkan instances or other APIs does not change the ownership of the underlying memory. The first entity to access the resource implicitly acquires ownership. Accessing a resource backed by memory that is owned by a particular instance or API has the same semantics as accessing a `VK_SHARING_MODE_EXCLUSIVE` resource, with one exception: Implementations must ensure layout transitions performed on one member of a set of identical subresources of identical images that alias the same range of an underlying memory object affect the layout of all the subresources in the set.

As a corollary, writes to any image subresources in such a set must not make the contents of memory used by other subresources in the set undefined. An application can define the content of a subresource of one image by performing device writes to an identical subresource of another image provided both images are bound to the same region of external memory. Applications may also add resources to such a set after the content of the existing set members has been defined without making the content undefined by creating a new image with the initial layout `VK_IMAGE_LAYOUT_UNDEFINED` and binding it to the same region of external memory as the existing images.

**Note**
Because layout transitions apply to all identical images aliasing the same region of external memory, the actual layout of the memory backing a new image as well as an existing image with defined content will not be undefined. Such an image is not usable until it acquires ownership of its memory from the existing owner. Therefore, the layout specified as part of this transition will be the true initial layout of the image. The undefined layout specified when creating it is a placeholder to simplify valid usage requirements.

### 11.8. Memory Aliasing

A range of a `VkDeviceMemory` allocation is aliased if it is bound to multiple resources simultaneously, as described below, via `vkBindImageMemory`, `vkBindBufferMemory`, `vkBindAccelerationStructureMemoryKHR`, via sparse memory bindings, or by binding the memory to resources in multiple Vulkan instances or external APIs using external memory handle export and import mechanisms.

Consider two resources, resource\(_A\) and resource\(_B\), bound respectively to memory range\(_A\) and range\(_B\). Let paddedRange\(_A\) and paddedRange\(_B\) be, respectively, range\(_A\) and range\(_B\) aligned to `bufferImageGranularity`. If the resources are both linear or both non-linear (as defined in the Glossary), then the resources alias the memory in the intersection of range\(_A\) and range\(_B\). If one resource is linear and the other is non-linear, then the resources alias the memory in the intersection of paddedRange\(_A\) and paddedRange\(_B\).

Applications can alias memory, but use of multiple aliases is subject to several constraints.

**Note**
Memory aliasing can be useful to reduce the total device memory footprint of an application, if some large resources are used for disjoint periods of time.
When a non-linear, non-VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT image is bound to an aliased range, all image subresources of the image overlap the range. When a linear image is bound to an aliased range, the image subresources that (according to the image's advertised layout) include bytes from the aliased range overlap the range. When a VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT image has sparse image blocks bound to an aliased range, only image subresources including those sparse image blocks overlap the range, and when the memory bound to the image's mip tail overlaps an aliased range all image subresources in the mip tail overlap the range.

Buffers, and linear image subresources in either the VK_IMAGE_LAYOUT_PREINITIALIZED or VK_IMAGE_LAYOUT_GENERAL layouts, are host-accessible subresources. That is, the host has a well-defined addressing scheme to interpret the contents, and thus the layout of the data in memory can be consistently interpreted across aliases if each of those aliases is a host-accessible subresource. Non-linear images, and linear image subresources in other layouts, are not host-accessible.

If two aliases are both host-accessible, then they interpret the contents of the memory in consistent ways, and data written to one alias can be read by the other alias.

If two aliases are both images that were created with identical creation parameters, both were created with the VK_IMAGE_CREATE_ALIAS_BIT flag set, and both are bound identically to memory except for VkBindImageMemoryDeviceGroupInfo::pDeviceIndices and VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions, then they interpret the contents of the memory in consistent ways, and data written to one alias can be read by the other alias.

Additionally, if an individual plane of a multi-planar image and a single-plane image aliases the same memory, then they also interpret the contents of the memory in consistent ways under the same conditions, but with the following modifications:

- Both must have been created with the VK_IMAGE_CREATE_DISJOINT_BIT flag.
- The single-plane image must have a VkFormat that is equivalent to that of the multi-planar image’s individual plane.
- The single-plane image and the individual plane of the multi-planar image must be bound identically to memory except for VkBindImageMemoryDeviceGroupInfo::pDeviceIndices and VkBindImageMemoryDeviceGroupInfo::pSplitInstanceBindRegions.
- The width and height of the single-plane image are derived from the multi-planar image’s dimensions in the manner listed for plane compatibility for the aliased plane.
- All other creation parameters must be identical.

Aliases created by binding the same memory to resources in multiple Vulkan instances or external APIs using external memory handle export and import mechanisms interpret the contents of the memory in consistent ways, and data written to one alias can be read by the other alias.

Otherwise, the aliases interpret the contents of the memory differently, and writes via one alias make the contents of memory partially or completely undefined to the other alias. If the first alias is a host-accessible subresource, then the bytes affected are those written by the memory operations according to its addressing scheme. If the first alias is not host-accessible, then the bytes affected are those overlapped by the image subresources that were written. If the second alias is a host-accessible subresource, the affected bytes become undefined. If the second alias is a not host-accessible, all sparse image blocks (for sparse partially-resident images) or all image subresources...
(for non-sparse image and fully resident sparse images) that overlap the affected bytes become undefined.

If any image subresources are made undefined due to writes to an alias, then each of those image subresources must have its layout transitioned from `VK_IMAGE_LAYOUT_UNDEFINED` to a valid layout before it is used, or from `VK_IMAGE_LAYOUT_PREINITIALIZED` if the memory has been written by the host. If any sparse blocks of a sparse image have been made undefined, then only the image subresources containing them must be transitioned.

Use of an overlapping range by two aliases must be separated by a memory dependency using the appropriate access types if at least one of those uses performs writes, whether the aliases interpret memory consistently or not. If buffer or image memory barriers are used, the scope of the barrier must contain the entire range and/or set of image subresources that overlap.

If two aliasing image views are used in the same framebuffer, then the render pass must declare the attachments using the `VK_ATTACHMENT_DESCRIPTION_MAY_ALIAS_BIT`, and follow the other rules listed in that section.

**Note**

Memory recycled via an application suballocator (i.e. without freeing and reallocating the memory objects) is not substantially different from memory aliasing. However, a suballocator usually waits on a fence before recycling a region of memory, and signaling a fence involves sufficient implicit dependencies to satisfy all the above requirements.

### 11.9. Acceleration Structures

Acceleration structures are an opaque structure that is built by the implementation to more efficiently perform spatial queries on the provided geometric data. For this extension, an acceleration structure is either a top-level acceleration structure containing a set of bottom-level acceleration structures or a bottom-level acceleration structure containing either a set of axis-aligned bounding boxes for custom geometry or a set of triangles.

Each instance in the top-level acceleration structure contains a reference to a bottom-level acceleration structure as well as an instance transform plus information required to index into the shader bindings. The top-level acceleration structure is what is bound to the acceleration descriptor to trace inside the shader in the ray tracing pipeline.

Acceleration structures are represented by `VkAccelerationStructureKHR` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkAccelerationStructureKHR)
```

To create an acceleration structure, call:
device is the logical device that creates the buffer object.

pCreateInfo is a pointer to a VkAccelerationStructureCreateInfoKHR structure containing parameters affecting creation of the acceleration structure.

pAllocator controls host memory allocation as described in the Memory Allocation chapter.

pAccelerationStructure is a pointer to a VkAccelerationStructureKHR handle in which the resulting acceleration structure object is returned.

Similar to other objects in Vulkan, the acceleration structure creation merely creates an object with a specific “shape”. The type and quantity of geometry that can be built into an acceleration structure is determined by the parameters of VkAccelerationStructureCreateInfoKHR.

Populating the data in the object after allocating and binding memory is done with commands such as vkCmdBuildAccelerationStructureKHR, vkBuildAccelerationStructureKHR, vkCmdCopyAccelerationStructureKHR, and vkCopyAccelerationStructureKHR.

Valid Usage

- The rayTracing or rayQuery feature must be enabled
- If VkAccelerationStructureCreateInfoKHR::deviceAddress is not zero, the rayTracingAccelerationStructureCaptureReplay feature must be enabled
- If device was created with multiple physical devices, then the bufferDeviceAddressMultiDevice feature must be enabled

Valid Usage (Implicit)

- device must be a valid VkDevice handle
- pCreateInfo must be a valid pointer to a valid VkAccelerationStructureCreateInfoKHR structure
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
- pAccelerationStructure must be a valid pointer to a VkAccelerationStructureKHR handle
Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR

The `VkAccelerationStructureCreateInfoKHR` structure is defined as:

```c
typedef struct VkAccelerationStructureCreateInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkDeviceSize compactedSize;
    VkAccelerationStructureTypeKHR type;
    VkBuildAccelerationStructureFlagsKHR flags;
    uint32_t maxGeometryCount;
    const VkAccelerationStructureCreateGeometryTypeInfoKHR* pGeometryInfos;
    VkDeviceAddress deviceAddress;
} VkAccelerationStructureCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `compactedSize` is the size from the result of `vkCmdWriteAccelerationStructuresPropertiesKHR` if this acceleration structure is going to be the target of a compacting copy.
- `type` is a `VkAccelerationStructureTypeKHR` value specifying the type of acceleration structure that will be created.
- `flags` is a bitmask of `VkBuildAccelerationStructureFlagBitsKHR` specifying additional parameters of the acceleration structure.
- `maxGeometryCount` specifies the number of geometries that will be in the new acceleration structure.
- `pGeometryInfos` is an array of `maxGeometryCount` `VkAccelerationStructureCreateGeometryTypeInfoKHR` structures, which describe the maximum size and format of the data that will be built into the acceleration structure.
- `deviceAddress` is the device address requested for the acceleration structure if the `rayTracingAccelerationStructureCaptureReplay` feature is being used.

If `deviceAddress` is zero, no specific address is requested.

If `deviceAddress` is not zero, `deviceAddress` must be an address retrieved from an identically created acceleration structure on the same implementation. The acceleration structure must also be bound to an identically created `VkDeviceMemory` object.
Apps **should** avoid creating acceleration structures with app-provided addresses and implementation-provided addresses in the same process, to reduce the likelihood of `VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR` errors.

### Valid Usage

- If `compactedSize` is not 0 then `maxGeometryCount` **must** be 0.
- If `type` is `VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL_KHR` then `maxGeometryCount` **must** be less than or equal to `VkPhysicalDeviceRayTracingPropertiesKHR::maxGeometryCount`.
- If `type` is `VK_ACCELERATION_STRUCTURE_TYPE_TOP_LEVEL_KHR` then `pGeometryInfos->pname:maxPrimitiveCount` **must** be less than or equal to `VkPhysicalDeviceRayTracingPropertiesKHR::maxInstanceCount`.
- The total number of triangles in all geometries **must** be less than or equal to `VkPhysicalDeviceRayTracingPropertiesKHR::maxPrimitiveCount`.
- The total number of AABBs in all geometries **must** be less than or equal to `VkPhysicalDeviceRayTracingPropertiesKHR::maxPrimitiveCount`.
- If `type` is `VK_ACCELERATION_STRUCTURE_TYPE_TOP_LEVEL_KHR` and `compactedSize` is 0, `maxGeometryCount` **must** be 1.
- If `type` is `VK_ACCELERATION_STRUCTURE_TYPE_TOP_LEVEL_KHR` and `compactedSize` is 0, the `geometryType` member of elements of `pGeometryInfos` **must** be `VK_GEOMETRY_TYPE_INSTANCES_KHR`.
- If `type` is `VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL_KHR` and `compactedSize` is 0, the `geometryType` member of elements of `pGeometryInfos` **must** not be `VK_GEOMETRY_TYPE_INSTANCES_KHR`.
- If `type` is `VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL_KHR` then the `geometryType` member of each geometry in `pGeometryInfos` **must** be the same.
- If `flags` has the `VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_TRACE_BIT_KHR` bit set, then it **must** not have the `VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_BUILD_BIT_KHR` bit set.
- If `deviceAddress` is not 0, `VkPhysicalDeviceRayTracingFeaturesKHR::rayTracingAccelerationStructureCaptureReplay` **must** be `VK_TRUE`.

### Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_CREATE_INFO_KHR`.
- `pNext` **must** be `NULL`.
- `type` **must** be a valid `VkAccelerationStructureTypeKHR` value.
- `flags` **must** be a valid combination of `VkBuildAccelerationStructureFlagBitsKHR` values.
- `pGeometryInfos` **must** be a valid pointer to an array of `maxGeometryCount` valid `VkAccelerationStructureCreateGeometryTypeInfoKHR` structures.
- `maxGeometryCount` **must** be greater than 0.
The `VkAccelerationStructureCreateGeometryTypeInfoKHR` structure specifies the shape of geometries that will be built into an acceleration structure and is defined as:

```c
typedef struct VkAccelerationStructureCreateGeometryTypeInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkGeometryTypeKHR geometryType;
    uint32_t maxPrimitiveCount;
    VkIndexType indexType;
    uint32_t maxVertexCount;
    VkFormat vertexFormat;
    VkBool32 allowsTransforms;
} VkAccelerationStructureCreateGeometryTypeInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **geometryType** is a `VkGeometryTypeKHR` that describes the type of an acceleration structure geometry.
- **maxPrimitiveCount** describes the maximum number of primitives that can be built into an acceleration structure geometry.
- **indexType** is a `VkIndexType` that describes the index type used to build this geometry when `geometryType` is `VK_GEOMETRY_TYPE_TRIANGLES_KHR`.
- **maxVertexCount** describes the maximum vertex count that can be used to build an acceleration structure geometry when `geometryType` is `VK_GEOMETRY_TYPE_TRIANGLES_KHR`.
- **vertexFormat** is a `VkFormat` that describes the vertex format used to build this geometry when `geometryType` is `VK_GEOMETRY_TYPE_TRIANGLES_KHR`.
- **allowsTransforms** indicates whether transform data can be used by this acceleration structure or not, when `geometryType` is `VK_GEOMETRY_TYPE_TRIANGLES_KHR`.

When `geometryType` is `VK_GEOMETRY_TYPE_TRIANGLES_KHR`:

- if `indexType` is `VK_INDEX_TYPE_NONE_KHR`, then this structure describes a set of triangles.
- if `indexType` is not `VK_INDEX_TYPE_NONE_KHR`, then this structure describes a set of indexed triangles.

### Valid Usage

- If `geometryType` is `VK_GEOMETRY_TYPE_TRIANGLES_KHR`, `vertexFormat` must support the `VK_FORMAT_FEATURE_ACCELERATION_STRUCTURE_VERTEX_BUFFER_BIT_KHR` in `VkFormatProperties::bufferFeatures` as returned by `vkGetPhysicalDeviceFormatProperties2`.
- If `geometryType` is `VK_GEOMETRY_TYPE_TRIANGLES_KHR`, `indexType` must be `VK_INDEX_TYPE_UINT16`, `VK_INDEX_TYPE_UINT32`, or `VK_INDEX_TYPE_NONE_KHR`. 

504 | Chapter 11. Resource Creation
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_CREATE_GEOMETRY_TYPE_INFO_KHR`
- **pNext** must be `NULL`
- **geometryType** must be a valid `VkGeometryTypeKHR` value
- **indexType** must be a valid `VkIndexType` value
- If `vertexFormat` is not `0`, `vertexFormat` must be a valid `VkFormat` value

Values which **can** be set in `VkAccelerationStructureCreateInfoKHR::type` specifying the type of acceleration structure, are:

```c
typedef enum VkAccelerationStructureTypeKHR {
    VK_ACCELERATION_STRUCTURE_TYPE_TOP_LEVEL_KHR = 0,
    VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL_KHR = 1,
    VK_ACCELERATION_STRUCTURE_TYPE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkAccelerationStructureTypeKHR;
```

- **VK_ACCELERATION_STRUCTURE_TYPE_TOP_LEVEL_KHR** is a top-level acceleration structure containing instance data referring to bottom-level level acceleration structures.
- **VK_ACCELERATION_STRUCTURE_TYPE_BOTTOM_LEVEL_KHR** is a bottom-level acceleration structure containing the AABBs or geometry to be intersected.

Bits which **can** be set in `VkAccelerationStructureCreateInfoKHR::flags` specifying additional parameters for acceleration structure builds, are:

```c
typedef enum VkBuildAccelerationStructureFlagBitsKHR {
    VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_UPDATE_BIT_KHR = 0x00000001,
    VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_COMPACTION_BIT_KHR = 0x00000002,
    VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_TRACE_BIT_KHR = 0x00000004,
    VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_BUILD_BIT_KHR = 0x00000008,
    VK_BUILD_ACCELERATION_STRUCTURE_LOW_MEMORY_BIT_KHR = 0x00000010,
    VK_BUILD_ACCELERATION_STRUCTURE_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkBuildAccelerationStructureFlagBitsKHR;
```

- **VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_UPDATE_BIT_KHR** indicates that the specified acceleration structure **can** be updated with `update` of `VK_TRUE` in `vkCmdBuildAccelerationStructureKHR`.
- **VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_COMPACTION_BIT_KHR** indicates that the specified acceleration structure **can** act as the source for a copy acceleration structure command with `mode` of `VK_COPY_ACCELERATION_STRUCTURE_MODE_COMPACT_KHR` to produce a compacted acceleration structure.
- **VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_TRACE_BIT_KHR** indicates that the given acceleration structure build **should** prioritize trace performance over build time.
- **VK_BUILD_ACCELERATION_STRUCTURE_PREFER_FAST_BUILD_BIT_KHR** indicates that the given
acceleration structure build **should** prioritize build time over trace performance.

- **VK_BUILD_ACCELERATION_STRUCTURE_LOW_MEMORY_BIT_KHR** indicates that this acceleration structure **should** minimize the size of the scratch memory and the final result build, potentially at the expense of build time or trace performance.

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_UPDATE_BIT_KHR</strong> and <strong>VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_COMPACTION_BIT_KHR</strong> may take more time and memory than a normal build, and so <strong>should</strong> only be used when those features are needed.</td>
</tr>
</tbody>
</table>

```c
typedef VkFlags VkBuildAccelerationStructureFlagsKHR;
```

**VkBuildAccelerationStructureFlagsKHR** is a bitmask type for setting a mask of zero or more **VkBuildAccelerationStructureFlagBitsKHR**.

Geometry types are specified by **VkGeometryTypeKHR**, which takes values:

```c
typedef enum VkGeometryTypeKHR {
    VK_GEOMETRY_TYPE_TRIANGLES_KHR = 0,
    VK_GEOMETRY_TYPE_AABBS_KHR = 1,
    VK_GEOMETRY_TYPE_INSTANCES_KHR = 1000150000,
    VK_GEOMETRY_TYPE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkGeometryTypeKHR;
```

- **VK_GEOMETRY_TYPE_TRIANGLES_KHR** specifies a geometry type consisting of triangles.
- **VK_GEOMETRY_TYPE_AABBS_KHR** specifies a geometry type consisting of axis-aligned bounding boxes.
- **VK_GEOMETRY_TYPE_INSTANCES_KHR** specifies a geometry type consisting of acceleration structure instances.

Bits specifying additional parameters for geometries in acceleration structure builds, are:

```c
typedef enum VkGeometryFlagBitsKHR {
    VK_GEOMETRY_OPAQUE_BIT_KHR = 0x00000001,
    VK_GEOMETRY_NO_DUPLICATE_ANY_HIT_INVOCATION_BIT_KHR = 0x00000002,
    VK_GEOMETRY_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkGeometryFlagBitsKHR;
```

- **VK_GEOMETRY_OPAQUE_BIT_KHR** indicates that this geometry does not invoke the any-hit shaders even if present in a hit group.
- **VK_GEOMETRY_NO_DUPLICATE_ANY_HIT_INVOCATION_BIT_KHR** indicates that the implementation **must** only call the any-hit shader a single time for each primitive in this geometry. If this bit is absent an implementation **may** invoke the any-hit shader more than once for this geometry.
typedef VkFlags VkGeometryFlagsKHR;

VkGeometryFlagsKHR is a bitmask type for setting a mask of zero or more VkGeometryFlagBitsKHR.

To destroy an acceleration structure, call:

```c
void vkDestroyAccelerationStructureKHR(
    VkDevice device,                  // device
    VkAccelerationStructureKHR accelerationStructure, // accelerationStructure
    const VkAllocationCallbacks* pAllocator);   // pAllocator
```

- **device** is the logical device that destroys the buffer.
- **accelerationStructure** is the acceleration structure to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage

- All submitted commands that refer to **accelerationStructure** must have completed execution.
- If **VkAllocationCallbacks** were provided when **accelerationStructure** was created, a compatible set of callbacks must be provided here.
- If no **VkAllocationCallbacks** were provided when **accelerationStructure** was created, **pAllocator** must be NULL.

### Valid Usage (Implicit)

- **device** must be a valid VkDevice handle.
- **accelerationStructure** must be a valid VkAccelerationStructureKHR handle.
- **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid VkAllocationCallbacks structure.
- **accelerationStructure** must have been created, allocated, or retrieved from **device**.

An acceleration structure has memory requirements for the structure object itself, scratch space for the build, and scratch space for the update.

Scratch space is allocated as a VkBuffer, so for VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_BUILD_SCRATCH_KHR and VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_UPDATE_SCRATCH_KHR the pMemoryRequirements->alignment and pMemoryRequirements->memoryTypeBits values returned by this call must be filled with zero, and should be ignored by the application.

To query the memory requirements call:
```c
void vkGetAccelerationStructureMemoryRequirementsKHR(
    VkDevice device, const VkAccelerationStructureMemoryRequirementsInfoKHR* pInfo, VkMemoryRequirements2* pMemoryRequirements);
```

- `device` is the logical device on which the acceleration structure was created.
- `pInfo` specifies the acceleration structure to get memory requirements for.
- `pMemoryRequirements` returns the requested acceleration structure memory requirements.

**Valid Usage (Implicit)**

- `device` **must** be a valid `VkDevice` handle
- `pInfo` **must** be a valid pointer to a valid `VkAccelerationStructureMemoryRequirementsInfoKHR` structure
- `pMemoryRequirements` **must** be a valid pointer to a `VkMemoryRequirements2` structure

The `VkAccelerationStructureMemoryRequirementsInfoKHR` structure is defined as:

```c
typedef struct VkAccelerationStructureMemoryRequirementsInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkAccelerationStructureMemoryRequirementsTypeKHR type;
    VkAccelerationStructureBuildTypeKHR buildType;
    VkAccelerationStructureKHR accelerationStructure;
} VkAccelerationStructureMemoryRequirementsInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is **NULL** or a pointer to an extension-specific structure.
- `buildType` selects the build types whose memory requirements are being queried.
- `type` selects the type of memory requirement being queried. `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_OBJECT_KHR` returns the memory requirements for the object itself. `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_BUILD_SCRATCH_KHR` returns the memory requirements for the scratch memory when doing a build. `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_UPDATE_SCRATCH_KHR` returns the memory requirements for the scratch memory when doing an update.
- `accelerationStructure` is the acceleration structure to be queried for memory requirements.
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_INFO_KHR`
- `pNext` must be `NULL`
- `type` must be a valid `VkAccelerationStructureMemoryRequirementsTypeKHR` value
- `buildType` must be a valid `VkAccelerationStructureBuildTypeKHR` value
- `accelerationStructure` must be a valid `VkAccelerationStructureKHR` handle

Possible values of `type` in `VkAccelerationStructureMemoryRequirementsInfoKHR` are:

```c
typedef enum VkAccelerationStructureMemoryRequirementsTypeKHR {
    VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_OBJECT_KHR = 0,
    VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_BUILD_SCRATCH_KHR = 1,
    VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_UPDATE_SCRATCH_KHR = 2,
    VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkAccelerationStructureMemoryRequirementsTypeKHR;
```

- `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_OBJECT_KHR` requests the memory requirement for the `VkAccelerationStructureKHR` backing store.
- `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_BUILD_SCRATCH_KHR` requests the memory requirement for scratch space during the initial build.
- `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_UPDATE_SCRATCH_KHR` requests the memory requirement for scratch space during an update.

Possible values of `buildType` in `VkAccelerationStructureMemoryRequirementsInfoKHR` are:

```c
typedef enum VkAccelerationStructureBuildTypeKHR {
    VK_ACCELERATION_STRUCTURE_BUILD_TYPE_HOST_KHR = 0,
    VK_ACCELERATION_STRUCTURE_BUILD_TYPE_DEVICE_KHR = 1,
    VK_ACCELERATION_STRUCTURE_BUILD_TYPE_HOST_OR_DEVICE_KHR = 2,
    VK_ACCELERATION_STRUCTURE_BUILD_TYPE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkAccelerationStructureBuildTypeKHR;
```

- `VK_ACCELERATION_STRUCTURE_BUILD_TYPE_HOST_KHR` requests the memory requirement for operations performed by the host.
- `VK_ACCELERATION_STRUCTURE_BUILD_TYPE_DEVICE_KHR` requests the memory requirement for operations performed by the device.
- `VK_ACCELERATION_STRUCTURE_BUILD_TYPE_HOST_OR_DEVICE_KHR` requests the memory requirement for operations performed by either the host, or the device.

To attach memory to one or more acceleration structures at a time, call:
VkResult vkBindAccelerationStructureMemoryKHR(
    VkDevice device,
    uint32_t bindInfoCount,
    const VkBindAccelerationStructureMemoryInfoKHR* pBindInfos);

- `device` is the logical device that owns the acceleration structures and memory.
- `bindInfoCount` is the number of elements in `pBindInfos`.
- `pBindInfos` is a pointer to an array of `VkBindAccelerationStructureMemoryInfoKHR` structures describing acceleration structures and memory to bind.

**Valid Usage (Implicit)**

- `device` **must** be a valid `VkDevice` handle
- `pBindInfos` **must** be a valid pointer to an array of `bindInfoCount` valid `VkBindAccelerationStructureMemoryInfoKHR` structures
- `bindInfoCount` **must** be greater than 0

**Return Codes**

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkBindAccelerationStructureMemoryInfoKHR` structure is defined as:

```c
typedef struct VkBindAccelerationStructureMemoryInfoKHR {
    VkStructureType sType;
    const void*pNext;
    VkAccelerationStructureKHR accelerationStructure;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
    uint32_t deviceIndexCount;
    const uint32_t*pDeviceIndices;
} VkBindAccelerationStructureMemoryInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is **NULL** or a pointer to an extension-specific structure.
- `accelerationStructure` is the acceleration structure to be attached to memory.
- `memory` is a `VkDeviceMemory` object describing the device memory to attach.
• `memoryOffset` is the start offset of the region of memory that is to be bound to the acceleration structure. The number of bytes returned in the `VkMemoryRequirements::size` member in `memory`, starting from `memoryOffset` bytes, will be bound to the specified acceleration structure.

• `deviceIndexCount` is the number of elements in `pDeviceIndices`.

• `pDeviceIndices` is a pointer to an array of device indices.

Valid Usage

• `accelerationStructure` must not already be backed by a memory object

• `memoryOffset` must be less than the size of `memory`

• `memory` must have been allocated using one of the memory types allowed in the `memoryTypeBits` member of the `VkMemoryRequirements` structure returned from a call to `vkGetAccelerationStructureMemoryRequirementsKHR` with `accelerationStructure` and type of `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_OBJECT_KHR`

• `memoryOffset` must be an integer multiple of the `alignment` member of the `VkMemoryRequirements` structure returned from a call to `vkGetAccelerationStructureMemoryRequirementsKHR` with `accelerationStructure` and type of `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_OBJECT_KHR`

• The `size` member of the `VkMemoryRequirements` structure returned from a call to `vkGetAccelerationStructureMemoryRequirementsKHR` with `accelerationStructure` and type of `VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_OBJECT_KHR` must be less than or equal to the size of `memory minus memoryOffset`

Valid Usage (Implicit)

• `sType` must be `VK_STRUCTURE_TYPE_BIND_ACCELERATION_STRUCTURE_MEMORY_INFO_KHR`

• `pNext` must be `NULL`

• `accelerationStructure` must be a valid `VkAccelerationStructureKHR` handle

• `memory` must be a valid `VkDeviceMemory` handle

• If `deviceIndexCount` is not 0, `pDeviceIndices` must be a valid pointer to an array of `deviceIndexCount` `uint32_t` values

• Both of `accelerationStructure`, and `memory` must have been created, allocated, or retrieved from the same `VkDevice`

To query the 64-bit device address for an acceleration structure, call:

```c
VkDeviceAddress vkGetAccelerationStructureDeviceAddressKHR(  
    VkDevice                                    device,  
    const VkAccelerationStructureDeviceAddressInfoKHR* pInfo);
```

• `device` is the logical device that the accelerationStructure was created on.
• pInfo is a pointer to a VkAccelerationStructureDeviceAddressInfoKHR structure specifying the acceleration structure to retrieve an address for.

The 64-bit return value is an address of the acceleration structure, which can be used for device and shader operations that involve acceleration structures, such as ray traversal and acceleration structure building.

If the acceleration structure was created with a non-zero value of VkAccelerationStructureCreateInfoKHR::deviceAddress the return value will be the same address.

Valid Usage

• If device was created with multiple physical devices, then the bufferDeviceAddressMultiDevice feature must be enabled

Valid Usage (Implicit)

• device must be a valid VkDevice handle
• pInfo must be a valid pointer to a valid VkAccelerationStructureDeviceAddressInfoKHR structure

The VkAccelerationStructureDeviceAddressInfoKHR structure is defined as:

```c
typedef struct VkAccelerationStructureDeviceAddressInfoKHR {
    VkStructureType               sType;
    const void*                   pNext;
    VkAccelerationStructureKHR    accelerationStructure;
} VkAccelerationStructureDeviceAddressInfoKHR;
```

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• accelerationStructure specifies the acceleration structure whose address is being queried.

Valid Usage

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_DEVICE_ADDRESS_INFO_KHR
• pNext must be NULL
• accelerationStructure must be a valid VkAccelerationStructureKHR handle
Chapter 12. Samplers

`VkSampler` objects represent the state of an image sampler which is used by the implementation to read image data and apply filtering and other transformations for the shader.

Samplers are represented by `VkSampler` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSampler)
```

To create a sampler object, call:

```c
VkResult vkCreateSampler(
    VkDevice                                    device,
    const VkSamplerCreateInfo*                  pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkSampler*                                  pSampler);
```

- `device` is the logical device that creates the sampler.
- `pCreateInfo` is a pointer to a `VkSamplerCreateInfo` structure specifying the state of the sampler object.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pSampler` is a pointer to a `VkSampler` handle in which the resulting sampler object is returned.

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pCreateInfo` must be a valid pointer to a valid `VkSamplerCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- `pSampler` must be a valid pointer to a `VkSampler` handle

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_TOO_MANY_OBJECTS`

The `VkSamplerCreateInfo` structure is defined as:
typedef struct VkSamplerCreateInfo {
    VkStructureType         sType;
    const void*             pNext;
    VkSamplerCreateFlags    flags;
    VkFilter                magFilter;
    VkFilter                minFilter;
    VkSamplerMipmapMode     mipmapMode;
    VkSamplerAddressMode    addressModeU;
    VkSamplerAddressMode    addressModeV;
    VkSamplerAddressMode    addressModeW;
    float                   mipLodBias;
    VkBool32                anisotropyEnable;
    float                   maxAnisotropy;
    VkBool32                compareEnable;
    VkCompareOp             compareOp;
    float                   minLod;
    float                   maxLod;
    VkBorderColor           borderColor;
    VkBool32                unnormalizedCoordinates;
} VkSamplerCreateInfo;

• **sType** is the type of this structure.
• **pNext** is NULL or a pointer to an extension-specific structure.
• **flags** is a bitmask of VkSamplerCreateFlagBits describing additional parameters of the sampler.
• **magFilter** is a VkFilter value specifying the magnification filter to apply to lookups.
• **minFilter** is a VkFilter value specifying the minification filter to apply to lookups.
• **mipmapMode** is a VkSamplerMipmapMode value specifying the mipmap filter to apply to lookups.
• **addressModeU** is a VkSamplerAddressMode value specifying the addressing mode for outside [0..1] range for U coordinate.
• **addressModeV** is a VkSamplerAddressMode value specifying the addressing mode for outside [0..1] range for V coordinate.
• **addressModeW** is a VkSamplerAddressMode value specifying the addressing mode for outside [0..1] range for W coordinate.
• **mipLodBias** is the bias to be added to mipmap LOD (level-of-detail) calculation and bias provided by image sampling functions in SPIR-V, as described in the Level-of-Detail Operation section.
• **anisotropyEnable** is VK_TRUE to enable anisotropic filtering, as described in the Texel Anisotropic Filtering section, or VK_FALSE otherwise.
• **maxAnisotropy** is the anisotropy value clamp used by the sampler when anisotropyEnable is VK_TRUE. If anisotropyEnable is VK_FALSE, maxAnisotropy is ignored.
• **compareEnable** is VK_TRUE to enable comparison against a reference value during lookups, or VK_FALSE otherwise.
  ◦ Note: Some implementations will default to shader state if this member does not match.
• `compareOp` is a `VkCompareOp` value specifying the comparison function to apply to fetched data before filtering as described in the Depth Compare Operation section.

• `minLod` and `maxLod` are the values used to clamp the computed LOD value, as described in the Level-of-Detail Operation section.

• `borderColor` is a `VkBorderColor` value specifying the predefined border color to use.

• `unnormalizedCoordinates` controls whether to use unnormalized or normalized texel coordinates to address texels of the image. When set to `VK_TRUE`, the range of the image coordinates used to lookup the texel is in the range of zero to the image dimensions for x, y and z. When set to `VK_FALSE` the range of image coordinates is zero to one.

When `unnormalizedCoordinates` is `VK_TRUE`, images the sampler is used with in the shader have the following requirements:

- The `viewType` must be either `VK_IMAGE_VIEW_TYPE_1D` or `VK_IMAGE_VIEW_TYPE_2D`.
- The image view must have a single layer and a single mip level.

When `unnormalizedCoordinates` is `VK_TRUE`, image built-in functions in the shader that use the sampler have the following requirements:

- The functions must not use projection.
- The functions must not use offsets.

---

**Mapping of OpenGL to Vulkan filter modes**

* `magFilter` values of `VK_FILTER_NEAREST` and `VK_FILTER_LINEAR` directly correspond to `GL_NEAREST` and `GL_LINEAR` magnification filters. `minFilter` and `mipmapMode` combine to correspond to the similarly named OpenGL minification filter of `GL_minFilter_MIPMAP_mipmapMode` (e.g. `minFilter` of `VK_FILTER_LINEAR` and `mipmapMode` of `VK_SAMPLER_MIPMAP_MODE_NEAREST` correspond to `GL_LINEAR_MIPMAP_NEAREST`).

There are no Vulkan filter modes that directly correspond to OpenGL minification filters of `GL_LINEAR` or `GL_NEAREST`, but they can be emulated using `VK_SAMPLER_MIPMAP_MODE_NEAREST`, `minLod = 0`, and `maxLod = 0.25`, and using `minFilter = VK_FILTER_LINEAR` or `minFilter = VK_FILTER_NEAREST`, respectively.

Note that using a `maxLod` of zero would cause magnification to always be performed, and the `magFilter` to always be used. This is valid, just not an exact match for OpenGL behavior. Clamping the maximum LOD to 0.25 allows the λ value to be non-zero and minification to be performed, while still always rounding down to the base level. If the `minFilter` and `magFilter` are equal, then using a `maxLod` of zero also works.

The maximum number of sampler objects which can be simultaneously created on a device is implementation-dependent and specified by the `maxSamplerAllocationCount` member of the `VkPhysicalDeviceLimits` structure. If `maxSamplerAllocationCount` is exceeded, `vkCreateSampler` will return `VK_ERROR_TOO_MANY_OBJECTS`.

Since `VkSampler` is a non-dispatchable handle type, implementations may return the same handle
for sampler state vectors that are identical. In such cases, all such objects would only count once against the `maxSamplerAllocationCount` limit.

**Valid Usage**

- The absolute value of `mipLodBias` must be less than or equal to `VkPhysicalDeviceLimits::maxSamplerLodBias`
- `maxLod` must be greater than or equal to `minLod`
- If the anisotropic sampling feature is not enabled, `anisotropyEnable` must be `VK_FALSE`
- If anisotropic sampling is `VK_TRUE`, `maxAnisotropy` must be between 1.0 and `VkPhysicalDeviceLimits::maxSamplerAnisotropy`, inclusive
- If sampler `Y’CbCr` conversion is enabled and the sampler `Y’CbCr` conversion’s features do not support
  `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT`, `minFilter` and `magFilter` must be equal to the sampler `Y’CbCr` conversion’s chromaFilter
- If `unnormalizedCoordinates` is `VK_TRUE`, `minFilter` and `magFilter` must be equal
- If `unnormalizedCoordinates` is `VK_TRUE`, `mipmapMode` must be `VK_SAMPLER_MIPMAP_MODE_NEAREST`
- If `unnormalizedCoordinates` is `VK_TRUE`, `minLod` and `maxLod` must be zero
- If `unnormalizedCoordinates` is `VK_TRUE`, `anisotropyEnable` must be `VK_FALSE`
- If `unnormalizedCoordinates` is `VK_TRUE`, `compareEnable` must be `VK_FALSE`
- If any of `addressModeU`, `addressModeV` or `addressModeW` are `VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER`, `borderColor` must be a valid `VkBorderColor` value
- If sampler `Y’CbCr` conversion is enabled, `addressModeU`, `addressModeV`, and `addressModeW` must be `VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE`, `anisotropyEnable` must be `VK_FALSE`, and `unnormalizedCoordinates` must be `VK_FALSE`
- If the `VK_KHR_sampler_mirror_clamp_to_edge` extension is not enabled, `addressModeU`, `addressModeV` and `addressModeW` must not be `VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE`
- If `compareEnable` is `VK_TRUE`, `compareOp` must be a valid `VkCompareOp` value
Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO`
- `pNext` **must** be `NULL` or a pointer to a valid instance of `VkSamplerYcbcrConversionInfo`
- The `sType` value of each struct in the `pNext` chain **must** be unique
- `flags` **must** be `0`
- `magFilter` **must** be a valid `VkFilter` value
- `minFilter` **must** be a valid `VkFilter` value
- `mipmapMode` **must** be a valid `VkSamplerMipmapMode` value
- `addressModeU` **must** be a valid `VkSamplerAddressMode` value
- `addressModeV` **must** be a valid `VkSamplerAddressMode` value
- `addressModeW` **must** be a valid `VkSamplerAddressMode` value

Bits which **can** be set in `VkSamplerCreateInfo::flags`, specifying additional parameters of a sampler, are:

```c
typedef enum VkSamplerCreateFlagBits {
    VK_SAMPLER_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSamplerCreateFlagBits;
```

```c
typedef VkFlags VkSamplerCreateFlags;
```

`VkSamplerCreateFlags` is a bitmask type for setting a mask of zero or more `VkSamplerCreateFlagBits`.

Possible values of the `VkSamplerCreateInfo::magFilter` and `minFilter` parameters, specifying filters used for texture lookups, are:

```c
typedef enum VkFilter {
    VK_FILTER_NEAREST = 0,
    VK_FILTER_LINEAR = 1,
    VK_FILTER_MAX_ENUM = 0x7FFFFFFF
} VkFilter;
```

- `VK_FILTER_NEAREST` specifies nearest filtering.
- `VK_FILTER_LINEAR` specifies linear filtering.

These filters are described in detail in **Texel Filtering**.

Possible values of the `VkSamplerCreateInfo::mipmapMode`, specifying the mipmap mode used for texture lookups, are:
typedef enum VkSamplerMipmapMode {
    VK_SAMPLER_MIPMAP_MODE_NEAREST = 0,
    VK_SAMPLER_MIPMAP_MODE_LINEAR = 1,
    VK_SAMPLER_MIPMAP_MODE_MAX_ENUM = 0x7FFFFFFF
} VkSamplerMipmapMode;

- **VK_SAMPLER_MIPMAP_MODE_NEAREST** specifies nearest filtering.
- **VK_SAMPLER_MIPMAP_MODE_LINEAR** specifies linear filtering.

These modes are described in detail in [Texel Filtering](#).

Possible values of the `VkSamplerCreateInfo::addressMode*` parameters, specifying the behavior of sampling with coordinates outside the range [0,1] for the respective u, v, or w coordinate as defined in the [Wrapping Operation](#) section, are:

typedef enum VkSamplerAddressMode {
    VK_SAMPLER_ADDRESS_MODE_REPEAT = 0,
    VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT = 1,
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE = 2,
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER = 3,
    VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE = 4,
    VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE_KHR = VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE,
    VK_SAMPLER_ADDRESS_MODE_MAX_ENUM = 0x7FFFFFFF
} VkSamplerAddressMode;

- **VK_SAMPLER_ADDRESS_MODE_REPEAT** specifies that the repeat wrap mode will be used.
- **VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT** specifies that the mirrored repeat wrap mode will be used.
- **VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE** specifies that the clamp to edge wrap mode will be used.
- **VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER** specifies that the clamp to border wrap mode will be used.
- **VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE** specifies that the mirror clamp to edge wrap mode will be used. This is only valid if the `VK_KHR_sampler_mirror_clamp_to_edge` extension is enabled.

Possible values of `VkSamplerCreateInfo::borderColor`, specifying the border color used for texture lookups, are:
typedef enum VkBorderColor {
    VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK = 0,
    VK_BORDER_COLOR_INT_TRANSPARENT_BLACK = 1,
    VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK = 2,
    VK_BORDER_COLOR_INT_OPAQUE_BLACK = 3,
    VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE = 4,
    VK_BORDER_COLOR_INT_OPAQUE_WHITE = 5,
    VK_BORDER_COLOR_MAX_ENUM = 0x7FFFFFFF
} VkBorderColor;

- **VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK** specifies a transparent, floating-point format, black color.
- **VK_BORDER_COLOR_INT_TRANSPARENT_BLACK** specifies a transparent, integer format, black color.
- **VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK** specifies an opaque, floating-point format, black color.
- **VK_BORDER_COLOR_INT_OPAQUE_BLACK** specifies an opaque, integer format, black color.
- **VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE** specifies an opaque, floating-point format, white color.
- **VK_BORDER_COLOR_INT_OPAQUE_WHITE** specifies an opaque, integer format, white color.

These colors are described in detail in [Texel Replacement](#).

To destroy a sampler, call:

```c
void vkDestroySampler(
    VkDevice device,  // device is the logical device that destroys the sampler.
    VkSampler sampler,  // sampler is the sampler to destroy.
    const VkAllocationCallbacks* pAllocator);  // pAllocator controls host memory allocation as described in the Memory Allocation chapter.
```

**Valid Usage**

- All submitted commands that refer to **sampler** must have completed execution.
- If **VkAllocationCallbacks** were provided when **sampler** was created, a compatible set of callbacks must be provided here.
- If no **VkAllocationCallbacks** were provided when **sampler** was created, **pAllocator** must be NULL.
Valid Usage (Implicit)

- **device** must be a valid **VkDevice** handle.
- If **sampler** is not **VK_NULL_HANDLE**, **sampler** must be a valid **VkSampler** handle.
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid **VkAllocationCallbacks** structure.
- If **sampler** is a valid handle, it must have been created, allocated, or retrieved from **device**.

Host Synchronization

- Host access to **sampler** must be externally synchronized.

12.1. Sampler Y'CbCr conversion

To create a sampler with Y'CbCr conversion enabled, add a **VkSamplerYcbcrConversionInfo** structure to the **pNext** chain of the **VkSamplerCreateInfo** structure. To create a sampler Y'CbCr conversion, the **samplerYcbcrConversion** feature must be enabled. Conversion must be fixed at pipeline creation time, through use of a combined image sampler with an immutable sampler in **VkDescriptorSetLayoutBinding**.

A **VkSamplerYcbcrConversionInfo** must be provided for samplers to be used with image views that access **VK_IMAGE_ASPECT_COLOR_BIT** if the format appears in **Formats requiring sampler Y'CbCr conversion for VK_IMAGE_ASPECT_COLOR_BIT image views**.

The **VkSamplerYcbcrConversionInfo** structure is defined as:

```c
typedef struct VkSamplerYcbcrConversionInfo {
    VkStructureType             sType;
    const void*                 pNext;
    VkSamplerYcbcrConversion    conversion;
} VkSamplerYcbcrConversionInfo;
```

or the equivalent

```c
typedef VkSamplerYcbcrConversionInfo VkSamplerYcbcrConversionInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **conversion** is a **VkSamplerYcbcrConversion** handle created with **vkCreateSamplerYcbcrConversion**.
Valid Usage (Implicit)

- **sType** **must** be `VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO`
- **conversion** **must** be a valid `VkSamplerYcbcrConversion` handle

A sampler Y'C'B'R conversion is an opaque representation of a device-specific sampler Y'C'B'R conversion description, represented as a `VkSamplerYcbcrConversion` handle:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSamplerYcbcrConversion)
```

or the equivalent

```
typedef VkSamplerYcbcrConversion VkSamplerYcbcrConversionKHR;
```

To create a `VkSamplerYcbcrConversion`, call:

```
VkResult vkCreateSamplerYcbcrConversion(
    VkDevice device, 
    const VkSamplerYcbcrConversionCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkSamplerYcbcrConversion* pYcbcrConversion);
```

or the equivalent command

```
VkResult vkCreateSamplerYcbcrConversionKHR(
    VkDevice device, 
    const VkSamplerYcbcrConversionCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkSamplerYcbcrConversion* pYcbcrConversion);
```

- **device** is the logical device that creates the sampler Y'C'B'R conversion.
- **pCreateInfo** is a pointer to a `VkSamplerYcbcrConversionCreateInfo` structure specifying the requested sampler Y'C'B'R conversion.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pYcbcrConversion** is a pointer to a `VkSamplerYcbcrConversion` handle in which the resulting sampler Y'C'B'R conversion is returned.

The interpretation of the configured sampler Y'C'B'R conversion is described in more detail in the description of sampler Y'C'B'R conversion in the Image Operations chapter.
Valid Usage

- The sampler Y’C₉₆C₉ conversion feature must be enabled.

Valid Usage (Implicit)

- device must be a valid VkDevice handle.
- pCreateInfo must be a valid pointer to a valid VkSamplerYcbcrConversionCreateInfo structure.
- If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure.
- pYcbcrConversion must be a valid pointer to a VkSamplerYcbcrConversion handle.

Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkSamplerYcbcrConversionCreateInfo structure is defined as:

```c
typedef struct VkSamplerYcbcrConversionCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkFormat format;
    VkSamplerYcbcrModelConversion ycbcrModel;
    VkSamplerYcbcrRange ycbcrRange;
    VkComponentMapping components;
    VkChromaLocation xChromaOffset;
    VkChromaLocation yChromaOffset;
    VkFilter chromaFilter;
    VkBool32 forceExplicitReconstruction;
} VkSamplerYcbcrConversionCreateInfo;
```

or the equivalent

```c
typedef VkSamplerYcbcrConversionCreateInfo VkSamplerYcbcrConversionCreateInfoKHR;
```

- sType is the type of this structure.
• `pNext` is NULL or a pointer to an extension-specific structure.
• `format` is the format of the image from which color information will be retrieved.
• `ycbcrModel` describes the color matrix for conversion between color models.
• `ycbcrRange` describes whether the encoded values have headroom and foot room, or whether the encoding uses the full numerical range.
• `components` applies a *swizzle* based on `VkComponentSwizzle` enums prior to range expansion and color model conversion.
• `xChromaOffset` describes the *sample location* associated with downsampled chroma channels in the x dimension. `xChromaOffset` has no effect for formats in which chroma channels are the same resolution as the luma channel.
• `yChromaOffset` describes the *sample location* associated with downsampled chroma channels in the y dimension. `yChromaOffset` has no effect for formats in which the chroma channels are not downsampled vertically.
• `chromaFilter` is the filter for chroma reconstruction.
• `forceExplicitReconstruction` can be used to ensure that reconstruction is done explicitly, if supported.

**Note**
Setting `forceExplicitReconstruction` to `VK_TRUE` may have a performance penalty on implementations where explicit reconstruction is not the default mode of operation.

If `format` supports `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT` the `forceExplicitReconstruction` value behaves as if it was set to `VK_TRUE`.

Sampler Y’CₐCₚR conversion objects do not support *external format conversion* without additional extensions defining *external formats.*
Valid Usage

- **format must not be** `VK_FORMAT_UNDEFINED`

- The sampler `Y'CbCr` conversion’s features **must** support
  `VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT`
  or `VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT`

- If the sampler `Y'CbCr` conversion’s features do not support
  `VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT`, `xChromaOffset` and `yChromaOffset` **must** not be `VK_CHROMA_LOCATION_COSITED_EVEN`

- If the sampler `Y'CbCr` conversion’s features do not support
  `VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT`, `xChromaOffset` and `yChromaOffset` **must** not be `VK_CHROMA_LOCATION_MIDPOINT`

- If an external format conversion is not being created, **format must** represent unsigned normalized values (i.e. the format must be a `UNORM` format)

- If the format has a `.422` or `.420` suffix, then `components.g` **must** be `VK_COMPONENT_SWIZZLE_IDENTITY`

- If the format has a `.422` or `.420` suffix, then `components.a` **must** be
  `VK_COMPONENT_SWIZZLE_IDENTITY`, `VK_COMPONENT_SWIZZLE_ONE`, or `VK_COMPONENT_SWIZZLE_ZERO`

- If the format has a `.422` or `.420` suffix, then `components.r` **must** be
  `VK_COMPONENT_SWIZZLE_IDENTITY` or `VK_COMPONENT_SWIZZLE_B`

- If the format has a `.422` or `.420` suffix, then `components.b` **must** be
  `VK_COMPONENT_SWIZZLE_IDENTITY` or `VK_COMPONENT_SWIZZLE_R`

- If the format has a `.422` or `.420` suffix, and if either `components.r` or `components.b` is `VK_COMPONENT_SWIZZLE_IDENTITY`, **both values must** be `VK_COMPONENT_SWIZZLE_IDENTITY`

- If `ycbcrModel` is not `VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY`, then `components.r`, `components.g`, and `components.b` **must** correspond to channels of the format; that is, `components.r`, `components.g`, and `components.b` **must** not be `VK_COMPONENT_SWIZZLE_ZERO` or `VK_COMPONENT_SWIZZLE_ONE`, and **must** not correspond to a channel which contains zero or one as a consequence of conversion to RGBA

- If `ycbcrRange` is `VK_SAMPLER_YCBCR_RANGE_ITU_NARROW` then the R, G and B channels obtained by applying the component swizzle to **format must** each have a bit-depth greater than or equal to 8.

- If the sampler `Y'CbCr` conversion’s features do not support
  `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCE_ABLE_BIT` `forceExplicitReconstruction` **must** be `VK_FALSE`

- If the sampler `Y'CbCr` conversion’s features do not support
  `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT`, `chromaFilter` **must** not be `VK_FILTER_LINEAR`
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO`
- `pNext` must be `NULL`
- `format` must be a valid `VkFormat` value
- `ycbcrModel` must be a valid `VkSamplerYcbcrModelConversion` value
- `ycbcrRange` must be a valid `VkSamplerYcbcrRange` value
- `components` must be a valid `VkComponentMapping` structure
- `xChromaOffset` must be a valid `VkChromaLocation` value
- `yChromaOffset` must be a valid `VkChromaLocation` value
- `chromaFilter` must be a valid `VkFilter` value

If `chromaFilter` is `VK_FILTER_NEAREST`, chroma samples are reconstructed to luma channel resolution using nearest-neighbour sampling. Otherwise, chroma samples are reconstructed using interpolation. More details can be found in the description of sampler Y’C_bC_r conversion in the Image Operations chapter.

`VkSamplerYcbcrModelConversion` defines the conversion from the source color model to the shader color model. Possible values are:

```c
typedef enum VkSamplerYcbcrModelConversion {
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY = 0,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_IDENTITY = 1,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709 = 2,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601 = 3,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020 = 4,
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY_KHR =
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_IDENTITY_KHR =
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709_KHR =
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601_KHR =
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020_KHR =
    VK_SAMPLER_YCBCR_MODEL_CONVERSION_MAX_ENUM = 0x7FFFFFFF
} VkSamplerYcbcrModelConversion;
```

or the equivalent

```c
typedef VkSamplerYcbcrModelConversion VkSamplerYcbcrModelConversionKHR;
```
• **VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY** specifies that the input values to the conversion are unmodified.

• **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_IDENTITY** specifies no model conversion but the inputs are range expanded as for Y’C_bC_r.

• **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709** specifies the color model conversion from Y’C_bC_r to R’G’B’ defined in BT.709 and described in the “BT.709 Y’C_bC_r conversion” section of the Khronos Data Format Specification.

• **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601** specifies the color model conversion from Y’C_bC_r to R’G’B’ defined in BT.601 and described in the “BT.601 Y’C_bC_r conversion” section of the Khronos Data Format Specification.

• **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020** specifies the color model conversion from Y’C_bC_r to R’G’B’ defined in BT.2020 and described in the “BT.2020 Y’C_bC_r conversion” section of the Khronos Data Format Specification.

In the **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_** color models, for the input to the sampler Y’C_bC_r range expansion and model conversion:

• the Y (Y’ luma) channel corresponds to the G channel of an RGB image.
• the CB (C_b or “U” blue color difference) channel corresponds to the B channel of an RGB image.
• the CR (C_r or “V” red color difference) channel corresponds to the R channel of an RGB image.
• the alpha channel, if present, is not modified by color model conversion.

These rules reflect the mapping of channels after the channel swizzle operation (controlled by `VkSamplerYcbcrConversionCreateInfo::components`).

---

**Note**

For example, an “YUVA” 32-bit format comprising four 8-bit channels can be implemented as `VK_FORMAT_R8G8B8A8_UNORM` with a component mapping:

• `components.a = VK_COMPONENT_SWIZZLE_IDENTITY`
• `components.r = VK_COMPONENT_SWIZZLE_B`
• `components.g = VK_COMPONENT_SWIZZLE_R`
• `components.b = VK_COMPONENT_SWIZZLE_G`

The **VkSamplerYcbcrRange** enum describes whether color channels are encoded using the full range of numerical values or whether values are reserved for headroom and foot room. **VkSamplerYcbcrRange** is defined as:
typedef enum VkSamplerYcbcrRange {
    VK_SAMPLER_YCBCR_RANGE_ITU_FULL = 0,
    VK_SAMPLER_YCBCR_RANGE_ITU_NARROW = 1,
    VK_SAMPLER_YCBCR_RANGE_ITU_FULL_KHR = VK_SAMPLER_YCBCR_RANGE_ITU_FULL,
    VK_SAMPLER_YCBCR_RANGE_ITU_NARROW_KHR = VK_SAMPLER_YCBCR_RANGE_ITU_NARROW,
    VK_SAMPLER_YCBCR_RANGE_MAX_ENUM = 0x7FFFFFFF
} VkSamplerYcbcrRange;

or the equivalent

typedef VkSamplerYcbcrRange VkSamplerYcbcrRangeKHR;

- **VK_SAMPLER_YCBCR_RANGE_ITU_FULL** specifies that the full range of the encoded values are valid and interpreted according to the ITU “full range” quantization rules.
- **VK_SAMPLER_YCBCR_RANGE_ITU_NARROW** specifies that headroom and foot room are reserved in the numerical range of encoded values, and the remaining values are expanded according to the ITU “narrow range” quantization rules.

The formulae for these conversions is described in the Sampler Y’CₙCₙ Range Expansion section of the Image Operations chapter.

No range modification takes place if ycbcrModel is **VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY**; the ycbcrRange field of VkSamplerYcbcrConversionCreateInfo is ignored in this case.

The **VkChromaLocation** enum defines the location of downsampled chroma channel samples relative to the luma samples, and is defined as:

typedef enum VkChromaLocation {
    VK_CHROMA_LOCATION_COSITED_EVEN = 0,
    VK_CHROMA_LOCATION_MIDPOINT = 1,
    VK_CHROMA_LOCATION_COSITED_EVEN_KHR = VK_CHROMA_LOCATION_COSITED_EVEN,
    VK_CHROMA_LOCATION_MIDPOINT_KHR = VK_CHROMA_LOCATION_MIDPOINT,
    VK_CHROMA_LOCATION_MAX_ENUM = 0x7FFFFFFF
} VkChromaLocation;

or the equivalent

typedef VkChromaLocation VkChromaLocationKHR;

- **VK_CHROMA_LOCATION_COSITED_EVEN** specifies that downsampled chroma samples are aligned with luma samples with even coordinates.
- **VK_CHROMA_LOCATION_MIDPOINT** specifies that downsampled chroma samples are located half way between each even luma sample and the nearest higher odd luma sample.

To destroy a sampler Y’CₙCₙ conversion, call:
```c
void vkDestroySamplerYcbcrConversion(
    VkDevice device,                      
    VkSamplerYcbcrConversion ycbcrConversion, 
    const VkAllocationCallbacks* pAllocator);
```
or the equivalent command
```c
void vkDestroySamplerYcbcrConversionKHR(
    VkDevice device,                      
    VkSamplerYcbcrConversion ycbcrConversion, 
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the Y'CbCr conversion.
- `ycbcrConversion` is the conversion to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

### Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- If `ycbcrConversion` is not `VK_NULL_HANDLE`, `ycbcrConversion` must be a valid `VkSamplerYcbcrConversion` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `ycbcrConversion` is a valid handle, it must have been created, allocated, or retrieved from `device`

### Host Synchronization

- Host access to `ycbcrConversion` must be externally synchronized

### 12.1.1. Sampler Ycbcr Conversion Format Features

Valid usage of a `VkSamplerYcbcrConversion` may be constrained by format features, defined below. Such constraints are documented in the affected valid usage statement.

- The format features of a `VkSamplerYcbcrConversion` include any feature that is supported for `VkSamplerYcbcrConversionCreateInfo::format` in one or more of `VK_IMAGE_TILING_OPTIMAL` or `VK_IMAGE_TILING_LINEAR`
Chapter 13. Resource Descriptors

A descriptor is an opaque data structure representing a shader resource such as a buffer, buffer view, image view, sampler, or combined image sampler. Descriptors are organised into descriptor sets, which are bound during command recording for use in subsequent draw commands. The arrangement of content in each descriptor set is determined by a descriptor set layout, which determines what descriptors can be stored within it. The sequence of descriptor set layouts that can be used by a pipeline is specified in a pipeline layout. Each pipeline object can use up to `maxBoundDescriptorSets` (see Limits) descriptor sets.

Shaders access resources via variables decorated with a descriptor set and binding number that link them to a descriptor in a descriptor set. The shader interface mapping to bound descriptor sets is described in the Shader Resource Interface section.

Shaders can also access buffers without going through descriptors by using Physical Storage Buffer Access to access them through 64-bit addresses.

13.1. Descriptor Types

There are a number of different types of descriptor supported by Vulkan, corresponding to different resources or usage. The following sections describe the API definitions of each descriptor type. The mapping of each type to SPIR-V is listed in the Shader Resource and Descriptor Type Correspondence and Shader Resource and Storage Class Correspondence tables in the Shader Interfaces chapter.

13.1.1. Storage Image

A storage image (VK_DESCRIPTOR_TYPE_STORAGE_IMAGE) is a descriptor type associated with an image resource via an image view that load, store, and atomic operations can be performed on.

Storage image loads are supported in all shader stages for image views whose format features contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT`.

Stores to storage images are supported in compute shaders for image views whose format features contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT`.

Atomic operations on storage images are supported in compute shaders for image views whose format features contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`.

When the `fragmentStoresAndAtomics` feature is enabled, stores and atomic operations are also supported for storage images in fragment shaders with the same set of image formats as supported in compute shaders. When the `vertexPipelineStoresAndAtomics` feature is enabled, stores and atomic operations are also supported in vertex, tessellation, and geometry shaders with the same set of image formats as supported in compute shaders.

The image subresources for a storage image must be in the `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR` or `VK_IMAGE_LAYOUT_GENERAL` layout in order to access its data in a shader.
13.1.2. Sampler

A sampler descriptor (VK_DESCRIPTOR_TYPE_SAMPLER) is a descriptor type associated with a sampler object, used to control the behavior of sampling operations performed on a sampled image.

13.1.3. Sampled Image

A sampled image (VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE) is a descriptor type associated with an image resource via an image view that sampling operations can be performed on.

Shaders combine a sampled image variable and a sampler variable to perform sampling operations.

Sampled images are supported in all shader stages for image views whose format features contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT.

The image subresources for a sampled image must be in the VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL, or VK_IMAGE_LAYOUT_GENERAL layout in order to access its data in a shader.

13.1.4. Combined Image Sampler

A combined image sampler (VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER) is a single descriptor type associated with both a sampler and an image resource, combining both a sampler and sampled image descriptor into a single descriptor.

If the descriptor refers to a sampler that performs Y’CbCr conversion, the sampler must only be used to sample the image in the same descriptor. Otherwise, the sampler and image in this type of descriptor can be used freely with any other samplers and images.

The image subresources for a combined image sampler must be in the VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, or VK_IMAGE_LAYOUT_GENERAL layout in order to access its data in a shader.

Note

On some implementations, it may be more efficient to sample from an image using a combination of sampler and sampled image that are stored together in the descriptor set in a combined descriptor.

13.1.5. Uniform Texel Buffer

A uniform texel buffer (VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER) is a descriptor type associated with a buffer resource via a buffer view that formatted load operations can be performed on.

Uniform texel buffers define a tightly-packed 1-dimensional linear array of texels, with texels going
through format conversion when read in a shader in the same way as they are for an image.

Load operations from uniform texel buffers are supported in all shader stages for image formats which report support for the `VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT` feature bit via `vkGetPhysicalDeviceFormatProperties` in `VkFormatProperties::bufferFeatures`.

### 13.1.6. Storage Texel Buffer

A **storage texel buffer** (`VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`) is a descriptor type associated with a **buffer resource** via a **buffer view** that formatted load, store, and atomic operations can be performed on.

Storage texel buffers define a tightly-packed 1-dimensional linear array of texels, with texels going through format conversion when read in a shader in the same way as they are for an image. Unlike **uniform texel buffers**, these buffers can also be written to in the same way as for **storage images**.

Storage texel buffer loads are supported in all shader stages for texel buffer formats which report support for the `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT` feature bit via `vkGetPhysicalDeviceFormatProperties` in `VkFormatProperties::bufferFeatures`.

Stores to storage texel buffers are supported in compute shaders for texel buffer formats which report support for the `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT` feature via `vkGetPhysicalDeviceFormatProperties` in `VkFormatProperties::bufferFeatures`.

Atomic operations on storage texel buffers are supported in compute shaders for texel buffer formats which report support for the `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT` feature via `vkGetPhysicalDeviceFormatProperties` in `VkFormatProperties::bufferFeatures`.

When the **fragmentStoresAndAtomics** feature is enabled, stores and atomic operations are also supported for storage texel buffers in fragment shaders with the same set of texel buffer formats as supported in compute shaders. When the **vertexPipelineStoresAndAtomics** feature is enabled, stores and atomic operations are also supported in vertex, tessellation, and geometry shaders with the same set of texel buffer formats as supported in compute shaders.

### 13.1.7. Storage Buffer

A **storage buffer** (`VK_DESCRIPTOR_TYPE_STORAGE_BUFFER`) is a descriptor type associated with a **buffer resource** directly, described in a shader as a structure with various members that load, store, and atomic operations can be performed on.

**Note**

Atomic operations can only be performed on members of certain types as defined in the **SPIR-V environment appendix**.

### 13.1.8. Uniform Buffer

A **uniform buffer** (`VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER`) is a descriptor type associated with a **buffer resource** directly, described in a shader as a structure with various members that load operations can be performed on.
13.1.9. Dynamic Uniform Buffer

A dynamic uniform buffer (VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC) is almost identical to a uniform buffer, and differs only in how the offset into the buffer is specified. The base offset calculated by the VkDescriptorBufferInfo when initially updating the descriptor set is added to a dynamic offset when binding the descriptor set.

13.1.10. Dynamic Storage Buffer

A dynamic storage buffer (VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC) is almost identical to a storage buffer, and differs only in how the offset into the buffer is specified. The base offset calculated by the VkDescriptorBufferInfo when initially updating the descriptor set is added to a dynamic offset when binding the descriptor set.

13.1.11. Input Attachment

An input attachment (VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT) is a descriptor type associated with an image resource via an image view that can be used for framebuffer local load operations in fragment shaders.

All image formats that are supported for color attachments (VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT) or depth/stencil attachments (VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT) for a given image tiling mode are also supported for input attachments.

The image subresources for an input attachment must be in the VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR, VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL, VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL, or VK_IMAGE_LAYOUT_GENERAL layout in order to access its data in a shader.


An acceleration structure (VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR) is a descriptor type that is used to retrieve scene geometry from within shaders bound to ray tracing pipelines. Shaders have read-only access to the memory.

13.2. Descriptor Sets

Descriptors are grouped together into descriptor set objects. A descriptor set object is an opaque object containing storage for a set of descriptors, where the types and number of descriptors is defined by a descriptor set layout. The layout object may be used to define the association of each descriptor binding with memory or other implementation resources. The layout is used both for determining the resources that need to be associated with the descriptor set, and determining the interface between shader stages and shader resources.
13.2.1. Descriptor Set Layout

A descriptor set layout object is defined by an array of zero or more descriptor bindings. Each individual descriptor binding is specified by a descriptor type, a count (array size) of the number of descriptors in the binding, a set of shader stages that can access the binding, and (if using immutable samplers) an array of sampler descriptors.

Descriptor set layout objects are represented by `VkDescriptorSetLayout` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorSetLayout)
```

To create descriptor set layout objects, call:

```c
VkResult vkCreateDescriptorSetLayout(
    VkDevice device,
    const VkDescriptorSetLayoutCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkDescriptorSetLayout* pSetLayout);
```

- **device** is the logical device that creates the descriptor set layout.
- **pCreateInfo** is a pointer to a `VkDescriptorSetLayoutCreateInfo` structure specifying the state of the descriptor set layout object.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
- **pSetLayout** is a pointer to a `VkDescriptorSetLayout` handle in which the resulting descriptor set layout object is returned.

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkDescriptorSetLayoutCreateInfo` structure
- If **pAllocator** is not `NULL`, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pSetLayout** must be a valid pointer to a `VkDescriptorSetLayout` handle

### Return Codes

**Success**
- **VK_SUCCESS**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**
Information about the descriptor set layout is passed in a `VkDescriptorSetLayoutCreateInfo` structure:

```
typedef struct VkDescriptorSetLayoutCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorSetLayoutCreateFlags flags;
    uint32_t bindingCount;
    const VkDescriptorSetLayoutBinding* pBindings;
} VkDescriptorSetLayoutCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is a bitmask of `VkDescriptorSetLayoutCreateFlagBits` specifying options for descriptor set layout creation.
- `bindingCount` is the number of elements in `pBindings`.
- `pBindings` is a pointer to an array of `VkDescriptorSetLayoutBinding` structures.

### Valid Usage

- The `VkDescriptorSetLayoutBinding::binding` members of the elements of the `pBindings` array must each have different values.
- If `flags` contains `VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR`, then all elements of `pBindings` must not have a `descriptorType` of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`.
- If `flags` contains `VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR`, then the total number of elements of all bindings must be less than or equal to `VkPhysicalDevicePushDescriptorPropertiesKHR::maxPushDescriptors`.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO`
- `pNext` must be `NULL`
- `flags` must be a valid combination of `VkDescriptorSetLayoutCreateFlagBits` values
- If `bindingCount` is not zero, `pBindings` must be a valid pointer to an array of `bindingCount` valid `VkDescriptorSetLayoutBinding` structures

Bits which can be set in `VkDescriptorSetLayoutCreateInfo::flags` to specify options for descriptor set layout are:
typedef enum VkDescriptorSetLayoutCreateFlagBits {
    VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR = 0x00000001,
    VK_DESCRIPTOR_SET_LAYOUT_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkDescriptorSetLayoutCreateFlagBits;

- **VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR** specifies that descriptor sets must not be allocated using this layout, and descriptors are instead pushed by `vkCmdPushDescriptorSetKHR`.

typedef VkFlags VkDescriptorSetLayoutCreateFlags;

`VkDescriptorSetLayoutCreateFlags` is a bitmask type for setting a mask of zero or more `VkDescriptorSetLayoutCreateFlagBits`.

The `VkDescriptorSetLayoutBinding` structure is defined as:

```c
typedef struct VkDescriptorSetLayoutBinding {
    uint32_t binding;
    VkDescriptorType descriptorType;
    uint32_t descriptorCount;
    VkShaderStageFlags stageFlags;
    const VkSampler* pImmutableSamplers;
} VkDescriptorSetLayoutBinding;
```

- **binding** is the binding number of this entry and corresponds to a resource of the same binding number in the shader stages.
- **descriptorType** is a `VkDescriptorType` specifying which type of resource descriptors are used for this binding.
- **descriptorCount** is the number of descriptors contained in the binding, accessed in a shader as an array. If `descriptorCount` is zero this binding entry is reserved and the resource must not be accessed from any stage via this binding within any pipeline using the set layout.
- **stageFlags** member is a bitmask of `VkShaderStageFlagBits` specifying which pipeline shader stages can access a resource for this binding. `VK_SHADER_STAGE_ALL` is a shorthand specifying that all defined shader stages, including any additional stages defined by extensions, can access the resource.

If a shader stage is not included in `stageFlags`, then a resource must not be accessed from that stage via this binding within any pipeline using the set layout. Other than input attachments which are limited to the fragment shader, there are no limitations on what combinations of stages can use a descriptor binding, and in particular a binding can be used by both graphics stages and the compute stage.

- **pImmutableSamplers** affects initialization of samplers. If `descriptorType` specifies a `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` type descriptor, then `pImmutableSamplers` can be used to initialize a set of immutable samplers. Immutable samplers
are permanently bound into the set layout and must not be changed; updating a `VK_DESCRIPTOR_TYPE_SAMPLER` descriptor with immutable samplers is not allowed and updates to a `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` descriptor with immutable samplers does not modify the samplers (the image views are updated, but the sampler updates are ignored). If `pImmutableSamplers` is not `NULL`, then it points to an array of sampler handles that will be copied into the set layout and used for the corresponding binding. Only the sampler handles are copied; the sampler objects must not be destroyed before the final use of the set layout and any descriptor pools and sets created using it. If `pImmutableSamplers` is `NULL`, then the sampler slots are dynamic and sampler handles must be bound into descriptor sets using this layout. If `descriptorType` is not one of these descriptor types, then `pImmutableSamplers` is ignored.

The above layout definition allows the descriptor bindings to be specified sparsely such that not all binding numbers between 0 and the maximum binding number need to be specified in the `pBindings` array. Bindings that are not specified have a `descriptorCount` and `stageFlags` of zero, and the value of `descriptorType` is undefined. However, all binding numbers between 0 and the maximum binding number in the `VkDescriptorSetLayoutCreateInfo::pBindings` array may consume memory in the descriptor set layout even if not all descriptor bindings are used, though it should not consume additional memory from the descriptor pool.

Note
The maximum binding number specified should be as compact as possible to avoid wasted memory.

### Valid Usage

- If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, and `descriptorCount` is not 0 and `pImmutableSamplers` is not `NULL`, `pImmutableSamplers` must be a valid pointer to an array of `descriptorCount` valid `VkSampler` handles.
- If `descriptorCount` is not 0, `stageFlags` must be a valid combination of `VkShaderStageFlagBits` values.
- If `descriptorType` is `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` and `descriptorCount` is not 0, then `stageFlags` must be 0 or `VK_SHADER_STAGE_FRAGMENT_BIT`.

### Valid Usage (Implicit)

- `descriptorType` must be a valid `VkDescriptorType` value.

To query information about whether a descriptor set layout can be created, call:

```c
void vkGetDescriptorSetLayoutSupport(
    VkDevice device,
    const VkDescriptorSetLayoutCreateInfo* pCreateInfo,
    VkDescriptorSetLayoutSupport* pSupport);
```
or the equivalent command

```c
void vkGetDescriptorSetLayoutSupportKHR(
    VkDevice                                    device,
    const VkDescriptorSetLayoutCreateInfo*      pCreateInfo,
    VkDescriptorSetLayoutSupport*               pSupport);
```

- `device` is the logical device that would create the descriptor set layout.
- `pCreateInfo` is a pointer to a `VkDescriptorSetLayoutCreateInfo` structure specifying the state of the descriptor set layout object.
- `pSupport` is a pointer to a `VkDescriptorSetLayoutSupport` structure, in which information about support for the descriptor set layout object is returned.

Some implementations have limitations on what fits in a descriptor set which are not easily expressible in terms of existing limits like `maxDescriptorSet`*, for example if all descriptor types share a limited space in memory but each descriptor is a different size or alignment. This command returns information about whether a descriptor set satisfies this limit. If the descriptor set layout satisfies the `VkPhysicalDeviceMaintenance3Properties::maxPerSetDescriptors` limit, this command is guaranteed to return `VK_TRUE` in `VkDescriptorSetLayoutSupport::supported`. If the descriptor set layout exceeds the `VkPhysicalDeviceMaintenance3Properties::maxPerSetDescriptors` limit, whether the descriptor set layout is supported is implementation-dependent and may depend on whether the descriptor sizes and alignments cause the layout to exceed an internal limit.

This command does not consider other limits such as `maxPerStageDescriptor`*, and so a descriptor set layout that is supported according to this command must still satisfy the pipeline layout limits such as `maxPerStageDescriptor`* in order to be used in a pipeline layout.

**Note**
This is a `VkDevice` query rather than `VkPhysicalDevice` because the answer may depend on enabled features.

### Valid Usage (Implicit)

- `device must` be a valid `VkDevice` handle
- `pCreateInfo must` be a valid pointer to a valid `VkDescriptorSetLayoutCreateInfo` structure
- `pSupport must` be a valid pointer to a `VkDescriptorSetLayoutSupport` structure

Information about support for the descriptor set layout is returned in a `VkDescriptorSetLayoutSupport` structure:
typedef struct VkDescriptorSetLayoutSupport {
    VkStructureType       sType;
    void*                  pNext;
    VkBool32               supported;
} VkDescriptorSetLayoutSupport;

or the equivalent

typedef VkDescriptorSetLayoutSupport VkDescriptorSetLayoutSupportKHR;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **supported** specifies whether the descriptor set layout can be created.

**supported** is set to **VK_TRUE** if the descriptor set can be created, or else is set to **VK_FALSE**.

**Valid Usage (Implicit)**

- **sType** must be **VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT**
- **pNext** must be **NULL**

The following examples show a shader snippet using two descriptor sets, and application code that creates corresponding descriptor set layouts.

**GLSL example**

```glsl
//
// binding to a single sampled image descriptor in set 0
// layout (set=0, binding=0) uniform texture2D mySampledImage;
//
// binding to an array of sampled image descriptors in set 0
// layout (set=0, binding=1) uniform texture2D myArrayOfSampledImages[12];
//
// binding to a single uniform buffer descriptor in set 1
// layout (set=1, binding=0) uniform myUniformBuffer
// {
//    vec4 myElement[32];
//};
```
SPIR-V example

...%1 = OpExtInstImport "GLSL.std.450"
...

OpName %9 "mySampledImage"
OpName %14 "myArrayOfSampledImages"
OpName %18 "myUniformBuffer"
OpMemberName %18 0 "myElement"
OpName %20 ""
OpDecorate %9 DescriptorSet 0
OpDecorate %9 Binding 0
OpDecorate %14 DescriptorSet 0
OpDecorate %14 Binding 1
OpDecorate %17 ArrayStride 16
OpMemberDecorate %18 0 Offset 0
OpDecorate %18 Block
OpDecorate %20 DescriptorSet 1
OpDecorate %20 Binding 0
%2 = OpTypeVoid
%3 = OpTypeFunction %2
%6 = OpTypeFloat 32
%7 = OpTypeImage %6 2D 0 0 0 1 Unknown
%8 = OpTypePointer UniformConstant %7
%9 = OpVariable %8 UniformConstant
%10 = OpTypeInt 32 0
%11 = OpConstant %10 12
%12 = OpTypeArray %7 %11
%13 = OpTypePointer UniformConstant %12
%14 = OpVariable %13 UniformConstant
%15 = OpTypeVector %6 4
%16 = OpConstant %10 32
%17 = OpTypeArray %15 %16
%18 = OpTypeStruct %17
%19 = OpTypePointer Uniform %18
%20 = OpVariable %19 Uniform
...

API example

VkResult myResult;

const VkDescriptorSetLayoutBinding myDescriptorSetLayoutBinding[] = {
    // binding to a single image descriptor
    
    0, // binding
    VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, // descriptorType
    1, // descriptorCount
    VK_SHADER_STAGE_FRAGMENT_BIT, // stageFlags
};
// pImmutableSamplers

// binding to an array of image descriptors
{
  1, // binding
  VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, // descriptorType
  12, // descriptorCount
  VK_SHADER_STAGE_FRAGMENT_BIT, // stageFlags
  NULL // pImmutableSamplers
},

// binding to a single uniform buffer descriptor
{
  0, // binding
  VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER, // descriptorType
  1, // descriptorCount
  VK_SHADER_STAGE_FRAGMENT_BIT, // stageFlags
  NULL // pImmutableSamplers
}
};

const VkDescriptorSetLayoutCreateInfo myDescriptorSetLayoutCreateInfo[] = {
  // Create info for first descriptor set with two descriptor bindings
  {
    VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO, // sType
    NULL, // pNext
    0, // flags
    2, // bindingCount
    &myDescriptorSetLayoutBinding[0] // pBindings
  },

  // Create info for second descriptor set with one descriptor binding
  {
    VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO, // sType
    NULL, // pNext
    0, // flags
    1, // bindingCount
  }
};

VkDescriptorSetLayout myDescriptorSetLayout[2];

// Create first descriptor set layout
myResult = vkCreateDescriptorSetLayout(
  myDevice,
  &myDescriptorSetLayoutCreateInfo[0],
  &myDescriptorSetLayout[0]);
To destroy a descriptor set layout, call:

```c
void vkDestroyDescriptorSetLayout(
    VkDevice device, 
    VkDescriptorSetLayout descriptorSetLayout, 
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the descriptor set layout.
- `descriptorSetLayout` is the descriptor set layout to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

**Valid Usage**

- If `VkAllocationCallbacks` were provided when `descriptorSetLayout` was created, a compatible set of callbacks **must** be provided here
- If no `VkAllocationCallbacks` were provided when `descriptorSetLayout` was created, `pAllocator` **must** be NULL

**Valid Usage (Implicit)**

- `device` **must** be a valid `VkDevice` handle
- If `descriptorSetLayout` is not `VK_NULL_HANDLE`, `descriptorSetLayout` **must** be a valid `VkDescriptorSetLayout` handle
- If `pAllocator` is not NULL, `pAllocator` **must** be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `descriptorSetLayout` is a valid handle, it **must** have been created, allocated, or retrieved from `device`
13.2.2. Pipeline Layouts

Access to descriptor sets from a pipeline is accomplished through a pipeline layout. Zero or more descriptor set layouts and zero or more push constant ranges are combined to form a pipeline layout object describing the complete set of resources that can be accessed by a pipeline. The pipeline layout represents a sequence of descriptor sets with each having a specific layout. This sequence of layouts is used to determine the interface between shader stages and shader resources. Each pipeline is created using a pipeline layout.

Pipeline layout objects are represented by VkPipelineLayout handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipelineLayout)
```

To create a pipeline layout, call:

```
VkResult vkCreatePipelineLayout(
    VkDevice device,
    const VkPipelineLayoutCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkPipelineLayout* pPipelineLayout);
```

- `device` is the logical device that creates the pipeline layout.
- `pCreateInfo` is a pointer to a `VkPipelineLayoutCreateInfo` structure specifying the state of the pipeline layout object.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pPipelineLayout` is a pointer to a `VkPipelineLayout` handle in which the resulting pipeline layout object is returned.

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pCreateInfo` must be a valid pointer to a valid `VkPipelineLayoutCreateInfo` structure
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- `pPipelineLayout` must be a valid pointer to a `VkPipelineLayout` handle
Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkPipelineLayoutCreateInfo` structure is defined as:

```c
typedef struct VkPipelineLayoutCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineLayoutCreateFlags flags;
    uint32_t setLayoutCount;
    const VkDescriptorSetLayout* pSetLayouts;
    uint32_t pushConstantRangeCount;
    const VkPushConstantRange* pPushConstantRanges;
} VkPipelineLayoutCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **setLayoutCount** is the number of descriptor sets included in the pipeline layout.
- **pSetLayouts** is a pointer to an array of `VkDescriptorSetLayout` objects.
- **pushConstantRangeCount** is the number of push constant ranges included in the pipeline layout.
- **pPushConstantRanges** is a pointer to an array of `VkPushConstantRange` structures defining a set of push constant ranges for use in a single pipeline layout. In addition to descriptor set layouts, a pipeline layout also describes how many push constants can be accessed by each stage of the pipeline.

**Note**

Push constants represent a high speed path to modify constant data in pipelines that is expected to outperform memory-backed resource updates.
Valid Usage

- `setLayoutCount` must be less than or equal to `VkPhysicalDeviceLimits::maxBoundDescriptorSets`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_SAMPLER` and `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` accessible to any shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorSamplers`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` and `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` accessible to any shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorUniformBuffers`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` and `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` accessible to any shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorStorageBuffers`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, and `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` accessible to any shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorSampledImages`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, and `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` accessible to any shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorStorageImages`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorInputAttachments`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_SAMPLER` and `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxDescriptorSetSamplers`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxDescriptorSetUniformBuffers`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxDescriptorSetUniformBuffersDynamic`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxDescriptorSetStorageBuffers`.

- The total number of descriptors of the type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` accessible across all shader stages and across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxDescriptorSetStorageBuffersDynamic`.
• The total number of descriptors of the type VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, and VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER accessible across all shader stages and across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceLimits::maxDescriptorSetSampledImages.

• The total number of descriptors of the type VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, and VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER accessible across all shader stages and across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceLimits::maxDescriptorSetStorageImages.

• The total number of descriptors of the type VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT accessible across all shader stages and across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceLimits::maxDescriptorSetInputAttachments.

• Any two elements of pPushConstantRanges must not include the same stage in stageFlags.

• pSetLayouts must not contain more than one descriptor set layout that was created with VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR set.

• The total number of bindings with a descriptorType of VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR accessible across all shader stages and across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceRayTracingPropertiesKHR::maxDescriptorSetAccelerationStructures.

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO

• pNext must be NULL

• flags must be 0

• IfsetLayoutCount is not 0, pSetLayouts must be a valid pointer to an array of setLayoutCount valid VkDescriptorSetLayout handles.

• IfpushConstantRangeCount is not 0, pPushConstantRanges must be a valid pointer to an array of pushConstantRangeCount valid VkPushConstantRange structures.

typedef VkFlags VkPipelineLayoutCreateFlags;

VkPipelineLayoutCreateFlags is a bitmask type for setting a mask, but is currently reserved for future use.

The VkPushConstantRange structure is defined as:

typedef struct VkPushConstantRange {
    VkShaderStageFlags stageFlags;
    uint32_t offset;
    uint32_t size;
} VkPushConstantRange;
• **stageFlags** is a set of stage flags describing the shader stages that will access a range of push constants. If a particular stage is not included in the range, then accessing members of that range of push constants from the corresponding shader stage will return undefined values.

• **offset** and **size** are the start offset and size, respectively, consumed by the range. Both **offset** and **size** are in units of bytes and **must** be a multiple of 4. The layout of the push constant variables is specified in the shader.

### Valid Usage

- **offset** **must** be less than `VkPhysicalDeviceLimits::maxPushConstantsSize`
- **offset** **must** be a multiple of 4
- **size** **must** be greater than 0
- **size** **must** be a multiple of 4
- **size** **must** be less than or equal to `VkPhysicalDeviceLimits::maxPushConstantsSize` minus **offset**

### Valid Usage (Implicit)

- **stageFlags** **must** be a valid combination of `VkShaderStageFlagBits` values
- **stageFlags** **must** not be 0

Once created, pipeline layouts are used as part of pipeline creation (see **Pipelines**), as part of binding descriptor sets (see **Descriptor Set Binding**), and as part of setting push constants (see **Push Constant Updates**). Pipeline creation accepts a pipeline layout as input, and the layout **may** be used to map (set, binding, arrayElement) tuples to implementation resources or memory locations within a descriptor set. The assignment of implementation resources depends only on the bindings defined in the descriptor sets that comprise the pipeline layout, and not on any shader source.

All resource variables **statically used** in all shaders in a pipeline **must** be declared with a (set,binding,arrayElement) that exists in the corresponding descriptor set layout and is of an appropriate descriptor type and includes the set of shader stages it is used by in **stageFlags**. The pipeline layout **can** include entries that are not used by a particular pipeline, or that are dead-code eliminated from any of the shaders. The pipeline layout allows the application to provide a consistent set of bindings across multiple pipeline compiles, which enables those pipelines to be compiled in a way that the implementation **may** cheaply switch pipelines without reprogramming the bindings.

Similarly, the push constant block declared in each shader (if present) **must** only place variables at offsets that are each included in a push constant range with **stageFlags** including the bit corresponding to the shader stage that uses it. The pipeline layout **can** include ranges or portions of ranges that are not used by a particular pipeline, or for which the variables have been dead-code eliminated from any of the shaders.

There is a limit on the total number of resources of each type that **can** be included in bindings in all
descriptor set layouts in a pipeline layout as shown in **Pipeline Layout Resource Limits**. The “Total Resources Available” column gives the limit on the number of each type of resource that **can** be included in bindings in all descriptor sets in the pipeline layout. Some resource types count against multiple limits. Additionally, there are limits on the total number of each type of resource that **can** be used in any pipeline stage as described in **Shader Resource Limits**.

**Table 14. Pipeline Layout Resource Limits**

<table>
<thead>
<tr>
<th>Total Resources Available</th>
<th>Resource Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxDescriptorSetSamplers</td>
<td>sampler</td>
</tr>
<tr>
<td></td>
<td>combined image sampler</td>
</tr>
<tr>
<td>maxDescriptorSetSampledImages</td>
<td>sampled image</td>
</tr>
<tr>
<td></td>
<td>combined image sampler</td>
</tr>
<tr>
<td></td>
<td>uniform texel buffer</td>
</tr>
<tr>
<td>maxDescriptorSetStorageImages</td>
<td>storage image</td>
</tr>
<tr>
<td></td>
<td>storage texel buffer</td>
</tr>
<tr>
<td>maxDescriptorSetUniformBuffers</td>
<td>uniform buffer</td>
</tr>
<tr>
<td></td>
<td>uniform buffer dynamic</td>
</tr>
<tr>
<td>maxDescriptorSetUniformBuffersDynamic</td>
<td>uniform buffer dynamic</td>
</tr>
<tr>
<td>maxDescriptorSetStorageBuffers</td>
<td>storage buffer</td>
</tr>
<tr>
<td></td>
<td>storage buffer dynamic</td>
</tr>
<tr>
<td>maxDescriptorSetStorageBuffersDynamic</td>
<td>storage buffer dynamic</td>
</tr>
<tr>
<td>maxDescriptorSetInputAttachments</td>
<td>input attachment</td>
</tr>
<tr>
<td>maxDescriptorSetAccelerationStructures</td>
<td>acceleration structure</td>
</tr>
</tbody>
</table>

To destroy a pipeline layout, call:

```c
void vkDestroyPipelineLayout(
    VkDevice device,
    VkPipelineLayout pipelineLayout,
    const VkAllocationCallbacks* pAllocator);
```

- **device** is the logical device that destroys the pipeline layout.
- **pipelineLayout** is the pipeline layout to destroy.
- **pAllocator** controls host memory allocation as described in the **Memory Allocation** chapter.
Valid Usage

- If `VkAllocationCallbacks` were provided when `pipelineLayout` was created, a compatible set of callbacks must be provided here.
- If no `VkAllocationCallbacks` were provided when `pipelineLayout` was created, `pAllocator` must be `NULL`.
- `pipelineLayout` must not have been passed to any `vkCmd*` command for any command buffers that are still in the recording state when `vkDestroyPipelineLayout` is called.

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle.
- If `pipelineLayout` is not `VK_NULL_HANDLE`, `pipelineLayout` must be a valid `VkPipelineLayout` handle.
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.
- If `pipelineLayout` is a valid handle, it must have been created, allocated, or retrieved from `device`.

Host Synchronization

- Host access to `pipelineLayout` must be externally synchronized.

Pipeline Layout Compatibility

Two pipeline layouts are defined to be “compatible for push constants” if they were created with identical push constant ranges. Two pipeline layouts are defined to be “compatible for set N” if they were created with identically defined descriptor set layouts for sets zero through N, and if they were created with identical push constant ranges.

When binding a descriptor set (see Descriptor Set Binding) to set number N, if the previously bound descriptor sets for sets zero through N-1 were all bound using compatible pipeline layouts, then performing this binding does not disturb any of the lower numbered sets. If, additionally, the previous bound descriptor set for set N was bound using a pipeline layout compatible for set N, then the bindings in sets numbered greater than N are also not disturbed.

Similarly, when binding a pipeline, the pipeline can correctly access any previously bound descriptor sets which were bound with compatible pipeline layouts, as long as all lower numbered sets were also bound with compatible layouts.

Layout compatibility means that descriptor sets can be bound to a command buffer for use by any pipeline created with a compatible pipeline layout, and without having bound a particular pipeline first. It also means that descriptor sets can remain valid across a pipeline change, and the same resources will be accessible to the newly bound pipeline.
Implementor’s Note

A consequence of layout compatibility is that when the implementation compiles a pipeline layout and maps pipeline resources to implementation resources, the mechanism for set N should only be a function of sets [0..N].

Note

Place the least frequently changing descriptor sets near the start of the pipeline layout, and place the descriptor sets representing the most frequently changing resources near the end. When pipelines are switched, only the descriptor set bindings that have been invalidated will need to be updated and the remainder of the descriptor set bindings will remain in place.

The maximum number of descriptor sets that can be bound to a pipeline layout is queried from physical device properties (see maxBoundDescriptorSets in Limits).
API example

```c
const VkDescriptorSetLayout layouts[] = { layout1, layout2 };;

const VkPushConstantRange ranges[] =
{
    {
        VK_PIPELINE_STAGE_VERTEX_SHADER_BIT, // stageFlags
        0, // offset
        4, // size
    },
    {
        VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, // stageFlags
        4, // offset
        4, // size
    },
};

const VkPipelineLayoutCreateInfo createInfo =
{
    VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO, // sType
    NULL, // pNext
    0, // flags
    2, // setLayoutCount
    layouts, // pSetLayouts
    2, // pushConstantRangeCount
    ranges // pPushConstantRanges
};

VkPipelineLayout myPipelineLayout;
myResult = vkCreatePipelineLayout(
    myDevice,
    &createInfo,
    NULL,
    &myPipelineLayout);
```

13.2.3. Allocation of Descriptor Sets

A *descriptor pool* maintains a pool of descriptors, from which descriptor sets are allocated. Descriptor pools are externally synchronized, meaning that the application **must** not allocate and/or free descriptor sets from the same pool in multiple threads simultaneously.

Descriptor pools are represented by *VkDescriptorPool* handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorPool)
```

To create a descriptor pool object, call:
VkResult vkCreateDescriptorPool(
    VkDevice                                    device,
    const VkDescriptorPoolCreateInfo*           pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkDescriptorPool*                           pDescriptorPool);

• device is the logical device that creates the descriptor pool.
• pCreateInfo is a pointer to a VkDescriptorPoolCreateInfo structure specifying the state of the descriptor pool object.
• pAllocator controls host memory allocation as described in the Memory Allocation chapter.
• pDescriptorPool is a pointer to a VkDescriptorPool handle in which the resulting descriptor pool object is returned.

pAllocator controls host memory allocation as described in the Memory Allocation chapter.

The created descriptor pool is returned in pDescriptorPool.

Valid Usage (Implicit)

• device must be a valid VkDevice handle
• pCreateInfo must be a valid pointer to a valid VkDescriptorPoolCreateInfo structure
• If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
• pDescriptorPool must be a valid pointer to a VkDescriptorPool handle

Return Codes

Success
• VK_SUCCESS

Failure
• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY

Additional information about the pool is passed in a VkDescriptorPoolCreateInfo structure:
typedef struct VkDescriptorPoolCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorPoolCreateFlags flags;
    uint32_t maxSets;
    uint32_t poolSizeCount;
    const VkDescriptorPoolSize* pPoolSizes;
} VkDescriptorPoolCreateInfo;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **flags** is a bitmask of *VkDescriptorPoolCreateFlagBits* specifying certain supported operations on the pool.
- **maxSets** is the maximum number of descriptor sets that **can** be allocated from the pool.
- **poolSizeCount** is the number of elements in **pPoolSizes**.
- **pPoolSizes** is a pointer to an array of *VkDescriptorPoolSize* structures, each containing a descriptor type and number of descriptors of that type to be allocated in the pool.

If multiple *VkDescriptorPoolSize* structures appear in the **pPoolSizes** array then the pool will be created with enough storage for the total number of descriptors of each type.

Fragmentation of a descriptor pool is possible and **may** lead to descriptor set allocation failures. A failure due to fragmentation is defined as failing a descriptor set allocation despite the sum of all outstanding descriptor set allocations from the pool plus the requested allocation requiring no more than the total number of descriptors requested at pool creation. Implementations provide certain guarantees of when fragmentation **must** not cause allocation failure, as described below.

If a descriptor pool has not had any descriptor sets freed since it was created or most recently reset then fragmentation **must** not cause an allocation failure (note that this is always the case for a pool created without the *VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT* bit set). Additionally, if all sets allocated from the pool since it was created or most recently reset use the same number of descriptors (of each type) and the requested allocation also uses that same number of descriptors (of each type), then fragmentation **must** not cause an allocation failure.

If an allocation failure occurs due to fragmentation, an application **can** create an additional descriptor pool to perform further descriptor set allocations.

### Valid Usage

- **maxSets** **must** be greater than 0

---

552 | Chapter 13. Resource Descriptors
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_CREATE_INFO`
- **pNext** must be `NULL`
- **flags** must be a valid combination of `VkDescriptorPoolCreateFlagBits` values
- **pPoolSizes** must be a valid pointer to an array of `poolSizeCount` valid `VkDescriptorPoolSize` structures
- **poolSizeCount** must be greater than 0

Bits which **can** be set in `VkDescriptorPoolCreateInfo::flags` to enable operations on a descriptor pool are:

```c
typedef enum VkDescriptorPoolCreateFlagBits {
    VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT = 0x00000001,
    VK_DESCRIPTOR_POOL_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkDescriptorPoolCreateFlagBits;
```

- **VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT** specifies that descriptor sets can return their individual allocations to the pool, i.e. all of `vkAllocateDescriptorSets`, `vkFreeDescriptorSets`, and `vkResetDescriptorPool` are allowed. Otherwise, descriptor sets allocated from the pool must not be individually freed back to the pool, i.e. only `vkAllocateDescriptorSets` and `vkResetDescriptorPool` are allowed.

```c
typedef VkFlags VkDescriptorPoolCreateFlags;
VkDescriptorPoolCreateFlags is a bitmask type for setting a mask of zero or more `VkDescriptorPoolCreateFlagBits`.
```

The **VkDescriptorPoolSize** structure is defined as:

```c
typedef struct VkDescriptorPoolSize {
    VkDescriptorType type;
    uint32_t descriptorCount;
} VkDescriptorPoolSize;
```

- **type** is the type of descriptor.
- **descriptorCount** is the number of descriptors of that type to allocate.
Note

When creating a descriptor pool that will contain descriptors for combined image samplers of multi-planar formats, an application needs to account for non-trivial descriptor consumption when choosing the `descriptorCount` value, as indicated by `VkSamplerYcbcrConversionImageFormatProperties::combinedImageSamplerDescriptorCount`.

**Valid Usage**

- `descriptorCount` must be greater than 0

**Valid Usage (Implicit)**

- `type` must be a valid `VkDescriptorType` value

To destroy a descriptor pool, call:

```c
void vkDestroyDescriptorPool(
    VkDevice            device,  
    VkDescriptorPool    descriptorPool,  
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the descriptor pool.
- `descriptorPool` is the descriptor pool to destroy.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.

When a pool is destroyed, all descriptor sets allocated from the pool are implicitly freed and become invalid. Descriptor sets allocated from a given pool do not need to be freed before destroying that descriptor pool.

**Valid Usage**

- All submitted commands that refer to `descriptorPool` (via any allocated descriptor sets) must have completed execution
- If `VkAllocationCallbacks` were provided when `descriptorPool` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `descriptorPool` was created, `pAllocator` must be `NULL`
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- If `descriptorPool` is not `VK_NULL_HANDLE`, `descriptorPool` must be a valid `VkDescriptorPool` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `descriptorPool` is a valid handle, it must have been created, allocated, or retrieved from `device`

Host Synchronization

- Host access to `descriptorPool` must be externally synchronized

Descriptor sets are allocated from descriptor pool objects, and are represented by `VkDescriptorSet` handles:

```cpp
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorSet)
```

To allocate descriptor sets from a descriptor pool, call:

```cpp
VkResult vkAllocateDescriptorSets(
    VkDevice device,
    const VkDescriptorSetAllocateInfo* pAllocateInfo,
    VkDescriptorSet* pDescriptorSets);
```

- **device** is the logical device that owns the descriptor pool.
- **pAllocateInfo** is a pointer to a `VkDescriptorSetAllocateInfo` structure describing parameters of the allocation.
- **pDescriptorSets** is a pointer to an array of `VkDescriptorSet` handles in which the resulting descriptor set objects are returned.

The allocated descriptor sets are returned in `pDescriptorSets`.

When a descriptor set is allocated, the initial state is largely uninitialized and all descriptors are undefined. Descriptors also become undefined if the underlying resource is destroyed. Descriptor sets containing undefined descriptors can still be bound and used, subject to the following conditions:

- Descriptors that are **statically used** must have been populated before the descriptor set is consumed.
- Entries that are not used by a pipeline can have undefined descriptors.
If a call to `vkAllocateDescriptorSets` would cause the total number of descriptor sets allocated from the pool to exceed the value of `VkDescriptorPoolCreateInfo::maxSets` used to create `pAllocateInfo->descriptorPool`, then the allocation may fail due to lack of space in the descriptor pool. Similarly, the allocation may fail due to lack of space if the call to `vkAllocateDescriptorSets` would cause the number of any given descriptor type to exceed the sum of all the `descriptorCount` members of each element of `VkDescriptorPoolCreateInfo::pPoolSizes` with a member equal to that type.

If the allocation fails due to no more space in the descriptor pool, and not because of system or device memory exhaustion, then `VK_ERROR_OUT_OF_POOL_MEMORY` must be returned.

`vkAllocateDescriptorSets` can be used to create multiple descriptor sets. If the creation of any of those descriptor sets fails, then the implementation must destroy all successfully created descriptor set objects from this command, set all entries of the `pDescriptorSets` array to `VK_NULL_HANDLE` and return the error.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `pAllocateInfo` must be a valid pointer to a valid `VkDescriptorSetAllocateInfo` structure
- `pDescriptorSets` must be a valid pointer to an array of `pAllocateInfo::descriptorSetCount` `VkDescriptorSet` handles
- The value referenced by `pAllocateInfo::descriptorSetCount` must be greater than 0

**Host Synchronization**

- Host access to `pAllocateInfo::descriptorPool` must be externally synchronized

**Return Codes**

**Success**

- `VK_SUCCESS`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_FRAGMENTED_POOL`
- `VK_ERROR_OUT_OF_POOL_MEMORY`

The `VkDescriptorSetAllocateInfo` structure is defined as:
typedef struct VkDescriptorSetAllocateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorPool descriptorPool;
    uint32_t descriptorSetCount;
    const VkDescriptorSetLayout* pSetLayouts;
} VkDescriptorSetAllocateInfo;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **descriptorPool** is the pool which the sets will be allocated from.
- **descriptorSetCount** determines the number of descriptor sets to be allocated from the pool.
- **pSetLayouts** is a pointer to an array of descriptor set layouts, with each member specifying how the corresponding descriptor set is allocated.

### Valid Usage

- Each element of **pSetLayouts** must not have been created with `VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR` set

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO`  
- **pNext** must be NULL  
- **descriptorPool** must be a valid `VkDescriptorPool` handle  
- **pSetLayouts** must be a valid pointer to an array of `descriptorSetCount` valid `VkDescriptorSetLayout` handles  
- **descriptorSetCount** must be greater than 0  
- Both of **descriptorPool**, and the elements of **pSetLayouts** must have been created, allocated, or retrieved from the same `VkDevice`

To free allocated descriptor sets, call:

\[
VkResult vkFreeDescriptorSets(
    VkDevice device,
    VkDescriptorPool descriptorPool,
    uint32_t descriptorSetCount,
    const VkDescriptorSet* pDescriptorSets);
\]

- **device** is the logical device that owns the descriptor pool.
- **descriptorPool** is the descriptor pool from which the descriptor sets were allocated.
• `descriptorSetCount` is the number of elements in the `pDescriptorSets` array.
• `pDescriptorSets` is a pointer to an array of handles to `VkDescriptorSet` objects.

After calling `vkFreeDescriptorSets`, all descriptor sets in `pDescriptorSets` are invalid.

### Valid Usage
- All submitted commands that refer to any element of `pDescriptorSets` must have completed execution
- `pDescriptorSets` must be a valid pointer to an array of `descriptorSetCount` `VkDescriptorSet` handles, each element of which must either be a valid handle or `VK_NULL_HANDLE`
- Each valid handle in `pDescriptorSets` must have been allocated from `descriptorPool`
- `descriptorPool` must have been created with the `VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT` flag

### Valid Usage (Implicit)
- `device` must be a valid `VkDevice` handle
- `descriptorPool` must be a valid `VkDescriptorPool` handle
- `descriptorSetCount` must be greater than 0
- `descriptorPool` must have been created, allocated, or retrieved from `device`
- Each element of `pDescriptorSets` that is a valid handle must have been created, allocated, or retrieved from `descriptorPool`

### Host Synchronization
- Host access to `descriptorPool` must be externally synchronized
- Host access to each member of `pDescriptorSets` must be externally synchronized

### Return Codes

**Success**
- `VK_SUCCESS`

To return all descriptor sets allocated from a given pool to the pool, rather than freeing individual descriptor sets, call:
VkResult vkResetDescriptorPool(
    VkDevice                                    device,
    VkDescriptorPool                            descriptorPool,
    VkDescriptorPoolResetFlags                  flags);

- **device** is the logical device that owns the descriptor pool.
- **descriptorPool** is the descriptor pool to be reset.
- **flags** is reserved for future use.

Resetting a descriptor pool recycles all of the resources from all of the descriptor sets allocated from the descriptor pool back to the descriptor pool, and the descriptor sets are implicitly freed.

### Valid Usage

- All uses of **descriptorPool** (via any allocated descriptor sets) **must** have completed execution

### Valid Usage (Implicit)

- **device** **must** be a valid **VkDevice** handle
- **descriptorPool** **must** be a valid **VkDescriptorPool** handle
- **flags** **must** be 0
- **descriptorPool** **must** have been created, allocated, or retrieved from **device**

### Host Synchronization

- Host access to **descriptorPool** **must** be externally synchronized
- Host access to any **VkDescriptorSet** objects allocated from **descriptorPool** **must** be externally synchronized

### Return Codes

**Success**
- **VK_SUCCESS**

typedef VkFlags VkDescriptorPoolResetFlags;

**VkDescriptorPoolResetFlags** is a bitmask type for setting a mask, but is currently reserved for future use.
13.2.4. Descriptor Set Updates

Once allocated, descriptor sets can be updated with a combination of write and copy operations. To update descriptor sets, call:

```c
void vkUpdateDescriptorSets(
    VkDevice device, // Logical device that updates the descriptor sets.
    uint32_t descriptorWriteCount, // Number of elements in the pDescriptorWrites array.
    const VkWriteDescriptorSet* pDescriptorWrites, // Pointer to an array of VkWriteDescriptorSet structures describing the descriptor sets to write to.
    uint32_t descriptorCopyCount, // Number of elements in the pDescriptorCopies array.
    const VkCopyDescriptorSet* pDescriptorCopies); // Pointer to an array of VkCopyDescriptorSet structures describing the descriptor sets to copy between.
```

- `device` is the logical device that updates the descriptor sets.
- `descriptorWriteCount` is the number of elements in the `pDescriptorWrites` array.
- `pDescriptorWrites` is a pointer to an array of `VkWriteDescriptorSet` structures describing the descriptor sets to write to.
- `descriptorCopyCount` is the number of elements in the `pDescriptorCopies` array.
- `pDescriptorCopies` is a pointer to an array of `VkCopyDescriptorSet` structures describing the descriptor sets to copy between.

The operations described by `pDescriptorWrites` are performed first, followed by the operations described by `pDescriptorCopies`. Within each array, the operations are performed in the order they appear in the array.

Each element in the `pDescriptorWrites` array describes an operation updating the descriptor set using descriptors for resources specified in the structure.

Each element in the `pDescriptorCopies` array is a `VkCopyDescriptorSet` structure describing an operation copying descriptors between sets.

If the `dstSet` member of any element of `pDescriptorWrites` or `pDescriptorCopies` is bound, accessed, or modified by any command that was recorded to a command buffer which is currently in the recording or executable state, that command buffer becomes invalid.

**Valid Usage**

- The `dstSet` member of each element of `pDescriptorWrites` or `pDescriptorCopies` must not be used by any command that was recorded to a command buffer which is in the pending state.
Valid Usage (Implicit)

- **device must** be a valid *VkDevice* handle
- If *descriptorWriteCount* is not 0, **pDescriptorWrites must** be a valid pointer to an array of *descriptorWriteCount* valid *VkWriteDescriptorSet* structures
- If *descriptorCopyCount* is not 0, **pDescriptorCopies must** be a valid pointer to an array of *descriptorCopyCount* valid *VkCopyDescriptorSet* structures

Host Synchronization

- Host access to **pDescriptorWrites[]**.dstSet **must** be externally synchronized
- Host access to **pDescriptorCopies[]**.dstSet **must** be externally synchronized

The *VkWriteDescriptorSet* structure is defined as:

```c
typedef struct VkWriteDescriptorSet {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorSet dstSet;
    uint32_t dstBinding;
    uint32_t dstArrayElement;
    uint32_t descriptorCount;
    VkDescriptorType descriptorType;
    const VkDescriptorImageInfo* pImageInfo;
    const VkDescriptorBufferInfo* pBufferInfo;
    const VkBufferView* pTexelBufferView;
} VkWriteDescriptorSet;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **dstSet** is the destination descriptor set to update.
- **dstBinding** is the descriptor binding within that set.
- **dstArrayElement** is the starting element in that array.
- **descriptorCount** is the number of descriptors to update (the number of elements in **pImageInfo**, **pBufferInfo**, or **pTexelBufferView**, or a value matching the accelerationStructureCount of a *VkWriteDescriptorSetAccelerationStructureKHR* structure in the **pNext** chain).
- **descriptorType** is a *VkDescriptorType* specifying the type of each descriptor in **pImageInfo**, **pBufferInfo**, or **pTexelBufferView**, as described below. It **must** be the same type as that specified in *VkDescriptorSetLayoutBinding* for **dstSet** at **dstBinding**. The type of the descriptor also controls which array the descriptors are taken from.
- **pImageInfo** is a pointer to an array of *VkDescriptorImageInfo* structures or is ignored, as
described below.

- **pBufferInfo** is a pointer to an array of `VkDescriptorBufferInfo` structures or is ignored, as described below.

- **pTexelBufferView** is a pointer to an array of `VkBufferView` handles as described in the `Buffer Views` section or is ignored, as described below.

Only one of `pImageInfo`, `pBufferInfo`, or `pTexelBufferView` members is used according to the descriptor type specified in the `descriptorType` member of the containing `VkWriteDescriptorSet` structure, or if `descriptorType` is `VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR`, in which case the source data for the descriptor writes is taken from the `VkWriteDescriptorSetAccelerationStructureKHR` structure in the `pNext` chain of `VkWriteDescriptorSet`, as specified below.

If the `dstBinding` has fewer than `descriptorCount` array elements remaining starting from `dstArrayElement`, then the remainder will be used to update the subsequent binding - `dstBinding+1` starting at array element zero. If a binding has a `descriptorCount` of zero, it is skipped. This behavior applies recursively, with the update affecting consecutive bindings as needed to update all `descriptorCount` descriptors.
Valid Usage

- **dstBinding** must be less than or equal to the maximum value of **binding** of all **VkDescriptorSetLayoutBinding** structures specified when **dstSet**'s descriptor set layout was created.

- **dstBinding** must be a binding with a non-zero **descriptorCount**.

- All consecutive bindings updated via a single **VkWriteDescriptorSet** structure, except those with a **descriptorCount** of zero, must have identical **descriptorType** and **stageFlags**.

- All consecutive bindings updated via a single **VkWriteDescriptorSet** structure, except those with a **descriptorCount** of zero, must all either use immutable samplers or must all not use immutable samplers.

- **descriptorType** must match the type of **dstBinding** within **dstSet**.

- **dstSet** must be a valid **VkDescriptorSet** handle.

- The sum of **dstArrayElement** and **descriptorCount** must be less than or equal to the number of array elements in the descriptor set binding specified by **dstBinding**, and all applicable consecutive bindings, as described by **consecutive binding updates**.

- If **descriptorType** is **VK_DESCRIPTOR_TYPE_SAMPLER**, **VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER**, **VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE**, **VK_DESCRIPTOR_TYPE_STORAGE_IMAGE**, or **VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT**, **pImageInfo** must be a valid pointer to an array of **descriptorCount** valid **VkDescriptorImageInfo** structures.

- If **descriptorType** is **VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER** or **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER**, **pTexelBufferView** must be a valid pointer to an array of **descriptorCount** valid **VkBufferView** handles.

- If **descriptorType** is **VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER**, **VK_DESCRIPTOR_TYPE_STORAGE_BUFFER**, or **VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC**, **pBufferInfo** must be a valid pointer to an array of **descriptorCount** valid **VkDescriptorBufferInfo** structures.

- If **descriptorType** is **VK_DESCRIPTOR_TYPE_SAMPLER** or **VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER**, and **dstSet** was not allocated with a layout that included immutable samplers for **dstBinding** with **descriptorType**, the **sampler** member of each element of **pImageInfo** must be a valid **VkSampler** object.

- If **descriptorType** is **VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER**, **VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE**, or **VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT**, the **imageView** and **imageLayout** members of each element of **pImageInfo** must be a valid **VkImageView** and **VkImageLayout**, respectively.

- If **descriptorType** is **VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR**, the **pNext** chain must include a **VkWriteDescriptorSetAccelerationStructureKHR** structure whose **accelerationStructureCount** member equals **descriptorCount**.

- If **descriptorType** is **VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE**, then the **imageView** member of each **pImageInfo** element must have been created without a **VkSamplerYcbcrConversionInfo** structure in its **pNext** chain.
• If `descriptorType` is `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, and if any element of `pImageInfo` has a `imageView` member that was created with a `VkSamplerYcbcrConversionInfo` structure in its `pNext` chain, then `dstSet` must have been allocated with a layout that included immutable samplers for `dstBinding`, and the corresponding immutable sampler must have been created with an identically defined `VkSamplerYcbcrConversionInfo` object.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, and `dstSet` was allocated with a layout that included immutable samplers for `dstBinding`, then the `imageView` member of each element of `pImageInfo` which corresponds to an immutable sampler that enables `sampler Y’C’C’R` conversion must have been created with a `VkSamplerYcbcrConversionInfo` structure in its `pNext` chain with an identically defined `VkSamplerYcbcrConversionInfo` to the corresponding immutable sampler.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, for each descriptor that will be accessed via load or store operations the `imageLayout` member for corresponding elements of `pImageInfo` must be `VK_IMAGE_LAYOUT_GENERAL`.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`, the `offset` member of each element of `pBufferInfo` must be a multiple of `VkPhysicalDeviceLimits::minUniformBufferOffsetAlignment`.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`, the `offset` member of each element of `pBufferInfo` must be a multiple of `VkPhysicalDeviceLimits::minStorageBufferOffsetAlignment`.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER`, `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`, `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER`, or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`, and the `buffer` member of any element of `pBufferInfo` is the handle of a non-sparse buffer, then that buffer must be bound completely and contiguously to a single `VkDeviceMemory` object.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER`, `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`, or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`, the `buffer` member of each element of `pBufferInfo` must have been created with `VK_BUFFER_USAGE_UNIFORM_BUFFER_BIT` set.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`, the `buffer` member of each element of `pBufferInfo` must have been created with `VK_BUFFER_USAGE_STORAGE_BUFFER_BIT` set.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`, the `range` member of each element of `pBufferInfo`, or the effective range if `range` is `VK_WHOLE_SIZE`, must be less than or equal to `VkPhysicalDeviceLimits::maxUniformBufferRange`.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`, the `range` member of each element of `pBufferInfo`, or the effective range if `range` is `VK_WHOLE_SIZE`, must be less than or equal to `VkPhysicalDeviceLimits::maxStorageBufferRange`.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER`, the `VkBuffer` that each element of `pTexelBufferView` was created from must have been created with `VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT` set.
• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`, the `VkBuffer` that each element of `pTexelBufferView` was created from must have been created with `VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT` set.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE` or `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT`, the `imageView` member of each element of `pImageInfo` must have been created with the identity swizzle.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE` or `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT`, the `imageView` member of each element of `pImageInfo` must have been created with `VK_IMAGE_USAGE_STORAGE_BIT` set.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, the `imageView` member of each element of `pImageInfo` must have been created with `VK_IMAGE_USAGE_SAMPLED_BIT` set.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, the `imageLayout` member of each element of `pImageInfo` must be a member of the list given in Sampled Image or Combined Image Sampler, corresponding to its type.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT`, the `imageView` member of each element of `pImageInfo` must have been created with `VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT` set.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, the `imageView` member of each element of `pImageInfo` must have been created with `VK_IMAGE_USAGE_STORAGE_BIT` set.

• If `descriptorType` is `VK_DESCRIPTOR_TYPE_SAMPLER`, then `dstSet` must not have been allocated with a layout that included immutable samplers for `dstBinding`.

---

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET`.
- **pNext** must be `NULL` or a pointer to a valid instance of `VkWriteDescriptorSetAccelerationStructureKHR`.
- The **sType** value of each struct in the **pNext** chain must be unique.
- **descriptorType** must be a valid `VkDescriptorType` value.
- **descriptorCount** must be greater than 0.
- Both of `dstSet`, and the elements of `pTexelBufferView` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`.

The type of descriptors in a descriptor set is specified by `VkWriteDescriptorSet::descriptorType`, which must be one of the values:
typedef enum VkDescriptorType {
    VK_DESCRIPTOR_TYPE_SAMPLER = 0,
    VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER = 1,
    VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE = 2,
    VK_DESCRIPTOR_TYPE_STORAGE_IMAGE = 3,
    VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER = 4,
    VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER = 5,
    VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER = 6,
    VK_DESCRIPTOR_TYPE_STORAGE_BUFFER = 7,
    VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC = 8,
    VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC = 9,
    VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT = 10,
    VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR = 1000165000,
    VK_DESCRIPTOR_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkDescriptorType;

• VK_DESCRIPTOR_TYPE_SAMPLER specifies a sampler descriptor.
• VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER specifies a combined image sampler descriptor.
• VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE specifies a sampled image descriptor.
• VK_DESCRIPTOR_TYPE_STORAGE_IMAGE specifies a storage image descriptor.
• VKDescriptorType_UNIFORM_TEXEL_BUFFER specifies a uniform texel buffer descriptor.
• VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER specifies a storage texel buffer descriptor.
• VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER specifies a uniform buffer descriptor.
• VK_DESCRIPTOR_TYPE_STORAGE_BUFFER specifies a storage buffer descriptor.
• VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC specifies a dynamic uniform buffer descriptor.
• VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC specifies a dynamic storage buffer descriptor.
• VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT specifies an input attachment descriptor.

When a descriptor set is updated via elements of VkWriteDescriptorSet, members of pImageInfo, pBufferInfo and pTexelBufferView are only accessed by the implementation when they correspond to descriptor type being defined - otherwise they are ignored. The members accessed are as follows for each descriptor type:

• For VK_DESCRIPTOR_TYPE_SAMPLER, only the sampler member of each element of VkWriteDescriptorSet::pImageInfo is accessed.

• For VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, or VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT, only the imageView and imageLayout members of each element of VkWriteDescriptorSet::pImageInfo are accessed.

• For VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, all members of each element of VkWriteDescriptorSet::pImageInfo are accessed.

• For VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER, VK_DESCRIPTOR_TYPE_STORAGE_BUFFER, VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC, or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, all members of each element of VkWriteDescriptorSet::pBufferInfo are accessed.
For `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`, each element of `VkWriteDescriptorSet::pTexelBufferView` is accessed.

When updating descriptors with a `descriptorType` of `VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR`, none of the `pImageInfo`, `pBufferInfo`, or `pTexelBufferView` members are accessed, instead the source data of the descriptor update operation is taken from the `VkWriteDescriptorSetAccelerationStructureKHR` structure in the `pNext` chain of `VkWriteDescriptorSet`.

The `VkDescriptorBufferInfo` structure is defined as:

```
typedef struct VkDescriptorBufferInfo {
    VkBuffer        buffer;
    VkDeviceSize    offset;
    VkDeviceSize    range;
} VkDescriptorBufferInfo;
```

- `buffer` is the buffer resource.
- `offset` is the offset in bytes from the start of `buffer`. Access to buffer memory via this descriptor uses addressing that is relative to this starting offset.
- `range` is the size in bytes that is used for this descriptor update, or `VK_WHOLE_SIZE` to use the range from `offset` to the end of the buffer.

**Note**
When setting `range` to `VK_WHOLE_SIZE`, the effective range **must** not be larger than the maximum range for the descriptor type (`maxUniformBufferRange` or `maxStorageBufferRange`). This means that `VK_WHOLE_SIZE` is not typically useful in the common case where uniform buffer descriptors are suballocated from a buffer that is much larger than `maxUniformBufferRange`.

For `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` and `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` descriptor types, `offset` is the base offset from which the dynamic offset is applied and `range` is the static size used for all dynamic offsets.

**Valid Usage**

- `offset` **must** be less than the size of `buffer`
- If `range` is not equal to `VK_WHOLE_SIZE`, `range` **must** be greater than 0
- If `range` is not equal to `VK_WHOLE_SIZE`, `range` **must** be less than or equal to the size of `buffer` minus `offset`
Valid Usage (Implicit)

- buffer must be a valid VkBuffer handle

The VkDescriptorImageInfo structure is defined as:

```c
typedef struct VkDescriptorImageInfo {
    VkSampler        sampler;
    VkImageView      imageView;
    VkImageLayout    imageLayout;
} VkDescriptorImageInfo;
```

- sampler is a sampler handle, and is used in descriptor updates for types VK_DESCRIPTOR_TYPE_SAMPLER and VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER if the binding being updated does not use immutable samplers.

- imageView is an image view handle, and is used in descriptor updates for types VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, and VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT.

- imageLayout is the layout that the image subresources accessible from imageView will be in at the time this descriptor is accessed. imageLayout is used in descriptor updates for types VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, VK_DESCRIPTOR_TYPE_STORAGE_IMAGE, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, and VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT.

Members of VkDescriptorImageInfo that are not used in an update (as described above) are ignored.

Valid Usage

- imageView must not be 2D or 2D array image view created from a 3D image

- If imageView is created from a depth/stencil image, the aspectMask used to create the imageView must include either VK_IMAGE_ASPECT_DEPTH_BIT or VK_IMAGE_ASPECT_STENCIL_BIT but not both.

- imageLayout must match the actual VkImageLayout of each subresource accessible from imageView at the time this descriptor is accessed as defined by the image layout matching rules

- If sampler is used and the VkFormat of the image is a multi-planar format, the image must have been created with VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT, and the aspectMask of the imageView must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT or (for three-plane formats only) VK_IMAGE_ASPECT_PLANE_2_BIT
Valid Usage (Implicit)

- Both of `imageView`, and `sampler` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`.

The `VkWriteDescriptorSetAccelerationStructureKHR` structure is defined as:

```c
typedef struct VkWriteDescriptorSetAccelerationStructureKHR {
    VkStructureType sType;
    const void* pNext;
    uint32_t accelerationStructureCount;
    const VkAccelerationStructureKHR* pAccelerationStructures;
} VkWriteDescriptorSetAccelerationStructureKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `accelerationStructureCount` is the number of elements in `pAccelerationStructures`.
- `pAccelerationStructures` are the acceleration structures to update.

Valid Usage

- `accelerationStructureCount` must be equal to `descriptorCount` in the extended structure.
- Each acceleration structure in `pAccelerationStructures` must have been created with `VK_ACCELERATION_STRUCTURE_TYPE_TOP_LEVEL_KHR`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET_ACCELERATION_STRUCTURE_KHR`.
- `pAccelerationStructures` must be a valid pointer to an array of `accelerationStructureCount` valid `VkAccelerationStructureKHR` handles.
- `accelerationStructureCount` must be greater than 0.

The `VkCopyDescriptorSet` structure is defined as:
typedef struct VkCopyDescriptorSet {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorSet srcSet;
    uint32_t srcBinding;
    uint32_t srcArrayElement;
    VkDescriptorSet dstSet;
    uint32_t dstBinding;
    uint32_t dstArrayElement;
    uint32_t descriptorCount;
} VkCopyDescriptorSet;

• **sType** is the type of this structure.
• **pNext** is **NULL** or a pointer to an extension-specific structure.
• **srcSet**, **srcBinding**, and **srcArrayElement** are the source set, binding, and array element, respectively.
• **dstSet**, **dstBinding**, and **dstArrayElement** are the destination set, binding, and array element, respectively.
• **descriptorCount** is the number of descriptors to copy from the source to destination. If **descriptorCount** is greater than the number of remaining array elements in the source or destination binding, those affect consecutive bindings in a manner similar to **VkWriteDescriptorSet** above.

### Valid Usage

• **srcBinding** must be a valid binding within **srcSet**
• The sum of **srcArrayElement** and **descriptorCount** must be less than or equal to the number of array elements in the descriptor set binding specified by **srcBinding**, and all applicable consecutive bindings, as described by consecutive binding updates
• **dstBinding** must be a valid binding within **dstSet**
• The sum of **dstArrayElement** and **descriptorCount** must be less than or equal to the number of array elements in the descriptor set binding specified by **dstBinding**, and all applicable consecutive bindings, as described by consecutive binding updates
• The type of **dstBinding** within **dstSet** must be equal to the type of **srcBinding** within **srcSet**
• If **srcSet** is equal to **dstSet**, then the source and destination ranges of descriptors must not overlap, where the ranges may include array elements from consecutive bindings as described by consecutive binding updates
• If the descriptor type of the descriptor set binding specified by **dstBinding** is **VK_DESCRIPTOR_TYPE_SAMPLER**, then **dstSet** must not have been allocated with a layout that included immutable samplers for **dstBinding**
Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_COPY_DESCRIPTOR_SET
- pNext must be NULL
- srcSet must be a valid VkDescriptorSet handle
- dstSet must be a valid VkDescriptorSet handle
- Both of dstSet, and srcSet must have been created, allocated, or retrieved from the same VkDevice

13.2.5. Descriptor Update Templates

A descriptor update template specifies a mapping from descriptor update information in host memory to descriptors in a descriptor set. It is designed to avoid passing redundant information to the driver when frequently updating the same set of descriptors in descriptor sets.

Descriptor update template objects are represented by VkDescriptorUpdateTemplate handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorUpdateTemplate)
```

or the equivalent

```c
typedef VkDescriptorUpdateTemplate VkDescriptorUpdateTemplateKHR;
```

13.2.6. Descriptor Set Updates with Templates

Updating a large VkDescriptorSet array can be an expensive operation since an application must specify one VkWriteDescriptorSet structure for each descriptor or descriptor array to update, each of which re-specifies the same state when updating the same descriptor in multiple descriptor sets. For cases when an application wishes to update the same set of descriptors in multiple descriptor sets allocated using the same VkDescriptorSetLayout, vkUpdateDescriptorSetWithTemplate can be used as a replacement for vkUpdateDescriptorSets.

VkDescriptorUpdateTemplate allows implementations to convert a set of descriptor update operations on a single descriptor set to an internal format that, in conjunction with vkUpdateDescriptorSetWithTemplate or vkCmdPushDescriptorSetWithTemplateKHR, can be more efficient compared to calling vkUpdateDescriptorSets or vkCmdPushDescriptorSetKHR. The descriptors themselves are not specified in the VkDescriptorUpdateTemplate, rather, offsets into an application provided pointer to host memory are specified, which are combined with a pointer passed to vkUpdateDescriptorSetWithTemplate or vkCmdPushDescriptorSetWithTemplateKHR. This allows large batches of updates to be executed without having to convert application data structures into a strictly-defined Vulkan data structure.

To create a descriptor update template, call:
VkResult vkCreateDescriptorUpdateTemplate(
    VkDevice                                    device,
    const VkDescriptorUpdateTemplateCreateInfo* pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkDescriptorUpdateTemplate*                 pDescriptorUpdateTemplate);

or the equivalent command

VkResult vkCreateDescriptorUpdateTemplateKHR(
    VkDevice                                    device,
    const VkDescriptorUpdateTemplateCreateInfo* pCreateInfo,
    const VkAllocationCallbacks*                pAllocator,
    VkDescriptorUpdateTemplate*                 pDescriptorUpdateTemplate);

- **device** is the logical device that creates the descriptor update template.
- **pCreateInfo** is a pointer to a *VkDescriptorUpdateTemplateCreateInfo* structure specifying the set of descriptors to update with a single call to *vkCmdPushDescriptorSetWithTemplateKHR* or *vkUpdateDescriptorSetWithTemplate*.
- **pAllocator** controls host memory allocation as described in the *Memory Allocation* chapter.
- **pDescriptorUpdateTemplate** is a pointer to a *VkDescriptorUpdateTemplate* handle in which the resulting descriptor update template object is returned.

Valid Usage (Implicit)

- **device** must be a valid *VkDevice* handle
- **pCreateInfo** must be a valid pointer to a valid *VkDescriptorUpdateTemplateCreateInfo* structure
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid *VkAllocationCallbacks* structure
- **pDescriptorUpdateTemplate** must be a valid pointer to a *VkDescriptorUpdateTemplate* handle

Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The *VkDescriptorUpdateTemplateCreateInfo* structure is defined as:
typedef struct VkDescriptorUpdateTemplateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorUpdateTemplateCreateFlags flags;
    uint32_t descriptorUpdateEntryCount;
    const VkDescriptorUpdateTemplateEntry* pDescriptorUpdateEntries;
    VkDescriptorUpdateTemplateType templateType;
    VkDescriptorSetLayout descriptorSetLayout;
    VkPipelineBindViewPoint pipelineBindPoint;
    VkPipelineLayout pipelineLayout;
    uint32_t set;
} VkDescriptorUpdateTemplateCreateInfo;

or the equivalent

typedef VkDescriptorUpdateTemplateCreateInfo VkDescriptorUpdateTemplateCreateInfoKHR;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• flags is reserved for future use.
• descriptorUpdateEntryCount is the number of elements in the pDescriptorUpdateEntries array.
• pDescriptorUpdateEntries is a pointer to an array of VkDescriptorUpdateTemplateEntry structures describing the descriptors to be updated by the descriptor update template.
• templateType Specifies the type of the descriptor update template. If set to VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET it can only be used to update descriptor sets with a fixed descriptorSetLayout. If set to VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR it can only be used to push descriptor sets using the provided pipelineBindPoint, pipelineLayout, and set number.
• descriptorSetLayout is the descriptor set layout the parameter update template will be used with. All descriptor sets which are going to be updated through the newly created descriptor update template must be created with this layout. descriptorSetLayout is the descriptor set layout used to build the descriptor update template. All descriptor sets which are going to be updated through the newly created descriptor update template must be created with a layout that matches (is the same as, or defined identically to) this layout. This parameter is ignored if templateType is not VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET.
• pipelineBindPoint is a VkPipelineBindPoint indicating whether the descriptors will be used by graphics pipelines or compute pipelines. This parameter is ignored if templateType is not VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR
• pipelineLayout is a VkPipelineLayout object used to program the bindings. This parameter is ignored if templateType is not VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR
• set is the set number of the descriptor set in the pipeline layout that will be updated. This parameter is ignored if templateType is not VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR
Valid Usage

- If `templateType` is `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET`, `descriptorSetLayout` must be a valid `VkDescriptorSetLayout` handle.
- If `templateType` is `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR`, `pipelineBindPoint` must be a valid `VkPipelineBindPoint` value.
- If `templateType` is `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR`, `pipelineLayout` must be a valid `VkPipelineLayout` handle.
- If `templateType` is `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR`, `set` must be the unique set number in the pipeline layout that uses a descriptor set layout that was created with `VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO`.
- `pNext` must be `NULL`.
- `flags` must be `0`.
- `pDescriptorUpdateEntries` must be a valid pointer to an array of `descriptorUpdateEntryCount` valid `VkDescriptorUpdateTemplateEntry` structures.
- `templateType` must be a valid `VkDescriptorUpdateTemplateType` value.
- `descriptorUpdateEntryCount` must be greater than `0`.
- Both of `descriptorSetLayout`, and `pipelineLayout` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`.

typedef VkFlags VkDescriptorUpdateTemplateCreateFlags;

or the equivalent

typedef VkDescriptorUpdateTemplateCreateFlags VkDescriptorUpdateTemplateCreateFlagsKHR;

`VkDescriptorUpdateTemplateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

The descriptor update template type is determined by the `VkDescriptorUpdateTemplateCreateInfo` ::`templateType` property, which takes the following values:
typedef enum VkDescriptorUpdateTemplateType {
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET = 0,
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR = 1,
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET_KHR =
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET,
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkDescriptorUpdateTemplateType;

• VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET specifies that the descriptor update template will be used for descriptor set updates only.
• VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR specifies that the descriptor update template will be used for push descriptor updates only.

The VkDescriptorUpdateTemplateEntry structure is defined as:

typedef struct VkDescriptorUpdateTemplateEntry {
    uint32_t            dstBinding;
    uint32_t            dstArrayElement;
    uint32_t            descriptorCount;
    VkDescriptorType    descriptorType;
    size_t              offset;
    size_t              stride;
} VkDescriptorUpdateTemplateEntry;

• dstBinding is the descriptor binding to update when using this descriptor update template.
• dstArrayElement is the starting element in the array belonging to dstBinding.
• descriptorCount is the number of descriptors to update. If descriptorCount is greater than the number of remaining array elements in the destination binding, those affect consecutive bindings in a manner similar to VkWriteDescriptorSet above.
• descriptorType is a VkDescriptorType specifying the type of the descriptor.
• offset is the offset in bytes of the first binding in the raw data structure.
• stride is the stride in bytes between two consecutive array elements of the descriptor update informations in the raw data structure. The actual pointer ptr for each array element j of update entry i is computed using the following formula:
const char *ptr = (const char *)pData + pDescriptorUpdateEntries[i].offset + j * pDescriptorUpdateEntries[i].stride

The stride is useful in case the bindings are stored in structs along with other data.

**Valid Usage**

- **dstBinding** must be a valid binding in the descriptor set layout implicitly specified when using a descriptor update template to update descriptors.
- **dstArrayElement** and **descriptorCount** must be less than or equal to the number of array elements in the descriptor set binding implicitly specified when using a descriptor update template to update descriptors, and all applicable consecutive bindings, as described by consecutive binding updates.

**Valid Usage (Implicit)**

- **descriptorType** must be a valid VkDescriptorType value

To destroy a descriptor update template, call:

```c
void vkDestroyDescriptorUpdateTemplate(
    VkDevice                                    device,
    VkDescriptorUpdateTemplate                  descriptorUpdateTemplate,
    const VkAllocationCallbacks*                pAllocator);
```

or the equivalent command

```c
void vkDestroyDescriptorUpdateTemplateKHR(
    VkDevice                                    device,
    VkDescriptorUpdateTemplate                  descriptorUpdateTemplate,
    const VkAllocationCallbacks*                pAllocator);
```

- **device** is the logical device that has been used to create the descriptor update template
- **descriptorUpdateTemplate** is the descriptor update template to destroy.
- **pAllocator** controls host memory allocation as described in the Memory Allocation chapter.
Valid Usage

- If `VkAllocationCallbacks` were provided when `descriptorsetLayout` was created, a compatible set of callbacks must be provided here.
- If no `VkAllocationCallbacks` were provided when `descriptorsetLayout` was created, `pAllocator` must be `NULL`.

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle.
- If `descriptorUpdateTemplate` is not `VK_NULL_HANDLE`, `descriptorUpdateTemplate` must be a valid `VkDescriptorUpdateTemplate` handle.
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.
- If `descriptorUpdateTemplate` is a valid handle, it must have been created, allocated, or retrieved from `device`.

Host Synchronization

- Host access to `descriptorUpdateTemplate` must be externally synchronized.

Once a `VkDescriptorUpdateTemplate` has been created, descriptor sets can be updated by calling:

```c
void vkUpdateDescriptorSetWithTemplate(
    VkDevice                                    device,
    VkDescriptorSet                             descriptorSet,
    VkDescriptorUpdateTemplate                  descriptorUpdateTemplate,
    const void*                                 pData);
```

or the equivalent command

```c
void vkUpdateDescriptorSetWithTemplateKHR(
    VkDevice                                    device,
    VkDescriptorSet                             descriptorSet,
    VkDescriptorUpdateTemplate                  descriptorUpdateTemplate,
    const void*                                 pData);
```

- `device` is the logical device that updates the descriptor sets.
- `descriptorSet` is the descriptor set to update.
- `descriptorUpdateTemplate` is a `VkDescriptorUpdateTemplate` object specifying the update mapping between `pData` and the descriptor set to update.
• **pData** is a pointer to memory containing one or more `VkDescriptorImageInfo`, `VkDescriptorBufferInfo`, or `VkBufferView` structures used to write the descriptors.

### Valid Usage

- **pData** must be a valid pointer to a memory containing one or more valid instances of `VkDescriptorImageInfo`, `VkDescriptorBufferInfo`, or `VkBufferView` in a layout defined by `descriptorUpdateTemplate` when it was created with `vkCreateDescriptorUpdateTemplate`

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **descriptorSet** must be a valid `VkDescriptorSet` handle
- **descriptorUpdateTemplate** must be a valid `VkDescriptorUpdateTemplate` handle
- **descriptorUpdateTemplate** must have been created, allocated, or retrieved from `device`

### Host Synchronization

- Host access to **descriptorSet** must be externally synchronized

### API example

```c
struct AppBufferView {
    VkBufferView bufferView;
    uint32_t     applicationRelatedInformation;
};

struct AppDataStructure {
    VkDescriptorImageInfo  imageInfo;   // a single image info
    VkDescriptorBufferInfo bufferInfoArray[3]; // 3 buffer infos in an array
    AppBufferView          bufferView[2];  // An application defined structure containing a bufferView
    // ... some more application related data
};

const VkDescriptorUpdateTemplateEntry descriptorUpdateTemplateEntries[] = {
    // binding to a single image descriptor
    {0, 0, 1, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, // binding
    offsetof(AppDataStructure, imageInfo), // dstArrayElement
    1,  // descriptorCount
    0, // descriptorType
    offsetof(AppDataStructure, imageInfo), // offset
```

578 | Chapter 13. Resource Descriptors
// stride is not required if
// descriptorCount is 1
},

// binding to an array of buffer descriptors
{
    1, // binding
    0, // dstArrayElement
    3, // descriptorCount
    VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER, // descriptorType
    offsetof(AppDataStructure, bufferInfoArray), // offset
    sizeof(VkDescriptorBufferInfo) // stride, descriptor buffer
}

// binding to an array of buffer views
{
    2, // binding
    0, // dstArrayElement
    2, // descriptorCount
    VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, // descriptorType
    offsetof(AppDataStructure, bufferView) +
    offsetof(AppBufferView, bufferView), // offset
    sizeof(AppBufferView) // stride, bufferViews do not
}

// create a descriptor update template for descriptor set updates
const VkDescriptorUpdateTemplateCreateInfo createInfo =
{
    VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO, // sType
    NULL, // pNext
    0, // flags
    3, // descriptorUpdateEntryCount
    descriptorUpdateTemplateEntries, // pDescriptorUpdateEntries
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET, // templateType
    myLayout, // descriptorSetLayout
    0, // pipelineBindPoint,
    ignored by given templateType
    0, // pipelineLayout,
    ignored by given templateType
    0, // set, ignored by
given templateType
};

VkDescriptorUpdateTemplate myDescriptorUpdateTemplate;
myResult = vkCreateDescriptorUpdateTemplate(
    myDevice,
13.2.7. Descriptor Set Binding

To bind one or more descriptor sets to a command buffer, call:

```c
void vkCmdBindDescriptorSets(
    VkCommandBuffer commandBuffer,       commandBuffer,
    VkPipelineBindPoint pipelineBindPoint,    pipelineBindPoint,
    VkPipelineLayout layout,              layout,
    uint32_t firstSet,                    firstSet,
    uint32_t descriptorSetCount,          descriptorSetCount,
    const VkDescriptorSet* pDescriptorSets,   pDescriptorSets,
    uint32_t dynamicOffsetCount,          dynamicOffsetCount,
    const uint32_t* pDynamicOffsets);     pDynamicOffsets);
```

- `commandBuffer` is the command buffer that the descriptor sets will be bound to.
- `pipelineBindPoint` is a `VkPipelineBindPoint` indicating whether the descriptors will be used by graphics pipelines or compute pipelines. There is a separate set of bind points for each of graphics and compute, so binding one does not disturb the other.
- `layout` is a `VkPipelineLayout` object used to program the bindings.
- `firstSet` is the set number of the first descriptor set to be bound.
- `descriptorSetCount` is the number of elements in the `pDescriptorSets` array.
- `pDescriptorSets` is a pointer to an array of handles to `VkDescriptorSet` objects describing the descriptor sets to write to.
- `dynamicOffsetCount` is the number of dynamic offsets in the `pDynamicOffsets` array.
- `pDynamicOffsets` is a pointer to an array of `uint32_t` values specifying dynamic offsets.

`vkCmdBindDescriptorSets` causes the sets numbered \([\text{firstSet}...\text{firstSet+descriptorSetCount}-1]\) to use the bindings stored in `pDescriptorSets[0..descriptorSetCount-1]` for subsequent rendering commands (either compute or graphics, according to the `pipelineBindPoint`). Any bindings that were previously applied via these sets are no longer valid.

Once bound, a descriptor set affects rendering of subsequent graphics or compute commands in the command buffer until a different set is bound to the same set number, or else until the set is
disturbed as described in Pipeline Layout Compatibility.

A compatible descriptor set must be bound for all set numbers that any shaders in a pipeline access, at the time that a draw or dispatch command is recorded to execute using that pipeline. However, if none of the shaders in a pipeline statically use any bindings with a particular set number, then no descriptor set need be bound for that set number, even if the pipeline layout includes a non-trivial descriptor set layout for that set number.

If any of the sets being bound include dynamic uniform or storage buffers, then pDynamicOffsets includes one element for each array element in each dynamic descriptor type binding in each set. Values are taken from pDynamicOffsets in an order such that all entries for set N come before set N+1; within a set, entries are ordered by the binding numbers in the descriptor set layouts; and within a binding array, elements are in order. dynamicOffsetCount must equal the total number of dynamic descriptors in the sets being bound.

The effective offset used for dynamic uniform and storage buffer bindings is the sum of the relative offset taken from pDynamicOffsets, and the base address of the buffer plus base offset in the descriptor set. The range of the dynamic uniform and storage buffer bindings is the buffer range as specified in the descriptor set.

Each of the pDescriptorSets must be compatible with the pipeline layout specified by layout. The layout used to program the bindings must also be compatible with the pipeline used in subsequent graphics or compute commands, as defined in the Pipeline Layout Compatibility section.

The descriptor set contents bound by a call to vkCmdBindDescriptorSets may be consumed at the following times:

- during host execution of the command, or during shader execution of the resulting draws and dispatches, or any time in between.

Thus, the contents of a descriptor set binding must not be altered (overwritten by an update command, or freed) between the first point in time that it may be consumed, and when the command completes executing on the queue.

The contents of pDynamicOffsets are consumed immediately during execution of vkCmdBindDescriptorSets. Once all pending uses have completed, it is legal to update and reuse a descriptor set.
Valid Usage

- Each element of `pDescriptorSets` **must** have been allocated with a `VkDescriptorSetLayout` that matches (is the same as, or identically defined as) the `VkDescriptorSetLayout` at set `n` in `layout`, where `n` is the sum of `firstSet` and the index into `pDescriptorSets`.

- `dynamicOffsetCount` **must** be equal to the total number of dynamic descriptors in `pDescriptorSets`.

- The sum of `firstSet` and `descriptorSetCount` **must** be less than or equal to `VkPipelineLayoutCreateInfo::setLayoutCount` provided when `layout` was created.

- `pipelineBindPoint` **must** be supported by the `commandBuffer`'s parent `VkCommandPool`'s queue family.

- Each element of `pDynamicOffsets` which corresponds to a descriptor binding with type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` **must** be a multiple of `VkPhysicalDeviceLimits::minUniformBufferOffsetAlignment`.

- Each element of `pDynamicOffsets` which corresponds to a descriptor binding with type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` **must** be a multiple of `VkPhysicalDeviceLimits::minStorageBufferOffsetAlignment`.

- For each dynamic uniform or storage buffer binding in `pDescriptorSets`, the sum of the effective offset, as defined above, and the range of the binding **must** be less than or equal to the size of the buffer.

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle.

- `pipelineBindPoint` **must** be a valid `VkPipelineBindPoint` value.

- `layout` **must** be a valid `VkPipelineLayout` handle.

- `pDescriptorSets` **must** be a valid pointer to an array of `descriptorSetCount` valid `VkDescriptorSet` handles.

- If `dynamicOffsetCount` is not 0, `pDynamicOffsets` **must** be a valid pointer to an array of `dynamicOffsetCount uint32_t` values.

- `commandBuffer` **must** be in the recording state.

- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics, or compute operations.

- `descriptorSetCount` **must** be greater than 0.

- Each of `commandBuffer`, `layout`, and the elements of `pDescriptorSets` **must** have been created, allocated, or retrieved from the same `VkDevice`.

---

582 | Chapter 13. Resource Descriptors
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

13.2.8. Push Descriptor Updates

In addition to allocating descriptor sets and binding them to a command buffer, an application can record descriptor updates into the command buffer.

To push descriptor updates into a command buffer, call:

```c
void vkCmdPushDescriptorSetKHR(
    VkCommandBuffer commandBuffer,  // commandBuffer is the command buffer that the descriptors will be recorded in.
    VkPipelineBindPoint pipelineBindPoint,  // pipelineBindPoint is a VkPipelineBindPoint indicating whether the descriptors will be used by graphics pipelines or compute pipelines. There is a separate set of push descriptor bindings for each of graphics and compute, so binding one does not disturb the other.
    VkPipelineLayout layout,  // layout is a VkPipelineLayout object used to program the bindings.
    uint32_t set,  // set is the set number of the descriptor set in the pipeline layout that will be updated.
    uint32_t descriptorWriteCount,  // descriptorWriteCount is the number of elements in the pDescriptorWrites array.
    const VkWriteDescriptorSet* pDescriptorWrites);  // pDescriptorWrites is a pointer to an array of VkWriteDescriptorSet structures describing the descriptors to be updated.
```

Push descriptors are a small bank of descriptors whose storage is internally managed by the command buffer rather than being written into a descriptor set and later bound to a command buffer. Push descriptors allow for incremental updates of descriptors without managing the lifetime of descriptor sets.
When a command buffer begins recording, all push descriptors are undefined. Push descriptors can be updated incrementally and cause shaders to use the updated descriptors for subsequent rendering commands (either compute or graphics, according to the pipelineBindPoint) until the descriptor is overwritten, or else until the set is disturbed as described in Pipeline Layout Compatibility. When the set is disturbed or push descriptors with a different descriptor set layout are set, all push descriptors are undefined.

Push descriptors that are statically used by a pipeline must not be undefined at the time that a draw or dispatch command is recorded to execute using that pipeline. This includes immutable sampler descriptors, which must be pushed before they are accessed by a pipeline (the immutable samplers are pushed, rather than the samplers in pDescriptorWrites). Push descriptors that are not statically used can remain undefined.

Push descriptors do not use dynamic offsets. Instead, the corresponding non-dynamic descriptor types can be used and the offset member of VkDescriptorBufferInfo can be changed each time the descriptor is written.

Each element of pDescriptorWrites is interpreted as in VkWriteDescriptorSet, except the dstSet member is ignored.

To push an immutable sampler, use a VkWriteDescriptorSet with dstBinding and dstArrayElement selecting the immutable sampler’s binding. If the descriptor type is VK_DESCRIPTOR_TYPE_SAMPLER, the pImageInfo parameter is ignored and the immutable sampler is taken from the push descriptor set layout in the pipeline layout. If the descriptor type is VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, the sampler member of the pImageInfo parameter is ignored and the immutable sampler is taken from the push descriptor set layout in the pipeline layout.

<table>
<thead>
<tr>
<th>Valid Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>pipelineBindPoint</em>* must be supported by the commandBuffer's parent VkCommandPool's queue family</td>
</tr>
<tr>
<td><em>set</em>* must be less than VkPipelineLayoutCreateInfo::setLayoutCount provided when layout was created</td>
</tr>
<tr>
<td><em>set</em>* must be the unique set number in the pipeline layout that uses a descriptor set layout that was created with VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR</td>
</tr>
</tbody>
</table>
Valid Usage (Implicit)

• **commandBuffer** must be a valid `VkCommandBuffer` handle
• **pipelineBindPoint** must be a valid `VkPipelineBindPoint` value
• **layout** must be a valid `VkPipelineLayout` handle
• **pDescriptorWrites** must be a valid pointer to an array of **descriptorWriteCount** valid `VkWriteDescriptorSet` structures
• **commandBuffer** must be in the **recording state**
• The `VkCommandPool` that **commandBuffer** was allocated from must support graphics, or compute operations
• **descriptorWriteCount** must be greater than 0
• Both of **commandBuffer**, and **layout** must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

• Host access to **commandBuffer** must be externally synchronized
• Host access to the `VkCommandPool` that **commandBuffer** was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

13.2.9. Push Descriptor Updates with Descriptor Update Templates

It is also possible to use a descriptor update template to specify the push descriptors to update. To do so, call:

```c
void vkCmdPushDescriptorSetWithTemplateKHR(
    VkCommandBuffer                             commandBuffer,
    VkDescriptorUpdateTemplate                  descriptorUpdateTemplate,
    VkPipelineLayout                            layout,
    uint32_t                                    set,
    const void*                                 pData);
```

• **commandBuffer** is the command buffer that the descriptors will be recorded in.
• descriptorUpdateTemplate is a descriptor update template defining how to interpret the descriptor information in pData.

• layout is a VkPipelineLayout object used to program the bindings. It must be compatible with the layout used to create the descriptorUpdateTemplate handle.

• set is the set number of the descriptor set in the pipeline layout that will be updated. This must be the same number used to create the descriptorUpdateTemplate handle.

• pData is a pointer to memory containing descriptors for the templated update.

Valid Usage

• The pipelineBindPoint specified during the creation of the descriptor update template must be supported by the commandBuffer's parent VkCommandPool's queue family

• pData must be a valid pointer to a memory containing one or more valid instances of VkDescriptorImageInfo, VkDescriptorBufferInfo, or VkBufferView in a layout defined by descriptorUpdateTemplate when it was created with vkCreateDescriptorUpdateTemplateKHR

Valid Usage (Implicit)

• commandBuffer must be a valid VkCommandBuffer handle

• descriptorUpdateTemplate must be a valid VkDescriptorUpdateTemplate handle

• layout must be a valid VkPipelineLayout handle

• commandBuffer must be in the recording state

• The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations

• Each of commandBuffer, descriptorUpdateTemplate, and layout must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized
### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Both</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### API example

```c
struct AppDataStructure
{
    VkDescriptorImageInfo  imageInfo;  // a single image info
    // ... some more application related data
};

const VkDescriptorUpdateTemplateEntry descriptorUpdateTemplateEntries[] =
{
    // binding to a single image descriptor
    {0, 0, 1, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, offsetof(AppDataStructure, imageInfo), 0},
    descriptorCount is 1
};

// create a descriptor update template for descriptor set updates
const VkDescriptorUpdateTemplateCreateInfo createInfo =
{
    VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO,  // sType
    NULL,  // pNext
    0,  // flags
    descriptorUpdateEntryCount,
    descriptorUpdateTemplateEntries,  // pDescriptorUpdateEntries
    VK_DESCRIPTOR.UPDATE.Template.Type_PUSH_DESCRIPTOR_KHR,  // templateType
    0,  // descriptorSetLayout
    VK_PIPELINE.BIND_POINT_GRAPHICS,  // pipelineBindPoint
    myPipelineLayout,  // pipelineLayout
    0,  // set
};

VkDescriptorUpdateTemplate myDescriptorUpdateTemplate;
myResult = vkCreateDescriptorUpdateTemplate(
```

13.2.10. Push Constant Updates

As described above in section Pipeline Layouts, the pipeline layout defines shader push constants which are updated via Vulkan commands rather than via writes to memory or copy commands.

Note

Push constants represent a high speed path to modify constant data in pipelines that is expected to outperform memory-backed resource updates.

The values of push constants are undefined at the start of a command buffer.

To update push constants, call:

```c
void vkCmdPushConstants(
    VkCommandBuffer commandBuffer,
    VkPipelineLayout layout,
    VkShaderStageFlags stageFlags,
    uint32_t offset,
    uint32_t size,
    const void* pValues);
```

- `commandBuffer` is the command buffer in which the push constant update will be recorded.
- `layout` is the pipeline layout used to program the push constant updates.
- `stageFlags` is a bitmask of `VkShaderStageFlagBits` specifying the shader stages that will use the push constants in the updated range.
- `offset` is the start offset of the push constant range to update, in units of bytes.
- `size` is the size of the push constant range to update, in units of bytes.
- `pValues` is a pointer to an array of `size` bytes containing the new push constant values.

Note

As `stageFlags` needs to include all flags the relevant push constant ranges were created with, any flags that are not supported by the queue family that the `VkCommandPool` used to allocate `commandBuffer` was created on are ignored.
Valid Usage

- For each byte in the range specified by offset and size and for each shader stage in stageFlags, there must be a push constant range in layout that includes that byte and that stage.
- For each byte in the range specified by offset and size and for each push constant range that overlaps that byte, stageFlags must include all stages in that push constant range's VkPushConstantRange::stageFlags.
- offset must be a multiple of 4.
- size must be a multiple of 4.
- offset must be less than VkPhysicalDeviceLimits::maxPushConstantsSize.
- size must be less than or equal to VkPhysicalDeviceLimits::maxPushConstantsSize minus offset.

Valid Usage (Implicit)

- commandBuffer must be a valid VkCommandBuffer handle.
- layout must be a valid VkPipelineLayout handle.
- stageFlags must be a valid combination of VkShaderStageFlagBits values.
- stageFlags must not be 0.
- pValues must be a valid pointer to an array of size bytes.
- commandBuffer must be in the recording state.
- The VkCommandPool that commandBuffer was allocated from must support graphics, or compute operations.
- size must be greater than 0.
- Both of commandBuffer, and layout must have been created, allocated, or retrieved from the same VkDevice.

Host Synchronization

- Host access to commandBuffer must be externally synchronized.
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized.
### 13.3. Physical Storage Buffer Access

To query a 64-bit buffer device address value through which buffer memory can be accessed in a shader, call:

```c
VkDeviceAddress vkGetBufferDeviceAddressKHR(VkDevice device, const VkBufferDeviceAddressInfo* pInfo);
```

- **device** is the logical device that the buffer was created on.
- **pInfo** is a pointer to a `VkBufferDeviceAddressInfo` structure specifying the buffer to retrieve an address for.

The 64-bit return value is an address of the start of `pInfo->buffer`. The address range starting at this value and whose size is the size of the buffer can be used in a shader to access the memory bound to that buffer, using the `SPV_KHR_physical_storage_buffer` extension and the `PhysicalStorageBuffer` storage class. For example, this value can be stored in a uniform buffer, and the shader can read the value from the uniform buffer and use it to do a dependent read/write to this buffer. A value of zero is reserved as a “null” pointer and must not be returned as a valid buffer device address. All loads, stores, and atomics in a shader through `PhysicalStorageBuffer` pointers must access addresses in the address range of some buffer.

If the buffer was created with a non-zero value of `VkBufferOpaqueCaptureAddressCreateInfo::opaqueCaptureAddress` the return value will be the same address that was returned at capture time.

#### Valid Usage

- The `bufferDeviceAddress` or `VkPhysicalDeviceBufferDeviceAddressFeaturesEXT::bufferDeviceAddress` feature must be enabled
- If `device` was created with multiple physical devices, then the `bufferDeviceAddressMultiDevice` or `VkPhysicalDeviceBufferDeviceAddressFeaturesEXT::bufferDeviceAddressMultiDevice` feature must be enabled
Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pInfo` must be a valid pointer to a valid `VkBufferDeviceAddressInfo` structure

The `VkBufferDeviceAddressInfo` structure is defined as:

```c
typedef struct VkBufferDeviceAddressInfo {
    VkStructureType sType;
    const void* pNext;
    VkBuffer buffer;
} VkBufferDeviceAddressInfo;
```

or the equivalent

```c
typedef VkBufferDeviceAddressInfo VkBufferDeviceAddressInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `buffer` specifies the buffer whose address is being queried.

Valid Usage

- If `buffer` is non-sparse and was not created with the `VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT` flag, then it must be bound completely and contiguously to a single `VkDeviceMemory` object
- `buffer` must have been created with `VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT`

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_BUFFER_DEVICE_ADDRESS_INFO`
- `pNext` must be `NULL`
- `buffer` must be a valid `VkBuffer` handle

To query a 64-bit buffer opaque capture address, call:

```c
uint64_t vkGetBufferOpaqueCaptureAddressKHR(
    VkDevice device,
    const VkBufferDeviceAddressInfo* pInfo);
```
• **device** is the logical device that the buffer was created on.

• **pInfo** is a pointer to a *VkBufferDeviceAddressInfo* structure specifying the buffer to retrieve an address for.

The 64-bit return value is an opaque capture address of the start of **pInfo->buffer**.

If the buffer was created with a non-zero value of *VkBufferOpaqueCaptureAddressCreateInfo*::opaqueCaptureAddress the return value **must** be the same address.

---

**Valid Usage**

- The **bufferDeviceAddress** feature **must** be enabled

- If **device** was created with multiple physical devices, then the **bufferDeviceAddressMultiDevice** feature **must** be enabled

---

**Valid Usage (Implicit)**

- **device** **must** be a valid *VkDevice* handle

- **pInfo** **must** be a valid pointer to a valid *VkBufferDeviceAddressInfo* structure
Chapter 14. Shader Interfaces

When a pipeline is created, the set of shaders specified in the corresponding VkPipelineCreateInfo structure are implicitly linked at a number of different interfaces.

- Shader Input and Output Interface
- Vertex Input Interface
- Fragment Output Interface
- Fragment Input Attachment Interface
- Shader Resource Interface

Interface definitions make use of the following SPIR-V decorations:

- DescriptorSet and Binding
- Location, Component, and Index
- Flat, NoPerspective, Centroid, and Sample
- Block and BufferBlock
- InputAttachmentIndex
- Offset, ArrayStride, and MatrixStride
- BuiltIn

This specification describes valid uses for Vulkan of these decorations. Any other use of one of these decorations is invalid.

14.1. Shader Input and Output Interfaces

When multiple stages are present in a pipeline, the outputs of one stage form an interface with the inputs of the next stage. When such an interface involves a shader, shader outputs are matched against the inputs of the next stage, and shader inputs are matched against the outputs of the previous stage.

All the variables forming the shader input and output interfaces are listed as operands to the OpEntryPoint instruction and are declared with the Input or Output storage classes, respectively, in the SPIR-V module. These generally form the interfaces between consecutive shader stages, regardless of any non-shader stages between the consecutive shader stages.

There are two classes of variables that can be matched between shader stages, built-in variables and user-defined variables. Each class has a different set of matching criteria.

Output variables of a shader stage have undefined values until the shader writes to them or uses the Initializer operand when declaring the variable.

14.1.1. Built-in Interface Block

Shader built-in variables meeting the following requirements define the built-in interface block.
They must

- be explicitly declared (there are no implicit built-ins),
- be identified with a `BuiltIn` decoration,
- form object types as described in the `Built-in Variables` section, and
- be declared in a block whose top-level members are the built-ins.

There must be no more than one built-in interface block per shader per interface.

Built-ins must not have any `Location` or `Component` decorations.

### 14.1.2. User-defined Variable Interface

The non-built-in variables listed by `OpEntryPoint` with the `Input` or `Output` storage class form the *user-defined variable interface*. These must have SPIR-V numerical types or, recursively, composite types of such types. By default, the components of such types have a width of 32 or 64 bits. If an implementation supports `storageInputOutput16`, components can also have a width of 16 bits. These variables must be identified with a `Location` decoration and can also be identified with a `Component` decoration.

### 14.1.3. Interface Matching

Interface matching rules only apply to built-ins when they are declared as members of the built-in interface block.

Tessellation control shader per-vertex output variables and blocks, and tessellation control, tessellation evaluation, and geometry shader per-vertex input variables and blocks are required to be declared as arrays, with each element representing input or output values for a single vertex of a multi-vertex primitive. For the purposes of interface matching, the outermost array dimension of such variables and blocks is ignored.

A user-defined output variable is considered to match an input variable in the subsequent stage if the two variables are declared with the same `Location` and `Component` decoration and match in type and decoration, except that interpolation decorations are not required to match. For the purposes of interface matching, variables declared without a `Component` decoration are considered to have a `Component` decoration of zero.

Variables or block members declared as structures are considered to match in type if and only if the structure members match in type, decoration, number, and declaration order. Variables or block members declared as arrays are considered to match in type only if both declarations specify the same element type and size.

At an interface between two non-fragment shader stages, the built-in interface block must match exactly, as described above. At an interface involving the fragment shader inputs, the presence or absence of any built-in output does not affect the interface matching.

At an interface between two shader stages, the user-defined variable interface must match exactly, as described above.
Any input value to a shader stage is well-defined as long as the preceding stages writes to a matching output, as described above.

Additionally, scalar and vector inputs are well-defined if there is a corresponding output satisfying all of the following conditions:

- the input and output match exactly in decoration,
- the output is a vector with the same basic type and has at least as many components as the input, and
- the common component type of the input and output is 16-bit integer or floating-point, or 32-bit integer or floating-point (64-bit component types are excluded).

In this case, the components of the input will be taken from the first components of the output, and any extra components of the output will be ignored.

### 14.1.4. Location Assignment

This section describes how many locations are consumed by a given type. As mentioned above, some inputs and outputs have an additional level of arrayness relative to other shader inputs and outputs. This outer array level is removed from the type before considering how many locations the type consumes.

The Location value specifies an interface slot comprised of a 32-bit four-component vector conveyed between stages. The Component specifies components within these vector locations. Only types with widths of 16, 32 or 64 are supported in shader interfaces.

Inputs and outputs of the following types consume a single interface location:

- 16-bit scalar and vector types, and
- 32-bit scalar and vector types, and
- 64-bit scalar and 2-component vector types.

64-bit three- and four-component vectors consume two consecutive locations.

If a declared input or output is an array of size \( n \) and each element takes \( m \) locations, it will be assigned \( m \times n \) consecutive locations starting with the location specified.

If the declared input or output is an \( n \times m \) 16-, 32- or 64-bit matrix, it will be assigned multiple locations starting with the location specified. The number of locations assigned for each matrix will be the same as for an \( n \)-element array of \( m \)-component vectors.

The layout of a structure type used as an Input or Output depends on whether it is also a Block (i.e. has a Block decoration).

If it is a not a Block, then the structure type must have a Location decoration. Its members are assigned consecutive locations in their declaration order, with the first member assigned to the location specified for the structure type. The members, and their nested types, must not themselves have Location decorations.
If the structure type is a Block but without a Location, then each of its members must have a Location decoration. If it is a Block with a Location decoration, then its members are assigned consecutive locations in declaration order, starting from the first member which is initially assigned the location specified for the Block. Any member with its own Location decoration is assigned that location. Each remaining member is assigned the location after the immediately preceding member in declaration order.

The locations consumed by block and structure members are determined by applying the rules above in a depth-first traversal of the instantiated members as though the structure or block member were declared as an input or output variable of the same type.

Any two inputs listed as operands on the same OpEntryPoint must not be assigned the same location, either explicitly or implicitly. Any two outputs listed as operands on the same OpEntryPoint must not be assigned the same location, either explicitly or implicitly.

The number of input and output locations available for a shader input or output interface are limited, and dependent on the shader stage as described in Shader Input and Output Locations. All variables in both the built-in interface block and the user-defined variable interface count against these limits. Each effective Location must have a value less than the number of locations available for the given interface, as specified in the "Locations Available" column in Shader Input and Output Locations.

<table>
<thead>
<tr>
<th>Shader Interface</th>
<th>Locations Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex input</td>
<td>maxVertexInputAttributes</td>
</tr>
<tr>
<td>vertex output</td>
<td>maxVertexOutputComponents / 4</td>
</tr>
<tr>
<td>tessellation control input</td>
<td>maxTessellationControlPerVertexComponents / 4</td>
</tr>
<tr>
<td>tessellation control output</td>
<td>maxTessellationControlPerVertexOutputComponents / 4</td>
</tr>
<tr>
<td>tessellation evaluation input</td>
<td>maxTessellationEvaluationInputComponents / 4</td>
</tr>
<tr>
<td>tessellation evaluation output</td>
<td>maxTessellationEvaluationOutputComponents / 4</td>
</tr>
<tr>
<td>geometry input</td>
<td>maxGeometryInputComponents / 4</td>
</tr>
<tr>
<td>geometry output</td>
<td>maxGeometryOutputComponents / 4</td>
</tr>
<tr>
<td>fragment input</td>
<td>maxFragmentInputComponents / 4</td>
</tr>
<tr>
<td>fragment output</td>
<td>maxFragmentOutputAttachments</td>
</tr>
</tbody>
</table>

14.1.5. Component Assignment

The Component decoration allows the Location to be more finely specified for scalars and vectors, down to the individual components within a location that are consumed. The components within a location are 0, 1, 2, and 3. A variable or block member starting at component N will consume components N, N+1, N+2, ... up through its size. For 16- and 32-bit types, it is invalid if this sequence of components gets larger than 3. A scalar 64-bit type will consume two of these components in sequence, and a two-component 64-bit vector type will consume all four components available within a location. A three- or four-component 64-bit vector type must not specify a Component.
A three-component 64-bit vector type will consume all four components of the first location and components 0 and 1 of the second location. This leaves components 2 and 3 available for other component-qualified declarations.

A scalar or two-component 64-bit data type must not specify a Component decoration of 1 or 3. A Component decoration must not be specified for any type that is not a scalar or vector.

14.2. Vertex Input Interface

When the vertex stage is present in a pipeline, the vertex shader input variables form an interface with the vertex input attributes. The vertex shader input variables are matched by the Location and Component decorations to the vertex input attributes specified in the pVertexInputState member of the VkGraphicsPipelineCreateInfo structure.

The vertex shader input variables listed by OpEntryPoint with the Input storage class form the vertex input interface. These variables must be identified with a Location decoration and can also be identified with a Component decoration.

For the purposes of interface matching: variables declared without a Component decoration are considered to have a Component decoration of zero. The number of available vertex input locations is given by the maxVertexInputAttributes member of the VkPhysicalDeviceLimits structure.

See Attribute Location and Component Assignment for details.

All vertex shader inputs declared as above must have a corresponding attribute and binding in the pipeline.

14.3. Fragment Output Interface

When the fragment stage is present in a pipeline, the fragment shader outputs form an interface with the output attachments of the current subpass. The fragment shader output variables are matched by the Location and Component decorations to the color attachments specified in the pColorAttachments array of the VkSubpassDescription structure describing the subpass that the fragment shader is executed in.

The fragment shader output variables listed by OpEntryPoint with the Output storage class form the fragment output interface. These variables must be identified with a Location decoration. They can also be identified with a Component decoration and/or an Index decoration. For the purposes of interface matching: variables declared without a Component decoration are considered to have a Component decoration of zero, and variables declared without an Index decoration are considered to have an Index decoration of zero.

A fragment shader output variable identified with a Location decoration of i is directed to the color attachment indicated by pColorAttachments[i], after passing through the blending unit as described in Blending, if enabled. Locations are consumed as described in Location Assignment. The number of available fragment output locations is given by the maxFragmentOutputAttachments member of the VkPhysicalDeviceLimits structure.

Components of the output variables are assigned as described in Component Assignment. Output
components identified as 0, 1, 2, and 3 will be directed to the R, G, B, and A inputs to the blending unit, respectively, or to the output attachment if blending is disabled. If two variables are placed within the same location, they **must** have the same underlying type (floating-point or integer). The input values to blending or color attachment writes are undefined for components which do not correspond to a fragment shader output.

Fragment outputs identified with an **Index** of zero are directed to the first input of the blending unit associated with the corresponding **Location**. Outputs identified with an **Index** of one are directed to the second input of the corresponding blending unit.

No **component aliasing** of output variables is allowed, that is there **must** not be two output variables which have the same location, component, and index, either explicitly declared or implied.

Output values written by a fragment shader **must** be declared with either **OpTypeFloat** or **OpTypeInt**, and a **Width** of 32. If **storageInputOutput16** is supported, output values written by a fragment shader **can** be also declared with either **OpTypeFloat** or **OpTypeInt** and a **Width** of 16. Composites of these types are also permitted. If the color attachment has a signed or unsigned normalized fixed-point format, color values are assumed to be floating-point and are converted to fixed-point as described in *Conversion from Floating-Point to Normalized Fixed-Point*; If the color attachment has an integer format, color values are assumed to be integers and converted to the bit-depth of the target. Any value that cannot be represented in the attachment's format is undefined. For any other attachment format no conversion is performed. If the type of the values written by the fragment shader do not match the format of the corresponding color attachment, the resulting values are undefined for those components.

### 14.4. Fragment Input Attachment Interface

When a fragment stage is present in a pipeline, the fragment shader subpass inputs form an interface with the input attachments of the current subpass. The fragment shader subpass input variables are matched by **InputAttachmentIndex** decorations to the input attachments specified in the **pInputAttachments** array of the **VkSubpassDescription** structure describing the subpass that the fragment shader is executed in.

The fragment shader subpass input variables with the **UniformConstant** storage class and a decoration of **InputAttachmentIndex** that are statically used by **OpEntryPoint** form the **fragment input attachment interface**. These variables **must** be declared with a type of **OpTypeImage**, a **Dim** operand of **SubpassData**, and a **Sampled** operand of 2.

A subpass input variable identified with an **InputAttachmentIndex** decoration of *i* reads from the input attachment indicated by **pInputAttachments[i]** member of **VkSubpassDescription**. If the subpass input variable is declared as an array of size N, it consumes N consecutive input attachments, starting with the index specified. There **must** not be more than one input variable with the same **InputAttachmentIndex** whether explicitly declared or implied by an array declaration. The number of available input attachment indices is given by the **maxPerStageDescriptorInputAttachments** member of the **VkPhysicalDeviceLimits** structure.

Variables identified with the **InputAttachmentIndex** **must** only be used by a fragment stage. The basic data type (floating-point, integer, unsigned integer) of the subpass input **must** match the basic format of the corresponding input attachment, or the values of subpass loads from these variables
14.5. Shader Resource Interface

When a shader stage accesses buffer or image resources, as described in the Resource Descriptors section, the shader resource variables must be matched with the pipeline layout that is provided at pipeline creation time.

The set of shader resources that form the shader resource interface for a stage are the variables statically used by OpEntryPoint with the storage class of Uniform, UniformConstant, or PushConstant. For the fragment shader, this includes the fragment input attachment interface.

The shader resource interface consists of two sub-interfaces: the push constant interface and the descriptor set interface.

14.5.1. Push Constant Interface

The shader variables defined with a storage class of PushConstant that are statically used by the shader entry points for the pipeline define the push constant interface. They must be:

- typed as OpTypeStruct,
- identified with a Block decoration, and
- laid out explicitly using the Offset, ArrayStride, and MatrixStride decorations as specified in Offset and Stride Assignment.

There must be no more than one push constant block statically used per shader entry point.

Each statically used member of a push constant block must be placed at an Offset such that the entire member is entirely contained within the VkPushConstantRange for each OpEntryPoint that uses it, and the stageFlags for that range must specify the appropriate VkShaderStageFlagBits for that stage. The Offset decoration for any member of a push constant block must not cause the space required for that member to extend outside the range [0, maxPushConstantsSize).

Any member of a push constant block that is declared as an array must only be accessed with dynamically uniform indices.

14.5.2. Descriptor Set Interface

The descriptor set interface is comprised of the shader variables with the storage class of StorageBuffer, Uniform or UniformConstant (including the variables in the fragment input attachment interface) that are statically used by the shader entry points for the pipeline.

These variables must have DescriptorSet and Binding decorations specified, which are assigned and matched with the VkDescriptorSetLayout objects in the pipeline layout as described in DescriptorSet and Binding Assignment.

The Image Format of an OpTypeImage declaration must not be Unknown, for variables which are used
for OpImageRead, OpImageSparseRead, or OpImageWrite operations, except under the following conditions:

- For OpImageWrite, if the shaderStorageImageWriteWithoutFormat feature is enabled and the shader module declares the StorageImageWriteWithoutFormat capability.
- For OpImageRead or OpImageSparseRead, if the shaderStorageImageReadWithoutFormat feature is enabled and the shader module declares the StorageImageReadWithoutFormat capability.
- For OpImageRead, if Dim is SubpassData (indicating a read from an input attachment).

The Image Format of an OpTypeImage declaration must not be Unknown, for variables which are used for OpAtomic* operations.

Variables identified with the Uniform storage class are used to access transparent buffer backed resources. Such variables must be:

- typed as OpTypeStruct, or an array of this type,
- identified with a Block or BufferBlock decoration, and
- laid out explicitly using the Offset, ArrayStride, and MatrixStride decorations as specified in Offset and Stride Assignment.

Variables identified with the StorageBuffer storage class are used to access transparent buffer backed resources. Such variables must be:

- typed as OpTypeStruct, or an array of this type,
- identified with a Block decoration, and
- laid out explicitly using the Offset, ArrayStride, and MatrixStride decorations as specified in Offset and Stride Assignment.

The Offset decoration for any member of a Block-decorated variable in the Uniform storage class must not cause the space required for that variable to extend outside the range [0, maxUniformBufferRange). The Offset decoration for any member of a Block-decorated variable in the StorageBuffer storage class must not cause the space required for that variable to extend outside the range [0, maxStorageBufferRange).

Variables identified with a storage class of UniformConstant and a decoration of InputAttachmentIndex must be declared as described in Fragment Input Attachment Interface.

SPIR-V variables decorated with a descriptor set and binding that identify a combined image sampler descriptor can have a type of OpTypeImage, OpTypeSampler (Sampled=1), or OpTypeSampledImage.

Arrays of any of these types can be indexed with constant integral expressions. The following features must be enabled and capabilities must be declared in order to index such arrays with dynamically uniform or non-uniform indices:

- Storage images (except storage texel buffers and input attachments):
  - Dynamically uniform: shaderStorageImageArrayDynamicIndexing and StorageImageArrayDynamicIndexing
• Sampled images (except uniform texel buffers), samplers and combined image samplers:
  ◦ Dynamically uniform: \texttt{shaderSampledImageArrayDynamicIndexing} and \texttt{SampledImageArrayDynamicIndexing}

• Uniform buffers:
  ◦ Dynamically uniform: \texttt{shaderUniformBufferArrayDynamicIndexing} and \texttt{UniformBufferArrayDynamicIndexing}

• Storage buffers:
  ◦ Dynamically uniform: \texttt{shaderStorageBufferArrayDynamicIndexing} and \texttt{StorageBufferArrayDynamicIndexing}

• Acceleration structures:
  ◦ No additional capabilities needed.

If an instruction loads from or stores to a resource (including atomics and image instructions) and the resource descriptor being accessed is not uniform, then the corresponding dynamic indexing feature must be enabled and the capability must be declared.

If the combined image sampler enables sampler \( Y'\text{CbCr} \) conversion, it must be indexed only by constant integral expressions when aggregated into arrays in shader code, irrespective of the \texttt{shaderSampledImageArrayDynamicIndexing} feature.

\textit{Table 16. Shader Resource and Descriptor Type Correspondence}

<table>
<thead>
<tr>
<th>Resource type</th>
<th>Descriptor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>sampler</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_SAMPLER} or \texttt{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER}</td>
</tr>
<tr>
<td>sampled image</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE} or \texttt{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER}</td>
</tr>
<tr>
<td>storage image</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_STORAGE_IMAGE}</td>
</tr>
<tr>
<td>combined image sampler</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER}</td>
</tr>
<tr>
<td>uniform texel buffer</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER}</td>
</tr>
<tr>
<td>storage texel buffer</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER}</td>
</tr>
<tr>
<td>uniform buffer</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER} or \texttt{VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC}</td>
</tr>
<tr>
<td>storage buffer</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER} or \texttt{VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC}</td>
</tr>
<tr>
<td>input attachment</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT}</td>
</tr>
<tr>
<td>acceleration structure</td>
<td>\texttt{VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR}</td>
</tr>
</tbody>
</table>

\textit{Table 17. Shader Resource and Storage Class Correspondence}

<table>
<thead>
<tr>
<th>Resource type</th>
<th>Storage Class</th>
<th>Type</th>
<th>Decoration(s)(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sampler</td>
<td>UniformConstant</td>
<td>OpTypeSampler</td>
<td></td>
</tr>
<tr>
<td>sampled image</td>
<td>UniformConstant</td>
<td>OpTypeImage (Sampled=1)</td>
<td></td>
</tr>
<tr>
<td>storage image</td>
<td>UniformConstant</td>
<td>OpTypeImage (Sampled=2)</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) OpType Sampler and OpType Image are the OpTypes for samplers and images, respectively.
<table>
<thead>
<tr>
<th>Resource type</th>
<th>Storage Class</th>
<th>Type</th>
<th>Decoration(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>combined image sampler</td>
<td>UniformConstant</td>
<td>OpTypeSampledImage OpTypeImage (Sampled=1) OpTypeSampler</td>
<td></td>
</tr>
<tr>
<td>uniform texel buffer</td>
<td>UniformConstant</td>
<td>OpTypeImage (Dim=Buffer, Sampled=1)</td>
<td></td>
</tr>
<tr>
<td>storage texel buffer</td>
<td>UniformConstant</td>
<td>OpTypeImage (Dim=Buffer, Sampled=2)</td>
<td></td>
</tr>
<tr>
<td>uniform buffer</td>
<td>Uniform</td>
<td>OpTypeStruct</td>
<td>Block, Offset, (ArrayStride), (MatrixStride)</td>
</tr>
<tr>
<td>storage buffer</td>
<td>Uniform</td>
<td>OpTypeStruct</td>
<td>BufferBlock, Offset, (ArrayStride), (MatrixStride)</td>
</tr>
<tr>
<td></td>
<td>StorageBuffer</td>
<td></td>
<td>Block, Offset, (ArrayStride), (MatrixStride)</td>
</tr>
<tr>
<td>input attachment</td>
<td>UniformConstant</td>
<td>OpTypeImage (Dim=SubpassData, Sampled=2)</td>
<td>InputAttachmentIndex</td>
</tr>
<tr>
<td>acceleration structure</td>
<td>UniformConstant</td>
<td>OpTypeAccelerationStructureKHR</td>
<td></td>
</tr>
</tbody>
</table>

1 in addition to DescriptorSet and Binding

### 14.5.3. DescriptorSet and Binding Assignment

A variable decorated with a DescriptorSet decoration of `s` and a Binding decoration of `b` indicates that this variable is associated with the VkDescriptorSetLayoutBinding that has a binding equal to `b` in `pSetLayouts[s]` that was specified in VkPipelineLayoutCreateInfo.

DescriptorSet decoration values must be between zero and `maxBoundDescriptorSets` minus one, inclusive. Binding decoration values can be any 32-bit unsigned integer value, as described in Descriptor Set Layout. Each descriptor set has its own binding name space.

If the Binding decoration is used with an array, the entire array is assigned that binding value. The array must be a single-dimensional array and size of the array must be no larger than the number of descriptors in the binding. The array must not be runtime-sized. The index of each element of the array is referred to as the arrayElement. For the purposes of interface matching and descriptor set operations, if a resource variable is not an array, it is treated as if it has an arrayElement of zero.

There is a limit on the number of resources of each type that can be accessed by a pipeline stage as shown in Shader Resource Limits. The “Resources Per Stage” column gives the limit on the number each type of resource that can be statically used for an entry point in any given stage in a pipeline. The “Resource Types” column lists which resource types are counted against the limit. Some resource types count against multiple limits.

The pipeline layout may include descriptor sets and bindings which are not referenced by any variables statically used by the entry points for the shader stages in the binding’s stageFlags.
However, if a variable assigned to a given DescriptorSet and Binding is statically used by the entry point for a shader stage, the pipeline layout must contain a descriptor set layout binding in that descriptor set layout and for that binding number, and that binding’s stageFlags must include the appropriate VkShaderStageFlagBits for that stage. The variable must be of a valid resource type determined by its SPIR-V type and storage class, as defined in Shader Resource and Storage Class Correspondence. The descriptor set layout binding must be of a corresponding descriptor type, as defined in Shader Resource and Descriptor Type Correspondence.

Note

There are no limits on the number of shader variables that can have overlapping set and binding values in a shader; but which resources are statically used has an impact. If any shader variable identifying a resource is statically used in a shader, then the underlying descriptor bound at the declared set and binding must support the declared type in the shader when the shader executes.

If multiple shader variables are declared with the same set and binding values, and with the same underlying descriptor type, they can all be statically used within the same shader. However, accesses are not automatically synchronized, and Aliased decorations should be used to avoid data hazards (see section 2.18.2 Aliasing in the SPIR-V specification).

If multiple shader variables with the same set and binding values are declared in a single shader, but with different declared types, where any of those are not supported by the relevant bound descriptor, that shader can only be executed if the variables with the unsupported type are not statically used.

A noteworthy example of using multiple statically-used shader variables sharing the same descriptor set and binding values is a descriptor of type VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER that has multiple corresponding shader variables in the UniformConstant storage class, where some could be OpTypeImage, some could be OpTypeSampler (Sampled=1), and some could be OpTypeSampledImage.

Table 18. Shader Resource Limits

<table>
<thead>
<tr>
<th>Resources per Stage</th>
<th>Resource Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxPerStageDescriptorSamplers</td>
<td>sampler</td>
</tr>
<tr>
<td></td>
<td>combined image sampler</td>
</tr>
<tr>
<td>maxPerStageDescriptorSampledImages</td>
<td>sampled image</td>
</tr>
<tr>
<td></td>
<td>combined image sampler</td>
</tr>
<tr>
<td></td>
<td>uniform texel buffer</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageImages</td>
<td>storage image</td>
</tr>
<tr>
<td></td>
<td>storage texel buffer</td>
</tr>
<tr>
<td>maxPerStageDescriptorUniformBuffers</td>
<td>uniform buffer</td>
</tr>
<tr>
<td></td>
<td>uniform buffer dynamic</td>
</tr>
</tbody>
</table>

Chapter 14. Shader Interfaces | 603
### Resources per Stage

<table>
<thead>
<tr>
<th>Resource Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxPerStageDescriptorStorageBuffers</td>
</tr>
<tr>
<td>storage buffer</td>
</tr>
<tr>
<td>storage buffer dynamic</td>
</tr>
<tr>
<td>maxPerStageDescriptorInputAttachments</td>
</tr>
<tr>
<td>input attachment</td>
</tr>
<tr>
<td>maxDescriptorSetAccelerationStructures</td>
</tr>
<tr>
<td>acceleration structure</td>
</tr>
</tbody>
</table>

1

Input attachments can only be used in the fragment shader stage.

### 14.5.4. Offset and Stride Assignment

All variables with a storage class of `Uniform`, `StorageBuffer`, or `PushConstant` must be explicitly laid out using the `Offset`, `ArrayStride`, and `MatrixStride` decorations.

**Note**

The numeric order of `Offset` decorations does not need to follow member declaration order.

### Alignment Requirements

There are different alignment requirements depending on the specific resources and on the features enabled on the device.

The scalar alignment of the type of an `OpTypeStruct` member is defined recursively as follows:

- A scalar of size N has a scalar alignment of N.
- A vector or matrix type has a scalar alignment equal to that of its component type.
- An array type has a scalar alignment equal to that of its element type.
- A structure has a scalar alignment equal to the largest scalar alignment of any of its members.

The base alignment of the type of an `OpTypeStruct` member is defined recursively as follows:

- A scalar has a base alignment equal to its scalar alignment.
- A two-component vector has a base alignment equal to twice its scalar alignment.
- A three- or four-component vector has a base alignment equal to four times its scalar alignment.
- An array has a base alignment equal to the base alignment of its element type.
- A structure has a base alignment equal to the largest base alignment of any of its members.
- A row-major matrix of C columns has a base alignment equal to the base alignment of a vector of C matrix components.
- A column-major matrix has a base alignment equal to the base alignment of the matrix column type.

The extended alignment of the type of an `OpTypeStruct` member is similarly defined as follows:
• A scalar, vector or matrix type has an extended alignment equal to its base alignment.

• An array or structure type has an extended alignment equal to the largest extended alignment of any of its members, rounded up to a multiple of 16.

A member is defined to *improperly straddle* if either of the following are true:

• It is a vector with total size less than or equal to 16 bytes, and has *Offset* decorations placing its first byte at F and its last byte at L, where \( \text{floor}(F / 16) \neq \text{floor}(L / 16) \).

• It is a vector with total size greater than 16 bytes and has its *Offset* decorations placing its first byte at a non-integer multiple of 16.

**Standard Buffer Layout**

Every member of an `OpTypeStruct` with storage class of `Uniform`, `StorageBuffer`, or `PushConstant` must be aligned according to the first matching rule as follows:

1. All vectors must be aligned according to their scalar alignment.

2. If the `uniformBufferStandardLayout` feature is not enabled on the device, then any member of an `OpTypeStruct` with a storage class of `Uniform` and a decoration of `Block` must be aligned according to its extended alignment.

3. Every other member must be aligned according to its base alignment.

The memory layout must obey the following rules:

• The *Offset* decoration of any member must be a multiple of its alignment.

• Any `ArrayStride` or `MatrixStride` decoration must be a multiple of the alignment of the array or matrix as defined above.

• Vectors must not improperly straddle, as defined above.

• The *Offset* decoration of a member must not place it between the end of a structure or an array and the next multiple of the alignment of that structure or array.

**Note**

The *std430 layout* in GLSL satisfies these rules for types using the base alignment. The *std140 layout* satisfies the rules for types using the extended alignment.

**14.6. Built-In Variables**

Built-in variables are accessed in shaders by declaring a variable decorated with a `BuiltIn SPIR-V` decoration. The meaning of each `BuiltIn` decoration is as follows. In the remainder of this section, the name of a built-in is used interchangeably with a term equivalent to a variable decorated with that particular built-in. Built-ins that represent integer values can be declared as either signed or unsigned 32-bit integers.

As mentioned above, some inputs and outputs have an additional level of arrayness relative to other shader inputs and outputs. This level of arrayness is not included in the type descriptions below, but must be included when declaring the built-in.
BaseInstance
Decorating a variable with the BaseInstance built-in will make that variable contain the integer value corresponding to the first instance that was passed to the command that invoked the current vertex shader invocation. BaseInstance is the firstInstance parameter to a direct drawing command or the firstInstance member of a structure consumed by an indirect drawing command.

The BaseInstance decoration must be used only within vertex shaders.

The variable decorated with BaseInstance must be declared using the input storage class.

The variable decorated with BaseInstance must be declared as a scalar 32-bit integer.

BaseVertex
Decorating a variable with the BaseVertex built-in will make that variable contain the integer value corresponding to the first vertex or vertex offset that was passed to the command that invoked the current vertex shader invocation. For non-indexed drawing commands, this variable is the firstVertex parameter to a direct drawing command or the firstVertex member of the structure consumed by an indirect drawing command. For indexed drawing commands, this variable is the vertexOffset parameter to a direct drawing command or the vertexOffset member of the structure consumed by an indirect drawing command.

The BaseVertex decoration must be used only within vertex shaders.

The variable decorated with BaseVertex must be declared using the input storage class.

The variable decorated with BaseVertex must be declared as a scalar 32-bit integer.

ClipDistance
Decorating a variable with the ClipDistance built-in decoration will make that variable contain the mechanism for controlling user clipping. ClipDistance is an array such that the i\textsuperscript{th} element of the array specifies the clip distance for plane i. A clip distance of 0 means the vertex is on the plane, a positive distance means the vertex is inside the clip half-space, and a negative distance means the point is outside the clip half-space.

The ClipDistance decoration must be used only within vertex, fragment, tessellation control, tessellation evaluation, and geometry shaders.

In vertex shaders, any variable decorated with ClipDistance must be declared using the Output storage class.

In fragment shaders, any variable decorated with ClipDistance must be declared using the Input storage class.

In tessellation control, tessellation evaluation, or geometry shaders, any variable decorated with ClipDistance must not be in a storage class other than Input or Output.

Any variable decorated with ClipDistance must be declared as an array of 32-bit floating-point values.
The array variable decorated with `ClipDistance` is explicitly sized by the shader.

In the last vertex processing stage, these values will be linearly interpolated across the primitive and the portion of the primitive with interpolated distances less than 0 will be considered outside the clip volume. If `ClipDistance` is then used by a fragment shader, `ClipDistance` contains these linearly interpolated values.

CullDistance

Decorating a variable with the `CullDistance` built-in decoration will make that variable contain the mechanism for controlling user culling. If any member of this array is assigned a negative value for all vertices belonging to a primitive, then the primitive is discarded before rasterization.

The `CullDistance` decoration must be used only within vertex, fragment, tessellation control, tessellation evaluation, and geometry shaders.

In vertex shaders, any variable decorated with `CullDistance` must be declared using the `Output` storage class.

In fragment shaders, any variable decorated with `CullDistance` must be declared using the `Input` storage class.

In tessellation control, tessellation evaluation, or geometry shaders, any variable decorated with `CullDistance` must not be declared in a storage class other than input or output.

Any variable decorated with `CullDistance` must be declared as an array of 32-bit floating-point values.

In fragment shaders, the values of the `CullDistance` array are linearly interpolated across each primitive.

If `CullDistance` decorates an input variable, that variable will contain the corresponding value from the `CullDistance` decorated output variable from the previous shader stage.

DeviceIndex

The `DeviceIndex` decoration can be applied to a shader input which will be filled with the device index of the physical device that is executing the current shader invocation. This value will be in the range \( [0, \max(1, \text{physicalDeviceCount})] \), where `physicalDeviceCount` is the `physicalDeviceCount` member of `VkDeviceGroupDeviceCreateInfo`.

The `DeviceIndex` decoration can be used in any shader.

The variable decorated with `DeviceIndex` must be declared using the `Input` storage class.
The variable decorated with \texttt{DeviceIndex} \textbf{must} be declared as a scalar 32-bit integer.

\textbf{DrawIndex}

Decorating a variable with the \texttt{DrawIndex} built-in will make that variable contain the integer value corresponding to the zero-based index of the drawing command that invoked the current vertex shader invocation. For \textit{indirect drawing commands}, \texttt{DrawIndex} begins at zero and increments by one for each draw command executed. The number of draw commands is given by the \texttt{drawCount} parameter. For \textit{direct drawing commands}, \texttt{DrawIndex} is always zero. \texttt{DrawIndex} is dynamically uniform.

The \texttt{DrawIndex} decoration \textbf{must} be used only within vertex shaders.

The variable decorated with \texttt{DrawIndex} \textbf{must} be declared using the input storage class.

The variable decorated with \texttt{DrawIndex} \textbf{must} be declared as a scalar 32-bit integer.

\textbf{FragCoord}

Decorating a variable with the \texttt{FragCoord} built-in decoration will make that variable contain the framebuffer coordinate \((x, y, z, \frac{1}{w})\) of the fragment being processed. The \((x,y)\) coordinate \((0,0)\) is the upper left corner of the upper left pixel in the framebuffer.

When \textbf{Sample Shading} is enabled, the \(x\) and \(y\) components of \texttt{FragCoord} reflect the location of one of the samples corresponding to the shader invocation.

Otherwise, the \(x\) and \(y\) components of \texttt{FragCoord} reflect the location of the center of the fragment.

The \(z\) component of \texttt{FragCoord} is the interpolated depth value of the primitive.

The \(w\) component is the interpolated \(\frac{1}{w}\).

The \texttt{FragCoord} decoration \textbf{must} be used only within fragment shaders.

The variable decorated with \texttt{FragCoord} \textbf{must} be declared using the \textbf{Input} storage class.

The \texttt{Centroid} interpolation decoration is ignored, but allowed, on \texttt{FragCoord}.

The variable decorated with \texttt{FragCoord} \textbf{must} be declared as a four-component vector of 32-bit floating-point values.

\textbf{FragDepth}

To have a shader supply a fragment-depth value, the shader \textbf{must} declare the \texttt{DepthReplacing} execution mode. Such a shader’s fragment-depth value will come from the variable decorated with the \texttt{FragDepth} built-in decoration.

This value will be used for any subsequent depth testing performed by the implementation or writes to the depth attachment.

The \texttt{FragDepth} decoration \textbf{must} be used only within fragment shaders.

The variable decorated with \texttt{FragDepth} \textbf{must} be declared using the \textbf{Output} storage class.
The variable decorated with \texttt{FragDepth} \textbf{must} be declared as a scalar 32-bit floating-point value.

**FrontFacing**

Decorating a variable with the \texttt{FrontFacing} built-in decoration will make that variable contain whether the fragment is front or back facing. This variable is non-zero if the current fragment is considered to be part of a \texttt{front-facing} polygon primitive or of a non-polygon primitive and is zero if the fragment is considered to be part of a back-facing polygon primitive.

The \texttt{FrontFacing} decoration \textbf{must} be used only within fragment shaders.

The variable decorated with \texttt{FrontFacing} \textbf{must} be declared using the \texttt{Input} storage class.

The variable decorated with \texttt{FrontFacing} \textbf{must} be declared as a boolean.

**GlobalInvocationId**

Decorating a variable with the \texttt{GlobalInvocationId} built-in decoration will make that variable contain the location of the current invocation within the global workgroup. Each component is equal to the index of the local workgroup multiplied by the size of the local workgroup plus \texttt{LocalInvocationId}.

The \texttt{GlobalInvocationId} decoration \textbf{must} be used only within compute shaders.

The variable decorated with \texttt{GlobalInvocationId} \textbf{must} be declared using the \texttt{Input} storage class.

The variable decorated with \texttt{GlobalInvocationId} \textbf{must} be declared as a three-component vector of 32-bit integers.

**HelperInvocation**

Decorating a variable with the \texttt{HelperInvocation} built-in decoration will make that variable contain whether the current invocation is a helper invocation. This variable is non-zero if the current fragment being shaded is a helper invocation and zero otherwise. A helper invocation is an invocation of the shader that is produced to satisfy internal requirements such as the generation of derivatives.

The \texttt{HelperInvocation} decoration \textbf{must} be used only within fragment shaders.

The variable decorated with \texttt{HelperInvocation} \textbf{must} be declared using the \texttt{Input} storage class.

The variable decorated with \texttt{HelperInvocation} \textbf{must} be declared as a boolean.

\begin{itemize}
  \item \textbf{Note}
  \begin{itemize}
    \item It is very likely that a helper invocation will have a value of \texttt{SampleMask} fragment shader input value that is zero.
  \end{itemize}
\end{itemize}

**HitKindKHR**

A variable decorated with the \texttt{HitKindKHR} decoration will describe the intersection that triggered the execution of the current shader. The values are determined by the intersection shader. For user-defined intersection shaders this is the value that was passed to the “Hit Kind” operand of \texttt{OpReportIntersectionKHR}. For triangle intersection candidates, this will be one of \texttt{HitKindFrontFacingTriangleKHR} or \texttt{HitKindBackFacingTriangleKHR}.
The `HitKindKHR` decoration must only be used in any-hit and closest hit shaders.

Any variable decorated with `HitKindKHR` must be declared using the `Input` storage class.

Any variable decorated with `HitKindKHR` must be declared as a scalar 32-bit integer.

**IncomingRayFlagsKHR**

A variable with the `IncomingRayFlagsKHR` decoration will contain the ray flags passed in to the trace call that invoked this particular shader.

The `IncomingRayFlagsKHR` decoration must only be used in the intersection, any-hit, closest hit, and miss shaders.

Any variable decorated with `IncomingRayFlagsKHR` must be declared using the `Input` storage class.

Any variable decorated with `IncomingRayFlagsKHR` must be declared as a scalar 32-bit integer.

**InstanceCustomIndexKHR**

A variable decorated with the `InstanceCustomIndexKHR` decoration will contain the application-defined value of the instance that intersects the current ray. Only the lower 24 bits are valid, the upper 8 bits will be ignored.

The `InstanceCustomIndexKHR` decoration must only be used in the intersection, any-hit, and closest hit shaders.

Any variable decorated with `InstanceCustomIndexKHR` must be declared using the `Input` storage class.

Any variable decorated with `InstanceCustomIndexKHR` must be declared as a scalar 32-bit integer.

**InstanceId**

Decorating a variable in an intersection, any-hit, or closest hit shader with the `InstanceId` decoration will make that variable contain the index of the instance that intersects the current ray.

The `InstanceId` decoration must be used only within intersection, any-hit, or closest hit shaders.

The variable decorated with `InstanceId` must be declared using the `Input` storage class.

The variable decorated with `InstanceId` must be declared as a scalar 32-bit integer.

**InvocationId**

Decorating a variable with the `InvocationId` built-in decoration will make that variable contain the index of the current shader invocation in a geometry shader, or the index of the output patch vertex in a tessellation control shader.

In a geometry shader, the index of the current shader invocation ranges from zero to the number of instances declared in the shader minus one. If the instance count of the geometry shader is one or is not specified, then `InvocationId` will be zero.

The `InvocationId` decoration must be used only within tessellation control and geometry shaders.
The variable decorated with `InvocationId` must be declared using the `Input` storage class.

The variable decorated with `InvocationId` must be declared as a scalar 32-bit integer.

**InstanceIndex**

Decorating a variable in a vertex shader with the `InstanceIndex` built-in decoration will make that variable contain the index of the instance that is being processed by the current vertex shader invocation. `InstanceIndex` begins at the `firstInstance` parameter to `vkCmdDraw` or `vkCmdDrawIndexed` or at the `firstInstance` member of a structure consumed by `vkCmdDrawIndirect` or `vkCmdDrawIndexedIndirect`.

The `InstanceIndex` decoration must be used only within vertex shaders.

The variable decorated with `InstanceIndex` must be declared using the `Input` storage class.

The variable decorated with `InstanceIndex` must be declared as a scalar 32-bit integer.

**LaunchIDKHR**

A variable decorated with the `LaunchIDKHR` decoration will specify the index of the work item being process. One work item is generated for each of the \( \text{width} \times \text{height} \times \text{depth} \) items dispatched by a `vkCmdTraceRaysKHR` command. All shader invocations inherit the same value for variables decorated with `LaunchIDKHR`.

The `LaunchIDKHR` decoration must only be used within the ray generation, intersection, any-hit, closest hit, and miss shaders.

Any variable decorated with `LaunchIDKHR` must be declared using the `Input` storage class.

Any variable decorated with `LaunchIDKHR` must be declared as a three-component vector of 32-bit integer values.

**LaunchSizeKHR**

A variable decorated with the `LaunchSizeKHR` decoration will contain the `width`, `height`, and `depth` dimensions passed to the `vkCmdTraceRaysKHR` command that initiated this shader execution. The `width` is in the first component, the `height` is in the second component, and the `depth` is in the third component.

The `LaunchSizeKHR` decoration must only be used within ray generation, intersection, any-hit, closest hit, and miss shaders.

Any variable decorated with `LaunchSizeKHR` must be declared using the `Input` storage class.

Any variable decorated with `LaunchSizeKHR` must be declared as a three-component vector of 32-bit integer values.

**Layer**

Decorating a variable with the `Layer` built-in decoration will make that variable contain the select layer of a multi-layer framebuffer attachment.

In a geometry shader, any variable decorated with `Layer` can be written with the framebuffer layer index to which the primitive produced by that shader will be directed.
If the last active vertex processing stage shader entry point’s interface does not include a variable decorated with `Layer`, then the first layer is used. If a vertex processing stage shader entry point’s interface includes a variable decorated with `Layer`, it must write the same value to `Layer` for all output vertices of a given primitive. If the `Layer` value is less than 0 or greater than or equal to the number of layers in the framebuffer, then primitives may still be rasterized, fragment shaders may be executed, and the framebuffer values for all layers are undefined.

The `Layer` decoration must be used only within geometry, and fragment shaders.

In a geometry shader, any variable decorated with `Layer` must be declared using the `Output` storage class.

In a fragment shader, a variable decorated with `Layer` contains the layer index of the primitive that the fragment invocation belongs to.

In a fragment shader, any variable decorated with `Layer` must be declared using the `Input` storage class.

Any variable decorated with `Layer` must be declared as a scalar 32-bit integer.

**LocalInvocationId**

Decorating a variable with the `LocalInvocationId` built-in decoration will make that variable contain the location of the current compute shader invocation within the local workgroup. Each component ranges from zero through to the size of the workgroup in that dimension minus one.

The `LocalInvocationId` decoration must be used only within compute shaders.

The variable decorated with `LocalInvocationId` must be declared using the `Input` storage class.

The variable decorated with `LocalInvocationId` must be declared as a three-component vector of 32-bit integers.

**Note**

If the size of the workgroup in a particular dimension is one, then the `LocalInvocationId` in that dimension will be zero. If the workgroup is effectively two-dimensional, then `LocalInvocationId.z` will be zero. If the workgroup is effectively one-dimensional, then both `LocalInvocationId.y` and `LocalInvocationId.z` will be zero.

**LocalInvocationIndex**

Decorating a variable with the `LocalInvocationIndex` built-in decoration will make that variable contain a one-dimensional representation of `LocalInvocationId`. This is computed as:

```
LocalInvocationIndex = 
LocalInvocationId.z * WorkgroupSize.x * WorkgroupSize.y + 
LocalInvocationId.y * WorkgroupSize.x + 
LocalInvocationId.x;
```

The `LocalInvocationIndex` decoration must be used only within compute shaders.
The variable decorated with `LocalInvocationIndex` must be declared using the `Input` storage class.

The variable decorated with `LocalInvocationIndex` must be declared as a scalar 32-bit integer.

**NumSubgroups**

Decorating a variable with the `NumSubgroups` built-in decoration will make that variable contain the number of subgroups in the local workgroup.

The `NumSubgroups` decoration must be used only within compute shaders.

The variable decorated with `NumSubgroups` must be declared using the `Input` storage class.

The object decorated with `NumSubgroups` must be declared as a scalar 32-bit integer.

**NumWorkgroups**

Decorating a variable with the `NumWorkgroups` built-in decoration will make that variable contain the number of local workgroups that are part of the dispatch that the invocation belongs to. Each component is equal to the values of the workgroup count parameters passed into the dispatch commands.

The `NumWorkgroups` decoration must be used only within compute shaders.

The variable decorated with `NumWorkgroups` must be declared using the `Input` storage class.

The variable decorated with `NumWorkgroups` must be declared as a three-component vector of 32-bit integers.

**ObjectRayDirectionKHR**

A variable decorated with the `ObjectRayDirectionKHR` decoration will specify the direction of the ray being processed, in object space.

The `ObjectRayDirectionKHR` decoration must only be used within intersection, any-hit, and closest hit shaders.

Any variable decorated with `ObjectRayDirectionKHR` must be declared using the `Input` storage class.

Any variable decorated with `ObjectRayDirectionKHR` must be declared as a three-component vector of 32-bit floating-point values.

**ObjectRayOriginKHR**

A variable decorated with the `ObjectRayOriginKHR` decoration will specify the origin of the ray being processed, in object space.

The `ObjectRayOriginKHR` decoration must only be used within intersection, any-hit, and closest hit shaders.

Any variable decorated with `ObjectRayOriginKHR` must be declared using the `Input` storage class.

Any variable decorated with `ObjectRayOriginKHR` must be declared as a three-component vector of 32-bit floating-point values.
ObjectToWorldKHR

A variable decorated with the `ObjectToWorldKHR` decoration will contain the current object-to-world transformation matrix, which is determined by the instance of the current intersection.

The `ObjectToWorldKHR` decoration **must** only be used within intersection, any-hit, and closest hit shaders.

Any variable decorated with `ObjectToWorldKHR` **must** be declared using the `Input` storage class.

Any variable decorated with `ObjectToWorldKHR` **must** be declared as a matrix with four columns of three-component vectors of 32-bit floating-point values.

PatchVertices

Decorating a variable with the `PatchVertices` built-in decoration will make that variable contain the number of vertices in the input patch being processed by the shader. A single tessellation control or tessellation evaluation shader can read patches of differing sizes, so the value of the `PatchVertices` variable **may** differ between patches.

The `PatchVertices` decoration **must** be used only within tessellation control and tessellation evaluation shaders.

The variable decorated with `PatchVertices` **must** be declared using the `Input` storage class.

The variable decorated with `PatchVertices` **must** be declared as a scalar 32-bit integer.

PointCoord

Decorating a variable with the `PointCoord` built-in decoration will make that variable contain the coordinate of the current fragment within the point being rasterized, normalized to the size of the point with origin in the upper left corner of the point, as described in Basic Point Rasterization. If the primitive the fragment shader invocation belongs to is not a point, then the variable decorated with `PointCoord` contains an undefined value.

The `PointCoord` decoration **must** be used only within fragment shaders.

The variable decorated with `PointCoord` **must** be declared using the `Input` storage class.

The variable decorated with `PointCoord` **must** be declared as two-component vector of 32-bit floating-point values.

```
Note

Depending on how the point is rasterized, `PointCoord` **may** never reach (0,0) or (1,1).
```

PointSize

Decorating a variable with the `PointSize` built-in decoration will make that variable contain the size of point primitives. The value written to the variable decorated with `PointSize` by the last vertex processing stage in the pipeline is used as the framebuffer-space size of points produced by rasterization.

The `PointSize` decoration **must** be used only within vertex, tessellation control, tessellation
evaluation, and geometry shaders.

In a vertex shader, any variable decorated with **PointSize must** be declared using the **Output** storage class.

In a tessellation control, tessellation evaluation, or geometry shader, any variable decorated with **PointSize must** be declared using either the **Input** or **Output** storage class.

Any variable decorated with **PointSize must** be declared as a scalar 32-bit floating-point value.

```
Note
When **PointSize** decorates a variable in the **Input** storage class, it contains the data written to the output variable decorated with **PointSize** from the previous shader stage.
```

**Position**

Decorating a variable with the **Position** built-in decoration will make that variable contain the position of the current vertex. In the last vertex processing stage, the value of the variable decorated with **Position** is used in subsequent primitive assembly, clipping, and rasterization operations.

The **Position** decoration **must** be used only within vertex, tessellation control, tessellation evaluation, and geometry shaders.

In a vertex shader, any variable decorated with **Position must** be declared using the **Output** storage class.

In a tessellation control, tessellation evaluation, or geometry shader, any variable decorated with **Position must** not be declared in a storage class other than **Input** or **Output**.

Any variable decorated with **Position must** be declared as a four-component vector of 32-bit floating-point values.

```
Note
When **Position** decorates a variable in the **Input** storage class, it contains the data written to the output variable decorated with **Position** from the previous shader stage.
```

**PrimitiveId**

Decorating a variable with the **PrimitiveId** built-in decoration will make that variable contain the index of the current primitive.

The index of the first primitive generated by a drawing command is zero, and the index is incremented after every individual point, line, or triangle primitive is processed.

For triangles drawn as points or line segments (see **Polygon Mode**), the primitive index is incremented only once, even if multiple points or lines are eventually drawn.

Variables decorated with **PrimitiveId** are reset to zero between each instance drawn.
Restarting a primitive topology using primitive restart has no effect on the value of variables decorated with `PrimitiveId`.

In tessellation control and tessellation evaluation shaders, it will contain the index of the patch within the current set of rendering primitives that correspond to the shader invocation.

In a geometry shader, it will contain the number of primitives presented as input to the shader since the current set of rendering primitives was started.

In a fragment shader, it will contain the primitive index written by the geometry shader if a geometry shader is present, or with the value that would have been presented as input to the geometry shader had it been present.

In an intersection, any-hit, or closest hit shader, it will contain the index within the geometry of the triangle or bounding box being processed.

If a geometry shader is present and the fragment shader reads from an input variable decorated with `PrimitiveId`, then the geometry shader must write to an output variable decorated with `PrimitiveId` in all execution paths.

The `PrimitiveId` decoration must be used only within intersection, any-hit, closest hit, fragment, tessellation control, tessellation evaluation, and geometry shaders.

In an intersection, any-hit, closest hit, a tessellation control, or tessellation evaluation shader, any variable decorated with `PrimitiveId` must be declared using the `Input` storage class.

In a geometry shader, any variable decorated with `PrimitiveId` must be declared using either the `Input` or `Output` storage class.

In a fragment shader, any variable decorated with `PrimitiveId` must be declared using the `Input` storage class, and either the `Geometry` or `Tessellation` capability must also be declared.

Any variable decorated with `PrimitiveId` must be declared as a scalar 32-bit integer.

### Note
When the `PrimitiveId` decoration is applied to an output variable in the geometry shader, the resulting value is seen through the `PrimitiveId` decorated input variable in the fragment shader.

`RayGeometryIndexKHR`

A variable decorated with the `RayGeometryIndexKHR` decoration will contain the generated index for the acceleration structure geometry currently being shaded.

The `RayGeometryIndexKHR` decoration must only be used within intersection, any-hit, and closest hit shaders.

Any variable decorated with `RayGeometryIndexKHR` must be declared using the `Input` storage class.

Any variable decorated with `RayGeometryIndexKHR` must be declared as a scalar 32-bit integer value.
**RayTmaxKHR**

A variable decorated with the `RayTmaxKHR` decoration will contain the parametric $t_{\text{max}}$ values of the ray being processed. The values are independent of the space in which the ray and origin exist.

The $t_{\text{max}}$ value changes throughout the lifetime of the ray query that produced the intersection. In the closest hit shader, the value reflects the closest distance to the intersected primitive. In the any-hit shader, it reflects the distance to the primitive currently being intersected. In the intersection shader, it reflects the distance to the closest primitive intersected so far. The value can change in the intersection shader after calling `OpReportIntersectionKHR` if the corresponding any-hit shader does not ignore the intersection. In a miss shader, the value is identical to the parameter passed into `OpTraceRayKHR`.

The `RayTmaxKHR` decoration **must** only be used with the intersection, any-hit, closest hit, and miss shaders.

Any variable decorated with `RayTmaxKHR` **must** be declared with the `Input` storage class.

Any variable decorated with `RayTmaxKHR` **must** be declared as a scalar 32-bit floating-point value.

**RayTminKHR**

A variable decorated with the `RayTminKHR` decoration will contain the parametric $t_{\text{min}}$ values of the ray being processed. The values are independent of the space in which the ray and origin exist.

The $t_{\text{min}}$ value remains constant for the duration of the ray query.

The `RayTminKHR` decoration **must** only be used with the intersection, any-hit, closest hit, and miss shaders.

Any variable decorated with `RayTminKHR` **must** be declared with the `Input` storage class.

Any variable decorated with `RayTminKHR` **must** be declared as a scalar 32-bit floating-point value.

**SampleId**

Decorating a variable with the `SampleId` built-in decoration will make that variable contain the zero-based index of the sample the invocation corresponds to. `SampleId` ranges from zero to the number of samples in the framebuffer minus one. If a fragment shader entry point’s interface includes an input variable decorated with `SampleId`, **Sample Shading** is considered enabled with a `minSampleShading` value of 1.0.

The `SampleId` decoration **must** be used only within fragment shaders.

The variable decorated with `SampleId` **must** be declared using the `Input` storage class.

The variable decorated with `SampleId` **must** be declared as a scalar 32-bit integer.

**SampleMask**

Decorating a variable with the `SampleMask` built-in decoration will make any variable contain the sample coverage mask for the current fragment shader invocation.

A variable in the `Input` storage class decorated with `SampleMask` will contain a bitmask of the set...
of samples covered by the primitive generating the fragment during rasterization. It has a sample bit set if and only if the sample is considered covered for this fragment shader invocation. SampleMask[] is an array of integers. Bits are mapped to samples in a manner where bit B of mask M (SampleMask[M]) corresponds to sample $32 \times M + B$.

When state specifies multiple fragment shader invocations for a given fragment, the sample mask for any single fragment shader invocation specifies the subset of the covered samples for the fragment that correspond to the invocation. In this case, the bit corresponding to each covered sample will be set in exactly one fragment shader invocation.

A variable in the Output storage class decorated with SampleMask is an array of integers forming a bit array in a manner similar an input variable decorated with SampleMask, but where each bit represents coverage as computed by the shader. Modifying the sample mask by writing zero to a bit of SampleMask causes the sample to be considered uncovered. However, setting sample mask bits to one will never enable samples not covered by the original primitive. If the fragment shader is being evaluated at any frequency other than per-fragment, bits of the sample mask not corresponding to the current fragment shader invocation are ignored. This array must be sized in the fragment shader either implicitly or explicitly, to be no larger than the implementation-dependent maximum sample-mask (as an array of 32-bit elements), determined by the maximum number of samples. If a fragment shader entry point's interface includes an output variable decorated with SampleMask, the sample mask will be undefined for any array elements of any fragment shader invocations that fail to assign a value. If a fragment shader entry point's interface does not include an output variable decorated with SampleMask, the sample mask has no effect on the processing of a fragment.

The SampleMask decoration must be used only within fragment shaders.

Any variable decorated with SampleMask must be declared using either the Input or Output storage class.

Any variable decorated with SampleMask must be declared as an array of 32-bit integers.

SamplePosition

Decorating a variable with the SamplePosition built-in decoration will make that variable contain the sub-pixel position of the sample being shaded. The top left of the pixel is considered to be at coordinate (0,0) and the bottom right of the pixel is considered to be at coordinate (1,1).

+ If a fragment shader entry point's interface includes an input variable decorated with SamplePosition, Sample Shading is considered enabled with a minSampleShading value of 1.0.

+ The SamplePosition decoration must be used only within fragment shaders.

+ The variable decorated with SamplePosition must be declared using the Input storage class.

+ The variable decorated with SamplePosition must be declared as a two-component vector of 32-bit floating-point values.

SubgroupId

Decorating a variable with the SubgroupId built-in decoration will make that variable contain the index of the subgroup within the local workgroup. This variable is in range [0, NumSubgroups-1].
The `SubgroupId` decoration **must** be used only within compute shaders.

The variable decorated with `SubgroupId` **must** be declared using the `Input` storage class.

The variable decorated with `SubgroupId` **must** be declared as a scalar 32-bit integer.

**SubgroupEqMask**

Decorating a variable with the `SubgroupEqMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bit corresponding to the `SubgroupLocalInvocationId` is set in the variable decorated with `SubgroupEqMask`. All other bits are set to zero.

The variable decorated with `SubgroupEqMask` **must** be declared using the `Input` storage class.

The variable decorated with `SubgroupEqMask` **must** be declared as a four-component vector of 32-bit integer values.

`SubgroupEqMaskKHR` is an alias of `SubgroupEqMask`.

**SubgroupGeMask**

Decorating a variable with the `SubgroupGeMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bits corresponding to the invocations greater than or equal to `SubgroupLocalInvocationId` through `SubgroupSize-1` are set in the variable decorated with `SubgroupGeMask`. All other bits are set to zero.

The variable decorated with `SubgroupGeMask` **must** be declared using the `Input` storage class.

The variable decorated with `SubgroupGeMask` **must** be declared as a four-component vector of 32-bit integer values.

`SubgroupGeMaskKHR` is an alias of `SubgroupGeMask`.

**SubgroupGtMask**

Decorating a variable with the `SubgroupGtMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bits corresponding to the invocations greater than `SubgroupLocalInvocationId` through `SubgroupSize-1` are set in the variable decorated with `SubgroupGtMask`. All other bits are set to zero.

The variable decorated with `SubgroupGtMask` **must** be declared using the `Input` storage class.

The variable decorated with `SubgroupGtMask` **must** be declared as a four-component vector of 32-bit integer values.

`SubgroupGtMaskKHR` is an alias of `SubgroupGtMask`.

**SubgroupLeMask**

Decorating a variable with the `SubgroupLeMask` builtin decoration will make that variable contain the *subgroup mask* of the current subgroup invocation. The bits corresponding to the invocations less than or equal to `SubgroupLocalInvocationId` are set in the variable decorated with `SubgroupLeMask`. All other bits are set to zero.

The variable decorated with `SubgroupLeMask` **must** be declared using the `Input` storage class.

The variable decorated with `SubgroupLeMask` **must** be declared as a four-component vector of 32-bit integer values.

`SubgroupLeMaskKHR` is an alias of `SubgroupLeMask`. 
The variable decorated with `SubgroupLeMask` must be declared as a four-component vector of 32-bit integer values.

`SubgroupLeMaskKHR` is an alias of `SubgroupLeMask`.

`SubgroupLtMask`

Decorating a variable with the `SubgroupLtMask` builtin decoration will make that variable contain the subgroup mask of the current subgroup invocation. The bits corresponding to the invocations less than `SubgroupLocalInvocationId` are set in the variable decorated with `SubgroupLtMask`. All other bits are set to zero.

The variable decorated with `SubgroupLtMask` must be declared using the `Input` storage class.

The variable decorated with `SubgroupLtMask` must be declared as a four-component vector of 32-bit integer values.

`SubgroupLtMaskKHR` is an alias of `SubgroupLtMask`.

`SubgroupLocalInvocationId`

Decorating a variable with the `SubgroupLocalInvocationId` builtin decoration will make that variable contain the index of the invocation within the subgroup. This variable is in range `[0,SubgroupSize-1]`.

The variable decorated with `SubgroupLocalInvocationId` must be declared using the `Input` storage class.

The variable decorated with `SubgroupLocalInvocationId` must be declared as a scalar 32-bit integer.

Note

There is no direct relationship between `SubgroupLocalInvocationId` and `LocalInvocationId` or `LocalInvocationIndex`.

`SubgroupSize`

Decorating a variable with the `SubgroupSize` builtin decoration will make that variable contain the implementation-dependent number of invocations in a subgroup. This value must be a power-of-two integer.

The variable decorated with `SubgroupSize` will match `subgroupSize`.

The maximum number of invocations that an implementation can support per subgroup is 128.

The variable decorated with `SubgroupSize` must be declared using the `Input` storage class.

The variable decorated with `SubgroupSize` must be declared as a scalar 32-bit integer.

`TessCoord`

Decorating a variable with the `TessCoord` built-in decoration will make that variable contain the three-dimensional (u,v,w) barycentric coordinate of the tessellated vertex within the patch. u, v, and w are in the range `[0,1]` and vary linearly across the primitive being subdivided. For the tessellation modes of `Quads` or `IsoLines`, the third component is always zero.
The **TessCoord** decoration must be used only within tessellation evaluation shaders.

The variable decorated with **TessCoord** must be declared using the **Input** storage class.

The variable decorated with **TessCoord** must be declared as three-component vector of 32-bit floating-point values.

**TessLevelOuter**

Decorating a variable with the **TessLevelOuter** built-in decoration will make that variable contain the outer tessellation levels for the current patch.

In tessellation control shaders, the variable decorated with **TessLevelOuter** can be written to, which controls the tessellation factors for the resulting patch. These values are used by the tessellator to control primitive tessellation and can be read by tessellation evaluation shaders.

In tessellation evaluation shaders, the variable decorated with **TessLevelOuter** can read the values written by the tessellation control shader.

The **TessLevelOuter** decoration must be used only within tessellation control and tessellation evaluation shaders.

In a tessellation control shader, any variable decorated with **TessLevelOuter** must be declared using the **Output** storage class.

In a tessellation evaluation shader, any variable decorated with **TessLevelOuter** must be declared using the **Input** storage class.

Any variable decorated with **TessLevelOuter** must be declared as an array of size four, containing 32-bit floating-point values.

**TessLevelInner**

Decorating a variable with the **TessLevelInner** built-in decoration will make that variable contain the inner tessellation levels for the current patch.

In tessellation control shaders, the variable decorated with **TessLevelInner** can be written to, which controls the tessellation factors for the resulting patch. These values are used by the tessellator to control primitive tessellation and can be read by tessellation evaluation shaders.

In tessellation evaluation shaders, the variable decorated with **TessLevelInner** can read the values written by the tessellation control shader.

The **TessLevelInner** decoration must be used only within tessellation control and tessellation evaluation shaders.

In a tessellation control shader, any variable decorated with **TessLevelInner** must be declared using the **Output** storage class.

In a tessellation evaluation shader, any variable decorated with **TessLevelInner** must be declared using the **Input** storage class.

Any variable decorated with **TessLevelInner** must be declared as an array of size two, containing
32-bit floating-point values.

**VertexIndex**

Decorating a variable with the `VertexIndex` built-in decoration will make that variable contain the index of the vertex that is being processed by the current vertex shader invocation. For non-indexed draws, this variable begins at the `firstVertex` parameter to `vkCmdDraw` or the `firstVertex` member of a structure consumed by `vkCmdDrawIndirect` and increments by one for each vertex in the draw. For indexed draws, its value is the content of the index buffer for the vertex plus the `vertexOffset` parameter to `vkCmdDrawIndexed` or the `vertexOffset` member of the structure consumed by `vkCmdDrawIndexedIndirect`.

The `VertexIndex` decoration **must** be used only within vertex shaders.

The variable decorated with `VertexIndex` **must** be declared using the `Input` storage class.

The variable decorated with `VertexIndex` **must** be declared as a scalar 32-bit integer.

*Note*

`VertexIndex` starts at the same starting value for each instance.

**ViewIndex**

The `ViewIndex` decoration **can** be applied to a shader input which will be filled with the index of the view that is being processed by the current shader invocation.

If multiview is enabled in the render pass, this value will be one of the bits set in the view mask of the subpass the pipeline is compiled against. If multiview is not enabled in the render pass, this value will be zero.

The `ViewIndex` decoration **must** not be used within compute shaders.

The variable decorated with `ViewIndex` **must** be declared using the `Input` storage class.

The variable decorated with `ViewIndex` **must** be declared as a scalar 32-bit integer.

**ViewportIndex**

Decorating a variable with the `ViewportIndex` built-in decoration will make that variable contain the index of the viewport.

In a geometry shader, the variable decorated with `ViewportIndex` can be written to with the viewport index to which the primitive produced by that shader will be directed.

The selected viewport index is used to select the viewport transform and scissor rectangle.

If the last active vertex processing stage shader entry point's interface does not include a variable decorated with `ViewportIndex`, then the first viewport is used. If a vertex processing stage shader entry point's interface includes a variable decorated with `ViewportIndex`, it **must** write the same value to `ViewportIndex` for all output vertices of a given primitive.

The `ViewportIndex` decoration **must** be used only within geometry, and fragment shaders.

In a geometry shader, any variable decorated with `ViewportIndex` **must** be declared using the
Output storage class.

In a fragment shader, the variable decorated with `ViewportIndex` contains the viewport index of the primitive that the fragment invocation belongs to.

In a fragment shader, any variable decorated with `ViewportIndex` **must** be declared using the `Input` storage class.

Any variable decorated with `ViewportIndex` **must** be declared as a scalar 32-bit integer.

**WorkgroupId**

Decorating a variable with the `WorkgroupId` built-in decoration will make that variable contain the global workgroup that the current invocation is a member of. Each component ranges from a base value to a base + count value, based on the parameters passed into the dispatch commands.

The `WorkgroupId` decoration **must** be used only within compute shaders.

The variable decorated with `WorkgroupId` **must** be declared using the `Input` storage class.

The variable decorated with `WorkgroupId` **must** be declared as a three-component vector of 32-bit integers.

**WorkgroupSize**

Decorating an object with the `WorkgroupSize` built-in decoration will make that object contain the dimensions of a local workgroup. If an object is decorated with the `WorkgroupSize` decoration, this **must** take precedence over any execution mode set for `LocalSize`.

The `WorkgroupSize` decoration **must** be used only within compute shaders.

The object decorated with `WorkgroupSize` **must** be a specialization constant or a constant.

The object decorated with `WorkgroupSize` **must** be declared as a three-component vector of 32-bit integers.

**WorldRayDirectionKHR**

A variable decorated with the `WorldRayDirectionKHR` decoration will specify the direction of the ray being processed, in world space.

The `WorldRayDirectionKHR` decoration **must** only be used within intersection, any-hit, closest hit, and miss shaders.

Any variable decorated with `WorldRayDirectionKHR` **must** be declared using the `Input` storage class.

Any variable decorated with `WorldRayDirectionKHR` **must** be declared as a three-component vector of 32-bit floating-point values.

**WorldRayOriginKHR**

A variable decorated with the `WorldRayOriginKHR` decoration will specify the origin of the ray being processed, in world space.

The `WorldRayOriginKHR` decoration **must** only be used within intersection, any-hit, closest hit, and miss shaders.
miss shaders.

Any variable decorated with `WorldRayOriginKHR` must be declared using the `Input` storage class.

Any variable decorated with `WorldRayOriginKHR` must be declared as a three-component vector of 32-bit floating-point values.

**WorldToObjectKHR**

A variable decorated with the `WorldToObjectKHR` decoration will contain the current world-to-object transformation matrix, which is determined by the instance of the current intersection.

The `WorldToObjectKHR` decoration must only be used within intersection, any-hit, and closest hit shaders.

Any variable decorated with `WorldToObjectKHR` must be declared using the `Input` storage class.

Any variable decorated with `WorldToObjectKHR` must be declared as a matrix with four columns of three-component vectors of 32-bit floating-point values.
Chapter 15. Image Operations

15.1. Image Operations Overview

Vulkan Image Operations are operations performed by those SPIR-V Image Instructions which take an OpTypeImage (representing a VkImageView) or OpTypeSampledImage (representing a (VkImageView, VkSampler) pair) and texel coordinates as operands, and return a value based on one or more neighboring texture elements (texels) in the image.

*Note*

Texel is a term which is a combination of the words texture and element. Early interactive computer graphics supported texture operations on textures, a small subset of the image operations on images described here. The discrete samples remain essentially equivalent, however, so we retain the historical term texel to refer to them.

Image Operations include the functionality of the following SPIR-V Image Instructions:

- OpImageSample and OpImageSparseSample read one or more neighboring texels of the image, and filter the texel values based on the state of the sampler.
  - Instructions with ImplicitLod in the name determine the LOD used in the sampling operation based on the coordinates used in neighboring fragments.
  - Instructions with ExplicitLod in the name determine the LOD used in the sampling operation based on additional coordinates.
  - Instructions with Proj in the name apply homogeneous projection to the coordinates.
- OpImageFetch and OpImageSparseFetch return a single texel of the image. No sampler is used.
- OpImage*Gather and OpImageSparse*Gather read neighboring texels and return a single component of each.
- OpImageRead (and OpImageSparseRead) and OpImageWrite read and write, respectively, a texel in the image. No sampler is used.
- Instructions with Dref in the name apply depth comparison on the texel values.
- Instructions with Sparse in the name additionally return a sparse residency code.

15.1.1. Texel Coordinate Systems

Images are addressed by texel coordinates. There are three texel coordinate systems:

- normalized texel coordinates [0.0, 1.0]
- unnormalized texel coordinates [0.0, width / height / depth]
- integer texel coordinates [0, width / height / depth]

unnormalized texel coordinates (selected by the `unnormalizedCoordinates` state of the sampler used in the instruction), but there are limitations on what operations, image state, and sampler state is supported. Normalized coordinates are logically converted to unnormalized as part of image operations, and certain steps are only performed on normalized coordinates. The array layer coordinate is always treated as unnormalized even when other coordinates are normalized.

Normalized texel coordinates are referred to as \((s,t,r,q,a)\), with the coordinates having the following meanings:

- **s**: Coordinate in the first dimension of an image.
- **t**: Coordinate in the second dimension of an image.
- **r**: Coordinate in the third dimension of an image.
  - \((s,t,r)\) are interpreted as a direction vector for Cube images.
- **q**: Fourth coordinate, for homogeneous (projective) coordinates.
- **a**: Coordinate for array layer.

The coordinates are extracted from the SPIR-V operand based on the dimensionality of the image variable and type of instruction. For `Proj` instructions, the components are in order \((s \[,t\] \[,r\] q)\), with \(t\) and \(r\) being conditionally present based on the `Dim` of the image. For non-`Proj` instructions, the coordinates are \((s \[,t\] \[,r\] \[,a\])\), with \(t\) and \(r\) being conditionally present based on the `Dim` of the image and \(a\) being conditionally present based on the `Arrayed` property of the image. Projective image instructions are not supported on `Arrayed` images.

Unnormalized texel coordinates are referred to as \((u,v,w,a)\), with the coordinates having the following meanings:

- **u**: Coordinate in the first dimension of an image.
- **v**: Coordinate in the second dimension of an image.
- **w**: Coordinate in the third dimension of an image.
- **a**: Coordinate for array layer.

Only the \(u\) and \(v\) coordinates are directly extracted from the SPIR-V operand, because only 1D and 2D (non-`Arrayed`) dimensionalities support unnormalized coordinates. The components are in order \((u \[,v\])\), with \(v\) being conditionally present when the dimensionality is 2D. When normalized coordinates are converted to unnormalized coordinates, all four coordinates are used.

Integer texel coordinates are referred to as \((i,j,k,l,n)\), with the coordinates having the following meanings:

- **i**: Coordinate in the first dimension of an image.
- **j**: Coordinate in the second dimension of an image.
- **k**: Coordinate in the third dimension of an image.
- **l**: Coordinate for array layer.
- **n**: Coordinate for the sample index.
They are extracted from the SPIR-V operand in order \( (i, j, k, l) \), with \( j \) and \( k \) conditionally present based on the \( \text{Dim} \) of the image, and \( l \) conditionally present based on the \( \text{Arrayed} \) property of the image. \( n \) is conditionally present and is taken from the \( \text{Sample} \) image operand.

For all coordinate types, unused coordinates are assigned a value of zero.

*Figure 3. Texel Coordinate Systems, Linear Filtering*

The Texel Coordinate Systems - For the example shown of an \( 8 \times 4 \) texel two dimensional image.

- **Normalized texel coordinates:**
  - The \( s \) coordinate goes from 0.0 to 1.0.
  - The \( t \) coordinate goes from 0.0 to 1.0.

- **Unnormalized texel coordinates:**
  - The \( u \) coordinate within the range 0.0 to 8.0 is within the image, otherwise it is outside the image.
  - The \( v \) coordinate within the range 0.0 to 4.0 is within the image, otherwise it is outside the image.

- **Integer texel coordinates:**
  - The \( i \) coordinate within the range 0 to 7 addresses texels within the image, otherwise it is outside the image.
  - The \( j \) coordinate within the range 0 to 3 addresses texels within the image, otherwise it is outside the image.

- **Also shown for linear filtering:**
  - Given the unnormalized coordinates \( (u,v) \), the four texels selected are \( i_0j_0, i_1j_0, i_0j_1, \) and \( i_1j_1 \).
  - The fractions \( \alpha \) and \( \beta \).
  - Given the offset \( \Delta_i \) and \( \Delta_j \), the four texels selected by the offset are \( i_0j_0', i_1j_0', i_0j_1', \) and \( i_1j_1' \).
For formats with reduced-resolution channels, \( \Delta_i \) and \( \Delta_j \) are relative to the resolution of the highest-resolution channel, and therefore may be divided by two relative to the unnormalized coordinate space of the lower-resolution channels.

![Texel Coordinate Systems, Nearest Filtering](image)

The Texel Coordinate Systems - For the example shown of an 8×4 texel two dimensional image.

- Texel coordinates as above. Also shown for nearest filtering:
  - Given the unnormalized coordinates \((u,v)\), the texel selected is \(ij\).
  - Given the offset \(\Delta_i\) and \(\Delta_j\), the texel selected by the offset is \(ij'\).

### 15.2. Conversion Formulas

#### 15.2.1. RGB to Shared Exponent Conversion

An RGB color (red, green, blue) is transformed to a shared exponent color \((\text{red}_{\text{shared}}, \text{green}_{\text{shared}}, \text{blue}_{\text{shared}}, \exp_{\text{shared}})\) as follows:

First, the components (red, green, blue) are clamped to \((\text{red}_{\text{clamped}}, \text{green}_{\text{clamped}}, \text{blue}_{\text{clamped}})\) as:

\[
\begin{align*}
\text{red}_{\text{clamped}} &= \max(0, \min(\exp_{\text{max}}, \text{red})) \\
\text{green}_{\text{clamped}} &= \max(0, \min(\exp_{\text{max}}, \text{green})) \\
\text{blue}_{\text{clamped}} &= \max(0, \min(\exp_{\text{max}}, \text{blue}))
\end{align*}
\]

where:
The largest clamped component, \( \text{max}_\text{clamped} \) is determined:

\[
\text{max}_\text{clamped} = \max(\text{red}_\text{clamped}, \text{green}_\text{clamped}, \text{blue}_\text{clamped})
\]

A preliminary shared exponent \( \exp' \) is computed:

\[
\exp' = \begin{cases} 
\lfloor \log_2(\text{max}_\text{clamped}) \rfloor + (B + 1) & \text{for } \text{max}_\text{clamped} > 2^{-(B + 1)} \\
0 & \text{for } \text{max}_\text{clamped} \leq 2^{-(B + 1)} 
\end{cases}
\]

The shared exponent \( \exp_{\text{shared}} \) is computed:

\[
\exp_{\text{shared}} = \begin{cases} 
\exp' & \text{for } 0 \leq \exp_{\text{shared}} < 2^N \\
\exp' + 1 & \text{for } \exp_{\text{shared}} = 2^N 
\end{cases}
\]

Finally, three integer values in the range 0 to \( 2^N \) are computed:

\[
\begin{align*}
\text{red}_{\text{shared}} &= \lfloor \frac{\text{red}_\text{clamped}}{2^{(\exp_{\text{shared}} - B - N)}} + \frac{1}{2} \rfloor \\
\text{green}_{\text{shared}} &= \lfloor \frac{\text{green}_\text{clamped}}{2^{(\exp_{\text{shared}} - B - N)}} + \frac{1}{2} \rfloor \\
\text{blue}_{\text{shared}} &= \lfloor \frac{\text{blue}_\text{clamped}}{2^{(\exp_{\text{shared}} - B - N)}} + \frac{1}{2} \rfloor
\end{align*}
\]

15.2.2. Shared Exponent to RGB

A shared exponent color \((\text{red}_{\text{shared}}, \text{green}_{\text{shared}}, \text{blue}_{\text{shared}}, \exp_{\text{shared}})\) is transformed to an RGB color \((\text{red}, \text{green}, \text{blue})\) as follows:

\[
\begin{align*}
\text{red} &= \text{red}_{\text{shared}} \times 2^{(\exp_{\text{shared}} - B - N)} \\
\text{green} &= \text{green}_{\text{shared}} \times 2^{(\exp_{\text{shared}} - B - N)} \\
\text{blue} &= \text{blue}_{\text{shared}} \times 2^{(\exp_{\text{shared}} - B - N)}
\end{align*}
\]

where:

\[N = 9 \text{ (number of mantissa bits per component)}\]
15.3. Texel Input Operations

 Texel input instructions are SPIR-V image instructions that read from an image. Texel input operations are a set of steps that are performed on state, coordinates, and texel values while processing a texel input instruction, and which are common to some or all texel input instructions. They include the following steps, which are performed in the listed order:

- Validation operations
  - Instruction/Sampler/Image validation
  - Coordinate validation
  - Sparse validation
  - Layout validation

- Format conversion
- Texel replacement
- Depth comparison
- Conversion to RGBA
- Component swizzle
- Chroma reconstruction
- \( Y'C_bC_r \) conversion

For texel input instructions involving multiple texels (for sampling or gathering), these steps are applied for each texel that is used in the instruction. Depending on the type of image instruction, other steps are conditionally performed between these steps or involving multiple coordinate or texel values.

If Chroma Reconstruction is implicit, Texel Filtering instead takes place during chroma reconstruction, before sampler \( Y'C_bC_r \) conversion occurs.

15.3.1. Texel Input Validation Operations

 Texel input validation operations inspect instruction/image/sampler state or coordinates, and in certain circumstances cause the texel value to be replaced or become undefined. There are a series of validations that the texel undergoes.

**Instruction/Sampler/Image View Validation**

There are a number of cases where a SPIR-V instruction can mismatch with the sampler, the image view, or both. There are a number of cases where the sampler can mismatch with the image view. In such cases the value of the texel returned is undefined.

These cases include:
• The sampler borderColor is an integer type and the image view format is not one of the VkFormat integer types or a stencil component of a depth/stencil format.

• The sampler borderColor is a float type and the image view format is not one of the VkFormat float types or a depth component of a depth/stencil format.

• The sampler borderColor is one of the opaque black colors (VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK or VK_BORDER_COLOR_INT_OPAQUE_BLACK) and the image view VkComponentSwizzle for any of the VkComponentMapping components is not VK_COMPONENT_SWIZZLE_IDENTITY.

• The VkImageLayout of any subresource in the image view does not match that specified in VkDescriptorImageInfo::imageLayout used to write the image descriptor.

• If the instruction is OpImageRead or OpImageSparseRead and the shaderStorageImageReadWithoutFormat feature is not enabled, or the instruction is OpImageWrite and the shaderStorageImageWriteWithoutFormat feature is not enabled, then the SPIR-V Image Format must be compatible with the image view's format.

• The sampler unnormalizedCoordinates is VK_TRUE and any of the limitations of unnormalized coordinates are violated.

• The SPIR-V instruction is one of the OpImage*Dref* instructions and the sampler compareEnable is VK_FALSE

• The SPIR-V instruction is not one of the OpImage*Dref* instructions and the sampler compareEnable is VK_TRUE

• The SPIR-V instruction is one of the OpImage*Dref* instructions and the image view format is not one of the depth/stencil formats with a depth component, or the image view aspect is not VK_IMAGE_ASPECT_DEPTH_BIT.

• The SPIR-V instruction's image variable's properties are not compatible with the image view:
  - Rules for viewType:
    - VK_IMAGE_VIEW_TYPE_1D must have Dim = 1D, Arrayed = 0, MS = 0.
    - VK_IMAGE_VIEW_TYPE_2D must have Dim = 2D, Arrayed = 0.
    - VK_IMAGE_VIEW_TYPE_3D must have Dim = 3D, Arrayed = 0, MS = 0.
    - VK_IMAGE_VIEW_TYPE_CUBE must have Dim = Cube, Arrayed = 0, MS = 0.
    - VK_IMAGE_VIEW_TYPE_1D_ARRAY must have Dim = 1D, Arrayed = 1, MS = 0.
    - VK_IMAGE_VIEW_TYPE_2D_ARRAY must have Dim = 2D, Arrayed = 1.
    - VK_IMAGE_VIEW_TYPE_CUBE_ARRAY must have Dim = Cube, Arrayed = 1, MS = 0.
  - If the image was created with VkImageCreateInfo::samples equal to VK_SAMPLE_COUNT_1_BIT, the instruction must have MS = 0.
  - If the image was created with VkImageCreateInfo::samples not equal to VK_SAMPLE_COUNT_1_BIT, the instruction must have MS = 1.

Only OpImageSample* and OpImageSparseSample* can be used with a sampler that enables sampler Y’CbCr conversion.

OpImageFetch, OpImageSparseFetch, OpImage*Gather, and OpImageSparse*Gather must not be used with a sampler that enables sampler Y’CbCr conversion.
The `ConstOffset` and `Offset` operands must not be used with a sampler that enables sampler $Y'CB_{R}$ conversion.

**Integer Texel Coordinate Validation**

Integer texel coordinates are validated against the size of the image level, and the number of layers and number of samples in the image. For SPIR-V instructions that use integer texel coordinates, this is performed directly on the integer coordinates. For instructions that use normalized or unnormalized texel coordinates, this is performed on the coordinates that result after conversion to integer texel coordinates.

If the integer texel coordinates do not satisfy all of the conditions

\[
\begin{align*}
0 & \leq i < w_s \\
0 & \leq j < h_s \\
0 & \leq k < d_s \\
0 & \leq l < \text{layers} \\
0 & \leq n < \text{samples}
\end{align*}
\]

where:

\[
\begin{align*}
w_s & = \text{width of the image level} \\
h_s & = \text{height of the image level} \\
d_s & = \text{depth of the image level} \\
\text{layers} & = \text{number of layers in the image} \\
\text{samples} & = \text{number of samples per texel in the image}
\end{align*}
\]

then the texel fails integer texel coordinate validation.

There are four cases to consider:

1. **Valid Texel Coordinates**
   - If the texel coordinates pass validation (that is, the coordinates lie within the image), then the texel value comes from the value in image memory.

2. **Border Texel**
   - If the texel coordinates fail validation, and
     - If the read is the result of an image sample instruction or image gather instruction, and
If the image is not a cube image,
then the texel is a border texel and texel replacement is performed.

3. Invalid Texel

- If the texel coordinates fail validation, and
- If the read is the result of an image fetch instruction, image read instruction, or atomic instruction,

then the texel is an invalid texel and texel replacement is performed.

4. Cube Map Edge or Corner

Otherwise the texel coordinates lie beyond the edges or corners of the selected cube map face, and Cube map edge handling is performed.

Cube Map Edge Handling

If the texel coordinates lie beyond the edges or corners of the selected cube map face, the following steps are performed. Note that this does not occur when using VK_FILTER_NEAREST filtering within a mip level, since VK_FILTER_NEAREST is treated as using VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE.

- Cube Map Edge Texel
  - If the texel lies beyond the selected cube map face in either only i or only j, then the coordinates (i,j) and the array layer l are transformed to select the adjacent texel from the appropriate neighboring face.

- Cube Map Corner Texel
  - If the texel lies beyond the selected cube map face in both i and j, then there is no unique neighboring face from which to read that texel. The texel should be replaced by the average of the three values of the adjacent texels in each incident face. However, implementations may replace the cube map corner texel by other methods. The methods are subject to the constraint that if the three available texels have the same value, the resulting filtered texel must have that value.

Sparse Validation

If the texel reads from an unbound region of a sparse image, the texel is a sparse unbound texel, and processing continues with texel replacement.

Layout Validation

If all planes of a disjoint multi-planar image are not in the same image layout, the image must not be sampled with sampler Y’C_bC_a conversion enabled.

15.3.2. Format Conversion

Texels undergo a format conversion from the VkFormat of the image view to a vector of either floating point or signed or unsigned integer components, with the number of components based on
the number of components present in the format.

- Color formats have one, two, three, or four components, according to the format.
- Depth/stencil formats are one component. The depth or stencil component is selected by the `aspectMask` of the image view.

Each component is converted based on its type and size (as defined in the Format Definition section for each `VkFormat`), using the appropriate equations in 16-Bit Floating-Point Numbers, Unsigned 11-Bit Floating-Point Numbers, Unsigned 10-Bit Floating-Point Numbers, Fixed-Point Data Conversion, and Shared Exponent to RGB. Signed integer components smaller than 32 bits are sign-extended.

If the image view format is sRGB, the color components are first converted as if they are UNORM, and then sRGB to linear conversion is applied to the R, G, and B components as described in the “sRGB EOTF” section of the Khronos Data Format Specification. The A component, if present, is unchanged.

If the image view format is block-compressed, then the texel value is first decoded, then converted based on the type and number of components defined by the compressed format.

### 15.3.3. Texel Replacement

A texel is replaced if it is one (and only one) of:

- a border texel,
- an invalid texel, or
- a sparse unbound texel.

Border texels are replaced with a value based on the image format and the `borderColor` of the sampler. The border color is:

**Table 19. Border Color B**

<table>
<thead>
<tr>
<th>Sampler</th>
<th>borderColor</th>
<th>Corresponding Border Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK</td>
<td>([B_r, B_g, B_b, B_a]) = [0.0, 0.0, 0.0, 0.0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK</td>
<td>([B_r, B_g, B_b, B_a]) = [0.0, 0.0, 0.0, 1.0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE</td>
<td>([B_r, B_g, B_b, B_a]) = [1.0, 1.0, 1.0, 1.0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_TRANSPARENT_BLACK</td>
<td>([B_r, B_g, B_b, B_a]) = [0, 0, 0, 0]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_OPAQUE_BLACK</td>
<td>([B_r, B_g, B_b, B_a]) = [0, 0, 0, 1]</td>
<td></td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_OPAQUE_WHITE</td>
<td>([B_r, B_g, B_b, B_a]) = [1, 1, 1, 1]</td>
<td></td>
</tr>
</tbody>
</table>

**Note**
The names `VK_BORDER_COLOR_*_TRANSPARENT_BLACK`, `VK_BORDER_COLOR_*_OPAQUE_BLACK`, and `VK_BORDER_COLOR_*_OPAQUE_WHITE` are meant to describe which components are zeros and ones in the vocabulary of compositing, and are not meant to imply that the numerical value of `VK_BORDER_COLOR_INT_OPAQUE_WHITE` is a saturating value for integers.
This is substituted for the texel value by replacing the number of components in the image format

Table 20. Border Texel Components After Replacement

<table>
<thead>
<tr>
<th>Texel Aspect or Format</th>
<th>Component Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth aspect</td>
<td>( D = B_r )</td>
</tr>
<tr>
<td>Stencil aspect</td>
<td>( S = B_r )</td>
</tr>
<tr>
<td>One component color format</td>
<td>( \text{Color}_r = B_r )</td>
</tr>
<tr>
<td>Two component color format</td>
<td>([\text{Color}_r,\text{Color}_g] = [B_r, B_g] )</td>
</tr>
<tr>
<td>Three component color format</td>
<td>([\text{Color}_r,\text{Color}_g,\text{Color}_b] = [B_r, B_g, B_b] )</td>
</tr>
<tr>
<td>Four component color format</td>
<td>([\text{Color}_r,\text{Color}_g,\text{Color}_b,\text{Color}_a] = [B_r, B_g, B_b, B_a] )</td>
</tr>
</tbody>
</table>

The value returned by a read of an invalid texel is undefined, unless that read operation is from a buffer resource and the `robustBufferAccess` feature is enabled. In that case, an invalid texel is replaced as described by the `robustBufferAccess` feature.

If the `VkPhysicalDeviceSparseProperties::residencyNonResidentStrict` property is `VK_TRUE`, a sparse unbound texel is replaced with 0 or 0.0 values for integer and floating-point components of the image format, respectively.

If `residencyNonResidentStrict` is `VK_FALSE`, the value of the sparse unbound texel is undefined.

### 15.3.4. Depth Compare Operation

If the image view has a depth/stencil format, the depth component is selected by the `aspectMask`, and the operation is a `Dref` instruction, a depth comparison is performed. The value of the result \( D \) is 1.0 if the result of the compare operation is true, and 0.0 otherwise. The compare operation is selected by the `compareOp` member of the sampler.

\[
\begin{align*}
D &= 1.0 \\
D &= 0.0 \\
\text{D}_{ref} &\leq D \quad \text{for LEQUAL} \\
\text{D}_{ref} &\geq D \quad \text{for GEQUAL} \\
\text{D}_{ref} < D &\quad \text{for LESS} \\
\text{D}_{ref} > D &\quad \text{for GREATER} \\
\text{D}_{ref} = D &\quad \text{for EQUAL} \\
\text{D}_{ref} \neq D &\quad \text{for NOTEQUAL} \\
\text{true} &\quad \text{for ALWAYS} \\
\text{false} &\quad \text{for NEVER}
\end{align*}
\]

where, in the depth comparison:

\[ \text{D}_{ref} = \text{shaderOp.D}_{ref} \text{ (from optional SPIR-V operand)} \]

\( D \) (texel depth value)

### 15.3.5. Conversion to RGBA

The texel is expanded from one, two, or three components to four components based on the image base color:
Table 21. Texel Color After Conversion To RGBA

<table>
<thead>
<tr>
<th>Texel Aspect or Format</th>
<th>RGBA Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth aspect</td>
<td>[Color_r, Color_g, Color_b, Color_a] = [D, 0, 0, one]</td>
</tr>
<tr>
<td>Stencil aspect</td>
<td>[Color_r, Color_g, Color_b, Color_a] = [S, 0, 0, one]</td>
</tr>
<tr>
<td>One component color format</td>
<td>[Color_r, Color_g, Color_b, Color_a] = [Color_r, 0, 0, one]</td>
</tr>
<tr>
<td>Two component color format</td>
<td>[Color_r, Color_g, Color_b, Color_a] = [Color_r, Color_g, 0, one]</td>
</tr>
<tr>
<td>Three component color format</td>
<td>[Color_r, Color_g, Color_b, Color_a] = [Color_r, Color_g, Color_b, one]</td>
</tr>
<tr>
<td>Four component color format</td>
<td>[Color_r, Color_g, Color_b, Color_a] = [Color_r, Color_g, Color_b, Color_a]</td>
</tr>
</tbody>
</table>

where one = 1.0f for floating-point formats and depth aspects, and one = 1 for integer formats and stencil aspects.

15.3.6. Component Swizzle

All texel input instructions apply a swizzle based on:

- the VkComponentSwizzle enums in the components member of the VkImageViewCreateInfo structure for the image being read if sampler Y’C_bR conversion is not enabled, and
- the VkComponentSwizzle enums in the components member of the VkSamplerYcbcrConversionCreateInfo structure for the sampler Y’C_bC_r conversion if sampler Y’C_bC_r conversion is enabled.

The swizzle can rearrange the components of the texel, or substitute zero or one for any components. It is defined as follows for each color component:

\[
Color_{\text{component}} = \begin{cases} 
    \text{Color}_r & \text{for RED swizzle} \\
    \text{Color}_g & \text{for GREEN swizzle} \\
    \text{Color}_b & \text{for BLUE swizzle} \\
    \text{Color}_a & \text{for ALPHA swizzle} \\
    0 & \text{for ZERO swizzle} \\
    \text{one} & \text{for ONE swizzle} \\
    \text{identity} & \text{for IDENTITY swizzle}
\end{cases}
\]

where:

\[
\text{one} = \begin{cases} 
    1.0f & \text{for floating point components} \\
    1 & \text{for integer components}
\end{cases}
\]

\[
\text{identity} = \begin{cases} 
    \text{Color}_r & \text{for component = r} \\
    \text{Color}_g & \text{for component = g} \\
    \text{Color}_b & \text{for component = b} \\
    \text{Color}_a & \text{for component = a}
\end{cases}
\]

If the border color is one of the VK_BORDER_COLOR_*_OPAQUE_BLACK enums and the VkComponentSwizzle is not VK_COMPONENT_SWIZZLE_IDENTITY for all components (or the equivalent identity mapping), the value of the texel after swizzle is undefined.
15.3.7. Sparse Residency

OpImageSparse* instructions return a structure which includes a residency code indicating whether any texels accessed by the instruction are sparse unbound texels. This code can be interpreted by the OpImageSparseTexelsResident instruction which converts the residency code to a boolean value.

15.3.8. Chroma Reconstruction

In some color models, the color representation is defined in terms of monochromatic light intensity (often called “luma”) and color differences relative to this intensity, often called “chroma”. It is common for color models other than RGB to represent the chroma channels at lower spatial resolution than the luma channel. This approach is used to take advantage of the eye’s lower spatial sensitivity to color compared with its sensitivity to brightness. Less commonly, the same approach is used with additive color, since the green channel dominates the eye's sensitivity to light intensity and the spatial sensitivity to color introduced by red and blue is lower.

Lower-resolution channels are “downsampled” by resizing them to a lower spatial resolution than the channel representing luminance. The process of reconstructing a full color value for texture access involves accessing both chroma and luma values at the same location. To generate the color accurately, the values of the lower-resolution channels at the location of the luma samples must be reconstructed from the lower-resolution sample locations, an operation known here as “chroma reconstruction” irrespective of the actual color model.

The location of the chroma samples relative to the luma coordinates is determined by the xChromaOffset and yChromaOffset members of the VkSamplerYcbcrConversionCreateInfo structure used to create the sampler Y’C_bC_r conversion.

The following diagrams show the relationship between unnormalized (u,v) coordinates and (i,j) integer texel positions in the luma channel (shown in black, with circles showing integer sample positions) and the texel coordinates of reduced-resolution chroma channels, shown as crosses in red.

Note

If the chroma values are reconstructed at the locations of the luma samples by means of interpolation, chroma samples from outside the image bounds are needed; these are determined according to Wrapping Operation. These diagrams represent this by showing the bounds of the “chroma texel” extending beyond the image bounds, and including additional chroma sample positions where required for interpolation. The limits of a sample for NEAREST sampling is shown as a grid.
<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.3</td>
<td>1.3</td>
<td>2.3</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>1.2</td>
<td>2.2</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>1.1</td>
<td>2.1</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.0</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. 422 downsampling, xChromaOffset=COSITED_EVEN

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.3</td>
<td>1.3</td>
<td>2.3</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>1.2</td>
<td>2.2</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>1.1</td>
<td>2.1</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.0</td>
<td>1.0</td>
<td>2.0</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. 422 downsampling, xChromaOffset=MIDPOINT
Figure 7. 420 downsampling, xChromaOffset=COSITED_EVEN, yChromaOffset=COSITED_EVEN

Figure 8. 420 downsampling, xChromaOffset=MIDPOINT, yChromaOffset=COSITED_EVEN
Reconstruction is implemented in one of two ways:

If the format of the image that is to be sampled sets `VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT`, or the `VkSamplerYcbcrConversionCreateInfo`'s `forceExplicitReconstruction` is set to `VK_TRUE`, reconstruction is performed as an explicit step independent of filtering, described in the `Explicit Reconstruction` section.
If the format of the image that is to be sampled does not set
VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT and if the
VkSamplerYcbcrConversionCreateInfo’s forceExplicitReconstruction is set to VK_FALSE, reconstruction
is performed as an implicit part of filtering prior to color model conversion, with no separate post-
conversion texel filtering step, as described in the Implicit Reconstruction section.

Explicit Reconstruction

- If the chromaFilter member of the VkSamplerYcbcrConversionCreateInfo structure is
  VK_FILTER_NEAREST:
  - If the format’s R and B channels are reduced in resolution in just width by a factor of two
    relative to the G channel (i.e. this is a “_422” format), the \( \tau_{ij,kl} \) values accessed by texel
    filtering are reconstructed as follows:

    \[
    \tau_R'(i, j) = \tau_R(i \times 0.5, j) \left[ \text{level} \right] \\
    \tau_B'(i, j) = \tau_B(i \times 0.5, j) \left[ \text{level} \right]
    \]

  - If the format’s R and B channels are reduced in resolution in width and height by a factor of
    two relative to the G channel (i.e. this is a “_420” format), the \( \tau_{ij,kl} \) values accessed by texel
    filtering are reconstructed as follows:

    \[
    \tau_R'(i, j) = \tau_B(i \times 0.5, j \times 0.5) \left[ \text{level} \right] \\
    \tau_B'(i, j) = \tau_B(i \times 0.5, j \times 0.5) \left[ \text{level} \right]
    \]

  Note
  xChromaOffset and yChromaOffset have no effect if chromaFilter is
  VK_FILTER_NEAREST for explicit reconstruction.

- If the chromaFilter member of the VkSamplerYcbcrConversionCreateInfo structure is
  VK_FILTER_LINEAR:
  - If the format’s R and B channels are reduced in resolution in just width by a factor of two
    relative to the G channel (i.e. this is a “422” format):
    - If xChromaOffset is VK_CHROMA_LOCATION_COSITED_EVEN:

      \[
      \tau_{RB}'(i, j) = \begin{cases} 
      \tau_{RB}(i \times 0.5, j \times 0.5) \left[ \text{level} \right], & 0.5 \times i = 0.5 \times i \\
      0.5 \times \tau_{RB}(i \times 0.5, j \times 0.5) \left[ \text{level} \right] + \\
      0.5 \times \tau_{RB}(i \times 0.5 + 1, j \times 0.5) \left[ \text{level} \right], & 0.5 \times i \neq 0.5 \times i
      \end{cases}
      \]

    - If xChromaOffset is VK_CHROMA_LOCATION_MIDPOINT:

      \[
      \tau_{RB}(i, j)' = \begin{cases} 
      0.25 \times \tau_{RB}(i \times 0.5 - 1, j \times 0.5) \left[ \text{level} \right] + \\
      0.75 \times \tau_{RB}(i \times 0.5, j \times 0.5) \left[ \text{level} \right], & 0.5 \times i = 0.5 \times i \\
      0.75 \times \tau_{RB}(i \times 0.5, j \times 0.5 + 1) \left[ \text{level} \right] + \\
      0.25 \times \tau_{RB}(i \times 0.5 + 1, j \times 0.5) \left[ \text{level} \right], & 0.5 \times i \neq 0.5 \times i
      \end{cases}
      \]

  - If the format’s R and B channels are reduced in resolution in width and height by a factor of
    two relative to the G channel (i.e. this is a “420” format), a similar relationship applies. Due
    to the number of options, these formulae are expressed more concisely as follows:
Note
In the case where the texture itself is bilinearly interpolated as described in Texel Filtering, thus requiring four full-color samples for the filtering operation, and where the reconstruction of these samples uses bilinear interpolation in the chroma channels due to chromaFilter=VK_FILTER_LINEAR, up to nine chroma samples may be required, depending on the sample location.

Implicit Reconstruction

Implicit reconstruction takes place by the samples being interpolated, as required by the filter settings of the sampler, except that chromaFilter takes precedence for the chroma samples.

If chromaFilter is VK_FILTER_NEAREST, an implementation may behave as if xChromaOffset and yChromaOffset were both VK_CHROMA_LOCATION_MIDPOINT, irrespective of the values set.

Note
This will not have any visible effect if the locations of the luma samples coincide with the location of the samples used for rasterization.

The sample coordinates are adjusted by the downsample factor of the channel (such that, for example, the sample coordinates are divided by two if the channel has a downsample factor of two relative to the luma channel):

\[
\begin{align*}
    u_{RB} & = \begin{cases} 
        0.5 \times (u) & \text{If xChromaOffset=COSITED\_EVEN} \\
        0.5 \times (u + 0.5) & \text{If xChromaOffset=MIDPOINT}
    \end{cases} \\
    v_{RB} & = \begin{cases} 
        0.5 \times (v) & \text{If yChromaOffset=COSITED\_EVEN} \\
        0.5 \times (v + 0.5) & \text{If yChromaOffset=MIDPOINT}
    \end{cases}
\end{align*}
\]

15.3.9. Sampler Y'C_bC_R Conversion

Sampler Y'C_bC_R conversion performs the following operations, which an implementation may combine into a single mathematical operation:

- Sampler Y'C_bC_R Range Expansion
Sampler Y′C_bC_r Model Conversion

Sampler Y′C_bC_r Range Expansion

Sampler Y′C_bC_r range expansion is applied to color channel values after all texel input operations which are not specific to sampler Y′C_bC_r conversion. For example, the input values to this stage have been converted using the normal format conversion rules.

Sampler Y′C_bC_r range expansion is not applied if ycbcrModel is VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY. That is, the shader receives the vector C_rgba as output by the Component Swizzle stage without further modification.

For other values of ycbcrModel, range expansion is applied to the texel channel values output by the Component Swizzle defined by the components member of VkSamplerYcbcrConversionCreateInfo. Range expansion applies independently to each channel of the image. For the purposes of range expansion and Y′C_bC_r model conversion, the R and B channels contain color difference (chroma) values and the G channel contains luma. The A channel is not modified by sampler Y′C_bC_r range expansion.

The range expansion to be applied is defined by the ycbcrRange member of the VkSamplerYcbcrConversionCreateInfo structure:

- If ycbcrRange is VK_SAMPLER_YCBCR_RANGE_ITU_FULL, the following transformations are applied:

\[
Y' = C'_\text{rgba}[G] \\
C_B = C'_\text{rgba}[B] - \frac{2^{n-1}}{(2^n-1)} \\
C_R = C'_\text{rgba}[R] - \frac{2^{n-1}}{(2^n-1)}
\]

**Note**
These formulae correspond to the “full range” encoding in the “Quantization schemes” chapter of the Khronos Data Format Specification.

Should any future amendments be made to the ITU specifications from which these equations are derived, the formulae used by Vulkan may also be updated to maintain parity.

- If ycbcrRange is VK_SAMPLER_YCBCR_RANGE_ITU_NARROW, the following transformations are applied:

\[
Y' = \frac{C'_\text{rgba}[G] \times (2^n - 1) - 16 \times 2^n - 8}{219 \times 2^n - 8} \\
C_B = \frac{C'_\text{rgba}[B] \times (2^n - 1) - 128 \times 2^n - 8}{224 \times 2^n - 8} \\
C_R = \frac{C'_\text{rgba}[R] \times (2^n - 1) - 128 \times 2^n - 8}{224 \times 2^n - 8}
\]

**Note**
These formulae correspond to the “narrow range” encoding in the “Quantization schemes” chapter of the Khronos Data Format Specification.
• $n$ is the bit-depth of the channels in the format.

The precision of the operations performed during range expansion **must** be at least that of the source format.

An implementation **may** clamp the results of these range expansion operations such that $Y'$ falls in the range $[0,1]$, and/or such that $C_a$ and $C_b$ fall in the range $[-0.5,0.5]$.

### Sampler $Y'C_aC_b$ Model Conversion

The range-expanded values are converted between color models, according to the color model conversion specified in the `ycbcrModel` member:

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY**

The color channels are not modified by the color model conversion since they are assumed already to represent the desired color model in which the shader is operating; $Y'C_aC_b$ range expansion is also ignored.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_IDENTITY**

The color channels are not modified by the color model conversion and are assumed to be treated as though in $Y'C_aC_b$ form both in memory and in the shader; $Y'C_aC_b$ range expansion is applied to the channels as for other $Y'C_aC_b$ models, with the vector $(C_R,Y',C_B,A)$ provided to the shader.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709**

The color channels are transformed from a $Y'C_aC_b$ representation to an $R'G'B'$ representation as described in the “BT.709 $Y'C_aC_b$ conversion” section of the Khronos Data Format Specification.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601**

The color channels are transformed from a $Y'C_aC_b$ representation to an $R'G'B'$ representation as described in the “BT.601 $Y'C_aC_b$ conversion” section of the Khronos Data Format Specification.

**VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020**

The color channels are transformed from a $Y'C_aC_b$ representation to an $R'G'B'$ representation as described in the “BT.2020 $Y'C_aC_b$ conversion” section of the Khronos Data Format Specification.

In this operation, each output channel is dependent on each input channel.

An implementation **may** clamp the $R'G'B'$ results of these conversions to the range $[0,1]$.

The precision of the operations performed during model conversion **must** be at least that of the source format.

The alpha channel is not modified by these model conversions.
Note
Sampling operations in a non-linear color space can introduce color and intensity shifts at sharp transition boundaries. To avoid this issue, the technically precise color correction sequence described in the “Introduction to Color Conversions” chapter of the Khronos Data Format Specification may be performed as follows:

- Calculate the unnormalized texel coordinates corresponding to the desired sample position.
- For a minFilter or magFilter of VK_FILTER_NEAREST:
  1. Calculate \((i, j)\) for the sample location as described under the “nearest filtering” formulae in \((u, v, w, a)\) to \((i, j, k, l, n)\) Transformation And Array Layer Selection
  2. Calculate the normalized texel coordinates corresponding to these integer coordinates.
  3. Sample using sampler Y'CbCr conversion at this location.
- For a minFilter or magFilter of VK_FILTER_LINEAR:
  1. Calculate \((i_{0,1}, j_{0,1})\) for the sample location as described under the “linear filtering” formulae in \((u, v, w, a)\) to \((i, j, k, l, n)\) Transformation And Array Layer Selection
  2. Calculate the normalized texel coordinates corresponding to these integer coordinates.
  3. Sample using sampler Y'CbCr conversion at each of these locations.
  4. Convert the non-linear A'R'G'B' outputs of the Y'CbCr conversions to linear ARGB values as described in the “Transfer Functions” chapter of the Khronos Data Format Specification.
  5. Interpolate the linear ARGB values using the \(\alpha\) and \(\beta\) values described in the “linear filtering” section of \((u, v, w, a)\) to \((i, j, k, l, n)\) Transformation And Array Layer Selection and the equations in Texel Filtering.

The additional calculations and, especially, additional number of sampling operations in the VK_FILTER_LINEAR case can be expected to have a performance impact compared with using the outputs directly; since the variation from “correct” results are subtle for most content, the application author should determine whether a more costly implementation is strictly necessary. Note that if chromaFilter, and minFilter or magFilter are both VK_FILTER_NEAREST, these operations are redundant and sampling using sampler Y'CbCr conversion at the desired sample coordinates will produce the “correct” results without further processing.

15.4. Texel Output Operations

Texel output instructions are SPIR-V image instructions that write to an image. Texel output operations are a set of steps that are performed on state, coordinates, and texel values while
processing a texel output instruction, and which are common to some or all texel output
instructions. They include the following steps, which are performed in the listed order:

- Validation operations
  - Format validation
  - Coordinate validation
  - Sparse validation
- Texel output format conversion

15.4.1. Texel Output Validation Operations

*Texel output validation operations* inspect instruction/image state or coordinates, and in certain
circumstances cause the write to have no effect. There are a series of validations that the texel
undergoes.

**Texel Format Validation**

If the image format of the `OpTypeImage` is not compatible with the `VkImageView`'s format, the write
causes the contents of the image's memory to become undefined.

15.4.2. Integer Texel Coordinate Validation

The integer texel coordinates are validated according to the same rules as for texel input coordinate
validation.

If the texel fails integer texel coordinate validation, then the write has no effect.

15.4.3. Sparse Texel Operation

If the texel attempts to write to an unbound region of a sparse image, the texel is a sparse unbound
texel. In such a case, if the `VkPhysicalDeviceSparseProperties::residencyNonResidentStrict` property
is `VK_TRUE`, the sparse unbound texel write has no effect. If `residencyNonResidentStrict` is `VK_FALSE`,
the write may have a side effect that becomes visible to other accesses to unbound texels in any
resource, but will not be visible to any device memory allocated by the application.

15.4.4. Texel Output Format Conversion

If the image format is sRGB, a linear to sRGB conversion is applied to the R, G, and B components as
described in the “sRGB EOTF” section of the Khronos Data Format Specification. The A component,
if present, is unchanged.

Texels then undergo a format conversion from the floating point, signed, or unsigned integer type
of the texel data to the `VkFormat` of the image view. Any unused components are ignored.

Each component is converted based on its type and size (as defined in the Format Definition section
for each `VkFormat`). Floating-point outputs are converted as described in Floating-Point Format
Conversions and Fixed-Point Data Conversion. Integer outputs are converted such that their value
is preserved. The converted value of any integer that cannot be represented in the target format is
15.5. Normalized Texel Coordinate Operations

If the image sampler instruction provides normalized texel coordinates, some of the following operations are performed.

15.5.1. Projection Operation

For Proj image operations, the normalized texel coordinates (s,t,r,q,a) and (if present) the D_ref coordinate are transformed as follows:

\[ s = \frac{s}{q}, \quad \text{for 1D, 2D, or 3D image} \]
\[ t = \frac{t}{q}, \quad \text{for 2D or 3D image} \]
\[ r = \frac{r}{q}, \quad \text{for 3D image} \]
\[ D_{\text{ref}} = \frac{D_{\text{ref}}}{q}, \quad \text{if provided} \]

15.5.2. Derivative Image Operations

Derivatives are used for LOD selection. These derivatives are either implicit (in an ImplicitLod image instruction in a fragment shader) or explicit (provided explicitly by shader to the image instruction in any shader).

For implicit derivatives image instructions, the derivatives of texel coordinates are calculated in the same manner as derivative operations. That is:

\[ \frac{\partial s}{\partial x} = dPdx(s), \quad \frac{\partial s}{\partial y} = dPdy(s), \quad \text{for 1D, 2D, Cube, or 3D image} \]
\[ \frac{\partial t}{\partial x} = dPdx(t), \quad \frac{\partial t}{\partial y} = dPdy(t), \quad \text{for 2D, Cube, or 3D image} \]
\[ \frac{\partial u}{\partial x} = dPdx(u), \quad \frac{\partial u}{\partial y} = dPdy(u), \quad \text{for Cube or 3D image} \]

Partial derivatives not defined above for certain image dimensionalities are set to zero.

For explicit LOD image instructions, if the optional SPIR-V operand Grad is provided, then the operand values are used for the derivatives. The number of components present in each derivative for a given image dimensionality matches the number of partial derivatives computed above.

If the optional SPIR-V operand Lod is provided, then derivatives are set to zero, the cube map derivative transformation is skipped, and the scale factor operation is skipped. Instead, the floating point scalar coordinate is directly assigned to \( \lambda_{\text{base}} \) as described in Level-of-Detail Operation.

15.5.3. Cube Map Face Selection and Transformations

For cube map image instructions, the (s,t,r) coordinates are treated as a direction vector \((r_x, r_y, r_z)\). The direction vector is used to select a cube map face. The direction vector is transformed to a per-face texel coordinate system \((s_{\text{face}}, t_{\text{face}})\). The direction vector is also used to transform the derivatives to per-face derivatives.
15.5.4. Cube Map Face Selection

The direction vector selects one of the cube map’s faces based on the largest magnitude coordinate direction (the major axis direction). Since two or more coordinates can have identical magnitude, the implementation must have rules to disambiguate this situation.

The rules should have as the first rule that \( r_z \) wins over \( r_y \) and \( r_x \), and the second rule that \( r_y \) wins over \( r_x \). An implementation may choose other rules, but the rules must be deterministic and depend only on \((r_x, r_y, r_z)\).

The layer number (corresponding to a cube map face), the coordinate selections for \( s_c \), \( t_c \), \( r_c \), and the selection of derivatives, are determined by the major axis direction as specified in the following two tables.

### Table 22. Cube map face and coordinate selection

<table>
<thead>
<tr>
<th>Major Axis Direction</th>
<th>Layer Number</th>
<th>Cube Map Face</th>
<th>( s_c )</th>
<th>( t_c )</th>
<th>( r_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+r_x)</td>
<td>0</td>
<td>Positive X</td>
<td>(-r_z)</td>
<td>(-r_y)</td>
<td>( r_x)</td>
</tr>
<tr>
<td>(-r_x)</td>
<td>1</td>
<td>Negative X</td>
<td>(+r_z)</td>
<td>(-r_y)</td>
<td>( r_x)</td>
</tr>
<tr>
<td>(+r_y)</td>
<td>2</td>
<td>Positive Y</td>
<td>(+r_x)</td>
<td>(+r_z)</td>
<td>( r_y)</td>
</tr>
<tr>
<td>(-r_y)</td>
<td>3</td>
<td>Negative Y</td>
<td>(+r_x)</td>
<td>(-r_z)</td>
<td>( r_y)</td>
</tr>
<tr>
<td>(+r_z)</td>
<td>4</td>
<td>Positive Z</td>
<td>(+r_x)</td>
<td>(-r_y)</td>
<td>( r_z)</td>
</tr>
<tr>
<td>(-r_z)</td>
<td>5</td>
<td>Negative Z</td>
<td>(-r_x)</td>
<td>(-r_y)</td>
<td>( r_z)</td>
</tr>
</tbody>
</table>

### Table 23. Cube map derivative selection

<table>
<thead>
<tr>
<th>Major Axis Direction</th>
<th>( \partial s_c / \partial x )</th>
<th>( \partial s_c / \partial y )</th>
<th>( \partial t_c / \partial x )</th>
<th>( \partial t_c / \partial y )</th>
<th>( \partial r_c / \partial x )</th>
<th>( \partial r_c / \partial y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+r_x)</td>
<td>(-\partial r_z / \partial x)</td>
<td>(-\partial r_z / \partial y)</td>
<td>(-\partial r_y / \partial x)</td>
<td>(-\partial r_y / \partial y)</td>
<td>(+\partial r_x / \partial x)</td>
<td>(+\partial r_x / \partial y)</td>
</tr>
<tr>
<td>(-r_x)</td>
<td>(+\partial r_z / \partial x)</td>
<td>(+\partial r_z / \partial y)</td>
<td>(-\partial r_y / \partial x)</td>
<td>(-\partial r_y / \partial y)</td>
<td>(-\partial r_x / \partial x)</td>
<td>(-\partial r_x / \partial y)</td>
</tr>
<tr>
<td>(+r_y)</td>
<td>(+\partial r_z / \partial x)</td>
<td>(+\partial r_z / \partial y)</td>
<td>(+\partial r_y / \partial x)</td>
<td>(+\partial r_y / \partial y)</td>
<td>(+\partial r_x / \partial x)</td>
<td>(+\partial r_x / \partial y)</td>
</tr>
<tr>
<td>(-r_y)</td>
<td>(+\partial r_z / \partial x)</td>
<td>(+\partial r_z / \partial y)</td>
<td>(-\partial r_y / \partial x)</td>
<td>(-\partial r_y / \partial y)</td>
<td>(-\partial r_x / \partial x)</td>
<td>(-\partial r_x / \partial y)</td>
</tr>
<tr>
<td>(+r_z)</td>
<td>(+\partial r_z / \partial x)</td>
<td>(+\partial r_z / \partial y)</td>
<td>(-\partial r_y / \partial x)</td>
<td>(-\partial r_y / \partial y)</td>
<td>(+\partial r_x / \partial x)</td>
<td>(+\partial r_x / \partial y)</td>
</tr>
<tr>
<td>(-r_z)</td>
<td>(-\partial r_z / \partial x)</td>
<td>(-\partial r_z / \partial y)</td>
<td>(-\partial r_y / \partial x)</td>
<td>(-\partial r_y / \partial y)</td>
<td>(-\partial r_x / \partial x)</td>
<td>(-\partial r_x / \partial y)</td>
</tr>
</tbody>
</table>

15.5.5. Cube Map Coordinate Transformation

\[
s_{face} = \frac{1}{2} \times \frac{s_c}{|r_c|} + \frac{1}{2}
\]
\[
t_{face} = \frac{1}{2} \times \frac{t_c}{|r_c|} + \frac{1}{2}
\]
15.5.6. Cube Map Derivative Transformation

\[
\begin{align*}
\frac{\partial s_{\text{face}}}{\partial x} &= \frac{\partial}{\partial x} \left( \frac{1}{2} \times \frac{s_c}{|r_c|} + \frac{1}{2} \right) \\
\frac{\partial s_{\text{face}}}{\partial y} &= \frac{1}{2} \times \frac{\partial}{\partial x} \left( \frac{s_c}{|r_c|} \right) \\
\frac{\partial s_{\text{face}}}{\partial z} &= \frac{1}{2} \times \left( \frac{r_c \times \partial s_c/\partial x - s_c \times \partial r_c/\partial x}{(r_c)^2} \right)
\end{align*}
\]

15.5.7. Scale Factor Operation, Level-of-Detail Operation and Image Level(s) Selection

LOD selection can be either explicit (provided explicitly by the image instruction) or implicit (determined from a scale factor calculated from the derivatives). The implicit LOD selected can be queried using the SPIR-V instruction `OpImageQueryLod`, which gives access to the \( \lambda' \) and \( d_l \) values, defined below. These values must be computed with `mipmapPrecisionBits` of accuracy and may be subject to implementation-specific maxima and minima for very large, out-of-range values.

Scale Factor Operation

The magnitude of the derivatives are calculated by:

\[
\begin{align*}
\mu_x &= |\partial s/\partial x| \times w_{\text{base}} \\
\mu_x &= |\partial t/\partial x| \times h_{\text{base}} \\
\mu_x &= |\partial r/\partial x| \times d_{\text{base}} \\
\mu_y &= |\partial s/\partial y| \times w_{\text{base}} \\
\mu_y &= |\partial t/\partial y| \times h_{\text{base}} \\
\mu_y &= |\partial r/\partial y| \times d_{\text{base}}
\end{align*}
\]

where:

\[
\begin{align*}
\partial t/\partial x = \partial t/\partial y = 0 \quad \text{(for 1D images)} \\
\partial r/\partial x = \partial r/\partial y = 0 \quad \text{(for 1D, 2D or Cube images)}
\end{align*}
\]

and:

\[
w_{\text{base}} = \text{image.w}
\]
A point sampled in screen space has an elliptical footprint in texture space. The minimum and maximum scale factors ($\rho_{\text{min}}, \rho_{\text{max}}$) should be the minor and major axes of this ellipse.

The scale factors $\rho_x$ and $\rho_y$, calculated from the magnitude of the derivatives in x and y, are used to compute the minimum and maximum scale factors.

$\rho_x$ and $\rho_y$ may be approximated with functions $f_x$ and $f_y$, subject to the following constraints:

\[
\begin{align*}
 f_x \text{is continuous and monotonically increasing in each of } m_{ux}, m_{vx}, \text{ and } m_{wx} \\
 f_y \text{is continuous and monotonically increasing in each of } m_{uy}, m_{vy}, \text{ and } m_{wy} \\
 \max(|m_{ux}|, |m_{vx}|, |m_{wx}|) \leq f_x \leq \sqrt{2}(|m_{ux}| + |m_{vx}| + |m_{wx}|) \\
 \max(|m_{uy}|, |m_{vy}|, |m_{wy}|) \leq f_y \leq \sqrt{2}(|m_{uy}| + |m_{vy}| + |m_{wy}|)
\end{align*}
\]

The minimum and maximum scale factors ($\rho_{\text{min}}, \rho_{\text{max}}$) are determined by:

\[
\begin{align*}
 \rho_{\text{max}} &= \max(\rho_x, \rho_y) \\
 \rho_{\text{min}} &= \min(\rho_x, \rho_y)
\end{align*}
\]

The ratio of anisotropy is determined by:

\[
\eta = \min(\rho_{\text{max}}/\rho_{\text{min}}, \max_{\text{Aniso}})
\]

where:

\[
\begin{align*}
 \text{sampler.max}_{\text{Aniso}} &= \text{maxAnisotropy} \text{ (from sampler descriptor)} \\
 \text{limits.max}_{\text{Aniso}} &= \text{maxSamplerAnisotropy} \text{ (from physical device limits)} \\
 \max_{\text{Aniso}} &= \min(\text{sampler.max}_{\text{Aniso}}, \text{limits.max}_{\text{Aniso}})
\end{align*}
\]

If $\rho_{\text{max}} = \rho_{\text{min}} = 0$, then all the partial derivatives are zero, the fragment’s footprint in texel space is a point, and $N$ should be treated as 1. If $\rho_{\text{max}} \neq 0$ and $\rho_{\text{min}} = 0$ then all partial derivatives along one axis are zero, the fragment’s footprint in texel space is a line segment, and $\eta$ should be treated as $\max_{\text{Aniso}}$. However, anytime the footprint is small in texel space the implementation may use a smaller value of $\eta$, even when $\rho_{\text{min}}$ is zero or close to zero. If either $\text{VkPhysicalDeviceFeatures}::\text{samplerAnisotropy}$ or $\text{VkSamplerCreateInfo}::\text{anisotropyEnable}$ are $\text{VK_FALSE}$, $\max_{\text{Aniso}}$ is set to 1.

If $\eta = 1$, sampling is isotropic. If $\eta > 1$, sampling is anisotropic.

The sampling rate ($N$) is derived as:

\[
N = \eta
\]
An implementation **may** round \( N \) up to the nearest supported sampling rate. An implementation **may** use the value of \( N \) as an approximation of \( \eta \).

### Level-of-Detail Operation

The LOD parameter \( \lambda \) is computed as follows:

\[
\lambda_{\text{base}}(x, y) = \begin{cases} 
  \text{shaderOp.Lod} & \text{(from optional SPIR-V operand)} \\
  \log_2 \left( \frac{D_{\text{max}}}{\eta} \right) & \text{otherwise}
\end{cases}
\]

\[
\lambda'(x, y) = \lambda_{\text{base}} + \text{clamp}(\text{sampler.bias} + \text{shaderOp.bias}, -\text{maxSamplerLodBias}, \text{maxSamplerLodBias})
\]

\[
\lambda = \begin{cases} 
  \lambda' & \text{lod}_{\text{max}} \leq \lambda' \leq \text{lod}_{\text{max}} \\
  \text{lod}_{\text{min}} & \lambda' < \text{lod}_{\text{min}} \\
  \text{undefined} & \text{lod}_{\text{min}} > \text{lod}_{\text{max}}
\end{cases}
\]

where:

\[
\text{sampler.bias} = \text{mipLodBias}
\]

\[
\text{shaderOp.bias} = \begin{cases} 
  \text{Bias} & \text{(from optional SPIR-V operand)} \\
  0 & \text{otherwise}
\end{cases}
\]

\[
\text{shaderOp.lod}_{\text{min}} = \text{minLod}
\]

\[
\text{lod}_{\text{min}} = \max(\text{sampler.lod}_{\text{min}}, \text{shaderOp.lod}_{\text{min}})
\]

\[
\text{lod}_{\text{max}} = \max\text{Lod}
\]

and \( \text{maxSamplerLodBias} \) is the value of the \( \text{VkPhysicalDeviceLimits} \) feature \( \text{maxSamplerLodBias} \).

### Image Level(s) Selection

The image level(s) \( d, d_{hi}, \) and \( d_{lo} \) which texels are read from are determined by an image-level parameter \( d_{l} \), which is computed based on the LOD parameter, as follows:

\[
d_{l} = \begin{cases} 
  \text{nearest}(d'), & \text{mipmapMode is VK_SAMPLER_MIPMAP_MODE_NEAREST} \\
  d', & \text{otherwise}
\end{cases}
\]

where:

\[
d' = \text{level}_{\text{base}} + \text{clamp}(\lambda, 0, q)
\]

\[
\text{nearest}(d') = \begin{cases} 
  [d' + 0.5] - 1, & \text{preferred} \\
  [d' + 0.5], & \text{alternative}
\end{cases}
\]

and:

\[
\text{level}_{\text{base}} = \text{baseMipLevel}
\]

\[
q = \text{levelCount} - 1
\]

\( \text{baseMipLevel} \) and \( \text{levelCount} \) are taken from the \( \text{subresourceRange} \) of the image view.

If the sampler’s \( \text{mipmapMode} \) is \( \text{VK_SAMPLER_MIPMAP_MODE_NEAREST} \), then the level selected is \( d = d_{l} \).
If the sampler’s `mipmapMode` is `VK_SAMPLER_MIPMAP_MODE_LINEAR`, two neighboring levels are selected:

\[
\begin{align*}
    d_{hi} &= \lfloor d_i \rfloor \\
    d_{lo} &= \min(d_{hi} + 1, q) \\
    \delta &= d_i - d_{hi}
\end{align*}
\]

\(\delta\) is the fractional value, quantized to the number of mipmap precision bits, used for linear filtering between levels.

### 15.5.8. \((s,t,r,q,a)\) to \((u,v,w,a)\) Transformation

The normalized texel coordinates are scaled by the image level dimensions and the array layer is selected.

This transformation is performed once for each level used in filtering (either \(d\), or \(d_{hi}\) and \(d_{lo}\)).

\[
\begin{align*}
    u(x, y) &= s(x, y) \times width_{\text{scale}} + \Delta_i \\
    v(x, y) &= \begin{cases} 
        0 & \text{for 1D images} \\
        t(x, y) \times height_{\text{scale}} + \Delta_j & \text{otherwise}
\end{cases} \\
    w(x, y) &= \begin{cases} 
        0 & \text{for 2D or Cube images} \\
        r(x, y) \times depth_{\text{scale}} + \Delta_k & \text{otherwise}
\end{cases} \\
    a(x, y) &= \begin{cases} 
        a(x, y) & \text{for array images} \\
        0 & \text{otherwise}
\end{cases}
\end{align*}
\]

where:

\[
\begin{align*}
    width_{\text{scale}} &= width_{\text{level}} \\
    height_{\text{scale}} &= height_{\text{level}} \\
    depth_{\text{scale}} &= depth_{\text{level}}
\end{align*}
\]

and where \((\Delta_i, \Delta_j, \Delta_k)\) are taken from the image instruction if it includes a `ConstOffset` or `Offset` operand, otherwise they are taken to be zero.

Operations then proceed to Unnormalized Texel Coordinate Operations.

### 15.6. Unnormalized Texel Coordinate Operations

#### 15.6.1. \((u,v,w,a)\) to \((i,j,k,l,n)\) Transformation And Array Layer Selection

The unnormalized texel coordinates are transformed to integer texel coordinates relative to the selected mipmap level.

The layer index \(l\) is computed as:

\[
l = \text{clamp}(RNE(a), 0, \text{layerCount} - 1) + baseArrayLayer
\]

where \text{layerCount} is the number of layers in the image subresource range of the image view, \text{baseArrayLayer} is the first layer from the subresource range, and where:
The sample index \( n \) is assigned the value zero.

Nearest filtering (VK_FILTER_NEAREST) computes the integer texel coordinates that the unnormalized coordinates lie within:

\[
i = \lfloor u + \text{shift} \rfloor \\
j = \lfloor v + \text{shift} \rfloor \\
k = \lfloor w + \text{shift} \rfloor
\]

where:

\[
\text{shift} = 0.0
\]

Linear filtering (VK_FILTER_LINEAR) computes a set of neighboring coordinates which bound the unnormalized coordinates. The integer texel coordinates are combinations of \( i_0 \) or \( i_1 \), \( j_0 \) or \( j_1 \), \( k_0 \) or \( k_1 \), as well as weights \( \alpha \), \( \beta \), and \( \gamma \).

\[
i_0 = \lfloor u - \text{shift} \rfloor \\
i_1 = i_0 + 1 \\
j_0 = \lfloor v - \text{shift} \rfloor \\
j_1 = j_0 + 1 \\
k_0 = \lfloor w - \text{shift} \rfloor k_1 = k_0 + 1
\]

\[
\alpha = \text{frac} (u - \text{shift}) \\
\beta = \text{frac} (v - \text{shift}) \\
\gamma = \text{frac} (w - \text{shift})
\]

where:

\[
\text{shift} = 0.5
\]

and where:

\[
\text{frac} (x) = x - \lfloor x \rfloor
\]

where the number of fraction bits retained is specified by VkPhysicalDeviceLimits::subTexelPrecisionBits.

### 15.7. Integer Texel Coordinate Operations

The OpImageFetch and OpImageFetchSparse SPIR-V instructions may supply a LOD from which texels are to be fetched using the optional SPIR-V operand Lod. Other integer-coordinate operations must not. If the Lod is provided then it must be an integer.

The image level selected is:

\[
d = \text{level}_{base} + \begin{cases} 
\text{Lod} & \text{(from optional SPIR-V operand)} \\
0 & \text{otherwise}
\end{cases}
\]
If \( d \) does not lie in the range \([\text{baseMipLevel}, \text{baseMipLevel} + \text{levelCount}]\) then any values fetched are undefined.

## 15.8. Image Sample Operations

### 15.8.1. Wrapping Operation

Cube images ignore the wrap modes specified in the sampler. Instead, if \( \text{VK_FILTER_NEAREST} \) is used within a mip level then \( \text{VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE} \) is used, and if \( \text{VK_FILTER_LINEAR} \) is used within a mip level then sampling at the edges is performed as described earlier in the Cube map edge handling section.

The first integer texel coordinate \( i \) is transformed based on the \( \text{addressModeU} \) parameter of the sampler.

\[
\begin{aligned}
i &= \begin{cases} 
    \frac{i \mod \text{size}}{\text{size}} & \text{for repeat} \\
    \left(\frac{i \mod (2 \times \text{size})}{\text{size}}\right) - \frac{1}{\text{size}} & \text{for mirrored repeat} \\
    \text{clamp}(i, 0, \text{size} - 1) & \text{for clamp to edge} \\
    \text{clamp}(i, -1, \text{size}) & \text{for clamp to border} \\
    \text{clamp}(\text{mirror}(i), 0, \text{size} - 1) & \text{for mirror clamp to edge}
\end{cases}
\end{aligned}
\]

where:

\[
mirror(n) = \begin{cases} 
    n & \text{for } n \geq 0 \\
    -1 + n & \text{otherwise}
\end{cases}
\]

\( j \) (for 2D and Cube image) and \( k \) (for 3D image) are similarly transformed based on the \( \text{addressModeV} \) and \( \text{addressModeW} \) parameters of the sampler, respectively.

### 15.8.2. Texel Gathering

SPIR-V instructions with \text{Gather} in the name return a vector derived from 4 texels in the base level of the image view. The rules for the \( \text{VK_FILTER_LINEAR} \) minification filter are applied to identify the four selected texels. Each texel is then converted to an RGBA value according to conversion to RGBA and then swizzled. A four-component vector is then assembled by taking the component indicated by the \( \text{Component} \) value in the instruction from the swizzled color value of the four texels. If the operation does not use the \( \text{ConstOffsets} \) image operand then the four texels form the \( 2 \times 2 \) rectangle used for texture filtering:

\[
\begin{aligned}
\tau[R] &= \tau_{i0, j1}[\text{level}_{\text{base}}, \text{comp}] \\
\tau[G] &= \tau_{i1, j1}[\text{level}_{\text{base}}, \text{comp}] \\
\tau[B] &= \tau_{i1, j0}[\text{level}_{\text{base}}, \text{comp}] \\
\tau[A] &= \tau_{i0, j0}[\text{level}_{\text{base}}, \text{comp}]
\end{aligned}
\]

If the operation does use the \( \text{ConstOffsets} \) image operand then the offsets allow a custom filter to be defined:
\[
\tau[R] = \tau_{i,j,k}[\text{level base}][\text{comp}],
\]
\[
\tau[G] = \tau_{i,j,k}[\text{level base}][\text{comp}],
\]
\[
\tau[B] = \tau_{i,j,k}[\text{level base}][\text{comp}],
\]
\[
\tau[A] = \tau_{i,j,k}[\text{level base}][\text{comp}],
\]

where:

\[
\tau_{\text{level base}}[\text{comp}] = \begin{cases} 
\tau_{\text{level base}}[R], & \text{for comp = 0} \\
\tau_{\text{level base}}[G], & \text{for comp = 1} \\
\tau_{\text{level base}}[B], & \text{for comp = 2} \\
\tau_{\text{level base}}[A], & \text{for comp = 3}
\end{cases}
\]

*OpImage* Gather must not be used on a sampled image with sampler Y’C_aC_b conversion enabled.

### 15.8.3. Texel Filtering

Texel filtering is first performed for each level (either \(d\) or \(d_{\text{hi}}\) and \(d_{\text{lo}}\)).

If \(\lambda\) is less than or equal to zero, the texture is said to be magnified, and the filter mode within a mip level is selected by the `magFilter` in the sampler. If \(\lambda\) is greater than zero, the texture is said to be minified, and the filter mode within a mip level is selected by the `minFilter` in the sampler.

#### Texel Nearest Filtering

Within a mip level, `VK_FILTER_NEAREST` filtering selects a single value using the \((i, j, k)\) texel coordinates, with all texels taken from layer \(l\).

\[
\tau_{i,j,k}[\text{level}] = \begin{cases} 
\tau_{i,j,k}[\text{level}], & \text{for 3D image} \\
\tau_{i,j}[\text{level}], & \text{for 2D or Cube image} \\
\tau_{i}[\text{level}], & \text{for 1D image}
\end{cases}
\]

#### Texel Linear Filtering

Within a mip level, `VK_FILTER_LINEAR` filtering combines 8 (for 3D), 4 (for 2D or Cube), or 2 (for 1D) texel values, together with their linear weights. The linear weights are derived from the fractions computed earlier:

\[
\begin{align*}
\alpha &= (1 - \alpha) \\
&= \alpha \\
(1 - \beta) & = \beta \\
&= (1 - \gamma) \\
&= \gamma
\end{align*}
\]

The values of multiple texels, together with their weights, are combined using a weighted average to produce a filtered value:
Texel Mipmap Filtering

**VK_SAMPLER_MIPMAP_MODE_NEAREST** filtering returns the value of a single mipmap level,

\[ \tau = \tau[d] \]

**VK_SAMPLER_MIPMAP_MODE_LINEAR** filtering combines the values of multiple mipmap levels (\(\tau[hi]\) and \(\tau[lo]\)), together with their linear weights.

The linear weights are derived from the fraction computed earlier:

\[ w_{hi} = (1 - \delta) \]
\[ w_{lo} = (\delta) \]

The values of multiple mipmap levels together with their linear weights, are combined using a weighted average to produce a final filtered value:

\[ \tau = (w_{hi})\tau[hi] + (w_{lo})\tau[lo] \]

Texel Anisotropic Filtering

Anisotropic filtering is enabled by the `anisotropyEnable` in the sampler. When enabled, the image filtering scheme accounts for a degree of anisotropy.

The particular scheme for anisotropic texture filtering is implementation dependent. Implementations should consider the `magFilter`, `minFilter` and `mipmapMode` of the sampler to control the specifics of the anisotropic filtering scheme used. In addition, implementations should consider `minLod` and `maxLod` of the sampler.

The following describes one particular approach to implementing anisotropic filtering for the 2D Image case, implementations may choose other methods:

Given a `magFilter`, `minFilter` of **VK_FILTER_LINEAR** and a `mipmapMode` of **VK_SAMPLER_MIPMAP_MODE_NEAREST**:

Instead of a single isotropic sample, \(N\) isotropic samples are be sampled within the image footprint of the image level \(d\) to approximate an anisotropic filter. The sum \(\tau_{2Daniso}\) is defined using the single isotropic \(\tau_{2D}(u,v)\) at level \(d\).

\[ \tau_{2Daniso} = \frac{1}{N} \sum_{i=1}^{N} \tau_{2D}(u\left(x - \frac{1}{2} + \frac{i}{N+1}, y\right), \left(v\left(x - \frac{1}{2} + \frac{i}{N+1}\right), y\right) \right) \]

when \(\rho_x > \rho_y\)

\[ \tau_{2Daniso} = \frac{1}{N} \sum_{i=1}^{N} \tau_{2D}(u\left(x, y - \frac{1}{2} + \frac{i}{N+1}\right), \left(v\left(x, y - \frac{1}{2} + \frac{i}{N+1}\right)\right) \right) \]

when \(\rho_y \geq \rho_x\)
15.9. Image Operation Steps

Each step described in this chapter is performed by a subset of the image instructions:

- Texel Input Validation Operations, Format Conversion, Texel Replacement, Conversion to RGBA, and Component Swizzle: Performed by all instructions except OpImageWrite.
- Depth Comparison: Performed by OpImage*Dref instructions.
- All Texel output operations: Performed by OpImageWrite.
- Projection: Performed by all OpImage*Proj instructions.
- Derivative Image Operations, Cube Map Operations, Scale Factor Operation, Level-of-Detail Operation and Image Level(s) Selection, and Texel Anisotropic Filtering: Performed by all OpImageSample* and OpImageSparseSample* instructions.
- (s,t,r,q,a) to (u,v,w,a) Transformation, Wrapping, and (u,v,w,a) to (i,j,k,l,n) Transformation And Array Layer Selection: Performed by all OpImageSample, OpImageSparseSample, and OpImage*Gather instructions.
- Texel Filtering: Performed by all OpImageSample* and OpImageSparseSample* instructions.
- Sparse Residency: Performed by all OpImageSparse* instructions.
Chapter 16. Queries

Queries provide a mechanism to return information about the processing of a sequence of Vulkan commands. Query operations are asynchronous, and as such, their results are not returned immediately. Instead, their results, and their availability status are stored in a Query Pool. The state of these queries can be read back on the host, or copied to a buffer object on the device.

The supported query types are Occlusion Queries, Pipeline Statistics Queries, and Timestamp Queries. Performance Queries are also supported if the associated extension is available.

16.1. Query Pools

Queries are managed using query pool objects. Each query pool is a collection of a specific number of queries of a particular type.

Query pools are represented by VkQueryPool handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkQueryPool)
```

To create a query pool, call:

```c
VkResult vkCreateQueryPool(
    VkDevice device,
    const VkQueryPoolCreateInfo* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkQueryPool* pQueryPool);
```

- `device` is the logical device that creates the query pool.
- `pCreateInfo` is a pointer to a VkQueryPoolCreateInfo structure containing the number and type of queries to be managed by the pool.
- `pAllocator` controls host memory allocation as described in the Memory Allocation chapter.
- `pQueryPool` is a pointer to a VkQueryPool handle in which the resulting query pool object is returned.

Valid Usage (Implicit)

- `device` must be a valid VkDevice handle
- `pCreateInfo` must be a valid pointer to a valid VkQueryPoolCreateInfo structure
- If `pAllocator` is not NULL, `pAllocator` must be a valid pointer to a valid VkAllocationCallbacks structure
- `pQueryPool` must be a valid pointer to a VkQueryPool handle
Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkQueryPoolCreateInfo` structure is defined as:

```c
typedef struct VkQueryPoolCreateInfo {
    VkStructureType                  sType;
    const void*                      pNext;
    VkQueryPoolCreateFlags           flags;
    VkQueryType                      queryType;
    uint32_t                         queryCount;
    VkQueryPipelineStatisticFlags    pipelineStatistics;
} VkQueryPoolCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `queryType` is a `VkQueryType` value specifying the type of queries managed by the pool.
- `queryCount` is the number of queries managed by the pool.
- `pipelineStatistics` is a bitmask of `VkQueryPipelineStatisticFlagBits` specifying which counters will be returned in queries on the new pool, as described below in Pipeline Statistics Queries.

`pipelineStatistics` is ignored if `queryType` is not `VK_QUERY_TYPE_PIPELINE_STATISTICS`.

**Valid Usage**

- If the pipeline statistics queries feature is not enabled, `queryType` must not be `VK_QUERY_TYPE_PIPELINE_STATISTICS`.
- If `queryType` is `VK_QUERY_TYPE_PIPELINE_STATISTICS`, `pipelineStatistics` must be a valid combination of `VkQueryPipelineStatisticFlagBits` values.
- If `queryType` is `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR`, the `pNext` chain must include a structure of type `VkQueryPoolPerformanceCreateInfoKHR`.
- `queryCount` must be greater than 0.
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO`.
- `pNext` must be `NULL` or a pointer to a valid instance of `VkQueryPoolPerformanceCreateInfoKHR`.
- The `sType` value of each struct in the `pNext` chain must be unique.
- `flags` must be `0`.
- `queryType` must be a valid `VkQueryType` value.

```c
typedef VkFlags VkQueryPoolCreateFlags;
```

`VkQueryPoolCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

The `VkQueryPoolPerformanceCreateInfoKHR` structure is defined as:

```c
typedef struct VkQueryPoolPerformanceCreateInfoKHR {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           queueFamilyIndex;
    uint32_t           counterIndexCount;
    const uint32_t*    pCounterIndices;
} VkQueryPoolPerformanceCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `queueFamilyIndex` is the queue family index to create this performance query pool for.
- `counterIndexCount` is size of the `pCounterIndices` array.
- `pCounterIndices` is the array of indices into the `vkEnumeratePhysicalDeviceQueueFamilyPerformanceQueryCountersKHR::pCounters` to enable in this performance query pool.

Valid Usage

- `queueFamilyIndex` must be a valid queue family index of the device.
- The `performanceCounterQueryPools` feature must be enabled.
- Each element of `pCounterIndices` must be in the range of counters reported by `vkEnumeratePhysicalDeviceQueueFamilyPerformanceQueryCountersKHR` for the queue family specified in `queueFamilyIndex`.
To query the number of passes required to query a performance query pool on a physical device, call:

```c
void vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR(  
    VkPhysicalDevice physicalDevice,  
    const VkQueryPoolPerformanceCreateInfoKHR* pPerformanceQueryCreateInfo,  
    uint32_t* pNumPasses);
```

- `physicalDevice` is the handle to the physical device whose queue family performance query counter properties will be queried.
- `pPerformanceQueryCreateInfo` is a pointer to a `VkQueryPoolPerformanceCreateInfoKHR` of the performance query that is to be created.
- `pNumPasses` is a pointer to an integer related to the number of passes required to query the performance query pool, as described below.

The `pPerformanceQueryCreateInfo` member `VkQueryPoolPerformanceCreateInfoKHR::queueFamilyIndex` must be a queue family of `physicalDevice`. The number of passes required to capture the counters specified in the `pPerformanceQueryCreateInfo` member `VkQueryPoolPerformanceCreateInfoKHR::pCounters` is returned in `pNumPasses`.

To destroy a query pool, call:

```c
void vkDestroyQueryPool(  
    VkDevice device,  
    VkQueryPool queryPool,  
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the query pool.
- `queryPool` is the query pool to destroy.
• \texttt{pAllocator} controls host memory allocation as described in the Memory Allocation chapter.

**Valid Usage**

• All submitted commands that refer to \texttt{queryPool} must have completed execution
• If \texttt{VkAllocationCallbacks} were provided when \texttt{queryPool} was created, a compatible set of callbacks must be provided here
• If no \texttt{VkAllocationCallbacks} were provided when \texttt{queryPool} was created, \texttt{pAllocator} must be NULL

**Valid Usage (Implicit)**

• \texttt{device} must be a valid \texttt{VkDevice} handle
• If \texttt{queryPool} is not \texttt{VK_NULL_HANDLE}, \texttt{queryPool} must be a valid \texttt{VkQueryPool} handle
• If \texttt{pAllocator} is not NULL, \texttt{pAllocator} must be a valid pointer to a valid \texttt{VkAllocationCallbacks} structure
• If \texttt{queryPool} is a valid handle, it must have been created, allocated, or retrieved from \texttt{device}

**Host Synchronization**

• Host access to \texttt{queryPool} must be externally synchronized

Possible values of \texttt{VkQueryPoolCreateInfo::queryType}, specifying the type of queries managed by the pool, are:

```c
typedef enum VkQueryType {
    VK_QUERY_TYPE_OCCLUSION = 0,
    VK_QUERY_TYPE_PIPELINE_STATISTICS = 1,
    VK_QUERY_TYPE_TIMESTAMP = 2,
    VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR = 1000116000,
    VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR = 1000165000,
    VK_QUERY_TYPE_ACCELERATION_STRUCTURE.Serialization_SIZE_KHR = 1000150000,
    VK_QUERY_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkQueryType;
```

• \texttt{VK_QUERY_TYPE_OCCLUSION} specifies an occlusion query.
• \texttt{VK_QUERY_TYPE_PIPELINE_STATISTICS} specifies a pipeline statistics query.
• \texttt{VK_QUERY_TYPE_TIMESTAMP} specifies a timestamp query.
• \texttt{VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR} specifies a performance query.
• \texttt{VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR} specifies a ray tracing acceleration
structure size query.

- VK_QUERY_TYPE_ACCELERATION_STRUCTURE_SERIALIZATION_SIZE_KHR specifies a ray tracing serialization acceleration structure size query

### 16.2. Query Operation

The operation of queries is controlled by the commands `vkCmdBeginQuery`, `vkCmdEndQuery`, `vkCmdResetQueryPool`, `vkCmdCopyQueryPoolResults`, and `vkCmdWriteTimestamp`.

In order for a `VkCommandBuffer` to record query management commands, the queue family for which its `VkCommandPool` was created **must** support the appropriate type of operations (graphics, compute) suitable for the query type of a given query pool.

Each query in a query pool has a status that is either *unavailable* or *available*, and also has state to store the numerical results of a query operation of the type requested when the query pool was created. Resetting a query via `vkCmdResetQueryPool` sets the status to unavailable and makes the numerical results undefined. Performing a query operation with `vkCmdBeginQuery` and `vkCmdEndQuery` changes the status to available when the query finishes, and updates the numerical results. Both the availability status and numerical results are retrieved by calling either `vkGetQueryPoolResults` or `vkCmdCopyQueryPoolResults`.

Query commands, for the same query and submitted to the same queue, execute in their entirety in submission order, relative to each other. In effect there is an implicit execution dependency from each such query command to all query command previously submitted to the same queue. There is one significant exception to this; if the flags parameter of `vkCmdCopyQueryPoolResults` does not include VK_QUERY_RESULT_WAIT_BIT, execution of `vkCmdCopyQueryPoolResults` **may** happen-before the results of `vkCmdEndQuery` are available.

After query pool creation, each query **must** be reset before it is used. Queries **must** also be reset between uses.

If a logical device includes multiple physical devices, then each command that writes a query **must** execute on a single physical device, and any call to `vkCmdBeginQuery` **must** execute the corresponding `vkCmdEndQuery` command on the same physical device.

To reset a range of queries in a query pool on a queue, call:

```c
void vkCmdResetQueryPool(
    VkCommandBuffer commandBuffer,
    VkQueryPool queryPool,
    uint32_t firstQuery,
    uint32_t queryCount);
```

- `commandBuffer` is the command buffer into which this command will be recorded.
- `queryPool` is the handle of the query pool managing the queries being reset.
- `firstQuery` is the initial query index to reset.
- `queryCount` is the number of queries to reset.
When executed on a queue, this command sets the status of query indices \([\text{firstQuery}, \text{firstQuery} + \text{queryCount} - 1]\) to unavailable.

If the \text{queryType} used to create \text{queryPool} was \text{VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR}, this command sets the status of query indices \([\text{firstQuery}, \text{firstQuery} + \text{queryCount} - 1]\) to unavailable for each pass of \text{queryPool}, as indicated by a call to \text{vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR}.

\begin{itemize}
  \item \text{firstQuery} must be less than the number of queries in \text{queryPool}
  \item The sum of \text{firstQuery} and \text{queryCount} must be less than or equal to the number of queries in \text{queryPool}
  \item All queries used by the command must not be active
  \item If \text{queryPool} was created with \text{VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR}, this command must not be recorded in a command buffer that, either directly or through secondary command buffers, also contains begin commands for a query from the set of queries \([\text{firstQuery}, \text{firstQuery} + \text{queryCount} - 1]\)
\end{itemize}

\begin{itemize}
  \item \text{commandBuffer} must be a valid \text{VkCommandBuffer} handle
  \item \text{queryPool} must be a valid \text{VkQueryPool} handle
  \item \text{commandBuffer} must be in the recording state
  \item The \text{VkCommandPool} that \text{commandBuffer} was allocated from must support graphics, or compute operations
  \item This command must only be called outside of a render pass instance
  \item Both of \text{commandBuffer}, and \text{queryPool} must have been created, allocated, or retrieved from the same \text{VkDevice}
\end{itemize}
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Compute</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Once queries are reset and ready for use, query commands can be issued to a command buffer. Occlusion queries and pipeline statistics queries count events - drawn samples and pipeline stage invocations, respectively - resulting from commands that are recorded between a `vkCmdBeginQuery` command and a `vkCmdEndQuery` command within a specified command buffer, effectively scoping a set of drawing and/or dispatch commands. Timestamp queries write timestamps to a query pool. Performance queries record performance counters to a query pool.

A query must begin and end in the same command buffer, although if it is a primary command buffer, and the inherited queries feature is enabled, it can execute secondary command buffers during the query operation. For a secondary command buffer to be executed while a query is active, it must set the `occlusionQueryEnable`, `queryFlags`, and/or `pipelineStatistics` members of `VkCommandBufferInheritanceInfo` to conservative values, as described in the Command Buffer Recording section. A query must either begin and end inside the same subpass of a render pass instance, or must both begin and end outside of a render pass instance (i.e. contain entire render pass instances).

If queries are used while executing a render pass instance that has multiview enabled, the query uses N consecutive query indices in the query pool (starting at query) where N is the number of bits set in the view mask in the subpass the query is used in. How the numerical results of the query are distributed among the queries is implementation-dependent. For example, some implementations may write each view's results to a distinct query, while other implementations may write the total result to the first query and write zero to the other queries. However, the sum of the results in all the queries must accurately reflect the total result of the query summed over all views. Applications can sum the results from all the queries to compute the total result.

Queries used with multiview rendering must not span subpasses, i.e. they must begin and end in the same subpass.

To begin a query, call:
void vkCmdBeginQuery(
    VkCommandBuffer                             commandBuffer,
    VkQueryPool                                 queryPool,
    uint32_t                                    query,
    VkQueryControlFlags                         flags);

• **commandBuffer** is the command buffer into which this command will be recorded.
• **queryPool** is the query pool that will manage the results of the query.
• **query** is the query index within the query pool that will contain the results.
• **flags** is a bitmask of **VkQueryControlFlagBits** specifying constraints on the types of queries that can be performed.

If the **queryType** of the pool is **VK_QUERY_TYPE_OCCLUSION** and **flags** contains **VK_QUERY_CONTROL_PRECISE_BIT**, an implementation must return a result that matches the actual number of samples passed. This is described in more detail in **Occlusion Queries**.

After beginning a query, that query is considered **active** within the command buffer it was called in until that same query is ended. Queries active in a primary command buffer when secondary command buffers are executed are considered active for those secondary command buffers.
Valid Usage

- `queryPool` must have been created with a `queryType` that differs from that of any queries that are active within `commandBuffer`.

- All queries used by the `commandBuffer` must be unavailable.

- The `queryType` used to create `queryPool` must not be `VK_QUERY_TYPE_TIMESTAMP`.

- If the precise occlusion queries feature is not enabled, or the `queryType` used to create `queryPool` was not `VK_QUERY_TYPE_OCCLUSION`, flags must not contain `VK_QUERY_CONTROL_PRECISE_BIT`.

- `query` must be less than the number of queries in `queryPool`.

- If the `queryType` used to create `queryPool` was `VK_QUERY_TYPE_OCCLUSION`, the `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations.

- If the `queryType` used to create `queryPool` was `VK_QUERY_TYPE_PIPELINE_STATISTICS` and any of the `pipelineStatistics` indicate graphics operations, the `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations.

- `commandBuffer` must not be a protected command buffer.

- If called within a render pass instance, the sum of `query` and the number of bits set in the current subpass’s view mask must be less than or equal to the number of queries in `queryPool`.

- If `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR`, the profiling lock must have been held before `vkBeginCommandBuffer` was called on `commandBuffer`.

- If `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR` and one of the counters used to create `queryPool` was `VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_BUFFER_KHR`, the query begin must be the first recorded command in `commandBuffer`.

- If `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR` and one of the counters used to create `queryPool` was `VK_PERFORMANCE_COUNTER_SCOPE_RENDER_PASS_KHR`, the begin command must not be recorded within a render pass instance.

- If `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR` and another query pool with a `queryType` `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR` has been used within `commandBuffer`, its parent primary command buffer or secondary command buffer recorded within the same parent primary command buffer as `commandBuffer`, the performanceCounterMultipleQueryPools feature must be enabled.

- If `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR`, this command must not be recorded in a command buffer that, either directly or through secondary command buffers, also contains a `vkCmdResetQueryPool` command affecting the same query.
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `queryPool` must be a valid `VkQueryPool` handle
- `flags` must be a valid combination of `VkQueryControlFlagBits` values
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, or compute operations
- Both of `commandBuffer`, and `queryPool` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td>Compute</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bits which can be set in `vkCmdBeginQuery::flags`, specifying constraints on the types of queries that can be performed, are:

```c
typedef enum VkQueryControlFlagBits {
    VK_QUERY_CONTROL_PRECISE_BIT = 0x00000001,
    VK_QUERY_CONTROL_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkQueryControlFlagBits;
```

- `VK_QUERY_CONTROL_PRECISE_BIT` specifies the precision of occlusion queries.

```c
typedef VkFlags VkQueryControlFlags;
```

`VkQueryControlFlags` is a bitmask type for setting a mask of zero or more `VkQueryControlFlagBits`.

To end a query after the set of desired draw or dispatch commands is executed, call:
```c
void vkCmdEndQuery(
    VkCommandBuffer                             commandBuffer,
    VkQueryPool                                 queryPool,
    uint32_t                                    query);
```

- `commandBuffer` is the command buffer into which this command will be recorded.
- `queryPool` is the query pool that is managing the results of the query.
- `query` is the query index within the query pool where the result is stored.

As queries operate asynchronously, ending a query does not immediately set the query's status to available. A query is considered *finished* when the final results of the query are ready to be retrieved by `vkGetQueryPoolResults` and `vkCmdCopyQueryPoolResults`, and this is when the query's status is set to available.

Once a query is ended the query must finish in finite time, unless the state of the query is changed using other commands, e.g. by issuing a reset of the query.

### Valid Usage

- All queries used by the command must be active
- `query` must be less than the number of queries in `queryPool`
- `commandBuffer` must not be a protected command buffer
- If `vkCmdEndQuery` is called within a render pass instance, the sum of `query` and the number of bits set in the current subpass's view mask must be less than or equal to the number of queries in `queryPool`
- If `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR` and one or more of the counters used to create `queryPool` was `VK_PERFORMANCE_COUNTER_SCOPE_COMMAND_BUFFER_KHR`, the `vkCmdEndQuery` must be the last recorded command in `commandBuffer`
- If `queryPool` was created with a `queryType` of `VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR` and one or more of the counters used to create `queryPool` was `VK_PERFORMANCE_COUNTER_SCOPE_RENDER_PASS_KHR`, the `vkCmdEndQuery` must not be recorded within a render pass instance
Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `queryPool` **must** be a valid `VkQueryPool` handle
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics, or compute operations
- Both of `commandBuffer`, and `queryPool` **must** have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

An application **can** retrieve results either by requesting they be written into application-provided memory, or by requesting they be copied into a `VkBuffer`. In either case, the layout in memory is defined as follows:

- The first query's result is written starting at the first byte requested by the command, and each subsequent query's result begins `stride` bytes later.
- Occlusion queries, pipeline statistics queries, and timestamp queries store results in a tightly packed array of unsigned integers, either 32- or 64-bits as requested by the command, storing the numerical results and, if requested, the availability status.
- Performance queries store results in a tightly packed array whose type is determined by the `unit` member of the corresponding `VkPerformanceCounterKHR`.
- If `VK_QUERY_RESULT_WITH_AVAILABILITY_BIT` is used, the final element of each query's result is an integer indicating whether the query's result is available, with any non-zero value indicating that it is available.
- Occlusion queries write one integer value - the number of samples passed. Pipeline statistics queries write one integer value for each bit that is enabled in the `pipelineStatistics` when the pool is created, and the statistics values are written in bit order starting from the least significant bit. Timestamp queries write one integer value. Performance queries write one...
 VkPerformanceCounterResultKHR value for each VkPerformanceCounterKHR in the query.

- If more than one query is retrieved and stride is not at least as large as the size of the array of values corresponding to a single query, the values written to memory are undefined.

To retrieve status and results for a set of queries, call:

```c
VkResult vkGetQueryPoolResults(
   VkDevice                                    device,  
    VkQueryPool                                 queryPool,  
    uint32_t                                    firstQuery,  
    uint32_t                                    queryCount,  
    size_t                                      dataSize,  
    void*                                       pData,  
    VkDeviceSize                                stride,  
    VkQueryResultFlags                          flags);
```

- **device** is the logical device that owns the query pool.
- **queryPool** is the query pool managing the queries containing the desired results.
- **firstQuery** is the initial query index.
- **queryCount** is the number of queries to read.
- **dataSize** is the size in bytes of the buffer pointed to by **pData**.
- **pData** is a pointer to a user-allocated buffer where the results will be written
- **stride** is the stride in bytes between results for individual queries within **pData**.
- **flags** is a bitmask of **VkQueryResultFlagBits** specifying how and when results are returned.

The range of queries read is defined by \([\text{firstQuery}, \text{firstQuery} + \text{queryCount} - 1]\). For pipeline statistics queries, each query index in the pool contains one integer value for each bit that is enabled in **VkQueryPoolCreateInfo**:pipelineStatistics when the pool is created.

If no bits are set in **flags**, and all requested queries are in the available state, results are written as an array of 32-bit unsigned integer values. The behavior when not all queries are available, is described below.

If **VK_QUERY_RESULT_64_BIT** is not set and the result overflows a 32-bit value, the value may either wrap or saturate. Similarly, if **VK_QUERY_RESULT_64_BIT** is set and the result overflows a 64-bit value, the value may either wrap or saturate.

If **VK_QUERY_RESULT_WAIT_BIT** is set, Vulkan will wait for each query to be in the available state before retrieving the numerical results for that query. In this case, **vkGetQueryPoolResults** is guaranteed to succeed and return **VK_SUCCESS** if the queries become available in a finite time (i.e. if they have been issued and not reset). If queries will never finish (e.g. due to being reset but not issued), then **vkGetQueryPoolResults** may not return in finite time.

If **VK_QUERY_RESULT_WAIT_BIT** and **VK_QUERY_RESULT_PARTIAL_BIT** are both not set then no result values are written to **pData** for queries that are in the unavailable state at the time of the call, and **vkGetQueryPoolResults** returns **VK_NOT_READY**. However, availability state is still written to **pData** for
those queries if VK_QUERY_RESULT_WITH_AVAILABILITY_BIT is set.

**Note**
Applications **must** take care to ensure that use of the VK_QUERY_RESULT_WAIT_BIT bit has the desired effect.

For example, if a query has been used previously and a command buffer records the commands `vkCmdResetQueryPool`, `vkCmdBeginQuery`, and `vkCmdEndQuery` for that query, then the query will remain in the available state until the `vkCmdResetQueryPool` command executes on a queue. Applications **can** use fences or events to ensure that a query has already been reset before checking for its results or availability status. Otherwise, a stale value could be returned from a previous use of the query.

The above also applies when VK_QUERY_RESULT_WAIT_BIT is used in combination with VK_QUERY_RESULT_WITH_AVAILABILITY_BIT. In this case, the returned availability status **may** reflect the result of a previous use of the query unless the `vkCmdResetQueryPool` command has been executed since the last use of the query.

**Note**
Applications **can** double-buffer query pool usage, with a pool per frame, and reset queries at the end of the frame in which they are read.

If VK_QUERY_RESULT_PARTIAL_BIT is set, VK_QUERY_RESULT_WAIT_BIT is not set, and the query’s status is unavailable, an intermediate result value between zero and the final result value is written to `pData` for that query.

If VK_QUERY_RESULT_WITH_AVAILABILITY_BIT is set, the final integer value written for each query is non-zero if the query’s status was available or zero if the status was unavailable. When VK_QUERY_RESULT_WITH_AVAILABILITY_BIT is used, implementations **must** guarantee that if they return a non-zero availability value then the numerical results **must** be valid, assuming the results are not reset by a subsequent command.

**Note**
Satisfying this guarantee **may** require careful ordering by the application, e.g. to read the availability status before reading the results.
Valid Usage

- **firstQuery must** be less than the number of queries in queryPool
- If VK_QUERY_RESULT_64_BIT is not set in flags, then pData and stride **must** be multiples of 4
- If VK_QUERY_RESULT_64_BIT is not set in flags and the queryType used to create queryPool was not VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR, then pData and stride **must** be multiples of 4
- If VK_QUERY_RESULT_64_BIT is set in flags then pData and stride **must** be multiples of 8
- If the queryType used to create queryPool was VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR, then pData and stride **must** be multiples of the size of VkPerformanceCounterResultKHR
- The sum of firstQuery and queryCount **must** be less than or equal to the number of queries in queryPool
- **dataSize must** be large enough to contain the result of each query, as described [here](#)
- If the queryType used to create queryPool was VK_QUERY_TYPE_TIMESTAMP, flags **must** not contain VK_QUERY_RESULT_PARTIAL_BIT
- If the queryType used to create queryPool was VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR, flags **must** not contain VK_QUERY_RESULT_WITH_AVAILABILITY_BIT, VK_QUERY_RESULT_PARTIAL_BIT or VK_QUERY_RESULT_64_BIT
- If the queryType used to create queryPool was VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR, the queryPool **must** have been recorded once for each pass as retrieved via a call to vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR

Valid Usage (Implicit)

- **device must** be a valid VkDevice handle
- **queryPool must** be a valid VkQueryPool handle
- **pData must** be a valid pointer to an array of dataSize bytes
- **flags must** be a valid combination of VkQueryResultFlagBits values
- **dataSize must** be greater than 0
- **queryPool must** have been created, allocated, or retrieved from device
Return Codes

**Success**

- VK_SUCCESS
- VK_NOT_READY

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST

Bits which can be set in `vkGetQueryPoolResults::flags` and `vkCmdCopyQueryPoolResults::flags`, specifying how and when results are returned, are:

```c
typedef enum VkQueryResultFlagBits {
    VK_QUERY_RESULT_64_BIT = 0x00000001,
    VK_QUERY_RESULT_WAIT_BIT = 0x00000002,
    VK_QUERY_RESULT_WITH_AVAILABILITY_BIT = 0x00000004,
    VK_QUERY_RESULT_PARTIAL_BIT = 0x00000008,
    VK_QUERY_RESULT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkQueryResultFlagBits;
```

- **VK_QUERY_RESULT_64_BIT** specifies the results will be written as an array of 64-bit unsigned integer values. If this bit is not set, the results will be written as an array of 32-bit unsigned integer values.

- **VK_QUERY_RESULT_WAIT_BIT** specifies that Vulkan will wait for each query’s status to become available before retrieving its results.

- **VK_QUERY_RESULT_WITH_AVAILABILITY_BIT** specifies that the availability status accompanies the results.

- **VK_QUERY_RESULT_PARTIAL_BIT** specifies that returning partial results is acceptable.

```c
typedef VkFlags VkQueryResultFlags;
```

`VkQueryResultFlags` is a bitmask type for setting a mask of zero or more `VkQueryResultFlagBits`.

To copy query statuses and numerical results directly to buffer memory, call:
void vkCmdCopyQueryPoolResults(
    VkCommandBuffer commandBuffer,  
    VkQueryPool queryPool,  
    uint32_t firstQuery,  
    uint32_t queryCount,  
    VkBuffer dstBuffer,  
    VkDeviceSize dstOffset,  
    VkDeviceSize stride,  
    VkQueryResultFlags flags);

- **commandBuffer** is the command buffer into which this command will be recorded.
- **queryPool** is the query pool managing the queries containing the desired results.
- **firstQuery** is the initial query index.
- **queryCount** is the number of queries. **firstQuery** and **queryCount** together define a range of queries.
- **dstBuffer** is a VkBuffer object that will receive the results of the copy command.
- **dstOffset** is an offset into dstBuffer.
- **stride** is the stride in bytes between results for individual queries within dstBuffer. The required size of the backing memory for dstBuffer is determined as described above for vkGetQueryPoolResults.
- **flags** is a bitmask of VkQueryResultFlagBits specifying how and when results are returned.

**vkCmdCopyQueryPoolResults** is guaranteed to see the effect of previous uses of **vkCmdResetQueryPool** in the same queue, without any additional synchronization. Thus, the results will always reflect the most recent use of the query.

**flags** has the same possible values described above for the **flags** parameter of **vkGetQueryPoolResults**, but the different style of execution causes some subtle behavioral differences. Because **vkCmdCopyQueryPoolResults** executes in order with respect to other query commands, there is less ambiguity about which use of a query is being requested.

Results for all requested occlusion queries, pipeline statistics queries, and timestamp queries are written as 64-bit unsigned integer values if **VK_QUERY_RESULT_64_BIT** is set or 32-bit unsigned integer values otherwise. Performance queries store results in a tightly packed array whose type is determined by the unit member of the corresponding VkPerformanceCounterKHR.

If neither of **VK_QUERY_RESULT_WAIT_BIT** and **VK_QUERY_RESULT_WITH_AVAILABILITY_BIT** are set, results are only written out for queries in the available state.

If **VK_QUERY_RESULT_WAIT_BIT** is set, the implementation will wait for each query’s status to be in the available state before retrieving the numerical results for that query. This is guaranteed to reflect the most recent use of the query on the same queue, assuming that the query is not being simultaneously used by other queues. If the query does not become available in a finite amount of time (e.g. due to not issuing a query since the last reset), a **VK_ERROR_DEVICE_LOST** error may occur.

Similarly, if **VK_QUERY_RESULT_WITH_AVAILABILITY_BIT** is set and **VK_QUERY_RESULT_WAIT_BIT** is not set,
the availability is guaranteed to reflect the most recent use of the query on the same queue, assuming that the query is not being simultaneously used by other queues. As with vkGetQueryPoolResults, implementations must guarantee that if they return a non-zero availability value, then the numerical results are valid.

If VK_QUERY_RESULT_PARTIAL_BIT is set, VK_QUERY_RESULT_WAIT_BIT is not set, and the query's status is unavailable, an intermediate result value between zero and the final result value is written for that query.

VK_QUERY_RESULT_PARTIAL_BIT must not be used if the pool's queryType is VK_QUERY_TYPE_TIMESTAMP.

vkCmdCopyQueryPoolResults is considered to be a transfer operation, and its writes to buffer memory must be synchronized using VK_PIPELINE_STAGE_TRANSFER_BIT and VK_ACCESS_TRANSFER_WRITE_BIT before using the results.

### Valid Usage

- **dstOffset** must be less than the size of **dstBuffer**
- **firstQuery** must be less than the number of queries in **queryPool**
- The sum of **firstQuery** and **queryCount** must be less than or equal to the number of queries in **queryPool**
- If VK_QUERY_RESULT_64_BIT is not set in **flags** then **dstOffset** and **stride** must be multiples of 4
- If VK_QUERY_RESULT_64_BIT is set in **flags** then **dstOffset** and **stride** must be multiples of 8
- **dstBuffer** must have enough storage, from **dstOffset**, to contain the result of each query, as described [here](#)
- **dstBuffer** must have been created with VK_BUFFER_USAGE_TRANSFER_DST_BIT usage flag
- If **dstBuffer** is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object
- If the **queryType** used to create **queryPool** was VK_QUERY_TYPE_TIMESTAMP, **flags** must not contain VK_QUERY_RESULT_PARTIAL_BIT
- If the **queryType** used to create **queryPool** was VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR, VkPhysicalDevicePerformanceQueryPropertiesKHR::allowCommandBufferQueryCopies must be VK_TRUE
- If the **queryType** used to create **queryPool** was VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR, **flags** must not contain VK_QUERY_RESULT_WITH_AVAILABILITY_BIT, VK_QUERY_RESULT_PARTIAL_BIT or VK_QUERY_RESULT_64_BIT
- If the **queryType** used to create **queryPool** was VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR, the **queryPool** must have been submitted once for each pass as retrieved via a call to vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `queryPool` must be a valid `VkQueryPool` handle
- `dstBuffer` must be a valid `VkBuffer` handle
- `flags` must be a valid combination of `VkQueryResultFlagBits` values
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics, or compute operations
- This command must only be called outside of a render pass instance
- Each of `commandBuffer`, `dstBuffer`, and `queryPool` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

Rendering operations such as clears, MSAA resolves, attachment load/store operations, and blits may count towards the results of queries. This behavior is implementation-dependent and may vary depending on the path used within an implementation. For example, some implementations have several types of clears, some of which may include vertices and some not.

16.3. Occlusion Queries

Occlusion queries track the number of samples that pass the per-fragment tests for a set of drawing commands. As such, occlusion queries are only available on queue families supporting graphics operations. The application can then use these results to inform future rendering decisions. An occlusion query is begun and ended by calling `vkCmdBeginQuery` and `vkCmdEndQuery`, respectively. When an occlusion query begins, the count of passing samples always starts at zero. For each drawing command, the count is incremented as described in Sample Counting. If `flags` does not contain `VK_QUERY_CONTROL_PRECISE_BIT` an implementation may generate any non-zero result value for the query if the count of passing samples is non-zero.
Note
Not setting `VK_QUERY_CONTROL_PRECISE_BIT` mode **may** be more efficient on some implementations, and **should** be used where it is sufficient to know a boolean result on whether any samples passed the per-fragment tests. In this case, some implementations **may** only return zero or one, indifferent to the actual number of samples passing the per-fragment tests.

When an occlusion query finishes, the result for that query is marked as available. The application **can** then either copy the result to a buffer (via `vkCmdCopyQueryPoolResults`) or request it be put into host memory (via `vkGetQueryPoolResults`).

**Note**
If occluding geometry is not drawn first, samples **can** pass the depth test, but still not be visible in a final image.

### 16.4. Pipeline Statistics Queries

Pipeline statistics queries allow the application to sample a specified set of `VkPipeline` counters. These counters are accumulated by Vulkan for a set of either draw or dispatch commands while a pipeline statistics query is active. As such, pipeline statistics queries are available on queue families supporting either graphics or compute operations. The availability of pipeline statistics queries is indicated by the `pipelineStatisticsQuery` member of the `VkPhysicalDeviceFeatures` object (see `vkGetPhysicalDeviceFeatures` and `vkCreateDevice` for detecting and requesting this query type on a `VkDevice`).

A pipeline statistics query is begun and ended by calling `vkCmdBeginQuery` and `vkCmdEndQuery`, respectively. When a pipeline statistics query begins, all statistics counters are set to zero. While the query is active, the pipeline type determines which set of statistics are available, but these **must** be configured on the query pool when it is created. If a statistic counter is issued on a command buffer that does not support the corresponding operation, the value of that counter is undefined after the query has finished. At least one statistic counter relevant to the operations supported on the recording command buffer **must** be enabled.

Bits which **can** be set to individually enable pipeline statistics counters for query pools with `VkQueryPoolCreateInfo::pipelineStatistics`, and for secondary command buffers with `VkCommandBufferInheritanceInfo::pipelineStatistics`, are:
typedef enum VkQueryPipelineStatisticFlagBits {
    VK_QUERY_PIPELINE_STATISTIC_INPUT.Assembley_VERTICES_BIT = 0x00000001,
    VK_QUERY_PIPELINE_STATISTIC_INPUT.Assembly_PRIMITIVES_BIT = 0x00000002,
    VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT = 0x00000004,
    VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT = 0x00000008,
    VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT = 0x00000010,
    VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT = 0x00000020,
    VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT = 0x00000040,
    VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT = 0x00000080,
    VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT = 0x00000100,
    VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT = 0x00000200,
    VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT = 0x00000400,
    VK_QUERY_PIPELINE_STATISTIC_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkQueryPipelineStatisticFlagBits;

- **VK_QUERY_PIPELINE_STATISTIC_INPUT.Assembly_VERTICES_BIT** specifies that queries managed by the pool will count the number of vertices processed by the **input assembly** stage. Vertices corresponding to incomplete primitives may contribute to the count.

- **VK_QUERY_PIPELINE_STATISTIC_INPUT.Assembly_PRIMITIVES_BIT** specifies that queries managed by the pool will count the number of primitives processed by the **input assembly** stage. If primitive restart is enabled, restarting the primitive topology has no effect on the count. Incomplete primitives may be counted.

- **VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of vertex shader invocations. This counter's value is incremented each time a vertex shader is invoked.

- **VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of geometry shader invocations. This counter's value is incremented each time a geometry shader is invoked. In the case of **instanced geometry shaders**, the geometry shader invocations count is incremented for each separate instanced invocation.

- **VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT** specifies that queries managed by the pool will count the number of primitives generated by geometry shader invocations. The counter's value is incremented each time the geometry shader emits a primitive. Restarting primitive topology using the SPIR-V instructions **OpEndPrimitive** or **OpEndStreamPrimitive** has no effect on the geometry shader output primitives count.

- **VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of primitives processed by the **Primitive Clipping** stage of the pipeline. The counter's value is incremented each time a primitive reaches the primitive clipping stage.

- **VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT** specifies that queries managed by the pool will count the number of primitives output by the **Primitive Clipping** stage of the pipeline. The counter's value is incremented each time a primitive passes the primitive clipping stage. The actual number of primitives output by the primitive clipping stage for a particular input primitive is implementation-dependent but must satisfy the following conditions:
If at least one vertex of the input primitive lies inside the clipping volume, the counter is incremented by one or more.

Otherwise, the counter is incremented by zero or more.

- **VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of fragment shader invocations. The counter's value is incremented each time the fragment shader is invoked.

- **VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT** specifies that queries managed by the pool will count the number of patches processed by the tessellation control shader. The counter's value is incremented once for each patch for which a tessellation control shader is invoked.

- **VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of invocations of the tessellation evaluation shader. The counter's value is incremented each time the tessellation evaluation shader is invoked.

- **VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT** specifies that queries managed by the pool will count the number of compute shader invocations. The counter's value is incremented every time the compute shader is invoked. Implementations may skip the execution of certain compute shader invocations or execute additional compute shader invocations for implementation-dependent reasons as long as the results of rendering otherwise remain unchanged.

These values are intended to measure relative statistics on one implementation. Various device architectures will count these values differently. Any or all counters may be affected by the issues described in *Query Operation*.

> **Note**
> For example, tile-based rendering devices may need to replay the scene multiple times, affecting some of the counts.

If a pipeline has *rasterizerDiscardEnable* enabled, implementations may discard primitives after the final vertex processing stage. As a result, if *rasterizerDiscardEnable* is enabled, the clipping input and output primitives counters may not be incremented.

When a pipeline statistics query finishes, the result for that query is marked as available. The application can copy the result to a buffer (via *vkCmdCopyQueryPoolResults*), or request it be put into host memory (via *vkGetQueryPoolResults*).

```typedef VkFlags VkQueryPipelineStatisticFlags;```

*VkQueryPipelineStatisticFlags* is a bitmask type for setting a mask of zero or more *VkQueryPipelineStatisticFlagBits*.

### 16.5. Timestamp Queries

*Timestamps* provide applications with a mechanism for timing the execution of commands. A
timestamp is an integer value generated by the VkPhysicalDevice. Unlike other queries, timestamps do not operate over a range, and so do not use vkCmdBeginQuery or vkCmdEndQuery. The mechanism is built around a set of commands that allow the application to tell the VkPhysicalDevice to write timestamp values to a query pool and then either read timestamp values on the host (using vkGetQueryPoolResults) or copy timestamp values to a VkBuffer (using vkCmdCopyQueryPoolResults). The application can then compute differences between timestamps to determine execution time.

The number of valid bits in a timestamp value is determined by the VkQueueFamilyProperties::timestampValidBits property of the queue on which the timestamp is written. Timestamps are supported on any queue which reports a non-zero value for timestampValidBits via vkGetPhysicalDeviceQueueFamilyProperties. If the timestampComputeAndGraphics limit is VK_TRUE, timestamps are supported by every queue family that supports either graphics or compute operations (see VkQueueFamilyProperties).

The number of nanoseconds it takes for a timestamp value to be incremented by 1 can be obtained from VkPhysicalDeviceLimits::timestampPeriod after a call to vkGetPhysicalDeviceProperties.

To request a timestamp, call:

```c
void vkCmdWriteTimestamp(
    VkCommandBuffer commandBuffer,
    VkPipelineStageFlagBits pipelineStage,
    VkQueryPool queryPool,
    uint32_t query);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `pipelineStage` is one of the VkPipelineStageFlagBits, specifying a stage of the pipeline.
- `queryPool` is the query pool that will manage the timestamp.
- `query` is the query within the query pool that will contain the timestamp.

vkCmdWriteTimestamp latches the value of the timer when all previous commands have completed executing as far as the specified pipeline stage, and writes the timestamp value to memory. When the timestamp value is written, the availability status of the query is set to available.

**Note**

If an implementation is unable to detect completion and latch the timer at any specific stage of the pipeline, it may instead do so at any logically later stage.

vkCmdCopyQueryPoolResults can then be called to copy the timestamp value from the query pool into buffer memory, with ordering and synchronization behavior equivalent to how other queries operate. Timestamp values can also be retrieved from the query pool using vkGetQueryPoolResults. As with other queries, the query must be reset using vkCmdResetQueryPool before requesting the timestamp value be written to it.

While vkCmdWriteTimestamp can be called inside or outside of a render pass instance, vkCmdCopyQueryPoolResults must only be called outside of a render pass instance.
Timestamps may only be meaningfully compared if they are written by commands submitted to the same queue.

Note
An example of such a comparison is determining the execution time of a sequence of commands.

If `vkCmdWriteTimestamp` is called while executing a render pass instance that has multiview enabled, the timestamp uses N consecutive query indices in the query pool (starting at `query`) where N is the number of bits set in the view mask of the subpass the command is executed in. The resulting query values are determined by an implementation-dependent choice of one of the following behaviors:

- The first query is a timestamp value and (if more than one bit is set in the view mask) zero is written to the remaining queries. If two timestamps are written in the same subpass, the sum of the execution time of all views between those commands is the difference between the first query written by each command.

- All N queries are timestamp values. If two timestamps are written in the same subpass, the sum of the execution time of all views between those commands is the sum of the difference between corresponding queries written by each command. The difference between corresponding queries may be the execution time of a single view.

In either case, the application can sum the differences between all N queries to determine the total execution time.

Valid Usage

- `queryPool` must have been created with a `queryType` of `VK_QUERY_TYPE_TIMESTAMP`
- The query identified by `queryPool` and `query` must be unavailable
- The command pool's queue family must support a non-zero `timestampValidBits`
- All queries used by the command must be unavailable
- If `vkCmdWriteTimestamp` is called within a render pass instance, the sum of `query` and the number of bits set in the current subpass's view mask must be less than or equal to the number of queries in `queryPool`
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `pipelineStage` must be a valid `VkPipelineStageFlagBits` value
- `queryPool` must be a valid `VkQueryPool` handle
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations
- Both of `commandBuffer`, and `queryPool` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Transfer</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

16.6. Performance Queries

*Performance queries* provide applications with a mechanism for getting performance counter information about the execution of command buffers, render passes, and commands.

Each queue family advertises the performance counters that can be queried on a queue of that family via a call to `vkEnumeratePhysicalDeviceQueueFamilyPerformanceQueryCountersKHR`. Implementations may limit access to performance counters based on platform requirements or only to specialized drivers for development purposes.

*Note*

This may include no performance counters being enumerated, or a reduced set. Please refer to platform-specific documentation for guidance on any such restrictions.

Performance queries use the existing `vkCmdBeginQuery` and `vkCmdEndQuery` to control what
command buffers, render passes, or commands to get performance information for.

Implementations may require multiple passes where the command buffer, render passes, or commands being recorded are the same and are executed on the same queue to record performance counter data. This is achieved by submitting the same batch and providing a `VkPerformanceQuerySubmitInfoKHR` structure containing a counter pass index. The number of passes required for a given performance query pool can be queried via a call to `vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR`.

Note

Command buffers created with `VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT` must not be re-submitted. Changing command buffer usage bits may affect performance. To avoid this, the application should re-record any command buffers with the `VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT` when multiple counter passes are required.

Performance counter results from a performance query pool can be obtained with the command `vkGetQueryPoolResults`.

Performance query results are returned in an array of `VkPerformanceCounterResultKHR` unions containing the data associated with each counter in the query, stored in the same order as the counters supplied in `pCounterIndices` when creating the performance query. The `VkPerformanceCounterKHR::unit` enumeration specifies how to parse the counter data.

typedef union VkPerformanceCounterResultKHR {
   int32_t     int32;
   int64_t     int64;
   uint32_t    uint32;
   uint64_t    uint64;
   float       float32;
   double      float64;
} VkPerformanceCounterResultKHR;

16.6.1. Profiling Lock

To record and submit a command buffer that contains a performance query pool the profiling lock must be held. The profiling lock must be acquired prior to any call to `vkBeginCommandBuffer` that will be using a performance query pool. The profiling lock must be held while any command buffer that contains a performance query pool is in the recording, executable, or pending state. To acquire the profiling lock, call:

```
VkResult vkAcquireProfilingLockKHR(
    VkDevice                                    device,
    const VkAcquireProfilingLockInfoKHR*        pInfo);
```

- device is the logical device to profile.
• pInfo is a pointer to a VkAcquireProfilingLockInfoKHR structure which contains information about how the profiling is to be acquired.

Implementations may allow multiple actors to hold the profiling lock concurrently.

### Valid Usage (Implicit)

- device must be a valid VkDevice handle
- pInfo must be a valid pointer to a valid VkAcquireProfilingLockInfoKHR structure

### Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_TIMEOUT

The VkAcquireProfilingLockInfoKHR structure is defined as:

```c
typedef struct VkAcquireProfilingLockInfoKHR {
    VkStructureType                   sType;
    const void*                       pNext;
    VkAcquireProfilingLockFlagsKHR    flags;
    uint64_t                          timeout;
} VkAcquireProfilingLockInfoKHR;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- flags is reserved for future use.
- timeout indicates how long the function waits, in nanoseconds, if the profiling lock is not available.

### Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_ACQUIRE_PROFILING_LOCK_INFO_KHR
- pNext must be NULL
- flags must be 0

If timeout is 0, vkAcquireProfilingLockKHR will not block while attempting to acquire the profiling lock. If timeout is UINT64_MAX, the function will not return until the profiling lock was acquired.
typedef enum VkAcquireProfilingLockFlagBitsKHR {
    VK_ACQUIRE_PROFILING_LOCK_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkAcquireProfilingLockFlagBitsKHR;

typedef VkFlags VkAcquireProfilingLockFlagsKHR;

VkAcquireProfilingLockFlagsKHR is a bitmask type for setting a mask, but is currently reserved for future use.

To release the profiling lock, call:

```c
void vkReleaseProfilingLockKHR(
    VkDevice device);
```

• device is the logical device to cease profiling on.

Valid Usage

• The profiling lock of device must have been held via a previous successful call to vkAcquireProfilingLockKHR

Valid Usage (Implicit)

• device must be a valid VkDevice handle
Chapter 17. Clear Commands

17.1. Clearing Images Outside A Render Pass Instance

Color and depth/stencil images can be cleared outside a render pass instance using `vkCmdClearColorImage` or `vkCmdClearDepthStencilImage`, respectively. These commands are only allowed outside of a render pass instance.

To clear one or more subranges of a color image, call:

```c
void vkCmdClearColorImage(
    VkCommandBuffer                             commandBuffer,
    VkImage                                     image,
    VkImageLayout                               imageLayout,
    const VkClearColorValue*                    pColor,
    uint32_t                                    rangeCount,
    const VkImageSubresourceRange*              pRanges);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `image` is the image to be cleared.
- `imageLayout` specifies the current layout of the image subresource ranges to be cleared, and must be `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR`, `VK_IMAGE_LAYOUT_GENERAL` or `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL`.
- `pColor` is a pointer to a `VkClearColorValue` structure containing the values that the image subresource ranges will be cleared to (see Clear Values below).
- `rangeCount` is the number of image subresource range structures in `pRanges`.
- `pRanges` is a pointer to an array of `VkImageSubresourceRange` structures describing a range of mipmap levels, array layers, and aspects to be cleared, as described in Image Views.

Each specified range in `pRanges` is cleared to the value specified by `pColor`. 
Valid Usage

- The format features of `image` must contain `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`.
- `image` must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` usage flag.
- `image` must not use a format listed in Formats requiring sampler Y’CBCR conversion for `VK_IMAGE_ASPECT_COLOR_BIT` image views.
- If `image` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.
- `imageLayout` must specify the layout of the image subresource ranges of `image` specified in `pRanges` at the time this command is executed on a `VkDevice`.
- `imageLayout` must be `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL`, `VK_IMAGE_LAYOUT_GENERAL`, or `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR`.
- The `VkImageSubresourceRange::aspectMask` members of the elements of the `pRanges` array must each only include `VK_IMAGE_ASPECT_COLOR_BIT`.
- The `VkImageSubresourceRange::baseMipLevel` members of the elements of the `pRanges` array must each be less than the `mipLevels` specified in `VkImageCreateInfo` when `image` was created.
- For each `VkImageSubresourceRange` element of `pRanges`, if the `levelCount` member is not `VK_REMAINING_MIP_LEVELS`, then `baseMipLevel + levelCount` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `image` was created.
- The `VkImageSubresourceRange::baseArrayLayer` members of the elements of the `pRanges` array must each be less than the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.
- For each `VkImageSubresourceRange` element of `pRanges`, if the `layerCount` member is not `VK_REMAINING_ARRAY_LAYERS`, then `baseArrayLayer + layerCount` must be less than the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.
- `image` must not have a compressed or depth/stencil format.
- If `commandBuffer` is an unprotected command buffer, then `image` must not be a protected image.
- If `commandBuffer` is a protected command buffer, then `image` must not be an unprotected image.
Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `image` **must** be a valid `VkImage` handle
- `imageLayout` **must** be a valid `VkImageLayout` value
- `pColor` **must** be a valid pointer to a valid `VkClearColorValue` union
- `pRanges` **must** be a valid pointer to an array of `rangeCount` valid `VkImageSubresourceRange` structures
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics, or compute operations
- This command **must** only be called outside of a render pass instance
- `rangeCount` **must** be greater than 0
- Both of `commandBuffer`, and `image` **must** have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

To clear one or more subranges of a depth/stencil image, call:

```c
void vkCmdClearDepthStencilImage(
    VkCommandBuffer                             commandBuffer,
    VkImage                                     image,
    VkImageLayout                               imageLayout,
    const VkClearColorValue*             pDepthStencil,
    uint32_t                                    rangeCount,
    const VkImageSubresourceRange*              pRanges);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
• **image** is the image to be cleared.

• **imageLayout** specifies the current layout of the image subresource ranges to be cleared, and **must** be **VK_IMAGE_LAYOUT_GENERAL** or **VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL**.

• **pDepthStencil** is a pointer to a **VkClearDepthStencilValue** structure containing the values that the depth and stencil image subresource ranges will be cleared to (see **Clear Values** below).

• **rangeCount** is the number of image subresource range structures in **pRanges**.

• **pRanges** is a pointer to an array of **VkImageSubresourceRange** structures describing a range of mipmap levels, array layers, and aspects to be cleared, as described in **Image Views**.
Valid Usage

- The format features of image must contain VK_FORMAT_FEATURE_TRANSFER_DST_BIT.
- image must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag
- If image is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object
- imageLayout must specify the layout of the image subresource ranges of image specified in pRanges at the time this command is executed on a VkDevice
- imageLayout must be either of VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL or VK_IMAGE_LAYOUT_GENERAL
- The VkImageSubresourceRange::aspectMask member of each element of the pRanges array must not include bits other than VK_IMAGE_ASPECT_DEPTH_BIT or VK_IMAGE_ASPECT_STENCIL_BIT
- If the image's format does not have a stencil component, then the VkImageSubresourceRange::aspectMask member of each element of the pRanges array must not include the VK_IMAGE_ASPECT_STENCIL_BIT bit
- If the image's format does not have a depth component, then the VkImageSubresourceRange::aspectMask member of each element of the pRanges array must not include the VK_IMAGE_ASPECT_DEPTH_BIT bit
- The VkImageSubresourceRange::baseMipLevel members of the elements of the pRanges array must each be less than the mipmap levels specified in VkImageCreateInfo when image was created
- For each VkImageSubresourceRange element of pRanges, if the levelCount member is not VK_REMAINING_MIP_LEVELS, then baseMipLevel + levelCount must be less than the mipmap levels specified in VkImageCreateInfo when image was created
- The VkImageSubresourceRange::baseArrayLayer members of the elements of the pRanges array must each be less than the arrayLayers specified in VkImageCreateInfo when image was created
- For each VkImageSubresourceRange element of pRanges, if the layerCount member is not VK_REMAINING_ARRAY_LAYERS, then baseArrayLayer + layerCount must be less than the arrayLayers specified in VkImageCreateInfo when image was created
- image must have a depth/stencil format
- If commandBuffer is an unprotected command buffer, then image must not be a protected image
- If commandBuffer is a protected command buffer, then image must not be an unprotected image
**Valid Usage (Implicit)**

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `image` **must** be a valid `VkImage` handle
- `imageLayout` **must** be a valid `VkImageLayout` value
- `pDepthStencil` **must** be a valid pointer to a valid `VkClearDepthStencilValue` structure
- `pRanges` **must** be a valid pointer to an array of `rangeCount` valid `VkImageSubresourceRange` structures
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations
- This command **must** only be called outside of a render pass instance
- `rangeCount` **must** be greater than 0
- Both of `commandBuffer`, and `image` **must** have been created, allocated, or retrieved from the same `VkDevice`

**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

**Command Properties**

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clears outside render pass instances are treated as transfer operations for the purposes of memory barriers.

**17.2. Clearing Images Inside A Render Pass Instance**

To clear one or more regions of color and depth/stencil attachments inside a render pass instance, call:
void vkCmdClearAttachments(
    VkCommandBuffer commandBuffer,
    uint32_t attachmentCount,
    const VkClearAttachment* pAttachments,
    uint32_t rectCount,
    const VkClearRect* pRects);

- *commandBuffer* is the command buffer into which the command will be recorded.
- *attachmentCount* is the number of entries in the *pAttachments* array.
- *pAttachments* is a pointer to an array of *VkClearAttachment* structures defining the attachments to clear and the clear values to use. If any attachment to be cleared in the current subpass is *VK_ATTACHMENT_UNUSED*, then the clear has no effect on that attachment.
- *rectCount* is the number of entries in the *pRects* array.
- *pRects* is a pointer to an array of *VkClearRect* structures defining regions within each selected attachment to clear.

*vkCmdClearAttachments* can clear multiple regions of each attachment used in the current subpass of a render pass instance. This command **must** be called only inside a render pass instance, and implicitly selects the images to clear based on the current framebuffer attachments and the command parameters.

Unlike other clear commands, *vkCmdClearAttachments* executes as a drawing command, rather than a transfer command, with writes performed by it executing in rasterization order. Clears to color attachments are executed as color attachment writes, by the *VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT* stage. Clears to depth/stencil attachments are executed as depth writes and writes by the *VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT* and *VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT* stages.
Valid Usage

- If the `aspectMask` member of any element of `pAttachments` contains `VK_IMAGE_ASPECT_COLOR_BIT`, then the `colorAttachment` member of that element **must** either refer to a color attachment which is `VK_ATTACHMENT_UNUSED`, or **must** be a valid color attachment.

- If the `aspectMask` member of any element of `pAttachments` contains `VK_IMAGE_ASPECT_DEPTH_BIT`, then the current subpass' depth/stencil attachment **must** either be `VK_ATTACHMENT_UNUSED`, or **must** have a depth component.

- If the `aspectMask` member of any element of `pAttachments` contains `VK_IMAGE_ASPECT_STENCIL_BIT`, then the current subpass' depth/stencil attachment **must** either be `VK_ATTACHMENT_UNUSED`, or **must** have a stencil component.

- The `rect` member of each element of `pRects` **must** have an `extent.width` greater than 0.
- The `rect` member of each element of `pRects` **must** have an `extent.height` greater than 0.
- The rectangular region specified by each element of `pRects` **must** be contained within the render area of the current render pass instance.
- The layers specified by each element of `pRects` **must** be contained within every attachment that `pAttachments` refers to.
- The `layerCount` member of each element of `pRects` **must** not be 0.
- If `commandBuffer` is an unprotected command buffer, then each attachment to be cleared **must** not be a protected image.
- If `commandBuffer` is a protected command buffer, then each attachment to be cleared **must** not be an unprotected image.
- If the render pass instance this is recorded in uses multiview, then `baseArrayLayer` **must** be zero and `layerCount` **must** be one.

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle.
- `pAttachments` **must** be a valid pointer to an array of `attachmentCount` valid `VkClearAttachment` structures.
- `pRects` **must** be a valid pointer to an array of `rectCount` `VkClearRect` structures.
- `commandBuffer` **must** be in the recording state.
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations.
- This command **must** only be called inside of a render pass instance.
- `attachmentCount` **must** be greater than 0.
- `rectCount` **must** be greater than 0.
Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VkClearRect structure is defined as:

```c
typedef struct VkClearRect {
    VkRect2D    rect;
    uint32_t    baseArrayLayer;
    uint32_t    layerCount;
} VkClearRect;
```

- `rect` is the two-dimensional region to be cleared.
- `baseArrayLayer` is the first layer to be cleared.
- `layerCount` is the number of layers to clear.

The layers `[baseArrayLayer, baseArrayLayer + layerCount)` counting from the base layer of the attachment image view are cleared.

The VkClearAttachment structure is defined as:

```c
typedef struct VkClearAttachment {
    VkImageAspectFlags    aspectMask;
    uint32_t              colorAttachment;
    VkClearValue          clearValue;
} VkClearAttachment;
```

- `aspectMask` is a mask selecting the color, depth and/or stencil aspects of the attachment to be cleared.
- `colorAttachment` is only meaningful if VK_IMAGE_ASPECT_COLOR_BIT is set in `aspectMask`, in which case it is an index to the `pColorAttachments` array in the VkSubpassDescription structure of the current subpass which selects the color attachment to clear.
- `clearValue` is the color or depth/stencil value to clear the attachment to, as described in Clear
No memory barriers are needed between `vkCmdClearAttachments` and preceding or subsequent draw or attachment clear commands in the same subpass.

The `vkCmdClearAttachments` command is not affected by the bound pipeline state.

Attachments can also be cleared at the beginning of a render pass instance by setting `loadOp` (or `stencilLoadOp`) of `VkAttachmentDescription` to `VK_ATTACHMENT_LOAD_OP_CLEAR`, as described for `vkCreateRenderPass`.

### Valid Usage

- If `aspectMask` includes `VK_IMAGE_ASPECT_COLOR_BIT`, it must not include `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT`
- `aspectMask` must not include `VK_IMAGE_ASPECT_METADATA_BIT`
- `clearValue` must be a valid `VkClearValue` union

### Valid Usage (Implicit)

- `aspectMask` must be a valid combination of `VkImageAspectFlagBits` values
- `aspectMask` must not be 0

### 17.3. Clear Values

The `VkClearColorValue` structure is defined as:

```c
typedef union VkClearColorValue {
    float float32[4];
    int32_t int32[4];
    uint32_t uint32[4];
} VkClearColorValue;
```

- `float32` are the color clear values when the format of the image or attachment is one of the formats in the Interpretation of Numeric Format table other than signed integer (`SINT`) or unsigned integer (`UINT`). Floating point values are automatically converted to the format of the image, with the clear value being treated as linear if the image is sRGB.

- `int32` are the color clear values when the format of the image or attachment is signed integer (`SINT`). Signed integer values are converted to the format of the image by casting to the smaller type (with negative 32-bit values mapping to negative values in the smaller type). If the integer clear value is not representable in the target type (e.g. would overflow in conversion to that type), the clear value is undefined.

- `uint32` are the color clear values when the format of the image or attachment is unsigned
integer (UINT). Unsigned integer values are converted to the format of the image by casting to the integer type with fewer bits.

The four array elements of the clear color map to R, G, B, and A components of image formats, in order.

If the image has more than one sample, the same value is written to all samples for any pixels being cleared.

The `VkClearDepthStencilValue` structure is defined as:

```c
typedef struct VkClearDepthStencilValue {
    float    depth;
    uint32_t stencil;
} VkClearDepthStencilValue;
```

- **depth** is the clear value for the depth aspect of the depth/stencil attachment. It is a floating-point value which is automatically converted to the attachment's format.
- **stencil** is the clear value for the stencil aspect of the depth/stencil attachment. It is a 32-bit integer value which is converted to the attachment's format by taking the appropriate number of LSBs.

### Valid Usage

- **depth** must be between 0.0 and 1.0, inclusive

The `VkClearValue` union is defined as:

```c
typedef union VkClearValue {
    VkClearColorValue color;
    VkClearDepthStencilValue depthStencil;
} VkClearValue;
```

- **color** specifies the color image clear values to use when clearing a color image or attachment.
- **depthStencil** specifies the depth and stencil clear values to use when clearing a depth/stencil image or attachment.

This union is used where part of the API requires either color or depth/stencil clear values, depending on the attachment, and defines the initial clear values in the `VkRenderPassBeginInfo` structure.

## 17.4. Filling Buffers

To clear buffer data, call:
void vkCmdFillBuffer(
    VkCommandBuffer                             commandBuffer,
    VkBuffer                                    dstBuffer,
    VkDeviceSize                                dstOffset,
    VkDeviceSize                                size,
    uint32_t                                    data);

- **commandBuffer** is the command buffer into which the command will be recorded.
- **dstBuffer** is the buffer to be filled.
- **dstOffset** is the byte offset into the buffer at which to start filling, and **must** be a multiple of 4.
- **size** is the number of bytes to fill, and **must** be either a multiple of 4, or **VK_WHOLE_SIZE** to fill the range from **offset** to the end of the buffer. If **VK_WHOLE_SIZE** is used and the remaining size of the buffer is not a multiple of 4, then the nearest smaller multiple is used.
- **data** is the 4-byte word written repeatedly to the buffer to fill **size** bytes of data. The data word is written to memory according to the hostendianness.

**vkCmdFillBuffer** is treated as “transfer” operation for the purposes of synchronization barriers. The **VK_BUFFER_USAGE_TRANSFER_DST_BIT** must be specified in usage of VkBufferCreateInfo in order for the buffer to be compatible with **vkCmdFillBuffer**.

**Valid Usage**

- **dstOffset** **must** be less than the size of **dstBuffer**
- **dstOffset** **must** be a multiple of 4
- If **size** is not equal to **VK_WHOLE_SIZE**, **size** **must** be greater than 0
- If **size** is not equal to **VK_WHOLE_SIZE**, **size** **must** be less than or equal to the size of **dstBuffer** minus **dstOffset**
- If **size** is not equal to **VK_WHOLE_SIZE**, **size** **must** be a multiple of 4
- **dstBuffer** **must** have been created with **VK_BUFFER_USAGE_TRANSFER_DST_BIT** usage flag
- If **dstBuffer** is non-sparse then it **must** be bound completely and contiguously to a single **VkDeviceMemory** object
- If **commandBuffer** is an unprotected command buffer, then **dstBuffer** **must** not be a protected buffer
- If **commandBuffer** is a protected command buffer, then **dstBuffer** **must** not be an unprotected buffer
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `dstBuffer` must be a valid `VkBuffer` handle
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics or compute operations
- This command must only be called outside of a render pass instance
- Both of `commandBuffer`, and `dstBuffer` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Transfer</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

17.5. Updating Buffers

To update buffer data inline in a command buffer, call:

```c
void vkCmdUpdateBuffer(  
    VkCommandBuffer commandBuffer,  
    VkBuffer dstBuffer,  
    VkDeviceSize dstOffset,  
    VkDeviceSize dataSize,  
    const void* pData);  
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `dstBuffer` is a handle to the buffer to be updated.
- `dstOffset` is the byte offset into the buffer to start updating, and must be a multiple of 4.
- `dataSize` is the number of bytes to update, and must be a multiple of 4.
• pData is a pointer to the source data for the buffer update, and must be at least dataSize bytes in size.

dataSize must be less than or equal to 65536 bytes. For larger updates, applications can use buffer to buffer copies.

Note
Buffer updates performed with vkCmdUpdateBuffer first copy the data into command buffer memory when the command is recorded (which requires additional storage and may incur an additional allocation), and then copy the data from the command buffer into dstBuffer when the command is executed on a device.

The additional cost of this functionality compared to buffer to buffer copies means it is only recommended for very small amounts of data, and is why it is limited to only 65536 bytes.

Applications can work around this by issuing multiple vkCmdUpdateBuffer commands to different ranges of the same buffer, but it is strongly recommended that they should not.

The source data is copied from the user pointer to the command buffer when the command is called.

vkCmdUpdateBuffer is only allowed outside of a render pass. This command is treated as “transfer” operation, for the purposes of synchronization barriers. The VK_BUFFER_USAGE_TRANSFER_DST_BIT must be specified in usage of VkBufferCreateInfo in order for the buffer to be compatible with vkCmdUpdateBuffer.

Valid Usage

• dstOffset must be less than the size of dstBuffer
• dataSize must be less than or equal to the size of dstBuffer minus dstOffset
• dstBuffer must have been created with VK_BUFFER_USAGE_TRANSFER_DST_BIT usage flag
• If dstBuffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object
• dstOffset must be a multiple of 4
• dataSize must be less than or equal to 65536
• dataSize must be a multiple of 4
• If commandBuffer is an unprotected command buffer, then dstBuffer must not be a protected buffer
• If commandBuffer is a protected command buffer, then dstBuffer must not be an unprotected buffer
Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `dstBuffer` **must** be a valid `VkBuffer` handle
- `pData` **must** be a valid pointer to an array of `dataSize` bytes
- `commandBuffer` **must** be in the *recording* state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations
- This command **must** only be called outside of a render pass instance
- `dataSize` **must** be greater than 0
- Both of `commandBuffer`, and `dstBuffer` **must** have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Transfer</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

**Note**

The `pData` parameter was of type `uint32_t*` instead of `void*` prior to version 1.0.19 of the Specification and `VK_HEADER_VERSION` 19 of the Vulkan Header Files. This was a historical anomaly, as the source data may be of other types.
Chapter 18. Copy Commands

An application can copy buffer and image data using several methods depending on the type of data transfer. Data can be copied between buffer objects with \texttt{vkCmdCopyBuffer} and a portion of an image can be copied to another image with \texttt{vkCmdCopyImage}. Image data can also be copied to and from buffer memory using \texttt{vkCmdCopyImageToBuffer} and \texttt{vkCmdCopyBufferToImage}. Image data can be blitted (with or without scaling and filtering) with \texttt{vkCmdBlitImage}. Multisampled images can be resolved to a non-multisampled image with \texttt{vkCmdResolveImage}.

18.1. Common Operation

The following valid usage rules apply to all copy commands:

- Copy commands \textbf{must} be recorded outside of a render pass instance.
- The set of all bytes bound to all the source regions \textbf{must} not overlap the set of all bytes bound to the destination regions.
- The set of all bytes bound to each destination region \textbf{must} not overlap the set of all bytes bound to another destination region.
- Copy regions \textbf{must} be non-empty.
- Regions \textbf{must} not extend outside the bounds of the buffer or image level, except that regions of compressed images \textbf{can} extend as far as the dimension of the image level rounded up to a complete compressed texel block.
- Source image subresources \textbf{must} be in either the \texttt{VK_IMAGE_LAYOUT_GENERAL} or \texttt{VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL} layout. Destination image subresources \textbf{must} be in the \texttt{VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR}, \texttt{VK_IMAGE_LAYOUT_GENERAL} or \texttt{VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL} layout. As a consequence, if an image subresource is used as both source and destination of a copy, it \textbf{must} be in the \texttt{VK_IMAGE_LAYOUT_GENERAL} layout.
- Source images \textbf{must} have \texttt{VK_FORMAT_FEATURE_TRANSFER_SRC_BIT} in their format features.
- Destination images \textbf{must} have \texttt{VK_FORMAT_FEATURE.Transfer_DST_BIT} in their format features.
- Source buffers \textbf{must} have been created with the \texttt{VK_BUFFER_USAGE_TRANSFER_SRC_BIT} usage bit enabled and destination buffers \textbf{must} have been created with the \texttt{VK_BUFFER_USAGE_TRANSFER_DST_BIT} usage bit enabled.
- Source images \textbf{must} have been created with \texttt{VK_IMAGE_USAGE_TRANSFER_SRC_BIT} set in \texttt{VkImageCreateInfo::usage}
- Destination images \textbf{must} have been created with \texttt{VK_IMAGE_USAGE_TRANSFER_DST_BIT} set in \texttt{VkImageCreateInfo::usage}

All copy commands are treated as “transfer” operations for the purposes of synchronization barriers.

All copy commands that have a source format with an X component in its format description read undefined values from those bits.

All copy commands that have a destination format with an X component in its format description
write undefined values to those bits.

18.2. Copying Data Between Buffers

To copy data between buffer objects, call:

```c
void vkCmdCopyBuffer(
    VkCommandBuffer commandBuffer,
    VkBuffer srcBuffer,
    VkBuffer dstBuffer,
    uint32_t regionCount,
    const VkBufferCopy* pRegions);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `srcBuffer` is the source buffer.
- `dstBuffer` is the destination buffer.
- `regionCount` is the number of regions to copy.
- `pRegions` is a pointer to an array of `VkBufferCopy` structures specifying the regions to copy.

Each region in `pRegions` is copied from the source buffer to the same region of the destination buffer. `srcBuffer` and `dstBuffer` can be the same buffer or alias the same memory, but the resulting values are undefined if the copy regions overlap in memory.
Valid Usage

- The `srcOffset` member of each element of `pRegions` **must** be less than the size of `srcBuffer`.
- The `dstOffset` member of each element of `pRegions` **must** be less than the size of `dstBuffer`.
- The `size` member of each element of `pRegions` **must** be less than or equal to the size of `srcBuffer` minus `srcOffset`.
- The `size` member of each element of `pRegions` **must** be less than or equal to the size of `dstBuffer` minus `dstOffset`.
- The union of the source regions, and the union of the destination regions, specified by the elements of `pRegions`, **must** not overlap in memory.
- `srcBuffer` **must** have been created with `VK_BUFFER_USAGE_TRANSFER_SRC_BIT` usage flag.
- If `srcBuffer` is non-sparse then it **must** be bound completely and contiguously to a single `VkDeviceMemory` object.
- `dstBuffer` **must** have been created with `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage flag.
- If `dstBuffer` is non-sparse then it **must** be bound completely and contiguously to a single `VkDeviceMemory` object.
- If `commandBuffer` is an unprotected command buffer, then `srcBuffer` **must** not be a protected buffer.
- If `commandBuffer` is an unprotected command buffer, then `dstBuffer` **must** not be a protected buffer.
- If `commandBuffer` is a protected command buffer, then `dstBuffer` **must** not be an unprotected buffer.

Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle.
- `srcBuffer` **must** be a valid `VkBuffer` handle.
- `dstBuffer` **must** be a valid `VkBuffer` handle.
- `pRegions` **must** be a valid pointer to an array of `regionCount` valid `VkBufferCopy` structures.
- `commandBuffer` **must** be in the `recording state`.
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support transfer, graphics, or compute operations.
- This command **must** only be called outside of a render pass instance.
- `regionCount` **must** be greater than 0.
- Each of `commandBuffer`, `dstBuffer`, and `srcBuffer` **must** have been created, allocated, or retrieved from the same `VkDevice`. 

704 | Chapter 18. Copy Commands
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Transfer</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

The `VkBufferCopy` structure is defined as:

```c
typedef struct VkBufferCopy {
    VkDeviceSize srcOffset;
    VkDeviceSize dstOffset;
    VkDeviceSize size;
} VkBufferCopy;
```

- `srcOffset` is the starting offset in bytes from the start of `srcBuffer`.
- `dstOffset` is the starting offset in bytes from the start of `dstBuffer`.
- `size` is the number of bytes to copy.

Valid Usage

- The `size` must be greater than 0

18.3. Copying Data Between Images

`vkCmdCopyImage` performs image copies in a similar manner to a host memcpy. It does not perform general-purpose conversions such as scaling, resizing, blending, color-space conversion, or format conversions. Rather, it simply copies raw image data. `vkCmdCopyImage` can copy between images with different formats, provided the formats are compatible as defined below.

To copy data between image objects, call:
void vkCmdCopyImage(
    VkCommandBuffer                             commandBuffer,
    VkImage                                     srcImage,
    VkImageLayout                               srcImageLayout,
    VkImage                                     dstImage,
    VkImageLayout                               dstImageLayout,
    uint32_t                                    regionCount,
    const VkImageCopy*                          pRegions);

• commandBuffer is the command buffer into which the command will be recorded.
• srcImage is the source image.
• srcImageLayout is the current layout of the source image subresource.
• dstImage is the destination image.
• dstImageLayout is the current layout of the destination image subresource.
• regionCount is the number of regions to copy.
• pRegions is a pointer to an array of VkImageCopy structures specifying the regions to copy.

Each region in pRegions is copied from the source image to the same region of the destination image. srcImage and dstImage can be the same image or alias the same memory.

The formats of srcImage and dstImage must be compatible. Formats are compatible if they share the same class, as shown in the Compatible Formats table. Depth/stencil formats must match exactly.

If the format of srcImage or dstImage is a multi-planar image format, regions of each plane to be copied must be specified separately using the srcSubresource and dstSubresource members of the VkImageCopy structure. In this case, the aspectMask of the srcSubresource or dstSubresource that refers to the multi-planar image must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT. For the purposes of vkCmdCopyImage, each plane of a multi-planar image is treated as having the format listed in Compatible formats of planes of multi-planar formats for the plane identified by the aspectMask of the corresponding subresource. This applies both to VkFormat and to coordinates used in the copy, which correspond to texels in the plane rather than how these texels map to coordinates in the image as a whole.

Note
For example, the VK_IMAGE_ASPECT_PLANE_1_BIT plane of a VK_FORMAT_G8_B8R8_2PLANE_420_UNORM image is compatible with an image of format VK_FORMAT_R8G8_UNORM and (less usefully) with the VK_IMAGE_ASPECT_PLANE_0_BIT plane of an image of format VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16, as each texel is 2 bytes in size.

vkCmdCopyImage allows copying between size-compatible compressed and uncompressed internal formats. Formats are size-compatible if the texel block size of the uncompressed format is equal to the texel block size of the compressed format. Such a copy does not perform on-the-fly compression or decompression. When copying from an uncompressed format to a compressed format, each
texel of uncompressed data of the source image is copied as a raw value to the corresponding compressed texel block of the destination image. When copying from a compressed format to an uncompressed format, each compressed texel block of the source image is copied as a raw value to the corresponding texel of uncompressed data in the destination image. Thus, for example, it is legal to copy between a 128-bit uncompressed format and a compressed format which has a 128-bit sized compressed texel block representing 4×4 texels (using 8 bits per texel), or between a 64-bit uncompressed format and a compressed format which has a 64-bit sized compressed texel block representing 4×4 texels (using 4 bits per texel).

When copying between compressed and uncompressed formats the extent members represent the texel dimensions of the source image and not the destination. When copying from a compressed image to an uncompressed image the image texel dimensions written to the uncompressed image will be source extent divided by the compressed texel block dimensions. When copying from an uncompressed image to a compressed image the image texel dimensions written to the compressed image will be the source extent multiplied by the compressed texel block dimensions. In both cases the number of bytes read and the number of bytes written will be identical.

Copying to or from block-compressed images is typically done in multiples of the compressed texel block size. For this reason the extent must be a multiple of the compressed texel block dimension. There is one exception to this rule which is required to handle compressed images created with dimensions that are not a multiple of the compressed texel block dimensions: if the srcImage is compressed, then:

- If extent.width is not a multiple of the compressed texel block width, then (extent.width + srcOffset.x) must equal the image subresource width.
- If extent.height is not a multiple of the compressed texel block height, then (extent.height + srcOffset.y) must equal the image subresource height.
- If extent.depth is not a multiple of the compressed texel block depth, then (extent.depth + srcOffset.z) must equal the image subresource depth.

Similarly, if the dstImage is compressed, then:

- If extent.width is not a multiple of the compressed texel block width, then (extent.width + dstOffset.x) must equal the image subresource width.
- If extent.height is not a multiple of the compressed texel block height, then (extent.height + dstOffset.y) must equal the image subresource height.
- If extent.depth is not a multiple of the compressed texel block depth, then (extent.depth + dstOffset.z) must equal the image subresource depth.

This allows the last compressed texel block of the image in each non-multiple dimension to be included as a source or destination of the copy.

“_422” image formats that are not multi-planar are treated as having a 2×1 compressed texel block for the purposes of these rules.

vkCmdCopyImage can be used to copy image data between multisample images, but both images must have the same number of samples.
Valid Usage

- The union of all source regions, and the union of all destination regions, specified by the elements of \texttt{pRegions}, \textbf{must} not overlap in memory.
- The format features of \texttt{srcImage} \textbf{must} contain \texttt{VK_FORMAT_FEATURE_TRANSFER_SRC_BIT}.
- \texttt{srcImage} \textbf{must} have been created with \texttt{VK_IMAGE_USAGE_TRANSFER_SRC_BIT} usage flag.
- If \texttt{srcImage} is non-sparse then the image or \textit{disjoint} plane to be copied \textbf{must} be bound completely and contiguously to a single \texttt{VkDeviceMemory} object.
- \texttt{srcImageLayout} \textbf{must} specify the layout of the image subresources of \texttt{srcImage} specified in \texttt{pRegions} at the time this command is executed on a \texttt{VkDevice}.
- \texttt{srcImageLayout} \textbf{must} be \texttt{VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL}, \texttt{VK_IMAGE_LAYOUT_GENERAL}, or \texttt{VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR}.
- The format features of \texttt{dstImage} \textbf{must} contain \texttt{VK_FORMAT_FEATURE_TRANSFER_DST_BIT}.
- \texttt{dstImage} \textbf{must} have been created with \texttt{VK_IMAGE_USAGE_TRANSFER_DST_BIT} usage flag.
- If \texttt{dstImage} is non-sparse then the image or \textit{disjoint} plane that is the destination of the copy \textbf{must} be bound completely and contiguously to a single \texttt{VkDeviceMemory} object.
- \texttt{dstImageLayout} \textbf{must} specify the layout of the image subresources of \texttt{dstImage} specified in \texttt{pRegions} at the time this command is executed on a \texttt{VkDevice}.
- \texttt{dstImageLayout} \textbf{must} be \texttt{VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL}, \texttt{VK_IMAGE_LAYOUT_GENERAL}, or \texttt{VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR}.
- If the \texttt{VkFormat} of each of \texttt{srcImage} and \texttt{dstImage} is not a \textit{multi-planar format}, the \texttt{VkFormat} of each of \texttt{srcImage} and \texttt{dstImage} \textbf{must} be compatible, as defined \textit{above}.
- In a copy to or from a plane of a \textit{multi-planar image}, the \texttt{VkFormat} of the image and plane \textbf{must} be compatible according to the \textit{description of compatible planes} for the plane being copied.
- The sample count of \texttt{srcImage} and \texttt{dstImage} \textbf{must} match.
- If \texttt{commandBuffer} is an unprotected command buffer, then \texttt{srcImage} \textbf{must} not be a protected image.
- If \texttt{commandBuffer} is an unprotected command buffer, then \texttt{dstImage} \textbf{must} not be a protected image.
- If \texttt{commandBuffer} is a protected command buffer, then \texttt{dstImage} \textbf{must} not be an unprotected image.
- The \texttt{srcSubresource.mipLevel} member of each element of \texttt{pRegions} \textbf{must} be less than the \texttt{mipLevels} specified in \texttt{VkImageCreateInfo} when \texttt{srcImage} was created.
- The \texttt{dstSubresource.mipLevel} member of each element of \texttt{pRegions} \textbf{must} be less than the \texttt{mipLevels} specified in \texttt{VkImageCreateInfo} when \texttt{dstImage} was created.
- The \texttt{srcSubresource.baseArrayLayer + srcSubresource.layerCount} of each element of \texttt{pRegions} \textbf{must} be less than or equal to the \texttt{arrayLayers} specified in \texttt{VkImageCreateInfo} when \texttt{srcImage} was created.
• The `dstSubresource.baseArrayLayer + dstSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `dstImage` was created.

• The `srcOffset` and `extent` members of each element of `pRegions` must respect the image transfer granularity requirements of `commandBuffer`'s command pool's queue family, as described in `VkQueueFamilyProperties`.

• The `dstOffset` and `extent` members of each element of `pRegions` must respect the image transfer granularity requirements of `commandBuffer`'s command pool's queue family, as described in `VkQueueFamilyProperties`.

### Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle.
- `srcImage` must be a valid `VkImage` handle.
- `srcImageLayout` must be a valid `VkImageLayout` value.
- `dstImage` must be a valid `VkImage` handle.
- `dstImageLayout` must be a valid `VkImageLayout` value.
- `pRegions` must be a valid pointer to an array of `regionCount` valid `VkImageCopy` structures.
- `commandBuffer` must be in the recording state.
- The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations.
- This command must only be called outside of a render pass instance.
- `regionCount` must be greater than 0.
- Each of `commandBuffer`, `dstImage`, and `srcImage` must have been created, allocated, or retrieved from the same `VkDevice`.

### Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.
Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Transfer</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

The VkImageCopy structure is defined as:

```c
typedef struct VkImageCopy {
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D                srcOffset;
    VkImageSubresourceLayers  dstSubresource;
    VkOffset3D                dstOffset;
    VkExtent3D                extent;
} VkImageCopy;
```

- `srcSubresource` and `dstSubresource` are VkImageSubresourceLayers structures specifying the image subresources of the images used for the source and destination image data, respectively.
- `srcOffset` and `dstOffset` select the initial x, y, and z offsets in texels of the sub-regions of the source and destination image data.
- `extent` is the size in texels of the image to copy in width, height and depth.

For VK_IMAGE_TYPE_3D images, copies are performed slice by slice starting with the z member of the `srcOffset` or `dstOffset`, and copying `depth` slices. For images with multiple layers, copies are performed layer by layer starting with the `baseArrayLayer` member of the `srcSubresource` or `dstSubresource` and copying `layerCount` layers. Image data can be copied between images with different image types. If one image is VK_IMAGE_TYPE_3D and the other image is VK_IMAGE_TYPE_2D with multiple layers, then each slice is copied to or from a different layer.

Copies involving a multi-planar image format specify the region to be copied in terms of the plane to be copied, not the coordinates of the multi-planar image. This means that copies accessing the R/B planes of “_422” format images **must** fit the copied region within half the width of the parent image, and that copies accessing the R/B planes of “_420” format images **must** fit the copied region within half the width and height of the parent image.
Valid Usage

- If neither the calling command’s srcImage nor the calling command’s dstImage has a multi-planar image format then the aspectMask member of srcSubresource and dstSubresource must match.

- If the calling command’s srcImage has a VkFormat with two planes then the srcSubresource aspectMask must be VK_IMAGE_ASPECT_PLANE_0_BIT or VK_IMAGE_ASPECT_PLANE_1_BIT.

- If the calling command’s srcImage has a VkFormat with three planes then the srcSubresource aspectMask must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT.

- If the calling command’s dstImage has a VkFormat with two planes then the dstSubresource aspectMask must be VK_IMAGE_ASPECT_PLANE_0_BIT or VK_IMAGE_ASPECT_PLANE_1_BIT.

- If the calling command’s dstImage has a VkFormat with three planes then the dstSubresource aspectMask must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT.

- If the calling command’s srcImage has a multi-planar image format and the dstImage does not have a multi-planar image format, the dstSubresource aspectMask must be VK_IMAGE_ASPECT_COLOR_BIT.

- If the calling command’s dstImage has a multi-planar image format and the srcImage does not have a multi-planar image format, the srcSubresource aspectMask must be VK_IMAGE_ASPECT_COLOR_BIT.

- The number of slices of the extent (for 3D) or layers of the srcSubresource (for non-3D) must match the number of slices of the extent (for 3D) or layers of the dstSubresource (for non-3D).

- If either of the calling command’s srcImage or dstImage parameters are of VkImageType VK_IMAGE_TYPE_3D, the baseArrayLayer and layerCount members of the corresponding subresource must be 0 and 1, respectively.

- The aspectMask member of srcSubresource must specify aspects present in the calling command’s srcImage.

- The aspectMask member of dstSubresource must specify aspects present in the calling command’s dstImage.

- srcOffset.x and (extent.width + srcOffset.x) must both be greater than or equal to 0 and less than or equal to the source image subresource width.

- srcOffset.y and (extent.height + srcOffset.y) must both be greater than or equal to 0 and less than or equal to the source image subresource height.

- If the calling command’s srcImage is of type VK_IMAGE_TYPE_1D, then srcOffset.y must be 0 and extent.height must be 1.

- srcOffset.z and (extent.depth + srcOffset.z) must both be greater than or equal to 0 and less than or equal to the source image subresource depth.

- If the calling command’s srcImage is of type VK_IMAGE_TYPE_1D, then srcOffset.z must be 0.
and \texttt{extent.depth} \textbf{must} be 1.

- If the calling command's \texttt{dstImage} is of type \texttt{VK_IMAGE_TYPE_1D}, then \texttt{dstOffset.z} \textbf{must} be 0 and \texttt{extent.depth} \textbf{must} be 1.

- If the calling command's \texttt{srcImage} is of type \texttt{VK_IMAGE_TYPE_2D}, then \texttt{srcOffset.z} \textbf{must} be 0.

- If the calling command's \texttt{dstImage} is of type \texttt{VK_IMAGE_TYPE_2D}, then \texttt{dstOffset.z} \textbf{must} be 0.

- If both \texttt{srcImage} and \texttt{dstImage} are of type \texttt{VK_IMAGE_TYPE_2D} then \texttt{extent.depth} \textbf{must} be 1.

- If the calling command's \texttt{srcImage} is of type \texttt{VK_IMAGE_TYPE_2D}, and the \texttt{dstImage} is of type \texttt{VK_IMAGE_TYPE_3D}, then \texttt{extent.depth} \textbf{must} equal to the \texttt{layerCount} member of \texttt{srcSubresource}.

- If the calling command's \texttt{dstImage} is of type \texttt{VK_IMAGE_TYPE_2D}, and the \texttt{srcImage} is of type \texttt{VK_IMAGE_TYPE_3D}, then \texttt{extent.depth} \textbf{must} equal to the \texttt{layerCount} member of \texttt{dstSubresource}.

- \texttt{dstOffset.x} and (\texttt{extent.width} + \texttt{dstOffset.x}) \textbf{must} both be greater than or equal to 0 and less than or equal to the destination image subresource width.

- \texttt{dstOffset.y} and (\texttt{extent.height} + \texttt{dstOffset.y}) \textbf{must} both be greater than or equal to 0 and less than or equal to the destination image subresource height.

- If the calling command's \texttt{dstImage} is of type \texttt{VK_IMAGE_TYPE_1D}, then \texttt{dstOffset.y} \textbf{must} be 0 and \texttt{extent.height} \textbf{must} be 1.

- \texttt{dstOffset.z} and (\texttt{extent.depth} + \texttt{dstOffset.z}) \textbf{must} both be greater than or equal to 0 and less than or equal to the destination image subresource depth.

- If the calling command's \texttt{srcImage} is a compressed image, or a single-plane, “.422” image format, all members of \texttt{srcOffset} \textbf{must} be a multiple of the corresponding dimensions of the compressed texel block.

- If the calling command's \texttt{srcImage} is a compressed image, or a single-plane, “.422” image format, \texttt{extent.width} \textbf{must} be a multiple of the compressed texel block width or (\texttt{extent.width} + \texttt{srcOffset.x}) \textbf{must} equal the source image subresource width.

- If the calling command's \texttt{srcImage} is a compressed image, or a single-plane, “.422” image format, \texttt{extent.height} \textbf{must} be a multiple of the compressed texel block height or (\texttt{extent.height} + \texttt{srcOffset.y}) \textbf{must} equal the source image subresource height.

- If the calling command's \texttt{srcImage} is a compressed image, or a single-plane, “.422” image format, \texttt{extent.depth} \textbf{must} be a multiple of the compressed texel block depth or (\texttt{extent.depth} + \texttt{srcOffset.z}) \textbf{must} equal the source image subresource depth.

- If the calling command's \texttt{dstImage} is a compressed format image, or a single-plane, “.422” image format, all members of \texttt{dstOffset} \textbf{must} be a multiple of the corresponding dimensions of the compressed texel block.

- If the calling command's \texttt{dstImage} is a compressed format image, or a single-plane, “.422” image format, \texttt{extent.width} \textbf{must} be a multiple of the compressed texel block width or (\texttt{extent.width} + \texttt{dstOffset.x}) \textbf{must} equal the destination image subresource width.

- If the calling command's \texttt{dstImage} is a compressed format image, or a single-plane, “.422” image format, \texttt{extent.height} \textbf{must} be a multiple of the compressed texel block height or (\texttt{extent.height} + \texttt{dstOffset.y}) \textbf{must} equal the destination image subresource height.
• If the calling command's dstImage is a compressed format image, or a single-plane, “.422” image format, extent.depth must be a multiple of the compressed texel block depth or (extent.depth + dstOffset.z) must equal the destination image subresource depth.

Valid Usage (Implicit)

• srcSubresource must be a valid VkImageSubresourceLayers structure
• dstSubresource must be a valid VkImageSubresourceLayers structure

The VkImageSubresourceLayers structure is defined as:

```c
typedef struct VkImageSubresourceLayers {
    VkImageAspectFlags aspectMask;
    uint32_t           mipLevel;
    uint32_t           baseArrayLayer;
    uint32_t           layerCount;
} VkImageSubresourceLayers;
```

• aspectMask is a combination of VkImageAspectFlagBits, selecting the color, depth and/or stencil aspects to be copied.
• mipLevel is the mipmap level to copy from.
• baseArrayLayer and layerCount are the starting layer and number of layers to copy.

Valid Usage

• If aspectMask contains VK_IMAGE_ASPECT_COLOR_BIT, it must not contain either of VK_IMAGE_ASPECT_DEPTH_BIT or VK_IMAGE_ASPECT_STENCIL_BIT
• aspectMask must not contain VK_IMAGE_ASPECT_METADATA_BIT
• layerCount must be greater than 0

Valid Usage (Implicit)

• aspectMask must be a valid combination of VkImageAspectFlagBits values
• aspectMask must not be 0

18.4. Copying Data Between Buffers and Images

To copy data from a buffer object to an image object, call:
void vkCmdCopyBufferToImage(
    VkCommandBuffer commandBuffer, 
    VkBuffer srcBuffer, 
    VkImage dstImage, 
    VkImageLayout dstImageLayout, 
    uint32_t regionCount, 
    const VkBufferImageCopy* pRegions);

- `commandBuffer` is the command buffer into which the command will be recorded.
- `srcBuffer` is the source buffer.
- `dstImage` is the destination image.
- `dstImageLayout` is the layout of the destination image subresources for the copy.
- `regionCount` is the number of regions to copy.
- `pRegions` is a pointer to an array of `VkBufferImageCopy` structures specifying the regions to copy.

Each region in `pRegions` is copied from the specified region of the source buffer to the specified region of the destination image.

If the format of `dstImage` is a multi-planar image format, regions of each plane to be a target of a copy must be specified separately using the `pRegions` member of the `VkBufferImageCopy` structure. In this case, the `aspectMask` of `imageSubresource` must be `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, or `VK_IMAGE_ASPECT_PLANE_2_BIT`. For the purposes of `vkCmdCopyBufferToImage`, each plane of a multi-planar image is treated as having the format listed in Compatible formats of planes of multi-planar formats for the plane identified by the `aspectMask` of the corresponding subresource. This applies both to `VkFormat` and to coordinates used in the copy, which correspond to texels in the plane rather than how these texels map to coordinates in the image as a whole.
Valid Usage

- **srcBuffer must** be large enough to contain all buffer locations that are accessed according to Buffer and Image Addressing, for each element of pRegions

- The image region specified by each element of pRegions must be a region that is contained within dstImage if the dstImage’s VkFormat is not a multi-planar format, and must be a region that is contained within the plane being copied to if the dstImage’s VkFormat is a multi-planar format

- The union of all source regions, and the union of all destination regions, specified by the elements of pRegions, must not overlap in memory

- srcBuffer must have been created with VK_BUFFER_USAGE_TRANSFER_SRC_BIT usage flag

- The format features of dstImage must contain VK_FORMAT_FEATURE_TRANSFER_DST_BIT.

- If srcBuffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

- dstImage must have been created with VK_IMAGE_USAGE_TRANSFER_DST_BIT usage flag

- If dstImage is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object

- dstImage must have a sample count equal to VK_SAMPLE_COUNT_1_BIT

- dstImageLayout must specify the layout of the image subresources of dstImage specified in pRegions at the time this command is executed on a VkDevice

- dstImageLayout must be VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, VK_IMAGE_LAYOUT_GENERAL, or VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR

- If commandBuffer is an unprotected command buffer, then srcBuffer must not be a protected buffer

- If commandBuffer is an unprotected command buffer, then dstImage must not be a protected image

- If commandBuffer is a protected command buffer, then dstImage must not be an unprotected image

- The imageSubresource.mipLevel member of each element of pRegions must be less than the mplevels specified in VkImageCreateInfo when dstImage was created

- The imageSubresource.baseArrayLayer + imageSubresource.layerCount of each element of pRegions must be less than or equal to the arrayLayers specified in VkImageCreateInfo when dstImage was created

- The imageOffset and imageExtent members of each element of pRegions must respect the image transfer granularity requirements of commandBuffer’s command pool’s queue family, as described in VkQueueFamilyProperties
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `srcBuffer` must be a valid `VkBuffer` handle
- `dstImage` must be a valid `VkImage` handle
- `dstImageLayout` must be a valid `VkImageLayout` value
- `pRegions` must be a valid pointer to an array of `regionCount` valid `VkBufferImageCopy` structures
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations
- This command must only be called outside of a render pass instance
- `regionCount` must be greater than 0
- Each of `commandBuffer`, `dstImage`, and `srcBuffer` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Transfer</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

To copy data from an image object to a buffer object, call:

```c
void vkCmdCopyImageToBuffer(
    VkCommandBuffer                             commandBuffer,
    VkImage                                     srcImage,
    VkImageLayout                               srcImageLayout,
    VkBuffer                                    dstBuffer,
    uint32_t                                    regionCount,
    const VkBufferImageCopy*                    pRegions);
```
• `commandBuffer` is the command buffer into which the command will be recorded.

• `srcImage` is the source image.

• `srcImageLayout` is the layout of the source image subresources for the copy.

• `dstBuffer` is the destination buffer.

• `regionCount` is the number of regions to copy.

• `pRegions` is a pointer to an array of `VkBufferImageCopy` structures specifying the regions to copy.

Each region in `pRegions` is copied from the specified region of the source image to the specified region of the destination buffer.

If the `VkFormat` of `srcImage` is a multi-planar image format, regions of each plane to be a source of a copy must be specified separately using the `pRegions` member of the `VkBufferImageCopy` structure. In this case, the `aspectMask` of `imageSubresource` must be `VK_IMAGE_ASPECT_PLANE_0_BIT`, `VK_IMAGE_ASPECT_PLANE_1_BIT`, or `VK_IMAGE_ASPECT_PLANE_2_BIT`. For the purposes of `vkCmdCopyBufferToImage`, each plane of a multi-planar image is treated as having the format listed in Compatible formats of planes of multi-planar formats for the plane identified by the `aspectMask` of the corresponding subresource. This applies both to `VkFormat` and to coordinates used in the copy, which correspond to texels in the `plane` rather than how these texels map to coordinates in the image as a whole.
Valid Usage

- The image region specified by each element of `pRegions` must be a region that is contained within `srcImage` if the `srcImage`'s VkFormat is not a multi-planar format, and must be a region that is contained within the plane being copied if the `srcImage`'s VkFormat is a multi-planar format.

- `dstBuffer` must be large enough to contain all buffer locations that are accessed according to `Buffer and Image Addressing`, for each element of `pRegions`.

- The union of all source regions, and the union of all destination regions, specified by the elements of `pRegions`, must not overlap in memory.

- The format features of `srcImage` must contain `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT`.

- `srcImage` must have been created with `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` usage flag.

- If `srcImage` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

- `srcImage` must have a sample count equal to `VK_SAMPLE_COUNT_1_BIT`.

- `srcImageLayout` must specify the layout of the image subresources of `srcImage` specified in `pRegions` at the time this command is executed on a `VkDevice`.

- `srcImageLayout` must be `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR`, `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`.

- `dstBuffer` must have been created with `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage flag.

- If `dstBuffer` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.

- If `commandBuffer` is an unprotected command buffer, then `srcImage` must not be a protected image.

- If `commandBuffer` is an unprotected command buffer, then `dstBuffer` must not be a protected buffer.

- If `commandBuffer` is a protected command buffer, then `dstBuffer` must not be an unprotected buffer.

- The `imageSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `srcImage` was created.

- The `imageSubresource.baseArrayLayer + imageSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `srcImage` was created.

- The `imageOffset` and `imageExtent` members of each element of `pRegions` must respect the image transfer granularity requirements of `commandBuffer`'s command pool's queue family, as described in `VkQueueFamilyProperties`.

---

718 | Chapter 18. Copy Commands
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `srcImage` must be a valid `VkImage` handle
- `srcImageLayout` must be a valid `VkImageLayout` value
- `dstBuffer` must be a valid `VkBuffer` handle
- `pRegions` must be a valid pointer to an array of `regionCount` valid `VkBufferImageCopy` structures
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support transfer, graphics, or compute operations
- This command must only be called outside of a render pass instance
- `regionCount` must be greater than 0
- Each of `commandBuffer`, `dstBuffer`, and `srcImage` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Transfer</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

For both `vkCmdCopyBufferToImage` and `vkCmdCopyImageToBuffer`, each element of `pRegions` is a structure defined as:
typedef struct VkBufferImageCopy {
    VkDeviceSize    bufferOffset;
    uint32_t        bufferRowLength;
    uint32_t        bufferImageHeight;
    VkImageSubresourceLayers imageSubresource;
    VkOffset3D      imageOffset;
    VkExtent3D      imageExtent;
} VkBufferImageCopy;

- `bufferOffset` is the offset in bytes from the start of the buffer object where the image data is copied from or to.

- `bufferRowLength` and `bufferImageHeight` specify in texels a subregion of a larger two- or three-dimensional image in buffer memory, and control the addressing calculations. If either of these values is zero, that aspect of the buffer memory is considered to be tightly packed according to the `imageExtent`.

- `imageSubresource` is a `VkImageSubresourceLayers` used to specify the specific image subresources of the image used for the source or destination image data.

- `imageOffset` selects the initial x, y, z offsets in texels of the sub-region of the source or destination image data.

- `imageExtent` is the size in texels of the image to copy in width, height and depth.

When copying to or from a depth or stencil aspect, the data in buffer memory uses a layout that is a (mostly) tightly packed representation of the depth or stencil data. Specifically:

- data copied to or from the stencil aspect of any depth/stencil format is tightly packed with one `VK_FORMAT_S8_UINT` value per texel.

- data copied to or from the depth aspect of a `VK_FORMAT_D16_UNORM` or `VK_FORMAT_D16_UNORM_S8_UINT` format is tightly packed with one `VK_FORMAT_D16_UNORM` value per texel.

- data copied to or from the depth aspect of a `VK_FORMAT_D32_SFLOAT` or `VK_FORMAT_D32_SFLOAT_S8_UINT` format is tightly packed with one `VK_FORMAT_D32_SFLOAT` value per texel.

- data copied to or from the depth aspect of a `VK_FORMAT_X8_D24_UNORM_PACK32` or `VK_FORMAT_D24_UNORM_S8_UINT` format is packed with one 32-bit word per texel with the D24 value in the LSBs of the word, and undefined values in the eight MSBs.

Note

To copy both the depth and stencil aspects of a depth/stencil format, two entries in `pRegions` can be used, where one specifies the depth aspect in `imageSubresource`, and the other specifies the stencil aspect.

Because depth or stencil aspect buffer to image copies may require format conversions on some implementations, they are not supported on queues that do not support graphics.

When copying to a depth aspect, the data in buffer memory must be in the range [0,1], or the resulting values are undefined.
Copies are done layer by layer starting with image layer `baseArrayLayer` member of `imageSubresource`. `layerCount` layers are copied from the source image or to the destination image.
Valid Usage

- If the calling command’s VkImage parameter’s format is not a depth/stencil format or a multi-planar format, then bufferOffset must be a multiple of the format’s texel block size.

- If the calling command’s VkImage parameter’s format is a multi-planar format, then bufferOffset must be a multiple of the element size of the compatible format for the format and the aspectMask of the imageSubresource as defined in Compatible formats of planes of multi-planar formats

- bufferOffset must be a multiple of 4

- bufferRowLength must be 0, or greater than or equal to the width member of imageExtent

- bufferOffsetHeight must be 0, or greater than or equal to the height member of imageExtent

- imageOffset.x and (imageExtent.width + imageOffset.x) must both be greater than or equal to 0 and less than or equal to the image subresource width where this refers to the width of the plane of the image involved in the copy in the case of a multi-planar format

- imageOffset.y and (imageExtent.height + imageOffset.y) must both be greater than or equal to 0 and less than or equal to the image subresource height where this refers to the height of the plane of the image involved in the copy in the case of a multi-planar format

- If the calling command’s srcImage (vkCmdCopyImageToBuffer) or dstImage (vkCmdCopyBufferToImage) is of type VK_IMAGE_TYPE_1D, then imageOffset.y must be 0 and imageExtent.height must be 1.

- imageOffset.z and (imageExtent.depth + imageOffset.z) must both be greater than or equal to 0 and less than or equal to the image subresource depth

- If the calling command’s srcImage (vkCmdCopyImageToBuffer) or dstImage (vkCmdCopyBufferToImage) is of type VK_IMAGE_TYPE_1D or VK_IMAGE_TYPE_2D, then imageOffset.z must be 0 and imageExtent.depth must be 1

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, bufferRowLength must be a multiple of the compressed texel block width

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, bufferImageHeight must be a multiple of the compressed texel block height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, all members of imageOffset must be a multiple of the corresponding dimensions of the compressed texel block

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, bufferOffset must be a multiple of the compressed texel block size in bytes

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.width must be a multiple of the compressed texel block width or (imageExtent.width + imageOffset.x) must equal the image subresource width

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.height must be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) must equal the image subresource height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.depth must be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) must equal the image subresource depth

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.width must be a multiple of the compressed texel block width or (imageExtent.width + imageOffset.x) must equal the image subresource width

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.height must be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) must equal the image subresource height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.depth must be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) must equal the image subresource depth

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.width must be a multiple of the compressed texel block width or (imageExtent.width + imageOffset.x) must equal the image subresource width

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.height must be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) must equal the image subresource height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.depth must be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) must equal the image subresource depth

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.width must be a multiple of the compressed texel block width or (imageExtent.width + imageOffset.x) must equal the image subresource width

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.height must be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) must equal the image subresource height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.depth must be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) must equal the image subresource depth

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.width must be a multiple of the compressed texel block width or (imageExtent.width + imageOffset.x) must equal the image subresource width

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.height must be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) must equal the image subresource height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.depth must be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) must equal the image subresource depth

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.width must be a multiple of the compressed texel block width or (imageExtent.width + imageOffset.x) must equal the image subresource width

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.height must be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) must equal the image subresource height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.depth must be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) must equal the image subresource depth
_422" image format, imageExtent.height must be a multiple of the compressed texel block height or (imageExtent.height + imageOffset.y) must equal the image subresource height

- If the calling command’s VkImage parameter is a compressed image, or a single-plane, “_422” image format, imageExtent.depth must be a multiple of the compressed texel block depth or (imageExtent.depth + imageOffset.z) must equal the image subresource depth

- The aspectMask member of imageSubresource must specify aspects present in the calling command’s VkImage parameter

- If the calling command’s VkImage parameter’s format is a multi-planar format, then the aspectMask member of imageSubresource must be VK_IMAGE_ASPECT_PLANE_0_BIT, VK_IMAGE_ASPECT_PLANE_1_BIT, or VK_IMAGE_ASPECT_PLANE_2_BIT (with VK_IMAGE_ASPECT_PLANE_2_BIT valid only for image formats with three planes)

- The aspectMask member of imageSubresource must only have a single bit set

- If the calling command’s VkImage parameter is of VkImageType VK_IMAGE_TYPE_3D, the baseArrayLayer and layerCount members of imageSubresource must be 0 and 1, respectively

- When copying to the depth aspect of an image subresource, the data in the source buffer must be in the range [0,1]

Valid Usage (Implicit)

- imageSubresource must be a valid VkImageSubresourceLayers structure

18.4.1. Buffer and Image Addressing

Pseudocode for image/buffer addressing of uncompressed formats is:

```c
rowLength = region->bufferRowLength;
if (rowLength == 0)
    rowLength = region->imageExtent.width;

imageHeight = region->bufferImageHeight;
if (imageHeight == 0)
    imageHeight = region->imageExtent.height;

texelBlockSize = <texel block size of the format of the src/dstImage>;

address of (x,y,z) = region->bufferOffset + (((z * imageHeight) + y) * rowLength + x) * texelBlockSize;

where x,y,z range from (0,0,0) to region->imageExtent.{width,height,depth}.
```

Note that imageOffset does not affect addressing calculations for buffer memory. Instead, bufferOffset can be used to select the starting address in buffer memory.

For block-compressed formats, all parameters are still specified in texels rather than compressed
texel blocks, but the addressing math operates on whole compressed texel blocks. Pseudocode for compressed copy addressing is:

```c
rowLength = region->bufferRowLength;
if (rowLength == 0)
    rowLength = region->imageExtent.width;

imageHeight = region->bufferImageHeight;
if (imageHeight == 0)
    imageHeight = region->imageExtent.height;

compressedTexelBlockSizeInBytes = <compressed texel block size taken from the src/dstImage>;
rowLength /= compressedTexelBlockWidth;
imageHeight /= compressedTexelBlockHeight;

address of (x,y,z) = region->bufferOffset + (((z * imageHeight) + y) * rowLength + x) * compressedTexelBlockSizeInBytes;

where x,y,z range from (0,0,0) to region->imageExtent.{width/compressedTexelBlockWidth,height/compressedTexelBlockHeight,depth/compressedTexelBlockDepth}.
```

Copying to or from block-compressed images is typically done in multiples of the compressed texel block size. For this reason the `imageExtent` must be a multiple of the compressed texel block dimension. There is one exception to this rule which is required to handle compressed images created with dimensions that are not a multiple of the compressed texel block dimensions:

- If `imageExtent.width` is not a multiple of the compressed texel block width, then `(imageExtent.width + imageOffset.x)` must equal the image subresource width.
- If `imageExtent.height` is not a multiple of the compressed texel block height, then `(imageExtent.height + imageOffset.y)` must equal the image subresource height.
- If `imageExtent.depth` is not a multiple of the compressed texel block depth, then `(imageExtent.depth + imageOffset.z)` must equal the image subresource depth.

This allows the last compressed texel block of the image in each non-multiple dimension to be included as a source or destination of the copy.

### 18.5. Image Copies with Scaling

To copy regions of a source image into a destination image, potentially performing format conversion, arbitrary scaling, and filtering, call:
void vkCmdBlitImage(
    VkCommandBuffer                             commandBuffer,
    VkImage                                     srcImage,
    VkImageLayout                               srcImageLayout,
    VkImage                                     dstImage,
    VkImageLayout                               dstImageLayout,
    uint32_t                                    regionCount,
    const VkImageBlit*                          pRegions,
    VkFilter                                    filter);

- `commandBuffer` is the command buffer into which the command will be recorded.
- `srcImage` is the source image.
- `srcImageLayout` is the layout of the source image subresources for the blit.
- `dstImage` is the destination image.
- `dstImageLayout` is the layout of the destination image subresources for the blit.
- `regionCount` is the number of regions to blit.
- `pRegions` is a pointer to an array of `VkImageBlit` structures specifying the regions to blit.
- `filter` is a `VkFilter` specifying the filter to apply if the blits require scaling.

`vkCmdBlitImage` must not be used for multisampled source or destination images. Use `vkCmdResolveImage` for this purpose.

As the sizes of the source and destination extents can differ in any dimension, texels in the source extent are scaled and filtered to the destination extent. Scaling occurs via the following operations:

- For each destination texel, the integer coordinate of that texel is converted to an unnormalized texture coordinate, using the effective inverse of the equations described in **unnormalized to integer conversion**:

  \[ u_{\text{base}} = i + \frac{1}{2} \]

  \[ v_{\text{base}} = j + \frac{1}{2} \]

  \[ w_{\text{base}} = k + \frac{1}{2} \]

- These base coordinates are then offset by the first destination offset:

  \[ u_{\text{offset}} = u_{\text{base}} - x_{\text{dst}0} \]

  \[ v_{\text{offset}} = v_{\text{base}} - y_{\text{dst}0} \]

  \[ w_{\text{offset}} = w_{\text{base}} - z_{\text{dst}0} \]

  \[ a_{\text{offset}} = a - \text{baseArrayCount}_{\text{dst}} \]
• The scale is determined from the source and destination regions, and applied to the offset coordinates:

\[
\begin{align*}
\text{scale}_u &= (x_{\text{src1}} - x_{\text{src0}}) / (x_{\text{dst1}} - x_{\text{dst0}}) \\
\text{scale}_v &= (y_{\text{src1}} - y_{\text{src0}}) / (y_{\text{dst1}} - y_{\text{dst0}}) \\
\text{scale}_w &= (z_{\text{src1}} - z_{\text{src0}}) / (z_{\text{dst1}} - z_{\text{dst0}})
\end{align*}
\]

\[
\begin{align*}
\text{u}\_\text{scaled} &= \text{u}\_\text{offset} \times \text{scale}_u \\
\text{v}\_\text{scaled} &= \text{v}\_\text{offset} \times \text{scale}_v \\
\text{w}\_\text{scaled} &= \text{w}\_\text{offset} \times \text{scale}_w
\end{align*}
\]

• Finally the source offset is added to the scaled coordinates, to determine the final unnormalized coordinates used to sample from \textit{srcImage}:

\[
\begin{align*}
\text{u} &= \text{u}\_\text{scaled} + x_{\text{src0}} \\
\text{v} &= \text{v}\_\text{scaled} + y_{\text{src0}} \\
\text{w} &= \text{w}\_\text{scaled} + z_{\text{src0}} \\
\text{q} &= \text{mipLevel} \\
\text{a} &= \text{a}\_\text{offset} + \text{baseArrayCount}_{\text{src}}
\end{align*}
\]

These coordinates are used to sample from the source image, as described in the \textit{Image Operations} chapter, with the filter mode equal to that of \textit{filter}, a mipmap mode of \texttt{VK_SAMPLER_MIPMAP_MODE_NEAREST} and an address mode of \texttt{VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE}. Implementations \textbf{must} clamp at the edge of the source image, and \textbf{may} additionally clamp to the edge of the source region.

\textbf{Note}

Due to allowable rounding errors in the generation of the source texture coordinates, it is not always possible to guarantee exactly which source texels will be sampled for a given blit. As rounding errors are implementation dependent, the exact results of a blitting operation are also implementation dependent.

Blits are done layer by layer starting with the \texttt{baseArrayLayer} member of \texttt{srcSubresource} for the source and \texttt{dstSubresource} for the destination. \texttt{layerCount} layers are blitted to the destination image.

3D textures are blitted slice by slice. Slices in the source region bounded by \texttt{srcOffsets[0].z} and \texttt{srcOffsets[1].z} are copied to slices in the destination region bounded by \texttt{dstOffsets[0].z} and \texttt{dstOffsets[1].z}. For each destination slice, a source \texttt{z} coordinate is linearly interpolated between \texttt{srcOffsets[0].z} and \texttt{srcOffsets[1].z}. If the \textit{filter} parameter is \texttt{VK_FILTER_LINEAR} then the value
sampled from the source image is taken by doing linear filtering using the interpolated $z$ coordinate. If `filter` parameter is `VK_FILTER_NEAREST` then the value sampled from the source image is taken from the single nearest slice, with an implementation-dependent arithmetic rounding mode.

The following filtering and conversion rules apply:

- Integer formats **can** only be converted to other integer formats with the same signedness.
- No format conversion is supported between depth/stencil images. The formats **must** match.
- Format conversions on unorm, snorm, unscaled and packed float formats of the copied aspect of the image are performed by first converting the pixels to float values.
- For sRGB source formats, nonlinear RGB values are converted to linear representation prior to filtering.
- After filtering, the float values are first clamped and then cast to the destination image format. In case of sRGB destination format, linear RGB values are converted to nonlinear representation before writing the pixel to the image.

Signed and unsigned integers are converted by first clamping to the representable range of the destination format, then casting the value.
Valid Usage

- The source region specified by each element of \( pRegions \) must be a region that is contained within \( srcImage \).
- The destination region specified by each element of \( pRegions \) must be a region that is contained within \( dstImage \).
- The union of all destination regions, specified by the elements of \( pRegions \), must not overlap in memory with any texel that may be sampled during the blit operation.
- The format features of \( srcImage \) must contain \texttt{VK\_FORMAT\_FEATURE\_BLIT\_SRC\_BIT}.
- \( srcImage \) must not use a format listed in \texttt{Formats requiring sampler Y’C_bC_r conversion for VK\_IMAGE\_ASPECT\_COLOR\_BIT image views}.
- \( srcImage \) must have been created with \texttt{VK\_IMAGE\_USAGE\_TRANSFER\_SRC\_BIT} usage flag.
- If \( srcImage \) is non-sparse then it must be bound completely and contiguously to a single \texttt{VkDeviceMemory} object.
- \( srcImageLayout \) must specify the layout of the image subresources of \( srcImage \) specified in \( pRegions \) at the time this command is executed on a \texttt{VkDevice}.
- \( srcImageLayout \) must be \texttt{VK\_IMAGE\_LAYOUT\_SHARED\_PRESENT\_KHR}, \texttt{VK\_IMAGE\_LAYOUT\_TRANSFER\_SRC\_OPTIMAL} or \texttt{VK\_IMAGE\_LAYOUT\_GENERAL}.
- The format features of \( dstImage \) must contain \texttt{VK\_FORMAT\_FEATURE\_BLIT\_DST\_BIT}.
- \( dstImage \) must not use a format listed in \texttt{Formats requiring sampler Y’C_bC_r conversion for VK\_IMAGE\_ASPECT\_COLOR\_BIT image views}.
- \( dstImage \) must have been created with \texttt{VK\_IMAGE\_USAGE\_TRANSFER\_DST\_BIT} usage flag.
- If \( dstImage \) is non-sparse then it must be bound completely and contiguously to a single \texttt{VkDeviceMemory} object.
- \( dstImageLayout \) must specify the layout of the image subresources of \( dstImage \) specified in \( pRegions \) at the time this command is executed on a \texttt{VkDevice}.
- \( dstImageLayout \) must be \texttt{VK\_IMAGE\_LAYOUT\_SHARED\_PRESENT\_KHR}, \texttt{VK\_IMAGE\_LAYOUT\_TRANSFER\_DST\_OPTIMAL} or \texttt{VK\_IMAGE\_LAYOUT\_GENERAL}.
- If either of \( srcImage \) or \( dstImage \) was created with a signed integer \texttt{VkFormat}, the other must also have been created with a signed integer \texttt{VkFormat}.
- If either of \( srcImage \) or \( dstImage \) was created with an unsigned integer \texttt{VkFormat}, the other must also have been created with an unsigned integer \texttt{VkFormat}.
- If either of \( srcImage \) or \( dstImage \) was created with a depth/stencil format, the other must have exactly the same format.
- If \( srcImage \) was created with a depth/stencil format, \texttt{filter} must be \texttt{VK\_FILTER\_NEAREST}.
- \( srcImage \) must have been created with a \texttt{samples} value of \texttt{VK\_SAMPLE\_COUNT\_1\_BIT}.
- \( dstImage \) must have been created with a \texttt{samples} value of \texttt{VK\_SAMPLE\_COUNT\_1\_BIT}.
- If \texttt{filter} is \texttt{VK\_FILTER\_LINEAR}, then the format features of \( srcImage \) must contain \texttt{VK\_FORMAT\_FEATURE\_SAMPLED\_IMAGE\_FILTER\_LINEAR\_BIT}.
• If `commandBuffer` is an unprotected command buffer, then `srcImage` must not be a protected image.

• If `commandBuffer` is an unprotected command buffer, then `dstImage` must not be a protected image.

• If `commandBuffer` is a protected command buffer, then `dstImage` must not be an unprotected image.

• The `srcSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `srcImage` was created.

• The `dstSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `dstImage` was created.

• The `srcSubresource.baseArrayLayer + srcSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `srcImage` was created.

• The `dstSubresource.baseArrayLayer + dstSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `dstImage` was created.

Valid Usage (Implicit)

• `commandBuffer` must be a valid `VkCommandBuffer` handle.

• `srcImage` must be a valid `VkImage` handle.

• `srcImageLayout` must be a valid `VkImageLayout` value.

• `dstImage` must be a valid `VkImage` handle.

• `dstImageLayout` must be a valid `VkImageLayout` value.

• `pRegions` must be a valid pointer to an array of `regionCount` valid `VkImageBlit` structures.

• `filter` must be a valid `VkFilter` value.

• `commandBuffer` must be in the recording state.

• The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations.

• This command must only be called outside of a render pass instance.

• `regionCount` must be greater than 0.

• Each of `commandBuffer`, `dstImage`, and `srcImage` must have been created, allocated, or retrieved from the same `VkDevice`.
Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Graphics</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VkImageBlit structure is defined as:

```c
typedef struct VkImageBlit {
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D srcOffsets[2];
    VkImageSubresourceLayers dstSubresource;
    VkOffset3D dstOffsets[2];
} VkImageBlit;
```

- `srcSubresource` is the subresource to blit from.
- `srcOffsets` is a pointer to an array of two VkOffset3D structures specifying the bounds of the source region within `srcSubresource`.
- `dstSubresource` is the subresource to blit into.
- `dstOffsets` is a pointer to an array of two VkOffset3D structures specifying the bounds of the destination region within `dstSubresource`.

For each element of the `pRegions` array, a blit operation is performed the specified source and destination regions.
Valid Usage

- The `aspectMask` member of `srcSubresource` and `dstSubresource` must match.
- The `layerCount` member of `srcSubresource` and `dstSubresource` must match.
- If either of the calling command's `srcImage` or `dstImage` parameters are of `VkImageType VK_IMAGE_TYPE_3D`, the `baseArrayLayer` and `layerCount` members of both `srcSubresource` and `dstSubresource` must be 0 and 1, respectively.
- The `aspectMask` member of `srcSubresource` must specify aspects present in the calling command's `srcImage`.
- The `aspectMask` member of `dstSubresource` must specify aspects present in the calling command's `dstImage`.
- `srcOffset[0].x` and `srcOffset[1].x` must both be greater than or equal to 0 and less than or equal to the source image subresource width.
- `srcOffset[0].y` and `srcOffset[1].y` must both be greater than or equal to 0 and less than or equal to the source image subresource height.
- If the calling command's `srcImage` is of type `VK_IMAGE_TYPE_1D`, then `srcOffset[0].y` must be 0 and `srcOffset[1].y` must be 1.
- `srcOffset[0].z` and `srcOffset[1].z` must both be greater than or equal to 0 and less than or equal to the source image subresource depth.
- If the calling command's `srcImage` is of type `VK_IMAGE_TYPE_1D` or `VK_IMAGE_TYPE_2D`, then `srcOffset[0].z` must be 0 and `srcOffset[1].z` must be 1.
- `dstOffset[0].x` and `dstOffset[1].x` must both be greater than or equal to 0 and less than or equal to the destination image subresource width.
- `dstOffset[0].y` and `dstOffset[1].y` must both be greater than or equal to 0 and less than or equal to the destination image subresource height.
- If the calling command's `dstImage` is of type `VK_IMAGE_TYPE_1D`, then `dstOffset[0].y` must be 0 and `dstOffset[1].y` must be 1.
- `dstOffset[0].z` and `dstOffset[1].z` must both be greater than or equal to 0 and less than or equal to the destination image subresource depth.
- If the calling command's `dstImage` is of type `VK_IMAGE_TYPE_1D` or `VK_IMAGE_TYPE_2D`, then `dstOffset[0].z` must be 0 and `dstOffset[1].z` must be 1.

Valid Usage (Implicit)

- `srcSubresource` must be a valid `VkImageSubresourceLayers` structure.
- `dstSubresource` must be a valid `VkImageSubresourceLayers` structure.
18.6. Resolving Multisample Images

To resolve a multisample image to a non-multisample image, call:

```c
void vkCmdResolveImage(
    VkCommandBuffer commandBuffer,  // commandBuffer is the command buffer into which the command will be recorded.
    VkImage srcImage,               // srcImage is the source image.
    VkImageLayout srcImageLayout,   // srcImageLayout is the layout of the source image subresources for the resolve.
    VkImage dstImage,               // dstImage is the destination image.
    VkImageLayout dstImageLayout,   // dstImageLayout is the layout of the destination image subresources for the resolve.
    uint32_t regionCount,           // regionCount is the number of regions to resolve.
    const VkImageResolve* pRegions); // pRegions is a pointer to an array of VkImageResolve structures specifying the regions to resolve.
```

During the resolve the samples corresponding to each pixel location in the source are converted to a single sample before being written to the destination. If the source formats are floating-point or normalized types, the sample values for each pixel are resolved in an implementation-dependent manner. If the source formats are integer types, a single sample's value is selected for each pixel.

`srcOffset` and `dstOffset` select the initial `x`, `y`, and `z` offsets in texels of the sub-regions of the source and destination image data. `extent` is the size in texels of the source image to resolve in `width`, `height` and `depth`.

Resolves are done layer by layer starting with `baseArrayLayer` member of `srcSubresource` for the source and `dstSubresource` for the destination. `layerCount` layers are resolved to the destination image.
Valid Usage

- The source region specified by each element of `pRegions` must be a region that is contained within `srcImage`.
- The destination region specified by each element of `pRegions` must be a region that is contained within `dstImage`.
- The union of all source regions, and the union of all destination regions, specified by the elements of `pRegions`, must not overlap in memory.
- If `srcImage` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.
- `srcImage` must have a sample count equal to any valid sample count value other than `VK_SAMPLE_COUNT_1_BIT`.
- If `dstImage` is non-sparse then it must be bound completely and contiguously to a single `VkDeviceMemory` object.
- `dstImage` must have a sample count equal to `VK_SAMPLE_COUNT_1_BIT`.
- `srcImageLayout` must specify the layout of the image subresources of `srcImage` specified in `pRegions` at the time this command is executed on a `VkDevice`.
- `srcImageLayout` must be `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR`, `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`.
- `dstImageLayout` must specify the layout of the image subresources of `dstImage` specified in `pRegions` at the time this command is executed on a `VkDevice`.
- `dstImageLayout` must be `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR`, `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`.
- The format features of `dstImage` must contain `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`.
- `srcImage` and `dstImage` must have been created with the same image format.
- If `commandBuffer` is an unprotected command buffer, then `srcImage` must not be a protected image.
- If `commandBuffer` is an unprotected command buffer, then `dstImage` must not be a protected image.
- If `commandBuffer` is a protected command buffer, then `dstImage` must not be an unprotected image.
- The `srcSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `srcImage` was created.
- The `dstSubresource.mipLevel` member of each element of `pRegions` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `dstImage` was created.
- The `srcSubresource.baseArrayLayer + srcSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `srcImage` was created.
- The `dstSubresource.baseArrayLayer + dstSubresource.layerCount` of each element of `pRegions` must be less than or equal to the `arrayLayers` specified in `VkImageCreateInfo` when `dstImage` was created.
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `srcImage` must be a valid `VkImage` handle
- `srcImageLayout` must be a valid `VkImageLayout` value
- `dstImage` must be a valid `VkImage` handle
- `dstImageLayout` must be a valid `VkImageLayout` value
- `pRegions` must be a valid pointer to an array of `regionCount` valid `VkImageResolve` structures
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- This command must only be called outside of a render pass instance
- `regionCount` must be greater than 0
- Each of `commandBuffer`, `dstImage`, and `srcImage` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Secondary</td>
<td>Outside</td>
<td>Graphics</td>
</tr>
</tbody>
</table>

The `VkImageResolve` structure is defined as:
typedef struct VkImageResolve {
    VkImageSubresourceLayers srcSubresource;
    VkOffset3D srcOffset;
    VkImageSubresourceLayers dstSubresource;
    VkOffset3D dstOffset;
    VkExtent3D extent;
} VkImageResolve;

- `srcSubresource` and `dstSubresource` are `VkImageSubresourceLayers` structures specifying the image subresources of the images used for the source and destination image data, respectively. Resolve of depth/stencil images is not supported.
- `srcOffset` and `dstOffset` select the initial $x$, $y$, and $z$ offsets in texels of the sub-regions of the source and destination image data.
- `extent` is the size in texels of the source image to resolve in width, height and depth.
Valid Usage

- The `aspectMask` member of `srcSubresource` and `dstSubresource` must only contain `VK_IMAGE_ASPECT_COLOR_BIT`

- The `layerCount` member of `srcSubresource` and `dstSubresource` must match

- If either of the calling command’s `srcImage` or `dstImage` parameters are of `VkImageType VK_IMAGE_TYPE_3D`, the `baseArrayLayer` and `layerCount` members of both `srcSubresource` and `dstSubresource` must be 0 and 1, respectively

- `srcOffset.x` and `(extent.width + srcOffset.x)` must both be greater than or equal to 0 and less than or equal to the source image subresource width

- `srcOffset.y` and `(extent.height + srcOffset.y)` must both be greater than or equal to 0 and less than or equal to the source image subresource height

- If the calling command’s `srcImage` is of type `VK_IMAGE_TYPE_1D`, then `srcOffset.y` must be 0 and `extent.height` must be 1.

- `srcOffset.z` and `(extent.depth + srcOffset.z)` must both be greater than or equal to 0 and less than or equal to the source image subresource depth

- If the calling command’s `srcImage` is of type `VK_IMAGE_TYPE_1D` or `VK_IMAGE_TYPE_2D`, then `srcOffset.z` must be 0 and `extent.depth` must be 1.

- `dstOffset.x` and `(extent.width + dstOffset.x)` must both be greater than or equal to 0 and less than or equal to the destination image subresource width

- `dstOffset.y` and `(extent.height + dstOffset.y)` must both be greater than or equal to 0 and less than or equal to the destination image subresource height

- If the calling command’s `dstImage` is of type `VK_IMAGE_TYPE_1D`, then `dstOffset.y` must be 0 and `extent.height` must be 1.

- `dstOffset.z` and `(extent.depth + dstOffset.z)` must both be greater than or equal to 0 and less than or equal to the destination image subresource depth

- If the calling command’s `dstImage` is of type `VK_IMAGE_TYPE_1D` or `VK_IMAGE_TYPE_2D`, then `dstOffset.z` must be 0 and `extent.depth` must be 1.

Valid Usage (Implicit)

- `srcSubresource` must be a valid `VkImageSubresourceLayers` structure

- `dstSubresource` must be a valid `VkImageSubresourceLayers` structure
Chapter 19. Drawing Commands

*Drawing commands* (commands with *Draw* in the name) provoke work in a graphics pipeline. Drawing commands are recorded into a command buffer and when executed by a queue, will produce work which executes according to the bound graphics pipeline. A graphics pipeline must be bound to a command buffer before any drawing commands are recorded in that command buffer.

Each draw is made up of zero or more vertices and zero or more instances, which are processed by the device and result in the assembly of primitives. Primitives are assembled according to the `pInputAssemblyState` member of the `VkGraphicsPipelineCreateInfo` structure, which is of type `VkPipelineInputAssemblyStateCreateInfo`:

```c
typedef struct VkPipelineInputAssemblyStateCreateInfo {
    VkStructureType sType;
    const void *pNext;
    VkPipelineInputAssemblyStateCreateFlags flags;
    VkPrimitiveTopology topology;
    VkBool32 primitiveRestartEnable;
} VkPipelineInputAssemblyStateCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `topology` is a `VkPrimitiveTopology` defining the primitive topology, as described below.
- `primitiveRestartEnable` controls whether a special vertex index value is treated as restarting the assembly of primitives. This enable only applies to indexed draws (`vkCmdDrawIndexed` and `vkCmdDrawIndexedIndirect`), and the special index value is either `0xFFFFFFFF` when the `indexType` parameter of `vkCmdBindIndexBuffer` is equal to `VK_INDEX_TYPE_UINT32`, or `0xFFFF` when `indexType` is equal to `VK_INDEX_TYPE_UINT16`. Primitive restart is not allowed for “list” topologies.

Restarting the assembly of primitives discards the most recent index values if those elements formed an incomplete primitive, and restarts the primitive assembly using the subsequent indices, but only assembling the immediately following element through the end of the originally specified elements. The primitive restart index value comparison is performed before adding the `vertexOffset` value to the index value.
Valid Usage

- If `topology` is `VK_PRIMITIVE_TOPOLOGY_POINT_LIST`, `VK_PRIMITIVE_TOPOLOGY_LINE_LIST`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST`, `VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY` or `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`, `primitiveRestartEnable` must be `VK_FALSE`.

- If the `geometry shaders` feature is not enabled, `topology` must not be any of `VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY`, `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY` or `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY`.

- If the `tessellation shaders` feature is not enabled, `topology` must not be `VK_PRIMITIVE_TOPOLOGY_PATCH_LIST`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO`.
- `pNext` must be `NULL`.
- `flags` must be `0`.
- `topology` must be a valid `VkPrimitiveTopology` value.

```c
typedef VkFlags VkPipelineInputAssemblyStateCreateInfo;
```

`VkPipelineInputAssemblyStateCreateInfo` is a bitmask type for setting a mask, but is currently reserved for future use.

### 19.1. Primitive Topologies

*Primitive topology* determines how consecutive vertices are organized into primitives, and determines the type of primitive that is used at the beginning of the graphics pipeline. The effective topology for later stages of the pipeline is altered by tessellation or geometry shading (if either is in use) and depends on the execution modes of those shaders.

The primitive topologies defined by `VkPrimitiveTopology` are:
```c
typedef enum VkPrimitiveTopology {
    VK_PRIMITIVE_TOPOLOGY_POINT_LIST = 0,
    VK_PRIMITIVE_TOPOLOGY_LINE_LIST = 1,
    VK_PRIMITIVE_TOPOLOGY_LINE_STRIP = 2,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST = 3,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP = 4,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN = 5,
    VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY = 6,
    VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY = 7,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY = 8,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY = 9,
    VK_PRIMITIVE_TOPOLOGY_PATCH_LIST = 10,
    VK_PRIMITIVE_TOPOLOGY_MAX_ENUM = 0x7FFFFFFF
} VkPrimitiveTopology;
```

- **VK_PRIMITIVE_TOPOLOGY_POINT_LIST** specifies a series of separate point primitives.
- **VK_PRIMITIVE_TOPOLOGY_LINE_LIST** specifies a series of separate line primitives.
- **VK_PRIMITIVE_TOPOLOGY_LINE_STRIP** specifies a series of connected line primitives with consecutive lines sharing a vertex.
- **VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST** specifies a series of separate triangle primitives.
- **VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP** specifies a series of connected triangle primitives with consecutive triangles sharing an edge.
- **VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN** specifies a series of connected triangle primitives with all triangles sharing a common vertex.
- **VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY** specifies a series of separate line primitives with adjacency.
- **VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY** specifies a series of connected line primitives with adjacency, with consecutive primitives sharing three vertices.
- **VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY** specifies a series of separate triangle primitives with adjacency.
- **VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY** specifies connected triangle primitives with adjacency, with consecutive triangles sharing an edge.
- **VK_PRIMITIVE_TOPOLOGY_PATCH_LIST** specifies separate patch primitives.

Each primitive topology, and its construction from a list of vertices, is described in detail below with a supporting diagram, according to the following key:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>●</td>
<td>Vertex</td>
</tr>
<tr>
<td>5</td>
<td>Vertex Number</td>
</tr>
<tr>
<td>•</td>
<td>Provoking Vertex</td>
</tr>
</tbody>
</table>

A point in 3-dimensional space. Positions chosen within the diagrams are arbitrary and for illustration only.

Sequence position of a vertex within the provided vertex data.

Provoking vertex within the main primitive. The arrow points along an edge of the relevant primitive, following winding order. Used in flat shading.
### Primitive Edge
An edge connecting the points of a main primitive.

### Adjacency Edge
Points connected by these lines do not contribute to a main primitive, and are only accessible in a geometry shader.

### Winding Order
The relative order in which vertices are defined within a primitive, used in the facing determination. This ordering has no specific start or end point.

The diagrams are supported with mathematical definitions where the vertices (v) and primitives (p) are numbered starting from 0; \( v_0 \) is the first vertex in the provided data and \( p_0 \) is the first primitive in the set of primitives defined by the vertices and topology.

#### 19.1.1. Point Lists
When the topology is `VK_PRIMITIVE_TOPOLOGY_POINT_LIST`, each consecutive vertex defines a single point primitive, according to the equation:

\[
p_i = \{v_i\}
\]

As there is only one vertex, that vertex is the provoking vertex. The number of primitives generated is equal to `vertexCount`.

#### 19.1.2. Line Lists
When the topology is `VK_PRIMITIVE_TOPOLOGY_LINE_LIST`, each consecutive pair of vertices defines a single line primitive, according to the equation:

\[
p_i = \{v_{2i}, v_{2i+1}\}
\]

The provoking vertex for \( p_i \) is \( v_{2i} \). The number of primitives generated is equal to \( \lfloor \text{vertexCount}/2 \rfloor \).

#### 19.1.3. Line Strips
When the topology is `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP`, one line primitive is defined by each vertex and the following vertex, according to the equation:
\[ p_i = \{v_i, v_{i+1}\} \]

The provoking vertex for \( p_i \) is \( v_i \). The number of primitives generated is equal to \( \max(0, \text{vertexCount} - 1) \).

19.1.4. Triangle Lists

When the topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST`, each consecutive set of three vertices defines a single triangle primitive, according to the equation:

\[ p_i = \{v_{3i}, v_{3i+1}, v_{3i+2}\} \]

The provoking vertex for \( p_i \) is \( v_{3i} \). The number of primitives generated is equal to \( \lfloor \text{vertexCount}/3 \rfloor \).

19.1.5. Triangle Strips

When the topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP`, one triangle primitive is defined by each vertex and the two vertices that follow it, according to the equation:

\[ p_i = \{v_i, v_{i+(1+i\%2)}, v_{i+(2-i\%2)}\} \]

The provoking vertex for \( p_i \) is \( v_i \). The number of primitives generated is equal to \( \max(0, \text{vertexCount} - 2) \).

**Note**

The ordering of the vertices in each successive triangle is reversed, so that the winding order is consistent throughout the strip.

19.1.6. Triangle Fans

When the topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN`, triangle primitives are defined around a shared common vertex, according to the equation:

\[ p_i = \{v_{i+1}, v_{i+2}, v_0\} \]
The provoking vertex for \( p_i \) is \( v_{i+1} \). The number of primitives generated is equal to \( \max(0, \text{vertexCount}-2) \).

![Diagram of line lists with adjacency]

19.1.7. Line Lists With Adjacency

When the topology is `VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY`, each consecutive set of four vertices defines a single line primitive with adjacency, according to the equation:

\[
q_i = \{ v_{4i}, v_{4i+1}, v_{4i+2}, v_{4i+3} \}
\]

A line primitive is described by the second and third vertices of the total primitive, with the remaining two vertices only accessible in a geometry shader.

The provoking vertex for \( p_i \) is \( v_{4i+1} \). The number of primitives generated is equal to \( \left\lfloor \frac{\text{vertexCount}}{4} \right\rfloor \).

![Diagram of line strips with adjacency]

19.1.8. Line Strips With Adjacency

When the topology is `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY`, one line primitive with adjacency is defined by each vertex and the following vertex, according to the equation:

\[
q_i = \{ v_i, v_{i+1}, v_{i+2}, v_{i+3} \}
\]

A line primitive is described by the second and third vertices of the total primitive, with the remaining two vertices only accessible in a geometry shader.

The provoking vertex for \( p_i \) is \( v_{i+1} \). The number of primitives generated is equal to \( \max(0, \text{vertexCount}-3) \).

![Diagram of triangle lists with adjacency]

19.1.9. Triangle Lists With Adjacency

When the topology is `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY`, each consecutive set of six vertices defines a single triangle primitive with adjacency, according to the equations:

\[
q_i = \{ v_{6i}, v_{6i+1}, v_{6i+2}, v_{6i+3}, v_{6i+4}, v_{6i+5} \}
\]
A triangle primitive is described by the first, third, and fifth vertices of the total primitive, with the remaining three vertices only accessible in a geometry shader.

The provoking vertex for $p_i$ is $v_{6i}$. The number of primitives generated is equal to $\lfloor \text{vertexCount}/6 \rfloor$.

19.1.10. Triangle Strips With Adjacency

When the topology is VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY, one triangle primitive with adjacency is defined by each vertex and the following 5 vertices.

The number of primitives generated, $n$, is equal to $\max(0, \text{vertexCount} - 4)/2$.

If $n=1$, the primitive is defined as:

$$p = \{v_0, v_1, v_5, v_4, v_3\}$$

If $n>1$, the total primitive consists of different vertices according to where it is in the strip:

$$p_i = \{v_{2i}, v_{2i+1}, v_{2i+2}, v_{2i+6}, v_{2i+4}, v_{2i+3}\} \text{ when } i=0$$

$$p_i = \{v_{2i}, v_{2i+3}, v_{2i+4}, v_{2i+6}, v_{2i+2}, v_{2i+1}\} \text{ when } i>0, i<n-1, \text{ and } i\%2=1$$

$$p_i = \{v_{2i}, v_{2i+2}, v_{2i+3}, v_{2i+4}, v_{2i+6}, v_{2i+1}\} \text{ when } i>0, i<n-1, \text{ and } i\%2=0$$

$$p_i = \{v_{2i}, v_{2i+3}, v_{2i+4}, v_{2i+5}, v_{2i+2}, v_{2i+1}\} \text{ when } i=n-1 \text{ and } i\%2=1$$

$$p_i = \{v_{2i}, v_{2i+2}, v_{2i+3}, v_{2i+4}, v_{2i+5}, v_{2i+3}\} \text{ when } i=n-1 \text{ and } i\%2=0$$

A triangle primitive is described by the first, third, and fifth vertices of the total primitive in all cases, with the remaining three vertices only accessible in a geometry shader.

**Note**

The ordering of the vertices in each successive triangle is altered so that the winding order is consistent throughout the strip.

The provoking vertex for $p_i$ is always $v_{2i}$.
19.1.11. Patch Lists

When the topology is VK_PRIMITIVE_TOPOLOGY_PATCH_LIST, each consecutive set of m vertices defines a single patch primitive, according to the equation:

\[ p_i = \{v_{mi}, v_{mi+1}, \ldots, v_{mi+(m-2)}, v_{mi+(m-1)}\} \]

where m is equal to VkPipelineTessellationStateCreateInfo::patchControlPoints.

Patch lists are never passed to vertex post-processing, and as such no provoking vertex is defined for patch primitives. The number of primitives generated is equal to \( \left\lfloor \frac{\text{vertexCount}}{m} \right\rfloor \).

The vertices comprising a patch have no implied geometry, and are used as inputs to tessellation shaders and the fixed-function tessellator to generate new point, line, or triangle primitives.

19.2. Primitive Order

Primitives generated by drawing commands progress through the stages of the graphics pipeline in primitive order. Primitive order is initially determined in the following way:

1. Submission order determines the initial ordering
2. For indirect draw commands, the order in which accessed instances of the VkDrawIndirectCommand are stored in buffer, from lower indirect buffer addresses to higher addresses.
3. If a draw command includes multiple instances, the order in which instances are executed, from lower numbered instances to higher.

4. The order in which primitives are specified by a draw command:
   - For non-indexed draws, from vertices with a lower numbered \textit{vertexIndex} to a higher numbered \textit{vertexIndex}.
   - For indexed draws, vertices sourced from a lower index buffer addresses to higher addresses.

Within this order implementations further sort primitives:

5. If tessellation shading is active, by an implementation-dependent order of new primitives generated by \textit{tessellation}.

6. If geometry shading is active, by the order new primitives are generated by \textit{geometry shading}.

7. If the \textit{polygon mode} is not \textit{VK_POLYGON_MODE_FILL}, by an implementation-dependent ordering of the new primitives generated within the original primitive.

Primitive order is later used to define \textit{rasterization order}, which determines the order in which fragments output results to a framebuffer.

### 19.3. Programmable Primitive Shading

Once primitives are assembled, they proceed to the vertex shading stage of the pipeline. If the draw includes multiple instances, then the set of primitives is sent to the vertex shading stage multiple times, once for each instance.

It is implementation-dependent whether vertex shading occurs on vertices that are discarded as part of incomplete primitives, but if it does occur then it operates as if they were vertices in complete primitives and such invocations can have side effects.

Vertex shading receives two per-vertex inputs from the primitive assembly stage - the \textit{vertexIndex} and the \textit{instanceIndex}. How these values are generated is defined below, with each command.

Drawing commands fall roughly into two categories:

- **Non-indexed drawing commands** present a sequential \textit{vertexIndex} to the vertex shader. The sequential index is generated automatically by the device (see Fixed-Function Vertex Processing for details on both specifying the vertex attributes indexed by \textit{vertexIndex}, as well as binding vertex buffers containing those attributes to a command buffer). These commands are:
  - \texttt{vkCmdDraw}
  - \texttt{vkCmdDrawIndirect}
  - \texttt{vkCmdDrawIndirectCountKHR}

- **Indexed drawing commands** read index values from an \textit{index buffer} and use this to compute the \textit{vertexIndex} value for the vertex shader. These commands are:
  - \texttt{vkCmdDrawIndexed}
  - \texttt{vkCmdDrawIndexedIndirect}
° vkCmdDrawIndexedIndirectCountKHR

To bind an index buffer to a command buffer, call:

```c
void vkCmdBindIndexBuffer(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    VkIndexType indexType);
```

- **commandBuffer** is the command buffer into which the command is recorded.
- **buffer** is the buffer being bound.
- **offset** is the starting offset in bytes within **buffer** used in index buffer address calculations.
- **indexType** is a **VkIndexType** value specifying whether indices are treated as 16 bits or 32 bits.

### Valid Usage

- **offset** must be less than the size of **buffer**
- The sum of **offset** and the address of the range of **VkDeviceMemory** object that is backing **buffer**, must be a multiple of the type indicated by **indexType**
- **buffer** must have been created with the **VK_BUFFER_USAGE_INDEX_BUFFER_BIT** flag
- If **buffer** is non-sparse then it must be bound completely and contiguously to a single **VkDeviceMemory** object
- **indexType** must not be **VK_INDEX_TYPE_NONE_KHR**.

### Valid Usage (Implicit)

- **commandBuffer** must be a valid **VkCommandBuffer** handle
- **buffer** must be a valid **VkBuffer** handle
- **indexType** must be a valid **VkIndexType** value
- **commandBuffer** must be in the recording state
- The **VkCommandPool** that **commandBuffer** was allocated from must support graphics operations
- Both of **buffer**, and **commandBuffer** must have been created, allocated, or retrieved from the same **VkDevice**
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Possible values of `vkCmdBindIndexBuffer::indexType`, specifying the size of indices, are:

```c
typedef enum VkIndexType {
    VK_INDEX_TYPE_UINT16 = 0,
    VK_INDEX_TYPE_UINT32 = 1,
    VK_INDEX_TYPE_NONE_KHR = 1000165000,
    VK_INDEX_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkIndexType;
```

- `VK_INDEX_TYPE_UINT16` specifies that indices are 16-bit unsigned integer values.
- `VK_INDEX_TYPE_UINT32` specifies that indices are 32-bit unsigned integer values.
- `VK_INDEX_TYPE_NONE_KHR` specifies that no indices are provided.

The parameters for each drawing command are specified directly in the command or read from buffer memory, depending on the command. Drawing commands that source their parameters from buffer memory are known as indirect drawing commands.

All drawing commands interact with the Robust Buffer Access feature.

To record a non-indexed draw, call:

```c
void vkCmdDraw(
    VkCommandBuffer commandBuffer,
    uint32_t vertexCount,
    uint32_t instanceCount,
    uint32_t firstVertex,
    uint32_t firstInstance);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `vertexCount` is the number of vertices to draw.
• `instanceCount` is the number of instances to draw.
• `firstVertex` is the index of the first vertex to draw.
• `firstInstance` is the instance ID of the first instance to draw.

When the command is executed, primitives are assembled using the current primitive topology and `vertexCount` consecutive vertex indices with the first `vertexIndex` value equal to `firstVertex`. The primitives are drawn `instanceCount` times with `instanceIndex` starting with `firstInstance` and increasing sequentially for each instance. The assembled primitives execute the bound graphics pipeline.
Valid Usage

- If a `VkImageView` is sampled with `VK_FILTER_LINEAR` as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`.

- If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`.

- For each set \( n \) that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a descriptor set must have been bound to \( n \) at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set \( n \), with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in "Pipeline Layout Compatibility".

- For each push constant that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in "Pipeline Layout Compatibility".

- Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid if they are statically used by the `VkPipeline` bound to the pipeline bind point used by this command.

- A valid pipeline must be bound to the pipeline bind point used by this command.

- If the `VkPipeline` object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for `commandBuffer`, and done so after any previously bound pipeline with the corresponding state not specified as dynamic.

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by this command, since that pipeline was bound.

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used to sample from any `VkImage` with a `VkImageView` of the type `VK_IMAGE_VIEW_TYPE_3D`, `VK_IMAGE_VIEW_TYPE_CUBE`, `VK_IMAGE_VIEW_TYPE_1D_ARRAY`, `VK_IMAGE_VIEW_TYPE_2D_ARRAY` or `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY`, in any shader stage.

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions with `ImplicitLod`, `Dref` or `Proj` in their name, in any shader stage.

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions that includes a LOD bias or any offset values, in any shader stage.

- If the robust buffer access feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• Every input attachment used by the current subpass must be bound to the pipeline via a descriptor set.

• Image subresources used as attachments in the current render pass must not be accessed in any way other than as an attachment by this command.

• If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex.

• If commandBuffer is a protected command buffer, any resource written to by the VkPipeline object bound to the pipeline bind point used by this command must not be an unprotected resource.

• If commandBuffer is a protected command buffer, pipeline stages other than the framebuffer-space and compute stages in the VkPipeline object bound to the pipeline bind point must not write to any resource.

• All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must have valid buffers bound.

• For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

Valid Usage (Implicit)

• commandBuffer must be a valid VkCommandBuffer handle

• commandBuffer must be in the recording state

• The VkCommandPool that commandBuffer was allocated from must support graphics operations.

• This command must only be called inside of a render pass instance.
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized.
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized.

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To record an indexed draw, call:

```c
void vkCmdDrawIndexed(
    VkCommandBuffer commandBuffer,
    uint32_t           indexCount,
    uint32_t           instanceCount,
    uint32_t           firstIndex,
    int32_t            vertexOffset,
    uint32_t           firstInstance);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `indexCount` is the number of vertices to draw.
- `instanceCount` is the number of instances to draw.
- `firstIndex` is the base index within the index buffer.
- `vertexOffset` is the value added to the vertex index before indexing into the vertex buffer.
- `firstInstance` is the instance ID of the first instance to draw.

When the command is executed, primitives are assembled using the current primitive topology and `indexCount` vertices whose indices are retrieved from the index buffer. The index buffer is treated as an array of tightly packed unsigned integers of size defined by the `vkCmdBindIndexBuffer ::indexType` parameter with which the buffer was bound.

The first vertex index is at an offset of `firstIndex * indexSize + offset` within the bound index buffer, where `offset` is the offset specified by `vkCmdBindIndexBuffer` and `indexSize` is the byte size of the type specified by `indexType`. Subsequent index values are retrieved from consecutive locations in the index buffer. Indices are first compared to the primitive restart value, then zero extended to 32 bits (if the `indexType` is `VK_INDEX_TYPE_UINT16`) and have `vertexOffset` added to them, before being supplied as the `vertexIndex` value.

The primitives are drawn `instanceCount` times with `instanceIndex` starting with `firstInstance` and
increasing sequentially for each instance. The assembled primitives execute the bound graphics pipeline.
Valid Usage

- If a VkImageView is sampled with VK_FILTER_LINEAR as a result of this command, then the image view’s format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT.

- If a VkImageView is accessed using atomic operations as a result of this command, then the image view’s format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT.

- For each set \( n \) that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a descriptor set must have been bound to \( n \) at the same pipeline bind point, with a VkPipelineLayout that is compatible for set \( n \), with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- For each push constant that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- Descriptors in each bound descriptor set, specified via vkCmdBindDescriptorSets, must be valid if they are statically used by the VkPipeline bound to the pipeline bind point used by this command.

- A valid pipeline must be bound to the pipeline bind point used by this command.

- If the VkPipeline object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for commandBuffer, and done so after any previously bound pipeline with the corresponding state not specified as dynamic.

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage.

- If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• Every input attachment used by the current subpass must be bound to the pipeline via a descriptor set.

• Image subresources used as attachments in the current render pass must not be accessed in any way other than as an attachment by this command.

• If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex.

• If commandBuffer is a protected command buffer, any resource written to by the VkPipeline object bound to the pipeline bind point used by this command must not be an unprotected resource.

• If commandBuffer is a protected command buffer, pipeline stages other than the framebuffer-space and compute stages in the VkPipeline object bound to the pipeline bind point must not write to any resource.

• All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point’s interface must have valid buffers bound.

• For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

• \((\text{indexSize} \times (\text{firstIndex} + \text{indexCount}) + \text{offset})\) must be less than or equal to the size of the bound index buffer, with indexSize being based on the type specified by indexType, where the index buffer, indexType, and offset are specified via vkCmdBindIndexBuffer.
Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support graphics operations
- This command **must** only be called inside of a render pass instance

Host Synchronization

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To record a non-indexed indirect draw, call:

```c
void vkCmdDrawIndirect(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    uint32_t drawCount,
    uint32_t stride);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `buffer` is the buffer containing draw parameters.
- `offset` is the byte offset into `buffer` where parameters begin.
- `drawCount` is the number of draws to execute, and **can** be zero.
- `stride` is the byte stride between successive sets of draw parameters.

`vkCmdDrawIndirect` behaves similarly to `vkCmdDraw` except that the parameters are read by the device from a buffer during execution. `drawCount` draws are executed by the command, with parameters taken from `buffer` starting at `offset` and increasing by `stride` bytes for each successive draw. The parameters of each draw are encoded in an array of `VkDrawIndirectCommand` structures. If `drawCount` is less than or equal to one, `stride` is ignored.
Valid Usage

• If a `VkImageView` is sampled with `VK_FILTER_LINEAR` as a result of this command, then the image view's `format features` must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

• If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's `format features` must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`

• For each set $n$ that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a descriptor set must have been bound to $n$ at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set $n$, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility

• For each push constant that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility

• Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid if they are statically used by the `VkPipeline` bound to the pipeline bind point used by this command

• A valid pipeline must be bound to the pipeline bind point used by this command

• If the `VkPipeline` object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for `commandBuffer`, and done so after any previously bound pipeline with the corresponding state not specified as dynamic

• There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by this command, since that pipeline was bound

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used to sample from any `VkImage` with a `VkImageView` of the type `VK_IMAGE_VIEW_TYPE_3D`, `VK_IMAGE_VIEW_TYPE_CUBE`, `VK_IMAGE_VIEW_TYPE_1D_ARRAY`, `VK_IMAGE_VIEW_TYPE_2D_ARRAY` or `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY`, in any shader stage

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions with `ImplicitLod`, `Dref` or `Proj` in their name, in any shader stage

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions that includes a LOD bias or any offset values, in any shader stage

• If the robust buffer access feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• Every input attachment used by the current subpass must be bound to the pipeline via a descriptor set.

• Image subresources used as attachments in the current render pass must not be accessed in any way other than as an attachment by this command.

• If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex.

• All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point’s interface must have valid buffers bound.

• For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

• If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

• buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.

• offset must be a multiple of 4.

• commandBuffer must not be a protected command buffer.

• If the multi-draw indirect feature is not enabled, drawCount must be 0 or 1.

• drawCount must be less than or equal to VkPhysicalDeviceLimits::maxDrawIndirectCount.

• If the drawIndirectFirstInstance feature is not enabled, all the firstInstance members of the VkDrawIndirectCommand structures accessed by this command must be 0.

• If drawCount is greater than 1, stride must be a multiple of 4 and must be greater than or equal to sizeof(VkDrawIndirectCommand).

• If drawCount is equal to 1, (offset + sizeof(VkDrawIndirectCommand)) must be less than or equal to the size of buffer.

• If drawCount is greater than 1, (stride × (drawCount - 1) + offset + sizeof(VkDrawIndirectCommand)) must be less than or equal to the size of buffer.
Valid Usage (Implicit)

- commandBuffer must be a valid VkCommandBuffer handle
- buffer must be a valid VkBuffer handle
- commandBuffer must be in the recording state
- The VkCommandPool that commandBuffer was allocated from must support graphics operations
- This command must only be called inside of a render pass instance
- Both of buffer, and commandBuffer must have been created, allocated, or retrieved from the same VkDevice

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VkDrawIndirectCommand structure is defined as:

```c
typedef struct VkDrawIndirectCommand {
    uint32_t vertexCount;
    uint32_t instanceCount;
    uint32_t firstVertex;
    uint32_t firstInstance;
} VkDrawIndirectCommand;
```

- vertexCount is the number of vertices to draw.
- instanceCount is the number of instances to draw.
- firstVertex is the index of the first vertex to draw.
- firstInstance is the instance ID of the first instance to draw.

The members of VkDrawIndirectCommand have the same meaning as the similarly named parameters of vkCmdDraw.
Valid Usage

• For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

• If the `drawIndirectFirstInstance` feature is not enabled, `firstInstance` must be 0.

To record a non-indexed draw call with a draw call count sourced from a buffer, call:

```c
void vkCmdDrawIndirectCountKHR(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,    
    VkDeviceSize offset,
    VkBuffer countBuffer,
    VkDeviceSize countBufferOffset,
    uint32_t maxDrawCount,
    uint32_t stride);
```

• `commandBuffer` is the command buffer into which the command is recorded.
• `buffer` is the buffer containing draw parameters.
• `offset` is the byte offset into `buffer` where parameters begin.
• `countBuffer` is the buffer containing the draw count.
• `countBufferOffset` is the byte offset into `countBuffer` where the draw count begins.
• `maxDrawCount` specifies the maximum number of draws that will be executed. The actual number of executed draw calls is the minimum of the count specified in `countBuffer` and `maxDrawCount`.
• `stride` is the byte stride between successive sets of draw parameters.

`vkCmdDrawIndirectCount` behaves similarly to `vkCmdDrawIndirect` except that the draw count is read by the device from a buffer during execution. The command will read an unsigned 32-bit integer from `countBuffer` located at `countBufferOffset` and use this as the draw count.
Valid Usage

• If a `VkImageView` is sampled with `VK_FILTER_LINEAR` as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

• If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`

• For each set $n$ that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a descriptor set must have been bound to $n$ at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set $n$, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility

• For each push constant that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility

• Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid if they are statically used by the `VkPipeline` bound to the pipeline bind point used by this command

• A valid pipeline must be bound to the pipeline bind point used by this command

• If the `VkPipeline` object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for `commandBuffer`, and done so after any previously bound pipeline with the corresponding state not specified as dynamic

• There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by this command, since that pipeline was bound

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used to sample from any `VkImage` with a `VkImageView` of the type `VK_IMAGE_VIEW_TYPE_3D`, `VK_IMAGE_VIEW_TYPE_CUBE`, `VK_IMAGE_VIEW_TYPE_1D_ARRAY`, `VK_IMAGE_VIEW_TYPE_2D_ARRAY` or `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY`, in any shader stage

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions with `ImplicitLod`, `Dref` or `Proj` in their name, in any shader stage

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions that includes a LOD bias or any offset values, in any shader stage

• If the robust buffer access feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• Every input attachment used by the current subpass must be bound to the pipeline via a descriptor set.

• Image subresources used as attachments in the current render pass must not be accessed in any way other than as an attachment by this command.

• If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex.

• All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface must have valid buffers bound.

• For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

• If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

• buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.

• offset must be a multiple of 4.

• commandBuffer must not be a protected command buffer.

• If countBuffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

• countBuffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.

• countBufferOffset must be a multiple of 4.

• The count stored in countBuffer must be less than or equal to VkPhysicalDeviceLimits::maxDrawIndirectCount.

• stride must be a multiple of 4 and must be greater than or equal to sizeof(VkDrawIndirectCommand).

• If maxDrawCount is greater than or equal to 1, (stride × (maxDrawCount - 1) + offset + sizeof(VkDrawIndirectCommand)) must be less than or equal to the size of buffer.

• If the count stored in countBuffer is equal to 1, (offset + sizeof(VkDrawIndirectCommand))
**Valid Usage (Implicit)**

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `buffer` must be a valid `VkBuffer` handle
- `countBuffer` must be a valid `VkBuffer` handle
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- This command must only be called inside of a render pass instance
- Each of `buffer`, `commandBuffer`, and `countBuffer` must have been created, allocated, or retrieved from the same `VkDevice`

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

**Command Properties**

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To record an indexed indirect draw, call:

```c
void vkCmdDrawIndexedIndirect(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    uint32_t drawCount,
    uint32_t stride);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `buffer` is the buffer containing draw parameters.
• **offset** is the byte offset into `buffer` where parameters begin.
• **drawCount** is the number of draws to execute, and **can** be zero.
• **stride** is the byte stride between successive sets of draw parameters.

`vkCmdDrawIndexedIndirect` behaves similarly to `vkCmdDrawIndexed` except that the parameters are read by the device from a buffer during execution. **drawCount** draws are executed by the command, with parameters taken from `buffer` starting at **offset** and increasing by **stride** bytes for each successive draw. The parameters of each draw are encoded in an array of `VkDrawIndexedIndirectCommand` structures. If **drawCount** is less than or equal to one, **stride** is ignored.
Valid Usage

- If a `VkImageView` is sampled with `VK_FILTER_LINEAR` as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`.

- If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`.

- For each set $n$ that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a descriptor set must have been bound to $n$ at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set $n$, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

- For each push constant that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

- Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid if they are statically used by the `VkPipeline` bound to the pipeline bind point used by this command.

- A valid pipeline must be bound to the pipeline bind point used by this command.

- If the `VkPipeline` object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for `commandBuffer`, and done so after any previously bound pipeline with the corresponding state not specified as dynamic.

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by this command, since that pipeline was bound.

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used to sample from any `VkImage` with a `VkImageView` of the type `VK_IMAGE_VIEW_TYPE_3D`, `VK_IMAGE_VIEW_TYPE_CUBE`, `VK_IMAGE_VIEW_TYPE_1D_ARRAY`, `VK_IMAGE_VIEW_TYPE_2D_ARRAY` or `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY`, in any shader stage.

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions with `ImplicitLod`, `Dref` or `Proj` in their name, in any shader stage.

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions that includes a LOD bias or any offset values, in any shader stage.

- If the robust buffer access feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• The current render pass must be compatible with the renderPass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• The subpass index of the current render pass must be equal to the subpass member of the VkGraphicsPipelineCreateInfo structure specified when creating the VkPipeline bound to VK_PIPELINE_BIND_POINT_GRAPHICS.

• Every input attachment used by the current subpass must be bound to the pipeline via a descriptor set.

• Image subresources used as attachments in the current render pass must not be accessed in any way other than as an attachment by this command.

• If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index must be less than or equal to VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex.

• All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point’s interface must have valid buffers bound.

• For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.

• If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

• buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.

• offset must be a multiple of 4.

• commandBuffer must not be a protected command buffer.

• If the multi-draw indirect feature is not enabled, drawCount must be 0 or 1.

• drawCount must be less than or equal to VkPhysicalDeviceLimits::maxDrawIndirectCount.

• If drawCount is greater than 1, stride must be a multiple of 4 and must be greater than or equal to sizeof(VkDrawIndexedIndirectCommand).

• If the drawIndirectFirstInstance feature is not enabled, all the firstInstance members of the VkDrawIndexedIndirectCommand structures accessed by this command must be 0.

• If drawCount is equal to 1, (offset + sizeof(VkDrawIndexedIndirectCommand)) must be less than or equal to the size of buffer.

• If drawCount is greater than 1, (stride × (drawCount - 1) + offset + sizeof(VkDrawIndexedIndirectCommand)) must be less than or equal to the size of buffer.
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `buffer` must be a valid `VkBuffer` handle
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- This command must only be called inside of a render pass instance
- Both of `buffer`, and `commandBuffer` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The `VkDrawIndexedIndirectCommand` structure is defined as:

```c
typedef struct VkDrawIndexedIndirectCommand {
    uint32_t    indexCount;
    uint32_t    instanceCount;
    uint32_t    firstIndex;
    int32_t     vertexOffset;
    uint32_t    firstInstance;
} VkDrawIndexedIndirectCommand;
```

- `indexCount` is the number of vertices to draw.
- `instanceCount` is the number of instances to draw.
- `firstIndex` is the base index within the index buffer.
- `vertexOffset` is the value added to the vertex index before indexing into the vertex buffer.
- `firstInstance` is the instance ID of the first instance to draw.
The members of `VkDrawIndexedIndirectCommand` have the same meaning as the similarly named parameters of `vkCmdDrawIndexed`.

### Valid Usage

- For a given vertex buffer binding, any attribute data fetched must be entirely contained within the corresponding vertex buffer binding, as described in Vertex Input Description.
- \((\text{indexSize} \times (\text{firstIndex} + \text{indexCount}) + \text{offset})\) must be less than or equal to the size of the bound index buffer, with \(\text{indexSize}\) being based on the type specified by `indexType`, where the index buffer, `indexType`, and `offset` are specified via `vkCmdBindIndexBuffer`.
- If the `drawIndirectFirstInstance` feature is not enabled, `firstInstance` must be 0.

To record an indexed draw call with a draw call count sourced from a buffer, call:

```c
void vkCmdDrawIndexedIndirectCountKHR(
    VkCommandBuffer commandBuffer,  
    VkBuffer buffer,                
    VkDeviceSize offset,            
    VkBuffer countBuffer,           
    VkDeviceSize countBufferOffset, 
    uint32_t maxDrawCount,          
    uint32_t stride);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `buffer` is the buffer containing draw parameters.
- `offset` is the byte offset into `buffer` where parameters begin.
- `countBuffer` is the buffer containing the draw count.
- `countBufferOffset` is the byte offset into `countBuffer` where the draw count begins.
- `maxDrawCount` specifies the maximum number of draws that will be executed. The actual number of executed draw calls is the minimum of the count specified in `countBuffer` and `maxDrawCount`.
- `stride` is the byte stride between successive sets of draw parameters.

`vkCmdDrawIndexedIndirectCount` behaves similarly to `vkCmdDrawIndexedIndirect` except that the draw count is read by the device from a buffer during execution. The command will read an unsigned 32-bit integer from `countBuffer` located at `countBufferOffset` and use this as the draw count.
Valid Usage

- If a VkImageView is sampled with VK_FILTER_LINEAR as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT.

- If a VkImageView is accessed using atomic operations as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT.

- For each set \( n \) that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a descriptor set must have been bound to \( n \) at the same pipeline bind point, with a VkPipelineLayout that is compatible for set \( n \), with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- For each push constant that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- Descriptors in each bound descriptor set, specified via vkCmdBindDescriptorSets, must be valid if they are statically used by the VkPipeline bound to the pipeline bind point used by this command.

- A valid pipeline must be bound to the pipeline bind point used by this command.

- If the VkPipeline object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for commandBuffer, and done so after any previously bound pipeline with the corresponding state not specified as dynamic.

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage.

- If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.
If the **robust buffer access** feature is not enabled, and if the **VkPipeline** object bound to the pipeline bind point used by this command accesses a storage buffer, it **must** not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

If **commandBuffer** is an unprotected command buffer, any resource accessed by the **VkPipeline** object bound to the pipeline bind point used by this command **must** not be a protected resource.

The current render pass **must** be compatible with the **renderPass** member of the **VkGraphicsPipelineCreateInfo** structure specified when creating the **VkPipeline** bound to **VK_PIPELINE_BIND_POINT_GRAPHICS**.

The subpass index of the current render pass **must** be equal to the **subpass** member of the **VkGraphicsPipelineCreateInfo** structure specified when creating the **VkPipeline** bound to **VK_PIPELINE_BIND_POINT_GRAPHICS**.

Every input attachment used by the current subpass **must** be bound to the pipeline via a descriptor set.

Image subresources used as attachments in the current render pass **must** not be accessed in any way other than as an attachment by this command.

If the draw is recorded in a render pass instance with multiview enabled, the maximum instance index **must** be less than or equal to **VkPhysicalDeviceMultiviewProperties::maxMultiviewInstanceIndex**.

All vertex input bindings accessed via vertex input variables declared in the vertex shader entry point's interface **must** have valid buffers bound.

For a given vertex buffer binding, any attribute data fetched **must** be entirely contained within the corresponding vertex buffer binding, as described in [Vertex Input Description](#).

If **buffer** is non-sparse then it **must** be bound completely and contiguously to a single **VkDeviceMemory** object.

**buffer** **must** have been created with the **VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT** bit set.

**offset** **must** be a multiple of 4.

**commandBuffer** **must** not be a protected command buffer.

If **countBuffer** is non-sparse then it **must** be bound completely and contiguously to a single **VkDeviceMemory** object.

**countBuffer** **must** have been created with the **VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT** bit set.

**countBufferOffset** **must** be a multiple of 4.

The count stored in **countBuffer** **must** be less than or equal to **VkPhysicalDeviceLimits::maxDrawIndirectCount**.

**stride** **must** be a multiple of 4 and **must** be greater than or equal to **sizeof(VkDrawIndexedIndirectCommand)**.

If **maxDrawCount** is greater than or equal to 1, \((\text{stride} \times (\text{maxDrawCount} - 1) + \text{offset} + \text{sizeof(VkDrawIndexedIndirectCommand)})\) **must** be less than or equal to the size of **buffer**.

If count stored in **countBuffer** is equal to 1, \((\text{offset} + \text{sizeof(VkDrawIndexedIndirectCommand)})\) **must** be less than or equal to the size of **buffer**.
must be less than or equal to the size of buffer

- If count stored in countBuffer is greater than 1, 
  \((\text{stride} \times (\text{drawCount} - 1) + \text{offset} + \text{sizeof(VkDrawIndexedIndirectCommand)})\) must be less than or equal to the size of buffer

### Valid Usage (Implicit)

- commandBuffer must be a valid VkCommandBuffer handle
- buffer must be a valid VkBuffer handle
- countBuffer must be a valid VkBuffer handle
- commandBuffer must be in the recording state
- The VkCommandPool that commandBuffer was allocated from must support graphics operations
- This command must only be called inside of a render pass instance
- Each of buffer, commandBuffer, and countBuffer must have been created, allocated, or retrieved from the same VkDevice

### Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary, Secondary</td>
<td>Inside</td>
<td>Graphics</td>
<td>Graphics</td>
</tr>
</tbody>
</table>
Chapter 20. Fixed-Function Vertex Processing

Vertex fetching is controlled via configurable state, as a logically distinct graphics pipeline stage.

20.1. Vertex Attributes

Vertex shaders can define input variables, which receive vertex attribute data transferred from one or more VkBuffer(s) by drawing commands. Vertex shader input variables are bound to buffers via an indirect binding where the vertex shader associates a vertex input attribute number with each variable, vertex input attributes are associated to vertex input bindings on a per-pipeline basis, and vertex input bindings are associated with specific buffers on a per-draw basis via the vkCmdBindVertexBuffers command. Vertex input attribute and vertex input binding descriptions also contain format information controlling how data is extracted from buffer memory and converted to the format expected by the vertex shader.

There are VkPhysicalDeviceLimits::maxVertexInputAttributes number of vertex input attributes and VkPhysicalDeviceLimits::maxVertexInputBindings number of vertex input bindings (each referred to by zero-based indices), where there are at least as many vertex input attributes as there are vertex input bindings. Applications can store multiple vertex input attributes interleaved in a single buffer, and use a single vertex input binding to access those attributes.

In GLSL, vertex shaders associate input variables with a vertex input attribute number using the location layout qualifier. The component layout qualifier associates components of a vertex shader input variable with components of a vertex input attribute.

**GLSL example**

```glsl
// Assign location M to variableName
layout (location=M, component=2) in vec2 variableName;

// Assign locations [N,N+L) to the array elements of variableNameArray
layout (location=N) in vec4 variableNameArray[L];
```

In SPIR-V, vertex shaders associate input variables with a vertex input attribute number using the Location decoration. The Component decoration associates components of a vertex shader input variable with components of a vertex input attribute. The Location and Component decorations are specified via the OpDecorate instruction.
20.1.1. Attribute Location and Component Assignment

Vertex shaders allow Location and Component decorations on input variable declarations. The Location decoration specifies which vertex input attribute is used to read and interpret the data that a variable will consume. The Component decoration allows the location to be more finely specified for scalars and vectors, down to the individual components within a location that are consumed. The components within a location are 0, 1, 2, and 3. A variable starting at component N will consume components N, N+1, N+2, ... up through its size. For single precision types, it is invalid if the sequence of components gets larger than 3.

When a vertex shader input variable declared using a scalar or vector 32-bit data type is assigned a location, its value(s) are taken from the components of the input attribute specified with the corresponding VkVertexInputAttributeDescription::location. The components used depend on the type of variable and the Component decoration specified in the variable declaration, as identified in Input attribute components accessed by 32-bit input variables. Any 32-bit scalar or vector input will consume a single location. For 32-bit data types, missing components are filled in with default values as described below.

Table 24. Input attribute components accessed by 32-bit input variables
Components indicated by “o” are available for use by other input variables which are sourced from the same attribute, and if used, are either filled with the corresponding component from the input format (if present), or the default value.

When a vertex shader input variable declared using a 32-bit floating point matrix type is assigned a location \( i \), its values are taken from consecutive input attributes starting with the corresponding `VkVertexInputAttributeDescription::location`. Such matrices are treated as an array of column vectors with values taken from the input attributes identified in Table 25. Input attributes accessed by 32-bit input matrix variables. The `VkVertexInputAttributeDescription::format` must be specified with a `VkFormat` that corresponds to the appropriate type of column vector. The `Component` decoration must not be used with matrix types.

### Table 25. Input attributes accessed by 32-bit input matrix variables

<table>
<thead>
<tr>
<th>Data type</th>
<th>Column vector type</th>
<th>Locations consumed</th>
<th>Components consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>mat2</td>
<td>two-component vector</td>
<td>i, i+1</td>
<td>(x, y, o, o), (x, y, o, o)</td>
</tr>
<tr>
<td>mat2x3</td>
<td>three-component vector</td>
<td>i, i+1</td>
<td>(x, y, z, o), (x, y, z, o)</td>
</tr>
<tr>
<td>mat2x4</td>
<td>four-component vector</td>
<td>i, i+1</td>
<td>(x, y, z, w), (x, y, z, w)</td>
</tr>
<tr>
<td>mat3x2</td>
<td>two-component vector</td>
<td>i, i+1, i+2</td>
<td>(x, y, o, o), (x, y, o, o), (x, y, o, o)</td>
</tr>
<tr>
<td>mat3</td>
<td>three-component vector</td>
<td>i, i+1, i+2</td>
<td>(x, y, z, o), (x, y, z, o), (x, y, z, o)</td>
</tr>
<tr>
<td>mat3x4</td>
<td>four-component vector</td>
<td>i, i+1, i+2</td>
<td>(x, y, z, w), (x, y, z, w), (x, y, z, w)</td>
</tr>
<tr>
<td>mat4x2</td>
<td>two-component vector</td>
<td>i, i+1, i+2, i+3</td>
<td>(x, y, o, o), (x, y, o, o), (x, y, o, o), (x, y, o, o)</td>
</tr>
<tr>
<td>mat4x3</td>
<td>three-component vector</td>
<td>i, i+1, i+2, i+3</td>
<td>(x, y, z, o), (x, y, z, o), (x, y, z, o), (x, y, z, o)</td>
</tr>
<tr>
<td>mat4</td>
<td>four-component vector</td>
<td>i, i+1, i+2, i+3</td>
<td>(x, y, z, w), (x, y, z, w), (x, y, z, w), (x, y, z, w)</td>
</tr>
</tbody>
</table>

Chapter 20. Fixed-Function Vertex Processing | 773
Components indicated by “o” are available for use by other input variables which are sourced from the same attribute, and if used, are either filled with the corresponding component from the input (if present), or the default value.

When a vertex shader input variable declared using a scalar or vector 64-bit data type is assigned a location \( i \), its values are taken from consecutive input attributes starting with the corresponding \( \text{VkVertexInputAttributeDescription}:\text{location} \). The locations and components used depend on the type of variable and the Component decoration specified in the variable declaration, as identified in Input attribute locations and components accessed by 64-bit input variables. For 64-bit data types, no default attribute values are provided. Input variables must not use more components than provided by the attribute. Input attributes which have one- or two-component 64-bit formats will consume a single location. Input attributes which have three- or four-component 64-bit formats will consume two consecutive locations. A 64-bit scalar data type will consume two components, and a 64-bit two-component vector data type will consume all four components available within a location. A three- or four-component 64-bit data type must not specify a component. A three-component 64-bit data type will consume all four components of the first location and components 0 and 1 of the second location. This leaves components 2 and 3 available for other component-qualified declarations. A four-component 64-bit data type will consume all four components of the first location and all four components of the second location. It is invalid for a scalar or two-component 64-bit data type to specify a component of 1 or 3.

### Table 26. Input attribute locations and components accessed by 64-bit input variables

<table>
<thead>
<tr>
<th>Input format</th>
<th>Locations consumed</th>
<th>64-bit data type</th>
<th>Location decoration</th>
<th>Component decoration</th>
<th>32-bit components consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>R64</td>
<td>i</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, -, -)</td>
</tr>
<tr>
<td>R64G64</td>
<td>i</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, o, z, w)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w)</td>
</tr>
<tr>
<td>R64G64B64</td>
<td>i, i+1</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, o, o), (o, o, -, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, z, w), (o, o, -, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i+1</td>
<td>0 or unspecified</td>
<td>(x, y, o, o), (x, y, -, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w), (o, o, -, -)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>three-component vector</td>
<td>i</td>
<td>unspecified</td>
<td>(x, y, z, w), (x, y, -, -)</td>
</tr>
<tr>
<td>Input format</td>
<td>Locations consumed</td>
<td>64-bit data type</td>
<td>Location decoration</td>
<td>Component decoration</td>
<td>32-bit components consumed</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------</td>
<td>------------------</td>
<td>---------------------</td>
<td>----------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>R64G64B64A64</td>
<td>i, i+1</td>
<td>scalar</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, o, o),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(o, o, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, z, w),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(o, o, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i+1</td>
<td>0 or unspecified</td>
<td>(o, o, o, o),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(x, y, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>scalar</td>
<td>i+1</td>
<td>2</td>
<td>(o, o, o, o),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(o, o, z, w)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(o, o, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>two-component vector</td>
<td>i+1</td>
<td>0 or unspecified</td>
<td>(o, o, o, o),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(x, y, z, w)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>three-component vector</td>
<td>i</td>
<td>unspecified</td>
<td>(x, y, z, w),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(x, y, o, o)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>four-component vector</td>
<td>i</td>
<td>unspecified</td>
<td>(x, y, z, w),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(x, y, z, w)</td>
</tr>
</tbody>
</table>

Components indicated by “o” are available for use by other input variables which are sourced from the same attribute. Components indicated by “-” are not available for input variables as there are no default values provided for 64-bit data types, and there is no data provided by the input format.

When a vertex shader input variable declared using a 64-bit floating-point matrix type is assigned a location i, its values are taken from consecutive input attribute locations. Such matrices are treated as an array of column vectors with values taken from the input attributes as shown in Input attribute locations and components accessed by 64-bit input variables. Each column vector starts at the location immediately following the last location of the previous column vector. The number of attributes and components assigned to each matrix is determined by the matrix dimensions and ranges from two to eight locations.

When a vertex shader input variable declared using an array type is assigned a location, its values are taken from consecutive input attributes starting with the corresponding VkVertexInputAttributeDescription::location. The number of attributes and components assigned to each element are determined according to the data type of the array elements and Component decoration (if any) specified in the declaration of the array, as described above. Each element of the array, in order, is assigned to consecutive locations, but all at the same specified component within each location.

Only input variables declared with the data types and component decorations as specified above are supported. **Location aliasing** is causing two variables to have the same location number. **Component aliasing** is assigning the same (or overlapping) component number for two location aliases. Location aliasing is allowed only if it does not cause component aliasing. Further, when location aliasing, the aliases sharing the location **must** all have the same SPIR-V floating-point component type or all have the same width integer-type components.
20.2. Vertex Input Description

Applications specify vertex input attribute and vertex input binding descriptions as part of graphics pipeline creation. VkGraphicsPipelineCreateInfo::pVertexInputState is a pointer to a VkPipelineVertexInputStateCreateInfo value.

The VkPipelineVertexInputStateCreateInfo structure is defined as:

```c
typedef struct VkPipelineVertexInputStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineVertexInputStateCreateFlags flags;
    uint32_t vertexBindingDescriptionCount;
    const VkVertexInputBindingDescription* pVertexBindingDescriptions;
    uint32_t vertexAttributeDescriptionCount;
    const VkVertexInputAttributeDescription* pVertexAttributeDescriptions;
} VkPipelineVertexInputStateCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **vertexBindingDescriptionCount** is the number of vertex binding descriptions provided in **pVertexBindingDescriptions**.
- **pVertexBindingDescriptions** is a pointer to an array of VkVertexInputBindingDescription structures.
- **vertexAttributeDescriptionCount** is the number of vertex attribute descriptions provided in **pVertexAttributeDescriptions**.
- **pVertexAttributeDescriptions** is a pointer to an array of VkVertexInputAttributeDescription structures.

### Valid Usage

- **vertexBindingDescriptionCount** must be less than or equal to VkPhysicalDeviceLimits::maxVertexInputBindings
- **vertexAttributeDescriptionCount** must be less than or equal to VkPhysicalDeviceLimits::maxVertexInputAttributes
- For every binding specified by each element of **pVertexAttributeDescriptions**, a VkVertexInputBindingDescription must exist in **pVertexBindingDescriptions** with the same value of binding
- All elements of **pVertexBindingDescriptions** must describe distinct binding numbers
- All elements of **pVertexAttributeDescriptions** must describe distinct attribute locations
**Valid Usage (Implicit)**

- `sType` **must** be `VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO`
- `pNext` **must** be `NULL`
- `flags` **must** be `0`
  - If `vertexBindingDescriptionCount` is not `0`, `pVertexBindingDescriptions` **must** be a valid pointer to an array of `vertexBindingDescriptionCount` valid `VkVertexInputBindingDescription` structures
  - If `vertexAttributeDescriptionCount` is not `0`, `pVertexAttributeDescriptions` **must** be a valid pointer to an array of `vertexAttributeDescriptionCount` valid `VkVertexInputAttributeDescription` structures

```c
typedef VkFlags VkPipelineVertexInputStateCreateFlags;
```

`VkPipelineVertexInputStateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

Each vertex input binding is specified by the `VkVertexInputBindingDescription` structure, defined as:

```c
typedef struct VkVertexInputBindingDescription {
    uint32_t             binding;
    uint32_t             stride;
    VkVertexInputRate    inputRate;
} VkVertexInputBindingDescription;
```

- `binding` is the binding number that this structure describes.
- `stride` is the distance in bytes between two consecutive elements within the buffer.
- `inputRate` is a `VkVertexInputRate` value specifying whether vertex attribute addressing is a function of the vertex index or of the instance index.

**Valid Usage**

- `binding` **must** be less than `VkPhysicalDeviceLimits::maxVertexInputBindings`
- `stride` **must** be less than or equal to `VkPhysicalDeviceLimits::maxVertexInputBindingStride`

**Valid Usage (Implicit)**

- `inputRate` **must** be a valid `VkVertexInputRate` value

Possible values of `VkVertexInputBindingDescription::inputRate`, specifying the rate at which vertex
attributes are pulled from buffers, are:

```c
typedef enum VkVertexInputRate {
    VK_VERTEX_INPUT_RATE_VERTEX = 0,
    VK_VERTEX_INPUT_RATE_INSTANCE = 1,
    VK_VERTEX_INPUT_RATE_MAX_ENUM = 0x7FFFFFFF
} VkVertexInputRate;
```

- **VK_VERTEX_INPUT_RATE_VERTEX** specifies that vertex attribute addressing is a function of the vertex index.
- **VK_VERTEX_INPUT_RATE_INSTANCE** specifies that vertex attribute addressing is a function of the instance index.

Each vertex input attribute is specified by the `VkVertexInputAttributeDescription` structure, defined as:

```c
typedef struct VkVertexInputAttributeDescription {
    uint32_t    location;
    uint32_t    binding;
    VkFormat    format;
    uint32_t    offset;
} VkVertexInputAttributeDescription;
```

- **location** is the shader binding location number for this attribute.
- **binding** is the binding number which this attribute takes its data from.
- **format** is the size and type of the vertex attribute data.
- **offset** is a byte offset of this attribute relative to the start of an element in the vertex input binding.

**Valid Usage**

- location must be less than `VkPhysicalDeviceLimits::maxVertexInputAttributes`
- binding must be less than `VkPhysicalDeviceLimits::maxVertexInputBindings`
- offset must be less than or equal to `VkPhysicalDeviceLimits::maxVertexInputAttributeOffset`
- format must be allowed as a vertex buffer format, as specified by the `VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT` flag in `VkFormatProperties::bufferFeatures` returned by `vkGetPhysicalDeviceFormatProperties`.

**Valid Usage (Implicit)**

- format must be a valid `VkFormat` value
To bind vertex buffers to a command buffer for use in subsequent draw commands, call:

```c
void vkCmdBindVertexBuffers(
    VkCommandBuffer                             commandBuffer,  
    uint32_t                                    firstBinding,    
    uint32_t                                    bindingCount,   
    const VkBuffer*                             pBuffers,        
    const VkDeviceSize*                         pOffsets);
```

- `commandBuffer` is the command buffer into which the command is recorded.
- `firstBinding` is the index of the first vertex input binding whose state is updated by the command.
- `bindingCount` is the number of vertex input bindings whose state is updated by the command.
- `pBuffers` is a pointer to an array of buffer handles.
- `pOffsets` is a pointer to an array of buffer offsets.

The values taken from elements $i$ of `pBuffers` and `pOffsets` replace the current state for the vertex input binding $\text{firstBinding} + i$, for $i$ in $[0, \text{bindingCount})$. The vertex input binding is updated to start at the offset indicated by `pOffsets[i]` from the start of the buffer `pBuffers[i]`. All vertex input attributes that use each of these bindings will use these updated addresses in their address calculations for subsequent draw commands.

**Valid Usage**

- `firstBinding` must be less than `VkPhysicalDeviceLimits::maxVertexInputBindings`
- The sum of `firstBinding` and `bindingCount` must be less than or equal to `VkPhysicalDeviceLimits::maxVertexInputBindings`
- All elements of `pOffsets` must be less than the size of the corresponding element in `pBuffers`
- All elements of `pBuffers` must have been created with the `VK_BUFFER_USAGE_VERTEX_BUFFER_BIT` flag
- Each element of `pBuffers` that is non-sparse must be bound completely and contiguously to a single `VkDeviceMemory` object
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `pBuffers` must be a valid pointer to an array of `bindingCount` valid `VkBuffer` handles
- `pOffsets` must be a valid pointer to an array of `bindingCount` `VkDeviceSize` values
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations
- `bindingCount` must be greater than 0
- Both of `commandBuffer`, and the elements of `pBuffers` must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The address of each attribute for each `vertexIndex` and `instanceIndex` is calculated as follows:

- Let `attribDesc` be the member of `VkPipelineVertexInputStateCreateInfo::pVertexAttributeDescriptions` with `VkVertexInputAttributeDescription::location` equal to the vertex input attribute number.
- Let `bindingDesc` be the member of `VkPipelineVertexInputStateCreateInfo::pVertexBindingDescriptions` with `VkVertexInputAttributeDescription::binding` equal to `attribDesc.binding`.
- Let `vertexIndex` be the index of the vertex within the draw (a value between `firstVertex` and `firstVertex+vertexCount` for `vkCmdDraw`, or a value taken from the index buffer for `vkCmdDrawIndexed`), and let `instanceIndex` be the instance number of the draw (a value between `firstInstance` and `firstInstance+instanceCount`).
bufferBindingAddress = buffer[binding].baseAddress + offset[binding];

if (bindingDesc.inputRate == VK_VERTEX_INPUT_RATE_VERTEX)
    vertexOffset = vertexIndex * bindingDesc.stride;
else
    vertexOffset = instanceIndex * bindingDesc.stride;

attribAddress = bufferBindingAddress + vertexOffset + attribDesc.offset;

For each attribute, raw data is extracted starting at attribAddress and is converted from the VkVertexInputAttributeDescription's format to either floating-point, unsigned integer, or signed integer based on the base type of the format; the base type of the format must match the base type of the input variable in the shader. If format is a packed format, attribAddress must be a multiple of the size in bytes of the whole attribute data type as described in Packed Formats. Otherwise, attribAddress must be a multiple of the size in bytes of the component type indicated by format (see Formats). If the format does not include G, B, or A components, then those are filled with (0,0,1) as needed (using either 1.0f or integer 1 based on the format) for attributes that are not 64-bit data types. The number of components in the vertex shader input variable need not exactly match the number of components in the format. If the vertex shader has fewer components, the extra components are discarded.

20.3. Example

To create a graphics pipeline that uses the following vertex description:

```c
struct Vertex
{
    float x, y, z, w;
    uint8_t u, v;
};
```

The application could use the following set of structures:
const VkVertexInputBindingDescription binding =
{
    0,                // binding
    sizeof(Vertex),   // stride
    VK_VERTEX_INPUT_RATE_VERTEX, // inputRate
};

const VkVertexInputAttributeDescription attributes[] =
{
    {
        0,                // location
        binding.binding, // binding
        VK_FORMAT_R32G32B32A32_SFLOAT, // format
        0                // offset
    },
    {
        1,                // location
        binding.binding, // binding
        VK_FORMAT_R8G8_UNORM, // format
        4 * sizeof(float) // offset
    }
};

const VkPipelineVertexInputStateCreateInfo viInfo =
{
    VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_CREATE_INFO, // sType
    NULL,                  // pNext
    0,                      // flags
    1,                      // vertexBindingDescriptionCount
    &binding,              // pVertexBindingDescriptions
    2,                      // vertexAttributeDescriptionCount
    &attributes[0]         // pVertexAttributeDescriptions
};
Chapter 21. Tessellation

Tessellation involves three pipeline stages. First, a tessellation control shader transforms control points of a patch and can produce per-patch data. Second, a fixed-function tessellator generates multiple primitives corresponding to a tessellation of the patch in \((u,v)\) or \((u,v,w)\) parameter space. Third, a tessellation evaluation shader transforms the vertices of the tessellated patch, for example to compute their positions and attributes as part of the tessellated surface. The tessellator is enabled when the pipeline contains both a tessellation control shader and a tessellation evaluation shader.

21.1. Tessellator

If a pipeline includes both tessellation shaders (control and evaluation), the tessellator consumes each input patch (after vertex shading) and produces a new set of independent primitives (points, lines, or triangles). These primitives are logically produced by subdividing a geometric primitive (rectangle or triangle) according to the per-patch outer and inner tessellation levels written by the tessellation control shader. These levels are specified using the built-in variables \texttt{TessLevelOuter} and \texttt{TessLevelInner}, respectively. This subdivision is performed in an implementation-dependent manner. If no tessellation shaders are present in the pipeline, the tessellator is disabled and incoming primitives are passed through without modification.

The type of subdivision performed by the tessellator is specified by an \texttt{OpExecutionMode} instruction in the tessellation evaluation or tessellation control shader using one of execution modes \texttt{Triangles}, \texttt{Quads}, and \texttt{IsoLines}. Other tessellation-related execution modes can also be specified in either the tessellation control or tessellation evaluation shaders, and if they are specified in both then the modes must be the same.

Tessellation execution modes include:

- \texttt{Triangles}, \texttt{Quads}, and \texttt{IsoLines}. These control the type of subdivision and topology of the output primitives. One mode must be set in at least one of the tessellation shader stages.
- \texttt{VertexOrderCw} and \texttt{VertexOrderCcw}. These control the orientation of triangles generated by the tessellator. One mode must be set in at least one of the tessellation shader stages.
- \texttt{PointMode}. Controls generation of points rather than triangles or lines. This functionality defaults to disabled, and is enabled if either shader stage includes the execution mode.
- \texttt{SpacingEqual}, \texttt{SpacingFractionalEven}, and \texttt{SpacingFractionalOdd}. Controls the spacing of segments on the edges of tessellated primitives. One mode must be set in at least one of the tessellation shader stages.
- \texttt{OutputVertices}. Controls the size of the output patch of the tessellation control shader. One value must be set in at least one of the tessellation shader stages.

For triangles, the tessellator subdivides a triangle primitive into smaller triangles. For quads, the tessellator subdivides a rectangle primitive into smaller triangles. For isolines, the tessellator subdivides a rectangle primitive into a collection of line segments arranged in strips stretching across the rectangle in the \(u\) dimension (i.e. the coordinates in \texttt{TessCoord} are of the form \((0,x)\) through \((1,x)\) for all tessellation evaluation shader invocations that share a line).
Each vertex produced by the tessellator has an associated (u,v,w) or (u,v) position in a normalized parameter space, with parameter values in the range [0,1], as illustrated in figures Domain parameterization for tessellation primitive modes (upper-left origin) and Domain parameterization for tessellation primitive modes (lower-left origin). The domain space can have either an upper-left or lower-left origin, selected by the domainOrigin member of VkPipelineTessellationDomainOriginStateCreateInfo.
In the domain parameterization diagrams, the coordinates illustrate the value of \texttt{TessCoord} at the corners of the domain. The labels on the edges indicate the inner (IL0 and IL1) and outer (OL0 through OL3) tessellation level values used to control the number of subdivisions along each edge of the domain.

For triangles, the vertex’s position is a barycentric coordinate \((u,v,w)\), where \(u + v + w = 1.0\), and indicates the relative influence of the three vertices of the triangle on the position of the vertex. For quads and isolines, the position is a \((u,v)\) coordinate indicating the relative horizontal and vertical position of the vertex relative to the subdivided rectangle. The subdivision process is explained in more detail in subsequent sections.

## 21.2. Tessellator Patch Discard

A patch is discarded by the tessellator if any relevant outer tessellation level is less than or equal to zero.

Patches will also be discarded if any relevant outer tessellation level corresponds to a floating-point \texttt{NaN} (not a number) in implementations supporting \texttt{NaN}.

No new primitives are generated and the tessellation evaluation shader is not executed for patches that are discarded. For \texttt{Quads}, all four outer levels are relevant. For \texttt{Triangles} and \texttt{IsoLines}, only the first three or two outer levels, respectively, are relevant. Negative inner levels will not cause a patch to be discarded; they will be clamped as described below.

## 21.3. Tessellator Spacing

Each of the tessellation levels is used to determine the number and spacing of segments used to subdivide a corresponding edge. The method used to derive the number and spacing of segments is specified by an \texttt{OpExecutionMode} in the tessellation control or tessellation evaluation shader using one of the identifiers \texttt{SpacingEqual}, \texttt{SpacingFractionalEven}, or \texttt{SpacingFractionalOdd}.

If \texttt{SpacingEqual} is used, the floating-point tessellation level is first clamped to \([1, \texttt{maxLevel}]\), where \texttt{maxLevel} is the implementation-dependent maximum tessellation level (\texttt{VkPhysicalDeviceLimits::maxTessellationGenerationLevel}). The result is rounded up to the nearest integer \(n\), and the corresponding edge is divided into \(n\) segments of equal length in \((u,v)\) space.

If \texttt{SpacingFractionalEven} is used, the tessellation level is first clamped to \([2, \texttt{maxLevel}]\) and then rounded up to the nearest even integer \(n\). If \texttt{SpacingFractionalOdd} is used, the tessellation level is clamped to \([1, \texttt{maxLevel} - 1]\) and then rounded up to the nearest odd integer \(n\). If \(n\) is one, the edge will not be subdivided. Otherwise, the corresponding edge will be divided into \(n - 2\) segments of equal length, and two additional segments of equal length that are typically shorter than the other segments. The length of the two additional segments relative to the others will decrease monotonically with \(n - f\), where \(f\) is the clamped floating-point tessellation level. When \(n - f\) is zero, the additional segments will have equal length to the other segments. As \(n - f\) approaches 2.0, the relative length of the additional segments approaches zero. The two additional segments \textbf{must} be...
placed symmetrically on opposite sides of the subdivided edge. The relative location of these two segments is implementation-dependent, but must be identical for any pair of subdivided edges with identical values of f.

When tessellating triangles or quads using point mode with fractional odd spacing, the tessellator may produce interior vertices that are positioned on the edge of the patch if an inner tessellation level is less than or equal to one. Such vertices are considered distinct from vertices produced by subdividing the outer edge of the patch, even if there are pairs of vertices with identical coordinates.

### 21.4. Tessellation Primitive Ordering

Few guarantees are provided for the relative ordering of primitives produced by tessellation, as they pertain to primitive order.

- The output primitives generated from each input primitive are passed to subsequent pipeline stages in an implementation-dependent order.
- All output primitives generated from a given input primitive are passed to subsequent pipeline stages before any output primitives generated from subsequent input primitives.

### 21.5. Tessellator Vertex Winding Order

When the tessellator produces triangles (in the Triangles or Quads modes), the orientation of all triangles is specified with an OpExecutionMode of VertexOrderCw or VertexOrderCcw in the tessellation control or tessellation evaluation shaders. If the order is VertexOrderCw, the vertices of all generated triangles will have clockwise ordering in (u,v) or (u,v,w) space. If the order is VertexOrderCcw, the vertices will have counter-clockwise ordering in that space.

If the tessellation domain has an upper-left origin, the vertices of a triangle have counter-clockwise ordering if

\[ a = u_0 v_1 - u_1 v_0 + u_1 v_2 - u_2 v_1 + u_2 v_0 - u_0 v_2 \]

is negative, and clockwise ordering if a is positive. \( u_i \) and \( v_i \) are the u and v coordinates in normalized parameter space of the ith vertex of the triangle. If the tessellation domain has a lower-left origin, the vertices of a triangle have counter-clockwise ordering if a is positive, and clockwise ordering if a is negative.

**Note**

The value a is proportional (with a positive factor) to the signed area of the triangle.

In Triangles mode, even though the vertex coordinates have a w value, it does not participate directly in the computation of a, being an affine combination of u and v.
21.6. Triangle Tessellation

If the tessellation primitive mode is Triangles, an equilateral triangle is subdivided into a collection of triangles covering the area of the original triangle. First, the original triangle is subdivided into a collection of concentric equilateral triangles. The edges of each of these triangles are subdivided, and the area between each triangle pair is filled by triangles produced by joining the vertices on the subdivided edges. The number of concentric triangles and the number of subdivisions along each triangle except the outermost is derived from the first inner tessellation level. The edges of the outermost triangle are subdivided independently, using the first, second, and third outer tessellation levels to control the number of subdivisions of the $u = 0$ (left), $v = 0$ (bottom), and $w = 0$ (right) edges, respectively. The second inner tessellation level and the fourth outer tessellation level have no effect in this mode.

If the first inner tessellation level and all three outer tessellation levels are exactly one after clamping and rounding, only a single triangle with $(u,v,w)$ coordinates of $(0,0,1)$, $(1,0,0)$, and $(0,1,0)$ is generated. If the inner tessellation level is one and any of the outer tessellation levels is greater than one, the inner tessellation level is treated as though it were originally specified as $1 + \varepsilon$ and will result in a two- or three-segment subdivision depending on the tessellation spacing. When used with fractional odd spacing, the three-segment subdivision may produce inner vertices positioned on the edge of the triangle.

If any tessellation level is greater than one, tessellation begins by producing a set of concentric inner triangles and subdividing their edges. First, the three outer edges are temporarily subdivided using the clamped and rounded first inner tessellation level and the specified tessellation spacing, generating $n$ segments. For the outermost inner triangle, the inner triangle is degenerate — a single point at the center of the triangle — if $n$ is two. Otherwise, for each corner of the outer triangle, an inner triangle corner is produced at the intersection of two lines extended perpendicular to the corner’s two adjacent edges running through the vertex of the subdivided outer edge nearest that corner. If $n$ is three, the edges of the inner triangle are not subdivided and is the final triangle in the set of concentric triangles. Otherwise, each edge of the inner triangle is divided into $n - 2$ segments, with the $n - 1$ vertices of this subdivision produced by intersecting the inner edge with lines perpendicular to the edge running through the $n - 1$ innermost vertices of the subdivision of the outer edge. Once the outermost inner triangle is subdivided, the previous subdivision process repeats itself, using the generated triangle as an outer triangle. This subdivision process is illustrated in Inner Triangle Tessellation.

![Figure 13. Inner Triangle Tessellation](image)
In the Inner Triangle Tessellation diagram, inner tessellation levels of (a) five and (b) four are shown (not to scale). Solid black circles depict vertices along the edges of the concentric triangles. The edges of inner triangles are subdivided by intersecting the edge with segments perpendicular to the edge passing through each inner vertex of the subdivided outer edge. Dotted lines depict edges connecting corresponding vertices on the inner and outer triangle edges.

Once all the concentric triangles are produced and their edges are subdivided, the area between each pair of adjacent inner triangles is filled completely with a set of non-overlapping triangles. In this subdivision, two of the three vertices of each triangle are taken from adjacent vertices on a subdivided edge of one triangle; the third is one of the vertices on the corresponding edge of the other triangle. If the innermost triangle is degenerate (i.e., a point), the triangle containing it is subdivided into six triangles by connecting each of the six vertices on that triangle with the center point. If the innermost triangle is not degenerate, that triangle is added to the set of generated triangles as-is.

After the area corresponding to any inner triangles is filled, the tessellator generates triangles to cover the area between the outermost triangle and the outermost inner triangle. To do this, the temporary subdivision of the outer triangle edge above is discarded. Instead, the \( u = 0, v = 0, \) and \( w = 0 \) edges are subdivided according to the first, second, and third outer tessellation levels, respectively, and the tessellation spacing. The original subdivision of the first inner triangle is retained. The area between the outer and first inner triangles is completely filled by non-overlapping triangles as described above. If the first (and only) inner triangle is degenerate, a set of triangles is produced by connecting each vertex on the outer triangle edges with the center point.

After all triangles are generated, each vertex in the subdivided triangle is assigned a barycentric \((u,v,w)\) coordinate based on its location relative to the three vertices of the outer triangle.

The algorithm used to subdivide the triangular domain in \((u,v,w)\) space into individual triangles is implementation-dependent. However, the set of triangles produced will completely cover the domain, and no portion of the domain will be covered by multiple triangles.

Output triangles are generated with a topology similar to triangle lists, except that the order in which each triangle is generated, and the order in which the vertices are generated for each triangle, are implementation-dependent. However, the order of vertices in each triangle is consistent across the domain as described in Tessellator Vertex Winding Order.

### 21.7. Quad Tessellation

If the tessellation primitive mode is Quads, a rectangle is subdivided into a collection of triangles covering the area of the original rectangle. First, the original rectangle is subdivided into a regular mesh of rectangles, where the number of rectangles along the \( u = 0 \) and \( u = 1 \) (vertical) and \( v = 0 \) and \( v = 1 \) (horizontal) edges are derived from the first and second inner tessellation levels, respectively. All rectangles, except those adjacent to one of the outer rectangle edges, are decomposed into triangle pairs. The outermost rectangle edges are subdivided independently, using
the first, second, third, and fourth outer tessellation levels to control the number of subdivisions of the $u = 0$ (left), $v = 0$ (bottom), $u = 1$ (right), and $v = 1$ (top) edges, respectively. The area between the inner rectangles of the mesh and the outer rectangle edges are filled by triangles produced by joining the vertices on the subdivided outer edges to the vertices on the edge of the inner rectangle mesh.

If both clamped inner tessellation levels and all four clamped outer tessellation levels are exactly one, only a single triangle pair covering the outer rectangle is generated. Otherwise, if either clamped inner tessellation level is one, that tessellation level is treated as though it were originally specified as $1 + \varepsilon$ and will result in a two- or three-segment subdivision depending on the tessellation spacing. When used with fractional odd spacing, the three-segment subdivision may produce inner vertices positioned on the edge of the rectangle.

If any tessellation level is greater than one, tessellation begins by subdividing the $u = 0$ and $u = 1$ edges of the outer rectangle into $m$ segments using the clamped and rounded first inner tessellation level and the tessellation spacing. The $v = 0$ and $v = 1$ edges are subdivided into $n$ segments using the second inner tessellation level. Each vertex on the $u = 0$ and $v = 0$ edges are joined with the corresponding vertex on the $u = 1$ and $v = 1$ edges to produce a set of vertical and horizontal lines that divide the rectangle into a grid of smaller rectangles. The primitive generator emits a pair of non-overlapping triangles covering each such rectangle not adjacent to an edge of the outer rectangle. The boundary of the region covered by these triangles forms an inner rectangle, the edges of which are subdivided by the grid vertices that lie on the edge. If either $m$ or $n$ is two, the inner rectangle is degenerate, and one or both of the rectangle’s edges consist of a single point. This subdivision is illustrated in Figure Inner Quad Tessellation.

![Inner Quad Tessellation](image)

**Caption**

In the Inner Quad Tessellation diagram, inner quad tessellation levels of (a) (4,2) and (b) (7,4) are shown. The regions highlighted in red in figure (b) depict the 10 inner rectangles, each of which will be subdivided into two triangles. Solid black circles depict vertices on the boundary of the outer and inner rectangles, where the inner rectangle on the top figure is degenerate (a single line segment). Dotted lines depict the horizontal and vertical edges connecting corresponding vertices on the inner and outer rectangle edges.
After the area corresponding to the inner rectangle is filled, the tessellator must produce triangles to cover the area between the inner and outer rectangles. To do this, the subdivision of the outer rectangle edge above is discarded. Instead, the $u = 0$, $v = 0$, $u = 1$, and $v = 1$ edges are subdivided according to the first, second, third, and fourth outer tessellation levels, respectively, and the tessellation spacing. The original subdivision of the inner rectangle is retained. The area between the outer and inner rectangles is completely filled by non-overlapping triangles. Two of the three vertices of each triangle are adjacent vertices on a subdivided edge of one rectangle; the third is one of the vertices on the corresponding edge of the other rectangle. If either edge of the innermost rectangle is degenerate, the area near the corresponding outer edges is filled by connecting each vertex on the outer edge with the single vertex making up the inner edge.

The algorithm used to subdivide the rectangular domain in (u,v) space into individual triangles is implementation-dependent. However, the set of triangles produced will completely cover the domain, and no portion of the domain will be covered by multiple triangles.

Output triangles are generated with a topology similar to triangle lists, except that the order in which each triangle is generated, and the order in which the vertices are generated for each triangle, are implementation-dependent. However, the order of vertices in each triangle is consistent across the domain as described in Tessellator Vertex Winding Order.

### 21.8. Isoline Tessellation

If the tessellation primitive mode is IsoLines, a set of independent horizontal line segments is drawn. The segments are arranged into connected strips called isolines, where the vertices of each isoline have a constant v coordinate and u coordinates covering the full range [0,1]. The number of isolines generated is derived from the first outer tessellation level; the number of segments in each isoline is derived from the second outer tessellation level. Both inner tessellation levels and the third and fourth outer tessellation levels have no effect in this mode.

As with quad tessellation above, isoline tessellation begins with a rectangle. The $u = 0$ and $u = 1$ edges of the rectangle are subdivided according to the first outer tessellation level. For the purposes of this subdivision, the tessellation spacing mode is ignored and treated as equal_spacing. An isoline is drawn connecting each vertex on the $u = 0$ rectangle edge to the corresponding vertex on the $u = 1$ rectangle edge, except that no line is drawn between (0,1) and (1,1). If the number of isolines on the subdivided $u = 0$ and $u = 1$ edges is n, this process will result in n equally spaced lines with constant v coordinates of $0, \frac{1}{n}, \frac{2}{n}, ..., \frac{n-1}{n}$.

Each of the n isolines is then subdivided according to the second outer tessellation level and the tessellation spacing, resulting in m line segments. Each segment of each line is emitted by the tessellator. These line segments are generated with a topology similar to line lists, except that the order in which each line is generated, and the order in which the vertices are generated for each line segment, are implementation-dependent.

### 21.9. Tessellation Point Mode

For all primitive modes, the tessellator is capable of generating points instead of lines or triangles. If the tessellation control or tessellation evaluation shader specifies the OpExecutionMode PointMode, the primitive generator will generate one point for each distinct vertex produced by tessellation.
rather than emitting triangles or lines. Otherwise, the tessellator will produce a collection of line segments or triangles according to the primitive mode. These points are generated with a topology similar to point lists, except the order in which the points are generated for each input primitive is undefined.

## 21.10. Tessellation Pipeline State

The `pTessellationState` member of `VkGraphicsPipelineCreateInfo` is a pointer to a `VkPipelineTessellationStateCreateInfo` structure.

The `VkPipelineTessellationStateCreateInfo` structure is defined as:

```c
typedef struct VkPipelineTessellationStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineTessellationStateCreateFlags flags;
    uint32_t patchControlPoints;
} VkPipelineTessellationStateCreateInfo;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `patchControlPoints` number of control points per patch.

### Valid Usage

- `patchControlPoints` must be greater than zero and less than or equal to `VkPhysicalDeviceLimits::maxTessellationPatchSize`

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO`
- `pNext` must be NULL or a pointer to a valid instance of `VkPipelineTessellationDomainOriginStateCreateInfo`
- The `sType` value of each struct in the `pNext` chain must be unique
- `flags` must be 0

```c
typedef VkFlags VkPipelineTessellationStateCreateFlags;
```

`VkPipelineTessellationStateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.
The `VkPipelineTessellationDomainOriginStateCreateInfo` structure is defined as:

```c
typedef struct VkPipelineTessellationDomainOriginStateCreateInfo {
    VkStructureType               sType;
    const void*                   pNext;
    VkTessellationDomainOrigin    domainOrigin;
} VkPipelineTessellationDomainOriginStateCreateInfo;
```

or the equivalent

```c
typedef VkPipelineTessellationDomainOriginStateCreateInfoKhr

VkPipelineTessellationDomainOriginStateCreateInfoKhr;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `domainOrigin` is a `VkTessellationDomainOrigin` value controlling the origin of the tessellation domain space.

If the `VkPipelineTessellationDomainOriginStateCreateInfo` structure is included in the `pNext` chain of `VkPipelineTessellationStateCreateInfo`, it controls the origin of the tessellation domain. If this structure is not present, it is as if `domainOrigin` were `VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT`.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_DOMAIN_ORIGIN_STATE_CREATE_INFO`
- `domainOrigin` must be a valid `VkTessellationDomainOrigin` value

The possible tessellation domain origins are specified by the `VkTessellationDomainOrigin` enumeration:

```c
typedef enum VkTessellationDomainOrigin {
    VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT = 0,
    VK_TESSELLATION_DOMAIN_ORIGIN_LOWER_LEFT = 1,
    VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT_KHR =
    VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT,
    VK_TESSELLATION_DOMAIN_ORIGIN_LOWER_LEFT_KHR =
    VK_TESSELLATION_DOMAIN_ORIGIN_LOWER_LEFT,
    VK_TESSELLATION_DOMAIN_ORIGIN_MAX_ENUM = 0x7FFFFFFF
} VkTessellationDomainOrigin;
```

or the equivalent

```c
typedef VkTessellationDomainOrigin VkTessellationDomainOriginKHR;
```
• \texttt{VK_TESSELLATION\_DOMAIN\_ORIGIN\_UPPER\_LEFT} specifies that the origin of the domain space is in the upper left corner, as shown in figure \textit{Domain parameterization for tessellation primitive modes (upper-left origin)}.

• \texttt{VK_TESSELLATION\_DOMAIN\_ORIGIN\_LOWER\_LEFT} specifies that the origin of the domain space is in the lower left corner, as shown in figure \textit{Domain parameterization for tessellation primitive modes (lower-left origin)}.

This enum affects how the \texttt{VertexOrderCw} and \texttt{VertexOrderCcw} tessellation execution modes are interpreted, since the winding is defined relative to the orientation of the domain.
Chapter 22. Geometry Shading

The geometry shader operates on a group of vertices and their associated data assembled from a single input primitive, and emits zero or more output primitives and the group of vertices and their associated data required for each output primitive. Geometry shading is enabled when a geometry shader is included in the pipeline.

22.1. Geometry Shader Input Primitives

Each geometry shader invocation has access to all vertices in the primitive (and their associated data), which are presented to the shader as an array of inputs.

The input primitive type expected by the geometry shader is specified with an \texttt{OpExecutionMode} instruction in the geometry shader, and \textbf{must} match the incoming primitive type specified by either the pipeline's \texttt{primitive topology} if tessellation is inactive, or the \texttt{tessellation mode} if tessellation is active, as follows:

- An input primitive type of \texttt{InputPoints} \textbf{must} only be used with a pipeline topology of \texttt{VK_PRIMITIVE_TOPOLOGY_POINT_LIST}, or with a tessellation shader that specifies \texttt{PointMode}. The input arrays always contain one element, as described by the \texttt{point list topology} or \texttt{tessellation in point mode}.

- An input primitive type of \texttt{InputLines} \textbf{must} only be used with a pipeline topology of \texttt{VK_PRIMITIVE_TOPOLOGY_LINE_LIST} or \texttt{VK_PRIMITIVE_TOPOLOGY_LINE_STRIP}, or with a tessellation shader specifying \texttt{IsoLines} that does not specify \texttt{PointMode}. The input arrays always contain two elements, as described by the \texttt{line list topology} or \texttt{line strip topology}, or by \texttt{isoline tessellation}.

- An input primitive type of \texttt{InputLinesAdjacency} \textbf{must} only be used when tessellation is inactive, with a pipeline topology of \texttt{VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY} or \texttt{VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY}. The input arrays always contain four elements, as described by the \texttt{line list with adjacency topology} or \texttt{line strip with adjacency topology}.

- An input primitive type of \texttt{Triangles} \textbf{must} only be used with a pipeline topology of \texttt{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST}, \texttt{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP}, or \texttt{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN}; or with a tessellation shader specifying \texttt{Quads} or \texttt{Triangles} that does not specify \texttt{PointMode}. The input arrays always contain three elements, as described by the \texttt{triangle list topology}, \texttt{triangle strip topology}, or \texttt{triangle fan topology}, or by \texttt{triangle} or \texttt{quad} \texttt{tessellation}. Vertices \textbf{may} be in a different absolute order to that specified by the topology, but \textbf{must} adhere to the specified winding order.

- An input primitive type of \texttt{InputTrianglesAdjacency} \textbf{must} only be used when tessellation is inactive, with a pipeline topology of \texttt{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY} or \texttt{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY}. The input arrays always contain six elements, as described by the \texttt{triangle list with adjacency topology} or \texttt{triangle strip with adjacency topology}. Vertices \textbf{may} be in a different absolute order to that specified by the topology, but \textbf{must} adhere to the specified winding order, and the vertices making up the main primitive \textbf{must} still occur at the first, third, and fifth index.
22.2. Geometry Shader Output Primitives

A geometry shader generates primitives in one of three output modes: points, line strips, or triangle strips. The primitive mode is specified in the shader using an `OpExecutionMode` instruction with the `OutputPoints`, `OutputLineStrip` or `OutputTriangleStrip` modes, respectively. Each geometry shader must include exactly one output primitive mode.

The vertices output by the geometry shader are assembled into points, lines, or triangles based on the output primitive type and the resulting primitives are then further processed as described in Rasterization. If the number of vertices emitted by the geometry shader is not sufficient to produce a single primitive, vertices corresponding to incomplete primitives are not processed by subsequent pipeline stages. The number of vertices output by the geometry shader is limited to a maximum count specified in the shader.

The maximum output vertex count is specified in the shader using an `OpExecutionMode` instruction with the mode set to `OutputVertices` and the maximum number of vertices that will be produced by the geometry shader specified as a literal. Each geometry shader must specify a maximum output vertex count.

22.3. Multiple Invocations of Geometry Shaders

Geometry shaders can be invoked more than one time for each input primitive. This is known as geometry shader instancing and is requested by including an `OpExecutionMode` instruction with `mode` specified as `Invocations` and the number of invocations specified as an integer literal.

In this mode, the geometry shader will execute at least n times for each input primitive, where n is the number of invocations specified in the `OpExecutionMode` instruction. The instance number is available to each invocation as a built-in input using `InvocationId`.

22.4. Geometry Shader Primitive Ordering

Limited guarantees are provided for the relative ordering of primitives produced by a geometry shader, as they pertain to primitive order.

- For instanced geometry shaders, the output primitives generated from each input primitive are passed to subsequent pipeline stages using the invocation number to order the primitives, from least to greatest.
- All output primitives generated from a given input primitive are passed to subsequent pipeline stages before any output primitives generated from subsequent input primitives.
Chapter 23. Fixed-Function Vertex Post-Processing

After programmable vertex processing, the following fixed-function operations are applied to vertices of the resulting primitives:

- Flat shading (see Flat Shading).
- Primitive clipping, including client-defined half-spaces (see Primitive Clipping).
- Shader output attribute clipping (see Clipping Shader Outputs).
- Perspective division on clip coordinates (see Coordinate Transformations).
- Viewport mapping, including depth range scaling (see Controlling the Viewport).
- Front face determination for polygon primitives (see Basic Polygon Rasterization).

Next, rasterization is performed on primitives as described in chapter Rasterization.

23.1. Flat Shading

Flat shading a vertex output attribute means to assign all vertices of the primitive the same value for that output. The output values assigned are those of the provoking vertex of the primitive. Flat shading is applied to those vertex attributes that match fragment input attributes which are decorated as Flat.

If neither geometry nor tessellation shading is active, the provoking vertex is determined by the primitive topology defined by VkPipelineInputAssemblyStateCreateInfo::topology used to execute the drawing command.

If geometry shading is active, the provoking vertex is determined by the primitive topology defined by the OutputPoints, OutputLineStrips, or OutputTriangleStrips execution mode.

If tessellation shading is active but geometry shading is not, the provoking vertex may be any of the vertices in each primitive.

23.2. Primitive Clipping

Primitives are culled against the cull volume and then clipped to the clip volume. In clip coordinates, the view volume is defined by:

\[-w_c \leq x_c \leq w_c\]
\[-w_c \leq y_c \leq w_c\]
\[0 \leq z_c \leq w_c\]

This view volume can be further restricted by as many as VkPhysicalDeviceLimits::maxClipDistances client-defined half-spaces.

The cull volume is the intersection of up to VkPhysicalDeviceLimits::maxCullDistances client-defined half-spaces (if no client-defined cull half-spaces are enabled, culling against the cull volume is...
A shader must write a single cull distance for each enabled cull half-space to elements of the \texttt{CullDistance} array. If the cull distance for any enabled cull half-space is negative for all of the vertices of the primitive under consideration, the primitive is discarded. Otherwise the primitive is clipped against the clip volume as defined below.

The clip volume is the intersection of up to \texttt{VkPhysicalDeviceLimits::maxClipDistances} client-defined half-spaces with the view volume (if no client-defined clip half-spaces are enabled, the clip volume is the view volume).

A shader must write a single clip distance for each enabled clip half-space to elements of the \texttt{ClipDistance} array. Clip half-space $i$ is then given by the set of points satisfying the inequality

$$c_i(P) \geq 0$$

where $c_i(P)$ is the clip distance $i$ at point $P$. For point primitives, $c_i(P)$ is simply the clip distance for the vertex in question. For line and triangle primitives, per-vertex clip distances are interpolated using a weighted mean, with weights derived according to the algorithms described in sections Basic Line Segment Rasterization and Basic Polygon Rasterization, using the perspective interpolation equations.

The number of client-defined clip and cull half-spaces that are enabled is determined by the explicit size of the built-in arrays \texttt{ClipDistance} and \texttt{CullDistance}, respectively, declared as an output in the interface of the entry point of the final shader stage before clipping.

Depth clamping is enabled or disabled via the \texttt{depthClampEnable} enable of the \texttt{VkPipelineRasterizationStateCreateInfo} structure. Depth clipping is disabled when \texttt{depthClampEnable} is \texttt{VK_TRUE}. When depth clipping is disabled, the plane equation

$$0 \leq z_c \leq w_c$$

(see the clip volume definition above) is ignored by view volume clipping (effectively, there is no near or far plane clipping).

If the primitive under consideration is a point or line segment, then clipping passes it unchanged if its vertices lie entirely within the clip volume.

Possible values of \texttt{VkPhysicalDevicePointClippingProperties::pointClippingBehavior}, specifying clipping behavior of a point primitive whose vertex lies outside the clip volume, are:
typedef enum VkPointClippingBehavior {
    VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIPPLANES = 0,
    VK_POINT_CLIPPING_BEHAVIOR_USER_CLIPPLANES_ONLY = 1,
    VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIPPLANES_KHR =
    VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIPPLANES,
    VK_POINT_CLIPPING_BEHAVIOR_USER_CLIPPLANES_ONLY_KHR =
    VK_POINT_CLIPPING_BEHAVIOR_USER_CLIPPLANES_ONLY,
    VK_POINT_CLIPPING_BEHAVIOR_MAX_ENUM = 0x7FFFFFFF
} VkPointClippingBehavior;

or the equivalent

typedef VkPointClippingBehavior VkPointClippingBehaviorKHR;

• **VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIPPLANES** specifies that the primitive is discarded if the vertex lies outside any clip plane, including the planes bounding the view volume.

• **VK_POINT_CLIPPING_BEHAVIOR_USER_CLIPPLANES_ONLY** specifies that the primitive is discarded only if the vertex lies outside any user clip plane.

If either of a line segment’s vertices lie outside of the clip volume, the line segment may be clipped, with new vertex coordinates computed for each vertex that lies outside the clip volume. A clipped line segment endpoint lies on both the original line segment and the boundary of the clip volume.

This clipping produces a value, $0 \leq t \leq 1$, for each clipped vertex. If the coordinates of a clipped vertex are $P$ and the original vertices' coordinates are $P_1$ and $P_2$, then $t$ is given by

$$P = tP_1 + (1-t)P_2.$$  

t is used to clip vertex output attributes as described in **Clipping Shader Outputs**.

If the primitive is a polygon, it passes unchanged if every one of its edges lie entirely inside the clip volume, and it is discarded if every one of its edges lie entirely outside the clip volume. If the edges of the polygon intersect the boundary of the clip volume, the intersecting edges are reconnected by new edges that lie along the boundary of the clip volume - in some cases requiring the introduction of new vertices into a polygon.

If a polygon intersects an edge of the clip volume’s boundary, the clipped polygon must include a point on this boundary edge.

Primitives rendered with user-defined half-spaces must satisfy a complementarity criterion. Suppose a series of primitives is drawn where each vertex $i$ has a single specified clip distance $d_i$ (or a number of similarly specified clip distances, if multiple half-spaces are enabled). Next, suppose that the same series of primitives are drawn again with each such clip distance replaced by $-d_i$ (and the graphics pipeline is otherwise the same). In this case, primitives must not be missing any pixels, and pixels must not be drawn twice in regions where those primitives are cut by the clip planes.
23.3. Clipping Shader Outputs

Next, vertex output attributes are clipped. The output values associated with a vertex that lies within the clip volume are unaffected by clipping. If a primitive is clipped, however, the output values assigned to vertices produced by clipping are clipped.

Let the output values assigned to the two vertices $P_1$ and $P_2$ of an unclipped edge be $c_1$ and $c_2$. The value of $t$ (see Primitive Clipping) for a clipped point $P$ is used to obtain the output value associated with $P$ as

$$c = t c_1 + (1-t) c_2.$$  

(Multiplying an output value by a scalar means multiplying each of $x, y, z,$ and $w$ by the scalar.)

Since this computation is performed in clip space before division by $w_c$, clipped output values are perspective-correct.

Polygon clipping creates a clipped vertex along an edge of the clip volume's boundary. This situation is handled by noting that polygon clipping proceeds by clipping against one half-space at a time. Output value clipping is done in the same way, so that clipped points always occur at the intersection of polygon edges (possibly already clipped) with the clip volume's boundary.

For vertex output attributes whose matching fragment input attributes are decorated with NoPerspective, the value of $t$ used to obtain the output value associated with $P$ will be adjusted to produce results that vary linearly in framebuffer space.

Output attributes of integer or unsigned integer type must always be flat shaded. Flat shaded attributes are constant over the primitive being rasterized (see Basic Line Segment Rasterization and Basic Polygon Rasterization), and no interpolation is performed. The output value $c$ is taken from either $c_1$ or $c_2$, since flat shading has already occurred and the two values are identical.

23.4. Coordinate Transformations

Clip coordinates for a vertex result from shader execution, which yields a vertex coordinate Position.

Perspective division on clip coordinates yields normalized device coordinates, followed by a viewport transformation (see Controlling the Viewport) to convert these coordinates into framebuffer coordinates.

If a vertex in clip coordinates has a position given by

$$\begin{pmatrix} x_c \\ y_c \\ z_c \\ w_c \end{pmatrix}$$

then the vertex's normalized device coordinates are
23.5. Controlling the Viewport

The viewport transformation is determined by the selected viewport’s width and height in pixels, \( p_x \) and \( p_y \), respectively, and its center \((o_x, o_y)\) (also in pixels), as well as its depth range \( \text{min} \) and \( \text{max} \) determining a depth range scale value \( p_z \) and a depth range bias value \( o_z \) (defined below). The vertex’s framebuffer coordinates \((x_f, y_f, z_f)\) are given by

\[
\begin{bmatrix}
    x_f \\
    y_f \\
    z_f
\end{bmatrix} = \begin{bmatrix}
    x_c \\
    y_c \\
    z_c
\end{bmatrix} - \begin{bmatrix}
    \frac{p_x}{2} \cdot d_x + o_x \\
    \frac{p_y}{2} \cdot d_y + o_y \\
    p_z \cdot z_d + o_z
\end{bmatrix}
\]

Multiple viewports are available, numbered zero up to \( \text{VkPhysicalDeviceLimits::maxViewports} \) minus one. The number of viewports used by a pipeline is controlled by the \( \text{viewportCount} \) member of the \( \text{VkPipelineViewportStateCreateInfo} \) structure used in pipeline creation.

The \( \text{VkPipelineViewportStateCreateInfo} \) structure is defined as:

```c
typedef struct VkPipelineViewportStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineViewportStateCreateFlags flags;
    uint32_t viewportCount;
    const VkViewport* pViewports;
    uint32_t scissorCount;
    const VkRect2D* pScissors;
} VkPipelineViewportStateCreateInfo;
```

- \( \text{sType} \) is the type of this structure.
- \( \text{pNext} \) is \( \text{NULL} \) or a pointer to an extension-specific structure.
- \( \text{flags} \) is reserved for future use.
- \( \text{viewportCount} \) is the number of viewports used by the pipeline.
- \( \text{pViewports} \) is a pointer to an array of \( \text{VkViewport} \) structures, defining the viewport transforms. If the viewport state is dynamic, this member is ignored.
- \( \text{scissorCount} \) is the number of \( \text{scissors} \) and \( \text{must} \) match the number of viewports.
- \( \text{pScissors} \) is a pointer to an array of \( \text{VkRect2D} \) structures defining the rectangular bounds of the scissor for the corresponding viewport. If the scissor state is dynamic, this member is ignored.
Valid Usage

- If the **multiple viewports** feature is not enabled, **viewportCount must be 1**
- If the **multiple viewports** feature is not enabled, **scissorCount must be 1**
- **viewportCount must be** between 1 and `VkPhysicalDeviceLimits::maxViewports`, inclusive
- **scissorCount must be** between 1 and `VkPhysicalDeviceLimits::maxViewports`, inclusive
- **scissorCount and viewportCount must be identical**
- The x and y members of **offset** member of any element of `pScissors` **must be** greater than or equal to 0
- Evaluation of `(offset.x + extent.width)` **must not** cause a signed integer addition overflow for any element of `pScissors`
- Evaluation of `(offset.y + extent.height)` **must not** cause a signed integer addition overflow for any element of `pScissors`

Valid Usage (Implicit)

- **sType must be** `VK_STRUCTURE_TYPE_PIPELINE_VIEWPORT_STATE_CREATE_INFO`
- **pNext must be** NULL
- **flags must be** 0
- **viewportCount must be** greater than 0
- **scissorCount must be** greater than 0

```c
typedef VkFlags VkPipelineViewportStateCreateFlags;
```

`VkPipelineViewportStateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

If a geometry shader is active and has an output variable decorated with `ViewportIndex`, the viewport transformation uses the viewport corresponding to the value assigned to `ViewportIndex` taken from an implementation-dependent vertex of each primitive. If `ViewportIndex` is outside the range zero to `viewportCount` minus one for a primitive, or if the geometry shader did not assign a value to `ViewportIndex` for all vertices of a primitive due to flow control, the values resulting from the viewport transformation of the vertices of such primitives are undefined. If no geometry shader is active, or if the geometry shader does not have an output decorated with `ViewportIndex`, the viewport numbered zero is used by the viewport transformation.

A single vertex **can** be used in more than one individual primitive, in primitives such as `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP`. In this case, the viewport transformation is applied separately for each primitive.

If the bound pipeline state object was not created with the `VK_DYNAMIC_STATE_VIEWPORT` dynamic state
enabled, viewport transformation parameters are specified using the \textit{pViewports} member of \textit{VkPipelineViewportStateCreateInfo} in the pipeline state object. If the pipeline state object was created with the \texttt{VK_DYNAMIC_STATE_VIEWPORT} dynamic state enabled, the viewport transformation parameters are dynamically set and changed with the command:

\begin{verbatim}
void vkCmdSetViewport(
    VkCommandBuffer                             commandBuffer,  
    uint32_t                                    firstViewport,   
    uint32_t                                    viewportCount,  
    const VkViewport*                           pViewports);
\end{verbatim}

- \textit{commandBuffer} is the command buffer into which the command will be recorded.
- \textit{firstViewport} is the index of the first viewport whose parameters are updated by the command.
- \textit{viewportCount} is the number of viewports whose parameters are updated by the command.
- \textit{pViewports} is a pointer to an array of \textit{VkViewport} structures specifying viewport parameters.

The viewport parameters taken from element i of \textit{pViewports} replace the current state for the viewport index \textit{firstViewport} + i, for i in \([0, \text{viewportCount})\).

**Valid Usage**

- \textit{firstViewport} must be less than \texttt{VkPhysicalDeviceLimits::maxViewports}
- The sum of \textit{firstViewport} and \textit{viewportCount} must be between 1 and \texttt{VkPhysicalDeviceLimits::maxViewports}, inclusive
- If the \texttt{multiple viewports} feature is not enabled, \textit{firstViewport} must be 0
- If the \texttt{multiple viewports} feature is not enabled, \textit{viewportCount} must be 1

**Valid Usage (Implicit)**

- \textit{commandBuffer} must be a valid \textit{VkCommandBuffer} handle
- \textit{pViewports} must be a valid pointer to an array of \textit{viewportCount} valid \textit{VkViewport} structures
- \textit{commandBuffer} must be in the recording state
- The \textit{VkCommandPool} that \textit{commandBuffer} was allocated from must support graphics operations
- \textit{viewportCount} must be greater than 0
**Host Synchronization**

- Host access to `commandBuffer` **must** be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both `VkPipelineViewportStateCreateInfo` and `vkCmdSetViewport` use `VkViewport` to set the viewport transformation parameters.

The `VkViewport` structure is defined as:

```c
typedef struct VkViewport {
    float x;
    float y;
    float width;
    float height;
    float minDepth;
    float maxDepth;
} VkViewport;
```

- `x` and `y` are the viewport's upper left corner (x,y).
- `width` and `height` are the viewport's width and height, respectively.
- `minDepth` and `maxDepth` are the depth range for the viewport. It is valid for `minDepth` to be greater than or equal to `maxDepth`.

The framebuffer depth coordinate $z_i$ **may** be represented using either a fixed-point or floating-point representation. However, a floating-point representation **must** be used if the depth/stencil attachment has a floating-point depth component. If an m-bit fixed-point representation is used, we assume that it represents each value $\frac{k}{2^{m-1}}$, where $k \in \{0, 1, ..., 2^m-1\}$, as $k$ (e.g. 1.0 is represented in binary as a string of all ones).

The viewport parameters shown in the above equations are found from these values as:

$$o_x = x + \frac{width}{2}$$

$$o_y = y + \frac{height}{2}$$
The application can specify a negative term for height, which has the effect of negating the y coordinate in clip space before performing the transform. When using a negative height, the application should also adjust the y value to point to the lower left corner of the viewport instead of the upper left corner. Using the negative height allows the application to avoid having to negate the y component of the Position output from the last vertex processing stage in shaders that also target other graphics APIs.

The width and height of the implementation-dependent maximum viewport dimensions must be greater than or equal to the width and height of the largest image which can be created and attached to a framebuffer.

The floating-point viewport bounds are represented with an implementation-dependent precision.

Valid Usage

- width must be greater than 0.0
- width must be less than or equal to VkPhysicalDeviceLimits::maxViewportDimensions[0]
- The absolute value of height must be less than or equal to VkPhysicalDeviceLimits::maxViewportDimensions[1]
- x must be greater than or equal to viewportBoundsRange[0]
- (x + width) must be less than or equal to viewportBoundsRange[1]
- y must be greater than or equal to viewportBoundsRange[0]
- y must be less than or equal to viewportBoundsRange[1]
- (y + height) must be greater than or equal to viewportBoundsRange[0]
- (y + height) must be less than or equal to viewportBoundsRange[1]
- minDepth must be between 0.0 and 1.0, inclusive
- maxDepth must be between 0.0 and 1.0, inclusive
Chapter 24. Rasterization

Rasterization is the process by which a primitive is converted to a two-dimensional image. Each point of this image contains associated data such as depth, color, or other attributes.

Rasterizing a primitive begins by determining which squares of an integer grid in framebuffer coordinates are occupied by the primitive, and assigning one or more depth values to each such square. This process is described below for points, lines, and polygons.

A grid square, including its (x,y) framebuffer coordinates, z (depth), and associated data added by fragment shaders, is called a fragment. A fragment is located by its upper left corner, which lies on integer grid coordinates.

Rasterization operations also refer to a fragment’s sample locations, which are offset by fractional values from its upper left corner. The rasterization rules for points, lines, and triangles involve testing whether each sample location is inside the primitive. Fragments need not actually be square, and rasterization rules are not affected by the aspect ratio of fragments. Display of non-square grids, however, will cause rasterized points and line segments to appear fatter in one direction than the other.

We assume that fragments are square, since it simplifies antialiasing and texturing. After rasterization, fragments are processed by the early per-fragment tests, if enabled.

Several factors affect rasterization, including the members of VkPipelineRasterizationStateCreateInfo and VkPipelineMultisampleStateCreateInfo.

The VkPipelineRasterizationStateCreateInfo structure is defined as:

```
typedef struct VkPipelineRasterizationStateCreateInfo {
    VkStructureType                            sType;
    const void*                                pNext;
    VkPipelineRasterizationStateCreateFlags    flags;
    VkBool32                                   depthClampEnable;
    VkBool32                                   rasterizerDiscardEnable;
    VkPolygonMode                              cullMode;
    VkFrontFace                                frontFace;
    float                                       lineWidth;
} VkPipelineRasterizationStateCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
• **depthClampEnable** controls whether to clamp the fragment’s depth values as described in *Depth Test*. Enabling depth clamp will also disable clipping primitives to the z planes of the frustrum as described in *Primitive Clipping*.

• **rasterizerDiscardEnable** controls whether primitives are discarded immediately before the rasterization stage.

• **polygonMode** is the triangle rendering mode. See *VkPolygonMode*.

• **cullMode** is the triangle facing direction used for primitive culling. See *VkCullModeFlagBits*.

• **frontFace** is a *VkFrontFace* value specifying the front-facing triangle orientation to be used for culling.

• **depthBiasEnable** controls whether to bias fragment depth values.

• **depthBiasConstantFactor** is a scalar factor controlling the constant depth value added to each fragment.

• **depthBiasClamp** is the maximum (or minimum) depth bias of a fragment.

• **depthBiasSlopeFactor** is a scalar factor applied to a fragment's slope in depth bias calculations.

• **lineWidth** is the width of rasterized line segments.

---

### Valid Usage

- If the **depth clamping** feature is not enabled, **depthClampEnable must** be **VK_FALSE**

- If the **non-solid fill modes** feature is not enabled, **polygonMode must** be **VK_POLYGON_MODE_FILL**

---

### Valid Usage (Implicit)

- **sType must** be **VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO**

- **pNext must** be **NULL**

- **flags must** be **0**

- **polygonMode must** be a valid *VkPolygonMode value*

- **cullMode must** be a valid combination of *VkCullModeFlagBits values*

- **frontFace must** be a valid *VkFrontFace value*

---

```plaintext
typedef VkFlags VkPipelineRasterizationStateCreateFlags;
```

*VkPipelineRasterizationStateCreateFlags* is a bitmask type for setting a mask, but is currently reserved for future use.

The *VkPipelineMultisampleStateCreateInfo* structure is defined as:
```c
typedef struct VkPipelineMultisampleStateCreateInfo {
    VkStructureType                          sType;
    const void*                              pNext;
    VkPipelineMultisampleStateCreateFlags    flags;
    VkSampleCountFlagBits                    rasterizationSamples;
    VkBool32                                 sampleShadingEnable;
    float                                    minSampleShading;
    const VkSampleMask*                      pSampleMask;
    VkBool32                                 alphaToCoverageEnable;
    VkBool32                                 alphaToOneEnable;
} VkPipelineMultisampleStateCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **rasterizationSamples** is a `VkSampleCountFlagBits` specifying the number of samples used in rasterization.
- **sampleShadingEnable** can be used to enable **Sample Shading**.
- **minSampleShading** specifies a minimum fraction of sample shading if **sampleShadingEnable** is set to `VK_TRUE`.
- **pSampleMask** is a bitmask of static coverage information that is ANDed with the coverage information generated during rasterization, as described in **Sample Mask**.
- **alphaToCoverageEnable** controls whether a temporary coverage value is generated based on the alpha component of the fragment's first color output as specified in the **Multisample Coverage** section.
- **alphaToOneEnable** controls whether the alpha component of the fragment's first color output is replaced with one as described in **Multisample Coverage**.

## Valid Usage

- If the **sample rate shading** feature is not enabled, **sampleShadingEnable** must be `VK_FALSE`.
- If the **alpha to one** feature is not enabled, **alphaToOneEnable** must be `VK_FALSE`.
- **minSampleShading** must be in the range `[0,1]`
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO`
- **pNext** must be `NULL`
- **flags** must be `0`
- **rasterizationSamples** must be a valid `VkSampleCountFlagBits` value
- If `pSampleMask` is not `NULL`, `pSampleMask` must be a valid pointer to an array of `VkSampleMask` values

```c
typedef VkFlags VkPipelineMultisampleStateCreateFlags;
```

`VkPipelineMultisampleStateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

Rasterization only generates fragments which cover one or more pixels inside the framebuffer. Pixels outside the framebuffer are never considered covered in the fragment. Fragments which would be produced by application of any of the primitive rasterization rules described below but which lie outside the framebuffer are not produced, nor are they processed by any later stage of the pipeline, including any of the early per-fragment tests described in Early Per-Fragment Tests.

Surviving fragments are processed by fragment shaders. Fragment shaders determine associated data for fragments, and can also modify or replace their assigned depth values.

When the `VK_AMD_mixed_attachment_samples` and `VK_NV_framebuffer_mixed_samples` extensions are not enabled, if the subpass for which this pipeline is being created uses color and/or depth/stencil attachments, then `rasterizationSamples` must be the same as the sample count for those subpass attachments.

If the subpass for which this pipeline is being created does not use color or depth/stencil attachments, `rasterizationSamples` must follow the rules for a zero-attachment subpass.

### 24.1. Discarding Primitives Before Rasterization

Primitives are discarded before rasterization if the `rasterizerDiscardEnable` member of `VkPipelineRasterizationStateCreateInfo` is enabled. When enabled, primitives are discarded after they are processed by the last active shader stage in the pipeline before rasterization.

### 24.2. Rasterization Order

Within a subpass of a render pass instance, for a given (x,y,layer,sample) sample location, the following operations are guaranteed to execute in rasterization order, for each separate primitive that includes that sample location:

1. **Scissor test**
Each of these operations is atomically executed for each primitive and sample location.

Execution of these operations for each primitive in a subpass occurs in **primitive order**.

## 24.3. Multisampling

Multisampling is a mechanism to antialias all Vulkan primitives: points, lines, and polygons. The technique is to sample all primitives multiple times at each pixel. Each sample in each framebuffer attachment has storage for a color, depth, and/or stencil value, such that per-fragment operations apply to each sample independently. The color sample values **can** be later resolved to a single color (see *Resolving Multisample Images* and the *Render Pass* chapter for more details on how to resolve multisample images to non-multisample images).

Vulkan defines rasterization rules for single-sample modes in a way that is equivalent to a multisample mode with a single sample in the center of each fragment.

Each fragment includes a coverage value with **rasterizationSamples** bits (see *Sample Mask*). Each fragment includes **rasterizationSamples** depth values and sets of associated data. An implementation **may** choose to assign the same associated data to more than one sample. The location for evaluating such associated data **may** be anywhere within the fragment area including the fragment's center location \((x_f, y_f)\) or any of the sample locations. When **rasterizationSamples** is **VK_SAMPLE_COUNT_1_BIT**, the fragment's center location **must** be used. The different associated data values need not all be evaluated at the same location. Each fragment thus consists of integer x and y grid coordinates, **rasterizationSamples** depth values and sets of associated data, and a coverage value with **rasterizationSamples** bits.

It is understood that each pixel has **rasterizationSamples** locations associated with it. These locations are exact positions, rather than regions or areas, and each is referred to as a sample point. The sample points associated with a pixel **must** be located inside or on the boundary of the unit square that is considered to bound the pixel. Furthermore, the relative locations of sample points **may** be identical for each pixel in the framebuffer, or they **may** differ.

If the current pipeline includes a fragment shader with one or more variables in its interface decorated with *Sample* and *Input*, the data associated with those variables will be assigned independently for each sample. The values for each sample **must** be evaluated at the location of the sample. The data associated with any other variables not decorated with *Sample* and *Input* need not be evaluated independently for each sample.

If the **standardSampleLocations** member of *VkPhysicalDeviceLimits* is **VK_TRUE**, then the sample...
counts `VK_SAMPLE_COUNT_1_BIT`, `VK_SAMPLE_COUNT_2_BIT`, `VK_SAMPLE_COUNT_4_BIT`, `VK_SAMPLE_COUNT_8_BIT`, and `VK_SAMPLE_COUNT_16_BIT` have sample locations as listed in the following table, with the \( i \)th entry in the table corresponding to bit \( i \) in the sample masks. `VK_SAMPLE_COUNT_32_BIT` and `VK_SAMPLE_COUNT_64_BIT` do not have standard sample locations. Locations are defined relative to an origin in the upper left corner of the fragment.
Table 27. Standard sample locations

<table>
<thead>
<tr>
<th>VK_SAMPLE_COUNT_1_BIT</th>
<th>VK_SAMPLE_COUNT_2_BIT</th>
<th>VK_SAMPLE_COUNT_4_BIT</th>
<th>VK_SAMPLE_COUNT_8_BIT</th>
<th>VK_SAMPLE_COUNT_16_BIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.5,0.5)</td>
<td>(0.75,0.75) (0.25,0.25)</td>
<td>(0.375, 0.125) (0.875, 0.375) (0.125, 0.625) (0.625, 0.875)</td>
<td>(0.5625, 0.3125) (0.4375, 0.6875) (0.8125, 0.5625) (0.3125, 0.1875) (0.1875, 0.8125) (0.0625, 0.4375) (0.6875, 0.9375) (0.9375, 0.0625)</td>
<td>(0.5625, 0.5625) (0.4375, 0.3125) (0.3125, 0.625) (0.75, 0.4375) (0.1875, 0.375) (0.625, 0.8125) (0.8125, 0.6875) (0.6875, 0.1875) (0.375, 0.875) (0.5, 0.0625) (0.25, 0.125) (0.125, 0.75) (0.0, 0.5) (0.9375, 0.25) (0.875, 0.9375) (0.0625, 0.0)</td>
</tr>
</tbody>
</table>

24.4. Sample Shading

Sample shading can be used to specify a minimum number of unique samples to process for each fragment. If sample shading is enabled an implementation must provide a minimum of \(\max(\minSampleShadingFactor \times \text{totalSamples}, 1)\) unique associated data for each fragment, where \(\minSampleShadingFactor\) is the minimum fraction of sample shading. \(\text{totalSamples}\) is the value of \(\text{VkPipelineMultisampleStateCreateInfo.rasterizationSamples}\) specified at pipeline creation time. These are associated with the samples in an implementation-dependent manner. When \(\minSampleShadingFactor\) is 1.0, a separate set of associated data are evaluated for each sample, and each set of values is evaluated at the sample location.

Sample shading is enabled for a graphics pipeline:

- If the interface of the fragment shader entry point of the graphics pipeline includes an input variable decorated with \(\text{SampleId}\) or \(\text{SamplePosition}\). In this case \(\minSampleShadingFactor\) takes the value 1.0.

- Else if the \(\text{sampleShadingEnable}\) member of the \(\text{VkPipelineMultisampleStateCreateInfo}\) structure specified when creating the graphics pipeline is set to \(\text{VK_TRUE}\). In this case \(\minSampleShadingFactor\) takes the value of \(\text{VkPipelineMultisampleStateCreateInfo.minSampleShading}\).

Otherwise, sample shading is considered disabled.
24.5. Points

A point is drawn by generating a set of fragments in the shape of a square centered around the vertex of the point. Each vertex has an associated point size that controls the width/height of that square. The point size is taken from the (potentially clipped) shader built-in `PointSize` written by:

- the geometry shader, if active;
- the tessellation evaluation shader, if active and no geometry shader is active;
- the vertex shader, otherwise

and clamped to the implementation-dependent point size range `[pointSizeRange[0], pointSizeRange[1]]`. The value written to `PointSize` must be greater than zero.

Not all point sizes need be supported, but the size 1.0 must be supported. The range of supported sizes and the size of evenly-spaced gradations within that range are implementation-dependent. The range and gradations are obtained from the `pointSizeRange` and `pointSizeGranularity` members of `VkPhysicalDeviceLimits`. If, for instance, the size range is from 0.1 to 2.0 and the gradation size is 0.1, then the size 0.1, 0.2, ..., 1.9, 2.0 are supported. Additional point sizes may also be supported. There is no requirement that these sizes be equally spaced. If an unsupported size is requested, the nearest supported size is used instead.

24.5.1. Basic Point Rasterization

Point rasterization produces a fragment for each fragment area group of framebuffer pixels with one or more sample points that intersect a region centered at the point’s \((x_f, y_f)\). This region is a square with side equal to the current point size. Coverage bits that correspond to sample points that intersect the region are 1, other coverage bits are 0. All fragments produced in rasterizing a point are assigned the same associated data, which are those of the vertex corresponding to the point. However, the fragment shader built-in `PointCoord` contains point sprite texture coordinates. The s and t point sprite texture coordinates vary from zero to one across the point horizontally left-to-right and top-to-bottom, respectively. The following formulas are used to evaluate s and t:

\[
\begin{align*}
    s &= \frac{1}{2} + \frac{(x_p - x_f)}{\text{size}} \\
    t &= \frac{1}{2} + \frac{(y_p - y_f)}{\text{size}}
\end{align*}
\]

where size is the point's size; \((x_p,y_p)\) is the location at which the point sprite coordinates are evaluated - this may be the framebuffer coordinates of the fragment center, or the location of a sample; and \((x_f,y_f)\) is the exact, unrounded framebuffer coordinate of the vertex for the point.

24.6. Line Segments

Each line segment has an associated width. The line width is specified by the `VkPipelineRasterizationStateCreateInfo::lineWidth` property of the currently active pipeline, if the pipeline was not created with `VK_DYNAMIC_STATE_LINE_WIDTH` enabled.

Otherwise, the line width is set by calling `vkCmdSetLineWidth`: 
```c
void vkCmdSetLineWidth(
    VkCommandBuffer                             commandBuffer,
    float                                       lineWidth);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `lineWidth` is the width of rasterized line segments.

**Valid Usage**

- If the wide lines feature is not enabled, `lineWidth` must be 1.0

**Valid Usage (Implicit)**

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

**Host Synchronization**

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

**Command Properties**

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Not all line widths need be supported for line segment rasterization, but width 1.0 antialiased segments must be provided. The range and gradations are obtained from the `lineWidthRange` and `lineWidthGranularity` members of `VkPhysicalDeviceLimits`. If, for instance, the size range is from 0.1 to 2.0 and the gradation size is 0.1, then the size 0.1, 0.2, ..., 1.9, 2.0 are supported. Additional line widths may also be supported. There is no requirement that these widths be equally spaced. If an unsupported width is requested, the nearest supported width is used instead.

**24.6.1. Basic Line Segment Rasterization**

Rasterized line segments produce fragments which intersect a rectangle centered on the line
segment. Two of the edges are parallel to the specified line segment; each is at a distance of one-half the current width from that segment in directions perpendicular to the direction of the line. The other two edges pass through the line endpoints and are perpendicular to the direction of the specified line segment. Coverage bits that correspond to sample points that intersect the rectangle are 1, other coverage bits are 0.

Next we specify how the data associated with each rasterized fragment are obtained. Let \( p_r = (x_d, y_d) \) be the framebuffer coordinates at which associated data are evaluated. This may be the center of a fragment or the location of a sample within the fragment. When \( \text{rasterizationSamples} \) is \( \text{VK_SAMPLE_COUNT_1_BIT} \), the fragment center must be used. Let \( p_a = (x_a, y_a) \) and \( p_b = (x_b, y_b) \) be initial and final endpoints of the line segment, respectively. Set

\[
t = \frac{(p_r - p_a) \cdot (p_b - p_a)}{\|p_b - p_a\|^2}
\]

(Note that \( t = 0 \) at \( p_a \) and \( t = 1 \) at \( p_b \). Also note that this calculation projects the vector from \( p_a \) to \( p_r \) onto the line, and thus computes the normalized distance of the fragment along the line.)

The value of an associated datum \( f \) for the fragment, whether it be a shader output or the clip \( w \) coordinate, must be determined using perspective interpolation:

\[
f = \frac{(1 - t) f_a / w_a + t f_b / w_b}{(1 - t) / w_a + t / w_b}
\]

where \( f_a \) and \( f_b \) are the data associated with the starting and ending endpoints of the segment, respectively; \( w_a \) and \( w_b \) are the clip \( w \) coordinates of the starting and ending endpoints of the segments, respectively.

Depth values for lines must be determined using linear interpolation:

\[
z = (1 - t) z_a + t z_b
\]

where \( z_a \) and \( z_b \) are the depth values of the starting and ending endpoints of the segment, respectively.

The \text{NoPerspective} and \text{Flat} interpolation decorations can be used with fragment shader inputs to declare how they are interpolated. When neither decoration is applied, perspective interpolation is performed as described above. When the \text{NoPerspective} decoration is used, linear interpolation is performed in the same fashion as for depth values, as described above. When the \text{Flat} decoration is used, no interpolation is performed, and outputs are taken from the corresponding input value of the \text{provoking vertex} corresponding to that primitive.

The above description documents the preferred method of line rasterization, and must be used when the implementation advertises the \text{strictLines} limit in \text{VkPhysicalDeviceLimits} as \text{VK_TRUE}.

When \text{strictLines} is \text{VK_FALSE}, the edges of the lines are generated as a parallelogram surrounding the original line. The major axis is chosen by noting the axis in which there is the greatest distance between the line start and end points. If the difference is equal in both directions then the X axis is chosen as the major axis. Edges 2 and 3 are aligned to the minor axis and are centered on the endpoints of the line as in \text{Non strict lines}, and each is \text{lineWidth} long. Edges 0 and 1 are parallel to the line and connect the endpoints of edges 2 and 3. Coverage bits that correspond to sample points
that intersect the parallelogram are 1, other coverage bits are 0.

Samples that fall exactly on the edge of the parallelogram follow the polygon rasterization rules.

Interpolation occurs as if the parallelogram was decomposed into two triangles where each pair of vertices at each end of the line has identical attributes.

![Figure 15. Non strict lines](image)

### 24.7. Polygons

A polygon results from the decomposition of a triangle strip, triangle fan or a series of independent triangles. Like points and line segments, polygon rasterization is controlled by several variables in the VkPipelineRasterizationStateCreateInfo structure.

#### 24.7.1. Basic Polygon Rasterization

The first step of polygon rasterization is to determine whether the triangle is back-facing or front-facing. This determination is made based on the sign of the (clipped or unclipped) polygon’s area computed in framebuffer coordinates. One way to compute this area is:

\[
a = -\frac{1}{2} \sum_{i=0}^{n-1} x_i y_{i+1} - x_{i+1} y_i
\]

where \(x_i\) and \(y_i\) are the x and y framebuffer coordinates of the ith vertex of the n-vertex polygon (vertices are numbered starting at zero for the purposes of this computation) and \(i \oplus 1\) is \((i + 1) \mod n\).

The interpretation of the sign of \(a\) is determined by the VkPipelineRasterizationStateCreateInfo::frontFace property of the currently active pipeline. Possible values are:

```c
typedef enum VkFrontFace {
    VK_FRONT_FACE_COUNTER_CLOCKWISE = 0,
    VK_FRONT_FACE_CLOCKWISE = 1,
    VK_FRONT_FACE_MAX_ENUM = 0x7FFFFFFF
} VkFrontFace;
```
• **VK_FRONT_FACE_COUNTER_CLOCKWISE** specifies that a triangle with positive area is considered front-facing.

• **VK_FRONT_FACE_CLOCKWISE** specifies that a triangle with negative area is considered front-facing.

Any triangle which is not front-facing is back-facing, including zero-area triangles.

Once the orientation of triangles is determined, they are culled according to the `VkPipelineRasterizationStateCreateInfo::cullMode` property of the currently active pipeline. Possible values are:

```c
typedef enum VkCullModeFlagBits {
    VK_CULL_MODE_NONE = 0,
    VK_CULL_MODE_FRONT_BIT = 0x00000001,
    VK_CULL_MODE_BACK_BIT = 0x00000002,
    VK_CULL_MODE_FRONT_AND_BACK = 0x00000003,
    VK_CULL_MODE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkCullModeFlagBits;
```

• **VK_CULL_MODE_NONE** specifies that no triangles are discarded

• **VK_CULL_MODE_FRONT_BIT** specifies that front-facing triangles are discarded

• **VK_CULL_MODE_BACK_BIT** specifies that back-facing triangles are discarded

• **VK_CULL_MODE_FRONT_AND_BACK** specifies that all triangles are discarded.

Following culling, fragments are produced for any triangles which have not been discarded.

```c
typedef VkFlags VkCullModeFlags;
```

**VkCullModeFlags** is a bitmask type for setting a mask of zero or more **VkCullModeFlagBits**.

The rule for determining which fragments are produced by polygon rasterization is called **point sampling**. The two-dimensional projection obtained by taking the x and y framebuffer coordinates of the polygon’s vertices is formed. Fragments are produced for any fragment area groups of pixels for which any sample points lie inside of this polygon. Coverage bits that correspond to sample points that satisfy the point sampling criteria are 1, other coverage bits are 0. Special treatment is given to a sample whose sample location lies on a polygon edge. In such a case, if two polygons lie on either side of a common edge (with identical endpoints) on which a sample point lies, then exactly one of the polygons must result in a covered sample for that fragment during rasterization. As for the data associated with each fragment produced by rasterizing a polygon, we begin by specifying how these values are produced for fragments in a triangle.

**Barycentric coordinates** are a set of three numbers, a, b, and c, each in the range [0,1], with a + b + c = 1. These coordinates uniquely specify any point p within the triangle or on the triangle’s boundary as

\[ p = a \mathbf{p}_a + b \mathbf{p}_b + c \mathbf{p}_c \]
where \( p_a, p_b, \) and \( p_c \) are the vertices of the triangle. \( a, b, \) and \( c \) are determined by:

\[
a = \frac{A(p_a p_b p_c)}{A(p_a p_b p_c)}, \quad b = \frac{A(p_a p_b p_c)}{A(p_a p_b p_c)}, \quad c = \frac{A(p_a p_b p_c)}{A(p_a p_b p_c)},
\]

where \( A(lmn) \) denotes the area in framebuffer coordinates of the triangle with vertices \( l, m, \) and \( n. \)

Denote an associated datum at \( p_a, p_b, \) or \( p_c \) as \( f_a, f_b, \) or \( f_c, \) respectively.

The value of an associated datum \( f \) for a fragment produced by rasterizing a triangle, whether it be a shader output or the clip \( w \) coordinate, \textbf{must} be determined using perspective interpolation:

\[
f = \frac{af_a + bf_b + cf_c}{aw_a + bw_b + cw_c}
\]

where \( w_a, w_b, \) and \( w_c \) are the clip \( w \) coordinates of \( p_a, p_b, \) and \( p_c \) respectively. \( a, b, \) and \( c \) are the barycentric coordinates of the location at which the data are produced - this \textbf{must} be the location of the fragment center or the location of a sample. When \texttt{rasterizationSamples} is \texttt{VK_SAMPLE_COUNT_1_BIT}, the fragment center \textbf{must} be used.

Depth values for triangles \textbf{must} be determined using linear interpolation:

\[
z = a z_a + b z_b + c z_c
\]

where \( z_a, z_b, \) and \( z_c \) are the depth values of \( p_a, p_b, \) and \( p_c \) respectively.

The \texttt{NoPerspective} and \texttt{Flat} interpolation decorations \textbf{can} be used with fragment shader inputs to declare how they are interpolated. When neither decoration is applied, \texttt{perspective interpolation} is performed as described above. When the \texttt{NoPerspective} decoration is used, \texttt{linear interpolation} is performed in the same fashion as for depth values, as described above. When the \texttt{Flat} decoration is used, no interpolation is performed, and outputs are taken from the corresponding input value of the \texttt{provoking vertex} corresponding to that primitive.

For a polygon with more than three edges, such as are produced by clipping a triangle, a convex combination of the values of the datum at the polygon’s vertices \textbf{must} be used to obtain the value assigned to each fragment produced by the rasterization algorithm. That is, it \textbf{must} be the case that at every fragment

\[
f = \sum_{i=1}^{n} a_i f_i
\]

where \( n \) is the number of vertices in the polygon and \( f_i \) is the value of \( f \) at vertex \( i. \) For each \( i, 0 \leq a_i \leq 1 \) and \( \sum_{i=1}^{n} a_i = 1. \) The values of \( a_i \) \textbf{may} differ from fragment to fragment, but at vertex \( i, a_i = 1 \) and \( a_j = 0 \) for \( j \neq i. \)
Note
One algorithm that achieves the required behavior is to triangulate a polygon (without adding any vertices) and then treat each triangle individually as already discussed. A scan-line rasterizer that linearly interpolates data along each edge and then linearly interpolates data across each horizontal span from edge to edge also satisfies the restrictions (in this case, the numerator and denominator of equation [triangle_perspective_interpolation] are iterated independently and a division performed for each fragment).

24.7.2. Polygon Mode

Possible values of the VkPipelineRasterizationStateCreateInfo::polygonMode property of the currently active pipeline, specifying the method of rasterization for polygons, are:

```cpp
typedef enum VkPolygonMode {
    VK_POLYGON_MODE_FILL = 0,
    VK_POLYGON_MODE_LINE = 1,
    VK_POLYGON_MODE_POINT = 2,
    VK_POLYGON_MODE_MAX_ENUM = 0x7FFFFFFF
} VkPolygonMode;
```

- **VK_POLYGON_MODE_POINT** specifies that polygon vertices are drawn as points.
- **VK_POLYGON_MODE_LINE** specifies that polygon edges are drawn as line segments.
- **VK_POLYGON_MODE_FILL** specifies that polygons are rendered using the polygon rasterization rules in this section.

These modes affect only the final rasterization of polygons: in particular, a polygon’s vertices are shaded and the polygon is clipped and possibly culled before these modes are applied.

24.7.3. Depth Bias

The depth values of all fragments generated by the rasterization of a polygon can be offset by a single value that is computed for that polygon. This behavior is controlled by the depthBiasEnable, depthBiasConstantFactor, depthBiasClamp, and depthBiasSlopeFactor members of VkPipelineRasterizationStateCreateInfo, or by the corresponding parameters to the vkCmdSetDepthBias command if depth bias state is dynamic.

```c
void vkCmdSetDepthBias(
    VkCommandBuffer          commandBuffer,
    float                    depthBiasConstantFactor,
    float                    depthBiasClamp,
    float                    depthBiasSlopeFactor);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **depthBiasConstantFactor** is a scalar factor controlling the constant depth value added to each
• **depthBiasClamp** is the maximum (or minimum) depth bias of a fragment.

• **depthBiasSlopeFactor** is a scalar factor applied to a fragment’s slope in depth bias calculations.

If **depthBiasEnable** is **VK_FALSE**, no depth bias is applied and the fragment’s depth values are unchanged.

depthBiasSlopeFactor scales the maximum depth slope of the polygon, and depthBiasConstantFactor scales an implementation-dependent constant that relates to the usable resolution of the depth buffer. The resulting values are summed to produce the depth bias value which is then clamped to a minimum or maximum value specified by depthBiasClamp. depthBiasSlopeFactor, depthBiasConstantFactor, and depthBiasClamp can each be positive, negative, or zero.

The maximum depth slope \( m \) of a triangle is

\[
m = \sqrt{\left(\frac{\partial z_f}{\partial x_f}\right)^2 + \left(\frac{\partial z_f}{\partial y_f}\right)^2}
\]

where \((x_0, y_0, z_0)\) is a point on the triangle. \( m \) may be approximated as

\[
m = \max\left(\left|\frac{\partial z_f}{\partial x_f}\right|, \left|\frac{\partial z_f}{\partial y_f}\right|\right).
\]

The minimum resolvable difference \( r \) is an implementation-dependent parameter that depends on the depth buffer representation. It is the smallest difference in framebuffer coordinate \( z \) values that is guaranteed to remain distinct throughout polygon rasterization and in the depth buffer. All pairs of fragments generated by the rasterization of two polygons with otherwise identical vertices, but \( z_f \) values that differ by \( r \), will have distinct depth values.

For fixed-point depth buffer representations, \( r \) is constant throughout the range of the entire depth buffer. For floating-point depth buffers, there is no single minimum resolvable difference. In this case, the minimum resolvable difference for a given polygon is dependent on the maximum exponent, \( e \), in the range of \( z \) values spanned by the primitive. If \( n \) is the number of bits in the floating-point mantissa, the minimum resolvable difference, \( r \), for the given primitive is defined as

\[
r = 2^{-n}
\]

If no depth buffer is present, \( r \) is undefined.

The bias value \( o \) for a polygon is

\[
o = \text{dbclamp}(m \times \text{depthBiasSlopeFactor} + r \times \text{depthBiasConstantFactor})
\]

where

\[
\text{dbclamp}(x) = \begin{cases} 
  x & \text{if } \text{depthBiasClamp} = 0 \text{ or } \text{NaN} \\
  \min(x, \text{depthBiasClamp}) & \text{if } \text{depthBiasClamp} > 0 \\
  \max(x, \text{depthBiasClamp}) & \text{if } \text{depthBiasClamp} < 0
\end{cases}
\]

\( m \) is computed as described above. If the depth buffer uses a fixed-point representation, \( m \) is a function of depth values in the range \([0,1]\), and \( o \) is applied to depth values in the same range.

For fixed-point depth buffers, fragment depth values are always limited to the range \([0,1]\) by...
clamping after depth bias addition is performed. Fragment depth values are clamped even when
the depth buffer uses a floating-point representation.

Valid Usage

- If the depth bias clamping feature is not enabled, depthBiasClamp must be 0.0

Valid Usage (Implicit)

- commandBuffer must be a valid VkCommandBuffer handle
- commandBuffer must be in the recording state
- The VkCommandPool that commandBuffer was allocated from must support graphics operations

Host Synchronization

- Host access to commandBuffer must be externally synchronized
- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 25. Fragment Operations

Fragment operations execute on a per-fragment or per-sample basis, affecting whether or how a fragment or sample is written to the framebuffer. Some operations execute before fragment shading, and others after. Fragment operations always adhere to rasterization order.

25.1. Early Per-Fragment Tests

Once fragments are produced by rasterization, a number of per-fragment operations are performed prior to fragment shader execution. If a fragment is discarded during any of these operations, it will not be processed by any subsequent stage, including fragment shader execution.

The scissor test and sample mask generation are always performed during early fragment tests.

Fragment operations are performed in the following order:

- the scissor test (see Scissor Test)
- multisample fragment operations (see Sample Mask)

If early per-fragment operations are enabled by the fragment shader, these operations are also performed:

- Depth bounds test
- Stencil test
- Depth test
- Sample counting for occlusion queries

25.2. Scissor Test

The scissor test determines if a fragment's framebuffer coordinates \((x_f, y_f)\) lie within the scissor rectangle corresponding to the viewport index (see Controlling the Viewport) used by the primitive that generated the fragment. If the pipeline state object is created without \(\text{VK_DYNAMIC_STATE_SCISSOR}\) enabled then the scissor rectangles are set by the \(\text{VkPipelineViewportStateCreateInfo}\) state of the pipeline state object. Otherwise, to dynamically set the scissor rectangles call:

```c
void vkCmdSetScissor(
    VkCommandBuffer                             commandBuffer,
    uint32_t                                    firstScissor,
    uint32_t                                    scissorCount,
    const VkRect2D*                             pScissors);
```

- \texttt{commandBuffer} is the command buffer into which the command will be recorded.
- \texttt{firstScissor} is the index of the first scissor whose state is updated by the command.
- \texttt{scissorCount} is the number of scissors whose rectangles are updated by the command.
• \texttt{pScissors} is a pointer to an array of \texttt{VkRect2D} structures defining scissor rectangles.

The scissor rectangles taken from element \(i\) of \texttt{pScissors} replace the current state for the scissor index \texttt{firstScissor} + \(i\), for \(i\) in \([0, \texttt{scissorCount})\).

Each scissor rectangle is described by a \texttt{VkRect2D} structure, with the \texttt{offset.x} and \texttt{offset.y} values determining the upper left corner of the scissor rectangle, and the \texttt{extent.width} and \texttt{extent.height} values determining the size in pixels.

**Valid Usage**

- \texttt{firstScissor} must be less than \texttt{VkPhysicalDeviceLimits::maxViewports}
- The sum of \texttt{firstScissor} and \texttt{scissorCount} must be between 1 and \texttt{VkPhysicalDeviceLimits::maxViewports}, inclusive
- If the \texttt{multiple viewports} feature is not enabled, \texttt{firstScissor} must be 0
- If the \texttt{multiple viewports} feature is not enabled, \texttt{scissorCount} must be 1
- The \(x\) and \(y\) members of \texttt{offset} member of any element of \texttt{pScissors} must be greater than or equal to 0
- Evaluation of \((\texttt{offset.x} + \texttt{extent.width})\) must not cause a signed integer addition overflow for any element of \texttt{pScissors}
- Evaluation of \((\texttt{offset.y} + \texttt{extent.height})\) must not cause a signed integer addition overflow for any element of \texttt{pScissors}

**Valid Usage (Implicit)**

- \texttt{commandBuffer} must be a valid \texttt{VkCommandBuffer} handle
- \texttt{pScissors} must be a valid pointer to an array of \texttt{scissorCount} \texttt{VkRect2D} structures
- \texttt{commandBuffer} must be in the recording state
- The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must support graphics operations
- \texttt{scissorCount} must be greater than 0

**Host Synchronization**

- Host access to \texttt{commandBuffer} must be externally synchronized
- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must be externally synchronized
If \( offset.x \leq x < offset.x + extent.width \) and \( offset.y \leq y < offset.y + extent.height \) for the selected scissor rectangle, then the scissor test passes. Otherwise, the test fails and the fragment is discarded. For points, lines, and polygons, the scissor rectangle for a primitive is selected in the same manner as the viewport (see Controlling the Viewport). The scissor rectangles test only applies to drawing commands, not to other commands like clears or copies.

It is legal for \( offset.x + extent.width \) or \( offset.y + extent.height \) to exceed the dimensions of the framebuffer - the scissor test still applies as defined above. Rasterization does not produce fragments outside of the framebuffer, so such fragments never have the scissor test performed on them.

The scissor test is always performed. Applications can effectively disable the scissor test by specifying a scissor rectangle that encompasses the entire framebuffer.

### 25.3. Sample Mask

This step modifies fragment coverage values based on the values in the `pSampleMask` array member of `VkPipelineMultisampleStateCreateInfo`, as described previously in section Graphics Pipelines.

`pSampleMask` contains an array of static coverage information that is ANDed with the coverage information generated during rasterization. Bits that are zero disable coverage for the corresponding sample. Bit B of mask word M corresponds to sample \( 32 \times M + B \). The array is sized to a length of \( \lceil \text{rasterizationSamples} / 32 \rceil \) words. If `pSampleMask` is NULL, it is treated as if the mask has all bits enabled, i.e. no coverage is removed from fragments.

The elements of the sample mask array are of type `VkSampleMask`, each representing 32 bits of coverage information:

```c
typedef uint32_t VkSampleMask;
```

### 25.4. Early Fragment Test Mode

The depth bounds test, stencil test, depth test, and occlusion query sample counting are performed before fragment shading if and only if early fragment tests are enabled by the fragment shader (see Early Fragment Tests). When early per-fragment operations are enabled, these operations are performed prior to fragment shader execution, and the stencil buffer, depth buffer, and occlusion query sample counts will be updated accordingly; these operations will not be performed again after fragment shader execution.
If a pipeline’s fragment shader has early fragment tests disabled, these operations are performed only after fragment program execution, in the order described below. If a pipeline does not contain a fragment shader, these operations are performed only once.

If early fragment tests are enabled, any depth value computed by the fragment shader has no effect. Additionally, the depth test (including depth writes), stencil test (including stencil writes) and sample counting operations are performed even for fragments or samples that would be discarded after fragment shader execution due to per-fragment operations such as alpha-to-coverage tests, or due to the fragment being discarded by the shader itself.

### 25.5. Late Per-Fragment Tests

After programmable fragment processing, per-fragment operations are performed before blending and color output to the framebuffer.

A fragment is produced by rasterization with framebuffer coordinates of \((x_f, y_f)\) and depth \(z\), as described in Rasterization. The fragment is then modified by programmable fragment processing, which adds associated data as described in Shaders. The fragment is then further modified, and possibly discarded by the late per-fragment operations described in this chapter. Finally, if the fragment was not discarded, it is used to update the framebuffer at the fragment’s framebuffer coordinates for any samples that remain covered.

The depth bounds test, stencil test, and depth test are performed for each sample, rather than just once for each fragment. Stencil and depth operations are performed for a sample only if that sample’s fragment coverage bit is a value of 1 when the fragment executes the corresponding stage of the graphics pipeline. If the corresponding coverage bit is 0, no operations are performed for that sample. Failure of the depth bounds, stencil, or depth test results in termination of the processing of that sample by means of disabling coverage for that sample, rather than discarding of the fragment. If, at any point, a fragment’s coverage becomes zero for all samples, then the fragment is discarded. All operations are performed on the depth and stencil values stored in the depth/stencil attachment of the framebuffer. The contents of the color attachments are not modified at this point.

The depth bounds test, stencil test, depth test, and occlusion query operations described in Depth Bounds Test, Stencil Test, Depth Test, Sample Counting are instead performed prior to fragment processing, as described in Early Fragment Test Mode, if requested by the fragment shader.

### 25.6. Multisample Coverage

If a fragment shader is active and its entry point’s interface includes a built-in output variable decorated with SampleMask, the fragment coverage is ANDed with the bits of the sample mask to generate a new fragment coverage value. If such a fragment shader did not assign a value to SampleMask due to flow of control, the value ANDed with the fragment coverage is undefined. If no fragment shader is active, or if the active fragment shader does not include SampleMask in its interface, the fragment coverage is not modified.

Next, the fragment alpha and coverage values are modified based on the alphaToCoverageEnable and alphaToOneEnable members of the VkPipelineMultisampleStateCreateInfo structure.
All alpha values in this section refer only to the alpha component of the fragment shader output that has a Location and Index decoration of zero (see the Fragment Output Interface section). If that shader output has an integer or unsigned integer type, then these operations are skipped.

If alphaToCoverageEnable is enabled, a temporary coverage value with rasterizationSamples bits is generated where each bit is determined by the fragment's alpha value. The temporary coverage value is then ANDed with the fragment coverage value to generate a new fragment coverage value.

No specific algorithm is specified for converting the alpha value to a temporary coverage mask. It is intended that the number of 1’s in this value be proportional to the alpha value (clamped to [0,1]), with all 1’s corresponding to a value of 1.0 and all 0’s corresponding to 0.0. The algorithm may be different at different framebuffer coordinates.

Using different algorithms at different framebuffer coordinates may help to avoid artifacts caused by regular coverage sample locations.

Next, if alphaToOneEnable is enabled, each alpha value is replaced by the maximum representable alpha value for fixed-point color buffers, or by 1.0 for floating-point buffers. Otherwise, the alpha values are not changed.

## 25.7. Depth and Stencil Operations

Pipeline state controlling the depth bounds tests, stencil test, and depth test is specified through the members of the VkPipelineDepthStencilStateCreateInfo structure.

The VkPipelineDepthStencilStateCreateInfo structure is defined as:

```c
typedef struct VkPipelineDepthStencilStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineDepthStencilStateCreateFlags flags;
    VkBool32 depthTestEnable;
    VkBool32 depthWriteEnable;
    VkCompareOp depthCompareOp;
    VkBool32 depthBoundsTestEnable;
    VkBool32 stencilTestEnable;
    VkStencilOpState front;
    VkStencilOpState back;
    float minDepthBounds;
    float maxDepthBounds;
} VkPipelineDepthStencilStateCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **depthTestEnable** controls whether depth testing is enabled.
• **depthWriteEnable** controls whether **depth writes** are enabled when **depthTestEnable** is **VK_TRUE**. Depth writes are always disabled when **depthTestEnable** is **VK_FALSE**.

• **depthCompareOp** is the comparison operator used in the **depth test**.

• **depthBoundsTestEnable** controls whether **depth bounds testing** is enabled.

• **stencilTestEnable** controls whether **stencil testing** is enabled.

• **front** and **back** control the parameters of the **stencil test**.

• **minDepthBounds** and **maxDepthBounds** define the range of values used in the **depth bounds test**.

---

**Valid Usage**

• If the **depth bounds testing** feature is not enabled, **depthBoundsTestEnable** must be **VK_FALSE**

---

**Valid Usage (Implicit)**

• **sType** must be **VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO**

• **pNext** must be **NULL**

• **flags** must be **0**

• **depthCompareOp** must be a valid **VkCompareOp** value

• **front** must be a valid **VkStencilOpState** structure

• **back** must be a valid **VkStencilOpState** structure

---

**typedef** **VkFlags** **VkPipelineDepthStencilStateCreateFlags**;

**VkPipelineDepthStencilStateCreateFlags** is a bitmask type for setting a mask, but is currently reserved for future use.

---

### 25.8. Depth Bounds Test

The depth bounds test conditionally disables coverage of a sample based on the outcome of a comparison between the value \(z_a\) in the depth attachment at location \((x_f, y_f)\) (for the appropriate sample) and a range of values. The test is enabled or disabled by the **depthBoundsTestEnable** member of **VkPipelineDepthStencilStateCreateInfo**: If the pipeline state object is created without the **VK_DYNAMIC_STATE_DEPTH_BOUNDS** dynamic state enabled then the range of values used in the depth bounds test are defined by the **minDepthBounds** and **maxDepthBounds** members of the **VkPipelineDepthStencilStateCreateInfo** structure. Otherwise, to dynamically set the depth bounds range values call:
void vkCmdSetDepthBounds(
    VkCommandBuffer commandBuffer,  // commandBuffer is the command buffer into which the command will be recorded.
    float minDepthBounds,          // minDepthBounds is the lower bound of the range of depth values used in the depth bounds test.
    float maxDepthBounds);         // maxDepthBounds is the upper bound of the range.

Valid Usage

• `minDepthBounds` must be between 0.0 and 1.0, inclusive
• `maxDepthBounds` must be between 0.0 and 1.0, inclusive

Valid Usage (Implicit)

• `commandBuffer` must be a valid `VkCommandBuffer` handle
• `commandBuffer` must be in the recording state
• The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

Host Synchronization

• Host access to `commandBuffer` must be externally synchronized
• Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If \( \text{minDepthBounds} \leq z_a \leq \text{maxDepthBounds} \), then the depth bounds test passes. Otherwise, the test fails and the sample’s coverage bit is cleared in the fragment. If there is no depth framebuffer attachment or if the depth bounds test is disabled, it is as if the depth bounds test always passes.
25.9. Stencil Test

The stencil test conditionally disables coverage of a sample based on the outcome of a comparison between the stencil value in the depth/stencil attachment at location \((x_f, y_f)\) (for the appropriate sample) and a reference value. The stencil test also updates the value in the stencil attachment, depending on the test state, the stencil value and the stencil write masks. The stencil test is enabled or disabled by the `stencilTestEnable` member of `VkPipelineDepthStencilStateCreateInfo`.

When stencil test is disabled, the stencil test and associated modifications are not made, and the sample’s coverage is not modified.

The stencil test is controlled by the `front` and `back` members of `VkPipelineDepthStencilStateCreateInfo`, which are of type `VkStencilOpState`.

The `VkStencilOpState` structure is defined as:

```c
typedef struct VkStencilOpState {
    VkStencilOp    failOp;
    VkStencilOp    passOp;
    VkStencilOp    depthFailOp;
    VkCompareOp    compareOp;
    uint32_t       compareMask;
    uint32_t       writeMask;
    uint32_t       reference;
} VkStencilOpState;
```

- `failOp` is a `VkStencilOp` value specifying the action performed on samples that fail the stencil test.
- `passOp` is a `VkStencilOp` value specifying the action performed on samples that pass both the depth and stencil tests.
- `depthFailOp` is a `VkStencilOp` value specifying the action performed on samples that pass the stencil test and fail the depth test.
- `compareOp` is a `VkCompareOp` value specifying the comparison operator used in the stencil test.
- `compareMask` selects the bits of the unsigned integer stencil values participating in the stencil test.
- `writeMask` selects the bits of the unsigned integer stencil values updated by the stencil test in the stencil framebuffer attachment.
- `reference` is an integer reference value that is used in the unsigned stencil comparison.
There are two sets of stencil-related state, the front stencil state set and the back stencil state set. Stencil tests and writes use the front set of stencil state when processing front-facing fragments and use the back set of stencil state when processing back-facing fragments. Fragments rasterized from non-polygon primitives (points and lines) are always considered front-facing. Fragments rasterized from polygon primitives inherit their facingness from the polygon, even if the polygon is rasterized as points or lines due to the current `VkPolygonMode`. Whether a polygon is front- or back-facing is determined in the same manner used for face culling (see Basic Polygon Rasterization).

The operation of the stencil test is also affected by the `compareMask`, `writeMask`, and `reference` members of `VkStencilOpState` set in the pipeline state object if the pipeline state object is created without the `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK`, `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK`, and `VK_DYNAMIC_STATE_STENCIL_REFERENCE` dynamic states enabled, respectively.

If the pipeline state object is created with the `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK` dynamic state enabled, then to dynamically set the stencil compare mask call:

```c
void vkCmdSetStencilCompareMask(
    VkCommandBuffer commandBuffer,
    VkStencilFaceFlags faceMask,
    uint32_t compareMask);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `faceMask` is a bitmask of `VkStencilFaceFlagBits` specifying the set of stencil state for which to update the compare mask.
- `compareMask` is the new value to use as the stencil compare mask.

Chapter 25. Fragment Operations | 829
Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bits which can be set in the `vkCmdSetStencilCompareMask::faceMask` parameter, and similar parameters of other commands specifying which stencil state to update stencil masks for, are:

```c
typedef enum VkStencilFaceFlagBits {
    VK_STENCIL_FACE_FRONT_BIT = 0x00000001,
    VK_STENCIL_FACE_BACK_BIT = 0x00000002,
    VK_STENCIL_FACE_FRONT_AND_BACK = 0x00000003,
    VK_STENCIL_FACE_FRONT_AND_BACK = VK_STENCIL_FACE_FRONT_AND_BACK,  // Note: The same value is assigned twice.
    VK_STENCIL_FACE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkStencilFaceFlagBits;
```

- `VK_STENCIL_FACE_FRONT_BIT` specifies that only the front set of stencil state is updated.
- `VK_STENCIL_FACE_BACK_BIT` specifies that only the back set of stencil state is updated.
- `VK_STENCIL_FACE_FRONT_AND_BACK` is the combination of `VK_STENCIL_FACE_FRONT_BIT` and `VK_STENCIL_FACE_BACK_BIT`, and specifies that both sets of stencil state are updated.

```c
typedef VkFlags VkStencilFaceFlags;
```

`VkStencilFaceFlags` is a bitmask type for setting a mask of zero or more `VkStencilFaceFlagBits`.

If the pipeline state object is created with the `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK` dynamic state enabled, then to dynamically set the stencil write mask call:

```c
void vkCmdSetStencilWriteMask(
    VkCommandBuffer commandBuffer,  // commandBuffer is the command buffer into which the command will be recorded.
    VkStencilFaceFlags faceMask,    // Only the faceMask parameter is used.
    uint32_t writeMask);
```
• **faceMask** is a bitmask of **VkStencilFaceFlagBits** specifying the set of stencil state for which to update the write mask, as described above for **vkCmdSetStencilCompareMask**.

• **writeMask** is the new value to use as the stencil write mask.

### Valid Usage (Implicit)

- **commandBuffer** must be a valid **VkCommandBuffer** handle
- **faceMask** must be a valid combination of **VkStencilFaceFlagBits** values
- **faceMask** must not be 0
- **commandBuffer** must be in the recording state
- The **VkCommandPool** that **commandBuffer** was allocated from must support graphics operations

### Host Synchronization

- Host access to **commandBuffer** must be externally synchronized
- Host access to the **VkCommandPool** that **commandBuffer** was allocated from must be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If the pipeline state object is created with the **VK_DYNAMIC_STATE_STENCIL_REFERENCE** dynamic state enabled, then to dynamically set the stencil reference value call:

```c
void vkCmdSetStencilReference(
    VkCommandBuffer                             commandBuffer,
    VkStencilFaceFlags                          faceMask,
    uint32_t                                    reference);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **faceMask** is a bitmask of **VkStencilFaceFlagBits** specifying the set of stencil state for which to update the reference value, as described above for **vkCmdSetStencilCompareMask**.
- **reference** is the new value to use as the stencil reference value.
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `faceMask` must be a valid combination of `VkStencilFaceFlagBits` values
- `faceMask` must not be 0
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

`reference` is an integer reference value that is used in the unsigned stencil comparison. The reference value used by stencil comparison must be within the range `[0,2^s-1]`, where `s` is the number of bits in the stencil framebuffer attachment, otherwise the reference value is considered undefined. The `s` least significant bits of `compareMask` are bitwise ANDed with both the reference and the stored stencil value, and the resulting masked values are those that participate in the comparison controlled by `compareOp`. Let `R` be the masked reference value and `S` be the masked stored stencil value.

Possible values of `VkStencilOpState::compareOp`, specifying the stencil comparison function, are:
typedef enum VkCompareOp {
    VK_COMPARE_OP_NEVER = 0,
    VK_COMPARE_OP_LESS = 1,
    VK_COMPARE_OP_EQUAL = 2,
    VK_COMPARE_OP_LESS_OR_EQUAL = 3,
    VK_COMPARE_OP_GREATER = 4,
    VK_COMPARE_OP_NOT_EQUAL = 5,
    VK_COMPARE_OP_GREATER_OR_EQUAL = 6,
    VK_COMPARE_OP_ALWAYS = 7,
    VK_COMPARE_OP_MAX_ENUM = 0x7FFFFFFF
} VkCompareOp;

- **VK_COMPARE_OP_NEVER** specifies that the test never passes.
- **VK_COMPARE_OP_LESS** specifies that the test passes when \( R < S \).
- **VK_COMPARE_OP_EQUAL** specifies that the test passes when \( R = S \).
- **VK_COMPARE_OP_LESS_OR_EQUAL** specifies that the test passes when \( R \leq S \).
- **VK_COMPARE_OP_GREATER** specifies that the test passes when \( R > S \).
- **VK_COMPARE_OP_NOT_EQUAL** specifies that the test passes when \( R \neq S \).
- **VK_COMPARE_OP_GREATER_OR_EQUAL** specifies that the test passes when \( R \geq S \).
- **VK_COMPARE_OP_ALWAYS** specifies that the test always passes.

Possible values of the `failOp`, `passOp`, and `depthFailOp` members of `VkStencilOpState`, specifying what happens to the stored stencil value if this or certain subsequent tests fail or pass, are:

typedef enum VkStencilOp {
    VK_STENCIL_OP_KEEP = 0,
    VK_STENCIL_OP_ZERO = 1,
    VK_STENCIL_OP_REPLACE = 2,
    VK_STENCIL_OP_INCREMENT_AND_CLAMP = 3,
    VK_STENCIL_OP_DECREMENT_AND_CLAMP = 4,
    VK_STENCIL_OP_INVERT = 5,
    VK_STENCIL_OP_INCREMENT_AND_WRAP = 6,
    VK_STENCIL_OP_DECREMENT_AND_WRAP = 7,
    VK_STENCIL_OP_MAX_ENUM = 0x7FFFFFFF
} VkStencilOp;

- **VK_STENCIL_OP_KEEP** keeps the current value.
- **VK_STENCIL_OP_ZERO** sets the value to 0.
- **VK_STENCIL_OP_REPLACE** sets the value to `reference`.
- **VK_STENCIL_OP_INCREMENT_AND_CLAMP** increments the current value and clamps to the maximum representable unsigned value.
- **VK_STENCIL_OP_DECREMENT_AND_CLAMP** decrements the current value and clamps to 0.
- **VK_STENCIL_OP_INVERT** bitwise-inverts the current value.
For purposes of increment and decrement, the stencil bits are considered as an unsigned integer.

If the stencil test fails, the sample’s coverage bit is cleared in the fragment. If there is no stencil framebuffer attachment, stencil modification cannot occur, and it is as if the stencil tests always pass.

If the stencil test passes, the writeMask member of the VkStencilOpState structures controls how the updated stencil value is written to the stencil framebuffer attachment.

The least significant s bits of writeMask, where s is the number of bits in the stencil framebuffer attachment, specify an integer mask. Where a 1 appears in this mask, the corresponding bit in the stencil value in the depth/stencil attachment is written; where a 0 appears, the bit is not written. The writeMask value uses either the front-facing or back-facing state based on the facingness of the fragment. Fragments generated by front-facing primitives use the front mask and fragments generated by back-facing primitives use the back mask.

### 25.10. Depth Test

The depth test conditionally disables coverage of a sample based on the outcome of a comparison between the fragment’s depth value at the sample location and the sample’s depth value in the depth/stencil attachment at location \((x_f, y_f)\). The comparison is enabled or disabled with the depthTestEnable member of the VkPipelineDepthStencilStateCreateInfo structure. When disabled, the depth comparison and subsequent possible updates to the value of the depth component of the depth/stencil attachment are bypassed and the fragment is passed to the next operation. The stencil value, however, can be modified as indicated above as if the depth test passed. If enabled, the comparison takes place and the depth/stencil attachment value can subsequently be modified.

The comparison is specified with the depthCompareOp member of VkPipelineDepthStencilStateCreateInfo. Let \(z_f\) be the incoming fragment’s depth value for a sample, and let \(z_a\) be the depth/stencil attachment value in memory for that sample. The depth test passes under the following conditions:

- **VK_COMPARE_OP_NEVER**: the test never passes.
- **VK_COMPARE_OP_LESS**: the test passes when \(z_f < z_a\).
- **VK_COMPARE_OP_EQUAL**: the test passes when \(z_f = z_a\).
- **VK_COMPARE_OP_LESS_OR_EQUAL**: the test passes when \(z_f \leq z_a\).
- **VK_COMPARE_OP_GREATER**: the test passes when \(z_f > z_a\).
- **VK_COMPARE_OP_NOT_EQUAL**: the test passes when \(z_f \neq z_a\).
- **VK_COMPARE_OP_GREATER_OR_EQUAL**: the test passes when \(z_f \geq z_a\).
- **VK_COMPARE_OP_ALWAYS**: the test always passes.
If \texttt{VkPipelineRasterizationStateCreateInfo::depthClampEnable} is enabled, before the incoming fragment’s \( z_f \) is compared to \( z_a \), \( z_f \) is clamped to \([\min(n,f),\max(n,f)]\), where \( n \) and \( f \) are the \texttt{minDepth} and \texttt{maxDepth} depth range values of the viewport used by this fragment, respectively.

If the depth test fails, the sample’s coverage bit is cleared in the fragment. The stencil value at the sample’s location is updated according to the function currently in effect for depth test failure.

If the depth test passes, the sample’s (possibly clamped) \( z_f \) value is conditionally written to the depth framebuffer attachment based on the \texttt{depthWriteEnable} member of \texttt{VkPipelineDepthStencilStateCreateInfo}. The value is written if \texttt{depthWriteEnable} is \texttt{VK_TRUE} and there is a depth framebuffer attachment. Otherwise, no value is written. The stencil value at the sample’s location is updated according to the function currently in effect for depth test success.

If there is no depth framebuffer attachment, it is as if the depth test always passes.

### 25.11. Sample Counting

Occlusion queries use query pool entries to track the number of samples that pass all the per-fragment tests. The mechanism of collecting an occlusion query value is described in \textit{Occlusion Queries}.

The occlusion query sample counter increments by one for each sample with a coverage value of 1 in each fragment that survives all the per-fragment tests, including scissor, sample mask, alpha to coverage, stencil, and depth tests.

### 25.12. Coverage Reduction

Coverage reduction generates a \textit{color sample mask} from the coverage mask, with one bit for each sample in the color attachment(s) for the subpass. If a bit in the color sample mask is 0, then blending and writing to the framebuffer are not performed for that sample.

When the \texttt{VK_NV_framebuffer_mixed_samples} extension is not enabled, each color sample is associated with a unique rasterization sample, and the value of the coverage mask is assigned to the color sample mask.
26.1. Blending

Blending combines the incoming source fragment’s R, G, B, and A values with the destination R, G, B, and A values of each sample stored in the framebuffer at the fragment’s \((x_f, y_f)\) location. Blending is performed for each color sample covered by the fragment, rather than just once for each fragment.

Source and destination values are combined according to the blend operation, quadruplets of source and destination weighting factors determined by the blend factors, and a blend constant, to obtain a new set of R, G, B, and A values, as described below.

Blending is computed and applied separately to each color attachment used by the subpass, with separate controls for each attachment.

Prior to performing the blend operation, signed and unsigned normalized fixed-point color components undergo an implied conversion to floating-point as specified by Conversion from Normalized Fixed-Point to Floating-Point. Blending computations are treated as if carried out in floating-point, and basic blend operations are performed with a precision and dynamic range no lower than that used to represent destination components.

Blending applies only to fixed-point and floating-point color attachments. If the color attachment has an integer format, blending is not applied.

The pipeline blend state is included in the VkPipelineColorBlendStateCreateInfo structure during graphics pipeline creation:

The VkPipelineColorBlendStateCreateInfo structure is defined as:

```c
typedef struct VkPipelineColorBlendStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineColorBlendStateCreateFlags flags;
    VkBool32 logicOpEnable;
    VkLogicOp logicOp;
    uint32_t attachmentCount;
    const VkPipelineColorBlendAttachmentState* pAttachments;
    float blendConstants[4];
} VkPipelineColorBlendStateCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **logicOpEnable** controls whether to apply Logical Operations.
- **logicOp** selects which logical operation to apply.
- **attachmentCount** is the number of VkPipelineColorBlendAttachmentState elements in pAttachments.
This value **must** equal the `colorAttachmentCount` for the subpass in which this pipeline is used.

- **pAttachments**: is a pointer to an array of per target attachment states.
- **blendConstants** is a pointer to an array of four values used as the R, G, B, and A components of the blend constant that are used in blending, depending on the blend factor.

Each element of the `pAttachments` array is a `VkPipelineColorBlendAttachmentState` structure specifying per-target blending state for each individual color attachment. If the **independent blending** feature is not enabled on the device, all `VkPipelineColorBlendAttachmentState` elements in the `pAttachments` array **must** be identical.

### Valid Usage

- If the **independent blending** feature is not enabled, all elements of `pAttachments` **must** be identical
- If the **logic operations** feature is not enabled, `logicOpEnable` **must** be **VK_FALSE**
- If `logicOpEnable` is **VK_TRUE**, `logicOp` **must** be a valid `VkLogicOp` value

### Valid Usage (Implicit)

- **sType** **must** be `VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO`
- **pNext** **must** be `NULL`
- **flags** **must** be `0`
- If `attachmentCount` is not `0`, `pAttachments` **must** be a valid pointer to an array of `attachmentCount` valid `VkPipelineColorBlendAttachmentState` structures

```typedef VkFlags VkPipelineColorBlendStateCreateFlags;
```

`VkPipelineColorBlendStateCreateFlags` is a bitmask type for setting a mask, but is currently reserved for future use.

The `VkPipelineColorBlendAttachmentState` structure is defined as:

```typedef struct VkPipelineColorBlendAttachmentState {
    VkBool32             blendEnable;
    VkBlendFactor        srcColorBlendFactor;
    VkBlendFactor        dstColorBlendFactor;
    VkBlendOp            colorBlendOp;
    VkBlendFactor        srcAlphaBlendFactor;
    VkBlendFactor        dstAlphaBlendFactor;
    VkBlendOp            alphaBlendOp;
    VkColorComponentFlags colorWriteMask;
} VkPipelineColorBlendAttachmentState;```
- **blendEnable** controls whether blending is enabled for the corresponding color attachment. If blending is not enabled, the source fragment’s color for that attachment is passed through unmodified.
- **srcColorBlendFactor** selects which blend factor is used to determine the source factors ($S_r, S_g, S_b$).
- **dstColorBlendFactor** selects which blend factor is used to determine the destination factors ($D_r, D_g, D_b$).
- **colorBlendOp** selects which blend operation is used to calculate the RGB values to write to the color attachment.
- **srcAlphaBlendFactor** selects which blend factor is used to determine the source factor $S_a$.
- **dstAlphaBlendFactor** selects which blend factor is used to determine the destination factor $D_a$.
- **alphaBlendOp** selects which blend operation is use to calculate the alpha values to write to the color attachment.
- **colorWriteMask** is a bitmask of VkColorComponentFlagBits specifying which of the R, G, B, and/or A components are enabled for writing, as described for the Color Write Mask.

### Valid Usage

- If the dual source blending feature is not enabled, **srcColorBlendFactor** must not be `VK_BLEND_FACTOR_SRC1_COLOR`, `VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR`, `VK_BLEND_FACTOR_SRC1_ALPHA`, or `VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA`.

- If the dual source blending feature is not enabled, **dstColorBlendFactor** must not be `VK_BLEND_FACTOR_SRC1_COLOR`, `VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR`, `VK_BLEND_FACTOR_SRC1_ALPHA`, or `VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA`.

- If the dual source blending feature is not enabled, **srcAlphaBlendFactor** must not be `VK_BLEND_FACTOR_SRC1_COLOR`, `VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR`, `VK_BLEND_FACTOR_SRC1_ALPHA`, or `VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA`.

- If the dual source blending feature is not enabled, **dstAlphaBlendFactor** must not be `VK_BLEND_FACTOR_SRC1_COLOR`, `VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR`, `VK_BLEND_FACTOR_SRC1_ALPHA`, or `VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA`.

### Valid Usage (Implicit)

- **srcColorBlendFactor** must be a valid VkBlendFactor value
- **dstColorBlendFactor** must be a valid VkBlendFactor value
- **colorBlendOp** must be a valid VkBlendOp value
- **srcAlphaBlendFactor** must be a valid VkBlendFactor value
- **dstAlphaBlendFactor** must be a valid VkBlendFactor value
- **alphaBlendOp** must be a valid VkBlendOp value
- **colorWriteMask** must be a valid combination of VkColorComponentFlagBits values
26.1.1. Blend Factors

The source and destination color and alpha blending factors are selected from the enum:

```c
typedef enum VkBlendFactor {
    VK_BLEND_FACTOR_ZERO = 0,
    VK_BLEND_FACTOR_ONE = 1,
    VK_BLEND_FACTOR_SRC_COLOR = 2,
    VK_BLEND_FACTOR_ONE_MINUS_SRC_COLOR = 3,
    VK_BLEND_FACTOR_DST_COLOR = 4,
    VK_BLEND_FACTOR_ONE_MINUS_DST_COLOR = 5,
    VK_BLEND_FACTOR_SRC_ALPHA = 6,
    VK_BLEND_FACTOR_ONE_MINUS_SRC_ALPHA = 7,
    VK_BLEND_FACTOR_DST_ALPHA = 8,
    VK_BLEND_FACTOR_ONE_MINUS_DST_ALPHA = 9,
    VK_BLEND_FACTOR_CONSTANT_COLOR = 10,
    VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_COLOR = 11,
    VK_BLEND_FACTOR_CONSTANT_ALPHA = 12,
    VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_ALPHA = 13,
    VK_BLEND_FACTOR_SRC_ALPHA_SATURATE = 14,
    VK_BLEND_FACTOR_SRC1_COLOR = 15,
    VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR = 16,
    VK_BLEND_FACTOR_SRC1_ALPHA = 17,
    VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA = 18,
    VK_BLEND_FACTOR_MAX_ENUM = 0x7FFFFFFF
} VkBlendFactor;
```

The semantics of each enum value is described in the table below:

<table>
<thead>
<tr>
<th>VkBlendFactor</th>
<th>RGB Blend Factors ((S_r,S_g,S_b)) or ((D_r,D_g,D_b))</th>
<th>Alpha Blend Factor ((S_s) or (D_s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_BLEND_FACTOR_ZERO</td>
<td>((0,0,0))</td>
<td>0</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE</td>
<td>((1,1,1))</td>
<td>1</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC_COLOR</td>
<td>((R_s0,G_s0,B_s0))</td>
<td>(A_s0)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC_COLOR</td>
<td>((1-R_s0,1-G_s0,1-B_s0))</td>
<td>(1-A_s0)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_DST_COLOR</td>
<td>((R_d,G_d,B_d))</td>
<td>(A_d)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_DST_COLOR</td>
<td>((1-R_d,1-G_d,1-B_d))</td>
<td>(1-A_d)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC_ALPHA</td>
<td>((A_s0,A_s0,A_s0))</td>
<td>(A_s0)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC_ALPHA</td>
<td>((1-A_s0,1-A_s0,1-A_s0))</td>
<td>(1-A_s0)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_DST_ALPHA</td>
<td>((A_d,A_d,A_d))</td>
<td>(A_d)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_DST_ALPHA</td>
<td>((1-A_d,1-A_d,1-A_d))</td>
<td>(1-A_d)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_CONSTANT_COLOR</td>
<td>((R_c,G_c,B_c))</td>
<td>(A_c)</td>
</tr>
</tbody>
</table>
In this table, the following conventions are used:

- \( R_{s0}, G_{s0}, B_{s0} \) and \( A_{s0} \) represent the first source color R, G, B, and A components, respectively, for the fragment output location corresponding to the color attachment being blended.

- \( R_{s1}, G_{s1}, B_{s1} \) and \( A_{s1} \) represent the second source color R, G, B, and A components, respectively, used in dual source blending modes, for the fragment output location corresponding to the color attachment being blended.

- \( R_d, G_d, B_d \) and \( A_d \) represent the R, G, B, and A components of the destination color. That is, the color currently in the corresponding color attachment for this fragment/sample.

- \( R_c, G_c, B_c \) and \( A_c \) represent the blend constant R, G, B, and A components, respectively.

If the pipeline state object is created without the `VK_DYNAMIC_STATE_BLEND_CONSTANTS` dynamic state enabled then the `blend constant` \( (R_c, G_c, B_c, A_c) \) is specified via the `blendConstants` member of `VkPipelineColorBlendStateCreateInfo`.

Otherwise, to dynamically set and change the blend constant, call:

```c
void vkCmdSetBlendConstants(
    VkCommandBuffer commandBuffer,           // the command buffer into which the command will be recorded.
    const float blendConstants[4]);        // pointer to an array of four values specifying the R, G, B, and A components of the blend constant color used in blending, depending on the blend factor.
```

840 | Chapter 26. The Framebuffer
Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support graphics operations

Host Synchronization

- Host access to `commandBuffer` must be externally synchronized
- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Both</td>
<td>Graphics</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

26.1.2. Dual-Source Blending

Blend factors that use the secondary color input \((R_{s1}, G_{s1}, B_{s1}, A_{s1})\) (\(VK\_BLEND\_FACTOR\_SRC1\_COLOR\), \(VK\_BLEND\_FACTOR\_ONE\_MINUS\_SRC1\_COLOR\), \(VK\_BLEND\_FACTOR\_SRC1\_ALPHA\), and \(VK\_BLEND\_FACTOR\_ONE\_MINUS\_SRC1\_ALPHA\)) may consume implementation resources that could otherwise be used for rendering to multiple color attachments. Therefore, the number of color attachments that can be used in a framebuffer may be lower when using dual-source blending.

Dual-source blending is only supported if the `dualSrcBlend` feature is enabled.

The maximum number of color attachments that can be used in a subpass when using dual-source blending functions is implementation-dependent and is reported as the `maxFragmentDualSrcAttachments` member of `VkPhysicalDeviceLimits`.

When using a fragment shader with dual-source blending functions, the color outputs are bound to the first and second inputs of the blender using the `Index` decoration, as described in Fragment Output Interface. If the second color input to the blender is not written in the shader, or if no output is bound to the second input of a blender, the result of the blending operation is not defined.

26.1.3. Blend Operations

Once the source and destination blend factors have been selected, they along with the source and destination components are passed to the blending operations. RGB and alpha components can use different operations. Possible values of `VkBlendOp`, specifying the operations, are:
typedef enum VkBlendOp {
    VK_BLEND_OP_ADD = 0,
    VK_BLEND_OP_SUBTRACT = 1,
    VK_BLEND_OP_REVERSE_SUBTRACT = 2,
    VK_BLEND_OP_MIN = 3,
    VK_BLEND_OP_MAX = 4,
    VK_BLEND_OP_MAX_ENUM = 0x7FFFFFFF
} VkBlendOp;
The semantics of each basic blend operations is described in the table below:

<table>
<thead>
<tr>
<th>VkBlendOp</th>
<th>RGB Components</th>
<th>Alpha Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_BLEND_OP_ADD</td>
<td>( R = R_{s0} \times S_r + R_d \times D_r )</td>
<td>( A = A_{s0} \times S_a + A_d \times D_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_{s0} \times S_g + G_d \times D_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_{s0} \times S_b + B_d \times D_b )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_OP_SUBTRACT</td>
<td>( R = R_{s0} \times S_r - R_d \times D_r )</td>
<td>( A = A_{s0} \times S_a - A_d \times D_a )</td>
</tr>
<tr>
<td></td>
<td>( G = G_{s0} \times S_g - G_d \times D_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = B_{s0} \times S_b - B_d \times D_b )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_OP_REVERSE_SUBTRACT</td>
<td>( R = D_r \times D_r - R_{s0} \times S_r )</td>
<td>( A = A_d \times D_a - A_{s0} \times S_a )</td>
</tr>
<tr>
<td></td>
<td>( G = D_g \times D_g - G_{s0} \times S_g )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = D_b \times D_b - B_{s0} \times S_b )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_OP_MIN</td>
<td>( R = \min(R_{s0}, R_d) )</td>
<td>( A = \min(A_{s0}, A_d) )</td>
</tr>
<tr>
<td></td>
<td>( G = \min(G_{s0}, G_d) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = \min(B_{s0}, B_d) )</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_OP_MAX</td>
<td>( R = \max(R_{s0}, R_d) )</td>
<td>( A = \max(A_{s0}, A_d) )</td>
</tr>
<tr>
<td></td>
<td>( G = \max(G_{s0}, G_d) )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( B = \max(B_{s0}, B_d) )</td>
<td></td>
</tr>
</tbody>
</table>

In this table, the following conventions are used:

- \( R_{s0}, G_{s0}, B_{s0}, \) and \( A_{s0} \) represent the first source color \( R, G, B, \) and \( A \) components, respectively.
- \( R_d, G_d, B_d, \) and \( A_d \) represent the \( R, G, B, \) and \( A \) components of the destination color. That is, the color currently in the corresponding color attachment for this fragment/samples.
- \( S_r, S_g, S_b, \) and \( S_a \) represent the source blend factor \( R, G, B, \) and \( A \) components, respectively.
- \( D_r, D_g, D_b, \) and \( D_a \) represent the destination blend factor \( R, G, B, \) and \( A \) components, respectively.

The blending operation produces a new set of values \( R, G, B, \) and \( A, \) which are written to the framebuffer attachment. If blending is not enabled for this attachment, then \( R, G, B, \) and \( A \) are assigned \( R_{s0}, G_{s0}, B_{s0}, \) and \( A_{s0}, \) respectively.

If the color attachment is fixed-point, the components of the source and destination values and blend factors are each clamped to \([0,1]\) or \([-1,1]\) respectively for an unsigned normalized or signed normalized color attachment prior to evaluating the blend operations. If the color attachment is floating-point, no clamping occurs.

If the numeric format of a framebuffer attachment uses sRGB encoding, the \( R, G, \) and \( B \) destination color values (after conversion from fixed-point to floating-point) are considered to be encoded for the sRGB color space and hence are linearized prior to their use in blending. Each \( R, G, \) and \( B \) component is converted from nonlinear to linear as described in the “sRGB EOTF” section of the Khronos Data Format Specification. If the format is not sRGB, no linearization is performed.

If the numeric format of a framebuffer attachment uses sRGB encoding, then the final \( R, G, \) and \( B \) values are converted into the nonlinear sRGB representation before being written to the framebuffer attachment as described in the “sRGB EOTF” section of the Khronos Data Format Specification.
If the framebuffer color attachment numeric format is not sRGB encoded then the resulting \( c_s \) values for R, G and B are unmodified. The value of A is never sRGB encoded. That is, the alpha component is always stored in memory as linear.

If the framebuffer color attachment is `VK_ATTACHMENT_UNUSED`, no writes are performed through that attachment. Framebuffer color attachments greater than or equal to `VkSubpassDescription::colorAttachmentCount` perform no writes.

### 26.2. Logical Operations

The application can enable a logical operation between the fragment’s color values and the existing value in the framebuffer attachment. This logical operation is applied prior to updating the framebuffer attachment. Logical operations are applied only for signed and unsigned integer and normalized integer framebuffers. Logical operations are not applied to floating-point or sRGB format color attachments.

Logical operations are controlled by the `logicOpEnable` and `logicOp` members of `VkPipelineColorBlendStateCreateInfo`. If `logicOpEnable` is `VK_TRUE`, then a logical operation selected by `logicOp` is applied between each color attachment and the fragment’s corresponding output value, and blending of all attachments is treated as if it were disabled. Any attachments using color formats for which logical operations are not supported simply pass through the color values unmodified. The logical operation is applied independently for each of the red, green, blue, and alpha components. The `logicOp` is selected from the following operations:

```c
typedef enum VkLogicOp {
    VK_LOGIC_OP_CLEAR = 0,
    VK_LOGIC_OP_AND = 1,
    VK_LOGIC_OP_AND_REVERSE = 2,
    VK_LOGIC_OP_COPY = 3,
    VK_LOGIC_OP_AND_INVERTED = 4,
    VK_LOGIC_OP_NO_OP = 5,
    VK_LOGIC_OP_XOR = 6,
    VK_LOGIC_OP_OR = 7,
    VK_LOGIC_OP_NOR = 8,
    VK_LOGIC_OP_EQUIVALENT = 9,
    VK_LOGIC_OP_INVERT = 10,
    VK_LOGIC_OP_OR_REVERSE = 11,
    VK_LOGIC_OP_COPY_INVERTED = 12,
    VK_LOGIC_OP_OR_INVERTED = 13,
    VK_LOGIC_OP_NAND = 14,
    VK_LOGIC_OP_SET = 15,
    VK_LOGIC_OP_MAX_ENUM = 0x7FFFFFFF
} VkLogicOp;
```
The logical operations supported by Vulkan are summarized in the following table in which

- \( \neg \) is bitwise invert,
- \( \land \) is bitwise and,
- \( \lor \) is bitwise or,
- \( \oplus \) is bitwise exclusive or,
- \( s \) is the fragment’s \( R_{s0} \), \( G_{s0} \), \( B_{s0} \) or \( A_{s0} \) component value for the fragment output corresponding to the color attachment being updated, and
- \( d \) is the color attachment’s \( R \), \( G \), \( B \) or \( A \) component value:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_LOGIC_OP_CLEAR</td>
<td>0</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND</td>
<td>( s \land d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND_REVERSE</td>
<td>( s \land \neg d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_COPY</td>
<td>( s )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND_INVERTED</td>
<td>( \neg s \land d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NO_OP</td>
<td>( d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_XOR</td>
<td>( s \oplus d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR</td>
<td>( s \lor d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NOR</td>
<td>( \neg (s \lor d) )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_EQUIVALENT</td>
<td>( \neg (s \oplus d) )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_INVERT</td>
<td>( \neg d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR_REVERSE</td>
<td>( s \lor \neg d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_COPY_INVERTED</td>
<td>( \neg s )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR_INVERTED</td>
<td>( \neg s \lor d )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NAND</td>
<td>( \neg (s \land d) )</td>
</tr>
<tr>
<td>VK_LOGIC_OP_SET</td>
<td>all 1s</td>
</tr>
</tbody>
</table>

The result of the logical operation is then written to the color attachment as controlled by the component write mask, described in **Blend Operations**.

### 26.3. Color Write Mask

Bits which **can** be set in `VkPipelineColorBlendAttachmentState::colorWriteMask` to determine whether the final color values \( R \), \( G \), \( B \) and \( A \) are written to the framebuffer attachment are:
typedef enum VkColorComponentFlagBits {
    VK_COLOR_COMPONENT_R_BIT = 0x00000001,
    VK_COLOR_COMPONENT_G_BIT = 0x00000002,
    VK_COLOR_COMPONENT_B_BIT = 0x00000004,
    VK_COLOR_COMPONENT_A_BIT = 0x00000008,
    VK_COLOR_COMPONENT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkColorComponentFlagBits;

- **VK_COLOR_COMPONENT_R_BIT** specifies that the R value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.
- **VK_COLOR_COMPONENT_G_BIT** specifies that the G value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.
- **VK_COLOR_COMPONENT_B_BIT** specifies that the B value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.
- **VK_COLOR_COMPONENT_A_BIT** specifies that the A value is written to the color attachment for the appropriate sample. Otherwise, the value in memory is unmodified.

The color write mask operation is applied regardless of whether blending is enabled.

typedef VkFlags VkColorComponentFlags;

**VkColorComponentFlags** is a bitmask type for setting a mask of zero or more **VkColorComponentFlagBits**.
Dispatching commands (commands with *Dispatch* in the name) provoke work in a compute pipeline. Dispatching commands are recorded into a command buffer and when executed by a queue, will produce work which executes according to the bound compute pipeline. A compute pipeline must be bound to a command buffer before any dispatch commands are recorded in that command buffer.

To record a dispatch, call:

```c
void vkCmdDispatch(
    VkCommandBuffer commandBuffer,
    uint32_t groupCountX,
    uint32_t groupCountY,
    uint32_t groupCountZ);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `groupCountX` is the number of local workgroups to dispatch in the X dimension.
- `groupCountY` is the number of local workgroups to dispatch in the Y dimension.
- `groupCountZ` is the number of local workgroups to dispatch in the Z dimension.

When the command is executed, a global workgroup consisting of `groupCountX × groupCountY × groupCountZ` local workgroups is assembled.
Valid Usage

- If a \texttt{VkImageView} is sampled with \texttt{VK_FILTER_LINEAR} as a result of this command, then the image view's format features must contain \texttt{VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT}

- If a \texttt{VkImageView} is accessed using atomic operations as a result of this command, then the image view's format features must contain \texttt{VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT}

- For each set \(n\) that is statically used by the \texttt{VkPipeline} bound to the pipeline bind point used by this command, a descriptor set must have been bound to \(n\) at the same pipeline bind point, with a \texttt{VkPipelineLayout} that is compatible for set \(n\), with the \texttt{VkPipelineLayout} used to create the current \texttt{VkPipeline}, as described in Pipeline Layout Compatibility

- For each push constant that is statically used by the \texttt{VkPipeline} bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a \texttt{VkPipelineLayout} that is compatible for push constants, with the \texttt{VkPipelineLayout} used to create the current \texttt{VkPipeline}, as described in Pipeline Layout Compatibility

- Descriptors in each bound descriptor set, specified via \texttt{vkCmdBindDescriptorSets}, must be valid if they are statically used by the \texttt{VkPipeline} bound to the pipeline bind point used by this command

- A valid pipeline must be bound to the pipeline bind point used by this command

- If the \texttt{VkPipeline} object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for \texttt{commandBuffer}, and done so after any previously bound pipeline with the corresponding state not specified as dynamic

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the \texttt{VkPipeline} object bound to the pipeline bind point used by this command, since that pipeline was bound

- If the \texttt{VkPipeline} object bound to the pipeline bind point used by this command accesses a \texttt{VkSampler} object that uses unnormalized coordinates, that sampler must not be used to sample from any \texttt{VkImage} with a \texttt{VkImageView} of the type \texttt{VK_IMAGE_VIEW_TYPE_3D}, \texttt{VK_IMAGE_VIEW_TYPE_CUBE}, \texttt{VK_IMAGE_VIEW_TYPE_1D_ARRAY}, \texttt{VK_IMAGE_VIEW_TYPE_2D_ARRAY} or \texttt{VK_IMAGE_VIEW_TYPE_CUBE_ARRAY}, in any shader stage

- If the \texttt{VkPipeline} object bound to the pipeline bind point used by this command accesses a \texttt{VkSampler} object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V \texttt{OpImageSample*} or \texttt{OpImageSparseSample*} instructions with \texttt{ImplicitLod}, \texttt{Dref} or \texttt{Proj} in their name, in any shader stage

- If the \texttt{VkPipeline} object bound to the pipeline bind point used by this command accesses a \texttt{VkSampler} object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V \texttt{OpImageSample*} or \texttt{OpImageSparseSample*} instructions that includes a LOD bias or any offset values, in any shader stage

- If the robust buffer access feature is not enabled, and if the \texttt{VkPipeline} object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• If commandBuffer is a protected command buffer, any resource written to by the VkPipeline object bound to the pipeline bind point used by this command must not be an unprotected resource.

• If commandBuffer is a protected command buffer, pipeline stages other than the framebuffer-space and compute stages in the VkPipeline object bound to the pipeline bind point must not write to any resource.

• groupCountX must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]

• groupCountY must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]

• groupCountZ must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2]

Valid Usage (Implicit)

• commandBuffer must be a valid VkCommandBuffer handle

• commandBuffer must be in the recording state

• The VkCommandPool that commandBuffer was allocated from must support compute operations

• This command must only be called outside of a render pass instance

Host Synchronization

• Host access to commandBuffer must be externally synchronized

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized
To record an indirect command dispatch, call:

```c
void vkCmdDispatchIndirect(
    VkCommandBuffer commandBuffer,
    VkBuffer       buffer,
    VkDeviceSize   offset);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `buffer` is the buffer containing dispatch parameters.
- `offset` is the byte offset into `buffer` where parameters begin.

`vkCmdDispatchIndirect` behaves similarly to `vkCmdDispatch` except that the parameters are read by the device from a buffer during execution. The parameters of the dispatch are encoded in a `VkDispatchIndirectCommand` structure taken from `buffer` starting at `offset`.

Valid Usage

- If a `VkImageView` is sampled with `VK_FILTER_LINEAR` as a result of this command, then the image view's `format features` must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`

- If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's `format features` must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`

- For each set \( n \) that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a descriptor set must have been bound to \( n \) at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set \( n \), with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility

- For each push constant that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility

- Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid if they are statically used by the `VkPipeline` bound to the pipeline bind point used by this command

- A valid pipeline must be bound to the pipeline bind point used by this command

- If the `VkPipeline` object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for `commandBuffer`, and done so after any previously bound pipeline with the corresponding state not specified as dynamic

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by this command, since that pipeline was bound

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used to sample from any `VkImage` with a `VkImageView` of the type `VK_IMAGE_VIEW_TYPE_3D`, `VK_IMAGE_VIEW_TYPE_CUBE`, `VK_IMAGE_VIEW_TYPE_1D_ARRAY`, `VK_IMAGE_VIEW_TYPE_2D_ARRAY` or `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY`, in any shader stage

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions with `ImplicitLod`, `Dref` or `Proj` in their name, in any shader stage

- If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions that includes a LOD bias or any offset values, in any shader stage

- If the robust buffer access feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

• buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.

• offset must be a multiple of 4.

• commandBuffer must not be a protected command buffer.

• The sum of offset and the size of VkDispatchIndirectCommand must be less than or equal to the size of buffer.

---

Valid Usage (Implicit)

• commandBuffer must be a valid VkCommandBuffer handle.

• buffer must be a valid VkBuffer handle.

• commandBuffer must be in the recording state.

• The VkCommandPool that commandBuffer was allocated from must support compute operations.

• This command must only be called outside of a render pass instance.

• Both of buffer, and commandBuffer must have been created, allocated, or retrieved from the same VkDevice.

---

Host Synchronization

• Host access to commandBuffer must be externally synchronized.

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized.

---

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td>Compute</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The `VkDispatchIndirectCommand` structure is defined as:

```c
typedef struct VkDispatchIndirectCommand {
    uint32_t    x;
    uint32_t    y;
    uint32_t    z;
} VkDispatchIndirectCommand;
```

- `x` is the number of local workgroups to dispatch in the X dimension.
- `y` is the number of local workgroups to dispatch in the Y dimension.
- `z` is the number of local workgroups to dispatch in the Z dimension.

The members of `VkDispatchIndirectCommand` have the same meaning as the corresponding parameters of `vkCmdDispatch`.

**Valid Usage**

- `x` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]`
- `y` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]`
- `z` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2]`

To record a dispatch using non-zero base values for the components of `WorkgroupId`, call:

```c
void vkCmdDispatchBase(
    VkCommandBuffer                             commandBuffer,
    uint32_t                                    baseGroupX,
    uint32_t                                    baseGroupY,
    uint32_t                                    baseGroupZ,
    uint32_t                                    groupCountX,
    uint32_t                                    groupCountY,
    uint32_t                                    groupCountZ);
```

or the equivalent command

```c
void vkCmdDispatchBaseKHR(
    VkCommandBuffer                             commandBuffer,
    uint32_t                                    baseGroupX,
    uint32_t                                    baseGroupY,
    uint32_t                                    baseGroupZ,
    uint32_t                                    groupCountX,
    uint32_t                                    groupCountY,
    uint32_t                                    groupCountZ);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
• `baseGroupX` is the start value for the X component of `WorkgroupId`.
• `baseGroupY` is the start value for the Y component of `WorkgroupId`.
• `baseGroupZ` is the start value for the Z component of `WorkgroupId`.
• `groupCountX` is the number of local workgroups to dispatch in the X dimension.
• `groupCountY` is the number of local workgroups to dispatch in the Y dimension.
• `groupCountZ` is the number of local workgroups to dispatch in the Z dimension.

When the command is executed, a global workgroup consisting of `groupCountX × groupCountY × groupCountZ` local workgroups is assembled, with `WorkgroupId` values ranging from `([baseGroup*, baseGroup* + groupCount*])` in each component. `vkCmdDispatch` is equivalent to `vkCmdDispatchBase(0,0,0,groupCountX,groupCountY,groupCountZ)`. 
Valid Usage

- If a VkImageView is sampled with VK_FILTER_LINEAR as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT.

- If a VkImageView is accessed using atomic operations as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT.

- For each set \( n \) that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a descriptor set must have been bound to \( n \) at the same pipeline bind point, with a VkPipelineLayout that is compatible for set \( n \), with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- For each push constant that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- Descriptors in each bound descriptor set, specified via vkCmdBindDescriptorSets, must be valid if they are statically used by the VkPipeline bound to the pipeline bind point used by this command.

- A valid pipeline must be bound to the pipeline bind point used by this command.

- If the VkPipeline object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for commandBuffer, and done so after any previously bound pipeline with the corresponding state not specified as dynamic.

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage.

- If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• baseGroupX must be less than VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]
• baseGroupY must be less than VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]
• baseGroupZ must be less than VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2]
• groupCountX must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0] minus baseGroupX
• groupCountY must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1] minus baseGroupY
• groupCountZ must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2] minus baseGroupZ

• If any of baseGroupX, baseGroupY, or baseGroupZ are not zero, then the bound compute pipeline must have been created with the VK_PIPELINE_CREATE_DISPATCH_BASE flag.

Valid Usage (Implicit)

• commandBuffer must be a valid VkCommandBuffer handle
• commandBuffer must be in the recording state
• The VkCommandPool that commandBuffer was allocated from must support compute operations
• This command must only be called outside of a render pass instance

Host Synchronization

• Host access to commandBuffer must be externally synchronized
• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

856 | Chapter 27. Dispatching Commands
Chapter 28. Sparse Resources

As documented in Resource Memory Association, VkBuffer and VkImage resources in Vulkan must be bound completely and contiguously to a single VkDeviceMemory object. This binding must be done before the resource is used, and the binding is immutable for the lifetime of the resource.

Sparse resources relax these restrictions and provide these additional features:

- Sparse resources can be bound non-contiguously to one or more VkDeviceMemory allocations.
- Sparse resources can be re-bound to different memory allocations over the lifetime of the resource.
- Sparse resources can have descriptors generated and used orthogonally with memory binding commands.

28.1. Sparse Resource Features

Sparse resources have several features that must be enabled explicitly at resource creation time. The features are enabled by including bits in the flags parameter of VkImageCreateInfo or VkBufferCreateInfo. Each feature also has one or more corresponding feature enables specified in VkPhysicalDeviceFeatures.

- Sparse binding is the base feature, and provides the following capabilities:
  - Resources can be bound at some defined (sparse block) granularity.
  - The entire resource must be bound to memory before use regardless of regions actually accessed.
  - No specific mapping of image region to memory offset is defined, i.e. the location that each texel corresponds to in memory is implementation-dependent.
  - Sparse buffers have a well-defined mapping of buffer range to memory range, where an offset into a range of the buffer that is bound to a single contiguous range of memory corresponds to an identical offset within that range of memory.
  - Requested via the VK_IMAGE_CREATE_SPARSE_BINDING_BIT and VK_BUFFER_CREATE_SPARSE_BINDING_BIT bits.
  - A sparse image created using VK_IMAGE_CREATE_SPARSE_BINDING_BIT (but not VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT) supports all formats that non-sparse usage supports, and supports both VK_IMAGE_TILING_OPTIMAL and VK_IMAGE_TILING_LINEAR tiling.

- Sparse Residency builds on (and requires) the sparseBinding feature. It includes the following capabilities:
  - Resources do not have to be completely bound to memory before use on the device.
  - Images have a prescribed sparse image block layout, allowing specific rectangular regions of the image to be bound to specific offsets in memory allocations.
  - Consistency of access to unbound regions of the resource is defined by the absence or presence of VkPhysicalDeviceSparseProperties::residencyNonResidentStrict. If this property is present, accesses to unbound regions of the resource are well defined and behave as if the
data bound is populated with all zeros; writes are discarded. When this property is absent, accesses are considered safe, but reads will return undefined values.

- Requested via the `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` and `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` bits.

- Sparse residency support is advertised on a finer grain via the following features:
  - `sparseResidencyBuffer`: Support for creating `VkBuffer` objects with the `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT`.
  - `sparseResidencyImage2D`: Support for creating 2D single-sampled `VkImage` objects with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  - `sparseResidencyImage3D`: Support for creating 3D `VkImage` objects with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  - `sparseResidency2Samples`: Support for creating 2D `VkImage` objects with 2 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  - `sparseResidency4Samples`: Support for creating 2D `VkImage` objects with 4 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  - `sparseResidency8Samples`: Support for creating 2D `VkImage` objects with 8 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
  - `sparseResidency16Samples`: Support for creating 2D `VkImage` objects with 16 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

Implementations supporting `sparseResidencyImage2D` are only required to support sparse 2D, single-sampled images. Support for sparse 3D and MSAA images is optional and can be enabled via `sparseResidencyImage3D`, `sparseResidency2Samples`, `sparseResidency4Samples`, `sparseResidency8Samples`, and `sparseResidency16Samples`.

- A sparse image created using `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` supports all non-compressed color formats with power-of-two element size that non-sparse usage supports. Additional formats may also be supported and can be queried via `vkGetPhysicalDeviceSparseImageFormatProperties`. `VK_IMAGE_TILING_LINEAR` tiling is not supported.

  - Sparse aliasing provides the following capability that can be enabled per resource:

    Allows physical memory ranges to be shared between multiple locations in the same sparse resource or between multiple sparse resources, with each binding of a memory location observing a consistent interpretation of the memory contents.

    See Sparse Memory Aliasing for more information.

## 28.2. Sparse Buffers and Fully-Resident Images

Both `VkBuffer` and `VkImage` objects created with the `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` or `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` bits can be thought of as a linear region of address space. In the `VkImage` case if `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` is not used, this linear region is entirely opaque, meaning that there is no application-visible mapping between texel location and memory.
offset.

Unless `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` or `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` are also used, the entire resource **must** be bound to one or more `VkDeviceMemory` objects before use.

### 28.2.1. Sparse Buffer and Fully-Resident Image Block Size

The sparse block size in bytes for sparse buffers and fully-resident images is reported as `VkMemoryRequirements::alignment.alignment`. `alignment` represents both the memory alignment requirement and the binding granularity (in bytes) for sparse resources.

### 28.3. Sparse Partially-Resident Buffers

`VkBuffer` objects created with the `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` bit allow the buffer to be made only partially resident. Partially resident `VkBuffer` objects are allocated and bound identically to `VkBuffer` objects using only the `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` feature. The only difference is the ability for some regions of the buffer to be unbound during device use.

### 28.4. Sparse Partially-Resident Images

`VkImage` objects created with the `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` bit allow specific rectangular regions of the image called sparse image blocks to be bound to specific ranges of memory. This allows the application to manage residency at either image subresource or sparse image block granularity. Each image subresource (outside of the **mip tail**) starts on a sparse block boundary and has dimensions that are integer multiples of the corresponding dimensions of the sparse image block.

**Note**

Applications **can** use these types of images to control LOD based on total memory consumption. If memory pressure becomes an issue the application **can** unbind and disable specific mipmap levels of images without having to recreate resources or modify texel data of unaffected levels.

The application **can** also use this functionality to access subregions of the image in a “megatexture” fashion. The application **can** create a large image and only populate the region of the image that is currently being used in the scene.

### 28.4.1. Accessing Unbound Regions

The following member of `VkPhysicalDeviceSparseProperties` affects how data in unbound regions of sparse resources are handled by the implementation:

- `residencyNonResidentStrict`

If this property is not present, reads of unbound regions of the image will return undefined values. Both reads and writes are still considered **safe** and will not affect other resources or populated regions of the image.

---

Chapter 28. Sparse Resources | 859
If this property is present, all reads of unbound regions of the image will behave as if the region was bound to memory populated with all zeros; writes will be discarded.

Formatted accesses to unbound memory may still alter some component values in the natural way for those accesses, e.g. substituting a value of one for alpha in formats that do not have an alpha component.

Example: Reading the alpha component of an unbacked VK_FORMAT_R8_UNORM image will return a value of 1.0f.

See Physical Device Enumeration for instructions for retrieving physical device properties.

Implementor’s Note

For implementations that cannot natively handle access to unbound regions of a resource, the implementation may allocate and bind memory to the unbound regions. Reads and writes to unbound regions will access the implementation-managed memory instead.

Given that the values resulting from reads of unbound regions are undefined in this scenario, implementations may use the same physical memory for all unbound regions of multiple resources within the same process.

28.4.2. Mip Tail Regions

Sparse images created using VK_IMAGE_CREATE_SPARSE_BINDING_BIT (without also using VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT) have no specific mapping of image region or image subresource to memory offset defined, so the entire image can be thought of as a linear opaque address region. However, images created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT do have a prescribed sparse image block layout, and hence each image subresource must start on a sparse block boundary. Within each array layer, the set of mip levels that have a smaller size than the sparse block size in bytes are grouped together into a mip tail region.

If the VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT flag is present in the flags member of VkSparseImageFormatProperties, for the image's format, then any mip level which has dimensions that are not integer multiples of the corresponding dimensions of the sparse image block, and all subsequent mip levels, are also included in the mip tail region.

The following member of VkPhysicalDeviceSparseProperties may affect how the implementation places mip levels in the mip tail region:

- residencyAlignedMipSize

Each mip tail region is bound to memory as an opaque region (i.e. must be bound using a VkSparseImageOpaqueMemoryBindInfo structure) and may be of a size greater than or equal to the sparse block size in bytes. This size is guaranteed to be an integer multiple of the sparse block size in bytes.

An implementation may choose to allow each array-layer's mip tail region to be bound to memory.
independently or require that all array-layer's mip tail regions be treated as one. This is dictated by
VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT in VkSparseImageMemoryRequirements::flags.

The following diagrams depict how VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT and
VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT alter memory usage and requirements.

![Sparse Image Diagram](image)

Figure 16. Sparse Image

In the absence of VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT and
VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT, each array layer contains a mip tail region containing
texel data for all mip levels smaller than the sparse image block in any dimension.

Mip levels that are as large or larger than a sparse image block in all dimensions can be bound
individually. Right-edges and bottom-edges of each level are allowed to have partially used sparse
blocks. Any bound partially-used-sparse-blocks must still have their full sparse block size in bytes
allocated in memory.
When `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` is present all array layers will share a single mip tail region.

*Note*

The mip tail regions are presented here in 2D arrays simply for figure size reasons. Each mip tail is logically a single array of sparse blocks with an implementation-dependent mapping of texels or compressed texel blocks to sparse blocks.
When `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` is present the first mip level that would contain partially used sparse blocks begins the mip tail region. This level and all subsequent levels are placed in the mip tail. Only the first \( N \) mip levels whose dimensions are an exact multiple of the sparse image block dimensions can be bound and unbound on a sparse block basis.

![Figure 19. Sparse Image with Aligned Mip Size and Single Mip Tail](image.png)

*Note*

The mip tail region is presented here in a 2D array simply for figure size reasons. It is logically a single array of sparse blocks with an implementation-dependent mapping of texels or compressed texel blocks to sparse blocks.

When both `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` and `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` are present the constraints from each of these flags are in effect.

### 28.4.3. Standard Sparse Image Block Shapes

Standard sparse image block shapes define a standard set of dimensions for sparse image blocks that depend on the format of the image. Layout of texels or compressed texel blocks within a sparse image block is implementation dependent. All currently defined standard sparse image block shapes are 64 KB in size.

For block-compressed formats (e.g. `VK_FORMAT_BC5_UNORM_BLOCK`), the texel size is the size of the compressed texel block (e.g. 128-bit for BC5) thus the dimensions of the standard sparse image block shapes apply in terms of compressed texel blocks.
For block-compressed formats, the dimensions of a sparse image block in terms of texels can be calculated by multiplying the sparse image block dimensions by the compressed texel block dimensions.
Table 31. Standard Sparse Image Block Shapes (Single Sample)

<table>
<thead>
<tr>
<th>TEXEL SIZE (bits)</th>
<th>Block Shape (2D)</th>
<th>Block Shape (3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-Bit</td>
<td>256 × 256 × 1</td>
<td>64 × 32 × 32</td>
</tr>
<tr>
<td>16-Bit</td>
<td>256 × 128 × 1</td>
<td>32 × 32 × 32</td>
</tr>
<tr>
<td>32-Bit</td>
<td>128 × 128 × 1</td>
<td>32 × 32 × 16</td>
</tr>
<tr>
<td>64-Bit</td>
<td>128 × 64 × 1</td>
<td>32 × 16 × 16</td>
</tr>
<tr>
<td>128-Bit</td>
<td>64 × 64 × 1</td>
<td>16 × 16 × 16</td>
</tr>
</tbody>
</table>

Table 32. Standard Sparse Image Block Shapes (MSAA)

<table>
<thead>
<tr>
<th>TEXEL SIZE (bits)</th>
<th>Block Shape (2X)</th>
<th>Block Shape (4X)</th>
<th>Block Shape (8X)</th>
<th>Block Shape (16X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-Bit</td>
<td>128 × 256 × 1</td>
<td>128 × 128 × 1</td>
<td>64 × 128 × 1</td>
<td>64 × 64 × 1</td>
</tr>
<tr>
<td>16-Bit</td>
<td>128 × 128 × 1</td>
<td>128 × 64 × 1</td>
<td>64 × 64 × 1</td>
<td>64 × 32 × 1</td>
</tr>
<tr>
<td>32-Bit</td>
<td>64 × 128 × 1</td>
<td>64 × 64 × 1</td>
<td>32 × 64 × 1</td>
<td>32 × 32 × 1</td>
</tr>
<tr>
<td>64-Bit</td>
<td>64 × 64 × 1</td>
<td>64 × 32 × 1</td>
<td>32 × 32 × 1</td>
<td>32 × 16 × 1</td>
</tr>
<tr>
<td>128-Bit</td>
<td>32 × 64 × 1</td>
<td>32 × 32 × 1</td>
<td>16 × 32 × 1</td>
<td>16 × 16 × 1</td>
</tr>
</tbody>
</table>

Implementations that support the standard sparse image block shape for all formats listed in the Standard Sparse Image Block Shapes (Single Sample) and Standard Sparse Image Block Shapes (MSAA) tables may advertise the following VkPhysicalDeviceSparseProperties:

- residencyStandard2DBlockShape
- residencyStandard2DMultisampleBlockShape
- residencyStandard3DBlockShape

Reporting each of these features does not imply that all possible image types are supported as sparse. Instead, this indicates that no supported sparse image of the corresponding type will use custom sparse image block dimensions for any formats that have a corresponding standard sparse image block shape.

### 28.4.4. Custom Sparse Image Block Shapes

An implementation that does not support a standard image block shape for a particular sparse partially-resident image may choose to support a custom sparse image block shape for it instead. The dimensions of such a custom sparse image block shape are reported in VkSparseImageFormatProperties::imageGranularity. As with standard sparse image block shapes, the size in bytes of the custom sparse image block shape will be reported in VkMemoryRequirements::alignment.

Custom sparse image block dimensions are reported through vkGetPhysicalDeviceSparseImageFormatProperties and vkGetImageSparseMemoryRequirements.

An implementation must not support both the standard sparse image block shape and a custom sparse image block shape for the same image. The standard sparse image block shape must be used if it is supported.
28.4.5. Multiple Aspects

Partially resident images are allowed to report separate sparse properties for different aspects of the image. One example is for depth/stencil images where the implementation separates the depth and stencil data into separate planes. Another reason for multiple aspects is to allow the application to manage memory allocation for implementation-private metadata associated with the image. See the figure below:

![Multiple Aspect Sparse Image](image)

*Figure 20. Multiple Aspect Sparse Image*

**Note**

The mip tail regions are presented here in 2D arrays simply for figure size reasons. Each mip tail is logically a single array of sparse blocks with an implementation-dependent mapping of texels or compressed texel blocks to sparse blocks.

In the figure above the depth, stencil, and metadata aspects all have unique sparse properties. The per-texel stencil data is \( \frac{1}{4} \) the size of the depth data, hence the stencil sparse blocks include \( 4 \times \) the number of texels. The sparse block size in bytes for all of the aspects is identical and defined by `VkMemoryRequirements.alignment`.

**Metadata**

The metadata aspect of an image has the following constraints:

- All metadata is reported in the mip tail region of the metadata aspect.
- All metadata **must** be bound prior to device use of the sparse image.
28.5. Sparse Memory Aliasing

By default sparse resources have the same aliasing rules as non-sparse resources. See Memory Aliasing for more information.

VkDevice objects that have the sparseResidencyAliased feature enabled are able to use the VK_BUFFER_CREATE_SPARSE_ALIASED_BIT and VK_IMAGE_CREATE_SPARSE_ALIASED_BIT flags for resource creation. These flags allow resources to access physical memory bound into multiple locations within one or more sparse resources in a data consistent fashion. This means that reading physical memory from multiple aliased locations will return the same value.

Care must be taken when performing a write operation to aliased physical memory. Memory dependencies must be used to separate writes to one alias from reads or writes to another alias. Writes to aliased memory that are not properly guarded against accesses to different aliases will have undefined results for all accesses to the aliased memory.

Applications that wish to make use of data consistent sparse memory aliasing must abide by the following guidelines:

- All sparse resources that are bound to aliased physical memory must be created with the VK_BUFFER_CREATE_SPARSE_ALIASED_BIT / VK_IMAGE_CREATE_SPARSE_ALIASED_BIT flag.

- All resources that access aliased physical memory must interpret the memory in the same way. This implies the following:
  - Buffers and images cannot alias the same physical memory in a data consistent fashion. The physical memory ranges must be used exclusively by buffers or used exclusively by images for data consistency to be guaranteed.
  - Memory in sparse image mip tail regions cannot access aliased memory in a data consistent fashion.
  - Sparse images that alias the same physical memory must have compatible formats and be using the same sparse image block shape in order to access aliased memory in a data consistent fashion.

Failure to follow any of the above guidelines will require the application to abide by the normal, non-sparse resource aliasing rules. In this case memory cannot be accessed in a data consistent fashion.

Note

Enabling sparse resource memory aliasing can be a way to lower physical memory use, but it may reduce performance on some implementations. An application developer can test on their target HW and balance the memory / performance trade-offs measured.

This section is Informative. It is included to aid in implementors’ understanding of sparse resources.

Device Virtual Address

The basic `sparseBinding` feature allows the resource to reserve its own device virtual address range at resource creation time rather than relying on a bind operation to set this. Without any other creation flags, no other constraints are relaxed compared to normal resources. All pages **must** be bound to physical memory before the device accesses the resource.

The `sparse residency` features allow sparse resources to be used even when not all pages are bound to memory. Implementations that support access to unbound pages without causing a fault **may** support `residencyNonResidentStrict`.

Not faulting on access to unbound pages is not enough to support `residencyNonResidentStrict`. An implementation **must** also guarantee that reads after writes to unbound regions of the resource always return data for the read as if the memory contains zeros. Depending on any caching hierarchy of the implementation this **may** not always be possible.

Any implementation that does not fault, but does not guarantee correct read values **must** not support `residencyNonResidentStrict`.

Any implementation that **cannot** access unbound pages without causing a fault will require the implementation to bind the entire device virtual address range to physical memory. Any pages that the application does not bind to memory **may** be bound to one (or more) “dummy” physical page(s) allocated by the implementation. Given the following properties:

- A process **must** not access memory from another process
- Reads return undefined values

It is sufficient for each host process to allocate these dummy pages and use them for all resources in that process. Implementations **may** allocate more often (per instance, per device, or per resource).

Binding Memory

The byte size reported in `VkMemoryRequirements::size` **must** be greater than or equal to the amount of physical memory **required** to fully populate the resource. Some implementations require “holes” in the device virtual address range that are never accessed. These holes **may** be included in the `size` reported for the resource.

Including or not including the device virtual address holes in the resource size will alter how the implementation provides support for `VkSparseImageOpaqueMemoryBindInfo`. This operation **must** be supported for all sparse images, even ones created with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.

- If the holes are included in the size, this bind function becomes very easy. In most cases the `resourceOffset` is simply a device virtual address offset and the implementation can easily determine what device virtual address to bind. The cost is that the application **may** allocate more physical memory for the resource than it needs.
• If the holes are not included in the size, the application can allocate less physical memory than otherwise for the resource. However, in this case the implementation must account for the holes when mapping resourceOffset to the actual device virtual address intended to be mapped.

Note

If the application always uses VkSparseImageMemoryBindInfo to bind memory for the non-tail mip levels, any holes that are present in the resource size may never be bound.

Since VkSparseImageMemoryBindInfo uses texel locations to determine which device virtual addresses to bind, it is impossible to bind device virtual address holes with this operation.

Binding Metadata Memory

All metadata for sparse images have their own sparse properties and are embedded in the mip tail region for said properties. See the Multiaspect section for details.

Given that metadata is in a mip tail region, and the mip tail region must be reported as contiguous (either globally or per-array-layer), some implementations will have to resort to complicated offset → device virtual address mapping for handling VkSparseImageOpaqueMemoryBindInfo.

To make this easier on the implementation, the VK_SPARSE_MEMORY_BIND_METADATA_BIT explicitly specifies when metadata is bound with VkSparseImageOpaqueMemoryBindInfo. When this flag is not present, the resourceOffset may be treated as a strict device virtual address offset.

When VK_SPARSE_MEMORY_BIND_METADATA_BIT is present, the resourceOffset must have been derived explicitly from the imageMipTailOffset in the sparse resource properties returned for the metadata aspect. By manipulating the value returned for imageMipTailOffset, the resourceOffset does not have to correlate directly to a device virtual address offset, and may instead be whatever values makes it easiest for the implementation to derive the correct device virtual address.

28.7. Sparse Resource API

The APIs related to sparse resources are grouped into the following categories:

• Physical Device Features
• Physical Device Sparse Properties
• Sparse Image Format Properties
• Sparse Resource Creation
• Sparse Resource Memory Requirements
• Binding Resource Memory
28.7.1. Physical Device Features

Some sparse-resource related features are reported and enabled in `VkPhysicalDeviceFeatures`. These features **must** be supported and enabled on the `VkDevice` object before applications **can** use them. See **Physical Device Features** for information on how to get and set enabled device features, and for more detailed explanations of these features.

**Sparse Physical Device Features**

- **sparseBinding**: Support for creating `VkBuffer` and `VkImage` objects with the `VK_BUFFER_CREATE_SPARSE_BINDING_BIT` and `VK_IMAGE_CREATE_SPARSE_BINDING_BIT` flags, respectively.
- **sparseResidencyBuffer**: Support for creating `VkBuffer` objects with the `VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT` flag.
- **sparseResidencyImage2D**: Support for creating 2D single-sampled `VkImage` objects with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
- **sparseResidencyImage3D**: Support for creating 3D `VkImage` objects with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
- **sparseResidency2Samples**: Support for creating 2D `VkImage` objects with 2 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
- **sparseResidency4Samples**: Support for creating 2D `VkImage` objects with 4 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
- **sparseResidency8Samples**: Support for creating 2D `VkImage` objects with 8 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
- **sparseResidency16Samples**: Support for creating 2D `VkImage` objects with 16 samples and `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`.
- **sparseResidencyAliased**: Support for creating `VkBuffer` and `VkImage` objects with the `VK_BUFFER_CREATE_SPARSE_ALIASED_BIT` and `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT` flags, respectively.

28.7.2. Physical Device Sparse Properties

Some features of the implementation are not possible to disable, and are reported to allow applications to alter their sparse resource usage accordingly. These read-only capabilities are reported in the `VkPhysicalDeviceProperties::sparseProperties` member, which is a structure of type `VkPhysicalDeviceSparseProperties`.

The `VkPhysicalDeviceSparseProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceSparseProperties {
    VkBool32    residencyStandard2DBlockShape;
    VkBool32    residencyStandard2DMultisampleBlockShape;
    VkBool32    residencyStandard3DBlockShape;
    VkBool32    residencyAlignedMipSize;
    VkBool32    residencyNonResidentStrict;
} VkPhysicalDeviceSparseProperties;
```
• `residencyStandard2DBlockShape` is `VK_TRUE` if the physical device will access all single-sample 2D sparse resources using the standard sparse image block shapes (based on image format), as described in the Standard Sparse Image Block Shapes (Single Sample) table. If this property is not supported the value returned in the `imageGranularity` member of the `VkSparseImageFormatProperties` structure for single-sample 2D images is not required to match the standard sparse image block dimensions listed in the table.

• `residencyStandard2DMultisampleBlockShape` is `VK_TRUE` if the physical device will access all multisample 2D sparse resources using the standard sparse image block shapes (based on image format), as described in the Standard Sparse Image Block Shapes (MSAA) table. If this property is not supported, the value returned in the `imageGranularity` member of the `VkSparseImageFormatProperties` structure for multisample 2D images is not required to match the standard sparse image block dimensions listed in the table.

• `residencyStandard3DBlockShape` is `VK_TRUE` if the physical device will access all 3D sparse resources using the standard sparse image block shapes (based on image format), as described in the Standard Sparse Image Block Shapes (Single Sample) table. If this property is not supported, the value returned in the `imageGranularity` member of the `VkSparseImageFormatProperties` structure for 3D images is not required to match the standard sparse image block dimensions listed in the table.

• `residencyAlignedMipSize` is `VK_TRUE` if images with mip level dimensions that are not integer multiples of the corresponding dimensions of the sparse image block may be placed in the mip tail. If this property is not reported, only mip levels with dimensions smaller than the `imageGranularity` member of the `VkSparseImageFormatProperties` structure will be placed in the mip tail. If this property is reported the implementation is allowed to return `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` in the `flags` member of `VkSparseImageFormatProperties`, indicating that mip level dimensions that are not integer multiples of the corresponding dimensions of the sparse image block will be placed in the mip tail.

• `residencyNonResidentStrict` specifies whether the physical device can consistently access non-resident regions of a resource. If this property is `VK_TRUE`, access to non-resident regions of resources will be guaranteed to return values as if the resource were populated with 0; writes to non-resident regions will be discarded.

28.7.3. Sparse Image Format Properties

Given that certain aspects of sparse image support, including the sparse image block dimensions, may be implementation-dependent, `vkGetPhysicalDeviceSparseImageFormatProperties` can be used to query for sparse image format properties prior to resource creation. This command is used to check whether a given set of sparse image parameters is supported and what the sparse image block shape will be.

Sparse Image Format Properties API

The `VkSparseImageFormatProperties` structure is defined as:
typedef struct VkSparseImageFormatProperties {
    VkImageAspectFlags aspectMask;
    VkExtent3D imageGranularity;
    VkSparseImageFormatFlags flags;
} VkSparseImageFormatProperties;

- **aspectMask** is a bitmask `VkImageAspectFlagBits` specifying which aspects of the image the properties apply to.
- **imageGranularity** is the width, height, and depth of the sparse image block in texels or compressed texel blocks.
- **flags** is a bitmask of `VkSparseImageFormatFlagBits` specifying additional information about the sparse resource.

Bits which **may** be set in `VkSparseImageFormatProperties::flags`, specifying additional information about the sparse resource, are:

typedef enum VkSparseImageFormatFlagBits {
    VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT = 0x00000001,
    VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT = 0x00000002,
    VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT = 0x00000004,
    VK_SPARSE_IMAGE_FORMAT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSparseImageFormatFlagBits;

- **VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT** specifies that the image uses a single mip tail region for all array layers.
- **VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT** specifies that the first mip level whose dimensions are not integer multiples of the corresponding dimensions of the sparse image block begins the mip tail region.
- **VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT** specifies that the image uses non-standard sparse image block dimensions, and the `imageGranularity` values do not match the standard sparse image block dimensions for the given format.

typedef VkFlags VkSparseImageFormatFlags;

`VkSparseImageFormatFlags` is a bitmask type for setting a mask of zero or more `VkSparseImageFormatFlagBits`.

`vkGetPhysicalDeviceSparseImageFormatProperties` returns an array of `VkSparseImageFormatProperties`. Each element will describe properties for one set of image aspects that are bound simultaneously in the image. This is usually one element for each aspect in the image, but for interleaved depth/stencil images there is only one element describing the combined aspects.
void vkGetPhysicalDeviceSparseImageFormatProperties(
    VkPhysicalDevice                            physicalDevice,
    VkFormat                                    format,
    VkImageType                                 type,
    VkSampleCountFlagBits                       samples,
    VkImageUsageFlags                           usage,
    VkImageTiling                               tiling,
    uint32_t*                                   pPropertyCount,
    VkSparseImageFormatProperties*              pProperties);

- **physicalDevice** is the physical device from which to query the sparse image capabilities.
- **format** is the image format.
- **type** is the dimensionality of image.
- **samples** is the number of samples per texel as defined in VkSampleCountFlagBits.
- **usage** is a bitmask describing the intended usage of the image.
- **tiling** is the tiling arrangement of the texel blocks in memory.
- **pPropertyCount** is a pointer to an integer related to the number of sparse format properties available or queried, as described below.
- **pProperties** is either NULL or a pointer to an array of VkSparseImageFormatProperties structures.

If pProperties is NULL, then the number of sparse format properties available is returned in pPropertyCount. Otherwise, pPropertyCount must point to a variable set by the user to the number of elements in the pProperties array, and on return the variable is overwritten with the number of structures actually written to pProperties. If pPropertyCount is less than the number of sparse format properties available, at most pPropertyCount structures will be written.

If VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT is not supported for the given arguments, pPropertyCount will be set to zero upon return, and no data will be written to pProperties.

Multiple aspects are returned for depth/stencil images that are implemented as separate planes by the implementation. The depth and stencil data planes each have unique VkSparseImageFormatProperties data.

Depth/stencil images with depth and stencil data interleaved into a single plane will return a single VkSparseImageFormatProperties structure with the aspectMask set to VK_IMAGE_ASPECT_DEPTH_BIT | VK_IMAGE_ASPECT_STENCIL_BIT.

### Valid Usage

- **samples** must be a bit value that is set in VkImageFormatProperties::sampleCounts returned by vkGetPhysicalDeviceImageFormatProperties with format, type, tiling, and usage equal to those in this command and flags equal to the value that is set in VkImageCreateInfo::flags when the image is created.
Valid Usage (Implicit)

- **physicalDevice** must be a valid `VkPhysicalDevice` handle
- **format** must be a valid `VkFormat` value
- **type** must be a valid `VkImageType` value
- **samples** must be a valid `VkSampleCountFlagBits` value
- **usage** must be a valid combination of `VkImageUsageFlagBits` values
- **usage** must not be 0
- **tiling** must be a valid `VkImageTiling` value
- **pPropertyCount** must be a valid pointer to a `uint32_t` value
  - If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not NULL, **pProperties** must be a valid pointer to an array of `VkSparseImageFormatProperties` structures

`vkGetPhysicalDeviceSparseImageFormatProperties2` returns an array of `VkSparseImageFormatProperties2`. Each element will describe properties for one set of image aspects that are bound simultaneously in the image. This is usually one element for each aspect in the image, but for interleaved depth/stencil images there is only one element describing the combined aspects.

```c
void vkGetPhysicalDeviceSparseImageFormatProperties2(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceSparseImageFormatInfo2* pFormatInfo,
    uint32_t* pPropertyCount,
    VkSparseImageFormatProperties2* pProperties);
```

or the equivalent command

```c
void vkGetPhysicalDeviceSparseImageFormatProperties2KHR(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceSparseImageFormatInfo2* pFormatInfo,
    uint32_t* pPropertyCount,
    VkSparseImageFormatProperties2* pProperties);
```

- **physicalDevice** is the physical device from which to query the sparse image capabilities.
- **pFormatInfo** is a pointer to a `VkPhysicalDeviceSparseImageFormatInfo2` structure containing input parameters to the command.
- **pPropertyCount** is a pointer to an integer related to the number of sparse format properties available or queried, as described below.
- **pProperties** is either NULL or a pointer to an array of `VkSparseImageFormatProperties2` structures.
vkGetPhysicalDeviceSparseImageFormatProperties2 behaves identically to vkGetPhysicalDeviceSparseImageFormatProperties, with the ability to return extended information by adding extension structures to the pNext chain of its pProperties parameter.

### Valid Usage (Implicit)

- **physicalDevice** must be a valid VkPhysicalDevice handle
- **pFormatInfo** must be a valid pointer to a valid VkPhysicalDeviceSparseImageFormatInfo2 structure
- **pPropertyCount** must be a valid pointer to a uint32_t value
- If the value referenced by pPropertyCount is not 0, and pProperties is not NULL, pProperties must be a valid pointer to an array of pPropertyCount VkSparseImageFormatProperties2 structures

The VkPhysicalDeviceSparseImageFormatInfo2 structure is defined as:

```c
typedef struct VkPhysicalDeviceSparseImageFormatInfo2 {
    VkStructureType          sType;
    const void*              pNext;
    VkFormat                 format;
    VkImageType              type;
    VkSampleCountFlagBits    samples;
    VkImageUsageFlags        usage;
    VkImageTiling            tiling;
} VkPhysicalDeviceSparseImageFormatInfo2;
```

or the equivalent

```c
typedef VkPhysicalDeviceSparseImageFormatInfo2
    VkPhysicalDeviceSparseImageFormatInfo2KHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **format** is the image format.
- **type** is the dimensionality of image.
- **samples** is the number of samples per texel as defined in VkSampleCountFlagBits.
- **usage** is a bitmask describing the intended usage of the image.
- **tiling** is the tiling arrangement of the texel blocks in memory.
Valid Usage

- samples must be a bit value that is set in VkImageFormatProperties::sampleCounts returned by vkGetPhysicalDeviceImageFormatProperties with format, type, tiling, and usage equal to those in this command and flags equal to the value that is set in VkImageCreateInfo::flags when the image is created.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SPARSE_IMAGE_FORMAT_INFO_2
- pNext must be NULL
- format must be a valid VkFormat value
- type must be a valid VkImageType value
- samples must be a valid VkSampleCountFlagBits value
- usage must be a valid combination of VkImageUsageFlagBits values
- usage must not be 0
- tiling must be a valid VkImageTiling value

The VkSparseImageFormatProperties2 structure is defined as:

```c
typedef struct VkSparseImageFormatProperties2 {
    VkStructureType sType;
    void* pNext;
    VkSparseImageFormatProperties properties;
} VkSparseImageFormatProperties2;
```

or the equivalent

```c
typedef VkSparseImageFormatProperties2 VkSparseImageFormatProperties2KHR;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- properties is a VkSparseImageFormatProperties structure which is populated with the same values as in vkGetPhysicalDeviceSparseImageFormatProperties.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_SPARSE_IMAGE_FORMAT_PROPERTIES_2
- pNext must be NULL
28.7.4. Sparse Resource Creation

Sparse resources require that one or more sparse feature flags be specified (as part of the VkPhysicalDeviceFeatures structure described previously in the Physical Device Features section) at CreateDevice time. When the appropriate device features are enabled, the VK_BUFFER_CREATE_SPARSE_* and VK_IMAGE_CREATE_SPARSE_* flags can be used. See vkCreateBuffer and vkCreateImage for details of the resource creation APIs.

Note
Specifying VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT or VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT requires specifying VK_BUFFER_CREATE_SPARSE_BINDING_BIT or VK_IMAGE_CREATE_SPARSE_BINDING_BIT, respectively, as well. This means that resources must be created with the appropriate *_SPARSE_BINDING_BIT to be used with the sparse binding command (vkQueueBindSparse).

28.7.5. Sparse Resource Memory Requirements

Sparse resources have specific memory requirements related to binding sparse memory. These memory requirements are reported differently for VkBuffer objects and VkImage objects.

Buffer and Fully-Resident Images

Buffers (both fully and partially resident) and fully-resident images can be bound to memory using only the data from VkMemoryRequirements. For all sparse resources the VkMemoryRequirements::alignment member specifies both the bindable sparse block size in bytes and required alignment of VkDeviceMemory.

Partially Resident Images

Partially resident images have a different method for binding memory. As with buffers and fully resident images, the VkMemoryRequirements::alignment field specifies the bindable sparse block size in bytes for the image.

Requesting sparse memory requirements for VkImage objects using vkGetImageSparseMemoryRequirements will return an array of one or more VkSparseImageMemoryRequirements structures. Each structure describes the sparse memory requirements for a group of aspects of the image.

The sparse image must have been created using the VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT flag to retrieve valid sparse image memory requirements.

Sparse Image Memory Requirements

The VkSparseImageMemoryRequirements structure is defined as:
typedef struct VkSparseImageMemoryRequirements {
    VkSparseImageFormatProperties formatProperties;
    uint32_t imageMipTailFirstLod;
    VkDeviceSize imageMipTailSize;
    VkDeviceSize imageMipTailOffset;
    VkDeviceSize imageMipTailStride;
} VkSparseImageMemoryRequirements;

- `formatProperties.aspectMask` is the set of aspects of the image that this sparse memory requirement applies to. This will usually have a single aspect specified. However, depth/stencil images may have depth and stencil data interleaved in the same sparse block, in which case both `VK_IMAGE_ASPECT_DEPTH_BIT` and `VK_IMAGE_ASPECT_STENCIL_BIT` would be present.

- `formatProperties.imageGranularity` describes the dimensions of a single bindable sparse image block in texel units. For aspect `VK_IMAGE_ASPECT_METADATA_BIT`, all dimensions will be zero. All metadata is located in the mip tail region.

- `formatProperties.flags` is a bitmask of `VkSparseImageFormatFlagBits`:
  - If `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` is set the image uses a single mip tail region for all array layers.
  - If `VK_SPARSE_IMAGE_FORMAT_ALIGNED_MIP_SIZE_BIT` is set the dimensions of mip levels must be integer multiples of the corresponding dimensions of the sparse image block for levels not located in the mip tail.
  - If `VK_SPARSE_IMAGE_FORMAT_NONSTANDARD_BLOCK_SIZE_BIT` is set the image uses non-standard sparse image block dimensions. The `formatProperties.imageGranularity` values do not match the standard sparse image block dimension corresponding to the image's format.

- `imageMipTailFirstLod` is the first mip level at which image subresources are included in the mip tail region.

- `imageMipTailSize` is the memory size (in bytes) of the mip tail region. If `formatProperties.flags` contains `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT`, this is the size of the whole mip tail, otherwise this is the size of the mip tail of a single array layer. This value is guaranteed to be a multiple of the sparse block size in bytes.

- `imageMipTailOffset` is the opaque memory offset used with `VkSparseImageOpaqueMemoryBindInfo` to bind the mip tail region(s).

- `imageMipTailStride` is the offset stride between each array-layer's mip tail, if `formatProperties.flags` does not contain `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` (otherwise the value is undefined).

To query sparse memory requirements for an image, call:

```c
void vkGetImageSparseMemoryRequirements(
    VkDevice device,  // The device to query.
    VkImage image,    // The image to query.
    uint32_t* pSparseMemoryRequirementCount,  // Pointer to count of memory requirements.
    VkSparseImageMemoryRequirements* pSparseMemoryRequirements);  // Pointer to memory requirements.
```
• **device** is the logical device that owns the image.

• **image** is the **VkImage** object to get the memory requirements for.

• **pSparseMemoryRequirementCount** is a pointer to an integer related to the number of sparse memory requirements available or queried, as described below.

• **pSparseMemoryRequirements** is either **NULL** or a pointer to an array of **VkSparseImageMemoryRequirements** structures.

If **pSparseMemoryRequirements** is **NULL**, then the number of sparse memory requirements available is returned in **pSparseMemoryRequirementCount**. Otherwise, **pSparseMemoryRequirementCount** must point to a variable set by the user to the number of elements in the **pSparseMemoryRequirements** array, and on return the variable is overwritten with the number of structures actually written to **pSparseMemoryRequirements**. If **pSparseMemoryRequirementCount** is less than the number of sparse memory requirements available, at most **pSparseMemoryRequirementCount** structures will be written.

If the image was not created with **VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT** then **pSparseMemoryRequirementCount** will be set to zero and **pSparseMemoryRequirements** will not be written to.

**Note**

It is legal for an implementation to report a larger value in **VkMemoryRequirements::size** than would be obtained by adding together memory sizes for all **VkSparseImageMemoryRequirements** returned by **vkGetImageSparseMemoryRequirements**. This may occur when the implementation requires unused padding in the address range describing the resource.

---

**Valid Usage (Implicit)**

• **device** **must** be a valid **VkDevice** handle

• **image** **must** be a valid **VkImage** handle

• **pSparseMemoryRequirementCount** **must** be a valid pointer to a **uint32_t** value

• If the value referenced by **pSparseMemoryRequirementCount** is not **0**, and **pSparseMemoryRequirements** is not **NULL**, **pSparseMemoryRequirements** **must** be a valid pointer to an array of **pSparseMemoryRequirementCount** **VkSparseImageMemoryRequirements** structures

• **image** **must** have been created, allocated, or retrieved from **device**

To query sparse memory requirements for an image, call:

```c
void vkGetImageSparseMemoryRequirements2(
    VkDevice                                    device,  
    const VkImageSparseMemoryRequirementsInfo2* pInfo,  
    uint32_t*                                   pSparseMemoryRequirementCount,  
    VkSparseImageMemoryRequirements2*           pSparseMemoryRequirements);
```
or the equivalent command

```c
void vkGetImageSparseMemoryRequirements2KHR(
    VkDevice                                    device,
    const VkImageSparseMemoryRequirementsInfo2* pInfo,
    uint32_t*                                   pSparseMemoryRequirementCount,
    VkSparseImageMemoryRequirements2*           pSparseMemoryRequirements);
```

- `device` is the logical device that owns the image.
- `pInfo` is a pointer to a `VkImageSparseMemoryRequirementsInfo2` structure containing parameters required for the memory requirements query.
- `pSparseMemoryRequirementCount` is a pointer to an integer related to the number of sparse memory requirements available or queried, as described below.
- `pSparseMemoryRequirements` is either `NULL` or a pointer to an array of `VkSparseImageMemoryRequirements2` structures.

### Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle.
- `pInfo` **must** be a valid pointer to a valid `VkImageSparseMemoryRequirementsInfo2` structure.
- `pSparseMemoryRequirementCount` **must** be a valid pointer to a uint32_t value.
- If the value referenced by `pSparseMemoryRequirementCount` is not 0, and `pSparseMemoryRequirements` is not NULL, `pSparseMemoryRequirements` **must** be a valid pointer to an array of `VkSparseImageMemoryRequirements2` structures.

The `VkImageSparseMemoryRequirementsInfo2` structure is defined as:

```c
typedef struct VkImageSparseMemoryRequirementsInfo2 {
    VkStructureType        sType;
    const void*            pNext;
    VkImage                image;
} VkImageSparseMemoryRequirementsInfo2;
```

or the equivalent

```c
typedef VkImageSparseMemoryRequirementsInfo2 VkImageSparseMemoryRequirementsInfo2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `image` is the image to query.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2`
- **pNext** must be `NULL`
- **image** must be a valid `VkImage` handle

The `VkSparseImageMemoryRequirements2` structure is defined as:

```c
typedef struct VkSparseImageMemoryRequirements2 {
    VkStructureType                    sType;
    void*                              pNext;
    VkSparseImageMemoryRequirements    memoryRequirements;
} VkSparseImageMemoryRequirements2;
```

or the equivalent

```c
typedef VkSparseImageMemoryRequirements2 VkSparseImageMemoryRequirements2KHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **memoryRequirements** is a `VkSparseImageMemoryRequirements` structure describing the memory requirements of the sparse image.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2`
- **pNext** must be `NULL`

28.7.6. Binding Resource Memory

Non-sparse resources are backed by a single physical allocation prior to device use (via `vkBindImageMemory` or `vkBindBufferMemory`), and their backing must not be changed. On the other hand, sparse resources can be bound to memory non-contiguously and these bindings can be altered during the lifetime of the resource.

**Note**

It is important to note that freeing a `VkDeviceMemory` object with `vkFreeMemory` will not cause resources (or resource regions) bound to the memory object to become unbound. Applications must not access resources bound to memory that has been freed.

Sparse memory bindings execute on a queue that includes the `VK_QUEUE_SPARSE_BINDING_BIT` bit.
Applications **must** use **synchronization primitives** to guarantee that other queues do not access ranges of memory concurrently with a binding change. Applications **can** access other ranges of the same resource while a bind operation is executing.

**Note**

Implementations **must** provide a guarantee that simultaneously binding sparse blocks while another queue accesses those same sparse blocks via a sparse resource **must** not access memory owned by another process or otherwise corrupt the system.

While some implementations **may** include `VK_QUEUE_SPARSE_BINDING_BIT` support in queue families that also include graphics and compute support, other implementations **may** only expose a `VK_QUEUE_SPARSE_BINDING_BIT-only queue family`. In either case, applications **must** use **synchronization primitives** to explicitly request any ordering dependencies between sparse memory binding operations and other graphics/compute/transfer operations, as sparse binding operations are not automatically ordered against command buffer execution, even within a single queue.

When binding memory explicitly for the `VK_IMAGE_ASPECT_METADATA_BIT` the application **must** use the `VK_SPARSE_MEMORY_BIND_METADATA_BIT` in the `VkSparseMemoryBind::flags` field when binding memory. Binding memory for metadata is done the same way as binding memory for the mip tail, with the addition of the `VK_SPARSE_MEMORY_BIND_METADATA_BIT` flag.

Binding the mip tail for any aspect **must** only be performed using `VkSparseImageOpaqueMemoryBindInfo`. If `formatProperties.flags` contains `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT`, then it **can** be bound with a single `VkSparseMemoryBind` structure, with `resourceOffset = imageMipTailOffset` and `size = imageMipTailSize`.

If `formatProperties.flags` does not contain `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT` then the offset for the mip tail in each array layer is given as:

\[
\text{arrayMipTailOffset} = \text{imageMipTailOffset} + \text{arrayLayer} \times \text{imageMipTailStride};
\]

and the mip tail **can** be bound with `layerCount` `VkSparseMemoryBind` structures, each using `size = imageMipTailSize` and `resourceOffset = arrayMipTailOffset` as defined above.

Sparse memory binding is handled by the following APIs and related data structures.

**Sparse Memory Binding Functions**

The `VkSparseMemoryBind` structure is defined as:
typedef struct VkSparseMemoryBind {
    VkDeviceSize resourceOffset;
    VkDeviceSize size;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
    VkSparseMemoryBindFlags flags;
} VkSparseMemoryBind;

- `resourceOffset` is the offset into the resource.
- `size` is the size of the memory region to be bound.
- `memory` is the `VkDeviceMemory` object that the range of the resource is bound to. If `memory` is `VK_NULL_HANDLE`, the range is unbound.
- `memoryOffset` is the offset into the `VkDeviceMemory` object to bind the resource range to. If `memory` is `VK_NULL_HANDLE`, this value is ignored.
- `flags` is a bitmask of `VkSparseMemoryBindFlagBits` specifying usage of the binding operation.

The binding range \([\text{resourceOffset}, \text{resourceOffset} + \text{size})\) has different constraints based on `flags`. If `flags` contains `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the binding range must be within the mip tail region of the metadata aspect. This metadata region is defined by:

\[
\text{metadataRegion} = [\text{base}, \text{base} + \text{imageMipTailSize})
\]

\[
\text{base} = \text{imageMipTailOffset} + \text{imageMipTailStride} \times n
\]

and `imageMipTailOffset`, `imageMipTailSize`, and `imageMipTailStride` values are from the `VkSparseImageMemoryRequirements` corresponding to the metadata aspect of the image, and \(n\) is a valid array layer index for the image,

`imageMipTailStride` is considered to be zero for aspects where `VkSparseImageMemoryRequirements::formatProperties.flags` contains `VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT`.

If `flags` does not contain `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the binding range must be within the range \([0, \text{VkMemoryRequirements::size})\).
Valid Usage

- If `memory` is not `VK_NULL_HANDLE`, `memory` and `memoryOffset` must match the memory requirements of the resource, as described in section Resource Memory Association.

- If `memory` is not `VK_NULL_HANDLE`, `memory` must not have been created with a memory type that reports `VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT` bit set.

  - `size` must be greater than 0
  - `resourceOffset` must be less than the size of the resource
  - `size` must be less than or equal to the size of the resource minus `resourceOffset`
  - `memoryOffset` must be less than the size of `memory`
  - `size` must be less than or equal to the size of `memory` minus `memoryOffset`

- If `memory` was created with `VkExportMemoryAllocateInfo::handleTypes` not equal to 0, at least one handle type it contained must also have been set in `VkExternalMemoryBufferCreateInfo::handleTypes` or `VkExternalMemoryImageCreateInfo::handleTypes` when the resource was created.

- If `memory` was created by a memory import operation, the external handle type of the imported memory must also have been set in `VkExternalMemoryBufferCreateInfo::handleTypes` or `VkExternalMemoryImageCreateInfo::handleTypes` when the resource was created.

Valid Usage (Implicit)

- If `memory` is not `VK_NULL_HANDLE`, `memory` must be a valid `VkDeviceMemory` handle.

  - `flags` must be a valid combination of `VkSparseMemoryBindFlagBits` values.

Bits which can be set in `VkSparseMemoryBind::flags`, specifying usage of a sparse memory binding operation, are:

```c
typedef enum VkSparseMemoryBindFlagBits {
    VK_SPARSE_MEMORY_BIND_METADATA_BIT = 0x00000001,
    VK_SPARSE_MEMORY_BIND_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSparseMemoryBindFlagBits;
```

- `VK_SPARSE_MEMORY_BIND_METADATA_BIT` specifies that the memory being bound is only for the metadata aspect.

```c
typedef VkFlags VkSparseMemoryBindFlags;
```

`VkSparseMemoryBindFlags` is a bitmask type for setting a mask of zero or more `VkSparseMemoryBindFlagBits`. 
Memory is bound to VkBuffer objects created with the VK_BUFFER_CREATE_SPARSE_BINDING_BIT flag using the following structure:

```c
typedef struct VkSparseBufferMemoryBindInfo {
    VkBuffer                     buffer;
    uint32_t                     bindCount;
    const VkSparseMemoryBind*    pBinds;
} VkSparseBufferMemoryBindInfo;
```

- `buffer` is the VkBuffer object to be bound.
- `bindCount` is the number of VkSparseMemoryBind structures in the `pBinds` array.
- `pBinds` is a pointer to array of VkSparseMemoryBind structures.

### Valid Usage (Implicit)

- `buffer` must be a valid VkBuffer handle
- `pBinds` must be a valid pointer to an array of `bindCount` valid VkSparseMemoryBind structures
- `bindCount` must be greater than 0

Memory is bound to opaque regions of VkImage objects created with the VK_IMAGE_CREATE_SPARSE_BINDING_BIT flag using the following structure:

```c
typedef struct VkSparseImageOpaqueMemoryBindInfo {
    VkImage                      image;
    uint32_t                     bindCount;
    const VkSparseMemoryBind*    pBinds;
} VkSparseImageOpaqueMemoryBindInfo;
```

- `image` is the VkImage object to be bound.
- `bindCount` is the number of VkSparseMemoryBind structures in the `pBinds` array.
- `pBinds` is a pointer to an array of VkSparseMemoryBind structures.

### Valid Usage

- If the flags member of any element of `pBinds` contains VK_SPARSE_MEMORY_BIND_METADATA_BIT, the binding range defined must be within the mip tail region of the metadata aspect of `image`
Valid Usage (Implicit)

- **image** must be a valid `VkImage` handle
- **pBinds** must be a valid pointer to an array of `bindCount` valid `VkSparseMemoryBind` structures
- **bindCount** must be greater than 0

**Note**
This operation is normally used to bind memory to fully-resident sparse images or for mip tail regions of partially resident images. However, it can also be used to bind memory for the entire binding range of partially resident images.

In case **flags** does not contain `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the `resourceOffset` is in the range `[0, VkMemoryRequirements::size)`. This range includes data from all aspects of the image, including metadata. For most implementations this will probably mean that the `resourceOffset` is a simple device address offset within the resource. It is possible for an application to bind a range of memory that includes both resource data and metadata. However, the application would not know what part of the image the memory is used for, or if any range is being used for metadata.

When **flags** contains `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the binding range specified must be within the mip tail region of the metadata aspect. In this case the `resourceOffset` is not required to be a simple device address offset within the resource. However, it is defined to be within `[imageMipTailOffset, imageMipTailOffset + imageMipTailSize)` for the metadata aspect. See `VkSparseMemoryBind` for the full constraints on binding region with this flag present.

Memory can be bound to sparse image blocks of `VkImage` objects created with the `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` flag using the following structure:

```c
typedef struct VkSparseImageMemoryBindInfo {
    VkImage image;
    uint32_t bindCount;
    const VkSparseImageMemoryBind* pBinds;
} VkSparseImageMemoryBindInfo;
```

- **image** is the `VkImage` object to be bound
- **bindCount** is the number of `VkSparseImageMemoryBind` structures in **pBinds** array
- **pBinds** is a pointer to an array of `VkSparseImageMemoryBind` structures
Valid Usage

- The `subresource.mipLevel` member of each element of `pBinds` must be less than the `mipLevels` specified in `VkImageCreateInfo` when `image` was created.
- The `subresource.arrayLayer` member of each element of `pBinds` must be less than the `arrayLayers` specified in `VkImageCreateInfo` when `image` was created.
- `image` must have been created with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` set.

Valid Usage (Implicit)

- `image` must be a valid `VkImage` handle.
- `pBinds` must be a valid pointer to an array of `bindCount` valid `VkSparseImageMemoryBind` structures.
- `bindCount` must be greater than 0.

The `VkSparseImageMemoryBind` structure is defined as:

```c
typedef struct VkSparseImageMemoryBind {
    VkImageSubresource subresource;
    VkOffset3D offset;
    VkExtent3D extent;
    VkDeviceMemory memory;
    VkDeviceSize memoryOffset;
    VkSparseMemoryBindFlags flags;
} VkSparseImageMemoryBind;
```

- `subresource` is the image aspect and region of interest in the image.
- `offset` are the coordinates of the first texel within the image subresource to bind.
- `extent` is the size in texels of the region within the image subresource to bind. The extent must be a multiple of the sparse image block dimensions, except when binding sparse image blocks along the edge of an image subresource it can instead be such that any coordinate of `offset + extent` equals the corresponding dimensions of the image subresource.
- `memory` is the `VkDeviceMemory` object that the sparse image blocks of the image are bound to. If `memory` is `VK_NULL_HANDLE`, the sparse image blocks are unbound.
- `memoryOffset` is an offset into `VkDeviceMemory` object. If `memory` is `VK_NULL_HANDLE`, this value is ignored.
- `flags` are sparse memory binding flags.
Valid Usage

- If the **sparse aliased residency** feature is not enabled, and if any other resources are bound to ranges of **memory**, the range of **memory** being bound must not overlap with those bound ranges.

- **memory** and **memoryOffset** must match the memory requirements of the calling command’s **image**, as described in section **Resource Memory Association**.

- **subresource** must be a valid image subresource for **image** (see **Image Views**).

- **offset.x** must be a multiple of the sparse image block width (VkSparseImageFormatProperties::imageGranularity.width) of the image.

- **extent.width** must either be a multiple of the sparse image block width of the image, or else (extent.width + offset.x) must equal the width of the image subresource.

- **offset.y** must be a multiple of the sparse image block height (VkSparseImageFormatProperties::imageGranularity.height) of the image.

- **extent.height** must either be a multiple of the sparse image block height of the image, or else (extent.height + offset.y) must equal the height of the image subresource.

- **offset.z** must be a multiple of the sparse image block depth (VkSparseImageFormatProperties::imageGranularity.depth) of the image.

- **extent.depth** must either be a multiple of the sparse image block depth of the image, or else (extent.depth + offset.z) must equal the depth of the image subresource.

- If **memory** was created with VkExportMemoryAllocateInfo::handleTypes not equal to 0, at least one handle type it contained must also have been set in VkExternalMemoryImageCreateInfo::handleTypes when the image was created.

- If **memory** was created by a memory import operation, the external handle type of the imported memory must also have been set in VkExternalMemoryImageCreateInfo::handleTypes when **image** was created.

Valid Usage (Implicit)

- **subresource** must be a valid VkImageSubresource structure.

- If **memory** is not **VK_NULL_HANDLE**, **memory** must be a valid VkDeviceMemory handle.

- **flags** must be a valid combination of VkSparseMemoryBindFlagBits values.

To submit sparse binding operations to a queue, call:

```c
VkResult vkQueueBindSparse(
    VkQueue queue,
    uint32_t bindInfoCount,
    const VkBindSparseInfo* pBindInfo,
    VkFence fence);
```
• **queue** is the queue that the sparse binding operations will be submitted to.

• **bindInfoCount** is the number of elements in the **pBindInfo** array.

• **pBindInfo** is a pointer to an array of **VkBindSparseInfo** structures, each specifying a sparse binding submission batch.

• **fence** is an optional handle to a fence to be signaled. If **fence** is not **VK_NULL_HANDLE**, it defines a fence signal operation.

**vkQueueBindSparse** is a queue submission command, with each batch defined by an element of **pBindInfo** as a **VkBindSparseInfo** structure. Batches begin execution in the order they appear in **pBindInfo**, but may complete out of order.

Within a batch, a given range of a resource **must** not be bound more than once. Across batches, if a range is to be bound to one allocation and offset and then to another allocation and offset, then the application **must** guarantee (usually using semaphores) that the binding operations are executed in the correct order, as well as to order binding operations against the execution of command buffer submissions.

As no operation to **vkQueueBindSparse** causes any pipeline stage to access memory, synchronization primitives used in this command effectively only define execution dependencies.

Additional information about fence and semaphore operation is described in the synchronization chapter.

---

**Valid Usage**

• If **fence** is not **VK_NULL_HANDLE**, **fence** **must** be unsignaled

• If **fence** is not **VK_NULL_HANDLE**, **fence** **must** not be associated with any other queue command that has not yet completed execution on that queue

• Each element of the **pSignalSemaphores** member of each element of **pBindInfo** **must** be unsignaled when the semaphore signal operation it defines is executed on the device

• When a semaphore wait operation referring to a binary semaphore defined by any element of the **pWaitSemaphores** member of any element of **pBindInfo** executes on **queue**, there **must** be no other queues waiting on the same semaphore.

• All elements of the **pWaitSemaphores** member of all elements of **pBindInfo** member referring to a binary semaphore **must** be semaphores that are signaled, or have semaphore signal operations previously submitted for execution.

• All elements of the **pWaitSemaphores** member of all elements of **pBindInfo** created with a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_BINARY** **must** reference a semaphore signal operation that has been submitted for execution and any semaphore signal operations on which it depends (if any) **must** have also been submitted for execution.
Valid Usage (Implicit)

- `queue` must be a valid `VkQueue` handle
- If `bindInfoCount` is not 0, `pBindInfo` must be a valid pointer to an array of `bindInfoCount` valid `VkBindSparseInfo` structures
- If `fence` is not `VK_NULL_HANDLE`, `fence` must be a valid `VkFence` handle
- The `queue` must support sparse binding operations
- Both of `fence`, and `queue` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to `queue` must be externally synchronized
- Host access to `pBindInfo[].pBufferBinds[].buffer` must be externally synchronized
- Host access to `pBindInfo[].pImageOpaqueBinds[].image` must be externally synchronized
- Host access to `pBindInfo[].pImageBinds[].image` must be externally synchronized
- Host access to `fence` must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td><code>SPARSE_BINDING</code></td>
<td>-</td>
</tr>
</tbody>
</table>

Return Codes

Success
- `VK_SUCCESS`

Failure
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_DEVICE_LOST`

The `VkBindSparseInfo` structure is defined as:
typedef struct VkBindSparseInfo {
    VkStructureType                             sType;
    const void*                                 pNext;
    uint32_t                                    waitSemaphoreCount;
    const VkSemaphore*                          pWaitSemaphores;
    uint32_t                                    bufferBindCount;
    const VkSparseBufferMemoryBindInfo*         pBufferBinds;
    uint32_t                                    imageOpaqueBindCount;
    const VkSparseImageOpaqueMemoryBindInfo*    pImageOpaqueBinds;
    uint32_t                                    imageBindCount;
    const VkSparseImageMemoryBindInfo*          pImageBinds;
    uint32_t                                    signalSemaphoreCount;
    const VkSemaphore*                          pSignalSemaphores;
} VkBindSparseInfo;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **waitSemaphoreCount** is the number of semaphores upon which to wait before executing the sparse binding operations for the batch.
- **pWaitSemaphores** is a pointer to an array of semaphores upon which to wait on before the sparse binding operations for this batch begin execution. If semaphores to wait on are provided, they define a semaphore wait operation.
- **bufferBindCount** is the number of sparse buffer bindings to perform in the batch.
- **pBufferBinds** is a pointer to an array of VkSparseBufferMemoryBindInfo structures.
- **imageOpaqueBindCount** is the number of opaque sparse image bindings to perform.
- **pImageOpaqueBinds** is a pointer to an array of VkSparseImageOpaqueMemoryBindInfo structures, indicating opaque sparse image bindings to perform.
- **imageBindCount** is the number of sparse image bindings to perform.
- **pImageBinds** is a pointer to an array of VkSparseImageMemoryBindInfo structures, indicating sparse image bindings to perform.
- **signalSemaphoreCount** is the number of semaphores to be signaled once the sparse binding operations specified by the structure have completed execution.
- **pSignalSemaphores** is a pointer to an array of semaphores which will be signaled when the sparse binding operations for this batch have completed execution. If semaphores to be signaled are provided, they define a semaphore signal operation.
## Valid Usage

- If any element of `pWaitSemaphores` or `pSignalSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` then the `pNext` chain **must** include a `VkTimelineSemaphoreSubmitInfo` structure.

- If the `pNext` chain of this structure includes a `VkTimelineSemaphoreSubmitInfo` structure and any element of `pWaitSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` then its `waitSemaphoreValueCount` member **must** equal `waitSemaphoreCount`.

- If the `pNext` chain of this structure includes a `VkTimelineSemaphoreSubmitInfo` structure and any element of `pSignalSemaphores` was created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` then its `signalSemaphoreValueCount` member **must** equal `signalSemaphoreCount`.

- For each element of `pSignalSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` the corresponding element of `VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues` **must** have a value greater than the current value of the semaphore when the semaphore signal operation is executed.

- For each element of `pWaitSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` the corresponding element of `VkTimelineSemaphoreSubmitInfo::pWaitSemaphoreValues` **must** have a value which does not differ from the current value of the semaphore or from the value of any outstanding semaphore wait or signal operation on that semaphore by more than `maxTimelineSemaphoreValueDifference`.

- For each element of `pSignalSemaphores` created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` the corresponding element of `VkTimelineSemaphoreSubmitInfo::pSignalSemaphoreValues` **must** have a value which does not differ from the current value of the semaphore or from the value of any outstanding semaphore wait or signal operation on that semaphore by more than `maxTimelineSemaphoreValueDifference`. 
**Valid Usage (Implicit)**

- **sType** must be `VK_STRUCTURE_TYPE_BIND_SPARSE_INFO`
- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkDeviceGroupBindSparseInfo` or `VkTimelineSemaphoreSubmitInfo`
- The `sType` value of each struct in the `pNext` chain must be unique
- If `waitSemaphoreCount` is not `0`, `pWaitSemaphores` must be a valid pointer to an array of `waitSemaphoreCount` valid `VkSemaphore` handles
- If `bufferBindCount` is not `0`, `pBufferBinds` must be a valid pointer to an array of `bufferBindCount` valid `VkSparseBufferMemoryBindInfo` structures
- If `imageOpaqueBindCount` is not `0`, `pImageOpaqueBinds` must be a valid pointer to an array of `imageOpaqueBindCount` valid `VkSparseImageOpaqueMemoryBindInfo` structures
- If `imageBindCount` is not `0`, `pImageBinds` must be a valid pointer to an array of `imageBindCount` valid `VkSparseImageMemoryBindInfo` structures
- If `signalSemaphoreCount` is not `0`, `pSignalSemaphores` must be a valid pointer to an array of `signalSemaphoreCount` valid `VkSemaphore` handles
- Both of the elements of `pSignalSemaphores`, and the elements of `pWaitSemaphores` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

To specify the values to use when waiting for and signaling semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE`, add a `VkTimelineSemaphoreSubmitInfo` structure to the `pNext` chain of the `VkBindSparseInfo` structure.

If the `pNext` chain of `VkBindSparseInfo` includes a `VkDeviceGroupBindSparseInfo` structure, then that structure includes device indices specifying which instance of the resources and memory are bound.

The `VkDeviceGroupBindSparseInfo` structure is defined as:

```c
typedef struct VkDeviceGroupBindSparseInfo {
    VkStructureType   sType;
    const void*        pNext;
    uint32_t           resourceDeviceIndex;
    uint32_t           memoryDeviceIndex;
} VkDeviceGroupBindSparseInfo;
```

or the equivalent

```c
typedef VkDeviceGroupBindSparseInfo VkDeviceGroupBindSparseInfoKHR;
```

- **sType** is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• resourceDeviceIndex is a device index indicating which instance of the resource is bound.
• memoryDeviceIndex is a device index indicating which instance of the memory the resource instance is bound to.

These device indices apply to all buffer and image memory binds included in the batch pointing to this structure. The semaphore waits and signals for the batch are executed only by the physical device specified by the resourceDeviceIndex.

If this structure is not present, resourceDeviceIndex and memoryDeviceIndex are assumed to be zero.

**Valid Usage**

- resourceDeviceIndex and memoryDeviceIndex must both be valid device indices.
- Each memory allocation bound in this batch must have allocated an instance for memoryDeviceIndex.

**Valid Usage (Implicit)**

- sType must be VK_STRUCTURE_TYPE_DEVICE_GROUP_BIND_SPARSE_INFO

### 28.8. Examples

The following examples illustrate basic creation of sparse images and binding them to physical memory.

#### 28.8.1. Basic Sparse Resources

This basic example creates a normal VkImage object but uses fine-grained memory allocation to back the resource with multiple memory ranges.

```c
VkDevice                device;
VkQueue                 queue;
VkImage                 sparseImage;
VkAllocationCallbacks*  pAllocator = NULL;
VkMemoryRequirements    memoryRequirements = {};
VkDeviceSize            offset = 0;
VkSparseMemoryBind      binds[MAX_CHUNKS] = {}; // MAX_CHUNKS is NOT part of Vulkan
uint32_t                bindCount = 0;

// ...

// Allocate image object
const VkImageCreateInfo sparseImageInfo = {
```
VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO,  // sType
NULL,  // pNext
VK_IMAGE_CREATE_SPARSE_BINDING_BIT | ...,  // flags
...
};
vkCreateImage(device, &sparseImageInfo, pAllocator, &sparseImage);

// Get memory requirements
vkGetImageMemoryRequirements(
    device,
    sparseImage,
    &memoryRequirements);

// Bind memory in fine-grained fashion, find available memory ranges
// from potentially multiple VkDeviceMemory pools.
// (Illustration purposes only, can be optimized for perf)
while (memoryRequirements.size && bindCount < MAX_CHUNKS)
{
    VkSparseMemoryBind* pBind = &binds[bindCount];
    pBind->resourceOffset = offset;

    AllocateOrGetMemoryRange(
        device,
        &memoryRequirements,
        &pBind->memory,
        &pBind->memoryOffset,
        &pBind->size);

    // memory ranges must be sized as multiples of the alignment
    assert(IsMultiple(pBind->size, memoryRequirements.alignment));
    assert(IsMultiple(pBind->memoryOffset, memoryRequirements.alignment));

    memoryRequirements.size -= pBind->size;
    offset                  += pBind->size;
    bindCount++;
}

// Ensure all image has backing
if (memoryRequirements.size)
{
    // Error condition - too many chunks
}

const VkSparseImageOpaqueMemoryBindInfo opaqueBindInfo =
{
    sparseImage,  // image
    bindCount,  // bindCount
    binds  // pBinds
};

const VkBindSparseInfo bindSparseInfo =
28.8.2. Advanced Sparse Resources

This more advanced example creates an arrayed color attachment / texture image and binds only LOD zero and the required metadata to physical memory.

```c
VkDevice                            device;
VkQueue                             queue;
VkImage                             sparseImage;
VkAllocationCallbacks*             pAllocator = NULL;
VkMemoryRequirements               memoryRequirements = {}; // pNext
uint32_t                            sparseRequirementsCount = 0;
VkSparseImageMemoryRequirements*   pSparseReqs = NULL;
VkSparseMemoryBind                 binds[MY_IMAGE_ARRAY_SIZE] = {}; // pNext
VkSparseImageMemoryBind            imageBinds[MY_IMAGE_ARRAY_SIZE] = {}; // pNext
uint32_t                            bindCount = 0;

// Allocate image object (both renderable and sampleable)
const VkImageCreateInfo sparseImageInfo =
{
    VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO, // sType
    NULL,                                 // pNext
    VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT | ..., // flags
    VK_FORMAT_R8G8B8A8_UNORM,            // format
    ...,                                  // arrayLayers
    ...                                  // usage
};
vkCreateImage(device, &sparseImageInfo, pAllocator, &sparseImage);
```
// Get memory requirements
vkGetImageMemoryRequirements(
    device,
    sparseImage,
    &memoryRequirements);

// Get sparse image aspect properties
vkGetImageSparseMemoryRequirements(
    device,
    sparseImage,
    &sparseRequirementsCount,
    NULL);

pSparseReqs = (VkSparseImageMemoryRequirements*)
    malloc(sparseRequirementsCount * sizeof(VkSparseImageMemoryRequirements));

vkGetImageSparseMemoryRequirements(
    device,
    sparseImage,
    &sparseRequirementsCount,
    pSparseReqs);

// Bind LOD level 0 and any required metadata to memory
for (uint32_t i = 0; i < sparseRequirementsCount; ++i)
{
    if (pSparseReqs[i].formatProperties.aspectMask &
        VK_IMAGE_ASPECT_METADATA_BIT)
    {
        // Metadata must not be combined with other aspects
        assert(pSparseReqs[i].formatProperties.aspectMask ==
            VK_IMAGE_ASPECT_METADATA_BIT);

        if (pSparseReqs[i].formatProperties.flags &
            VK_SPARSE_IMAGE_FORMAT_SINGLE_MIPTAIL_BIT)
        {
            VkSparseMemoryBind* pBind = &binds[bindCount];
            pBind->memorySize = pSparseReqs[i].imageMipTailSize;
            bindCount++;

            // ... Allocate memory range

            pBind->resourceOffset = pSparseReqs[i].imageMipTailOffset;
            pBind->memoryOffset = /* allocated memoryOffset */;
            pBind->memory = /* allocated memory */;
            pBind->flags = VK_SPARSE_MEMORY_BIND_METADATA_BIT;
        }
        else
        {
            // Need a mip tail region per array layer.
            for (uint32_t a = 0; a < sparseImageInfo.arrayLayers; ++a)
            {

            }
        }
    }
}
 VkSparseMemoryBind* pBind = &binds[bindCount];
 pBind->memorySize = pSparseReqs[i].imageMipTailSize;
 bindCount++;

 // ... Allocate memory range

 pBind->resourceOffset = pSparseReqs[i].imageMipTailOffset +
 (a * pSparseReqs[i].imageMipTailStride);

 pBind->memoryOffset = /* allocated memoryOffset */;
 pBind->memory = /* allocated memory */
 pBind->flags = VK_SPARSE_MEMORY_BIND_METADATA_BIT;

 else
 {
 // resource data

 VkExtent3D lod0BlockSize =
 {
  AlignedDivide(
   sparseImageInfo.extent.width,
   pSparseReqs[i].formatProperties.imageGranularity.width);
  AlignedDivide(
   sparseImageInfo.extent.height,
   pSparseReqs[i].formatProperties.imageGranularity.height);
  AlignedDivide(
   sparseImageInfo.extent.depth,
   pSparseReqs[i].formatProperties.imageGranularity.depth);
 }
 size_t totalBlocks =
  lod0BlockSize.width *
  lod0BlockSize.height *
  lod0BlockSize.depth;

 // Each block is the same size as the alignment requirement,
 // calculate total memory size for level 0
 VkDeviceSize lod0MemSize = totalBlocks * memoryRequirements.alignment;

 // Allocate memory for each array layer
 for (uint32_t a = 0; a < sparseImageInfo.arrayLayers; ++a)
 {
  // ... Allocate memory range

  VkSparseImageMemoryBind* pBind = &imageBinds[a];
  aspectMask;
  pBind->subresource.mipLevel = 0;
  pBind->subresource.arrayLayer = a;
pBind->offset = (VkOffset3D){0, 0, 0};
pBind->extent = sparseImageInfo.extent;
pBind->memoryOffset = /* allocated memoryOffset */;
pBind->memory = /* allocated memory */;
pBind->flags = 0;
}

free(pSparseReqs);
}

const VkSparseImageOpaqueMemoryBindInfo opaqueBindInfo =
{
    sparseImage,       // image
    bindCount,        // bindCount
    binds             // pBinds
};

const VkSparseImageMemoryBindInfo imageBindInfo =
{
    sparseImage,       // image
    sparseImageInfo.arrayLayers, // bindCount
    imageBinds         // pBinds
};

const VkBindSparseInfo bindSparseInfo =
{
    VK_STRUCTURE_TYPE_BIND_SPARSE_INFO, // sType
    NULL,                               // pNext
    ... 1,                              // imageOpaqueBindCount
    &opaqueBindInfo,                    // pImageOpaqueBinds
    1,                                 // imageBindCount
    &imageBindInfo,                     // pImageBinds
    ...
};

// vkQueueBindSparse is externally synchronized per queue object.
AcquireQueueOwnership(queue);

// Actually bind memory
vkQueueBindSparse(queue, 1, &bindSparseInfo, VK_NULL_HANDLE);

ReleaseQueueOwnership(queue);
Chapter 29. Window System Integration (WSI)

This chapter discusses the window system integration (WSI) between the Vulkan API and the various forms of displaying the results of rendering to a user. Since the Vulkan API can be used without displaying results, WSI is provided through the use of optional Vulkan extensions. This chapter provides an overview of WSI. See the appendix for additional details of each WSI extension, including which extensions must be enabled in order to use each of the functions described in this chapter.

29.1. WSI Platform

A platform is an abstraction for a window system, OS, etc. Some examples include MS Windows, Android, and Wayland. The Vulkan API may be integrated in a unique manner for each platform.

The Vulkan API does not define any type of platform object. Platform-specific WSI extensions are defined, each containing platform-specific functions for using WSI. Use of these extensions is guarded by preprocessor symbols as defined in the Window System-Specific Header Control appendix.

In order for an application to be compiled to use WSI with a given platform, it must either:

- #define the appropriate preprocessor symbol prior to including the vulkan.h header file, or
- include vulkan_core.h and any native platform headers, followed by the appropriate platform-specific header.

The preprocessor symbols and platform-specific headers are defined in the Window System Extensions and Headers table.

Each platform-specific extension is an instance extension. The application must enable instance extensions with vkCreateInstance before using them.

29.2. WSI Surface

Native platform surface or window objects are abstracted by surface objects, which are represented by VkSurfaceKHR handles:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSurfaceKHR)
```

The VK_KHR_surface extension declares the VkSurfaceKHR object, and provides a function for destroying VkSurfaceKHR objects. Separate platform-specific extensions each provide a function for creating a VkSurfaceKHR object for the respective platform. From the application’s perspective this is an opaque handle, just like the handles of other Vulkan objects.
On certain platforms, the Vulkan loader and ICDs may have conventions that treat the handle as a pointer to a structure containing the platform-specific information about the surface. This will be described in the documentation for the loader-ICD interface, and in the \texttt{vk.icd.h} header file of the LoaderAndTools source-code repository. This does not affect the loader-layer interface; layers may wrap \texttt{VkSurfaceKHR} objects.

### 29.2.1. Android Platform

To create a \texttt{VkSurfaceKHR} object for an Android native window, call:

\begin{verbatim}
VkResult vkCreateAndroidSurfaceKHR(
    VkInstance instance,
    const VkAndroidSurfaceCreateInfoKHR* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkSurfaceKHR* pSurface);
\end{verbatim}

- \texttt{instance} is the instance to associate the surface with.
- \texttt{pCreateInfo} is a pointer to a \texttt{VkAndroidSurfaceCreateInfoKHR} structure containing parameters affecting the creation of the surface object.
- \texttt{pAllocator} is the allocator used for host memory allocated for the surface object when there is no more specific allocator available (see Memory Allocation).
- \texttt{pSurface} is a pointer to a \texttt{VkSurfaceKHR} handle in which the created surface object is returned.

During the lifetime of a surface created using a particular \texttt{ANativeWindow} handle any attempts to create another surface for the same \texttt{ANativeWindow} and any attempts to connect to the same \texttt{ANativeWindow} through other platform mechanisms will fail.

\begin{verbatim}
Note
In particular, only one \texttt{VkSurfaceKHR} can exist at a time for a given window. Similarly, a native window cannot be used by both a \texttt{VkSurfaceKHR} and \texttt{EGLSurface} simultaneously.
\end{verbatim}

If successful, \texttt{vkCreateAndroidSurfaceKHR} increments the \texttt{ANativeWindow}'s reference count, and \texttt{vkDestroySurfaceKHR} will decrement it.

On Android, when a swapchain's \texttt{imageExtent} does not match the surface's \texttt{currentExtent}, the presentable images will be scaled to the surface's dimensions during presentation. \texttt{minImageExtent} is (1,1), and \texttt{maxImageExtent} is the maximum image size supported by the consumer. For the system compositor, \texttt{currentExtent} is the window size (i.e. the consumer's preferred size).
Valid Usage (Implicit)

- **instance** must be a valid VkInstance handle
- **pCreateInfo** must be a valid pointer to a valid VkAndroidSurfaceCreateInfoKHR structure
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid VkAllocationCallbacks structure
- **pSurface** must be a valid pointer to a VkSurfaceKHR handle

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_NATIVE_WINDOW_IN_USE_KHR

The VkAndroidSurfaceCreateInfoKHR structure is defined as:

```c
typedef struct VkAndroidSurfaceCreateInfoKHR {
    VkStructureType                   sType;
    const void*                       pNext;
    VkAndroidSurfaceCreateFlagsKHR    flags;
    struct ANativeWindow*             window;
} VkAndroidSurfaceCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **window** is a pointer to the ANativeWindow to associate the surface with.

Valid Usage

- **window** must point to a valid Android ANativeWindow.
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_ANDROID_SURFACE_CREATE_INFO_KHR`
- `pNext` must be `NULL`
- `flags` must be `0`

To remove an unnecessary compile-time dependency, an incomplete type definition of `ANativeWindow` is provided in the Vulkan headers:

```c
struct ANativeWindow;
```

The actual `ANativeWindow` type is defined in Android NDK headers.

### 29.2.2. Wayland Platform

To create a `VkSurfaceKHR` object for a Wayland surface, call:

```c
VkResult vkCreateWaylandSurfaceKHR(
    VkInstance instance,  // instance is the instance to associate the surface with.
    const VkWaylandSurfaceCreateInfoKHR* pCreateInfo,  // pCreateInfo is a pointer to a VkWaylandSurfaceCreateInfoKHR structure containing parameters affecting the creation of the surface object.
    const VkAllocationCallbacks* pAllocator,  // pAllocator is the allocator used for host memory allocated for the surface object when there is no more specific allocator available (see Memory Allocation).
    VkSurfaceKHR* pSurface);  // pSurface is a pointer to a VkSurfaceKHR handle in which the created surface object is returned.
```

Valid Usage (Implicit)

- `instance` must be a valid `VkInstance` handle
- `pCreateInfo` must be a valid pointer to a valid `VkWaylandSurfaceCreateInfoKHR` structure
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- `pSurface` must be a valid pointer to a `VkSurfaceKHR` handle
Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkWaylandSurfaceCreateInfoKHR` structure is defined as:

```c
typedef struct VkWaylandSurfaceCreateInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkWaylandSurfaceCreateFlagsKHR flags;
    struct wl_display* display;
    struct wl_surface* surface;
} VkWaylandSurfaceCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **display** and **surface** are pointers to the Wayland `wl_display` and `wl_surface` to associate the surface with.

**Valid Usage**

- **display** must point to a valid Wayland `wl_display`.
- **surface** must point to a valid Wayland `wl_surface`.

**Valid Usage (Implicit)**

- **sType** must be `VK_STRUCTURE_TYPE_WAYLAND_SURFACE_CREATE_INFO_KHR`
- **pNext** must be NULL
- **flags** must be 0

On Wayland, **currentExtent** is the special value (0xFFFFFFFF, 0xFFFFFFFF), indicating that the surface size will be determined by the extent of a swapchain targeting the surface. Whatever the application sets a swapchain's **imageExtent** to will be the size of the window, after the first image is presented. **minImageExtent** is (1,1), and **maxImageExtent** is the maximum supported surface size. Any calls to `vkGetPhysicalDeviceSurfacePresentModesKHR` on a surface created with `vkCreateWaylandSurfaceKHR` are required to return `VK_PRESENT_MODE_MAILBOX_KHR` as one of the valid...
present modes.

Some Vulkan functions may send protocol over the specified \texttt{wl_display} connection when using a swapchain or presentable images created from a \texttt{VkSurfaceKHR} referring to a \texttt{wl_surface}. Applications must therefore ensure that both the \texttt{wl_display} and the \texttt{wl_surface} remain valid for the lifetime of any \texttt{VkSwapchainKHR} objects created from a particular \texttt{wl_display} and \texttt{wl_surface}. Also, calling \texttt{vkQueuePresentKHR} will result in Vulkan sending \texttt{wl_surface.commit} requests to the underlying \texttt{wl_surface} of each \texttt{VkSwapchainKHR} objects referenced by \texttt{pPresentInfo}. If the swapchain is created with a present mode of \texttt{VK_PRESENT_MODE_MAILBOX_KHR} or \texttt{VK_PRESENT_MODE_IMMEDIATE_KHR}, then the corresponding \texttt{wl_surface.attach}, \texttt{wl_surface.damage}, and \texttt{wl_surface.commit} request must be issued by the implementation during the call to \texttt{vkQueuePresentKHR} and must not be issued by the implementation outside of \texttt{vkQueuePresentKHR}. This ensures that any Wayland requests sent by the client after the call to \texttt{vkQueuePresentKHR} returns will be received by the compositor after the \texttt{wl_surface.commit}. Regardless of the mode of swapchain creation, a new \texttt{wl_event_queue} must be created for each successful \texttt{vkCreateWaylandSurfaceKHR} call, and every Wayland object created by the implementation must be assigned to this event queue. If the platform provides Wayland 1.11 or greater, this must be implemented by the use of Wayland proxy object wrappers, to avoid race conditions.

If the application wishes to synchronize any window changes with a particular frame, such requests must be sent to the Wayland display server prior to calling \texttt{vkQueuePresentKHR}. For full control over interactions between Vulkan rendering and other Wayland protocol requests and events, a present mode of \texttt{VK_PRESENT_MODE_MAILBOX_KHR} should be used.

### 29.2.3. Win32 Platform

To create a \texttt{VkSurfaceKHR} object for a Win32 window, call:

```c
VkResult vkCreateWin32SurfaceKHR(
    VkInstance instance,
    const VkWin32SurfaceCreateInfoKHR* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkSurfaceKHR* pSurface);
```

- \texttt{instance} is the instance to associate the surface with.
- \texttt{pCreateInfo} is a pointer to a \texttt{VkWin32SurfaceCreateInfoKHR} structure containing parameters affecting the creation of the surface object.
- \texttt{pAllocator} is the allocator used for host memory allocated for the surface object when there is no more specific allocator available (see Memory Allocation).
- \texttt{pSurface} is a pointer to a \texttt{VkSurfaceKHR} handle in which the created surface object is returned.
Valid Usage (Implicit)

- `instance` must be a valid `VkInstance` handle
- `pCreateInfo` must be a valid pointer to a valid `VkWin32SurfaceCreateInfoKHR` structure
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- `pSurface` must be a valid pointer to a `VkSurfaceKHR` handle

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkWin32SurfaceCreateInfoKHR` structure is defined as:

```c
typedef struct VkWin32SurfaceCreateInfoKHR {
    VkStructureType           sType;
    const void*               pNext;
    VkWin32SurfaceCreateFlagsKHR flags;
    HINSTANCE                 hinstance;
    HWND                       hwnd;
} VkWin32SurfaceCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `hinstance` is the Win32 `HINSTANCE` for the window to associate the surface with.
- `hwnd` is the Win32 `HWND` for the window to associate the surface with.

Valid Usage

- `hinstance` must be a valid Win32 `HINSTANCE`.
- `hwnd` must be a valid Win32 `HWND`.
Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_WIN32_SURFACE_CREATE_INFO_KHR
- pNext must be NULL
- flags must be 0

With Win32, minImageExtent, maxImageExtent, and currentExtent must always equal the window size.

The currentExtent of a Win32 surface must have both width and height greater than 0, or both of them 0.

Note
Due to above restrictions, it is only possible to create a new swapchain on this platform with imageExtent being equal to the current size of the window.

The window size may become (0, 0) on this platform (e.g. when the window is minimized), and so a swapchain cannot be created until the size changes.

typedef VkFlags VkWin32SurfaceCreateFlagsKHR;

VkWin32SurfaceCreateFlagsKHR is a bitmask type for setting a mask, but is currently reserved for future use.

29.2.4. XCB Platform

To create a VkSurfaceKHR object for an X11 window, using the XCB client-side library, call:

```c
VkResult vkCreateXcbSurfaceKHR(
    VkInstance instance,
    const VkXcbSurfaceCreateInfoKHR* pCreateInfo,
    const VkAllocationCallbacks* pAllocator,
    VkSurfaceKHR* pSurface);
```

- instance is the instance to associate the surface with.
- pCreateInfo is a pointer to a VkXcbSurfaceCreateInfoKHR structure containing parameters affecting the creation of the surface object.
- pAllocator is the allocator used for host memory allocated for the surface object when there is no more specific allocator available (see Memory Allocation).
- pSurface is a pointer to a VkSurfaceKHR handle in which the created surface object is returned.
Valid Usage (Implicit)

- `instance` must be a valid `VkInstance` handle.
- `pCreateInfo` must be a valid pointer to a valid `VkXcbSurfaceCreateInfoKHR` structure.
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure.
- `pSurface` must be a valid pointer to a `VkSurfaceKHR` handle.

Return Codes

Success
- `VK_SUCCESS`

Failure
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkXcbSurfaceCreateInfoKHR` structure is defined as:

```c
typedef struct VkXcbSurfaceCreateInfoKHR {
    VkStructureType           sType;
    const void*               pNext;
    VkXcbSurfaceCreateFlagsKHR flags;
    xcb_connection_t*         connection;
    xcb_window_t              window;
} VkXcbSurfaceCreateInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `connection` is a pointer to an `xcb_connection_t` to the X server.
- `window` is the `xcb_window_t` for the X11 window to associate the surface with.

Valid Usage

- `connection` must point to a valid X11 `xcb_connection_t`.
- `window` must be a valid X11 `xcb_window_t`. 

908 | Chapter 29. Window System Integration (WSI)
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_XCB_SURFACE_CREATE_INFO_KHR`
- **pNext** must be `NULL`
- **flags** must be `0`

With Xcb, `minImageExtent`, `maxImageExtent`, and `currentExtent` must always equal the window size.

The `currentExtent` of an Xcb surface must have both **width** and **height** greater than 0, or both of them 0.

**Note**

Due to above restrictions, it is only possible to create a new swapchain on this platform with `imageExtent` being equal to the current size of the window.

The window size may become (0, 0) on this platform (e.g. when the window is minimized), and so a swapchain cannot be created until the size changes.

Some Vulkan functions may send protocol over the specified xcb connection when using a swapchain or presentable images created from a `VkSurfaceKHR` referring to an xcb window. Applications must therefore ensure the xcb connection is available to Vulkan for the duration of any functions that manipulate such swapchains or their presentable images, and any functions that build or queue command buffers that operate on such presentable images. Specifically, applications using Vulkan with xcb-based swapchains must

- Avoid holding a server grab on an xcb connection while waiting for Vulkan operations to complete using a swapchain derived from a different xcb connection referring to the same X server instance. Failing to do so may result in deadlock.

### 29.2.5. Xlib Platform

To create a `VkSurfaceKHR` object for an X11 window, using the Xlib client-side library, call:

```c
VkResult vkCreateXlibSurfaceKHR(
    VkInstance instance,        // instance,
    const VkXlibSurfaceCreateInfoKHR* pCreateInfo, // pCreateInfo,
    const VkAllocationCallbacks* pAllocator,     // pAllocator,
    VkSurfaceKHR* pSurface);   // pSurface);
```

- **instance** is the instance to associate the surface with.
- **pCreateInfo** is a pointer to a `VkXlibSurfaceCreateInfoKHR` structure containing the parameters affecting the creation of the surface object.
- **pAllocator** is the allocator used for host memory allocated for the surface object when there is no more specific allocator available (see Memory Allocation).
- **pSurface** is a pointer to a `VkSurfaceKHR` handle in which the created surface object is returned.
Valid Usage (Implicit)

- **instance** must be a valid `VkInstance` handle.
- **pCreateInfo** must be a valid pointer to a valid `VkXlibSurfaceCreateInfoKHR` structure.
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure.
- **pSurface** must be a valid pointer to a `VkSurfaceKHR` handle.

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkXlibSurfaceCreateInfoKHR` structure is defined as:

```c
typedef struct VkXlibSurfaceCreateInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkXlibSurfaceCreateFlagsKHR flags;
    Display* dpy;
    Window window;
} VkXlibSurfaceCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is reserved for future use.
- **dpy** is a pointer to an Xlib Display connection to the X server.
- **window** is an Xlib Window to associate the surface with.

Valid Usage

- **dpy** must point to a valid Xlib Display.
- **window** must be a valid Xlib Window.
Valid Usage (Implicit)

• `sType` must be `VK_STRUCTURE_TYPE_XLIB_SURFACE_CREATE_INFO_KHR`  
• `pNext` must be `NULL`  
• `flags` must be `0`

With Xlib, `minImageExtent`, `maxImageExtent`, and `currentExtent` must always equal the window size.

The `currentExtent` of an Xlib surface must have both width and height greater than 0, or both of them 0.

Note

Due to above restrictions, it is only possible to create a new swapchain on this platform with `imageExtent` being equal to the current size of the window.

The window size may become (0, 0) on this platform (e.g. when the window is minimized), and so a swapchain cannot be created until the size changes.

Some Vulkan functions may send protocol over the specified Xlib Display connection when using a swapchain or presentable images created from a `VkSurfaceKHR` referring to an Xlib window. Applications must therefore ensure the display connection is available to Vulkan for the duration of any functions that manipulate such swapchains or their presentable images, and any functions that build or queue command buffers that operate on such presentable images. Specifically, applications using Vulkan with Xlib-based swapchains must

• Avoid holding a server grab on a display connection while waiting for Vulkan operations to complete using a swapchain derived from a different display connection referring to the same X server instance. Failing to do so may result in deadlock.

Some implementations may require threads to implement some presentation modes so applications must call `XInitThreads()` before calling any other Xlib functions.

29.2.6. Platform-Independent Information

Once created, `VkSurfaceKHR` objects can be used in this and other extensions, in particular the `VK_KHR_swapchain` extension.

Several WSI functions return `VK_ERROR_SURFACE_LOST_KHR` if the surface becomes no longer available. After such an error, the surface (and any child swapchain, if one exists) should be destroyed, as there is no way to restore them to a not-lost state. Applications may attempt to create a new `VkSurfaceKHR` using the same native platform window object, but whether such re-creation will succeed is platform-dependent and may depend on the reason the surface became unavailable. A lost surface does not otherwise cause devices to be lost.

To destroy a `VkSurfaceKHR` object, call:
### vi void vkDestroySurfaceKHR

- `instance` is the instance used to create the surface.
- `surface` is the surface to destroy.
- `pAllocator` is the allocator used for host memory allocated for the surface object when there is no more specific allocator available (see Memory Allocation).

Destroying a `VkSurfaceKHR` merely severs the connection between Vulkan and the native surface, and does not imply destroying the native surface, closing a window, or similar behavior.

### Valid Usage

- All `VkSwapchainKHR` objects created for `surface` must have been destroyed prior to destroying `surface`
- If `VkAllocationCallbacks` were provided when `surface` was created, a compatible set of callbacks must be provided here
- If no `VkAllocationCallbacks` were provided when `surface` was created, `pAllocator` must be `NULL`

### Valid Usage (Implicit)

- `instance` must be a valid `VkInstance` handle
- If `surface` is not `VK_NULL_HANDLE`, `surface` must be a valid `VkSurfaceKHR` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `surface` is a valid handle, it must have been created, allocated, or retrieved from `instance`

### Host Synchronization

- Host access to `surface` must be externally synchronized

### 29.3. Presenting Directly to Display Devices

In some environments applications can also present Vulkan rendering directly to display devices without using an intermediate windowing system. This can be useful for embedded applications, or implementing the rendering/presentation backend of a windowing system using Vulkan. The `VK_KHR_display` extension provides the functionality necessary to enumerate display devices and...
create `VkSurfaceKHR` objects that target displays.

### 29.3.1. Display Enumeration

Displays are represented by `VkDisplayKHR` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDisplayKHR)
```

Various functions are provided for enumerating the available display devices present on a Vulkan physical device. To query information about the available displays, call:

```c
VkResult vkGetPhysicalDeviceDisplayPropertiesKHR(
    VkPhysicalDevice physicalDevice,
    uint32_t* pPropertyCount,
    VkDisplayPropertiesKHR* pProperties);
```

- `physicalDevice` is a physical device.
- `pPropertyCount` is a pointer to an integer related to the number of display devices available or queried, as described below.
- `pProperties` is either `NULL` or a pointer to an array of `VkDisplayPropertiesKHR` structures.

If `pProperties` is `NULL`, then the number of display devices available for `physicalDevice` is returned in `pPropertyCount`. Otherwise, `pPropertyCount` must point to a variable set by the user to the number of elements in the `pProperties` array, and on return the variable is overwritten with the number of structures actually written to `pProperties`. If the value of `pPropertyCount` is less than the number of display devices for `physicalDevice`, at most `pPropertyCount` structures will be written. If `pPropertyCount` is smaller than the number of display devices available for `physicalDevice`, `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS` to indicate that not all the available values were returned.

### Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pPropertyCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pPropertyCount` is not 0, and `pProperties` is not `NULL`, `pProperties` must be a valid pointer to an array of `pPropertyCount` `VkDisplayPropertiesKHR` structures
Return Codes

Success
- VK_SUCCESS
- VK_INCOMPLETE

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkDisplayPropertiesKHR` structure is defined as:

```c
typedef struct VkDisplayPropertiesKHR {
    VkDisplayKHR display;
    const char* displayName;
    VkExtent2D physicalDimensions;
    VkExtent2D physicalResolution;
    VkSurfaceTransformFlagsKHR supportedTransforms;
    VkBool32 planeReorderPossible;
    VkBool32 persistentContent;
} VkDisplayPropertiesKHR;
```

- `display` is a handle that is used to refer to the display described here. This handle will be valid for the lifetime of the Vulkan instance.

- `displayName` is a pointer to a null-terminated UTF-8 string containing the name of the display. Generally, this will be the name provided by the display’s EDID. It can be `NULL` if no suitable name is available. If not `NULL`, the memory it points to must remain accessible as long as `display` is valid.

- `physicalDimensions` describes the physical width and height of the visible portion of the display, in millimeters.

- `physicalResolution` describes the physical, native, or preferred resolution of the display.

  **Note**
  For devices which have no natural value to return here, implementations should return the maximum resolution supported.

- `supportedTransforms` is a bitmask of `VkSurfaceTransformFlagBitsKHR` describing which transforms are supported by this display.

- `planeReorderPossible` tells whether the planes on this display can have their z order changed. If this is `VK_TRUE`, the application can re-arrange the planes on this display in any order relative to each other.

- `persistentContent` tells whether the display supports self-refresh/internal buffering. If this is true, the application can submit persistent present operations on swapchains created against this display.
Note
Persistent presents **may** have higher latency, and **may** use less power when the screen content is updated infrequently, or when only a portion of the screen needs to be updated in most frames.

To query information about the available displays, call:

```c
VkResult vkGetPhysicalDeviceDisplayProperties2KHR(
    VkPhysicalDevice                            physicalDevice,
    uint32_t*                                   pPropertyCount,
    VkDisplayProperties2KHR*                    pProperties);
```

- **physicalDevice** is a physical device.
- **pPropertyCount** is a pointer to an integer related to the number of display devices available or queried, as described below.
- **pProperties** is either **NULL** or a pointer to an array of **VkDisplayProperties2KHR** structures.

vkGetPhysicalDeviceDisplayProperties2KHR behaves similarly to vkGetPhysicalDeviceDisplayPropertiesKHR, with the ability to return extended information via chained output structures.

### Valid Usage (Implicit)

- **physicalDevice** **must** be a valid `VkPhysicalDevice` handle
- **pPropertyCount** **must** be a valid pointer to a `uint32_t` value
- If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not **NULL**, **pProperties** **must** be a valid pointer to an array of `pPropertyCount` `VkDisplayProperties2KHR` structures

### Return Codes

**Success**
- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkDisplayProperties2KHR` structure is defined as:
typedef struct VkDisplayProperties2KHR {
    VkStructureType    sType;
    void*               pNext;
    VkDisplayPropertiesKHR displayProperties;
} VkDisplayProperties2KHR;

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `displayProperties` is a `VkDisplayPropertiesKHR` structure.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_DISPLAY_PROPERTIES_2_KHR`
- `pNext` must be NULL

Display Planes

Images are presented to individual planes on a display. Devices **must** support at least one plane on each display. Planes **can** be stacked and blended to composite multiple images on one display. Devices **may** support only a fixed stacking order and fixed mapping between planes and displays, or they **may** allow arbitrary application specified stacking orders and mappings between planes and displays. To query the properties of device display planes, call:

```c
VkResult vkGetPhysicalDeviceDisplayPlanePropertiesKHR(
    VkPhysicalDevice   physicalDevice,  
    uint32_t*          pPropertyCount,  
    VkDisplayPlanePropertiesKHR* pProperties);
```

- `physicalDevice` is a physical device.
- `pPropertyCount` is a pointer to an integer related to the number of display planes available or queried, as described below.
- `pProperties` is either NULL or a pointer to an array of `VkDisplayPlanePropertiesKHR` structures.

If `pProperties` is NULL, then the number of display planes available for `physicalDevice` is returned in `pPropertyCount`. Otherwise, `pPropertyCount` **must** point to a variable set by the user to the number of elements in the `pProperties` array, and on return the variable is overwritten with the number of structures actually written to `pProperties`. If the value of `pPropertyCount` is less than the number of display planes for `physicalDevice`, at most `pPropertyCount` structures will be written.
Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pPropertyCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pPropertyCount` is not 0, and `pProperties` is not NULL, `pProperties` must be a valid pointer to an array of `pPropertyCount` `VkDisplayPlanePropertiesKHR` structures

Return Codes

Success

- `VK_SUCCESS`
- `VK_INCOMPLETE`

Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkDisplayPlanePropertiesKHR` structure is defined as:

```c
typedef struct VkDisplayPlanePropertiesKHR {
    VkDisplayKHR currentDisplay;
    uint32_t currentStackIndex;
} VkDisplayPlanePropertiesKHR;
```

- `currentDisplay` is the handle of the display the plane is currently associated with. If the plane is not currently attached to any displays, this will be `VK_NULL_HANDLE`.
- `currentStackIndex` is the current z-order of the plane. This will be between 0 and the value returned by `vkGetPhysicalDeviceDisplayPlanePropertiesKHR` in `pPropertyCount`.

To query the properties of a device's display planes, call:

```c
VkResult vkGetPhysicalDeviceDisplayPlaneProperties2KHR(
    VkPhysicalDevice physicalDevice,       physicalDevice,
    uint32_t* pPropertyCount,              pPropertyCount,
    VkDisplayPlaneProperties2KHR* pProperties);
```

- `physicalDevice` is a physical device.
- `pPropertyCount` is a pointer to an integer related to the number of display planes available or queried, as described below.
- `pProperties` is either NULL or a pointer to an array of `VkDisplayPlaneProperties2KHR` structures.

`vkGetPhysicalDeviceDisplayPlaneProperties2KHR` behaves similarly to...
VkGetPhysicalDeviceDisplayPlaneProperties2KHR, with the ability to return extended information via chained output structures.

**Valid Usage (Implicit)**

- **physicalDevice** must be a valid VkPhysicalDevice handle
- **pPropertyCount** must be a valid pointer to a uint32_t value
- If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not NULL, **pProperties** must be a valid pointer to an array of **pPropertyCount** VkDisplayPlaneProperties2KHR structures

**Return Codes**

**Success**

- VK_SUCCESS
- VK_INCOMPLETE

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The **VkDisplayPlaneProperties2KHR** structure is defined as:

```c
typedef struct VkDisplayPlaneProperties2KHR {
    VkStructureType               sType;
    void*                         pNext;
    VkDisplayPlanePropertiesKHR    displayPlaneProperties;
} VkDisplayPlaneProperties2KHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **displayPlaneProperties** is a VkDisplayPlanePropertiesKHR structure.

**Valid Usage (Implicit)**

- **sType** must be VK_STRUCTURE_TYPE_DISPLAY_PLANE_PROPERTIES_2_KHR
- **pNext** must be NULL

To determine which displays a plane is usable with, call
VkResult vkGetDisplayPlaneSupportedDisplaysKHR(
    VkPhysicalDevice                            physicalDevice,
    uint32_t                                    planeIndex,
    uint32_t*                                   pDisplayCount,
    VkDisplayKHR*                               pDisplays);

- `physicalDevice` is a physical device.
- `planeIndex` is the plane which the application wishes to use, and **must** be in the range [0, physical device plane count - 1].
- `pDisplayCount` is a pointer to an integer related to the number of displays available or queried, as described below.
- `pDisplays` is either **NULL** or a pointer to an array of `VkDisplayKHR` handles.

If `pDisplays` is **NULL**, then the number of displays usable with the specified `planeIndex` for `physicalDevice` is returned in `pDisplayCount`. Otherwise, `pDisplayCount` **must** point to a variable set by the user to the number of elements in the `pDisplays` array, and on return the variable is overwritten with the number of handles actually written to `pDisplays`. If the value of `pDisplayCount` is less than the number of display planes for `physicalDevice`, at most `pDisplayCount` handles will be written. If `pDisplayCount` is smaller than the number of displays usable with the specified `planeIndex` for `physicalDevice`, `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS` to indicate that not all the available values were returned.

### Valid Usage

- `planeIndex` **must** be less than the number of display planes supported by the device as determined by calling `vkGetPhysicalDeviceDisplayPlanePropertiesKHR`

### Valid Usage (Implicit)

- `physicalDevice` **must** be a valid `VkPhysicalDevice` handle
- `pDisplayCount` **must** be a valid pointer to a `uint32_t` value
- If the value referenced by `pDisplayCount` is not 0, and `pDisplays` is not **NULL**, `pDisplays` **must** be a valid pointer to an array of `pDisplayCount` `VkDisplayKHR` handles
Return Codes

Success
- VK_SUCCESS
- VK_INCOMPLETE

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

Additional properties of displays are queried using specialized query functions.

Display Modes

Display modes are represented by VkDisplayModeKHR handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDisplayModeKHR)
```

Each display has one or more supported modes associated with it by default. These built-in modes are queried by calling:

```c
VkResult vkGetDisplayModePropertiesKHR(
    VkPhysicalDevice physicalDevice,
    VkDisplayKHR display,
    uint32_t* pPropertyCount,
    VkDisplayModePropertiesKHR* pProperties);
```

- **physicalDevice** is the physical device associated with **display**.
- **display** is the display to query.
- **pPropertyCount** is a pointer to an integer related to the number of display modes available or queried, as described below.
- **pProperties** is either NULL or a pointer to an array of VkDisplayModePropertiesKHR structures.

If **pProperties** is NULL, then the number of display modes available on the specified **display** for **physicalDevice** is returned in **pPropertyCount**. Otherwise, **pPropertyCount** must point to a variable set by the user to the number of elements in the **pProperties** array, and on return the variable is overwritten with the number of structures actually written to **pProperties**. If the value of **pPropertyCount** is less than the number of display modes for **physicalDevice**, at most **pPropertyCount** structures will be written. If **pPropertyCount** is smaller than the number of display modes available on the specified **display** for **physicalDevice**, **VK_INCOMPLETE** will be returned instead of **VK_SUCCESS** to indicate that not all the available values were returned.
Valid Usage (Implicit)

- **physicalDevice** must be a valid VkPhysicalDevice handle
- **display** must be a valid VkDisplayKHR handle
- **pPropertyCount** must be a valid pointer to a uint32_t value
- If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not NULL, **pProperties** must be a valid pointer to an array of **pPropertyCount** VkDisplayModePropertiesKHR structures
- **display** must have been created, allocated, or retrieved from **physicalDevice**

Return Codes

**Success**
- VK_SUCCESS
- VK_INCOMPLETE

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkDisplayModePropertiesKHR structure is defined as:

```c
typedef struct VkDisplayModePropertiesKHR {
    VkDisplayModeKHR displayMode;
    VkDisplayModeParametersKHR parameters;
} VkDisplayModePropertiesKHR;
```

- **displayMode** is a handle to the display mode described in this structure. This handle will be valid for the lifetime of the Vulkan instance.
- **parameters** is a VkDisplayModeParametersKHR structure describing the display parameters associated with **displayMode**.

```c
typedef VkFlags VkDisplayModeCreateFlagsKHR;
```

**VkDisplayModeCreateFlagsKHR** is a bitmask type for setting a mask, but is currently reserved for future use.

To query the properties of a device’s built-in display modes, call:
vkGetDisplayModeProperties2KHR(physicalDevice, display, pPropertyCount, pProperties);

- **physicalDevice** is the physical device associated with **display**.
- **display** is the display to query.
- **pPropertyCount** is a pointer to an integer related to the number of display modes available or queried, as described below.
- **pProperties** is either **NULL** or a pointer to an array of **VkDisplayModeProperties2KHR** structures.

**vkGetDisplayModeProperties2KHR** behaves similarly to **vkGetDisplayModePropertiesKHR**, with the ability to return extended information via chained output structures.

### Valid Usage (Implicit)

- **physicalDevice** must be a valid **VkPhysicalDevice** handle
- **display** must be a valid **VkDisplayKHR** handle
- **pPropertyCount** must be a valid pointer to a **uint32_t** value
- If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not **NULL**, **pProperties** must be a valid pointer to an array of **pPropertyCount** **VkDisplayModeProperties2KHR** structures
- **display** must have been created, allocated, or retrieved from **physicalDevice**

### Return Codes

**Success**
- **VK_SUCCESS**
- **VK_INCOMPLETE**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

The **VkDisplayModeProperties2KHR** structure is defined as:

```c
typedef struct VkDisplayModeProperties2KHR {
    VkStructureType               sType;
    void*                         pNext;
    VkDisplayModePropertiesKHR    displayModeProperties;
} VkDisplayModeProperties2KHR;
```
• **sType** is the type of this structure.
• **pNext** is **NULL** or a pointer to an extension-specific structure.
• **displayModeProperties** is a **VkDisplayModePropertiesKHR** structure.

### Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_DISPLAY_MODE_PROPERTIES_2_KHR**
- **pNext** must be **NULL**

The **VkDisplayModeParametersKHR** structure is defined as:

```c
typedef struct VkDisplayModeParametersKHR {
    VkExtent2D visibleRegion;
    uint32_t refreshRate;
} VkDisplayModeParametersKHR;
```

- **visibleRegion** is the 2D extents of the visible region.
- **refreshRate** is a **uint32_t** that is the number of times the display is refreshed each second multiplied by 1000.

**Note**
For example, a 60Hz display mode would report a **refreshRate** of 60,000.

### Valid Usage

- The **width** member of **visibleRegion** must be greater than 0
- The **height** member of **visibleRegion** must be greater than 0
- **refreshRate** must be greater than 0

Additional modes **may** also be created by calling:

```c
VkResult vkCreateDisplayModeKHR(
    VkPhysicalDevice physicalDevice,                  
    VkDisplayKHR display,                              
    const VkDisplayModeCreateInfoKHR* pCreateInfo,    
    const VkAllocationCallbacks* pAllocator,          
    VkDisplayModeKHR* pMode);
```

- **physicalDevice** is the physical device associated with **display**.
- **display** is the display to create an additional mode for.
- **pCreateInfo** is a **VkDisplayModeCreateInfoKHR** structure describing the new mode to create.
• \texttt{pAllocator} is the allocator used for host memory allocated for the display mode object when there is no more specific allocator available (see Memory Allocation).

• \texttt{pMode} returns the handle of the mode created.

<table>
<thead>
<tr>
<th>Valid Usage (Implicit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textbf{physicalDevice must} be a valid \texttt{VkPhysicalDevice} handle</td>
</tr>
<tr>
<td>\textbf{display must} be a valid \texttt{VkDisplayKHR} handle</td>
</tr>
<tr>
<td>\textbf{pCreateInfo must} be a valid pointer to a valid \texttt{VkDisplayModeCreateInfoKHR} structure</td>
</tr>
</tbody>
</table>

  • If \texttt{pAllocator} is not NULL, \textbf{pAllocator must} be a valid pointer to a valid \texttt{VkAllocationCallbacks} structure

  • \textbf{pMode must} be a valid pointer to a \texttt{VkDisplayModeKHR} handle

  • \textbf{display must} have been created, allocated, or retrieved from \texttt{physicalDevice}

<table>
<thead>
<tr>
<th>Host Synchronization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host access to \textbf{display} must be externally synchronized</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Return Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Success</strong></td>
</tr>
<tr>
<td>\textbf{VK_SUCCESS}</td>
</tr>
</tbody>
</table>

| **Failure** |
| \textbf{VK\_ERROR\_OUT\_OF\_HOST\_MEMORY} |
| \textbf{VK\_ERROR\_OUT\_OF\_DEVICE\_MEMORY} |
| \textbf{VK\_ERROR\_INITIALIZATION\_FAILED} |

The \texttt{VkDisplayModeCreateInfoKHR} structure is defined as:

```c
typedef struct VkDisplayModeCreateInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkDisplayModeCreateFlagsKHR flags;
    VkDisplayModeParametersKHR parameters;
} VkDisplayModeCreateInfoKHR;
```

• \texttt{sType} is the type of this structure.

• \texttt{pNext} is \texttt{NULL} or a pointer to an extension-specific structure.

• \texttt{flags} is reserved for future use, and \textbf{must} be zero.

• \texttt{parameters} is a \texttt{VkDisplayModeParametersKHR} structure describing the display parameters to
use in creating the new mode. If the parameters are not compatible with the specified display, the implementation must return `VK_ERROR_INITIALIZATION_FAILED`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_DISPLAY_MODE_CREATE_INFO_KHR`
- `pNext` must be `NULL`
- `flags` must be `0`
- `parameters` must be a valid `VkDisplayModeParametersKHR` structure

Applications that wish to present directly to a display must select which layer, or “plane” of the display they wish to target, and a mode to use with the display. Each display supports at least one plane. The capabilities of a given mode and plane combination are determined by calling:

```
VkResult vkGetDisplayPlaneCapabilitiesKHR(
    VkPhysicalDevice                            physicalDevice,
    VkDisplayModeKHR                            mode,
    uint32_t                                    planeIndex,
    VkDisplayPlaneCapabilitiesKHR*              pCapabilities);
```

- `physicalDevice` is the physical device associated with display
- `mode` is the display mode the application intends to program when using the specified plane. Note this parameter also implicitly specifies a display.
- `planeIndex` is the plane which the application intends to use with the display, and is less than the number of display planes supported by the device.
- `pCapabilities` is a pointer to a `VkDisplayPlaneCapabilitiesKHR` structure in which the capabilities are returned.

Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `mode` must be a valid `VkDisplayModeKHR` handle
- `pCapabilities` must be a valid pointer to a `VkDisplayPlaneCapabilitiesKHR` structure

Host Synchronization

- Host access to `mode` must be externally synchronized
Return Codes

Success

- VK_SUCCESS

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

The VkDisplayPlaneCapabilitiesKHR structure is defined as:

```c
typedef struct VkDisplayPlaneCapabilitiesKHR {
    VkDisplayPlaneAlphaFlagsKHR supportedAlpha;
    VkOffset2D minSrcPosition;
    VkOffset2D maxSrcPosition;
    VkExtent2D minSrcExtent;
    VkExtent2D maxSrcExtent;
    VkOffset2D minDstPosition;
    VkOffset2D maxDstPosition;
    VkExtent2D minDstExtent;
    VkExtent2D maxDstExtent;
} VkDisplayPlaneCapabilitiesKHR;
```

- `supportedAlpha` is a bitmask of VkDisplayPlaneAlphaFlagBitsKHR describing the supported alpha blending modes.
- `minSrcPosition` is the minimum source rectangle offset supported by this plane using the specified mode.
- `maxSrcPosition` is the maximum source rectangle offset supported by this plane using the specified mode. The x and y components of `maxSrcPosition` must each be greater than or equal to the x and y components of `minSrcPosition`, respectively.
- `minSrcExtent` is the minimum source rectangle size supported by this plane using the specified mode.
- `maxSrcExtent` is the maximum source rectangle size supported by this plane using the specified mode.
- `minDstPosition`, `maxDstPosition`, `minDstExtent`, `maxDstExtent` all have similar semantics to their corresponding *Src* equivalents, but apply to the output region within the mode rather than the input region within the source image. Unlike the *Src* offsets, `minDstPosition` and `maxDstPosition` may contain negative values.

The minimum and maximum position and extent fields describe the implementation limits, if any, as they apply to the specified display mode and plane. Vendors may support displaying a subset of a swapchain's presentable images on the specified display plane. This is expressed by returning `minSrcPosition`, `maxSrcPosition`, `minSrcExtent`, and `maxSrcExtent` values that indicate a range of possible positions and sizes may be used to specify the region within the presentable images that source pixels will be read from when creating a swapchain on the specified display mode and
plane.

Vendors may also support mapping the presentable images' content to a subset or superset of the visible region in the specified display mode. This is expressed by returning minDstPosition, maxDstPosition, minDstExtent and maxDstExtent values that indicate a range of possible positions and sizes may be used to describe the region within the display mode that the source pixels will be mapped to.

Other vendors may support only a 1-1 mapping between pixels in the presentable images and the display mode. This may be indicated by returning (0,0) for minSrcPosition, maxSrcPosition, minDstPosition, and maxDstPosition, and (display mode width, display mode height) for minSrcExtent, maxSrcExtent, minDstExtent, and maxDstExtent.

These values indicate the limits of the implementation's individual fields. Not all combinations of values within the offset and extent ranges returned in VkDisplayPlaneCapabilitiesKHR are guaranteed to be supported. Presentation requests specifying unsupported combinations may fail.

To query the capabilities of a given mode and plane combination, call:

```c
VkResult vkGetDisplayPlaneCapabilities2KHR(
    VkPhysicalDevice physicalDevice,
    const VkDisplayPlaneInfo2KHR* pDisplayPlaneInfo,
    VkDisplayPlaneCapabilities2KHR* pCapabilities);
```

- physicalDevice is the physical device associated with pDisplayPlaneInfo.
- pDisplayPlaneInfo is a pointer to a VkDisplayPlaneInfo2KHR structure describing the plane and mode.
- pCapabilities is a pointer to a VkDisplayPlaneCapabilities2KHR structure in which the capabilities are returned.

vkGetDisplayPlaneCapabilities2KHR behaves similarly to vkGetDisplayPlaneCapabilitiesKHR, with the ability to specify extended inputs via chained input structures, and to return extended information via chained output structures.

### Valid Usage (Implicit)

- physicalDevice must be a valid VkPhysicalDevice handle
- pDisplayPlaneInfo must be a valid pointer to a valid VkDisplayPlaneInfo2KHR structure
- pCapabilities must be a valid pointer to a VkDisplayPlaneCapabilities2KHR structure
Return Codes

Success

• VK_SUCCESS

Failure

• VK_ERROR_OUT_OF_HOST_MEMORY
• VK_ERROR_OUT_OF_DEVICE_MEMORY

The `VkDisplayPlaneInfo2KHR` structure is defined as:

```c
typedef struct VkDisplayPlaneInfo2KHR {
    VkStructureType sType;
    const void* pNext;
    VkDisplayModeKHR mode;
    uint32_t planeIndex;
} VkDisplayPlaneInfo2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `mode` is the display mode the application intends to program when using the specified plane.

**Note**

This parameter also implicitly specifies a display.

- `planeIndex` is the plane which the application intends to use with the display.

The members of `VkDisplayPlaneInfo2KHR` correspond to the arguments to `vkGetDisplayPlaneCapabilitiesKHR`, with `sType` and `pNext` added for extensibility.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_DISPLAY_PLANE_INFO_2_KHR`
- `pNext` must be `NULL`
- `mode` must be a valid `VkDisplayModeKHR` handle

Host Synchronization

- Host access to `mode` must be externally synchronized

The `VkDisplayPlaneCapabilities2KHR` structure is defined as:
typedef struct VkDisplayPlaneCapabilities2KHR {
    VkStructureType                  sType;
    void*                            pNext;
    VkDisplayPlaneCapabilitiesKHR    capabilities;
} VkDisplayPlaneCapabilities2KHR;

• sType is the type of this structure.
• pNext is NULL or a pointer to an extension-specific structure.
• capabilities is a VkDisplayPlaneCapabilitiesKHR structure.

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_DISPLAY_PLANE_CAPABILITIES_2_KHR
• pNext must be NULL

29.3.2. Display Surfaces

A complete display configuration includes a mode, one or more display planes and any parameters describing their behavior, and parameters describing some aspects of the images associated with those planes. Display surfaces describe the configuration of a single plane within a complete display configuration. To create a VkSurfaceKHR structure for a display surface, call:

VkResult vkCreateDisplayPlaneSurfaceKHR(                        
    VkInstance                                  instance, 
    const VkDisplaySurfaceCreateInfoKHR*        pCreateInfo, 
    const VkAllocationCallbacks*                pAllocator, 
    VkSurfaceKHR*                               pSurface);

• instance is the instance corresponding to the physical device the targeted display is on.
• pCreateInfo is a pointer to a VkDisplaySurfaceCreateInfoKHR structure specifying which mode, plane, and other parameters to use, as described below.
• pAllocator is the allocator used for host memory allocated for the surface object when there is no more specific allocator available (see Memory Allocation).
• pSurface is a pointer to a VkSurfaceKHR handle in which the created surface is returned.
Valid Usage (Implicit)

- **instance** must be a valid `VkInstance` handle
- **pCreateInfo** must be a valid pointer to a valid `VkDisplaySurfaceCreateInfoKHR` structure
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pSurface** must be a valid pointer to a `VkSurfaceKHR` handle

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkDisplaySurfaceCreateInfoKHR` structure is defined as:

```c
typedef struct VkDisplaySurfaceCreateInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkDisplaySurfaceCreateFlagsKHR flags;
    VkDisplayModeKHR displayMode;
    uint32_t planeIndex;
    uint32_t planeStackIndex;
    VkSurfaceTransformFlagBitsKHR transform;
    float globalAlpha;
    VkDisplayPlaneAlphaFlagBitsKHR alphaMode;
    VkExtent2D imageExtent;
} VkDisplaySurfaceCreateInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **flags** is reserved for future use, and **must** be zero.
- **displayMode** is a `VkDisplayModeKHR` handle specifying the mode to use when displaying this surface.
- **planeIndex** is the plane on which this surface appears.
- **planeStackIndex** is the z-order of the plane.
- **transform** is a `VkSurfaceTransformFlagBitsKHR` value specifying the transformation to apply to images as part of the scanout operation.
- **globalAlpha** is the global alpha value. This value is ignored if `alphaMode` is not
• **alphaMode** is a `VkDisplayPlaneAlphaFlagBitsKHR` value specifying the type of alpha blending to use.

• **imageExtent** The size of the presentable images to use with the surface.

**Note**
Creating a display surface must not modify the state of the displays, planes, or other resources it names. For example, it must not apply the specified mode to be set on the associated display. Application of display configuration occurs as a side effect of presenting to a display surface.

**Valid Usage**

• **planeIndex** must be less than the number of display planes supported by the device as determined by calling `vkGetPhysicalDeviceDisplayPlanePropertiesKHR`

• If the **planeReorderPossible** member of the `VkDisplayPropertiesKHR` structure returned by `vkGetPhysicalDeviceDisplayPropertiesKHR` for the display corresponding to **displayMode** is **VK_TRUE** then **planeStackIndex** must be less than the number of display planes supported by the device as determined by calling `vkGetPhysicalDeviceDisplayPlanePropertiesKHR`; otherwise **planeStackIndex** must equal the **currentStackIndex** member of `VkDisplayPlanePropertiesKHR` returned by `vkGetPhysicalDeviceDisplayPlanePropertiesKHR` for the display plane corresponding to **displayMode**

• If **alphaMode** is **VK_DISPLAY_PLANE_ALPHA_GLOBAL_BIT_KHR** then **globalAlpha** must be between 0 and 1, inclusive

• **alphaMode** must be 0 or one of the bits present in the **supportedAlpha** member of `VkDisplayPlaneCapabilitiesKHR` returned by `vkGetDisplayPlaneCapabilitiesKHR` for the display plane corresponding to **displayMode**

• The **width** and **height** members of **imageExtent** must be less than the **maxImageDimensions2D** member of `VkPhysicalDeviceLimits`

**Valid Usage (Implicit)**

• **sType** must be `VK_STRUCTURE_TYPE_DISPLAY_SURFACE_CREATE_INFO_KHR`

• **pNext** must be NULL

• **flags** must be 0

• **displayMode** must be a valid `VkDisplayModeKHR` handle

• **transform** must be a valid `VkSurfaceTransformFlagBitsKHR` value

• **alphaMode** must be a valid `VkDisplayPlaneAlphaFlagBitsKHR` value

```c
typedef VkFlags VkDisplaySurfaceCreateFlagsKHR;
```
VkDisplaySurfaceCreateFlagsKHR is a bitmask type for setting a mask, but is currently reserved for future use.

Possible values of VkDisplaySurfaceCreateInfoKHR::alphaMode, specifying the type of alpha blending to use on a display, are:

```c
typedef enum VkDisplayPlaneAlphaFlagBitsKHR {
    VK_DISPLAY_PLANE_ALPHA_OPAQUE_BIT_KHR = 0x00000001,
    VK_DISPLAY_PLANE_ALPHA_GLOBAL_BIT_KHR = 0x00000002,
    VK_DISPLAY_PLANE_ALPHA_PER_PIXEL_BIT_KHR = 0x00000004,
    VK_DISPLAY_PLANE_ALPHA_PER_PIXEL_PREMULTIPLIED_BIT_KHR = 0x00000008,
    VK_DISPLAY_PLANE_ALPHA_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkDisplayPlaneAlphaFlagBitsKHR;
```

- **VK_DISPLAY_PLANE_ALPHA_OPAQUE_BIT_KHR** specifies that the source image will be treated as opaque.
- **VK_DISPLAY_PLANE_ALPHA_GLOBAL_BIT_KHR** specifies that a global alpha value must be specified that will be applied to all pixels in the source image.
- **VK_DISPLAY_PLANE_ALPHA_PER_PIXEL_BIT_KHR** specifies that the alpha value will be determined by the alpha channel of the source image’s pixels. If the source format contains no alpha values, no blending will be applied. The source alpha values are not premultiplied into the source image’s other color channels.
- **VK_DISPLAY_PLANE_ALPHA_PER_PIXEL_PREMULTIPLIED_BIT_KHR** is equivalent to **VK_DISPLAY_PLANE_ALPHA_PER_PIXEL_BIT_KHR**, except the source alpha values are assumed to be premultiplied into the source image’s other color channels.

```c
typedef VkFlags VkDisplayPlaneAlphaFlagsKHR;
```

VkDisplayPlaneAlphaFlagsKHR is a bitmask type for setting a mask of zero or more VkDisplayPlaneAlphaFlagBitsKHR.

### 29.4. Querying for WSI Support

Not all physical devices will include WSI support. Within a physical device, not all queue families will support presentation. WSI support and compatibility can be determined in a platform-neutral manner (which determines support for presentation to a particular surface object) and additionally may be determined in platform-specific manners (which determine support for presentation on the specified physical device but do not guarantee support for presentation to a particular surface object).

To determine whether a queue family of a physical device supports presentation to a given surface, call:
VkResult vkGetPhysicalDeviceSurfaceSupportKHR(
    VkPhysicalDevice physicalDevice,
    uint32_t queueFamilyIndex,
    VkSurfaceKHR surface,
    VkBool32* pSupported);

- **physicalDevice** is the physical device.
- **queueFamilyIndex** is the queue family.
- **surface** is the surface.
- **pSupported** is a pointer to a VkBool32, which is set to VK_TRUE to indicate support, and VK_FALSE otherwise.

### Valid Usage
- **queueFamilyIndex** must be less than pQueueFamilyPropertyCount returned by vkGetPhysicalDeviceQueueFamilyProperties for the given physicalDevice

### Valid Usage (Implicit)
- **physicalDevice** must be a valid VkPhysicalDevice handle
- **surface** must be a valid VkSurfaceKHR handle
- **pSupported** must be a valid pointer to a VkBool32 value
- Both of physicalDevice, and surface must have been created, allocated, or retrieved from the same VkInstance

### Return Codes

#### Success
- VK_SUCCESS

#### Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_SURFACE_LOST_KHR

### 29.4.1. Android Platform

On Android, all physical devices and queue families must be capable of presentation with any native window. As a result there is no Android-specific query for these capabilities.
29.4.2. Wayland Platform

To determine whether a queue family of a physical device supports presentation to a Wayland compositor, call:

```c
VkBool32 vkGetPhysicalDeviceWaylandPresentationSupportKHR(
    VkPhysicalDevice physicalDevice,
    uint32_t queueFamilyIndex,
    struct wl_display* display);
```

- `physicalDevice` is the physical device.
- `queueFamilyIndex` is the queue family index.
- `display` is a pointer to the `wl_display` associated with a Wayland compositor.

This platform-specific function can be called prior to creating a surface.

**Valid Usage**

- `queueFamilyIndex` must be less than `pQueueFamilyPropertyCount` returned by
  `vkGetPhysicalDeviceQueueFamilyProperties` for the given `physicalDevice`

**Valid Usage (Implicit)**

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `display` must be a valid pointer to a `wl_display` value

29.4.3. Win32 Platform

To determine whether a queue family of a physical device supports presentation to the Microsoft Windows desktop, call:

```c
VkBool32 vkGetPhysicalDeviceWin32PresentationSupportKHR(
    VkPhysicalDevice physicalDevice,
    uint32_t queueFamilyIndex);
```

- `physicalDevice` is the physical device.
- `queueFamilyIndex` is the queue family index.

This platform-specific function can be called prior to creating a surface.
Valid Usage

- `queueFamilyIndex` must be less than `pQueueFamilyPropertyCount` returned by `vkGetPhysicalDeviceQueueFamilyProperties` for the given `physicalDevice`

Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle

29.4.4. XCB Platform

To determine whether a queue family of a physical device supports presentation to an X11 server, using the XCB client-side library, call:

```c
VkBool32 vkGetPhysicalDeviceXcbPresentationSupportKHR(
    VkPhysicalDevice physicalDevice,
    uint32_t queueFamilyIndex,
    xcb_connection_t* connection,
    xcb_visualid_t visual_id);
```

- `physicalDevice` is the physical device.
- `queueFamilyIndex` is the queue family index.
- `connection` is a pointer to an `xcb_connection_t` to the X server.
- `visual_id` is an X11 visual (`xcb_visualid_t`).

This platform-specific function can be called prior to creating a surface.

Valid Usage

- `queueFamilyIndex` must be less than `pQueueFamilyPropertyCount` returned by `vkGetPhysicalDeviceQueueFamilyProperties` for the given `physicalDevice`

Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `connection` must be a valid pointer to an `xcb_connection_t` value

29.4.5. Xlib Platform

To determine whether a queue family of a physical device supports presentation to an X11 server, using the Xlib client-side library, call:
VkBool32 vkGetPhysicalDeviceXlibPresentationSupportKHR(
    VkPhysicalDevice physicalDevice,
    uint32_t queueFamilyIndex,
    Display* dpy,
    VisualID visualID);

- `physicalDevice` is the physical device.
- `queueFamilyIndex` is the queue family index.
- `dpy` is a pointer to an Xlib `Display` connection to the server.
- `visualID` is an X11 visual (`VisualID`).

This platform-specific function can be called prior to creating a surface.

### Valid Usage

- `queueFamilyIndex` must be less than `pQueueFamilyPropertyCount` returned by `vkGetPhysicalDeviceQueueFamilyProperties` for the given `physicalDevice`

### Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `dpy` must be a valid pointer to a `Display` value

## 29.5. Surface Queries

The capabilities of a swapchain targeting a surface are the intersection of the capabilities of the WSI platform, the native window or display, and the physical device. The resulting capabilities can be obtained with the queries listed below in this section.

### Note

In addition to the surface capabilities as obtained by surface queries below, swapchain images are also subject to ordinary image creation limits as reported by `vkGetPhysicalDeviceImageFormatProperties`. As an application is instructed by the appropriate Valid Usage sections, both the surface capabilities and the image creation limits have to be satisfied whenever swapchain images are created.

### 29.5.1. Surface Capabilities

To query the basic capabilities of a surface, needed in order to create a swapchain, call:
VkResult vkGetPhysicalDeviceSurfaceCapabilitiesKHR(
    VkPhysicalDevice                            physicalDevice,
    VkSurfaceKHR                                surface,
    VkSurfaceCapabilitiesKHR*                   pSurfaceCapabilities);

• **physicalDevice** is the physical device that will be associated with the swapchain to be created, as described for `vkCreateSwapchainKHR`.

• **surface** is the surface that will be associated with the swapchain.

• **pSurfaceCapabilities** is a pointer to a `VkSurfaceCapabilitiesKHR` structure in which the capabilities are returned.

### Valid Usage (Implicit)

- **physicalDevice** must be a valid `VkPhysicalDevice` handle
- **surface** must be a valid `VkSurfaceKHR` handle
- **pSurfaceCapabilities** must be a valid pointer to a `VkSurfaceCapabilitiesKHR` structure
- Both of **physicalDevice**, and **surface** must have been created, allocated, or retrieved from the same `VkInstance`

### Return Codes

**Success**
- **VK_SUCCESS**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**
- **VK_ERROR_SURFACE_LOST_KHR**

The `VkSurfaceCapabilitiesKHR` structure is defined as:
```c
typedef struct VkSurfaceCapabilitiesKHR {
    uint32_t minImageCount;
    uint32_t maxImageCount;
    VkExtent2D currentExtent;
    VkExtent2D minImageExtent;
    VkExtent2D maxImageExtent;
    uint32_t maxImageArrayLayers;
    VkSurfaceTransformFlagsKHR supportedTransforms;
    VkSurfaceTransformFlagBitsKHR currentTransform;
    VkCompositeAlphaFlagsKHR supportedCompositeAlpha;
    VkImageUsageFlags supportedUsageFlags;
} VkSurfaceCapabilitiesKHR;
```

- **minImageCount** is the minimum number of images the specified device supports for a swapchain created for the surface, and will be at least one.

- **maxImageCount** is the maximum number of images the specified device supports for a swapchain created for the surface, and will be either 0, or greater than or equal to minImageCount. A value of 0 means that there is no limit on the number of images, though there may be limits related to the total amount of memory used by presentable images.

- **currentExtent** is the current width and height of the surface, or the special value (0xFFFFFFFF, 0xFFFFFFFF) indicating that the surface size will be determined by the extent of a swapchain targeting the surface.

- **minImageExtent** contains the smallest valid swapchain extent for the surface on the specified device. The width and height of the extent will each be less than or equal to the corresponding width and height of currentExtent, unless currentExtent has the special value described above.

- **maxImageExtent** contains the largest valid swapchain extent for the surface on the specified device. The width and height of the extent will each be greater than or equal to the corresponding width and height of minImageExtent. The width and height of the extent will each be greater than or equal to the corresponding width and height of currentExtent, unless currentExtent has the special value described above.

- **maxImageArrayLayers** is the maximum number of layers presentable images can have for a swapchain created for this device and surface, and will be at least one.

- **supportedTransforms** is a bitmask of VkSurfaceTransformFlagBitsKHR indicating the presentation transforms supported for the surface on the specified device. At least one bit will be set.

- **currentTransform** is VkSurfaceTransformFlagBitsKHR value indicating the surface's current transform relative to the presentation engine's natural orientation.

- **supportedCompositeAlpha** is a bitmask of VkCompositeAlphaFlagBitsKHR, representing the alpha compositing modes supported by the presentation engine for the surface on the specified device, and at least one bit will be set. Opaque composition can be achieved in any alpha compositing mode by either using an image format that has no alpha component, or by ensuring that all pixels in the presentable images have an alpha value of 1.0.

- **supportedUsageFlags** is a bitmask of VkImageUsageFlagBits representing the ways the application can use the presentable images of a swapchain created with VkPresentModeKHR set.
to VK_PRESENT_MODE_IMMEDIATE_KHR, VK_PRESENT_MODE_MAILBOX_KHR, VK_PRESENT_MODE_FIFO_KHR or VK_PRESENT_MODE_FIFO_RELAXED_KHR for the surface on the specified device. VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT must be included in the set but implementations may support additional usages.

Note

Supported usage flags of a presentable image when using VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR or VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR presentation mode are provided by VkSharedPresentSurfaceCapabilitiesKHR::sharedPresentSupportedUsageFlags.

Note

Formulas such as min(N, maxImageCount) are not correct, since maxImageCount may be zero.

To query the basic capabilities of a surface defined by the core or extensions, call:

```c
VkResult vkGetPhysicalDeviceSurfaceCapabilities2KHR(
    VkPhysicalDevice                            physicalDevice,
    const VkPhysicalDeviceSurfaceInfo2KHR*      pSurfaceInfo,
    VkSurfaceCapabilities2KHR*                  pSurfaceCapabilities);
```

- **physicalDevice** is the physical device that will be associated with the swapchain to be created, as described for vkCreateSwapchainKHR.
- **pSurfaceInfo** is a pointer to a VkPhysicalDeviceSurfaceInfo2KHR structure describing the surface and other fixed parameters that would be consumed by vkCreateSwapchainKHR.
- **pSurfaceCapabilities** is a pointer to a VkSurfaceCapabilities2KHR structure in which the capabilities are returned.

vkGetPhysicalDeviceSurfaceCapabilities2KHR behaves similarly to vkGetPhysicalDeviceSurfaceCapabilitiesKHR, with the ability to specify extended inputs via chained input structures, and to return extended information via chained output structures.

**Valid Usage (Implicit)**

- **physicalDevice** must be a valid VkPhysicalDevice handle
- **pSurfaceInfo** must be a valid pointer to a valid VkPhysicalDeviceSurfaceInfo2KHR structure
- **pSurfaceCapabilities** must be a valid pointer to a VkSurfaceCapabilities2KHR structure
Return Codes

Success
- VK_SUCCESS

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_SURFACE_LOST_KHR

The `VkPhysicalDeviceSurfaceInfo2KHR` structure is defined as:

```c
typedef struct VkPhysicalDeviceSurfaceInfo2KHR {
    VkStructureType    sType;
    const void*        pNext;
    VkSurfaceKHR       surface;
} VkPhysicalDeviceSurfaceInfo2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `surface` is the surface that will be associated with the swapchain.

The members of `VkPhysicalDeviceSurfaceInfo2KHR` correspond to the arguments to `vkGetPhysicalDeviceSurfaceCapabilitiesKHR`, with `sType` and `pNext` added for extensibility.

Valid Usage (Implicit)
- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SURFACE_INFO_2_KHR`
- `pNext` must be `NULL`
- `surface` must be a valid `VkSurfaceKHR` handle

The `VkSurfaceCapabilities2KHR` structure is defined as:

```c
typedef struct VkSurfaceCapabilities2KHR {
    VkStructureType             sType;
    void*                       pNext;
    VkSurfaceCapabilitiesKHR    surfaceCapabilities;
} VkSurfaceCapabilities2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `surfaceCapabilities` is a `VkSurfaceCapabilitiesKHR` structure describing the capabilities of the
An application queries if a protected `VkSurfaceKHR` is displayable on a specific windowing system using `VkSurfaceProtectedCapabilitiesKHR`, which can be passed in `pNext` parameter of `VkSurfaceCapabilities2KHR`.

The `VkSurfaceProtectedCapabilitiesKHR` structure is defined as:

```c
typedef struct VkSurfaceProtectedCapabilitiesKHR {
    VkStructureType    sType;
    const void*        pNext;
    VkBool32           supportsProtected;
} VkSurfaceProtectedCapabilitiesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `supportsProtected` specifies whether a protected swapchain created from `VkPhysicalDeviceSurfaceInfo2KHR:surface` for a particular windowing system can be displayed on screen or not. If `supportsProtected` is `VK_TRUE`, then creation of swapchains with the `VK_SWAPCHAIN_CREATE_PROTECTED_BIT_KHR` flag set must be supported for `surface`.

The `VkSharedPresentSurfaceCapabilitiesKHR` structure is defined as:

```c
typedef struct VkSharedPresentSurfaceCapabilitiesKHR {
    VkStructureType      sType;
    void*                pNext;
    VkImageUsageFlags    sharedPresentSupportedUsageFlags;
} VkSharedPresentSurfaceCapabilitiesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_SURFACE_PROTECTED_CAPABILITIES_KHR`
- `sharedPresentSupportedUsageFlags` is a bitmask of `VkImageUsageFlagBits` representing the ways the application can use the shared presentable image from a swapchain created with `VkPresentModeKHR` set to `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR` or `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR` for the surface on the specified device. `VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT` must be included in the set but implementations may support additional usages.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_SHARED_PRESENT_SURFACE_CAPABILITIES_KHR`.

Bits which may be set in `VkSurfaceCapabilitiesKHR::supportedTransforms` indicating the presentation transforms supported for the surface on the specified device, and possible values of `VkSurfaceCapabilitiesKHR::currentTransform` is indicating the surface's current transform relative to the presentation engine’s natural orientation, are:

```c
typedef enum VkSurfaceTransformFlagBitsKHR {
    VK_SURFACE_TRANSFORM_IDENTITY_BIT_KHR = 0x00000001,
    VK_SURFACE_TRANSFORM.Rotate_90_BIT_KHR = 0x00000002,
    VK_SURFACE_TRANSFORM.Rotate_180_BIT_KHR = 0x00000004,
    VK_SURFACE_TRANSFORM.Rotate_270_BIT_KHR = 0x00000008,
    VK_SURFACE_TRANSFORM.Horizontal_Mirror_BIT_KHR = 0x00000010,
    VK_SURFACE_TRANSFORM.Horizontal_Mirror.Rotate_90_BIT_KHR = 0x00000020,
    VK_SURFACE_TRANSFORM.Horizontal_Mirror.Rotate_180_BIT_KHR = 0x00000040,
    VK_SURFACE_TRANSFORM.Horizontal_Mirror.Rotate_270_BIT_KHR = 0x00000080,
    VK_SURFACE_TRANSFORM.Inherit_BIT_KHR = 0x00000100,
    VK_SURFACE_TRANSFORM_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkSurfaceTransformFlagBitsKHR;
```

- `VK_SURFACE_TRANSFORM_IDENTITY_BIT_KHR` specifies that image content is presented without being transformed.
- `VK_SURFACE_TRANSFORM.Rotate_90_BIT_KHR` specifies that image content is rotated 90 degrees clockwise.
- `VK_SURFACE_TRANSFORM.Rotate_180_BIT_KHR` specifies that image content is rotated 180 degrees clockwise.
- `VK_SURFACE_TRANSFORM.Rotate_270_BIT_KHR` specifies that image content is rotated 270 degrees clockwise.
- `VK_SURFACE_TRANSFORM.Horizontal_Mirror_BIT_KHR` specifies that image content is mirrored horizontally.
- `VK_SURFACE_TRANSFORM.Horizontal_Mirror.Rotate_90_BIT_KHR` specifies that image content is mirrored horizontally, then rotated 90 degrees clockwise.
- `VK_SURFACE_TRANSFORM.Horizontal_Mirror.Rotate_180_BIT_KHR` specifies that image content is mirrored horizontally, then rotated 180 degrees clockwise.
- `VK_SURFACE_TRANSFORM.Horizontal_Mirror.Rotate_270_BIT_KHR` specifies that image content is mirrored horizontally, then rotated 270 degrees clockwise.
mirrored horizontally, then rotated 270 degrees clockwise.

- **VK_SURFACE_TRANSFORM_INHERIT_BIT_KHR** specifies that the presentation transform is not specified, and is instead determined by platform-specific considerations and mechanisms outside Vulkan.

```c
typedef VkFlags VkSurfaceTransformFlagsKHR;
```

**VkSurfaceTransformFlagsKHR** is a bitmask type for setting a mask of zero or more **VkSurfaceTransformFlagBitsKHR**.

The **supportedCompositeAlpha** member is of type **VkCompositeAlphaFlagBitsKHR**, which contains the following values:

```c
typedef enum VkCompositeAlphaFlagBitsKHR {
    VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR = 0x00000001,
    VK_COMPOSITE_ALPHA_PRE_MULTIPLIED_BIT_KHR = 0x00000002,
    VK_COMPOSITE_ALPHA_POST_MULTIPLIED_BIT_KHR = 0x00000004,
    VK_COMPOSITE_ALPHA_INHERIT_BIT_KHR = 0x00000008,
    VK_COMPOSITE_ALPHA_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkCompositeAlphaFlagBitsKHR;
```

These values are described as follows:

- **VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR**: The alpha channel, if it exists, of the images is ignored in the compositing process. Instead, the image is treated as if it has a constant alpha of 1.0.

- **VK_COMPOSITE_ALPHA_PRE_MULTIPLIED_BIT_KHR**: The alpha channel, if it exists, of the images is respected in the compositing process. The non-alpha channels of the image are expected to already be multiplied by the alpha channel by the application.

- **VK_COMPOSITE_ALPHA_POST_MULTIPLIED_BIT_KHR**: The alpha channel, if it exists, of the images is respected in the compositing process. The non-alpha channels of the image are not expected to already be multiplied by the alpha channel by the application; instead, the compositor will multiply the non-alpha channels of the image by the alpha channel during compositing.

- **VK_COMPOSITE_ALPHA_INHERIT_BIT_KHR**: The way in which the presentation engine treats the alpha channel in the images is unknown to the Vulkan API. Instead, the application is responsible for setting the composite alpha blending mode using native window system commands. If the application does not set the blending mode using native window system commands, then a platform-specific default will be used.

```c
typedef VkFlags VkCompositeAlphaFlagsKHR;
```

**VkCompositeAlphaFlagsKHR** is a bitmask type for setting a mask of zero or more **VkCompositeAlphaFlagBitsKHR**.
29.5.2. Surface Format Support

To query the supported swapchain format-color space pairs for a surface, call:

```c
VkResult vkGetPhysicalDeviceSurfaceFormatsKHR(
    VkPhysicalDevice physicalDevice,
    VkSurfaceKHR surface,
    uint32_t* pSurfaceFormatCount,
    VkSurfaceFormatKHR* pSurfaceFormats);
```

- `physicalDevice` is the physical device that will be associated with the swapchain to be created, as described for `vkCreateSwapchainKHR`.
- `surface` is the surface that will be associated with the swapchain.
- `pSurfaceFormatCount` is a pointer to an integer related to the number of format pairs available or queried, as described below.
- `pSurfaceFormats` is either `NULL` or a pointer to an array of `VkSurfaceFormatKHR` structures.

If `pSurfaceFormats` is `NULL`, then the number of format pairs supported for the given `surface` is returned in `pSurfaceFormatCount`. Otherwise, `pSurfaceFormatCount` must point to a variable set by the user to the number of elements in the `pSurfaceFormats` array, and on return the variable is overwritten with the number of structures actually written to `pSurfaceFormats`. If the value of `pSurfaceFormatCount` is less than the number of format pairs supported, at most `pSurfaceFormatCount` structures will be written. If `pSurfaceFormatCount` is smaller than the number of format pairs supported for the given `surface`, `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS` to indicate that not all the available values were returned.

The number of format pairs supported must be greater than or equal to 1. `pSurfaceFormats` must not contain an entry whose value for `format` is `VK_FORMAT_UNDEFINED`.

If `pSurfaceFormats` includes an entry whose value for `colorSpace` is `VK_COLOR_SPACE_SRGB_NONLINEAR_KHR` and whose value for `format` is a UNORM (or SRGB) format and the corresponding SRGB (or UNORM) format is a color renderable format for `VK_IMAGE_TILING_OPTIMAL`, then `pSurfaceFormats` must also contain an entry with the same value for `colorSpace` and `format` equal to the corresponding SRGB (or UNORM) format.

**Valid Usage**

- `surface` must be supported by `physicalDevice`, as reported by `vkGetPhysicalDeviceSurfaceSupportKHR` or an equivalent platform-specific mechanism.
Valid Usage (Implicit)

- **physicalDevice** must be a valid `VkPhysicalDevice` handle
- **surface** must be a valid `VkSurfaceKHR` handle
- **pSurfaceFormatCount** must be a valid pointer to a `uint32_t` value
- If the value referenced by `pSurfaceFormatCount` is not 0, and `pSurfaceFormats` is not NULL, `pSurfaceFormats` must be a valid pointer to an array of `VkSurfaceFormatKHR` structures
- Both of **physicalDevice**, and **surface** must have been created, allocated, or retrieved from the same `VkInstance`

Return Codes

**Success**

- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_SURFACE_LOST_KHR`

The `VkSurfaceFormatKHR` structure is defined as:

```c
typedef struct VkSurfaceFormatKHR {
    VkFormat format;
    VkColorSpaceKHR colorSpace;
} VkSurfaceFormatKHR;
```

- **format** is a `VkFormat` that is compatible with the specified surface.
- **colorSpace** is a presentation `VkColorSpaceKHR` that is compatible with the surface.

To query the supported swapchain format tuples for a surface, call:

```c
VkResult vkGetPhysicalDeviceSurfaceFormats2KHR(
    VkPhysicalDevice physicalDevice,  
    const VkPhysicalDeviceSurfaceInfo2KHR* pSurfaceInfo, 
    uint32_t* pSurfaceFormatCount, 
    VkSurfaceFormat2KHR* pSurfaceFormats); 
```

- **physicalDevice** is the physical device that will be associated with the swapchain to be created, as described for `vkCreateSwapchainKHR`.

• `pSurfaceInfo` is a pointer to a `VkPhysicalDeviceSurfaceInfo2KHR` structure describing the surface and other fixed parameters that would be consumed by `vkCreateSwapchainKHR`.

• `pSurfaceFormatCount` is a pointer to an integer related to the number of format tuples available or queried, as described below.

• `pSurfaceFormats` is either `NULL` or a pointer to an array of `VkSurfaceFormat2KHR` structures.

`vkGetPhysicalDeviceSurfaceFormats2KHR` behaves similarly to `vkGetPhysicalDeviceSurfaceFormatsKHR`, with the ability to be extended via `pNext` chains.

If `pSurfaceFormats` is `NULL`, then the number of format tuples supported for the given surface is returned in `pSurfaceFormatCount`. Otherwise, `pSurfaceFormatCount` must point to a variable set by the user to the number of elements in the `pSurfaceFormats` array, and on return the variable is overwritten with the number of structures actually written to `pSurfaceFormats`. If the value of `pSurfaceFormatCount` is less than the number of format tuples supported, at most `pSurfaceFormatCount` structures will be written. If `pSurfaceFormatCount` is smaller than the number of format tuples supported for the surface parameters described in `pSurfaceInfo`, `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS` to indicate that not all the available values were returned.

---

**Valid Usage**

- `pSurfaceInfo->surface` must be supported by `physicalDevice`, as reported by `vkGetPhysicalDeviceSurfaceSupportKHR` or an equivalent platform-specific mechanism.

---

**Valid Usage (Implicit)**

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pSurfaceInfo` must be a valid pointer to a valid `VkPhysicalDeviceSurfaceInfo2KHR` structure
- `pSurfaceFormatCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pSurfaceFormatCount` is not 0, and `pSurfaceFormats` is not `NULL`, `pSurfaceFormats` must be a valid pointer to an array of `pSurfaceFormatCount` `VkSurfaceFormat2KHR` structures

---

**Return Codes**

**Success**

- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_SURFACE_LOST_KHR`
The `VkSurfaceFormat2KHR` structure is defined as:

```c
typedef struct VkSurfaceFormat2KHR {
    VkStructureType sType;
    void* pNext;
    VkSurfaceFormatKHR surfaceFormat;
} VkSurfaceFormat2KHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `surfaceFormat` is a `VkSurfaceFormatKHR` structure describing a format-color space pair that is compatible with the specified surface.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_SURFACE_FORMAT_2_KHR`
- `pNext` must be `NULL`

While the `format` of a presentable image refers to the encoding of each pixel, the `colorSpace` determines how the presentation engine interprets the pixel values. A color space in this document refers to a specific color space (defined by the chromaticities of its primaries and a white point in CIE Lab), and a transfer function that is applied before storing or transmitting color data in the given color space.

Possible values of `VkSurfaceFormatKHR::colorSpace`, specifying supported color spaces of a presentation engine, are:

```c
typedef enum VkColorSpaceKHR {
    VK_COLOR_SPACE_SRGB_NONLINEAR_KHR = 0,
    VK_COLORSPACE_SRGB_NONLINEAR_KHR = VK_COLOR_SPACE_SRGB_NONLINEAR_KHR,
    VK_COLOR_SPACE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkColorSpaceKHR;
```

- `VK_COLOR_SPACE_SRGB_NONLINEAR_KHR` specifies support for the sRGB color space.

### 29.5.3. Surface Presentation Mode Support

To query the supported presentation modes for a surface, call:

```c
VkResult vkGetPhysicalDeviceSurfacePresentModesKHR(
    VkPhysicalDevice physicalDevice,
    VkSurfaceKHR surface,
    uint32_t* pPresentModeCount,
    VkPresentModeKHR* pPresentModes);
```
• **physicalDevice** is the physical device that will be associated with the swapchain to be created, as described for `vkCreateSwapchainKHR`.

• **surface** is the surface that will be associated with the swapchain.

• **pPresentModeCount** is a pointer to an integer related to the number of presentation modes available or queried, as described below.

• **pPresentModes** is either **NULL** or a pointer to an array of `VkPresentModeKHR` values, indicating the supported presentation modes.

If `pPresentModes` is **NULL**, then the number of presentation modes supported for the given `surface` is returned in `pPresentModeCount`. Otherwise, `pPresentModeCount` **must** point to a variable set by the user to the number of elements in the `pPresentModes` array, and on return the variable is overwritten with the number of values actually written to `pPresentModes`. If the value of `pPresentModeCount` is less than the number of presentation modes supported, at most `pPresentModeCount` values will be written. If `pPresentModeCount` is smaller than the number of presentation modes supported for the given `surface`, **VK_INCOMPLETE** will be returned instead of **VK_SUCCESS** to indicate that not all the available values were returned.

---

**Valid Usage (Implicit)**

- **physicalDevice** **must** be a valid `VkPhysicalDevice` handle
- **surface** **must** be a valid `VkSurfaceKHR` handle
- **pPresentModeCount** **must** be a valid pointer to a `uint32_t` value
- If the value referenced by `pPresentModeCount` is not 0, and `pPresentModes` is not **NULL**, `pPresentModes` **must** be a valid pointer to an array of `pPresentModeCount` `VkPresentModeKHR` values
- Both of **physicalDevice**, and **surface** **must** have been created, allocated, or retrieved from the same `VkInstance`

---

**Return Codes**

**Success**
- **VK_SUCCESS**
- **VK_INCOMPLETE**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**
- **VK_ERROR_SURFACE_LOST_KHR**

Possible values of elements of the `vkGetPhysicalDeviceSurfacePresentModesKHR::pPresentModes` array, indicating the supported presentation modes for a surface, are:
typedef enum VkPresentModeKHR {
    VK_PRESENT_MODE_IMMEDIATE_KHR = 0,
    VK_PRESENT_MODE_MAILBOX_KHR = 1,
    VK_PRESENT_MODE_FIFO_KHR = 2,
    VK_PRESENT_MODE_FIFO_RELAXED_KHR = 3,
    VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR = 1000111000,
    VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR = 1000111001,
    VK_PRESENT_MODE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkPresentModeKHR;

- **VK_PRESENT_MODE_IMMEDIATE_KHR** specifies that the presentation engine does not wait for a vertical blanking period to update the current image, meaning this mode may result in visible tearing. No internal queuing of presentation requests is needed, as the requests are applied immediately.

- **VK_PRESENT_MODE_MAILBOX_KHR** specifies that the presentation engine waits for the next vertical blanking period to update the current image. Tearing cannot be observed. An internal single-entry queue is used to hold pending presentation requests. If the queue is full when a new presentation request is received, the new request replaces the existing entry, and any images associated with the prior entry become available for re-use by the application. One request is removed from the queue and processed during each vertical blanking period in which the queue is non-empty.

- **VK_PRESENT_MODE_FIFO_KHR** specifies that the presentation engine waits for the next vertical blanking period to update the current image. Tearing cannot be observed. An internal queue is used to hold pending presentation requests. New requests are appended to the end of the queue, and one request is removed from the beginning of the queue and processed during each vertical blanking period in which the queue is non-empty. This is the only value of presentMode that is required to be supported.

- **VK_PRESENT_MODE_FIFO_RELAXED_KHR** specifies that the presentation engine generally waits for the next vertical blanking period to update the current image. If a vertical blanking period has already passed since the last update of the current image then the presentation engine does not wait for another vertical blanking period for the update, meaning this mode may result in visible tearing in this case. This mode is useful for reducing visual stutter with an application that will mostly present a new image before the next vertical blanking period, but may occasionally be late, and present a new image just after the next vertical blanking period. An internal queue is used to hold pending presentation requests. New requests are appended to the end of the queue, and one request is removed from the beginning of the queue and processed during or after each vertical blanking period in which the queue is non-empty.

- **VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR** specifies that the presentation engine and application have concurrent access to a single image, which is referred to as a shared presentable image. The presentation engine is only required to update the current image after a new presentation request is received. Therefore the application must make a presentation request whenever an update is required. However, the presentation engine may update the current image at any point, meaning this mode may result in visible tearing.

- **VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR** specifies that the presentation engine and application have concurrent access to a single image, which is referred to as a shared
presentable image. The presentation engine periodically updates the current image on its regular refresh cycle. The application is only required to make one initial presentation request, after which the presentation engine must update the current image without any need for further presentation requests. The application can indicate the image contents have been updated by making a presentation request, but this does not guarantee the timing of when it will be updated. This mode may result in visible tearing if rendering to the image is not timed correctly.

The supported VkImageUsageFlagBits of the presentable images of a swapchain created for a surface may differ depending on the presentation mode, and can be determined as per the table below:

Table 33. Presentable image usage queries

<table>
<thead>
<tr>
<th>Presentation mode</th>
<th>Image usage flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_PRESENT_MODE_IMMEDIATE_KHR</td>
<td>VkSurfaceCapabilitiesKHR::supportedUsageFlags</td>
</tr>
<tr>
<td>VK_PRESENT_MODE_MAILBOX_KHR</td>
<td>VkSurfaceCapabilitiesKHR::supportedUsageFlags</td>
</tr>
<tr>
<td>VK_PRESENT_MODE_FIFO_KHR</td>
<td>VkSurfaceCapabilitiesKHR::supportedUsageFlags</td>
</tr>
<tr>
<td>VK_PRESENT_MODE_FIFO_RELAXED_KHR</td>
<td>VkSurfaceCapabilitiesKHR::supportedUsageFlags</td>
</tr>
<tr>
<td>VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR</td>
<td>VkSharedPresentSurfaceCapabilitiesKHR::sharedPresentSupportedUsageFlags</td>
</tr>
<tr>
<td>VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR</td>
<td>VkSharedPresentSurfaceCapabilitiesKHR::sharedPresentSupportedUsageFlags</td>
</tr>
</tbody>
</table>

Note
For reference, the mode indicated by VK_PRESENT_MODE_FIFO_KHR is equivalent to the behavior of {wgl|glX|egl}SwapBuffers with a swap interval of 1, while the mode indicated by VK_PRESENT_MODE_FIFO_RELAXED_KHR is equivalent to the behavior of {wgl|glX}SwapBuffers with a swap interval of -1 (from the {WGL|GLX}_EXT_swap_control_tear extensions).

29.6. Device Group Queries

A logical device that represents multiple physical devices may support presenting from images on more than one physical device, or combining images from multiple physical devices.

To query these capabilities, call:

```c
VkResult vkGetDeviceGroupPresentCapabilitiesKHR(
    VkDevice                                    device,    
    VkDeviceGroupPresentCapabilitiesKHR*        pDeviceGroupPresentCapabilities);
```

- device is the logical device.
- pDeviceGroupPresentCapabilities is a pointer to a VkDeviceGroupPresentCapabilitiesKHR structure in which the device’s capabilities are returned.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- `pDeviceGroupPresentCapabilities` must be a valid pointer to a `VkDeviceGroupPresentCapabilitiesKHR` structure

Return Codes

Success
- `VK_SUCCESS`

Failure
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkDeviceGroupPresentCapabilitiesKHR` structure is defined as:

```c
typedef struct VkDeviceGroupPresentCapabilitiesKHR {
    VkStructureType                      sType;
    const void*                           pNext;
    uint32_t                              presentMask[VK_MAX_DEVICE_GROUP_SIZE];
    VkDeviceGroupPresentModeFlagsKHR      modes;
} VkDeviceGroupPresentCapabilitiesKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **presentMask** is an array of `VK_MAX_DEVICE_GROUP_SIZE` uint32_t masks, where the mask at element i is non-zero if physical device i has a presentation engine, and where bit j is set in element i if physical device i can present swapchain images from physical device j. If element i is non-zero, then bit i must be set.
- **modes** is a bitmask of `VkDeviceGroupPresentModeFlagBitsKHR` indicating which device group presentation modes are supported. **modes** always has `VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR` set.

The present mode flags are also used when presenting an image, in `VkDeviceGroupPresentInfoKHR::mode`.

If a device group only includes a single physical device, then **modes** must equal `VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR`.
Valid Usage (Implicit)

- **sType must** be `VK_STRUCTURE_TYPE_DEVICE_GROUP_PRESENT_CAPABILITIES_KHR`
- **pNext must** be `NULL`

Bits which **may** be set in `VkDeviceGroupPresentCapabilitiesKHR::modes` to indicate which device group presentation modes are supported are:

```c
typedef enum VkDeviceGroupPresentModeFlagBitsKHR {
    VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR = 0x00000001,
    VK_DEVICE_GROUP_PRESENT_MODE_REMOTE_BIT_KHR = 0x00000002,
    VK_DEVICE_GROUP_PRESENT_MODE_SUM_BIT_KHR = 0x00000004,
    VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_MULTI_DEVICE_BIT_KHR = 0x00000008,
    VK_DEVICE_GROUP_PRESENT_MODE_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkDeviceGroupPresentModeFlagBitsKHR;
```

- **VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR** specifies that any physical device with a presentation engine **can** present its own swapchain images.
- **VK_DEVICE_GROUP_PRESENT_MODE_REMOTE_BIT_KHR** specifies that any physical device with a presentation engine **can** present swapchain images from any physical device in its `presentMask`.
- **VK_DEVICE_GROUP_PRESENT_MODE_SUM_BIT_KHR** specifies that any physical device with a presentation engine **can** present the sum of swapchain images from any physical devices in its `presentMask`.
- **VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_MULTI_DEVICE_BIT_KHR** specifies that multiple physical devices with a presentation engine **can** each present their own swapchain images.

```c
typedef VkFlags VkDeviceGroupPresentModeFlagsKHR;
```

`VkDeviceGroupPresentModeFlagsKHR` is a bitmask type for setting a mask of zero or more `VkDeviceGroupPresentModeFlagBitsKHR`.

Some surfaces **may** not be capable of using all the device group present modes.

To query the supported device group present modes for a particular surface, call:

```c
VkResult vkGetDeviceGroupSurfacePresentModesKHR(
    VkDevice device,
    VkSurfaceKHR surface,
    VkDeviceGroupPresentModeFlagsKHR* pModes);
```

- **device** is the logical device.
- **surface** is the surface.
- **pModes** is a pointer to a `VkDeviceGroupPresentModeFlagsKHR` in which the supported device group present modes for the surface are returned.
The modes returned by this command are not invariant, and may change in response to the surface being moved, resized, or occluded. These modes must be a subset of the modes returned by vkGetDeviceGroupPresentCapabilitiesKHR.

Valid Usage (Implicit)

- **device** must be a valid VkDevice handle
- **surface** must be a valid VkSurfaceKHR handle
- **pModes** must be a valid pointer to a VkDeviceGroupPresentModeFlagsKHR value
- Both of **device**, and **surface** must have been created, allocated, or retrieved from the same VkInstance

Host Synchronization

- Host access to **surface** must be externally synchronized

Return Codes

**Success**
- VK_SUCCESS

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_SURFACE_LOST_KHR

When using VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_MULTI_DEVICE_BIT_KHR, the application may need to know which regions of the surface are used when presenting locally on each physical device. Presentation of swapchain images to this surface need only have valid contents in the regions returned by this command.

To query a set of rectangles used in presentation on the physical device, call:

```c
VkResult vkGetPhysicalDevicePresentRectanglesKHR(
    VkPhysicalDevice physicalDevice,
    VkSurfaceKHR surface,
    uint32_t* pRectCount,
    VkRect2D* pRects);
```

- **physicalDevice** is the physical device.
- **surface** is the surface.
- **pRectCount** is a pointer to an integer related to the number of rectangles available or queried, as
pRects is either NULL or a pointer to an array of VkRect2D structures.

If pRects is NULL, then the number of rectangles used when presenting the given surface is returned in pRectCount. Otherwise, pRectCount must point to a variable set by the user to the number of elements in the pRects array, and on return the variable is overwritten with the number of structures actually written to pRects. If the value of pRectCount is less than the number of rectangles, at most pRectCount structures will be written. If pRectCount is smaller than the number of rectangles used for the given surface, VK_INCOMPLETE will be returned instead of VK_SUCCESS to indicate that not all the available values were returned.

The values returned by this command are not invariant, and may change in response to the surface being moved, resized, or occluded.

The rectangles returned by this command must not overlap.

Valid Usage (Implicit)

- physicalDevice must be a valid VkPhysicalDevice handle
- surface must be a valid VkSurfaceKHR handle
- pRectCount must be a valid pointer to a uint32_t value
- If the value referenced by pRectCount is not 0, and pRects is not NULL, pRects must be a valid pointer to an array of pRectCount VkRect2D structures
- Both of physicalDevice, and surface must have been created, allocated, or retrieved from the same VkInstance

Host Synchronization

- Host access to surface must be externally synchronized

Return Codes

Success

- VK_SUCCESS
- VK_INCOMPLETE

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY

29.7. WSI Swapchain

A swapchain object (a.k.a. swapchain) provides the ability to present rendering results to a surface.
Swapchain objects are represented by `VkSwapchainKHR` handles:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSwapchainKHR)
```

A swapchain is an abstraction for an array of presentable images that are associated with a surface. The presentable images are represented by `VkImage` objects created by the platform. One image (which can be an array image for multiview/stereoscopic-3D surfaces) is displayed at a time, but multiple images can be queued for presentation. An application renders to the image, and then queues the image for presentation to the surface.

A native window cannot be associated with more than one non-retired swapchain at a time. Further, swapchains cannot be created for native windows that have a non-Vulkan graphics API surface associated with them.

```quote
Note

The presentation engine is an abstraction for the platform’s compositor or display engine.

The presentation engine may be synchronous or asynchronous with respect to the application and/or logical device.

Some implementations may use the device’s graphics queue or dedicated presentation hardware to perform presentation.
```

The presentable images of a swapchain are owned by the presentation engine. An application can acquire use of a presentable image from the presentation engine. Use of a presentable image must occur only after the image is returned by `vkAcquireNextImageKHR`, and before it is presented by `vkQueuePresentKHR`. This includes transitioning the image layout and rendering commands.

```quote
An application can acquire use of a presentable image with `vkAcquireNextImageKHR`. After acquiring a presentable image and before modifying it, the application must use a synchronization primitive to ensure that the presentation engine has finished reading from the image. The application can then transition the image's layout, queue rendering commands to it, etc. Finally, the application presents the image with `vkQueuePresentKHR`, which releases the acquisition of the image.
```

The presentation engine controls the order in which presentable images are acquired for use by the application.

```quote
Note

This allows the platform to handle situations which require out-of-order return of images after presentation. At the same time, it allows the application to generate command buffers referencing all of the images in the swapchain at initialization time, rather than in its main loop.
```

How this all works is described below.

If a swapchain is created with `presentMode` set to either `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR` or `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`, a single presentable image can be acquired,
referred to as a shared presentable image. A shared presentable image may be concurrently accessed by the application and the presentation engine, without transitioning the image's layout after it is initially presented.

- With `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR`, the presentation engine is only required to update to the latest contents of a shared presentable image after a present. The application must call `vkQueuePresentKHR` to guarantee an update. However, the presentation engine may update from it at any time.

- With `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`, the presentation engine will automatically present the latest contents of a shared presentable image during every refresh cycle. The application is only required to make one initial call to `vkQueuePresentKHR`, after which the presentation engine will update from it without any need for further present calls. The application can indicate the image contents have been updated by calling `vkQueuePresentKHR`, but this does not guarantee the timing of when updates will occur.

The presentation engine may access a shared presentable image at any time after it is first presented. To avoid tearing, an application should coordinate access with the presentation engine. This requires presentation engine timing information through platform-specific mechanisms and ensuring that color attachment writes are made available during the portion of the presentation engine's refresh cycle they are intended for.

*Note*
The `VK_KHR_shared_presentable_image` extension does not provide functionality for determining the timing of the presentation engine's refresh cycles.

In order to query a swapchain's status when rendering to a shared presentable image, call:

```c
VkResult vkGetSwapchainStatusKHR(
    VkDevice device, 
    VkSwapchainKHR swapchain);
```

- `device` is the device associated with `swapchain`.
- `swapchain` is the swapchain to query.

**Valid Usage (Implicit)**

- `device` must be a valid `VkDevice` handle
- `swapchain` must be a valid `VkSwapchainKHR` handle
- Both of `device`, and `swapchain` must have been created, allocated, or retrieved from the same `VkInstance`
Host Synchronization

- Host access to swapchain must be externally synchronized

Return Codes

**Success**
- VK_SUCCESS
- VK_SUBOPTIMAL_KHR

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST
- VK_ERROR_OUT_OF_DATE_KHR
- VK_ERROR_SURFACE_LOST_KHR

The possible return values for `vkGetSwapchainStatusKHR` should be interpreted as follows:

- **VK_SUCCESS** specifies the presentation engine is presenting the contents of the shared presentable image, as per the swapchain’s `VkPresentModeKHR`.
- **VK_SUBOPTIMAL_KHR** the swapchain no longer matches the surface properties exactly, but the presentation engine is presenting the contents of the shared presentable image, as per the swapchain’s `VkPresentModeKHR`.
- **VK_ERROR_OUT_OF_DATE_KHR** the surface has changed in such a way that it is no longer compatible with the swapchain.
- **VK_ERROR_SURFACE_LOST_KHR** the surface is no longer available.

**Note**
The swapchain state may be cached by implementations, so applications should regularly call `vkGetSwapchainStatusKHR` when using a swapchain with `VkPresentModeKHR` set to `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`.

To create a swapchain, call:

```c
VkResult vkCreateSwapchainKHR(  
    VkDevice device,  
    const VkSwapchainCreateInfoKHR* pCreateInfo,  
    const VkAllocationCallbacks* pAllocator,  
    VkSwapchainKHR* pSwapchain);  
```

- **device** is the device to create the swapchain for.
- **pCreateInfo** is a pointer to a `VkSwapchainCreateInfoKHR` structure specifying the parameters of
the created swapchain.

- **pAllocator** is the allocator used for host memory allocated for the swapchain object when there is no more specific allocator available (see Memory Allocation).
- **pSwapchain** is a pointer to a `VkSwapchainKHR` handle in which the created swapchain object will be returned.

### Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkSwapchainCreateInfoKHR` structure
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pSwapchain** must be a valid pointer to a `VkSwapchainKHR` handle

### Host Synchronization

- Host access to **pCreateInfo.surface** must be externally synchronized
- Host access to **pCreateInfo.oldSwapchain** must be externally synchronized

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERRORDEVICELOST`
- `VK_ERROR_SURFACE_LOST_KHR`
- `VK_ERROR_NATIVE_WINDOW_IN_USE_KHR`
- `VK_ERROR_INITIALIZATION_FAILED`

The `VkSwapchainCreateInfoKHR` structure is defined as:
typedef struct VkSwapchainCreateInfoKHR {
    VkStructureType                  sType;
    const void*                      pNext;
    VkSwapchainCreateFlagsKHR        flags;
    VkSurfaceKHR                     surface;
    uint32_t                         minImageCount;
    VkFormat                         imageFormat;
    VkColorSpaceKHR                  imageColorSpace;
    VkExtent2D                       imageExtent;
    uint32_t                         imageArrayLayers;
    VkImageUsageFlags                imageUsage;
    VkSharingMode                    imageSharingMode;
    uint32_t                         queueFamilyIndexCount;
    const uint32_t*                  pQueueFamilyIndices;
    VkSurfaceTransformFlagBitsKHR    preTransform;
    VkCompositeAlphaFlagBitsKHR      compositeAlpha;
    VkPresentModeKHR                 presentMode;
    VkBool32                         clipped;
    VkSwapchainKHR                   oldSwapchain;
} VkSwapchainCreateInfoKHR;

• **sType** is the type of this structure.

• **pNext** is NULL or a pointer to an extension-specific structure.

• **flags** is a bitmask of VkSwapchainCreateFlagBitsKHR indicating parameters of the swapchain creation.

• **surface** is the surface onto which the swapchain will present images. If the creation succeeds, the swapchain becomes associated with surface.

• **minImageCount** is the minimum number of presentable images that the application needs. The implementation will either create the swapchain with at least that many images, or it will fail to create the swapchain.

• **imageFormat** is a VkFormat value specifying the format the swapchain image(s) will be created with.

• **imageColorSpace** is a VkColorSpaceKHR value specifying the way the swapchain interprets image data.

• **imageExtent** is the size (in pixels) of the swapchain image(s). The behavior is platform-dependent if the image extent does not match the surface’s currentExtent as returned by vkGetPhysicalDeviceSurfaceCapabilitiesKHR.

**Note**

On some platforms, it is normal that maxImageExtent may become (0, 0), for example when the window is minimized. In such a case, it is not possible to create a swapchain due to the Valid Usage requirements.

• **imageArrayLayers** is the number of views in a multiview/stereo surface. For non-stereoscopic-3D applications, this value is 1.
• **imageUsage** is a bitmask of `VkImageUsageFlagBits` describing the intended usage of the (acquired) swapchain images.

• **imageSharingMode** is the sharing mode used for the image(s) of the swapchain.

• **queueFamilyIndexCount** is the number of queue families having access to the image(s) of the swapchain when `imageSharingMode` is `VK_SHARING_MODE_CONCURRENT`.

• **pQueueFamilyIndices** is a pointer to an array of queue family indices having access to the images(s) of the swapchain when `imageSharingMode` is `VK_SHARING_MODE_CONCURRENT`.

• **preTransform** is a `VkSurfaceTransformFlagBitsKHR` value describing the transform, relative to the presentation engine’s natural orientation, applied to the image content prior to presentation. If it does not match the `currentTransform` value returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR`, the presentation engine will transform the image content as part of the presentation operation.

• **compositeAlpha** is a `VkCompositeAlphaFlagBitsKHR` value indicating the alpha compositing mode to use when this surface is composited together with other surfaces on certain window systems.

• **presentMode** is the presentation mode the swapchain will use. A swapchain’s present mode determines how incoming present requests will be processed and queued internally.

• **clipped** specifies whether the Vulkan implementation is allowed to discard rendering operations that affect regions of the surface that are not visible.

  ◦ If set to `VK_TRUE`, the presentable images associated with the swapchain may not own all of their pixels. Pixels in the presentable images that correspond to regions of the target surface obscured by another window on the desktop, or subject to some other clipping mechanism will have undefined content when read back. Fragment shaders may not execute for these pixels, and thus any side effects they would have had will not occur. `VK_TRUE` value does not guarantee any clipping will occur, but allows more optimal presentation methods to be used on some platforms.

  ◦ If set to `VK_FALSE`, presentable images associated with the swapchain will own all of the pixels they contain.

  **Note**
  
  Applications should set this value to `VK_TRUE` if they do not expect to read back the content of presentable images before presenting them or after reacquiring them, and if their fragment shaders do not have any side effects that require them to run for all pixels in the presentable image.

• **oldSwapchain** is `VK_NULL_HANDLE`, or the existing non-retired swapchain currently associated with `surface`. Providing a valid `oldSwapchain` may aid in the resource reuse, and also allows the application to still present any images that are already acquired from it.

Upon calling `vkCreateSwapchainKHR` with an `oldSwapchain` that is not `VK_NULL_HANDLE`, `oldSwapchain` is retired — even if creation of the new swapchain fails. The new swapchain is created in the non-retired state whether or not `oldSwapchain` is `VK_NULL_HANDLE`.

Upon calling `vkCreateSwapchainKHR` with an `oldSwapchain` that is not `VK_NULL_HANDLE`, any images from `oldSwapchain` that are not acquired by the application may be freed by the implementation,
which may occur even if creation of the new swapchain fails. The application can destroy oldSwapchain to free all memory associated with oldSwapchain.

**Note**

Multiple retired swapchains can be associated with the same VkSurfaceKHR through multiple uses of oldSwapchain that outnumber calls to vkDestroySwapchainKHR.

After oldSwapchain is retired, the application can pass to vkQueuePresentKHR any images it had already acquired from oldSwapchain. E.g., an application may present an image from the old swapchain before an image from the new swapchain is ready to be presented. As usual, vkQueuePresentKHR may fail if oldSwapchain has entered a state that causes VK_ERROR_OUT_OF_DATE_KHR to be returned.

The application can continue to use a shared presentable image obtained from oldSwapchain until a presentable image is acquired from the new swapchain, as long as it has not entered a state that causes it to return VK_ERROR_OUT_OF_DATE_KHR.
Valid Usage

- **surface** **must** be a surface that is supported by the device as determined using `vkGetPhysicalDeviceSurfaceSupportKHR`.

- **minImageCount** **must** be less than or equal to the value returned in the `maxImageCount` member of the `VkSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR` for the surface if the returned `maxImageCount` is not zero.

- If `presentMode` is not `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR` nor `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`, then **minImageCount** **must** be greater than or equal to the value returned in the `minImageCount` member of the `VkSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR` for the surface.

- **minImageCount** **must** be 1 if `presentMode` is either `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR` or `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`.

- **imageFormat** and **imageColorSpace** **must** match the `format` and `colorSpace` members, respectively, of one of the `VkSurfaceFormatKHR` structures returned by `vkGetPhysicalDeviceSurfaceFormatsKHR` for the surface.

- **imageExtent** **must** be between `minImageExtent` and `maxImageExtent`, inclusive, where `minImageExtent` and `maxImageExtent` are members of the `VkSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR` for the surface.

- **imageExtent** members `width` and `height` **must** both be non-zero.

- **imageArrayLayers** **must** be greater than 0 and less than or equal to the `maxImageArrayLayers` member of the `VkSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR` for the surface.

- If `presentMode` is `VK_PRESENT_MODE_IMMEDIATE_KHR`, `VK_PRESENT_MODE_MAILBOX_KHR`, `VK_PRESENT_MODE_FIFO_KHR` or `VK_PRESENT_MODE_FIFO_RELAXED_KHR`, **imageUsage** **must** be a subset of the supported usage flags present in the `supportedUsageFlags` member of the `VkSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR` for the surface.

- If `presentMode` is `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR` or `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`, **imageUsage** **must** be a subset of the supported usage flags present in the `sharedPresentSupportedUsageFlags` member of the `VkSharedPresentSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilities2KHR` for the surface.

- If `imageSharingMode` is `VK_SHARING_MODE_CONCURRENT`, **pQueueFamilyIndices** **must** be a valid pointer to an array of `queueFamilyIndexCount` `uint32_t` values.

- If `imageSharingMode` is `VK_SHARING_MODE_CONCURRENT`, **queueFamilyIndexCount** **must** be greater than 1.

- If `imageSharingMode` is `VK_SHARING_MODE_CONCURRENT`, each element of **pQueueFamilyIndices** **must** be unique and **must** be less than `pQueueFamilyPropertyCount` returned by either `vkGetPhysicalDeviceQueueFamilyProperties` or
**vkGetPhysicalDeviceQueueFamilyProperties2** for the `physicalDevice` that was used to create device

- **preTransform** must be one of the bits present in the `supportedTransforms` member of the `VkSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR` for the surface.

- **compositeAlpha** must be one of the bits present in the `supportedCompositeAlpha` member of the `VkSurfaceCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilitiesKHR` for the surface.

- **presentMode** must be one of the `VkPresentModeKHR` values returned by `vkGetPhysicalDeviceSurfacePresentModesKHR` for the surface.

- If the logical device was created with `VkDeviceGroupDeviceCreateInfo`::`physicalDeviceCount` equal to 1, **flags** must not contain `VK_SWAPCHAIN_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR`.

- If `oldSwapchain` is not `VK_NULL_HANDLE`, `oldSwapchain` must be a non-retired swapchain associated with native window referred to by `surface`.

- The implied image creation parameters of the swapchain must be supported as reported by `vkGetPhysicalDeviceImageFormatProperties`.

- If **flags** contains `VK_SWAPCHAIN_CREATE_MUTABLE_FORMAT_BIT_KHR` then the `pNext` chain must include a `VkImageFormatListCreateInfo` structure with a `viewFormatCount` greater than zero and `pViewFormats` must have an element equal to `imageFormat`.

- If **flags** contains `VK_SWAPCHAIN_CREATE_PROTECTED_BIT_KHR`, then `VkSurfaceProtectedCapabilitiesKHR`::`supportsProtected` must be `VK_TRUE` in the `VkSurfaceProtectedCapabilitiesKHR` structure returned by `vkGetPhysicalDeviceSurfaceCapabilities2KHR` for `surface`.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO_KHR`
- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkDeviceGroupSwapchainCreateInfoKHR` or `VkImageFormatListCreateInfo`
- The `sType` value of each struct in the `pNext` chain must be unique
- `flags` must be a valid combination of `VkSwapchainCreateFlagBitsKHR` values
- `surface` must be a valid `VkSurfaceKHR` handle
- `imageFormat` must be a valid `VkFormat` value
- `imageColorSpace` must be a valid `VkColorSpaceKHR` value
- `imageUsage` must be a valid combination of `VkImageUsageFlagBits` values
- `imageUsage` must not be `0`
- `imageSharingMode` must be a valid `VkSharingMode` value
- `preTransform` must be a valid `VkSurfaceTransformFlagBitsKHR` value
- `compositeAlpha` must be a valid `VkCompositeAlphaFlagBitsKHR` value
- `presentMode` must be a valid `VkPresentModeKHR` value
- If `oldSwapchain` is not `VK_NULL_HANDLE`, `oldSwapchain` must be a valid `VkSwapchainKHR` handle
- If `oldSwapchain` is a valid handle, it must have been created, allocated, or retrieved from `surface`
- Both of `oldSwapchain`, and `surface` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkInstance`

Bits which can be set in `VkSwapchainCreateInfoKHR::flags`, specifying parameters of swapchain creation, are:

```c
typedef enum VkSwapchainCreateFlagBitsKHR {
    VK_SWAPCHAIN_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR = 0x00000001,
    VK_SWAPCHAIN_CREATE_PROTECTED_BIT_KHR = 0x00000002,
    VK_SWAPCHAIN_CREATE_MUTABLE_FORMAT_BIT_KHR = 0x00000004,
    VK_SWAPCHAIN_CREATE_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkSwapchainCreateFlagBitsKHR;
```

- `VK_SWAPCHAIN_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR` specifies that images created from the swapchain (i.e. with the `swapchain` member of `VkImageSwapchainCreateInfoKHR` set to this swapchain’s handle) must use `VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT`.
- `VK_SWAPCHAIN_CREATE_PROTECTED_BIT_KHR` specifies that images created from the swapchain are protected images.
- `VK_SWAPCHAIN_CREATE_MUTABLE_FORMAT_BIT_KHR` specifies that the images of the swapchain can be
used to create a VkImageView with a different format than what the swapchain was created with. The list of allowed image view formats are specified by adding a VkImageFormatListCreateInfo structure to the pNext chain of VkSwapchainCreateInfoKHR. In addition, this flag also specifies that the swapchain can be created with usage flags that are not supported for the format the swapchain is created with but are supported for at least one of the allowed image view formats.

typedef VkFlags VkSwapchainCreateFlagsKHR;

VkSwapchainCreateFlagsKHR is a bitmask type for setting a mask of zero or more VkSwapchainCreateFlagBitsKHR.

If the pNext chain of VkSwapchainCreateInfoKHR includes a VkDeviceGroupSwapchainCreateInfoKHR structure, then that structure includes a set of device group present modes that the swapchain can be used with.

The VkDeviceGroupSwapchainCreateInfoKHR structure is defined as:

typedef struct VkDeviceGroupSwapchainCreateInfoKHR {
    VkStructureType                     sType;
    const void*                         pNext;
    VkDeviceGroupPresentModeFlagsKHR    modes;
} VkDeviceGroupSwapchainCreateInfoKHR;

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- modes is a bitfield of modes that the swapchain can be used with.

If this structure is not present, modes is considered to be VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_DEVICE_GROUP_SWAPCHAIN_CREATE_INFO_KHR
- modes must be a valid combination of VkDeviceGroupPresentModeFlagBitsKHR values
- modes must not be 0

As mentioned above, if vkCreateSwapchainKHR succeeds, it will return a handle to a swapchain containing an array of at least minImageCount presentable images.

While acquired by the application, presentable images can be used in any way that equivalent non-presentable images can be used. A presentable image is equivalent to a non-presentable image created with the following VkImageCreateInfo parameters:
### VkImageCreateInfo Field | Value

<table>
<thead>
<tr>
<th>Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>flags</td>
<td>VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT is set if VK_SWAPCHAIN_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR is set</td>
</tr>
<tr>
<td></td>
<td>VK_IMAGE_CREATE_PROTECTED_BIT is set if VK_SWAPCHAIN_CREATE_PROTECTED_BIT_KHR is set</td>
</tr>
<tr>
<td></td>
<td>VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT and VK_IMAGE_CREATE_EXTENDED_USAGE_BIT_KHR are both set if VK_SWAPCHAIN_CREATE_MUTABLE_FORMAT_BIT_KHR is set</td>
</tr>
<tr>
<td></td>
<td>all other bits are unset</td>
</tr>
<tr>
<td>imageType</td>
<td>VK_IMAGE_TYPE_2D</td>
</tr>
<tr>
<td>format</td>
<td>pCreateInfo-&gt;imageFormat</td>
</tr>
<tr>
<td>extent</td>
<td>{pCreateInfo-&gt;imageExtent.width, pCreateInfo-&gt;imageExtent.height, 1}</td>
</tr>
<tr>
<td>mipLevels</td>
<td>1</td>
</tr>
<tr>
<td>arrayLayers</td>
<td>pCreateInfo-&gt;imageArrayLayers</td>
</tr>
<tr>
<td>samples</td>
<td>VK_SAMPLE_COUNT_1_BIT</td>
</tr>
<tr>
<td>tiling</td>
<td>VK_IMAGE_TILING_OPTIMAL</td>
</tr>
<tr>
<td>usage</td>
<td>pCreateInfo-&gt;imageUsage</td>
</tr>
<tr>
<td>sharingMode</td>
<td>pCreateInfo-&gt;imageSharingMode</td>
</tr>
<tr>
<td>queueFamilyIndexCount</td>
<td>pCreateInfo-&gt;queueFamilyIndexCount</td>
</tr>
<tr>
<td>pQueueFamilyIndices</td>
<td>pCreateInfo-&gt;pQueueFamilyIndices</td>
</tr>
<tr>
<td>initialLayout</td>
<td>VK_IMAGE_LAYOUT_UNDEFINED</td>
</tr>
</tbody>
</table>

The surface must not be destroyed until after the swapchain is destroyed.

If oldSwapchain is VK_NULL_HANDLE, and the native window referred to by surface is already associated with a Vulkan swapchain, VK_ERROR_NATIVE_WINDOW_IN_USE_KHR must be returned.

If the native window referred to by surface is already associated with a non-Vulkan graphics API surface, VK_ERROR_NATIVE_WINDOW_IN_USE_KHR must be returned.

The native window referred to by surface must not become associated with a non-Vulkan graphics API surface before all associated Vulkan swapchains have been destroyed.

Like core functions, several WSI functions, including vkCreateSwapchainKHR return VK_ERROR_DEVICE_LOST if the logical device was lost. See Lost Device. As with most core objects, VkSwapchainKHR is a child of the device and is affected by the lost state; it must be destroyed before destroying the VkDevice. However, VkSurfaceKHR is not a child of any VkDevice and is not otherwise affected by the lost device. After successfully recreating a VkDevice, the same VkSurfaceKHR can be used to create a new VkSwapchainKHR, provided the previous one was destroyed.
As mentioned in Lost Device, after a lost device event, the VkPhysicalDevice may also be lost. If other VkPhysicalDevice are available, they can be used together with the same VkSurfaceKHR to create the new VkSwapchainKHR, however the application must query the surface capabilities again, because they may differ on a per-physical device basis.

To destroy a swapchain object call:

```c
void vkDestroySwapchainKHR(
    VkDevice device,        /* device is the VkDevice associated with swapchain. */
    VkSwapchainKHR swapchain,  /* swapchain is the swapchain to destroy. */
    const VkAllocationCallbacks* pAllocator);  /* pAllocator is the allocator used for host memory allocated for the swapchain object when there is no more specific allocator available (see Memory Allocation). */
```

The application must not destroy a swapchain until after completion of all outstanding operations on images that were acquired from the swapchain. swapchain and all associated VkImage handles are destroyed, and must not be acquired or used any more by the application. The memory of each VkImage will only be freed after that image is no longer used by the presentation engine. For example, if one image of the swapchain is being displayed in a window, the memory for that image may not be freed until the window is destroyed, or another swapchain is created for the window. Destroying the swapchain does not invalidate the parent VkSurfaceKHR, and a new swapchain can be created with it.

When a swapchain associated with a display surface is destroyed, if the image most recently presented to the display surface is from the swapchain being destroyed, then either any display resources modified by presenting images from any swapchain associated with the display surface must be reverted by the implementation to their state prior to the first present performed on one of these swapchains, or such resources must be left in their current state.

### Valid Usage

- All uses of presentable images acquired from swapchain must have completed execution
- If VkAllocationCallbacks were provided when swapchain was created, a compatible set of callbacks must be provided here
- If no VkAllocationCallbacks were provided when swapchain was created, pAllocator must be NULL
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- If `swapchain` is not `VK_NULL_HANDLE`, `swapchain` must be a valid `VkSwapchainKHR` handle
- If `pAllocator` is not `NULL`, `pAllocator` must be a valid pointer to a valid `VkAllocationCallbacks` structure
- Both of `device`, and `swapchain` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkInstance`

Host Synchronization

- Host access to `swapchain` must be externally synchronized

When the `VK_KHR_display_swapchain` extension is enabled, multiple swapchains that share presentable images are created by calling:

```c
VkResult vkCreateSharedSwapchainsKHR(
    VkDevice                                    device,                     // device
    uint32_t                                    swapchainCount,           // swapchainCount
    const VkSwapchainCreateInfoKHR*             pCreateInfos,              // pCreateInfos
    const VkAllocationCallbacks*                pAllocator,                // pAllocator
    VkSwapchainKHR*                             pSwapchains);              // pSwapchains
```

- `device` is the device to create the swapchains for.
- `swapchainCount` is the number of swapchains to create.
- `pCreateInfos` is a pointer to an array of `VkSwapchainCreateInfoKHR` structures specifying the parameters of the created swapchains.
- `pAllocator` is the allocator used for host memory allocated for the swapchain objects when there is no more specific allocator available (see Memory Allocation).
- `pSwapchains` is a pointer to an array of `VkSwapchainKHR` handles in which the created swapchain objects will be returned.

`vkCreateSharedSwapchainsKHR` is similar to `vkCreateSwapchainKHR`, except that it takes an array of `VkSwapchainCreateInfoKHR` structures, and returns an array of swapchain objects.

The swapchain creation parameters that affect the properties and number of presentable images must match between all the swapchains. If the displays used by any of the swapchains do not use the same presentable image layout or are incompatible in a way that prevents sharing images, swapchain creation will fail with the result code `VK_ERROR_INCOMPATIBLE_DISPLAY_KHR`. If any error occurs, no swapchains will be created. Images presented to multiple swapchains must be re-acquired from all of them before transitioning away from `VK_IMAGE_LAYOUT_PRESENT_SRC_KHR`. After destroying one or more of the swapchains, the remaining swapchains and the presentable images
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfos** must be a valid pointer to an array of `swapchainCount` valid `VkSwapchainCreateInfoKHR` structures
- If **pAllocator** is not `NULL`, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pSwapchains** must be a valid pointer to an array of `swapchainCount` `VkSwapchainKHR` handles
- **swapchainCount** must be greater than 0

Host Synchronization

- Host access to **pCreateInfos[]**.surface must be externally synchronized
- Host access to **pCreateInfos[]**.oldSwapchain must be externally synchronized

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_INCOMPATIBLE_DISPLAY_KHR`
- `VK_ERROR_DEVICE_LOST`
- `VK_ERROR_SURFACE_LOST_KHR`

To obtain the array of presentable images associated with a swapchain, call:

```c
VkResult vkGetSwapchainImagesKHR(
    VkDevice device,
    VkSwapchainKHR swapchain,
    uint32_t* pSwapchainImageCount,
    VkImage* pSwapchainImages);
```

- **device** is the device associated with `swapchain`.
- **swapchain** is the swapchain to query.
- **pSwapchainImageCount** is a pointer to an integer related to the number of presentable images
available or queried, as described below.

- **pSwapchainImages** is either **NULL** or a pointer to an array of **VkImage** handles.

If **pSwapchainImages** is **NULL**, then the number of presentable images for **swapchain** is returned in **pSwapchainImageCount**. Otherwise, **pSwapchainImageCount** must point to a variable set by the user to the number of elements in the **pSwapchainImages** array, and on return the variable is overwritten with the number of structures actually written to **pSwapchainImages**. If the value of **pSwapchainImageCount** is less than the number of presentable images for **swapchain**, at most **pSwapchainImageCount** structures will be written. If **pSwapchainImageCount** is smaller than the number of presentable images for **swapchain**, **VK_INCOMPLETE** will be returned instead of **VK_SUCCESS** to indicate that not all the available values were returned.

### Valid Usage (Implicit)

- **device** must be a valid **VkDevice** handle
- **swapchain** must be a valid **VkSwapchainKHR** handle
- **pSwapchainImageCount** must be a valid pointer to a **uint32_t** value
- If the value referenced by **pSwapchainImageCount** is not 0, and **pSwapchainImages** is not **NULL**, **pSwapchainImages** must be a valid pointer to an array of **pSwapchainImageCount** **VkImage** handles
- Both of **device**, and **swapchain** must have been created, allocated, or retrieved from the same **VkInstance**

### Return Codes

**Success**

- **VK_SUCCESS**
- **VK_INCOMPLETE**

**Failure**

- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

**Note**

By knowing all presentable images used in the swapchain, the application can create command buffers that reference these images prior to entering its main rendering loop.

Images returned by **vkGetSwapchainImagesKHR** are fully backed by memory before they are passed to the application. All presentable images are initially in the **VK_IMAGE_LAYOUT_UNDEFINED** layout, thus before using presentable images, the application must transition them to a valid layout for the intended use.

Further, the lifetime of presentable images is controlled by the implementation, so applications
must not destroy a presentable image. See vkDestroySwapchainKHR for further details on the lifetime of presentable images.

Images can also be created by using vkCreateImage with VkImageSwapchainCreateInfoKHR and bound to swapchain memory using vkBindImageMemory2KHR with VkBindImageMemorySwapchainInfoKHR. These images can be used anywhere swapchain images are used, and are useful in logical devices with multiple physical devices to create peer memory bindings of swapchain memory. These images and bindings have no effect on what memory is presented. Unlike images retrieved from vkGetSwapchainImagesKHR, these images must be destroyed with vkDestroyImage.

To acquire an available presentable image to use, and retrieve the index of that image, call:

```
VkResult vkAcquireNextImageKHR(
    VkDevice                                    device,
    VkSwapchainKHR                              swapchain,
    uint64_t                                    timeout,
    VkSemaphore                                 semaphore,
    VkFence                                     fence,
    uint32_t*                                   pImageIndex);
```

- **device** is the device associated with swapchain.
- **swapchain** is the non-retired swapchain from which an image is being acquired.
- **timeout** specifies how long the function waits, in nanoseconds, if no image is available.
- **semaphore** is VK_NULL_HANDLE or a semaphore to signal.
- **fence** is VK_NULL_HANDLE or a fence to signal.
- **pImageIndex** is a pointer to a uint32_t in which the index of the next image to use (i.e. an index into the array of images returned by vkGetSwapchainImagesKHR) is returned.
Valid Usage

- **swapchain** must not be in the retired state
- If **semaphore** is not **VK_NULL_HANDLE** it must be unsignaled
- If **semaphore** is not **VK_NULL_HANDLE** it must not have any uncompleted signal or wait operations pending
- If **fence** is not **VK_NULL_HANDLE** it must be unsignaled and must not be associated with any other queue command that has not yet completed execution on that queue
- **semaphore** and **fence** must not both be equal to **VK_NULL_HANDLE**
- If the number of currently acquired images is greater than the difference between the number of images in **swapchain** and the value of **VkSurfaceCapabilitiesKHR::minImageCount** as returned by a call to **vkGetPhysicalDeviceSurfaceCapabilities2KHR** with the **surface** used to create **swapchain**, **timeout** must not be **UINT64_MAX**
- **semaphore** must have a **VkSemaphoreType** of **VK_SEMAPHORE_TYPE_BINARY**

Valid Usage (Implicit)

- **device** must be a valid **VkDevice** handle
- **swapchain** must be a valid **VkSwapchainKHR** handle
- If **semaphore** is not **VK_NULL_HANDLE**, **semaphore** must be a valid **VkSemaphore** handle
- If **fence** is not **VK_NULL_HANDLE**, **fence** must be a valid **VkFence** handle
- **pImageIndex** must be a valid pointer to a **uint32_t** value
- If **semaphore** is a valid handle, it must have been created, allocated, or retrieved from **device**
- If **fence** is a valid handle, it must have been created, allocated, or retrieved from **device**
- Both of **device**, and **swapchain** that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same **VkInstance**

Host Synchronization

- Host access to **swapchain** must be externally synchronized
- Host access to **semaphore** must be externally synchronized
- Host access to **fence** must be externally synchronized
### Return Codes

**Success**
- VK_SUCCESS
- VK_TIMEOUT
- VK_NOT_READY
- VK_SUBOPTIMAL_KHR

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST
- VK_ERROR_OUT_OF_DATE_KHR
- VK_ERROR_SURFACE_LOST_KHR

When successful, `vkAcquireNextImageKHR` acquires a presentable image from the swapchain that an application can use, and sets `pImageIndex` to the index of that image within the swapchain. The presentation engine may not have finished reading from the image at the time it is acquired, so the application must use semaphore and/or fence to ensure that the image layout and contents are not modified until the presentation engine reads have completed. If semaphore is not `VK_NULL_HANDLE`, the application may assume that, once `vkAcquireNextImageKHR` returns, the semaphore signal operation referenced by semaphore has been submitted for execution. The order in which images are acquired is implementation-dependent, and may be different than the order the images were presented.

If timeout is zero, then `vkAcquireNextImageKHR` does not wait, and will either successfully acquire an image, or fail and return VK_NOT_READY if no image is available.

If the specified timeout period expires before an image is acquired, `vkAcquireNextImageKHR` returns VK_TIMEOUT. If timeout is `UINT64_MAX`, the timeout period is treated as infinite, and `vkAcquireNextImageKHR` will block until an image is acquired or an error occurs.

An image will eventually be acquired if the number of images that the application has currently acquired (but not yet presented) is less than or equal to the difference between the number of images in swapchain and the value of ` VkSurfaceCapabilitiesKHR::minImageCount`. If the number of currently acquired images is greater than this, `vkAcquireNextImageKHR` should not be called; if it is, timeout must not be `UINT64_MAX`.

If an image is acquired successfully, `vkAcquireNextImageKHR` must either return VK_SUCCESS, or VK_SUBOPTIMAL_KHR if the swapchain no longer matches the surface properties exactly, but can still be used for presentation.
This may happen, for example, if the platform surface has been resized but the platform is able to scale the presented images to the new size to produce valid surface updates. It is up to the application to decide whether it prefers to continue using the current swapchain in this state, or to re-create the swapchain to better match the platform surface properties.

If the swapchain images no longer match native surface properties, either `VK_SUBOPTIMAL_KHR` or `VK_ERROR_OUT_OF_DATE_KHR` must be returned. If `VK_ERROR_OUT_OF_DATE_KHR` is returned, no image is acquired and attempts to present previously acquired images to the swapchain will also fail with `VK_ERROR_OUT_OF_DATE_KHR`. Applications need to create a new swapchain for the surface to continue presenting if `VK_ERROR_OUT_OF_DATE_KHR` is returned.

If device loss occurs (see Lost Device) before the timeout has expired, `vkAcquireNextImageKHR` must return in finite time with either one of the allowed success codes, or `VK_ERROR_DEVICE_LOST`.

If `semaphore` is not `VK_NULL_HANDLE`, the semaphore must be unsignaled, with no signal or wait operations pending. It will become signaled when the application can use the image.

Use of `semaphore` allows rendering operations to be recorded and submitted before the presentation engine has completed its use of the image.

If `fence` is not equal to `VK_NULL_HANDLE`, the fence must be unsignaled, with no signal operations pending. It will become signaled when the application can use the image.

Applications should not rely on `vkAcquireNextImageKHR` blocking in order to meter their rendering speed. The implementation may return from this function immediately regardless of how many presentation requests are queued, and regardless of when queued presentation requests will complete relative to the call. Instead, applications can use `fence` to meter their frame generation work to match the presentation rate.

An application must wait until either the `semaphore` or `fence` is signaled before accessing the image's data.

When the presentable image will be accessed by some stage S, the recommended idiom for ensuring correct synchronization is:

- The `VkSubmitInfo` used to submit the image layout transition for execution includes `vkAcquireNextImageKHR::semaphore` in its `pWaitSemaphores` member, with the corresponding element of `pWaitDstStageMask` including S.

- The synchronization command that performs any necessary image layout transition includes S in both the `srcStageMask` and `dstStageMask`.
After a successful return, the image indicated by `pImageIndex` and its data will be unmodified compared to when it was presented.

**Note**
Exclusive ownership of presentable images corresponding to a swapchain created with `VK_SHARING_MODE_EXCLUSIVE` as defined in Resource Sharing is not altered by a call to `vkAcquireNextImageKHR`. That means upon the first acquisition from such a swapchain presentable images are not owned by any queue family, while at subsequent acquisitions the presentable images remain owned by the queue family the image was previously presented on.

The possible return values for `vkAcquireNextImageKHR` depend on the `timeout` provided:

- **VK_SUCCESS** is returned if an image became available.
- **VK_ERROR_SURFACE_LOST_KHR** if the surface becomes no longer available.
- **VK_NOT_READY** is returned if `timeout` is zero and no image was available.
- **VK_TIMEOUT** is returned if `timeout` is greater than zero and less than `UINT64_MAX`, and no image became available within the time allowed.
- **VK_SUBOPTIMAL_KHR** is returned if an image became available, and the swapchain no longer matches the surface properties exactly, but can still be used to present to the surface successfully.

**Note**
This may happen, for example, if the platform surface has been resized but the platform is able to scale the presented images to the new size to produce valid surface updates. It is up to the application to decide whether it prefers to continue using the current swapchain indefinitely or temporarily in this state, or to recreate the swapchain to better match the platform surface properties.

- **VK_ERROR_OUT_OF_DATE_KHR** is returned if the surface has changed in such a way that it is no longer compatible with the swapchain, and further presentation requests using the swapchain will fail. Applications must query the new surface properties and recreate their swapchain if they wish to continue presenting to the surface.

If the native surface and presented image sizes no longer match, presentation may fail. If presentation does succeed, the mapping from the presented image to the native surface is implementation-defined. It is the application’s responsibility to detect surface size changes and react appropriately. If presentation fails because of a mismatch in the surface and presented image sizes, a **VK_ERROR_OUT_OF_DATE_KHR** error will be returned.
Note
For example, consider a 4x3 window/surface that gets resized to be 3x4 (taller than wider). On some window systems, the portion of the window/surface that was previously and still is visible (the 3x3 part) will contain the same contents as before, while the remaining parts of the window will have undefined contents. Other window systems may squash/stretch the image to fill the new window size without any undefined contents, or apply some other mapping.

To acquire an available presentable image to use, and retrieve the index of that image, call:

```c
VkResult vkAcquireNextImage2KHR(
    VkDevice                                    device,
    const VkAcquireNextImageInfoKHR*            pAcquireInfo,
    uint32_t*                                   pImageIndex);
```

- **device** is the device associated with `swapchain`.
- **pAcquireInfo** is a pointer to a `VkAcquireNextImageInfoKHR` structure containing parameters of the acquire.
- **pImageIndex** is a pointer to a `uint32_t` that is set to the index of the next image to use.

**Valid Usage**

- If the number of currently acquired images is greater than the difference between the number of images in the `swapchain` member of `pAcquireInfo` and the value of `VkSurfaceCapabilitiesKHR::minImageCount` as returned by a call to `vkGetPhysicalDeviceSurfaceCapabilities2KHR` with the `surface` used to create `swapchain`, the `timeout` member of `pAcquireInfo` must not be `UINT64_MAX`

**Valid Usage (Implicit)**

- **device** must be a valid `VkDevice` handle
- **pAcquireInfo** must be a valid pointer to a valid `VkAcquireNextImageInfoKHR` structure
- **pImageIndex** must be a valid pointer to a `uint32_t` value
Return Codes

Success

- VK_SUCCESS
- VK_TIMEOUT
- VK_NOT_READY
- VK_SUBOPTIMAL_KHR

Failure

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST
- VK_ERROR_OUT_OF_DATE_KHR
- VK_ERROR_SURFACE_LOST_KHR

The `VkAcquireNextImageInfoKHR` structure is defined as:

```c
typedef struct VkAcquireNextImageInfoKHR {
    VkStructureType    sType;
    const void*        pNext;
    VkSwapchainKHR     swapchain;
    uint64_t           timeout;
    VkSemaphore        semaphore;
    VkFence            fence;
    uint32_t           deviceMask;
} VkAcquireNextImageInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `swapchain` is a non-retired swapchain from which an image is acquired.
- `timeout` specifies how long the function waits, in nanoseconds, if no image is available.
- `semaphore` is `VK_NULL_HANDLE` or a semaphore to signal.
- `fence` is `VK_NULL_HANDLE` or a fence to signal.
- `deviceMask` is a mask of physical devices for which the swapchain image will be ready to use when the semaphore or fence is signaled.

If `vkAcquireNextImageInfoKHR` is used, the device mask is considered to include all physical devices in the logical device.
Note

vkAcquireNextImage2KHR signals at most one semaphore, even if the application requests waiting for multiple physical devices to be ready via the deviceMask. However, only a single physical device can wait on that semaphore, since the semaphore becomes unsignaled when the wait succeeds. For other physical devices to wait for the image to be ready, it is necessary for the application to submit semaphore signal operation(s) to that first physical device to signal additional semaphore(s) after the wait succeeds, which the other physical device(s) can wait upon.

Valid Usage

- swapchain must not be in the retired state
- If semaphore is not VK_NULL_HANDLE it must be unsignaled
- If semaphore is not VK_NULL_HANDLE it must not have any uncompleted signal or wait operations pending
- If fence is not VK_NULL.Handle it must be unsignaled and must not be associated with any other queue command that has not yet completed execution on that queue
- semaphore and fence must not both be equal to VK_NULL_HANDLE
- deviceMask must be a valid device mask
- deviceMask must not be zero
- semaphore must have a VkSemaphoreType of VK_SEMAPHORE_TYPE_BINARY

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_ACQUIRE_NEXT_IMAGE_INFO_KHR
- pNext must be NULL
- swapchain must be a valid VkSwapchainKHR handle
- If semaphore is not VK_NULL_HANDLE, semaphore must be a valid VkSemaphore handle
- If fence is not VK_NULL_HANDLE, fence must be a valid VkFence handle
- Each of fence, semaphore, and swapchain that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same VkInstance

Host Synchronization

- Host access to swapchain must be externally synchronized
- Host access to semaphore must be externally synchronized
- Host access to fence must be externally synchronized
After queueing all rendering commands and transitioning the image to the correct layout, to queue an image for presentation, call:

```c
VkResult vkQueuePresentKHR(
    VkQueue                                     queue,
    const VkPresentInfoKHR*                     pPresentInfo);
```

- `queue` is a queue that is capable of presentation to the target surface's platform on the same device as the image's swapchain.
- `pPresentInfo` is a pointer to a `VkPresentInfoKHR` structure specifying parameters of the presentation.

**Note**

There is no requirement for an application to present images in the same order that they were acquired - applications can arbitrarily present any image that is currently acquired.

**Valid Usage**

- Each element of `pSwapchains` member of `pPresentInfo` **must** be a swapchain that is created for a surface for which presentation is supported from `queue` as determined using a call to `vkGetPhysicalDeviceSurfaceSupportKHR`.
- If more than one member of `pSwapchains` was created from a display surface, all display surfaces referenced that refer to the same display **must** use the same display mode.
- When a semaphore wait operation referring to a binary semaphore defined by the elements of the `pWaitSemaphores` member of `pPresentInfo` executes on `queue`, there **must** be no other queues waiting on the same semaphore.
- All elements of the `pWaitSemaphores` member of `pPresentInfo` **must** be semaphores that are signaled, or have semaphore signal operations previously submitted for execution.
- All elements of the `pWaitSemaphores` member of `pPresentInfo` **must** be created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY`.
- All elements of the `pWaitSemaphores` member of `pPresentInfo` **must** reference a semaphore signal operation that has been submitted for execution and any semaphore signal operations on which it depends (if any) **must** have also been submitted for execution.

Any writes to memory backing the images referenced by the `pImageIndices` and `pSwapchains` members of `pPresentInfo`, that are available before `vkQueuePresentKHR` is executed, are automatically made visible to the read access performed by the presentation engine. This automatic visibility operation for an image happens-after the semaphore signal operation, and happens-before the presentation engine accesses the image.

Queueing an image for presentation defines a set of *queue operations*, including waiting on the semaphores and submitting a presentation request to the presentation engine. However, the scope of this set of queue operations does not include the actual processing of the image by the
If `vkQueuePresentKHR` fails to enqueue the corresponding set of queue operations, it may return `VK_ERROR_OUT_OF_HOST_MEMORY` or `VK_ERROR_OUT_OF_DEVICE_MEMORY`. If it does, the implementation must ensure that the state and contents of any resources or synchronization primitives referenced is unaffected by the call or its failure.

If `vkQueuePresentKHR` fails in such a way that the implementation is unable to make that guarantee, the implementation must return `VK_ERROR_DEVICE_LOST`.

However, if the presentation request is rejected by the presentation engine with an error `VK_ERROR_OUT_OF_DATE_KHR` or `VK_ERROR_SURFACE_LOST_KHR`, the set of queue operations are still considered to be enqueued and thus any semaphore wait operation specified in `VkPresentInfoKHR` will execute when the corresponding queue operation is complete.

### Valid Usage (Implicit)

- `queue` must be a valid `VkQueue` handle
- `pPresentInfo` must be a valid pointer to a valid `VkPresentInfoKHR` structure

### Host Synchronization

- Host access to `queue` must be externally synchronized
- Host access to `pPresentInfo.pWaitSemaphores[]` must be externally synchronized
- Host access to `pPresentInfo.pSwapchains[]` must be externally synchronized

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>Any</td>
<td>-</td>
</tr>
</tbody>
</table>
### Return Codes

**Success**
- VK_SUCCESS
- VK_SUBOPTIMAL_KHR

**Failure**
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_DEVICE_LOST
- VK_ERROR_OUT_OF_DATE_KHR
- VK_ERROR_SURFACE_LOST_KHR

The `VkPresentInfoKHR` structure is defined as:

```c
typedef struct VkPresentInfoKHR {
    VkStructureType          sType;
    const void*              pNext;
    uint32_t                 waitSemaphoreCount;
    const VkSemaphore*       pWaitSemaphores;
    uint32_t                 swapchainCount;
    const VkSwapchainKHR*    pSwapchains;
    const uint32_t*          pImageIndices;
    VkResult*                pResults;
} VkPresentInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `waitSemaphoreCount` is the number of semaphores to wait for before issuing the present request. The number may be zero.
- `pWaitSemaphores` is `NULL` or a pointer to an array of `VkSemaphore` objects with `waitSemaphoreCount` entries, and specifies the semaphores to wait for before issuing the present request.
- `swapchainCount` is the number of swapchains being presented to by this command.
- `pSwapchains` is a pointer to an array of `VkSwapchainKHR` objects with `swapchainCount` entries. A given swapchain must not appear in this list more than once.
- `pImageIndices` is a pointer to an array of indices into the array of each swapchain’s presentable images, with `swapchainCount` entries. Each entry in this array identifies the image to present on the corresponding entry in the `pSwapchains` array.
- `pResults` is a pointer to an array of `VkResult` typed elements with `swapchainCount` entries. Applications that do not need per-swapchain results can use `NULL` for `pResults`. If non-`NULL`, each entry in `pResults` will be set to the `VkResult` for presenting the swapchain corresponding to the same index in `pSwapchains`. 

Before an application can present an image, the image's layout must be transitioned to the `VK_IMAGE_LAYOUT_PRESENT_SRC_KHR` layout, or for a shared presentable image the `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR` layout.

**Note**
When transitioning the image to `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR` or `VK_IMAGE_LAYOUT_PRESENT_SRC_KHR`, there is no need to delay subsequent processing, or perform any visibility operations (as `vkQueuePresentKHR` performs automatic visibility operations). To achieve this, the `dstAccessMask` member of the `VkImageMemoryBarrier` should be set to 0, and the `dstStageMask` parameter should be set to `VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT`.

**Valid Usage**

- Each element of `pImageIndices` must be the index of a presentable image acquired from the swapchain specified by the corresponding element of the `pSwapchains` array, and the presented image subresource must be in the `VK_IMAGE_LAYOUT_PRESENT_SRC_KHR` or `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR` layout at the time the operation is executed on a `VkDevice`.

- All elements of the `pWaitSemaphores` must have a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_BINARY`.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_PRESENT_INFO_KHR`

- Each `pNext` member of any structure (including this one) in the `pNext` chain must be either `NULL` or a pointer to a valid instance of `VkDeviceGroupPresentInfoKHR`, `VkDisplayPresentInfoKHR`, or `VkPresentRegionsKHR`.

- The `sType` value of each struct in the `pNext` chain must be unique.

- If `waitSemaphoreCount` is not 0, `pWaitSemaphores` must be a valid pointer to an array of `waitSemaphoreCount` valid `VkSemaphore` handles.

- `pSwapchains` must be a valid pointer to an array of `swapchainCount` valid `VkSwapchainKHR` handles.

- `pImageIndices` must be a valid pointer to an array of `swapchainCount` `uint32_t` values.

- If `pResults` is not `NULL`, `pResults` must be a valid pointer to an array of `swapchainCount` `VkResult` values.

- `swapchainCount` must be greater than 0.

- Both of the elements of `pSwapchains`, and the elements of `pWaitSemaphores` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkInstance`.

When the `VK_KHR_incremental_present` extension is enabled, additional fields can be specified that
allow an application to specify that only certain rectangular regions of the presentable images of a swapchain are changed. This is an optimization hint that a presentation engine may use to only update the region of a surface that is actually changing. The application still must ensure that all pixels of a presented image contain the desired values, in case the presentation engine ignores this hint. An application can provide this hint by adding a VkPresentRegionsKHR structure to the pNext chain of the VkPresentInfoKHR structure.

The VkPresentRegionsKHR structure is defined as:

```c
typedef struct VkPresentRegionsKHR {
    VkStructureType              sType;
    const void*                  pNext;
    uint32_t                     swapchainCount;
    const VkPresentRegionKHR*    pRegions;
} VkPresentRegionsKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **swapchainCount** is the number of swapchains being presented to by this command.
- **pRegions** is NULL or a pointer to an array of VkPresentRegionKHR elements with swapchainCount entries. If not NULL, each element of pRegions contains the region that has changed since the last present to the swapchain in the corresponding entry in the VkPresentInfoKHR::pSwapchains array.

**Valid Usage**

- **swapchainCount must** be the same value as VkPresentInfoKHR:swapchainCount, where VkPresentInfoKHR is included in the pNext chain of this VkPresentRegionsKHR structure.

**Valid Usage (Implicit)**

- **sType must** be VK_STRUCTURE_TYPE_PRESENT_REGIONS_KHR
- If pRegions is not NULL, pRegions must be a valid pointer to an array of swapchainCount valid VkPresentRegionKHR structures
- swapchainCount must be greater than 0

For a given image and swapchain, the region to present is specified by the VkPresentRegionKHR structure, which is defined as:

```c
typedef struct VkPresentRegionKHR {
    uint32_t                 rectangleCount;
    const VkRectLayerKHR*    pRectangles;
} VkPresentRegionKHR;
```
• **rectangleCount** is the number of rectangles in **pRectangles**, or zero if the entire image has changed and should be presented.

• **pRectangles** is either **NULL** or a pointer to an array of **VkRectLayerKHR** structures. The **VkRectLayerKHR** structure is the framebuffer coordinates, plus layer, of a portion of a presentable image that has changed and **must** be presented. If non-**NULL**, each entry in **pRectangles** is a rectangle of the given image that has changed since the last image was presented to the given swapchain.

### Valid Usage (Implicit)

- If **rectangleCount** is not 0, and **pRectangles** is not **NULL**, **pRectangles** must be a valid pointer to an array of **rectangleCount** valid **VkRectLayerKHR** structures.

The **VkRectLayerKHR** structure is defined as:

```c
typedef struct VkRectLayerKHR {
    VkOffset2D    offset;
    VkExtent2D    extent;
    uint32_t      layer;
} VkRectLayerKHR;
```

- **offset** is the origin of the rectangle, in pixels.
- **extent** is the size of the rectangle, in pixels.
- **layer** is the layer of the image. For images with only one layer, the value of **layer** must be 0.

### Valid Usage

- The sum of **offset** and **extent** must be no greater than the **imageExtent** member of the **VkSwapchainCreateInfoKHR** structure given to **vkCreateSwapchainKHR**.
- **layer** must be less than **imageArrayLayers** member of the **VkSwapchainCreateInfoKHR** structure given to **vkCreateSwapchainKHR**.

Some platforms allow the size of a surface to change, and then scale the pixels of the image to fit the surface. **VkRectLayerKHR** specifies pixels of the swapchain's image(s), which will be constant for the life of the swapchain.

When the VK_KHR_display_swapchain extension is enabled additional fields can be specified when presenting an image to a swapchain by setting **VkPresentInfoKHR**:::pNext to point to a **VkDisplayPresentInfoKHR** structure.

The **VkDisplayPresentInfoKHR** structure is defined as:
typedef struct VkDisplayPresentInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkRect2D srcRect;
    VkRect2D dstRect;
    VkBool32 persistent;
} VkDisplayPresentInfoKHR;

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- srcRect is a rectangular region of pixels to present. It must be a subset of the image being presented. If VkDisplayPresentInfoKHR is not specified, this region will be assumed to be the entire presentable image.
- dstRect is a rectangular region within the visible region of the swapchain's display mode. If VkDisplayPresentInfoKHR is not specified, this region will be assumed to be the entire visible region of the swapchain's display mode. If the specified rectangle is a subset of the display mode's visible region, content from display planes below the swapchain's plane will be visible outside the rectangle. If there are no planes below the swapchain's, the area outside the specified rectangle will be black. If portions of the specified rectangle are outside of the display's visible region, pixels mapping only to those portions of the rectangle will be discarded.
- persistent: If this is VK_TRUE, the display engine will enable buffered mode on displays that support it. This allows the display engine to stop sending content to the display until a new image is presented. The display will instead maintain a copy of the last presented image. This allows less power to be used, but may increase presentation latency. If VkDisplayPresentInfoKHR is not specified, persistent mode will not be used.

If the extent of the srcRect and dstRect are not equal, the presented pixels will be scaled accordingly.

Valid Usage

- srcRect must specify a rectangular region that is a subset of the image being presented
- dstRect must specify a rectangular region that is a subset of the visibleRegion parameter of the display mode the swapchain being presented uses
- If the persistentContent member of the VkDisplayPropertiesKHR structure returned by vkGetPhysicalDeviceDisplayPropertiesKHR for the display the present operation targets then persistent must be VK_FALSE

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_DISPLAY_PRESENT_INFO_KHR

If the pNext chain of VkPresentInfoKHR includes a VkDeviceGroupPresentInfoKHR structure, then that
structure includes an array of device masks and a device group present mode.

The `VkDeviceGroupPresentInfoKHR` structure is defined as:

```c
typedef struct VkDeviceGroupPresentInfoKHR {
    VkStructureType                        sType;  
    const void*                            pNext;  
    uint32_t                               swapchainCount; 
    const uint32_t*                        pDeviceMasks; 
    VkDeviceGroupPresentModeFlagBitsKHR    mode; 
} VkDeviceGroupPresentInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `swapchainCount` is zero or the number of elements in `pDeviceMasks`.
- `pDeviceMasks` is a pointer to an array of device masks, one for each element of `VkPresentInfoKHR`::pSwapchains.
- `mode` is the device group present mode that will be used for this present.

If `mode` is `VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR`, then each element of `pDeviceMasks` selects which instance of the swapchain image is presented. Each element of `pDeviceMasks` must have exactly one bit set, and the corresponding physical device must have a presentation engine as reported by `VkDeviceGroupPresentCapabilitiesKHR`.

If `mode` is `VK_DEVICE_GROUP_PRESENT_MODE_REMOTE_BIT_KHR`, then each element of `pDeviceMasks` selects which instance of the swapchain image is presented. Each element of `pDeviceMasks` must have exactly one bit set, and some physical device in the logical device must include that bit in its `VkDeviceGroupPresentCapabilitiesKHR`::presentMask.

If `mode` is `VK_DEVICE_GROUP_PRESENT_MODE_SUM_BIT_KHR`, then each element of `pDeviceMasks` selects which instances of the swapchain image are component-wise summed and the sum of those images is presented. If the sum in any component is outside the representable range, the value of that component is undefined. Each element of `pDeviceMasks` must have a value for which all set bits are set in one of the elements of `VkDeviceGroupPresentCapabilitiesKHR`::presentMask.

If `mode` is `VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_MULTI_DEVICE_BIT_KHR`, then each element of `pDeviceMasks` selects which instance(s) of the swapchain images are presented. For each bit set in each element of `pDeviceMasks`, the corresponding physical device must have a presentation engine as reported by `VkDeviceGroupPresentCapabilitiesKHR`.

If `VkDeviceGroupPresentInfoKHR` is not provided or `swapchainCount` is zero then the masks are considered to be 1. If `VkDeviceGroupPresentInfoKHR` is not provided, `mode` is considered to be `VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR`.  

986 | Chapter 29. Window System Integration (WSI)
Valid Usage

• swapchainCount must equal 0 or VkPresentInfoKHR::swapchainCount

• If mode is VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_BIT_KHR, then each element of pDeviceMasks must have exactly one bit set, and the corresponding element of VkDeviceGroupPresentCapabilitiesKHR::presentMask must be non-zero

• If mode is VK_DEVICE_GROUP_PRESENT_MODE_REMOTE_BIT_KHR, then each element of pDeviceMasks must have exactly one bit set, and some physical device in the logical device must include that bit in its VkDeviceGroupPresentCapabilitiesKHR::presentMask.

• If mode is VK_DEVICE_GROUP_PRESENT_MODE_SUM_BIT_KHR, then each element of pDeviceMasks must have a value for which all set bits are set in one of the elements of VkDeviceGroupPresentCapabilitiesKHR::presentMask

• If mode is VK_DEVICE_GROUP_PRESENT_MODE_LOCAL_MULTI_DEVICE_BIT_KHR, then for each bit set in each element of pDeviceMasks, the corresponding element of VkDeviceGroupPresentCapabilitiesKHR::presentMask must be non-zero

• The value of each element of pDeviceMasks must be equal to the device mask passed in VkAcquireNextImageInfoKHR::deviceMask when the image index was last acquired

• mode must have exactly one bit set, and that bit must have been included in VkDeviceGroupSwapchainCreateInfoKHR::modes

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_DEVICE_GROUP_PRESENT_INFO_KHR

• If swapchainCount is not 0, pDeviceMasks must be a valid pointer to an array of swapchainCount uint32_t values

• mode must be a valid VkDeviceGroupPresentModeFlagBitsKHR value

vkQueuePresentKHR, releases the acquisition of the images referenced by imageIndices. The queue family corresponding to the queue vkQueuePresentKHR is executed on must have ownership of the presented images as defined in Resource Sharing. vkQueuePresentKHR does not alter the queue family ownership, but the presented images must not be used again before they have been reacquired using vkAcquireNextImageKHR.

The processing of the presentation happens in issue order with other queue operations, but semaphores have to be used to ensure that prior rendering and other commands in the specified queue complete before the presentation begins. The presentation command itself does not delay processing of subsequent commands on the queue, however, presentation requests sent to a particular queue are always performed in order. Exact presentation timing is controlled by the semantics of the presentation engine and native platform in use.

If an image is presented to a swapchain created from a display surface, the mode of the associated display will be updated, if necessary, to match the mode specified when creating the display surface. The mode switch and presentation of the specified image will be performed as one atomic
The result codes `VK_ERROR_OUT_OF_DATE_KHR` and `VK_SUBOPTIMAL_KHR` have the same meaning when returned by `vkQueuePresentKHR` as they do when returned by `vkAcquireNextImageKHR`. If multiple swapchains are presented, the result code is determined applying the following rules in order:

- If the device is lost, `VK_ERROR_DEVICE_LOST` is returned.
- If any of the target surfaces are no longer available the error `VK_ERROR_SURFACE_LOST_KHR` is returned.
- If any of the presents would have a result of `VK_ERROR_OUT_OF_DATE_KHR` if issued separately then `VK_ERROR_OUT_OF_DATE_KHR` is returned.
- If any of the presents would have a result of `VK_SUBOPTIMAL_KHR` if issued separately then `VK_SUBOPTIMAL_KHR` is returned.
- Otherwise `VK_SUCCESS` is returned.

Presentation is a read-only operation that will not affect the content of the presentable images. Upon reacquiring the image and transitioning it away from the `VK_IMAGE_LAYOUT_PRESENT_SRC_KHR` layout, the contents will be the same as they were prior to transitioning the image to the present source layout and presenting it. However, if a mechanism other than Vulkan is used to modify the platform window associated with the swapchain, the content of all presentable images in the swapchain becomes undefined.

**Note**
The application can continue to present any acquired images from a retired swapchain as long as the swapchain has not entered a state that causes `vkQueuePresentKHR` to return `VK_ERROR_OUT_OF_DATE_KHR`.
Chapter 30. Deferred Host Operations

Certain Vulkan commands are inherently expensive for the host CPU to execute. It is often desirable to offload such work onto background threads, and to parallelize the work across multiple CPUs. The concept of deferred operations allows applications and drivers to coordinate the execution of expensive host commands using an application-managed thread pool.

The VK_KHR_deferred_host_operations extension defines the infrastructure and usage patterns for deferrable commands, but does not specify any commands as deferrable. This is left to additional dependant extensions. Commands must not be deferred unless the deferral is specifically allowed by another extension which depends on VK_KHR_deferred_host_operations. This specification will refer to such extensions as deferral extensions.

30.1. Requesting Deferral

The VkDeferredOperationInfoKHR structure is defined as:

```c
typedef struct VkDeferredOperationInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkDeferredOperationKHR operationHandle;
} VkDeferredOperationInfoKHR;
```

- `sType` is the type of this structure.
- `pNext` is NULL or a pointer to an extension-specific structure.
- `operationHandle` is a handle to a tracking object to associate with the deferred operation.

The application can request deferral of an operation by adding this structure to the argument list of a command or by providing this in the `pNext` chain of a relevant structure for an operation when the corresponding command is invoked. If this structure is not present, no deferral is requested. If `operationHandle` is VK_NULL_HANDLE, no deferral is requested and the command proceeds as if no `VkDeferredOperationInfoKHR` structure was provided.

When an application requests an operation deferral, the implementation may defer the operation. When deferral is requested and the implementation defers any operation, the implementation must return VK_OPERATION_DEFERRED_KHR as the success code if no errors occurred. When deferral is requested, the implementation should defer the operation when the workload is significant, however if the implementation chooses not to defer any of the requested operations and instead executes all of them immediately, the implementation must return VK_OPERATION_NOT_DEFERRED_KHR as the success code if no errors occurred.

A deferred operation is created complete with an initial result value of VK_SUCCESS. The deferred operation becomes pending when an operation has been successfully deferred with that `operationHandle`.

A deferred operation is considered pending until the deferred operation completes. A pending deferred operation becomes complete when it has been fully executed by one or more threads.
Pending deferred operations will never complete until they are *joined* by an application thread, using `vkDeferredOperationJoinKHR`. Applications can join multiple threads to the same deferred operation, enabling concurrent execution of subtasks within that operation.

The application *can* query the status of a `VkDeferredOperationKHR` using the `vkGetDeferredOperationMaxConcurrencyKHR` or `vkGetDeferredOperationResultKHR` commands.

From the perspective of other commands - parameters to the original command that are externally synchronized *must* not be accessed before the deferred operation completes, and the result of the deferred operation (e.g. object creation) are not considered complete until the deferred operation completes.

If the deferred operation is one which creates an object (for example, a pipeline object), the implementation *must* allocate that object as it normally would, and return a valid handle to the application. This object is a *pending* object, and *must* not be used by the application until the deferred operation is completed (unless otherwise specified by the deferral extension). When the deferred operation is complete, the application *should* call `vkGetDeferredOperationResultKHR` to obtain the result of the operation. If `vkGetDeferredOperationResultKHR` indicates failure, the application *must* destroy the pending object using an appropriate command, so that the implementation has an opportunity to recover the handle. The application *must* not perform this destruction until the deferred operation is complete. Construction of the pending object uses the same allocator which would have been used if the operation had not been deferred.

### Valid Usage

- Any previous deferred operation that was associated with `operationHandle` *must* be complete

### Valid Usage (Implicit)

- `sType` *must* be `VK_STRUCTURE_TYPE_DEFERRED_OPERATION_INFO_KHR`

### 30.2. Deferred Host Operations API

The `VkDeferredOperationKHR` handle is defined as:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDeferredOperationKHR)
```

This handle refers to a tracking structure which manages the execution state for a deferred command.

To construct the tracking object for a deferred command, call:
 VkResult vkCreateDeferredOperationKHR(VkDevice device, const VkAllocationCallbacks* pAllocator, VkDeferredOperationKHR* pDeferredOperation);

- **device** is the device which owns **operation**.
- **pAllocator** controls host memory allocation as described in the [Memory Allocation](#) chapter.
- **pDeferredOperation** is a pointer to a handle in which the created [VkDeferredOperationKHR](#) is returned.

**Valid Usage (Implicit)**

- **device** must be a valid [VkDevice](#) handle
- If **pAllocator** is not NULL, **pAllocator** must be a valid pointer to a valid [VkAllocationCallbacks](#) structure
- **pDeferredOperation** must be a valid pointer to a [VkDeferredOperationKHR](#) handle

**Return Codes**

**Success**

- VK_SUCCESS

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY

To assign a thread to a deferred operation, call:

 VkResult vkDeferredOperationJoinKHR(VkDevice device, VkDeferredOperationKHR operation);

- **device** is the device which owns **operation**.
- **operation** is the deferred operation that the calling thread should work on.

The [vkDeferredOperationJoinKHR](#) command will execute a portion of the deferred operation on the calling thread.

The return value will be one of the following:

- A return value of VK_SUCCESS indicates that **operation** is complete. The application **should** use [vkGetDeferredOperationResultKHR](#) to retrieve the result of **operation**.
- A return value of VK_THREAD_DONE_KHR indicates that the deferred operation is not complete, but there is no work remaining to assign to threads. Future calls to [vkDeferredOperationJoinKHR](#)
are not necessary and will simply harm performance. This situation may occur when other threads executing `vkDeferredOperationJoinKHR` are about to complete `operation`, and the implementation is unable to partition the workload any further.

- A return value of `VK_THREAD_IDLE_KHR` indicates that the deferred operation is not complete, and there is no work for the thread to do at the time of the call. This situation may occur if the operation encounters a temporary reduction in parallelism. By returning `VK_THREAD_IDLE_KHR`, the implementation is signaling that it expects that more opportunities for parallelism will emerge as execution progresses, and that future calls to `vkDeferredOperationJoinKHR` can be beneficial. In the meantime, the application can perform other work on the calling thread.

Implementations must guarantee forward progress by enforcing the following invariants:

1. If only one thread has invoked `vkDeferredOperationJoinKHR` on a given operation, that thread must execute the operation to completion and return `VK_SUCCESS`.
2. If multiple threads have concurrently invoked `vkDeferredOperationJoinKHR` on the same operation, then at least one of them must complete the operation and return `VK_SUCCESS`.

Valid Usage (Implicit)

- device must be a valid `VkDevice` handle
- operation must be a valid `VkDeferredOperationKHR` handle
- operation must have been created, allocated, or retrieved from device

Return Codes

Success
- `VK_SUCCESS`
- `VK_THREAD_DONE_KHR`
- `VK_THREAD_IDLE_KHR`

Failure
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

When a deferred operation is completed, the application can destroy the tracking object by calling:

```c
void vkDestroyDeferredOperationKHR(  
    VkDevice                                    device,  
    VkDeferredOperationKHR                      operation,  
    const VkAllocationCallbacks*                pAllocator);
```

- device is the device which owns operation.
- operation is the completed operation to be destroyed.
• pAllocator controls host memory allocation as described in the Memory Allocation chapter.

Valid Usage

• If VkAllocationCallbacks were provided when operation was created, a compatible set of callbacks must be provided here
• If no VkAllocationCallbacks were provided when operation was created, pAllocator must be NULL
• operation must be completed

Valid Usage (Implicit)

• device must be a valid VkDevice handle
• operation must be a valid VkDeferredOperationKHR handle
• If pAllocator is not NULL, pAllocator must be a valid pointer to a valid VkAllocationCallbacks structure
• operation must have been created, allocated, or retrieved from device

The vkGetDeferredOperationMaxConcurrencyKHR function is defined as:

```c
uint32_t vkGetDeferredOperationMaxConcurrencyKHR(
    VkDevice device,  
    VkDeferredOperationKHR operation);
```

• device is the device which owns operation.
• operation is the deferred operation to be queried.

The returned value is the maximum number of threads that can usefully execute a deferred operation concurrently, reported for the state of the deferred operation at the point this command is called. This value is intended to be used to better schedule work onto available threads. Applications can join any number of threads to the deferred operation and expect it to eventually complete, though excessive joins may return VK_THREAD_IDLE_KHR immediately, performing no useful work.

If the deferred operation is currently joined to any threads, the value returned by this command may immediately be out of date.

Implementations must not return zero.

Implementations may return $2^{32}-1$ to indicate that the maximum concurrency is unknown and cannot be easily derived. Implementations may return values larger than the maximum concurrency available on the host CPU. In these situations, an application should clamp the return value rather than oversubscribing the machine.
Valid Usage

Valid Usage (Implicit)

- **device** must be a valid *VkDevice* handle
- **operation** must be a valid *VkDeferredOperationKHR* handle
- **operation** must have been created, allocated, or retrieved from **device**

The `vkGetDeferredOperationResultKHR` function is defined as:

```c
VkResult vkGetDeferredOperationResultKHR(
  VkDevice                                    device,
  VkDeferredOperationKHR                      operation);
```

- **device** is the device which owns **operation**.
- **operation** is the operation whose deferred result is being queried.

If the deferred operation is pending, `vkGetDeferredOperationResultKHR` returns **VK_NOT_READY**. Otherwise, it returns the result of the deferred operation. This value must be one of the *VkResult* values which could have been returned by the original command if the operation had not been deferred.

Valid Usage

Valid Usage (Implicit)

- **device** must be a valid *VkDevice* handle
- **operation** must be a valid *VkDeferredOperationKHR* handle
- **operation** must have been created, allocated, or retrieved from **device**

Return Codes

**Success**

- **VK_SUCCESS**
- **VK_NOT_READY**
Chapter 31. Ray Traversal

Ray traversal is the process which handles intersections between a traced ray and geometry in an acceleration structure.

Ray traversal cannot be started by a Vulkan API command directly - a shader must execute OpRayQueryProceedKHR or OpTraceRayKHR. When the rayTracing feature is enabled, OpTraceRayKHR can be used for ray tracing in a ray tracing pipeline. When the rayQuery feature is enabled, OpRayQueryProceedKHR can be used in any shader stage.

31.1. Ray Intersection Candidate Determination

Once tracing begins, rays will be tested against geometries in an acceleration structure to determine if a hit occurred between them, initially based only on their geometric properties (i.e. their vertices). The implementation performs similar operations to that of rasterization, but with the effective viewport determined by the parameters of the ray, and the geometry transformed into a space determined by that viewport.

The acceleration structure space coordinates of each primitive are transformed according to the origin and direction of the ray as follows:

\[
\begin{pmatrix}
x_r \\
y_r \\
z_r
\end{pmatrix} = \begin{pmatrix}
x_{as} - o_x \\
y_{as} - o_y \\
z_{as} - o_z
\end{pmatrix} \times \begin{pmatrix}
a_x^2(1-c) + c & a_xa_y(1-c) - sa_z & a_xa_z(1-c) + sa_y \\
a_xa_y(1-c) + sa_z & a_y^2(1-c) + c & a_ya_z(1-c) - sa_x \\
a_xa_z(1-c) - sa_y & a_ya_z(1-c) + sa_x & a_z^2(1-c) + c
\end{pmatrix}
\]

a is the axis of rotation between k and d

\[a = \frac{k \times d}{\|k \times d\|}\]

s and c are the sine and cosine of the angle \(\alpha\) between k and d

\[
\begin{align*}
\alpha &= \arccos(u \cdot d) \\
c &= \cos(\alpha) \\
s &= \sin(\alpha)
\end{align*}
\]

k is the unit vector

\[k = \begin{pmatrix}
0 \\
0 \\
1
\end{pmatrix}\]

o and d are the ray origin and direction, respectively; the vector described by \(x_{as}, y_{as}, z_{as}\) is any position in acceleration structure space; and the vector described by \(x_r, y_r, z_r\) is the same position in ray space.

An intersection candidate is a unique point of intersection between a ray and a geometric primitive. For any primitive that has within its bounds a position \(xyz_{as}\) such that

\[
\begin{align*}
x_r &= 0 \\
y_r &= 0 \\
T_{Min} &\leq z_r \leq T_{Max}
\end{align*}
\]
an intersection candidate exists.

The determination of this condition is performed in an implementation specific manner, and may be performed with floating point operations. Due to the complexity and number of operations involved, inaccuracies are expected, particularly as the scale of values involved begins to diverge. Implementations should take efforts to maintain as much precision as possible.

Note

One very common case is when geometries are close to each other at some distance from the origin in acceleration structure space, where an effect similar to "z-fighting" is likely to be observed. Applications can mitigate this by ensuring their detailed geometries remain close to the origin.

Another likely case is when the origin of a ray is set to a position on a previously intersected surface, and its $t_{\text{min}}$ is zero or near zero; an intersection may be detected on the emitting surface. This case can usually be mitigated by offsetting $t_{\text{min}}$ slightly.

In the case of AABB geometries, implementations may increase their size in an acceleration structure in order to mitigate precision issues. This may result in false positives being reported to the application.

For triangle intersection candidates, the $a$ and $b$ barycentric coordinates on the triangle where the above condition is met are made available to future shading. If the ray was traced with `OpTraceRayKHR`, these values are available as a vector of 2 32-bit floating point values in the `HitAttributeKHR` storage class.

Once an intersection candidate is determined, it proceeds through the following operations, in order:

1. Ray Intersection Culling
2. Ray Intersection Confirmation
3. Ray Closest Hit Determination
4. Ray Result Determination

The sections below describe the exact details of these tests. There is no ordering guarantee between operations performed on different intersection candidates.

### 31.1.1. Watertightness

For a set of triangles with identical transforms, within a single instance:

- Any set of two or more triangles where all triangles have one vertex with an identical position value, that vertex is a *shared vertex*.

- Any set of two triangles with two shared vertices that were specified in the same *winding order* in each triangle have a *shared edge* defined by those vertices.

A *closed fan* is a set of three or more triangles where:
• All triangles in the set have the same shared vertex as one of their vertices.
• All edges that include the above vertex are shared edges.
• All above shared edges are shared by exactly two triangles from the set.
• No two triangles in the set intersect, except at shared edges.
• Every triangle in the set is joined to every other triangle in the set by a series of the above shared edges.

Implementations should not double-hit or miss when a ray intersects a shared edge, or a shared vertex of a closed fan.

31.2. Ray Intersection Culling

Candidate intersections go through several phases of culling before confirmation as an actual hit. There is no particular ordering dependency between the different culling operations.

31.2.1. Ray Primitive Culling

If the rayTracingPrimitiveCulling feature is enabled, the SkipTrianglesKHR and SkipAABBsKHR ray flags can be specified when tracing a ray.

If SkipTrianglesKHR was included in the Ray Flags operand of the ray trace instruction, and the intersection is with a triangle primitive, the intersection is dropped, and no further processing of this intersection occurs. If VK_PIPELINE_CREATE_RAY_TRACING_SKIP_TRIANGLES_BIT_KHR was included in the pipeline, traversal with OpTraceKHR calls will all behave as if SkipTrianglesKHR was included in its Ray Flags operand.

If SkipAABBsKHR was included in the Ray Flags operand of the ray trace instruction, and the intersection is with an AABB primitive, the intersection is dropped, and no further processing of this intersection occurs. If VK_PIPELINE_CREATE_RAY_TRACING_SKIP_AABBS_BIT_KHR was included in the pipeline, traversal with OpTraceKHR calls will all behave as if SkipTrianglesKHR was included in its Ray Flags operand.

31.2.2. Ray Mask Culling

Instances can be made invisible to particular rays based on the value of VkAccelerationStructureInstanceKHR::mask used to add that instance to a top-level acceleration structure, and the Cull Mask parameter used to trace the ray.

For the instance which is intersected, if mask & Cull Mask == 0, the intersection is dropped, and no further processing occurs.

31.2.3. Ray Face Culling

As in polygon rasterization, one of the stages of ray traversal is to determine if a triangle primitive is back- or front-facing, and primitives can be culled based on that facing.

If the intersection candidate is with an AABB primitive, this operation is skipped.
**Determination**

When a ray intersects a triangle primitive, the order that vertices are specified for the polygon affects whether the ray intersects the front or back face. Front or back facing is determined in the same way as they are for rasterization, based on the sign of the polygon's area but using the ray space coordinates instead of framebuffer coordinates. One way to compute this area is:

\[
a = -\frac{1}{2} \sum_{i=0}^{n-1} x_i y_{i+1} - x_{i+1} y_i
\]

where \(x_i\) and \(y_i\) are the x and y ray space coordinates of the ith vertex of the n-vertex polygon (vertices are numbered starting at zero for the purposes of this computation) and \(i \oplus 1\) is \((i + 1) \mod n\).

If \(\text{VK\_GEOMETRY\_INSTANCE\_TRIANGLE\_FRONT\_COUNTERCLOCKWISE\_BIT\_KHR}\) is included in \(\text{VkAccelerationStructureInstanceKHR}\)::flags for the instance containing the intersected triangle, if \(a\) is positive then the intersection is with the front face of the triangle, otherwise it is with the back face. If \(\text{VK\_GEOMETRY\_INSTANCE\_TRIANGLE\_FRONT\_COUNTERCLOCKWISE\_BIT\_KHR}\) was not included, this determination is reversed. Additionally, if \(a\) is 0, the intersection candidate is treated as not intersecting with any face, irrespective of the sign.

If the ray was traced with \(\text{Op\_Trace\_Ray\_KHR}\), the \(\text{HitKindKHR}\) built-in is set to \(\text{HitKind\_Front\_Facing\_Triangle\_KHR}\) if the intersection is with front-facing geometry, and \(\text{HitKind\_Back\_Facing\_Triangle\_KHR}\) if the intersection is with back-facing geometry, for shader stages considering this intersection.

If the ray was traced with \(\text{Op\_Ray\_Query\_Proceed\_KHR}\), \(\text{Op\_Ray\_Query\_Get\_Intersection\_Front\_Face\_KHR}\) will return true for intersection candidates with front faces, or false for back faces.

**Culling**

If \(\text{Cull\_Back\_Facing\_Triangles\_KHR}\) was included in the Ray Flags parameter of the ray trace instruction, and the intersection is determined as with the back face of a triangle primitive, the intersection is dropped, and no further processing of this intersection occurs.

If \(\text{Cull\_Front\_Facing\_Triangles\_KHR}\) was included in the Ray Flags parameter of the ray trace instruction, and the intersection is determined as with the front face of a triangle primitive, the intersection is dropped, and no further processing of this intersection occurs.

This culling is disabled if \(\text{VK\_GEOMETRY\_INSTANCE\_TRIANGLE\_FACING\_CULL\_DISABLE\_BIT\_KHR}\) was included in \(\text{VkAccelerationStructureInstanceKHR}\)::flags for the instance which the intersected geometry belongs to.

Intersection candidates that have not intersected with any face (\(a == 0\)) are unconditionally culled, irrespective of ray flags and geometry instance flags.

### 31.2.4. Ray Opacity Culling

Each geometry in the acceleration structure may be considered either opaque or not. Opaque geometries continue through traversal as normal, whereas non-opaque geometries need to be either confirmed or discarded by shader code. Intersection candidates can also be culled based on their opacity.
Each individual intersection candidate is initially determined as opaque if `VK_GEOMETRY_OPAQUE_BIT_KHR` was included in the `VkAccelerationStructureGeometryKHR::flags` when the geometry it intersected with was built, otherwise it is considered non-opaque.

If the intersection candidate was generated by an intersection shader, the intersection is initially considered to have opacity matching the AABB candidate that it was generated from.

However, this opacity can be overridden when it is built into an instance. Setting `VK_GEOMETRY_INSTANCE_FORCE_OPAQUE_BIT_KHR` in `VkAccelerationStructureInstanceKHR::flags` will force all geometries in the instance to be considered opaque. Similarly, setting `VK_GEOMETRY_INSTANCE_FORCE_NO_OPAQUE_BIT_KHR` will force all geometries in the instance to be considered non-opaque.

This can again be overridden by including `OpaqueKHR` or `NoOpaqueKHR` in the `Ray Flags` parameter when tracing a ray. `OpaqueKHR` forces all geometries to behave as if they are opaque, regardless of their build parameters. Similarly, `NoOpaqueKHR` forces all geometries to behave as if they are non-opaque.

If the ray was traced with `OpRayQueryProceedKHR`, to determine the opacity of AABB intersection candidates, `OpRayQueryGetIntersectionCandidateAABBOpaqueKHR` can be used. This instruction will return `true` for opaque intersection candidates, and `false` for non-opaque intersection candidates.

### Culling

If `CullOpaqueKHR` is included in the `Ray Flags` parameter when tracing a ray, an intersection with a geometry that is considered opaque is dropped, and no further processing occurs.

If `CullNoOpaqueKHR` is included in the `Ray Flags` parameter when tracing a ray, an intersection with a geometry that is considered non-opaque is dropped, and no further processing occurs.

### 31.3. Ray Intersection Confirmation

Depending on the opacity of intersected geometry and whether it's a triangle or AABB, candidate intersections are further processed to determine the eventual hit result. Candidates generated from AABB intersections run through the same confirmation process as triangle hits.

### 31.3.1. AABB Intersection Candidates

For intersection candidates with an AABB geometry generated by [Ray Intersection Candidate Determination], shader code is executed to determine whether any hits should be reported to the traversal infrastructure; no further processing of this intersection candidate occurs.

If the ray was traced with `OpTraceRayKHR`, an intersection shader is invoked from the Shader Binding Table according to the specified indexing for the intersected geometry. If this shader calls `OpReportIntersectionKHR`, a new intersection candidate is generated as described below.

Each new candidate generated as a result of this processing is a generated intersection candidate that intersects the AABB geometry, with a t value equal to the `Hit` parameter of the `OpReportIntersectionKHR` instruction. The new generated candidate is then independently run...
through [Ray Intersection Confirmation] as a generated intersection.

If the ray was traced with `OpRayQueryProceedKHR`, control is returned to the shader which executed `OpRayQueryProceedKHR`, returning `true`. The resulting ray query has a candidate intersection type of `RayQueryCandidateIntersectionAABBKHR`. `OpRayQueryGenerateIntersectionKHR` can be called to commit a new intersection candidate with committed intersection type of `RayQueryCommittedIntersectionGeneratedKHR`. Further ray query processing can be continued by executing `OpRayQueryProceedKHR` with the same ray query, or intersection can be terminated with `OpRayQueryTerminateKHR`. Unlike rays traced with `OpTraceKHR`, candidates generated in this way skip generated intersection candidate confirmation; applications should make this determination before generating the intersection.

This operation may be executed multiple times for the same intersection candidate.

### 31.3.2. Triangle and Generated Intersection Candidates

For triangle and generated intersection candidates, additional shader code may be executed based on the intersections opacity.

If the intersection is opaque, the candidate is immediately confirmed as a valid hit and passes to the next stage of processing.

For non-opaque intersection candidates, shader code is executed to determine whether a hit occurred or not.

If the ray was traced with `OpTraceKHR`, an any hit shader is invoked from the Shader Binding Table according to the specified indexing. If this shader calls `OpIgnoreIntersectionKHR`, the candidate is dropped and no further processing of the candidate occurs. If the any hit shader identified is `VK_SHADER_UNUSED_KHR`, the candidate is immediately confirmed as a valid hit and passes to the next stage of processing.

If the ray was traced with `OpRayQueryProceedKHR`, control is returned to the shader which executed `OpRayQueryProceedKHR`, returning `true`. As only triangle candidates participate in this operation with ray queries, the resulting candidate intersection type is always `RayQueryCandidateIntersectionTriangleKHR`. `OpRayQueryConfirmIntersectionKHR` can be called on the ray query to confirm the candidate as a hit with committed intersection type of `RayQueryCommittedIntersectionTriangleKHR`. Further ray query processing can be continued by executing `OpRayQueryProceedKHR` with the same ray query, or intersection can be terminated with `OpRayQueryTerminateKHR`. If `OpRayQueryConfirmIntersectionKHR` has not been executed, the candidate is dropped and no further processing of the candidate occurs.

This operation may be executed multiple times for the same intersection candidate unless `VK_GEOMETRY_NO_DUPLICATE_ANY_HIT_INVOCATION_BIT_KHR` was specified for the intersected geometry.

### 31.4. Ray Closest Hit Determination

Unless the ray was traced with the `TerminateOnFirstHitKHR` ray flag, the implementation must track the closest confirmed hit until all geometries have been tested and either confirmed or dropped.
After an intersection candidate is confirmed, its t value is compared to \( t_{\text{max}} \) to determine which intersection is closer, where t is the parametric distance along the ray at which the intersection occurred.

- If \( t < t_{\text{max}} \), \( t_{\text{max}} \) is set to t and the candidate is set as the current closest hit.
- If \( t > t_{\text{max}} \), the candidate is dropped and no further processing of that candidate occurs.
- If \( t = t_{\text{max}} \), the candidate may be set as the current closest hit or dropped.

If `TerminateOnFirstHitKHR` was included in the Ray Flags used to trace the ray, once the first hit is confirmed, the ray trace is terminated.

### 31.5. Ray Result Determination

Once all candidates have finished processing the prior stages, or if the ray is forcibly terminated, the final result of the ray trace is determined.

If a closest hit result was identified by Ray Closest Hit Determination, a closest hit has occurred, otherwise the final result is a miss.

For rays traced with `OpTraceRayKHR`, if a closest hit result was identified, a closest-hit shader is invoked from the Shader Binding Table according to the specified indexing for the intersected geometry. Control returns to the shader that executed `OpTraceRayKHR` once this shader returns. This shader is skipped if either the ray flags included `SkipClosestHitShaderKHR`, or if the closest-hit shader identified is `VK_SHADER_UNUSED_NV`.

For rays traced with `OpTraceRayKHR` where no hit result was identified, the miss shader identified by the Miss Index parameter of `OpTraceRayKHR` is invoked. Control returns to the shader that executed `OpTraceRayKHR` once this shader returns.

If the ray was traced with `OpRayQueryProceedKHR`, control is returned to the shader which executed `OpRayQueryProceedKHR`, returning `false`. If a closest hit was identified by Ray Closest Hit Determination, the ray query will now have a committed intersection type of `RayQueryCommittedIntersectionGeneratedKHR` or `RayQueryCommittedIntersectionTriangleKHR`. If no closest hit was identified, the committed intersection type will be `RayQueryCommittedIntersectionNoneKHR`.

No further processing of a ray query occurs after this result is determined.
Chapter 32. Ray Tracing

Ray tracing uses a separate rendering pipeline from both the graphics and compute pipelines (see Ray Tracing Pipeline).

![Ray tracing pipeline execution](image)

*Figure 21. Ray tracing pipeline execution*

**Caption**

Interaction between the different shader stages in the ray tracing pipeline

Within the ray tracing pipeline, `OpTraceRayKHR` can be called to perform a ray traversal that invokes the various ray tracing shader stages during its execution. The relationship between the ray tracing pipeline object and the geometries present in the acceleration structure traversed is passed into the ray tracing command in a `VkBuffer` object known as a shader binding table. `OpExecuteCallableKHR` can also be used in ray tracing pipelines to invoke a callable shader.

During execution, control alternates between scheduling and other operations. The scheduling functionality is implementation-specific and is responsible for workload execution. The shader stages are programmable. *Traversal*, which refers to the process of traversing acceleration structures to find potential intersections of rays with geometry, is fixed function.

The programmable portions of the pipeline are exposed in a single-ray programming model, with each invocation handling one ray at a time. Memory operations can be synchronized using standard memory barriers. The Workgroup scope and variables with a storage class of Workgroup must not be used in the ray tracing pipeline.

### 32.1. Shader Call Instructions

A shader call is an instruction which may cause execution to continue elsewhere by creating one or more invocations that execute a different shader stage.

The shader call instructions are:

- `OpTraceRayKHR` which may invoke intersection, any-hit, closest hit, or miss shaders,
- `OpReportIntersectionKHR` which may invoke any-hit shaders, and
- `OpExecuteCallableKHR` which will invoke a callable shader.
The invocations created by shader call instructions are grouped into subgroups by the implementation. Those subgroups may be unrelated to the subgroup of the parent invocation.

Shader call instructions can be used recursively; invoked shaders can themselves execute shader call instructions, to a maximum depth defined by the maxRecursionDepth limit.

Shaders directly invoked from the API always have a recursion depth of 0; each shader executed by a shader call instruction has a recursion depth one higher than the recursion depth of the shader which invoked it. Applications must not invoke a shader with a recursion depth greater than the value of maxRecursionDepth specified in the pipeline.

An invocation repack instruction is a ray tracing shader call instruction where the implementation may change the set of invocations that are executing. When a repack instruction is encountered, the invocation is suspended and a new invocation begins and executes the instruction. After executing the repack instruction (which may result in other ray tracing shader stages executing) the new invocation ends and the original invocation is resumed, but it may be resumed in a different subgroup or at a different SubgroupLocalInvocationId within the same subgroup. When a subset of invocations in a subgroup execute the invocation repack instruction, those that do not execute it remain in the same subgroup at the same SubgroupLocalInvocationId.

The OpTraceRayKHR, OpReportIntersectionKHR, and OpExecuteCallableKHR instructions are invocation repack instructions.

The invocations that are executing before an invocation repack instruction, after the instruction, or are created by the instruction, are shader-call-related.

If the implementation changes the composition of subgroups, the values of SubgroupLocalInvocationId, and builtin variables that are derived from them (SubgroupEqMask, SubgroupGeMask, SubgroupGtMask, SubgroupLeMask, SubgroupLtMask) must be changed accordingly by the invocation repack instruction.

Note

Subgroup operations are permitted in the programmable ray tracing shader stages. However, shader call instructions place a bound on where results of subgroup instructions or subgroup-scoped instructions that execute the dynamic instance of that instruction are potentially valid. For example, care must be taken when using the result of a ballot operation that was computed before an invocation repack instruction, after that repack instruction. The ballot may be incorrect as the set of invocations could have changed.

For clock operations, the value of a Subgroup scoped OpReadClockKHR read before the dynamic instance of a repack instruction should not be compared to the result of that clock instruction after the repack instruction.

When a ray tracing shader executes a dynamic instance of an invocation repack instruction which results in another ray tracing shader being invoked, their instructions are related by shader-call-order.

For ray tracing invocations that are shader-call-related:
• memory operations on StorageBuffer, Image, and ShaderRecordBufferKHR storage classes can be synchronized using the ShaderCallKHR scope.

• the CallableDataKHR, IncomingCallableDataKHR, RayPayloadKHR, HitAttributeKHR, and IncomingRayPayloadKHR storage classes are system-synchronized and no application availability and visibility operations are required.

• memory operations within a single invocation before and after the invocation repack instruction are ordered by program-order and do not require explicit synchronization.

32.2. Ray Tracing Commands

Ray tracing commands provoke work in the ray tracing pipeline. Ray tracing commands are recorded into a command buffer and when executed by a queue will produce work that executes according to the currently bound ray tracing pipeline. A ray tracing pipeline must be bound to a command buffer before any ray tracing commands are recorded in that command buffer.

To dispatch ray tracing use:

```c
void vkCmdTraceRaysKHR(
  VkCommandBuffer commandBuffer,
  const VkStridedBufferRegionKHR* pRaygenShaderBindingTable,
  const VkStridedBufferRegionKHR* pMissShaderBindingTable,
  const VkStridedBufferRegionKHR* pHitShaderBindingTable,
  const VkStridedBufferRegionKHR* pCallableShaderBindingTable,
  uint32_t width,
  uint32_t height,
  uint32_t depth);
```

• commandBuffer is the command buffer into which the command will be recorded.

• pRaygenShaderBindingTable is the strided buffer range that holds the shader binding table data for the ray generation shader stage.

• pMissShaderBindingTable is the strided buffer range that holds the shader binding table data for the miss shader stage.

• pHitShaderBindingTable is the strided buffer range that holds the shader binding table data for the hit shader stage.

• pCallableShaderBindingTable is the strided buffer range that holds the shader binding table data for the callable shader stage.

• width is the width of the ray trace query dimensions.

• height is height of the ray trace query dimensions.

• depth is depth of the ray trace query dimensions.

When the command is executed, a ray generation group of width × height × depth rays is assembled.
Valid Usage

- If a VkImageView is sampled with VK_FILTER_LINEAR as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT.

- If a VkImageView is accessed using atomic operations as a result of this command, then the image view's format features must contain VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT.

- For each set $n$ that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a descriptor set must have been bound to $n$ at the same pipeline bind point, with a VkPipelineLayout that is compatible for set $n$, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- For each push constant that is statically used by the VkPipeline bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a VkPipelineLayout that is compatible for push constants, with the VkPipelineLayout used to create the current VkPipeline, as described in Pipeline Layout Compatibility.

- Descriptors in each bound descriptor set, specified via vkCmdBindDescriptorSets, must be valid if they are statically used by the VkPipeline bound to the pipeline bind point used by this command.

- A valid pipeline must be bound to the pipeline bind point used by this command.

- If the VkPipeline object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for commandBuffer, and done so after any previously bound pipeline with the corresponding state not specified as dynamic.

- There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the VkPipeline object bound to the pipeline bind point used by this command, since that pipeline was bound.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used to sample from any VkImage with a VkImageView of the type VK_IMAGE_VIEW_TYPE_3D, VK_IMAGE_VIEW_TYPE_CUBE, VK_IMAGE_VIEW_TYPE_1D_ARRAY, VK_IMAGE_VIEW_TYPE_2D_ARRAY or VK_IMAGE_VIEW_TYPE_CUBE_ARRAY, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions with ImplicitLod, Dref or Proj in their name, in any shader stage.

- If the VkPipeline object bound to the pipeline bind point used by this command accesses a VkSampler object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V OpImageSample* or OpImageSparseSample* instructions that includes a LOD bias or any offset values, in any shader stage.

- If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.
If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

- raygenShaderBindingOffset must be less than the size of raygenShaderBindingTableBuffer
- raygenShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment
- missShaderBindingOffset must be less than the size of missShaderBindingTableBuffer
- missShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment
- hitShaderBindingOffset must be less than the size of hitShaderBindingTableBuffer
- hitShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment
- callableShaderBindingOffset must be less than the size of callableShaderBindingTableBuffer
- callableShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment
- missShaderBindingStride must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupHandleSize
- missShaderBindingStride must be less than or equal to VkPhysicalDeviceRayTracingPropertiesKHR::maxShaderGroupStride
- hitShaderBindingStride must be less than or equal to VkPhysicalDeviceRayTracingPropertiesKHR::maxShaderGroupStride
- callableShaderBindingStride must be less than or equal to VkPhysicalDeviceRayTracingPropertiesKHR::maxShaderGroupStride
- Any shader group handle referenced by this call must have been queried from the currently bound ray tracing shader pipeline.

This command must not cause a shader call instruction to be executed from a shader invocation with a recursion depth greater than the value of maxRecursionDepth used to create the bound ray tracing pipeline.

If commandBuffer is a protected command buffer, any resource written to by the VkPipeline object bound to the pipeline bind point used by this command must not be an unprotected resource.

If commandBuffer is a protected command buffer, pipeline stages other than the...
framebuffer-space and compute stages in the VkPipeline object bound to the pipeline bind point must not write to any resource

- width must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]
- height must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]
- depth must be less than or equal to VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2]

- If the currently bound ray tracing pipeline was created with flags that included VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_ANY_HIT_SHADERS_BIT_KHR, the buffer member of hitShaderBindingTable must not be VK_NULL_HANDLE
- If the currently bound ray tracing pipeline was created with flags that included VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_CLOSEST_HIT_SHADERS_BIT_KHR, the buffer member of hitShaderBindingTable must not be VK_NULL_HANDLE
- If the currently bound ray tracing pipeline was created with flags that included VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_INTERSECTION_SHADERS_BIT_KHR, the buffer member of hitShaderBindingTable must not be VK_NULL_HANDLE
- If the currently bound ray tracing pipeline was created with flags that included VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_MISS_SHADERS_BIT_KHR, the shader group handle identified by missShaderBindingTable must contain a valid miss shader
- If the currently bound ray tracing pipeline was created with flags that included VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_ANY_HIT_SHADERS_BIT_KHR, entries in hitShaderBindingTable accessed as a result of this command in order to execute an any hit shader must not be set to zero
- If the currently bound ray tracing pipeline was created with flags that included VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_CLOSEST_HIT_SHADERS_BIT_KHR, entries in hitShaderBindingTable accessed as a result of this command in order to execute a closest hit shader must not be set to zero
- If the currently bound ray tracing pipeline was created with flags that included VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_INTERSECTION_SHADERS_BIT_KHR, entries in hitShaderBindingTable accessed as a result of this command in order to execute an intersection shader must not be set to zero
Valid Usage (Implicit)

- `commandBuffer` **must** be a valid `VkCommandBuffer` handle
- `pRaygenShaderBindingTable` **must** be a valid pointer to a valid `VkStridedBufferRegionKHR` structure
- `pMissShaderBindingTable` **must** be a valid pointer to a valid `VkStridedBufferRegionKHR` structure
- `pHitShaderBindingTable` **must** be a valid pointer to a valid `VkStridedBufferRegionKHR` structure
- `pCallableShaderBindingTable` **must** be a valid pointer to a valid `VkStridedBufferRegionKHR` structure
- `commandBuffer` **must** be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from **must** support compute operations
- This command **must** only be called outside of a render pass instance

Host Synchronization

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from **must** be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The `VkStridedBufferRegionKHR` structure is defined as:

```c
typedef struct VkStridedBufferRegionKHR {
    VkBuffer buffer;
    VkDeviceSize offset;
    VkDeviceSize stride;
    VkDeviceSize size;
} VkStridedBufferRegionKHR;
```

- `buffer` is the buffer containing this region.
- `offset` is the byte offset in `buffer` at which the region starts.
- `stride` is the byte stride between consecutive elements.
- **size** is the size in bytes of the region starting at `offset`.

### Valid Usage

- If `buffer` is not `VK_NULL_HANDLE`, `size` plus `offset` must be less than or equal to the size of `buffer`.
- If `buffer` is not `VK_NULL_HANDLE`, `stride` must be less than the size of `buffer`.

### Valid Usage (Implicit)

- If `buffer` is not `VK_NULL_HANDLE`, `buffer` must be a valid `VkBuffer` handle.

To dispatch ray tracing, with some parameters sourced on the device, use:

```c
void vkCmdTraceRaysIndirectKHR(
    VkCommandBuffer commandBuffer,
    const VkStridedBufferRegionKHR* pRaygenShaderBindingTable,
    const VkStridedBufferRegionKHR* pMissShaderBindingTable,
    const VkStridedBufferRegionKHR* pHitShaderBindingTable,
    const VkStridedBufferRegionKHR* pCallableShaderBindingTable,
    VkBuffer buffer,
    VkDeviceSize offset);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `pRaygenShaderBindingTable` is the strided buffer range that holds the shader binding table data for the ray generation shader stage.
- `pMissShaderBindingTable` is the strided buffer range that holds the shader binding table data for the miss shader stage.
- `pHitShaderBindingTable` is the strided buffer range that holds the shader binding table data for the hit shader stage.
- `pCallableShaderBindingTable` is the strided buffer range that holds the shader binding table data for the callable shader stage.
- `buffer` is the buffer containing the trace ray parameters.
- `offset` is the byte offset into `buffer` where parameters begin.

`vkCmdTraceRaysIndirectKHR` behaves similarly to `vkCmdTraceRaysKHR` except that the ray trace query dimensions are read by the device from a buffer during execution. The parameters of trace ray are encoded in the `VkTraceRaysIndirectCommandKHR` structure.
Valid Usage

• If a `VkImageView` is sampled with `VK_FILTER_LINEAR` as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`.

• If a `VkImageView` is accessed using atomic operations as a result of this command, then the image view's format features must contain `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`.

• For each set \( n \) that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a descriptor set must have been bound to \( n \) at the same pipeline bind point, with a `VkPipelineLayout` that is compatible for set \( n \), with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

• For each push constant that is statically used by the `VkPipeline` bound to the pipeline bind point used by this command, a push constant value must have been set for the same pipeline bind point, with a `VkPipelineLayout` that is compatible for push constants, with the `VkPipelineLayout` used to create the current `VkPipeline`, as described in Pipeline Layout Compatibility.

• Descriptors in each bound descriptor set, specified via `vkCmdBindDescriptorSets`, must be valid if they are statically used by the `VkPipeline` bound to the pipeline bind point used by this command.

• A valid pipeline must be bound to the pipeline bind point used by this command.

• If the `VkPipeline` object bound to the pipeline bind point used by this command requires any dynamic state, that state must have been set for `commandBuffer`, and done so after any previously bound pipeline with the corresponding state not specified as dynamic.

• There must not have been any calls to dynamic state setting commands for any state not specified as dynamic in the `VkPipeline` object bound to the pipeline bind point used by this command, since that pipeline was bound.

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used to sample from any `VkImage` with a `VkImageView` of the type `VK_IMAGE_VIEW_TYPE_3D`, `VK_IMAGE_VIEW_TYPE_CUBE`, `VK_IMAGE_VIEW_TYPE_1D_ARRAY`, `VK_IMAGE_VIEW_TYPE_2D_ARRAY` or `VK_IMAGE_VIEW_TYPE_CUBE_ARRAY`, in any shader stage.

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions with `ImplicitLod`, `Dref` or `Proj` in their name, in any shader stage.

• If the `VkPipeline` object bound to the pipeline bind point used by this command accesses a `VkSampler` object that uses unnormalized coordinates, that sampler must not be used with any of the SPIR-V `OpImageSample*` or `OpImageSparseSample*` instructions that includes a LOD bias or any offset values, in any shader stage.

• If the robust buffer access feature is not enabled, and if the `VkPipeline` object bound to the pipeline bind point used by this command accesses a uniform buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.
• If the robust buffer access feature is not enabled, and if the VkPipeline object bound to the pipeline bind point used by this command accesses a storage buffer, it must not access values outside of the range of the buffer as specified in the descriptor set bound to the same pipeline bind point.

• If commandBuffer is an unprotected command buffer, any resource accessed by the VkPipeline object bound to the pipeline bind point used by this command must not be a protected resource.

• raygenShaderBindingOffset must be less than the size of raygenShaderBindingTableBuffer.

• raygenShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment.

• missShaderBindingOffset must be less than the size of missShaderBindingTableBuffer.

• missShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment.

• hitShaderBindingOffset must be less than the size of hitShaderBindingTableBuffer.

• hitShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment.

• callableShaderBindingOffset must be less than the size of callableShaderBindingTableBuffer.

• callableShaderBindingOffset must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupBaseAlignment.

• missShaderBindingStride must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupHandleSize.

• hitShaderBindingStride must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupHandleSize.

• callableShaderBindingStride must be a multiple of VkPhysicalDeviceRayTracingPropertiesKHR::shaderGroupHandleSize.

• missShaderBindingStride must be less than or equal to VkPhysicalDeviceRayTracingPropertiesKHR::maxShaderGroupStride.

• hitShaderBindingStride must be less than or equal to VkPhysicalDeviceRayTracingPropertiesKHR::maxShaderGroupStride.

• callableShaderBindingStride must be less than or equal to VkPhysicalDeviceRayTracingPropertiesKHR::maxShaderGroupStride.

• Any shader group handle referenced by this call must have been queried from the currently bound ray tracing shader pipeline.

• This command must not cause a shader call instruction to be executed from a shader invocation with a recursion depth greater than the value of maxRecursionDepth used to create the bound ray tracing pipeline.

• If buffer is non-sparse then it must be bound completely and contiguously to a single VkDeviceMemory object.

• buffer must have been created with the VK_BUFFER_USAGE_INDIRECT_BUFFER_BIT bit set.
• **offset** must be a multiple of 4
• **commandBuffer** must not be a protected command buffer
• 
  (offset + sizeof(VkTraceRaysIndirectCommandKHR)) must be less than or equal to the size of buffer
• the VkPhysicalDeviceRayTracingFeaturesKHR → rayTracingIndirectTraceRays feature must be enabled

---

### Valid Usage (Implicit)

• **commandBuffer** must be a valid VkCommandBuffer handle
• **pRaygenShaderBindingTable** must be a valid pointer to a valid VkStridedBufferRegionKHR structure
• **pMissShaderBindingTable** must be a valid pointer to a valid VkStridedBufferRegionKHR structure
• **pHitShaderBindingTable** must be a valid pointer to a valid VkStridedBufferRegionKHR structure
• **pCallableShaderBindingTable** must be a valid pointer to a valid VkStridedBufferRegionKHR structure
• **buffer** must be a valid VkBuffer handle
• **commandBuffer** must be in the recording state
• The VkCommandPool that **commandBuffer** was allocated from must support compute operations
• This command must only be called outside of a render pass instance
• Both of **buffer**, and **commandBuffer** must have been created, allocated, or retrieved from the same VkDevice

---

### Host Synchronization

• Host access to the VkCommandPool that **commandBuffer** was allocated from must be externally synchronized

---

### Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VkTraceRaysIndirectCommandKHR structure is defined as:
typedef struct VkTraceRaysIndirectCommandKHR {
    uint32_t    width;
    uint32_t    height;
    uint32_t    depth;
} VkTraceRaysIndirectCommandKHR;

- `width` is the width of the ray trace query dimensions.
- `height` is height of the ray trace query dimensions.
- `depth` is depth of the ray trace query dimensions.

The members of `VkTraceRaysIndirectCommandKHR` have the same meaning as the similarly named parameters of `vkCmdTraceRaysKHR`.

### Valid Usage

- `width` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[0]`
- `height` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[1]`
- `depth` must be less than or equal to `VkPhysicalDeviceLimits::maxComputeWorkGroupCount[2]`

### 32.3. Shader Binding Table

A *shader binding table* is a resource which establishes the relationship between the ray tracing pipeline and the acceleration structures that were built for the ray tracing query. It indicates the shaders that operate on each geometry in an acceleration structure. In addition, it contains the resources accessed by each shader, including indices of textures and constants. The application allocates and manages shader binding tables as `VkBuffer` objects.

Each entry in the shader binding table consists of `shaderGroupHandleSize` bytes of data as queried by `vkGetRayTracingShaderGroupHandlesKHR` to refer to the shader that it invokes. The remainder of the data specified by the stride is application-visible data that can be referenced by a `ShaderRecordBufferKHR` block in the shader.

The shader binding tables to use in a ray tracing query are passed to `vkCmdTraceRaysKHR`. Shader binding tables are read-only in shaders that are executing on the ray tracing pipeline.

### 32.3.1. Indexing Rules

In order to execute the correct shaders and access the correct resources during a ray tracing dispatch, the implementation must be able to locate shader binding table entries at various stages of execution. This is accomplished by defining a set of indexing rules that compute shader binding table record positions relative to the buffer's base address in memory. The application must organize the contents of the shader binding table's memory in a way that application of the indexing rules will lead to correct records.
Ray Generation Shaders

Only one ray generation shader is executed per ray tracing dispatch. Its location is passed into `vkCmdTraceRaysKHR` using the `pRaygenShaderBindingTable::buffer` and `pRaygenShaderBindingTable::offset` parameters — there is no indexing. `pRaygenShaderBindingTable::stride` is unused.

All data accessed must be less than `pRaygenShaderBindingTable::size` bytes from the base offset.

Hit Shaders

The base for the computation of intersection, any-hit and closest hit shader locations is the `instanceShaderBindingTableRecordOffset` value stored with each instance of a top-level acceleration structure. This value determines the beginning of the shader binding table records for a given instance. Each geometry in the instance must map to at least one hit program record.

In the following rule, `geometryIndex` refers to the location of the geometry within the instance. This index is available to ray shaders via the `RayGeometryIndexKHR` built-in.

The `sbtRecordStride` and `sbtRecordOffset` values are passed in as parameters to calls made in the shaders. See Section 8.19 (Ray Tracing Functions) of the OpenGL Shading Language Specification for more details. In SPIR-V, these correspond to the `SBTOffset` and `SBTStride` parameters to the `OpTraceRayKHR` instruction.

The result of this computation is then added to `pHitShaderBindingTable::offset`, a base offset passed to `vkCmdTraceRaysKHR`.

The complete rule to compute a hit shader binding table record address in the `pHitShaderBindingTable::buffer` is:

\[
P_{\text{hit}} = \text{pHitShaderBindingTable::offset} + \text{pHitShaderBindingTable::stride} \times (\text{instanceShaderBindingTableRecordOffset} + \text{geometryIndex} \times \text{sbtRecordStride} + \text{sbtRecordOffset})
\]

All data accessed must be less than `pHitShaderBindingTable::size` bytes from the base offset.

Miss Shaders

A miss shader is executed whenever a ray query fails to find an intersection for the given scene geometry. Multiple miss shaders may be executed throughout a ray tracing dispatch.

The base for the computation of miss shader locations is `pMissShaderBindingTable::offset`, a base offset passed into `vkCmdTraceRaysKHR`.

The `missIndex` value is passed in as a parameter to calls made in the shaders. See Section 8.19 (Ray Tracing Functions) of the OpenGL Shading Language Specification for more details. In SPIR-V, this corresponds to the `MissIndex` parameter to the `OpTraceRayKHR` instruction.

The complete rule to compute a miss shader binding table record address in the `pMissShaderBindingTable::buffer` is:

\[
P_{\text{miss}} = \text{pMissShaderBindingTable::offset} + \text{pMissShaderBindingTable::stride} \times \text{missIndex}
\]
All data accessed must be less than pMissShaderBindingTable::size bytes from the base offset.

Callable Shaders

A callable shader is executed when requested by a ray tracing shader. Multiple callable shaders may be executed throughout a ray tracing dispatch.

The base for the computation of callable shader locations is pCallableShaderBindingTable::offset, a base offset passed into vkCmdTraceRaysKHR.

The sbtRecordIndex value is passed in as a parameter to calls made in the shaders. See Section 8.19 (Ray Tracing Functions) of the OpenGL Shading Language Specification for more details. In SPIR-V, this corresponds to the SBTIndex parameter to the OpExecuteCallableKHR instruction.

The complete rule to compute a callable shader binding table record address in the pCallableShaderBindingTable::buffer is:

\[ \text{pCallableShaderBindingTable::offset} + \text{pCallableShaderBindingTable::stride} \times \text{sbtRecordIndex} \]

All data accessed must be less than pCallableShaderBindingTable::size bytes from the base offset.

32.4. Acceleration Structures

Acceleration structures are data structures used by the implementation to efficiently manage scene geometry as it is traversed during a ray tracing query. The application is responsible for managing acceleration structure objects (see Acceleration Structures), including allocation, destruction, executing builds or updates, and synchronizing resources used during ray tracing queries.

There are two types of acceleration structures, top level acceleration structures and bottom level acceleration structures.

![Figure 22. Acceleration Structure](image)
32.4.1. Geometry

Geometries refer to a triangle or axis-aligned bounding box.

32.4.2. Inactive Primitives and Instances

Acceleration structures allow the use of particular input values to signal inactive primitives or instances.

An inactive triangle is one for which the first (X) component of each vertex is NaN. If any other vertex component is NaN, and the first is not, the behavior is undefined. If the vertex format does not have a NaN representation, then all triangles are considered active.

An inactive instance is one whose acceleration structure handle is NULL.

An inactive AABB is one for which the minimum X coordinate is NaN. If any other component is NaN, and the first is not, the behavior is undefined.

In the above definitions, "NaN" refers to any type of NaN. Signaling, non-signaling, quiet, loud, or otherwise.

An inactive object is considered invisible to all rays, and should not be represented in the acceleration structure. Implementations should ensure that the presence of inactive objects does not seriously degrade ray tracing performance.

Inactive objects are counted in the auto-generated index sequences which are provided to shaders via InstanceId and PrimitiveId SPIR-V decorations. This allows objects in the scene to change freely between the active and inactive states, without affecting the layout of any arrays which are being indexed using the ID values.

Any transition between the active and inactive states requires a full acceleration structure rebuild. An update is not sufficient. If an inactive object is made active by an update operation (or vice versa), the results are undefined.

32.4.3. Top Level Acceleration Structures

Opaque acceleration structure for an array of instances. The descriptor referencing this is the starting point for tracing.

32.4.4. Bottom Level Acceleration Structures

Opaque acceleration structure for an array of geometries.
32.4.5. Building Acceleration Structures

To build acceleration structures call:

```c
void vkCmdBuildAccelerationStructureKHR(
    VkCommandBuffer commandBuffer,
    uint32_t infoCount,
    const VkAccelerationStructureBuildGeometryInfoKHR* pInfos,
    const VkAccelerationStructureBuildOffsetInfoKHR* const* ppOffsetInfos);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `infoCount` is the number of acceleration structures to build. It specifies the number of the `pInfos` structures and `ppOffsetInfos` pointers that must be provided.
- `pInfos` is an array of `infoCount` `VkAccelerationStructureBuildGeometryInfoKHR` structures defining the geometry used to build each acceleration structure.
- `ppOffsetInfos` is an array of `infoCount` pointers to arrays of `VkAccelerationStructureBuildOffsetInfoKHR` structures. Each `ppOffsetInfos[i]` is an array of `pInfos[i]→geometryCount` `VkAccelerationStructureBuildOffsetInfoKHR` structures defining dynamic offsets to the addresses where geometry data is stored, as defined by `pInfos[i].`

The `vkCmdBuildAccelerationStructureKHR` command provides the ability to initiate multiple acceleration structures builds, however there is no ordering or synchronization implied between any of the individual acceleration structure builds.

**Note**

This means that an application cannot build a top-level acceleration structure in the same `vkCmdBuildAccelerationStructureKHR` call as the associated bottom-level or instance acceleration structures are being built. There also cannot be any memory aliasing between any acceleration structure memories or scratch memories being used by any of the builds.
Valid Usage

- **pOffsetInfos[i]** must be a valid pointer to an array of **pInfos[i]→geometryCount** VkAccelerationStructureBuildOffsetInfoKHR structures.

- Each **pInfos[i].srcAccelerationStructure** must not refer to the same acceleration structure as any **pInfos[i].dstAccelerationStructure** that is provided to the same build command unless it is identical for an update.

- For each **pInfos[i]**, **dstAccelerationStructure** must have been created with compatible **VkAccelerationStructureCreateInfoKHR** where **VkAccelerationStructureCreateInfoKHR::type** and **VkAccelerationStructureCreateInfoKHR::flags** are identical to **VkAccelerationStructureBuildGeometryInfoKHR::type** and **VkAccelerationStructureBuildGeometryInfoKHR::flags** respectively, **VkAccelerationStructureBuildGeometryInfoKHR::geometryCount** for **dstAccelerationStructure** are greater than or equal to the build size, and each geometry in **VkAccelerationStructureBuildGeometryInfoKHR::ppGeometries** for **dstAccelerationStructure** has greater than or equal to the number of vertices, indices, and AABBs, **VkAccelerationStructureGeometryTrianglesDataKHR::transformData** is both 0 or both non-zero, and all other parameters are the same.

- For each **pInfos[i]**, if **update** is **VK_TRUE**, then objects that were previously active for that acceleration structure must not be made inactive as per Inactive Primitives and Instances.

- For each **pInfos[i]**, if **update** is **VK_TRUE**, then objects that were previously inactive for that acceleration structure must not be made active as per Inactive Primitives and Instances.

- Any acceleration structure instance in any top level build in this command must not reference any bottom level acceleration structure built by this command.

- There must not be any memory aliasing between the scratch memories that are provided in all the **pInfos[i].scratchData** memories for the acceleration structure builds.

- There must not be any memory aliasing between memory bound to any top level, bottom level, or instance acceleration structure accessed by this command.

- If **update** is **VK_FALSE**, all addresses between **pInfos[i].scratchData** and **pInfos[i].scratchData + N - 1** must be in the buffer device address range of the same buffer, where N is given by the **size** member of the **VkMemoryRequirements** structure returned from a call to **vkGetAccelerationStructureMemoryRequirementsKHR** with **VkAccelerationStructureMemoryRequirementsInfoKHR::accelerationStructure** set to **pInfos[i].dstAccelerationStructure** and **VkAccelerationStructureMemoryRequirementsInfoKHR::type** set to **VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_BUILD_SCRATCH_KHR**.

- If **update** is **VK_TRUE**, all addresses between **pInfos[i].scratchData** and **pInfos[i].scratchData + N - 1** must be in the buffer device address range of the same buffer, where N is given by the **size** member of the **VkMemoryRequirements** structure returned from a call to **vkGetAccelerationStructureMemoryRequirementsKHR** with **VkAccelerationStructureMemoryRequirementsInfoKHR::accelerationStructure** set to **pInfos[i].dstAccelerationStructure** and **VkAccelerationStructureMemoryRequirementsInfoKHR::type** set to **VK_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_TYPE_UPDATE_SCRATCH_KHR**.
• The buffer from which the buffer device address pInfos[i].scratchData is queried must have been created with VK_BUFFER_USAGE_RAY_TRACING_BIT_KHR usage flag
• All VkDeviceOrHostAddressKHR or VkDeviceOrHostAddressConstKHR referenced by this command must contain valid device addresses
• All VkAccelerationStructureKHR objects referenced by this command must be bound to device memory
• The VkDeferredOperationInfoKHR structure must not be included in the pNext chain of any of the provided VkAccelerationStructureBuildGeometryInfoKHR structures.

Valid Usage (Implicit)

• commandBuffer must be a valid VkCommandBuffer handle
• pInfos must be a valid pointer to an array of infoCount valid VkAccelerationStructureBuildGeometryInfoKHR structures
• ppOffsetInfos must be a valid pointer to an array of infoCount VkAccelerationStructureBuildOffsetInfoKHR structures
• commandBuffer must be in the recording state
• The VkCommandPool that commandBuffer was allocated from must support compute operations
• This command must only be called outside of a render pass instance
• infoCount must be greater than 0

Host Synchronization

• Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To build an acceleration structure with some parameters sourced on the device call:
void vkCmdBuildAccelerationStructureIndirectKHR(
    VkCommandBuffer                             commandBuffer,
    const VkAccelerationStructureBuildGeometryInfoKHR* pInfo,
    VkBuffer                                    indirectBuffer,
    VkDeviceSize                                indirectOffset,
    uint32_t                                    indirectStride);

• commandBuffer is the command buffer into which the command will be recorded.
• pInfo is a pointer to a VkAccelerationStructureBuildGeometryInfoKHR structure defining the geometry used to build the acceleration structure.
• indirectBuffer is the VkBuffer containing pInfo->pname:geometryCount VkAccelerationStructureBuildOffsetInfoKHR structures defining dynamic offsets to the addresses where geometry data is stored, as defined by pInfo.
• indirectOffset is the byte offset into indirectBuffer where offset parameters begin.
• stride is the byte stride between successive sets of offset parameters.

Valid Usage

• All VkDeviceOrHostAddressKHR or VkDeviceOrHostAddressConstKHR referenced by this command must contain valid device addresses
• All VkAccelerationStructureKHR objects referenced by this command must be bound to device memory
• The VkPhysicalDeviceRayTracingFeaturesKHR →rayTracingIndirectAccelerationStructureBuild feature must be enabled
• The VkDeferredOperationInfoKHR structure must not be included in the pNext chain of any of the provided VkAccelerationStructureBuildGeometryInfoKHR structures.

Valid Usage (Implicit)

• commandBuffer must be a valid VkCommandBuffer handle
• pInfo must be a valid pointer to a valid VkAccelerationStructureBuildGeometryInfoKHR structure
• indirectBuffer must be a valid VkBuffer handle
• commandBuffer must be in the recording state
• The VkCommandPool that commandBuffer was allocated from must support compute operations
• This command must only be called outside of a render pass instance
• Both of commandBuffer, and indirectBuffer must have been created, allocated, or retrieved from the same VkDevice
Host Synchronization

- Host access to the VkCommandPool that commandBuffer was allocated from must be externally synchronized.

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VkAccelerationStructureBuildGeometryInfoKHR structure is defined as:

```c
typedef struct VkAccelerationStructureBuildGeometryInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkAccelerationStructureTypeKHR type;
    VkBuildAccelerationStructureFlagsKHR flags;
    VkBool32 update;
    VkAccelerationStructureKHR srcAccelerationStructure;
    VkAccelerationStructureKHR dstAccelerationStructure;
    const VkAccelerationStructureGeometryKHR* const* ppGeometries;
    const VkDeviceOrHostAddressKHR scratchData;
} VkAccelerationStructureBuildGeometryInfoKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **type** is a VkAccelerationStructureTypeKHR value specifying the type of acceleration structure being built.
- **flags** is a bitmask of VkBuildAccelerationStructureFlagBitsKHR specifying additional parameters of the acceleration structure.
- **update** specifies whether to update dstAccelerationStructure with the data in srcAccelerationStructure or not.
- **srcAccelerationStructure** points to an existing acceleration structure that is to be used to update the dst acceleration structure when update is VK_TRUE.
- **dstAccelerationStructure** points to the target acceleration structure for the build.
- **geometryArrayOfPointers** specifies whether ppGeometries is used as a pointer to an array of pointers or a pointer to a pointer to an array.
- **geometryCount** specifies the number of geometries that will be built into
• **ppGeometries** is either a pointer to an array of pointers to `VkAccelerationStructureGeometryKHR` structures if `geometryArrayOfPointers` is `VK_TRUE`, or a pointer to a pointer to an array of `VkAccelerationStructureGeometryKHR` structures if it's `VK_FALSE`. Each element of the array describes the data used to build each acceleration structure geometry.

• **scratchData** is the device or host address to memory that will be used as scratch memory for the build.

**Note**

Elements of **ppGeometries** are accessed as follows, based on `geometryArrayofPointers`:

```c
if (geometryArrayofPointers) {
    use *(ppGeometries[i]);
} else {
    use (*ppGeometries)[i];
}
```

**Valid Usage**

• **If update** is `VK_TRUE`, **srcAccelerationStructure** **must** not be `VK_NULL_HANDLE`

• **If update** is `VK_TRUE`, **srcAccelerationStructure** **must** have been built before with `VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_UPDATE_BIT_KHR` set in `VkAccelerationStructureBuildGeometryInfoKHR::flags`

• **scratchData** **must** have been created with `VK_BUFFER_USAGE_RAY_TRACING_BIT_KHR` usage flag

• **If update** is `enam:VK_TRUE`, the **srcAccelerationStructure** and **dstAccelerationStructure** objects **must** either be the same object or not have any **memory aliasing**
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_BUILD_GEOMETRY_INFO_KHR`
- **pNext** must be `NULL` or a pointer to a valid instance of `VkDeferredOperationInfoKHR`
- The **sType** value of each struct in the **pNext** chain must be unique
- **type** must be a valid `VkAccelerationStructureTypeKHR` value
- **flags** must be a valid combination of `VkBuildAccelerationStructureFlagBitsKHR` values
- If `srcAccelerationStructure` is not `VK_NULL_HANDLE`, `srcAccelerationStructure` must be a valid `VkAccelerationStructureKHR` handle
- **dstAccelerationStructure** must be a valid `VkAccelerationStructureKHR` handle
- **scratchData** must be a valid `VkDeviceOrHostAddressKHR` union
- Both of `dstAccelerationStructure`, and `srcAccelerationStructure` that are valid handles of non-ignored parameters must have been created, allocated, or retrieved from the same `VkDevice`

The `VkDeviceOrHostAddressKHR` union is defined as:

```c
typedef union VkDeviceOrHostAddressKHR {
    VkDeviceAddress    deviceAddress;
    void*              hostAddress;
} VkDeviceOrHostAddressKHR;
```

- **deviceAddress** is a buffer device address as returned by the `vkGetBufferDeviceAddressKHR` command.
- **hostAddress** is a host memory address.

The `VkDeviceOrHostAddressConstKHR` union is defined as:

```c
typedef union VkDeviceOrHostAddressConstKHR {
    VkDeviceAddress    deviceAddress;
    const void*        hostAddress;
} VkDeviceOrHostAddressConstKHR;
```

- **deviceAddress** is a buffer device address as returned by the `vkGetBufferDeviceAddressKHR` command.
- **hostAddress** is a const host memory address.

The `VkAccelerationStructureGeometryKHR` structure is defined as:
typedef struct VkAccelerationStructureGeometryKHR {
    VkStructureType sType;
    const void* pNext;
    VkGeometryTypeKHR geometryType;
    VkAccelerationStructureGeometryDataKHR geometry;
    VkGeometryFlagsKHR flags;
} VkAccelerationStructureGeometryKHR;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **geometryType** describes which type of geometry this *VkAccelerationStructureGeometryKHR* refers to.
- **geometry** is a *VkAccelerationStructureGeometryDataKHR* union describing the geometry data for the relevant geometry type.
- **flags** is a bitmask of *VkGeometryFlagBitsKHR* values describing additional properties of how the geometry should be built.

### Valid Usage

- If **geometryType** is VK_GEOMETRY_TYPE_AABBS_KHR, the *aabb*s member of **geometry** must be a valid *VkAccelerationStructureGeometryAabbsDataKHR* structure.
- If **geometryType** is VK_GEOMETRY_TYPE_TRIANGLES_KHR, the *triangles* member of **geometry** must be a valid *VkAccelerationStructureGeometryTrianglesDataKHR* structure.
- If **geometryType** is VK_GEOMETRY_TYPE_INSTANCES_KHR, the *instances* member of **geometry** must be a valid *VkAccelerationStructureGeometryInstancesDataKHR* structure.

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR
- **pNext** must be **NULL**
- **geometryType** must be a valid *VkGeometryTypeKHR* value
- **geometry** must be a valid *VkAccelerationStructureGeometryDataKHR* union
- **flags** must be a valid combination of *VkGeometryFlagBitsKHR* values

The *VkAccelerationStructureGeometryDataKHR* union is defined as:
typedef union VkAccelerationStructureGeometryDataKHR {
    VkAccelerationStructureGeometryTrianglesDataKHR triangles;
    VkAccelerationStructureGeometryAabbsDataKHR aabbs;
    VkAccelerationStructureGeometryInstancesDataKHR instances;
} VkAccelerationStructureGeometryDataKHR;

• **triangles** is a `VkAccelerationStructureGeometryTrianglesDataKHR` structure.
• **aabbs** is a `VkAccelerationStructureGeometryAabbsDataKHR` structure.
• **instances** is a `VkAccelerationStructureGeometryInstancesDataKHR` structure.

### Valid Usage (Implicit)

- **triangles** must be a valid `VkAccelerationStructureGeometryTrianglesDataKHR` structure.
- **aabbs** must be a valid `VkAccelerationStructureGeometryAabbsDataKHR` structure.
- **instances** must be a valid `VkAccelerationStructureGeometryInstancesDataKHR` structure.

The `VkAccelerationStructureGeometryTrianglesDataKHR` structure is defined as:

```c
typedef struct VkAccelerationStructureGeometryTrianglesDataKHR {
    VkStructureType sType;
    const void* pNext;
    VkFormat vertexFormat;
    VkDeviceOrHostAddressConstKHR vertexData;
    VkDeviceSize vertexStride;
    VkIndexType indexType;
    VkDeviceOrHostAddressConstKHR indexData;
    VkDeviceOrHostAddressConstKHR transformData;
} VkAccelerationStructureGeometryTrianglesDataKHR;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **vertexFormat** is the `VkFormat` of each vertex element.
- **vertexData** is a device or host address to memory containing vertex data for this geometry.
- **vertexStride** is the stride in bytes between each vertex.
- **indexType** is the `VkIndexType` of each index element.
- **indexData** is the device or host address to memory containing index data for this geometry.
- **transformData** is a device or host address to memory containing an optional reference to a `VkTransformMatrixKHR` structure defining a transformation that should be applied to vertices in this geometry.
Valid Usage

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR`
- `pNext` must be `NULL`
- `vertexFormat` must be a valid `VkFormat` value
- `vertexData` must be a valid `VkDeviceOrHostAddressConstKHR` union
- `indexType` must be a valid `VkIndexType` value
- If `indexData` is not 0, `indexData` must be a valid `VkDeviceOrHostAddressConstKHR` union
- If `transformData` is not 0, `transformData` must be a valid `VkDeviceOrHostAddressConstKHR` union

The `VkTransformMatrixKHR` structure is defined as:

```c
typedef struct VkTransformMatrixKHR {
    float    matrix[3][4];
} VkTransformMatrixKHR;
```

- `matrix` is a 3x4 row-major affine transformation matrix.

The `VkAccelerationStructureGeometryAabbsDataKHR` structure is defined as:

```c
typedef struct VkAccelerationStructureGeometryAabbsDataKHR {
    VkStructureType                  sType;
    const void*                      pNext;
    VkDeviceOrHostAddressConstKHR    data;
    VkDeviceSize                     stride;
} VkAccelerationStructureGeometryAabbsDataKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `data` is a device or host address to memory containing `VkAabbPositionsKHR` structures containing position data for each axis-aligned bounding box in the geometry.
- `stride` is the stride in bytes between each entry in `data`. 
Valid Usage

- **data** must be aligned to 8 bytes
- **stride** must be a multiple of 8

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_AABBS_DATA_KHR`
- **pNext** must be `NULL`
- **data** must be a valid `VkDeviceOrHostAddressConstKHR` union

An axis-aligned bounding box positions are defined by the structure:

```c
typedef struct VkAabbPositionsKHR {
    float minX;
    float minY;
    float minZ;
    float maxX;
    float maxY;
    float maxZ;
} VkAabbPositionsKHR;
```

- **minX** is the x position of one opposing corner of a bounding box.
- **minY** is the y position of one opposing corner of a bounding box.
- **minZ** is the z position of one opposing corner of a bounding box.
- **maxX** is the x position of the other opposing corner of a bounding box.
- **maxY** is the y position of the other opposing corner of a bounding box.
- **maxZ** is the z position of the other opposing corner of a bounding box.

Valid Usage

- **minX** must be less than or equal to **maxX**
- **minY** must be less than or equal to **maxY**
- **minZ** must be less than or equal to **maxZ**

The `VkAccelerationStructureGeometryInstancesDataKHR` structure is defined as:
typedef struct VkAccelerationStructureGeometryInstancesDataKHR {
    VkStructureType sType;
    const void* pNext;
    VkBool32 arrayOfPointers;
    VkDeviceOrHostAddressConstKHR data;
} VkAccelerationStructureGeometryInstancesDataKHR;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **arrayOfPointers** specifies whether **data** is used as an array of addresses or just an array.
- **data** is either the address of an array of device or host addresses referencing individual VkAccelerationStructureInstanceKHR structures if arrayOfPointers is VK_TRUE, or the address of an array of VkAccelerationStructureInstanceKHR structures.

**Valid Usage**

- **data** must be aligned to 16 bytes
- If arrayOfPointers is true, each pointer must be aligned to 16 bytes

**Valid Usage (Implicit)**

- **sType** must be VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_INSTANCES_DATA_KHR
- **pNext** must be NULL
- **data** must be a valid VkDeviceOrHostAddressConstKHR union

**Acceleration structure instances** can be built into top-level acceleration structures. Each acceleration structure instance is a separate entry in the top-level acceleration structure which includes all the geometry of a bottom-level acceleration structure at a transformed location. Multiple instances can point to the same bottom level acceleration structure.

An acceleration structure instance is defined by the structure:

typedef struct VkAccelerationStructureInstanceKHR {
    VkTransformMatrixKHR transform;
    uint32_t instanceCustomIndex:24;
    uint32_t mask:8;
    uint32_t instanceShaderBindingTableRecordOffset:24;
    VkGeometryInstanceFlagsKHR flags:8;
    uint64_t accelerationStructureReference;
} VkAccelerationStructureInstanceKHR;

- **transform** is a VkTransformMatrixKHR structure describing a transformation to be applied to
the acceleration structure.

- **instanceCustomIndex** a 24-bit user-specified index value accessible to ray shaders in the `InstanceCustomIndexKHR` built-in.

- **mask** is an 8-bit visibility mask for the geometry. The instance **may** only be hit if `rayMask & instance.mask != 0`

- **instanceShaderBindingTableRecordOffset** is a 24-bit offset used in calculating the hit shader binding table index.

- **flags** is an 8-bit mask of `VkGeometryInstanceFlagBitsKHR` values to apply to this instance.

- **accelerationStructureReference** is either:
  - a device address containing the value obtained from `vkGetAccelerationStructureDeviceAddressKHR` (used by device operations which reference acceleration structures) or,
  - a `VkAccelerationStructureKHR` object (used by host operations which reference acceleration structures).

The C language spec does not define the ordering of bit-fields, but in practice, this struct produces the correct layout with existing compilers. The intended bit pattern is for the following:

- **instanceCustomIndex** and **mask** occupy the same memory as if a single `int32_t` was specified in their place
  - **instanceCustomIndex** occupies the 24 least significant bits of that memory
  - **mask** occupies the 8 most significant bits of that memory

- **instanceShaderBindingTableRecordOffset** and **flags** occupy the same memory as if a single `int32_t` was specified in their place
  - **instanceShaderBindingTableRecordOffset** occupies the 24 least significant bits of that memory
  - **flags** occupies the 8 most significant bits of that memory

If a compiler produces code that diverges from that pattern, applications **must** employ another method to set values according to the correct bit pattern.

---

**Valid Usage**

**Valid Usage (Implicit)**

- **flags** **must** be a valid combination of `VkGeometryInstanceFlagBitsKHR` values

Possible values of **flags** in the instance modifying the behavior of that instance are:
typedef enum VkGeometryInstanceFlagBitsKHR {
    VK_GEOMETRY_INSTANCE_TRIANGLE_FACING_CULL_DISABLE_BIT_KHR = 0x00000001,
    VK_GEOMETRY_INSTANCE_TRIANGLE_FRONT_COUNTERCLOCKWISE_BIT_KHR = 0x00000002,
    VK_GEOMETRY_INSTANCE_FORCE_OPAQUE_BIT_KHR = 0x00000004,
    VK_GEOMETRY_INSTANCE_FORCE_NO_OPAQUE_BIT_KHR = 0x00000008,
    VK_GEOMETRY_INSTANCE_FLAG_BITS_MAX_ENUM_KHR = 0x7FFFFFFF
} VkGeometryInstanceFlagBitsKHR;

- **VK_GEOMETRY_INSTANCE_TRIANGLE_FACING_CULL_DISABLE_BIT_KHR** disables face culling for this instance.
- **VK_GEOMETRY_INSTANCE_TRIANGLE_FRONT_COUNTERCLOCKWISE_BIT_KHR** indicates that the front face of the triangle for culling purposes is the face that is counter clockwise in object space relative to the ray origin. Because the facing is determined in object space, an instance transform matrix does not change the winding, but a geometry transform does.
- **VK_GEOMETRY_INSTANCE_FORCE_OPAQUE_BIT_KHR** causes this instance to act as though **VK_GEOMETRY_OPAQUE_BIT_KHR** were specified on all geometries referenced by this instance. This behavior can be overridden by the SPIR-V **NoOpaqueKHR** ray flag.
- **VK_GEOMETRY_INSTANCE_FORCE_NO_OPAQUE_BIT_KHR** causes this instance to act as though **VK_GEOMETRY_OPAQUE_BIT_KHR** were not specified on all geometries referenced by this instance. This behavior can be overridden by the SPIR-V **OpaqueKHR** ray flag.

**VK_GEOMETRY_INSTANCE_FORCE_NO_OPAQUE_BIT_KHR** and **VK_GEOMETRY_INSTANCE_FORCE_OPAQUE_BIT_KHR** must not be used in the same flag.

typedef VkFlags VkGeometryInstanceFlagsKHR;

**VkGeometryInstanceFlagsKHR** is a bitmask type for setting a mask of zero or more **VkGeometryInstanceFlagBitsKHR**.

**VkAccelerationStructureBuildOffsetInfoKHR** is defined as:

typedef struct VkAccelerationStructureBuildOffsetInfoKHR {
    uint32_t primitiveCount;
    uint32_t primitiveOffset;
    uint32_t firstVertex;
    uint32_t transformOffset;
} VkAccelerationStructureBuildOffsetInfoKHR;

- **primitiveCount** defines the number of primitives for a corresponding acceleration structure geometry.
- **primitiveOffset** defines an offset in bytes into the memory where primitive data is defined.
- **firstVertex** is the index of the first vertex to build from for triangle geometry.
- **transformOffset** defines an offset in bytes into the memory where a transform matrix is defined.
The primitive count and primitive offset are interpreted differently depending on the VkGeometryTypeKHR used:

- For geometries of type VK_GEOMETRY_TYPE_TRIANGLES_KHR, primitiveCount is the number of triangles to be built, where each triangle is treated as 3 vertices.
  - If the geometry uses indices, primitiveCount × 3 indices are consumed from VkAccelerationStructureGeometryTrianglesDataKHR::indexData, starting at an offset of primitiveOffset. The value of firstVertex is added to the index values before fetching vertices.
  - If the geometry does not use indices, primitiveCount × 3 vertices are consumed from VkAccelerationStructureGeometryTrianglesDataKHR::vertexData, starting at an offset of primitiveOffset + VkAccelerationStructureGeometryTrianglesDataKHR::vertexStride × firstVertex.
  - A single VkTransformMatrixKHR structure is consumed from VkAccelerationStructureGeometryTrianglesDataKHR::transformData, at an offset of transformOffset. This transformation matrix is used by all triangles.

- For geometries of type VK_GEOMETRY_TYPE_AABBS_KHR, primitiveCount is the number of axis-aligned bounding boxes. primitiveCount VkAabbPositionsKHR structures are consumed from VkAccelerationStructureGeometryAabbsDataKHR::data, starting at an offset of primitiveOffset.

- For geometries of type VK_GEOMETRY_TYPE_INSTANCES_KHR, primitiveCount is the number of acceleration structures. primitiveCount VkAccelerationStructureInstanceKHR structures are consumed from VkAccelerationStructureGeometryInstancesDataKHR::data, starting at an offset of primitiveOffset.

### Valid Usage

- For geometries of type VK_GEOMETRY_TYPE_TRIANGLES_KHR, if the geometry uses indices, the offset primitiveOffset from VkAccelerationStructureGeometryTrianglesDataKHR::indexData must be a multiple of the element size of VkAccelerationStructureGeometryTrianglesDataKHR::indexType

- For geometries of type VK_GEOMETRY_TYPE_TRIANGLES_KHR, if the geometry doesn’t use indices, the offset primitiveOffset from VkAccelerationStructureGeometryTrianglesDataKHR::vertexData must be a multiple of the component size of VkAccelerationStructureGeometryTrianglesDataKHR::vertexType

- For geometries of type VK_GEOMETRY_TYPE_TRIANGLES_KHR, the offset transformOffset from VkAccelerationStructureGeometryTrianglesDataKHR::transformData must be a multiple of 16

- For geometries of type VK_GEOMETRY_TYPE_AABBS_KHR, the offset primitiveOffset from VkAccelerationStructureGeometryAabbsDataKHR::data must be a multiple of 8

- For geometries of type VK_GEOMETRY_TYPE_INSTANCES_KHR, the offset primitiveOffset from VkAccelerationStructureGeometryInstancesDataKHR::data must be a multiple of 16 // TODO - Almost certainly should be more here
32.4.6. Copying Acceleration Structures

An additional command exists for copying acceleration structures without updating their contents. The acceleration structure object can be compacted in order to improve performance. Before copying, an application must query the size of the resulting acceleration structure.

To query acceleration structure size parameters call:

```c
void vkCmdWriteAccelerationStructuresPropertiesKHR(
    VkCommandBuffer commandBuffer,
    uint32_t accelerationStructureCount,
    const VkAccelerationStructureKHR* pAccelerationStructures,
    VkQueryType queryType,
    VkQueryPool queryPool,
    uint32_t firstQuery);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `accelerationStructureCount` is the count of acceleration structures for which to query the property.
- `pAccelerationStructures` is a pointer to an array of existing previously built acceleration structures.
- `queryType` is a `VkQueryType` value specifying the type of queries managed by the pool.
- `queryPool` is the query pool that will manage the results of the query.
- `firstQuery` is the first query index within the query pool that will contain the `accelerationStructureCount` number of results.

### Valid Usage

- `queryPool` must have been created with a `queryType` matching `queryType`
- The queries identified by `queryPool` and `firstQuery` must be unavailable
- All acceleration structures in `accelerationStructures` must have been built with `VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_COMPACTION_BIT_KHR` if `queryType` is `VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR`
- `queryType` must be `VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR` or `VK_QUERY_TYPE_ACCELERATION_STRUCTURE.Serialization_SIZE_KHR`
Valid Usage (Implicit)

- **commandBuffer** must be a valid `VkCommandBuffer` handle
- **pAccelerationStructures** must be a valid pointer to an array of `accelerationStructureCount` valid `VkAccelerationStructureKHR` handles
- **queryType** must be a valid `VkQueryType` value
- **queryPool** must be a valid `VkQueryPool` handle
- **commandBuffer** must be in the recording state
- The `VkCommandPool` that **commandBuffer** was allocated from must support compute operations
- This command must only be called outside of a render pass instance
- **accelerationStructureCount** must be greater than 0
- Each of **commandBuffer**, **queryPool**, and the elements of **pAccelerationStructures** must have been created, allocated, or retrieved from the same `VkDevice`

Host Synchronization

- Host access to the `VkCommandPool` that **commandBuffer** was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To copy an acceleration structure call:

```c
void vkCmdCopyAccelerationStructureKHR(
    VkCommandBuffer                             commandBuffer,
    const VkCopyAccelerationStructureInfoKHR*   pInfo);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **pInfo** is a pointer to a `VkCopyAccelerationStructureInfoKHR` structure defining the copy operation.
Valid Usage

- All `VkAccelerationStructureKHR` objects referenced by this command must be bound to device memory.
- The `VkDeferredOperationInfoKHR` structure must not be included in the `pNext` chain of the `VkCopyAccelerationStructureInfoKHR` structure.

Valid Usage (Implicit)

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `pInfo` must be a valid pointer to a valid `VkCopyAccelerationStructureInfoKHR` structure
- `commandBuffer` must be in the recording state
- The `VkCommandPool` that `commandBuffer` was allocated from must support compute operations
- This command must only be called outside of a render pass instance

Host Synchronization

- Host access to the `VkCommandPool` that `commandBuffer` was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The `VkCopyAccelerationStructureInfoKHR` structure is defined as:

```c
typedef struct VkCopyAccelerationStructureInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkAccelerationStructureKHR src;
    VkAccelerationStructureKHR dst;
    VkCopyAccelerationStructureModeKHR mode;
} VkCopyAccelerationStructureInfoKHR;
```

- `src` is the source acceleration structure for the copy.
- `dst` is the target acceleration structure for the copy.
• **mode** is a VkCopyAccelerationStructureModeKHR value that specifies additional operations to perform during the copy.

### Valid Usage

- **mode** must be VK_COPY_ACCELERATION_STRUCTURE_MODE_COMPACT_KHR or VK_COPY_ACCELERATION_STRUCTURE_MODE_CLONE_KHR
- **src** must have been built with VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_COMPACTION_BIT_KHR if **mode** is VK_COPY_ACCELERATION_STRUCTURE_MODE_COMPACT_KHR

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_COPY_ACCELERATION_STRUCTURE_INFO_KHR
- **pNext** must be NULL or a pointer to a valid instance of VkDeferredOperationInfoKHR
- The **sType** value of each struct in the **pNext** chain must be unique
- **src** must be a valid VkAccelerationStructureKHR handle
- **dst** must be a valid VkAccelerationStructureKHR handle
- **mode** must be a valid VkCopyAccelerationStructureModeKHR value
- Both of **dst**, and **src** must have been created, allocated, or retrieved from the same VkDevice

Possible values of **mode** specifying additional operations to perform during the copy, are:

```c
typedef enum VkCopyAccelerationStructureModeKHR {
    VK_COPY_ACCELERATION_STRUCTURE_MODE_CLONE_KHR = 0,
    VK_COPY_ACCELERATION_STRUCTURE_MODE_COMPACT_KHR = 1,
    VK_COPY_ACCELERATION_STRUCTURE_MODE_SERIALIZE_KHR = 2,
    VK_COPY_ACCELERATION_STRUCTURE_MODE_DESERIALIZE_KHR = 3,
    VK_COPY_ACCELERATION_STRUCTURE_MODE_MAX_ENUM_KHR = 0x7FFFFFFF
} VkCopyAccelerationStructureModeKHR;
```

- **VK_COPY_ACCELERATION_STRUCTURE_MODE_CLONE_KHR** creates a direct copy of the acceleration structure specified in **src** into the one specified by **dst**. The **dst** acceleration structure must have been created with the same parameters as **src**.
- **VK_COPY_ACCELERATION_STRUCTURE_MODE_COMPACT_KHR** creates a more compact version of an acceleration structure **src** into **dst**. The acceleration structure **dst** must have been created with a compactedSize corresponding to the one returned by vkCmdWriteAccelerationStructuresPropertiesKHR after the build of the acceleration structure specified by **src**.
- **VK_COPY_ACCELERATION_STRUCTURE_MODE_SERIALIZE_KHR** serializes the acceleration structure to a semi-opaque format which can be reloaded on a compatible implementation.
- **VK_COPY_ACCELERATION_STRUCTURE_MODE_DESERIALIZE_KHR** deserializes the semi-opaque serialization
format in the buffer to the acceleration structure.

To copy an acceleration structure to device memory call:

```c
void vkCmdCopyAccelerationStructureToMemoryKHR(
    VkCommandBuffer commandBuffer,
    const VkCopyAccelerationStructureToMemoryInfoKHR* pInfo);
```

This command produces the same results as `vkCopyAccelerationStructureToMemoryKHR`, but writes its result to a device address, and is executed on the device rather than the host. The output may not necessarily be bit-for-bit identical, but it can be equally used by either `vkCmdCopyMemoryToAccelerationStructureKHR` or `vkCopyMemoryToAccelerationStructureKHR`.

- `commandBuffer` is the command buffer into which the command will be recorded.
- `pInfo` is an a pointer to a `VkCopyAccelerationStructureToMemoryInfoKHR` structure defining the copy operation.

The defined header structure for the serialized data consists of:

- `VK_UUID_SIZE` bytes of data matching `VkPhysicalDeviceIDProperties::driverUUID`
- `VK_UUID_SIZE` bytes of data identifying the compatibility for comparison using `vkGetDeviceAccelerationStructureCompatibilityKHR`
- A 64-bit integer of the total size matching the value queried using `VK_QUERY_TYPE_ACCELERATION_STRUCTURE_SERIALIZATION_SIZE_KHR`
- A 64-bit integer of the deserialized size to be passed in to `VkAccelerationStructureCreateInfoKHR::compactedSize`
- A 64-bit integer of the count of the number of acceleration structure handles following. This will be zero for a bottom-level acceleration structure.

The corresponding handles matching the values returned by `vkGetAccelerationStructureDeviceAddressKHR` are tightly packed in the buffer following the count. The application is expected to store a mapping between those handles and the original application-generated bottom-level acceleration structures to provide when deserializing.

**Valid Usage**

- All `VkDeviceOrHostAddressConstKHR` referenced by this command must contain valid device addresses.
- All `VkAccelerationStructureKHR` objects referenced by this command must be bound to device memory.
- The `VkDeferredOperationInfoKHR` structure must not be included in the `pNext` chain of the `VkCopyAccelerationStructureToMemoryInfoKHR` structure.
- `mode` must be `VK_COPY_ACCELERATION_STRUCTURE_MODE_SERIALIZE_KHR`
Valid Usage (Implicit)

- \texttt{commandBuffer} must be a valid \texttt{VkCommandBuffer} handle
- \texttt{pInfo} must be a valid pointer to a valid \texttt{VkCopyAccelerationStructureToMemoryInfoKHR} structure
- \texttt{commandBuffer} must be in the recording state
- The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must support compute operations
- This command must only be called outside of a render pass instance

Host Synchronization

- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

typedef struct \texttt{VkCopyAccelerationStructureToMemoryInfoKHR} {
    VkStructureType sType;
    const void* pNext;
    VkAccelerationStructureKHR src;
    VkDeviceOrHostAddressKHR dst;
    VkCopyAccelerationStructureModeKHR mode;
} \texttt{VkCopyAccelerationStructureToMemoryInfoKHR};

- \texttt{src} is the source acceleration structure for the copy
- \texttt{dst} is the device or host address to memory which is the target for the copy
- \texttt{mode} is a \texttt{VkCopyAccelerationStructureModeKHR} value that specifies additional operations to perform during the copy.
Valid Usage

- The memory pointed to by `dst` must be at least as large as the serialization size of `src`, as reported by `VK_QUERY_TYPE_ACCELERATION_STRUCTURE_SERIALIZATION_SIZE_KHR`.
- `mode` must be `VK_COPY_ACCELERATION_STRUCTURE_MODE_SERIALIZE_KHR`.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_COPY_ACCELERATION_STRUCTURE_TO_MEMORY_INFO_KHR`.
- `pNext` must be `NULL` or a pointer to a valid instance of `VkDeferredOperationInfoKHR`.
- The `sType` value of each struct in the `pNext` chain must be unique.
- `src` must be a valid `VkAccelerationStructureKHR` handle.
- `dst` must be a valid `VkDeviceOrHostAddressKHR` union.
- `mode` must be a valid `VkCopyAccelerationStructureModeKHR` value.

To copy device memory to an acceleration structure call:

```c
void vkCmdCopyMemoryToAccelerationStructureKHR(
    VkCommandBuffer commandBuffer,
    const VkCopyMemoryToAccelerationStructureInfoKHR* pInfo);
```

This command can accept acceleration structures produced by either `vkCmdCopyAccelerationStructureToMemoryKHR` or `vkCopyAccelerationStructureToMemoryKHR`.

- `commandBuffer` is the command buffer into which the command will be recorded.
- `pInfo` is a pointer to a `VkCopyMemoryToAccelerationStructureInfoKHR` structure defining the copy operation.

The structure provided as input to deserialize is as described in `vkCmdCopyAccelerationStructureToMemoryKHR`, with any acceleration structure handles filled in with the newly-queried handles to bottom level acceleration structures created before deserialization. These do not need to be built at deserialize time, but `must` be created.
Valid Usage

- All \texttt{VkDeviceOrHostAddressKHR} referenced by this command \textbf{must} contain valid device addresses.
- All \texttt{VkAccelerationStructureKHR} objects referenced by this command \textbf{must} be bound to device memory.
- The \texttt{VkDeferredOperationInfoKHR} structure \textbf{must} not be included in the \texttt{pNext} chain of the \texttt{VkCopyMemoryToAccelerationStructureInfoKHR} structure.
- \texttt{mode} \textbf{must} be \texttt{VK_COPY_ACCELERATION_STRUCTURE_MODE_DESERIALIZE_KHR}
- The data in \texttt{pInfo->pname}:src \textbf{must} have a format compatible with the destination physical device as returned by \texttt{vkGetDeviceAccelerationStructureCompatibilityKHR}

Valid Usage (Implicit)

- \texttt{commandBuffer} \textbf{must} be a valid \texttt{VkCommandBuffer} handle
- \texttt{pInfo} \textbf{must} be a valid pointer to a valid \texttt{VkCopyMemoryToAccelerationStructureInfoKHR} structure
- \texttt{commandBuffer} \textbf{must} be in the \textit{recording state}
- The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} support compute operations
- This command \textbf{must} only be called outside of a render pass instance

Host Synchronization

- Host access to the \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from \textbf{must} be externally synchronized

Command Properties

<table>
<thead>
<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Outside</td>
<td>Compute</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The \texttt{VkCopyMemoryToAccelerationStructureInfoKHR} structure is defined as:
typedef struct VkCopyMemoryToAccelerationStructureInfoKHR {
    VkStructureType sType;
    const void* pNext;
    VkDeviceOrHostAddressConstKHR src;
    VkAccelerationStructureKHR dst;
    VkCopyAccelerationStructureModeKHR mode;
} VkCopyMemoryToAccelerationStructureInfoKHR;

- **src** is the device or host address to memory containing the source data for the copy.
- **dst** is the target acceleration structure for the copy.
- **mode** is a VkCopyAccelerationStructureModeKHR value that specifies additional operations to perform during the copy.

### Valid Usage

- **mode** must be VK_COPY_ACCELERATION_STRUCTURE_MODE_DESERIALIZE_KHR
- The data in pInfo->pname:src must have a format compatible with the destination physical device as returned by vkGetDeviceAccelerationStructureCompatibilityKHR

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_COPY_MEMORY_TO_ACCELERATION_STRUCTURE_INFO_KHR
- **pNext** must be NULL or a pointer to a valid instance of VkDeferredOperationInfoKHR
- The sType value of each struct in the pNext chain must be unique
- **src** must be a valid VkDeviceOrHostAddressConstKHR union
- **dst** must be a valid VkAccelerationStructureKHR handle
- **mode** must be a valid VkCopyAccelerationStructureModeKHR value

To check if a serialized acceleration structure is compatible with the current device call:

```c
VkResult vkGetDeviceAccelerationStructureCompatibilityKHR(
    VkDevice device,
    const VkAccelerationStructureVersionKHR* version);
```

- **device** is the device to check the version against.
- **version** points to the VkAccelerationStructureVersionKHR version information to check against the device.

This possible return values for vkGetDeviceAccelerationStructureCompatibilityKHR are:

- **VK_SUCCESS** is returned if an acceleration structure serialized with version as the version
information is compatible with `device`.

- `VK_ERROR_INCOMPATIBLE_VERSION_KHR` is returned if an acceleration structure serialized with `version` as the version information is not compatible with `device`.

**Valid Usage**

- The `rayTracing` or `rayQuery` feature **must** be enabled

**Valid Usage (Implicit)**

- `device` **must** be a valid `VkDevice` handle
- `version` **must** be a valid pointer to a valid `VkAccelerationStructureVersionKHR` structure

**Return Codes**

**Success**

- `VK_SUCCESS`

**Failure**

- `VK_ERROR_INCOMPATIBLE_VERSION_KHR`

The `VkAccelerationStructureVersionKHR` structure is defined as:

```c
typedef struct VkAccelerationStructureVersionKHR {
    VkStructureType sType;
    const void* pNext;
    const uint8_t* versionData;
} VkAccelerationStructureVersionKHR;
```

- `versionData` is a pointer to the version header as defined in `VkCopyAccelerationStructureModeKHR`

**Valid Usage**

- TBD

**Valid Usage (Implicit)**

- `sType` **must** be `VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_VERSION_KHR`
- `pNext` **must** be `NULL`
- `versionData` **must** be a valid pointer to an array of `2*VK_UUID_SIZE uint8_t` values
32.5. Host Acceleration Structure Operations

Implementations are also required to provide host implementations of the acceleration structure operations if the `rayTracingHostAccelerationStructureCommands` feature is enabled:

- `vkBuildAccelerationStructureKHR` corresponding to `vkCmdBuildAccelerationStructureKHR`
- `vkCopyAccelerationStructureKHR` corresponding to `vkCmdCopyAccelerationStructureKHR`
- `vkCopyAccelerationStructureToMemoryKHR` corresponding to `vkCmdCopyAccelerationStructureToMemoryKHR`
- `vkCopyMemoryToAccelerationStructureKHR` corresponding to `vkCmdCopyMemoryToAccelerationStructureKHR`
- `vkWriteAccelerationStructuresPropertiesKHR` corresponding to `vkCmdWriteAccelerationStructuresPropertiesKHR`

These commands are functionally equivalent to their device counterparts, except that they are executed on the host timeline, rather than being enqueued into command buffers.

All acceleration structures used by the host commands **must** be bound to host-visible memory, and all input data for acceleration structure builds **must** be referenced using host addresses instead of device addresses. Applications are not required to map acceleration structure memory when using the host commands.

**Note**

The `vkBuildAccelerationStructureKHR` and `vkCmdBuildAccelerationStructureKHR` may use different algorithms, and thus are not required to produce identical structures. The structures produced by these two commands may exhibit different memory footprints or traversal performance, but should strive to be similar where possible.

Apart from these details, the host and device operations are interchangeable. For example, an application can use `vkBuildAccelerationStructureKHR` to build a structure, compact it on the device using `vkCmdCopyAccelerationStructureKHR`, and serialize the result using `vkCopyAccelerationStructureToMemoryKHR`.

To build acceleration structures on the host, call:

```c
VkResult vkBuildAccelerationStructureKHR(
  VkDevice                      device, 
  uint32_t                      infoCount,
  const VkAccelerationStructureBuildGeometryInfoKHR* pInfos,
  const VkAccelerationStructureBuildOffsetInfoKHR* const* ppOffsetInfos);
```

This command fulfills the same task as `vkCmdBuildAccelerationStructureKHR` but executed by the host.

- `device` is the `VkDevice` for which the acceleration structures are being built.
• **infoCount** is the number of acceleration structures to build. It specifies the number of the **pInfos** structures and **ppOffsetInfos** pointers that **must** be provided.

• **pInfos** is a pointer to an array of **infoCount** **VkAccelerationStructureBuildGeometryInfoKHR** structures defining the geometry used to build each acceleration structure.

• **ppOffsetInfos** is an array of **infoCount** pointers to arrays of **VkAccelerationStructureBuildOffsetInfoKHR** structures. Each **ppOffsetInfos[i]** is an array of **pInfos[i]**→ **geometryCount** **VkAccelerationStructureBuildOffsetInfoKHR** structures defining dynamic offsets to the addresses where geometry data is stored, as defined by **pInfos[i]**.

The **vkBuildAccelerationStructureKHR** command provides the ability to initiate multiple acceleration structures builds, however there is no ordering or synchronization implied between any of the individual acceleration structure builds.

**Note**

This means that an application **cannot** build a top-level acceleration structure in the same **vkBuildAccelerationStructureKHR** call as the associated bottom-level or instance acceleration structures are being built. There also **cannot** be any memory aliasing between any acceleration structure memories or scratch memories being used by any of the builds.

If the **VkDeferredOperationInfoKHR** structure is included in the **pNext** chain of any **VkAccelerationStructureBuildGeometryInfoKHR** structure, the operation of this command is **deferred**, as defined in the Deferred Host Operations chapter.
Valid Usage

• `pOffsetInfos[i]` **must** be a valid pointer to an array of `pInfos[i]→geometryCount` `VkAccelerationStructureBuildOffsetInfoKHR` structures.

• Each `pInfos[i].srcAccelerationStructure` **must** not refer to the same acceleration structure as any `pInfos[i].dstAccelerationStructure` that is provided to the same build command unless it is identical for an update.

• For each `pInfos[i]`, `dstAccelerationStructure` **must** have been created with compatible `VkAccelerationStructureCreateInfoKHR` where `VkAccelerationStructureCreateInfoKHR::type` and `VkAccelerationStructureCreateInfoKHR::flags` are identical to `VkAccelerationStructureBuildGeometryInfoKHR::type` and `VkAccelerationStructureBuildGeometryInfoKHR::flags` respectively, `VkAccelerationStructureBuildGeometryInfoKHR::geometryCount` for `dstAccelerationStructure` are greater than or equal to the build size, and each geometry in `VkAccelerationStructureBuildGeometryInfoKHR::ppGeometries` for `dstAccelerationStructure` has greater than or equal to the number of vertices, indices, and AABBs, `VkAccelerationStructureGeometryTrianglesDataKHR::transformData` is both 0 or both non-zero, and all other parameters are the same.

• For each `pInfos[i]`, if `update` is `VK_TRUE`, then objects that were previously active for that acceleration structure **must** not be made inactive as per Inactive Primitives and Instances.

• For each `pInfos[i]`, if `update` is `VK_TRUE`, then objects that were previously inactive for that acceleration structure **must** not be made active as per Inactive Primitives and Instances.

• Any acceleration structure instance in any top level build in this command **must** not reference any bottom level acceleration structure built by this command.

• There **must** not be any memory aliasing between the scratch memories that are provided in all the `pInfos[i].scratchData` memories for the acceleration structure builds.

• There **must** not be any memory aliasing between memory bound to any top level, bottom level, or instance acceleration structure accessed by this command.

• All `VkDeviceOrHostAddressKHR` or `VkDeviceOrHostAddressConstKHR` referenced by this command **must** contain valid host addresses.

• All `VkAccelerationStructureKHR` objects referenced by this command **must** be bound to host-visible memory.

• The `VkPhysicalDeviceRayTracingFeaturesKHR→rayTracingHostAccelerationStructureCommands` feature **must** be enabled.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pInfos** must be a valid pointer to an array of `infoCount` valid `VkAccelerationStructureBuildGeometryInfoKHR` structures
- **ppOffsetInfos** must be a valid pointer to an array of `infoCount` `VkAccelerationStructureBuildOffsetInfoKHR` structures
- **infoCount** must be greater than 0

Return Codes

**Success**
- **VK_SUCCESS**
- **VK_OPERATION_DEFERRED_KHR**
- **VK_OPERATION_NOT_DEFERRED_KHR**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

To copy or compact an acceleration structure on the host, call:

```c
VkResult vkCopyAccelerationStructureKHR(
    VkDevice device,
    constVkCopyAccelerationStructureInfoKHR*pInfo);
```

This command fulfills the same task as `vkCmdCopyAccelerationStructureKHR` but executed by the host.

- **device** is the device which owns the acceleration structures.
- **pInfo** is a pointer to a `VkCopyAccelerationStructureInfoKHR` structure defining the copy operation.

If the `VkDeferredOperationInfoKHR` structure is included in the **pNext** chain of the `VkCopyAccelerationStructureInfoKHR` structure, the operation of this command is **deferred**, as defined in the Deferred Host Operations chapter.
Valid Usage

- All `VkAccelerationStructureKHR` objects referenced by this command must be bound to host-visible memory.
- The `VkPhysicalDeviceRayTracingFeaturesKHR→rayTracingHostAccelerationStructureCommands` feature must be enabled

Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `pInfo` must be a valid pointer to a valid `VkCopyAccelerationStructureInfoKHR` structure

Return Codes

**Success**

- `VK_SUCCESS`
- `VK_OPERATION_DEFERRED_KHR`
- `VK_OPERATION_NOT_DEFERRED_KHR`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

```c
VkResult vkCopyMemoryToAccelerationStructureKHR(
    VkDevice                                    device,
    constVkCopyMemoryToAccelerationStructureInfoKHR* pInfo);
```

This command fulfills the same task as `vkCmdCopyMemoryToAccelerationStructureKHR` but is executed by the host.

This command can accept acceleration structures produced by either `vkCmdCopyAccelerationStructureToMemoryKHR` or `vkCopyAccelerationStructureToMemoryKHR`.

- `device` is the device which owns `pInfo->pname`:dst.
- `pInfo` is a pointer to a `VkCopyMemoryToAccelerationStructureInfoKHR` structure defining the copy operation.

If the `VkDeferredOperationInfoKHR` structure is included in the `pNext` chain of the `VkCopyMemoryToAccelerationStructureInfoKHR` structure, the operation of this command is deferred, as defined in the Deferred Host Operations chapter.
Valid Usage

• All VkAccelerationStructureKHR objects referenced by this command must be bound to host-visible memory.

• All VkDeviceOrHostAddressConstKHR referenced by this command must contain valid host pointers.

• the VkPhysicalDeviceRayTracingFeaturesKHR → rayTracingHostAccelerationStructureCommands feature must be enabled

Valid Usage (Implicit)

• device must be a valid VkDevice handle

• pInfo must be a valid pointer to a valid VkCopyMemoryToAccelerationStructureInfoKHR structure

Return Codes

Success

• VK_SUCCESS

• VK_OPERATION_DEFERRED_KHR

• VK_OPERATION_NOT_DEFERRED_KHR

Failure

• VK_ERROR_OUT_OF_HOST_MEMORY

• VK_ERROR_OUT_OF_DEVICE_MEMORY

VkResult vkCopyAccelerationStructureToMemoryKHR(
    VkDevice                                    device,
    const VkCopyAccelerationStructureToMemoryInfoKHR* pInfo);

This command fulfills the same task as vkCmdCopyAccelerationStructureToMemoryKHR but executed by the host.

This command produces the same results as vkCmdCopyAccelerationStructureToMemoryKHR, but writes its result directly to a host pointer, and is executed on the host rather than the device. The output may not necessarily be bit-for-bit identical, but it can be equally used by either vkCmdCopyMemoryToAccelerationStructureKHR or vkCopyMemoryToAccelerationStructureKHR.

• device is the device which owns pInfo->pname:src.

• pInfo is a pointer to a VkCopyAccelerationStructureToMemoryInfoKHR structure defining the copy operation.
If the `VkDeferredOperationInfoKHR` structure is included in the `pNext` chain of the `VkCopyAccelerationStructureToMemoryInfoKHR` structure, the operation of this command is *deferred*, as defined in the Deferred Host Operations chapter.

### Valid Usage

- All `VkAccelerationStructureKHR` objects referenced by this command **must** be bound to host-visible memory.
- All `VkDeviceOrHostAddressKHR` referenced by this command **must** contain valid host pointers.
- The `VkPhysicalDeviceRayTracingFeaturesKHR -> rayTracingHostAccelerationStructureCommands` feature **must** be enabled.

### Valid Usage (Implicit)

- `device` **must** be a valid `VkDevice` handle
- `pInfo` **must** be a valid pointer to a valid `VkCopyAccelerationStructureToMemoryInfoKHR` structure

### Return Codes

#### Success

- `VK_SUCCESS`
- `VK_OPERATION_DEFERRED_KHR`
- `VK_OPERATION_NOT_DEFERRED_KHR`

#### Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

```c
VkResult vkWriteAccelerationStructuresPropertiesKHR(
    VkDevice                                    device,  // device
    uint32_t                                    accelerationStructureCount,  // accelerationStructureCount
    const VkAccelerationStructureKHR*           pAccelerationStructures,  // pAccelerationStructures
    VkQueryType                                 queryType,  // queryType
    size_t                                      dataSize,  // dataSize
    void*                                       pData,  // pData
    size_t                                      stride);  // stride
```

This command fulfills the same task as `vkCmdWriteAccelerationStructuresPropertiesKHR` but executed by the host.

- `device` is the device which owns the acceleration structures in `pAccelerationStructures`.

• accelerationStructureCount is the count of acceleration structures for which to query the property.
• pAccelerationStructures points to an array of existing previously built acceleration structures.
• queryType is a VkQueryType value specifying the property to be queried.
• dataSize is the size in bytes of the buffer pointed to by pData.
• pData is a pointer to a user-allocated buffer where the results will be written.
• stride is the stride in bytes between results for individual queries within pData.

Valid Usage

- If queryType is VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR, then stride must be a multiple of the size of VkDeviceSize
- If queryType is VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR, then data must point to a VkDeviceSize
- If queryType is VK_QUERY_TYPE_ACCELERATION_STRUCTURE_SERIALIZATION_SIZE_KHR, then stride must be a multiple of the size of VkDeviceSize
- If queryType is VK_QUERY_TYPE_ACCELERATION_STRUCTURE_SERIALIZATION_SIZE_KHR, then data must point to a VkDeviceSize
- dataSize must be greater than or equal to accelerationStructureCount*stride
- The acceleration structures referenced by pAccelerationStructures must be bound to host-visible memory
- All acceleration structures in accelerationStructures must have been built with VK_BUILD_ACCELERATION_STRUCTURE_ALLOW_COMPACTION_BIT_KHR if queryType is VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR
- queryType must be VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR or VK_QUERY_TYPE_ACCELERATION_STRUCTURE_SERIALIZATION_SIZE_KHR
- the VkPhysicalDeviceRayTracingFeaturesKHR → rayTracingHostAccelerationStructureCommands feature must be enabled
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pAccelerationStructures** must be a valid pointer to an array of `accelerationStructureCount` valid `VkAccelerationStructureKHR` handles
- **queryType** must be a valid `VkQueryType` value
- **pData** must be a valid pointer to an array of `dataSize` bytes
- **accelerationStructureCount** must be greater than 0
- **dataSize** must be greater than 0
- Each element of **pAccelerationStructures** must have been created, allocated, or retrieved from **device**

Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
Chapter 33. Extending Vulkan

New functionality may be added to Vulkan via either new extensions or new versions of the core, or new versions of an extension in some cases.

This chapter describes how Vulkan is versioned, how compatibility is affected between different versions, and compatibility rules that are followed by the Vulkan Working Group.

33.1. Instance and Device Functionality

Commands that enumerate instance properties, or that accept a VkInstance object as a parameter, are considered instance-level functionality. Commands that enumerate physical device properties, or that accept a VkDevice object or any of a device's child objects as a parameter, are considered device-level functionality.

Note
Applications usually interface to Vulkan using a loader that implements only instance-level functionality, passing device-level functionality to implementations of the full Vulkan API on the system. In some circumstances, as these may be implemented independently, it is possible that the loader and device implementations on a given installation will support different versions. To allow for this and call out when it happens, the Vulkan specification enumerates device and instance level functionality separately - they have independent version queries.

Note
Vulkan 1.0 initially specified new physical device enumeration functionality as instance-level, requiring it to be included in an instance extension. As the capabilities of device-level functionality require discovery via physical device enumeration, this led to the situation where many device extensions required an instance extension as well. To alleviate this extra work, VK_KHR_get_physical_device_properties2 (and subsequently Vulkan 1.1) redefined device-level functionality to include physical device enumeration.

33.2. Core Versions

The Vulkan Specification is regularly updated with bug fixes and clarifications. Occasionally new functionality is added to the core and at some point it is expected that there will be a desire to perform a large, breaking change to the API. In order to indicate to developers how and when these changes are made to the specification, and to provide a way to identify each set of changes, the Vulkan API maintains a version number.

33.2.1. Version Numbers

The Vulkan version number comprises three parts indicating the major, minor and patch version of the Vulkan API Specification.
The major version indicates a significant change in the API, which will encompass a wholly new version of the specification.

The minor version indicates the incorporation of new functionality into the core specification.

The patch version indicates bug fixes, clarifications, and language improvements have been incorporated into the specification.

Compatibility guarantees made about versions of the API sharing any of the same version numbers are documented in Core Versions

The version number is used in several places in the API. In each such use, the version numbers are packed into a 32-bit integer as follows:

- The major version is a 10-bit integer packed into bits 31-22.
- The minor version number is a 10-bit integer packed into bits 21-12.
- The patch version number is a 12-bit integer packed into bits 11-0.

VK_VERSION_MAJOR extracts the API major version number from a packed version number:

```c
#define VK_VERSION_MAJOR(version) ((uint32_t)(version) >> 22)
```

VK_VERSION_MINOR extracts the API minor version number from a packed version number:

```c
#define VK_VERSION_MINOR(version) (((uint32_t)(version) >> 12) & 0x3ff)
```

VK_VERSION_PATCH extracts the API patch version number from a packed version number:

```c
#define VK_VERSION_PATCH(version) ((uint32_t)(version) & 0xfff)
```

VK_MAKE_VERSION constructs an API version number.

```c
#define VK_MAKE_VERSION(major, minor, patch) 
(((major) << 22) | ((minor) << 12) | (patch))
```

- major is the major version number.
- minor is the minor version number.
- patch is the patch version number.

VK_API_VERSION_1_0 returns the API version number for Vulkan 1.0.0.
// Vulkan 1.0 version number
#define VK_API_VERSION_1_0 VK_MAKE_VERSION(1, 0, 0)  // Patch version should always be set to 0

**VK_API_VERSION_1_1** returns the API version number for Vulkan 1.1.0.

// Vulkan 1.1 version number
#define VK_API_VERSION_1_1 VK_MAKE_VERSION(1, 1, 0)  // Patch version should always be set to 0

### 33.2.2. Querying Version Support

The version of instance-level functionality can be queried by calling `vkEnumerateInstanceVersion`.

The version of device-level functionality can be queried by calling `vkGetPhysicalDeviceProperties` or `vkGetPhysicalDeviceProperties2`, and is returned in `VkPhysicalDeviceProperties::apiVersion`, encoded as described in *Version Numbers*.

### 33.3. Layers

When a layer is enabled, it inserts itself into the call chain for Vulkan commands the layer is interested in. Layers can be used for a variety of tasks that extend the base behavior of Vulkan beyond what is required by the specification - such as call logging, tracing, validation, or providing additional extensions.

#### Note

For example, an implementation is not expected to check that the value of enums used by the application fall within allowed ranges. Instead, a validation layer would do those checks and flag issues. This avoids a performance penalty during production use of the application because those layers would not be enabled in production.

#### Note

Vulkan layers may wrap object handles (i.e. return a different handle value to the application than that generated by the implementation). This is generally discouraged, as it increases the probability of incompatibilities with new extensions. The validation layers wrap handles in order to track the proper use and destruction of each object. See the “Vulkan Loader Specification and Architecture Overview” document for additional information.

To query the available layers, call:
 VkResult vkEnumerateInstanceLayerProperties(  
    uint32_t* pPropertyCount,  
    VkLayerProperties* pProperties);  

• `pPropertyCount` is a pointer to an integer related to the number of layer properties available or queried, as described below.

• `pProperties` is either NULL or a pointer to an array of `VkLayerProperties` structures.

If `pProperties` is NULL, then the number of layer properties available is returned in `pPropertyCount`. Otherwise, `pPropertyCount` must point to a variable set by the user to the number of elements in the `pProperties` array, and on return the variable is overwritten with the number of structures actually written to `pProperties`. If `pPropertyCount` is less than the number of layer properties available, at most `pPropertyCount` structures will be written. If `pPropertyCount` is smaller than the number of layers available, `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS`, to indicate that not all the available layer properties were returned.

The list of available layers may change at any time due to actions outside of the Vulkan implementation, so two calls to `vkEnumerateInstanceLayerProperties` with the same parameters may return different results, or retrieve different `pPropertyCount` values or `pProperties` contents. Once an instance has been created, the layers enabled for that instance will continue to be enabled and valid for the lifetime of that instance, even if some of them become unavailable for future instances.

### Valid Usage (Implicit)

• `pPropertyCount` must be a valid pointer to a `uint32_t` value.

• If the value referenced by `pPropertyCount` is not 0, and `pProperties` is not NULL, `pProperties` must be a valid pointer to an array of `pPropertyCount` `VkLayerProperties` structures.

### Return Codes

#### Success

- `VK_SUCCESS`
- `VK_INCOMPLETE`

#### Failure

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `VkLayerProperties` structure is defined as:
typedef struct VkLayerProperties {
    char     layerName [VK_MAX_EXTENSION_NAME_SIZE];
    uint32_t specVersion;
    uint32_t implementationVersion;
    char     description [VK_MAX_DESCRIPTION_SIZE];
} VkLayerProperties;

- **layerName** is an array of **VK_MAX_EXTENSION_NAME_SIZE** char containing a null-terminated UTF-8 string which is the name of the layer. Use this name in the **ppEnabledLayerNames** array passed in the **VkInstanceCreateInfo** structure to enable this layer for an instance.

- **specVersion** is the Vulkan version the layer was written to, encoded as described in **Version Numbers**.

- **implementationVersion** is the version of this layer. It is an integer, increasing with backward compatible changes.

- **description** is an array of **VK_MAX_DESCRIPTION_SIZE** char containing a null-terminated UTF-8 string which provides additional details that can be used by the application to identify the layer.

To enable a layer, the name of the layer **should** be added to the **ppEnabledLayerNames** member of **VkInstanceCreateInfo** when creating a **VkInstance**.

Loader implementations **may** provide mechanisms outside the Vulkan API for enabling specific layers. Layers enabled through such a mechanism are **implicitly enabled**, while layers enabled by including the layer name in the **ppEnabledLayerNames** member of **VkInstanceCreateInfo** are **explicitly enabled**. Implicitly enabled layers are loaded before explicitly enabled layers, such that implicitly enabled layers are closer to the application, and explicitly enabled layers are closer to the driver. Except where otherwise specified, implicitly enabled and explicitly enabled layers differ only in the way they are enabled, and the order in which they are loaded. Explicitly enabling a layer that is implicitly enabled results in this layer being loaded as an implicitly enabled layer; it has no additional effect.

### 33.3.1. Device Layer Deprecation

Previous versions of this specification distinguished between instance and device layers. Instance layers were only able to intercept commands that operate on **VkInstance** and **VkPhysicalDevice**, except they were not able to intercept **vkCreateDevice**. Device layers were enabled for individual devices when they were created, and could only intercept commands operating on that device or its child objects.

Device-only layers are now deprecated, and this specification no longer distinguishes between instance and device layers. Layers are enabled during instance creation, and are able to intercept all commands operating on that instance or any of its child objects. At the time of deprecation there were no known device-only layers and no compelling reason to create one.

In order to maintain compatibility with implementations released prior to device-layer deprecation, applications **should** still enumerate and enable device layers. The behavior of **vkEnumerateDeviceLayerProperties** and valid usage of the **ppEnabledLayerNames** member of **VkDeviceCreateInfo** maximizes compatibility with applications written to work with the previous
requirements.

To enumerate device layers, call:

```c
VkResult vkEnumerateDeviceLayerProperties(
    VkPhysicalDevice physicalDevice,
    uint32_t* pPropertyCount,
    VkLayerProperties* pProperties);
```

- `pPropertyCount` is a pointer to an integer related to the number of layer properties available or queried.
- `pProperties` is either `NULL` or a pointer to an array of `VkLayerProperties` structures.

If `pProperties` is `NULL`, then the number of layer properties available is returned in `pPropertyCount`. Otherwise, `pPropertyCount` must point to a variable set by the user to the number of elements in the `pProperties` array, and on return the variable is overwritten with the number of structures actually written to `pProperties`. If `pPropertyCount` is less than the number of layer properties available, at most `pPropertyCount` structures will be written. If `pPropertyCount` is smaller than the number of layers available, `VK_INCOMPLETE` will be returned instead of `VK_SUCCESS`, to indicate that not all the available layer properties were returned.

The list of layers enumerated by `vkEnumerateDeviceLayerProperties` must be exactly the sequence of layers enabled for the instance. The members of `VkLayerProperties` for each enumerated layer must be the same as the properties when the layer was enumerated by `vkEnumerateInstanceLayerProperties`.

**Valid Usage (Implicit)**

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pPropertyCount` must be a valid pointer to a `uint32_t` value
- If the value referenced by `pPropertyCount` is not 0, and `pProperties` is not `NULL`, `pProperties` must be a valid pointer to an array of `pPropertyCount` `VkLayerProperties` structures

**Return Codes**

**Success**

- `VK_SUCCESS`
- `VK_INCOMPLETE`

**Failure**

- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`

The `ppEnabledLayerNames` and `enabledLayerCount` members of `VkDeviceCreateInfo` are deprecated and their values must be ignored by implementations. However, for compatibility, only an empty list of
layers or a list that exactly matches the sequence enabled at instance creation time are valid, and validation layers should issue diagnostics for other cases.

Regardless of the enabled layer list provided in `VkDeviceCreateInfo`, the sequence of layers active for a device will be exactly the sequence of layers enabled when the parent instance was created.

### 33.4. Extensions

Extensions may define new Vulkan commands, structures, and enumerants. For compilation purposes, the interfaces defined by registered extensions, including new structures and enumerants as well as function pointer types for new commands, are defined in the Khronos-supplied `vulkan_core.h` together with the core API. However, commands defined by extensions may not be available for static linking - in which case function pointers to these commands should be queried at runtime as described in Command Function Pointers. Extensions may be provided by layers as well as by a Vulkan implementation.

Because extensions may extend or change the behavior of the Vulkan API, extension authors should add support for their extensions to the Khronos validation layers. This is especially important for new commands whose parameters have been wrapped by the validation layers. See the “Vulkan Loader Specification and Architecture Overview” document for additional information.

---

**Note**

To enable an instance extension, the name of the extension can be added to the `.ppEnabledExtensionNames` member of `VkInstanceCreateInfo` when creating a `VkInstance`.

To enable a device extension, the name of the extension can be added to the `.ppEnabledExtensionNames` member of `VkDeviceCreateInfo` when creating a `VkDevice`.

Physical-Device-Level functionality does not have any enabling mechanism and can be used as long as the `VkPhysicalDevice` supports the device extension as determined by `vkEnumerateDeviceExtensionProperties`.

Enabling an extension does not change the behavior of functionality exposed by the core Vulkan API or any other extension, other than making valid the use of the commands, enums and structures defined by that extension.

Valid Usage sections for individual commands and structures do not currently contain which extensions have to be enabled in order to make their use valid, although they might do so in the future. It is defined only in the Valid Usage for Extensions section.

### 33.4.1. Instance Extensions

Instance extensions add new instance-level functionality to the API, outside of the core specification.

To query the available instance extensions, call:
VkResult vkEnumerateInstanceExtensionProperties(
        const char* pLayerName,
        uint32_t* pPropertyCount,
        VkExtensionProperties* pProperties);

- **pLayerName** is either **NULL** or a pointer to a null-terminated UTF-8 string naming the layer to retrieve extensions from.
- **pPropertyCount** is a pointer to an integer related to the number of extension properties available or queried, as described below.
- **pProperties** is either **NULL** or a pointer to an array of **VkExtensionProperties** structures.

When **pLayerName** parameter is **NULL**, only extensions provided by the Vulkan implementation or by implicitly enabled layers are returned. When **pLayerName** is the name of a layer, the instance extensions provided by that layer are returned.

If **pProperties** is **NULL**, then the number of extensions properties available is returned in **pPropertyCount**. Otherwise, **pPropertyCount** must point to a variable set by the user to the number of elements in the **pProperties** array, and on return the variable is overwritten with the number of structures actually written to **pProperties**. If **pPropertyCount** is less than the number of extension properties available, at most **pPropertyCount** structures will be written. If **pPropertyCount** is smaller than the number of extensions available, **VK_INCOMPLETE** will be returned instead of **VK_SUCCESS**, to indicate that not all the available properties were returned.

Because the list of available layers may change externally between calls to **vkEnumerateInstanceExtensionProperties**, two calls may retrieve different results if a **pLayerName** is available in one call but not in another. The extensions supported by a layer may also change between two calls, e.g. if the layer implementation is replaced by a different version between those calls.

Implementations **must** not advertise any pair of extensions that cannot be enabled together due to behavioral differences, or any extension that cannot be enabled against the advertised version.

---

**Valid Usage (Implicit)**

- If **pLayerName** is not **NULL**, **pLayerName** must be a null-terminated UTF-8 string.
- **pPropertyCount** must be a valid pointer to a **uint32_t** value.
- If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not **NULL**, **pProperties** must be a valid pointer to an array of **pPropertyCount** **VkExtensionProperties** structures.
Return Codes

Success
- VK_SUCCESS
- VK_INCOMPLETE

Failure
- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_LAYER_NOT_PRESENT

33.4.2. Device Extensions

Device extensions add new device-level functionality to the API, outside of the core specification.

To query the extensions available to a given physical device, call:

```
VkResult vkEnumerateDeviceExtensionProperties(
    VkPhysicalDevice physicalDevice,
    const char* pLayerName,
    uint32_t* pPropertyCount,
    VkExtensionProperties* pProperties);
```

- **physicalDevice** is the physical device that will be queried.
- **pLayerName** is either **NULL** or a pointer to a null-terminated UTF-8 string naming the layer to retrieve extensions from.
- **pPropertyCount** is a pointer to an integer related to the number of extension properties available or queried, and is treated in the same fashion as the `vkEnumerateInstanceExtensionProperties` ::`pPropertyCount` parameter.
- **pProperties** is either **NULL** or a pointer to an array of `VkExtensionProperties` structures.

When **pLayerName** parameter is **NULL**, only extensions provided by the Vulkan implementation or by implicitly enabled layers are returned. When **pLayerName** is the name of a layer, the device extensions provided by that layer are returned.

Implementations **must** not advertise any pair of extensions that cannot be enabled together due to behavioral differences, or any extension that cannot be enabled against the advertised version.
Valid Usage (Implicit)

- **physicalDevice** must be a valid **VkPhysicalDevice** handle
- If **pLayerName** is not NULL, **pLayerName** must be a null-terminated UTF-8 string
- **pPropertyCount** must be a valid pointer to a `uint32_t` value
- If the value referenced by **pPropertyCount** is not 0, and **pProperties** is not NULL, **pProperties** must be a valid pointer to an array of **pPropertyCount** **VkExtensionProperties** structures

Return Codes

**Success**
- **VK_SUCCESS**
- **VK_INCOMPLETE**

**Failure**
- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**
- **VK_ERROR_LAYER_NOT_PRESENT**

The **VkExtensionProperties** structure is defined as:

```c
typedef struct VkExtensionProperties {
    char extensionName[VK_MAX_EXTENSION_NAME_SIZE];
    uint32_t specVersion;
} VkExtensionProperties;
```

- **extensionName** is an array of **VK_MAX_EXTENSION_NAME_SIZE** `char` containing a null-terminated UTF-8 string which is the name of the extension.
- **specVersion** is the version of this extension. It is an integer, incremented with backward compatible changes.

### 33.5. Extension Dependencies

Some extensions are dependent on other extensions to function. To enable extensions with dependencies, such **required extensions** must also be enabled through the same API mechanisms when creating an instance with **vkCreateInstance** or a device with **vkCreateDevice**. Each extension which has such dependencies documents them in the appendix summarizing that extension.

If an extension is supported (as queried by **vkEnumerateInstanceExtensionProperties** or **vkEnumerateDeviceExtensionProperties**), then **required extensions** of that extension must also be supported for the same instance or physical device.

Any device extension that has an instance extension dependency that is not enabled by
vkCreateInstance is considered to be unsupported, hence it **must** not be returned by `vkEnumerateDeviceExtensionProperties` for any `VkPhysicalDevice` child of the instance.

If a required extension has been **promoted** to another extension or to a core API version, then as a *general* rule, the dependency is also satisfied by the promoted extension or core version. This will be true so long as any features required by the original extension are also required or enabled by the promoted extension or core version. However, in some cases an extension is promoted while making some of its features optional in the promoted extension or core version. In this case, the dependency **may** not be satisfied. The only way to be certain is to look at the descriptions of the original dependency and the promoted version in the [Layers & Extensions](https://www.khronos.org/vulkan/specs/1.3-extensions/extensions.html) and [Core Revisions](https://www.khronos.org/vulkan/specs/1.3-extensions/core-revisions.html) appendices.

---

**Note**

There is metadata in `vk.xml` describing some aspects of promotion, especially `requires`, `promotedTo` and `deprecatedBy` attributes of `<extension>` tags. However, the metadata does not yet fully describe this scenario. In the future, we may extend the XML schema to describe the full set of extensions and versions satisfying a dependency.

---

### 33.6. Compatibility Guarantees (Informative)

This section is marked as informal as there is no binding responsibility on implementations of the Vulkan API - these guarantees are however a contract between the Vulkan Working Group and developers using this Specification.

#### 33.6.1. Core Versions

Each of the **major**, **minor**, and **patch versions** of the Vulkan specification provide different compatibility guarantees.

#### Patch Versions

A difference in the patch version indicates that a set of bug fixes or clarifications have been made to the Specification. Informative enums returned by Vulkan commands that will not affect the runtime behavior of a valid application may be added in a patch version (e.g. `VkVendorId`).

The specification’s patch version is strictly increasing for a given major version of the specification; any change to a specification as described above will result in the patch version being increased by 1. Patch versions are applied to all minor versions, even if a given minor version is not affected by the provoking change.

Specifications with different patch versions but the same major and minor version are **fully compatible** with each other - such that a valid application written against one will work with an implementation of another.
Note

If a patch version includes a bug fix or clarification that could have a significant impact on developer expectations, these will be highlighted in the change log. Generally the Vulkan Working Group tries to avoid these kinds of changes, instead fixing them in either an extension or core version.

Minor Versions

Changes in the minor version of the specification indicate that new functionality has been added to the core specification. This will usually include new interfaces in the header, and may also include behavior changes and bug fixes. Core functionality may be deprecated in a minor version, but will not be obsoleted or removed.

The specification’s minor version is strictly increasing for a given major version of the specification; any change to a specification as described above will result in the minor version being increased by 1. Changes that can be accommodated in a patch version will not increase the minor version.

Specifications with a lower minor version are backwards compatible with an implementation of a specification with a higher minor version for core functionality and extensions issued with the KHR vendor tag. Vendor and multi-vendor extensions are not guaranteed to remain functional across minor versions, though in general they are with few exceptions - see Obsoletion for more information.

Major Versions

A difference in the major version of specifications indicates a large set of changes which will likely include interface changes, behavioral changes, removal of deprecated functionality, and the modification, addition, or replacement of other functionality.

The specification’s major version is monotonically increasing; any change to the specification as described above will result in the major version being increased. Changes that can be accommodated in a patch or minor version will not increase the major version.

The Vulkan Working Group intends to only issue a new major version of the Specification in order to realise significant improvements to the Vulkan API that will necessarily require breaking compatibility.

A new major version will likely include a wholly new version of the specification to be issued - which could include an overhaul of the versioning semantics for the minor and patch versions. The patch and minor versions of a specification are therefore not meaningful across major versions. If a major version of the specification includes similar versioning semantics, it is expected that the patch and minor version will be reset to 0 for that major version.

33.6.2. Extensions

A KHR extension must be able to be enabled alongside any other KHR extension, and for any minor or patch version of the core Specification beyond the minimum version it requires. A multi-vendor extension should be able to be enabled alongside any KHR extension or other multi-vendor
extension, and for any minor or patch version of the core Specification beyond the minimum version it requires. A vendor extension should be able to be enabled alongside any KHR extension, multi-vendor extension, or other vendor extension from the same vendor, and for any minor or patch version of the core Specification beyond the minimum version it requires. A vendor extension may be able to be enabled alongside vendor extensions from another vendor.

The one other exception to this is if a vendor or multi-vendor extension is made obsolete by either a core version or another extension, which will be highlighted in the extension appendix.

Promotion

Extensions, or features of an extension, may be promoted to a new core version of the API, or a newer extension which an equal or greater number of implementors are in favour of.

When extension functionality is promoted, minor changes may be introduced, limited to the following:

- Naming
- Non-intrusive parameters changes
- Feature advertisement/enablement
- Combining structure parameters into larger structures
- Author ID suffixes changed or removed

Note

If extension functionality is promoted, there is no guarantee of direct compatibility, however it should require little effort to port code from the original feature to the promoted one.

The Vulkan Working Group endeavours to ensure that larger changes are marked as either deprecated or obsoleted as appropriate, and can do so retroactively if necessary.

Extensions that are promoted are listed as being promoted in their extension appendices, with reference to where they were promoted to.

When an extension is promoted, any backwards compatibility aliases which exist in the extension will not be promoted.

Note

As a hypothetical example, if the VK_KHR_surface extension were promoted to part of a future core version, the VK_COLOR_SPACE_SRGB_NONLINEAR_KHR token defined by that extension would be promoted to VK_COLOR_SPACE_SRGB_NONLINEAR. However, the VK_COLORSPACE_SRGB_NONLINEAR_KHR token aliases VK_COLOR_SPACE_SRGB_NONLINEAR_KHR. The VK_COLORSPACE_SRGB_NONLINEAR_KHR would not be promoted, because it is a backwards compatibility alias that exists only due to a naming mistake when the extension was initially published.
Deprecation

Extensions **may** be marked as deprecated when the intended use cases either become irrelevant or can be solved in other ways. Generally, a new feature will become available to solve the use case in another extension or core version of the API, but it is not guaranteed.

```
Note
Features that are intended to replace deprecated functionality have no guarantees of compatibility, and applications may require drastic modification in order to make use of the new features.
```

Extensions that are deprecated are listed as being deprecated in their extension appendices, with an explanation of the deprecation and any features that are relevant.

Obsoletion

Occasionally, an extension will be marked as obsolete if a new version of the core API or a new extension is fundamentally incompatible with it. An obsoleted extension **must** not be used with the extension or core version that obsoleted it.

Extensions that are obsoleted are listed as being obsoleted in their extension appendices, with reference to what they were obsoleted by.

Aliases

When an extension is promoted or deprecated by a newer feature, some or all of its functionality **may** be replicated into the newer feature. Rather than duplication of all the documentation and definitions, the specification instead identifies the identical commands and types as **aliases** of one another. Each alias is mentioned together with the definition it aliases, with the older aliases marked as “equivalents”. Each alias of the same command has identical behavior, and each alias of the same type has identical meaning - they can be used interchangeably in an application with no compatibility issues.

```
Note
For promoted types, the aliased extension type is semantically identical to the new core type. The C99 headers simply `typedef` the older aliases to the promoted types.
```

For promoted command aliases, however, there are two separate entry point definitions, due to the fact that the C99 ABI has no way to alias command definitions without resorting to macros. Calling via either entry point definition will produce identical behavior within the bounds of the specification, and should still invoke the same entry point in the implementation. Debug tools may use separate entry points with different debug behavior; to write the appropriate command name to an output log, for instance.
Chapter 34. Features

Features describe functionality which is not supported on all implementations. Features are properties of the physical device. Features are optional, and must be explicitly enabled before use. Support for features is reported and enabled on a per-feature basis.

Note
Features are reported via the basic VkPhysicalDeviceFeatures structure, as well as the extensible structure VkPhysicalDeviceFeatures2, which was added in the VK_KHR_get_physical_device_properties2 extension and included in Vulkan 1.1. When new features are added in future Vulkan versions or extensions, each extension should introduce one new feature structure, if needed. This structure can be added to thepNext chain of the VkPhysicalDeviceFeatures2 structure.

For convenience, new core versions of Vulkan may introduce new unified features structures for features promoted from extensions. At the same time, the extension's original features structure (if any) is also promoted to the core API, and is an alias of the extension's structure. This results in multiple names for the same feature: in the original extension's feature structure and the promoted structure alias, in the unified feature structure. When a feature was implicitly supported and enabled in the extension, but an explicit name was added during promotion, then the extension itself acts as an alias for the feature as listed in the table below.

All aliases of the same feature in the core API must be reported consistently: either all must be reported as supported, or none of them. When a promoted extension is available, any corresponding feature aliases must be supported.

Table 34. Extension Feature Aliases

<table>
<thead>
<tr>
<th>Extension</th>
<th>Feature(s)</th>
</tr>
</thead>
</table>

To query supported features, call:

```c
void vkGetPhysicalDeviceFeatures(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceFeatures* pFeatures);
```

- `physicalDevice` is the physical device from which to query the supported features.
- `pFeatures` is a pointer to a VkPhysicalDeviceFeatures structure in which the physical device features are returned. For each feature, a value of VK_TRUE specifies that the feature is supported on this physical device, and VK_FALSE specifies that the feature is not supported.

Valid Usage (Implicit)

- `physicalDevice` must be a valid VkPhysicalDevice handle
- `pFeatures` must be a valid pointer to a VkPhysicalDeviceFeatures structure
Fine-grained features used by a logical device must be enabled at VkDevice creation time. If a feature is enabled that the physical device does not support, VkDevice creation will fail and return VK_ERROR_FEATURE_NOT_PRESENT.

The fine-grained features are enabled by passing a pointer to the VkPhysicalDeviceFeatures structure via the pEnabledFeatures member of the VkDeviceCreateInfo structure that is passed into the vkCreateDevice call. If a member of pEnabledFeatures is set to VK_TRUE or VK_FALSE, then the device will be created with the indicated feature enabled or disabled, respectively. Features can also be enabled by using the VkPhysicalDeviceFeatures2 structure.

If an application wishes to enable all features supported by a device, it can simply pass in the VkPhysicalDeviceFeatures structure that was previously returned by vkGetPhysicalDeviceFeatures. To disable an individual feature, the application can set the desired member to VK_FALSE in the same structure. Setting pEnabledFeatures to NULL and not including a VkPhysicalDeviceFeatures2 in the pNext chain of VkDeviceCreateInfo is equivalent to setting all members of the structure to VK_FALSE.

Note
Some features, such as robustBufferAccess, may incur a run-time performance cost. Application writers should carefully consider the implications of enabling all supported features.

To query supported features defined by the core or extensions, call:

```c
void vkGetPhysicalDeviceFeatures2(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceFeatures2* pFeatures);
```

or the equivalent command

```c
void vkGetPhysicalDeviceFeatures2KHR(
    VkPhysicalDevice physicalDevice,
    VkPhysicalDeviceFeatures2* pFeatures);
```

- physicalDevice is the physical device from which to query the supported features.
- pFeatures is a pointer to a VkPhysicalDeviceFeatures2 structure in which the physical device features are returned.

Each structure in pFeatures and its pNext chain contains members corresponding to fine-grained features. vkGetPhysicalDeviceFeatures2 writes each member to a boolean value indicating whether that feature is supported.
Valid Usage (Implicit)

- **physicalDevice** must be a valid `VkPhysicalDevice` handle
- **pFeatures** must be a valid pointer to a `VkPhysicalDeviceFeatures2` structure

The `VkPhysicalDeviceFeatures2` structure is defined as:

```c
typedef struct VkPhysicalDeviceFeatures2 {
    VkStructureType sType;
    void* pNext;
    VkPhysicalDeviceFeatures features;
} VkPhysicalDeviceFeatures2;
```

or the equivalent

```c
typedef VkPhysicalDeviceFeatures2 VkPhysicalDeviceFeatures2KHR;
```

The `VkPhysicalDeviceFeatures2` structure is defined as:

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **features** is a `VkPhysicalDeviceFeatures` structure describing the fine-grained features of the Vulkan 1.0 API.

The `pNext` chain of this structure is used to extend the structure with features defined by extensions. This structure can be used in `vkGetPhysicalDeviceFeatures2` or can be included in the `pNext` chain of a `VkDeviceCreateInfo` structure, in which case it controls which features are enabled in the device in lieu of `pEnabledFeatures`.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2`

The `VkPhysicalDeviceFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceFeatures {
    VkBool32 robustBufferAccess;
    VkBool32 fullDrawIndexUint32;
    VkBool32 imageCubeArray;
    VkBool32 independentBlend;
    VkBool32 geometryShader;
    VkBool32 tessellationShader;
    VkBool32 sampleRateShading;
    VkBool32 dualSrcBlend;
} VkPhysicalDeviceFeatures;
```
The members of the `VkPhysicalDeviceFeatures` structure describe the following features:
• robustBufferAccess specifies that accesses to buffers are bounds-checked against the range of the buffer descriptor (as determined by VkDescriptorBufferInfo::range, VkBufferViewCreateInfo::range, or the size of the buffer). Out of bounds accesses must not cause application termination, and the effects of shader loads, stores, and atomics must conform to an implementation-dependent behavior as described below.

- A buffer access is considered to be out of bounds if any of the following are true:
  
  • The pointer was formed by OpImageTexelPointer and the coordinate is less than zero or greater than or equal to the number of whole elements in the bound range.

  • The pointer was not formed by OpImageTexelPointer and the object pointed to is not wholly contained within the bound range. This includes accesses performed via variable pointers where the buffer descriptor being accessed cannot be statically determined. Uninitialized pointers and pointers equal to OpConstantNull are treated as pointing to a zero-sized object, so all accesses through such pointers are considered to be out of bounds. Buffer accesses through buffer device addresses are not bounds-checked.

- If a SPIR-V OpLoad instruction loads a structure and the tail end of the structure is out of bounds, then all members of the structure are considered out of bounds even if the members at the end are not statically used.

- Out-of-bounds buffer loads will return any of the following values:
  
  • Values from anywhere within the memory range(s) bound to the buffer (possibly including bytes of memory past the end of the buffer, up to the end of the bound range).

  • Zero values, or (0,0,0,x) vectors for vector reads where x is a valid value represented in the type of the vector components and may be any of:
    
    • 0, 1, or the maximum representable positive integer value, for signed or unsigned integer components

    • 0.0 or 1.0, for floating-point components

- Out-of-bounds writes may modify values within the memory range(s) bound to the buffer, but must not modify any other memory.

- Out-of-bounds atomics may modify values within the memory range(s) bound to the buffer, but must not modify any other memory, and return an undefined value.

- Vertex input attributes are considered out of bounds if the offset of the attribute in the bound vertex buffer range plus the size of the attribute is greater than either:

  • vertexBufferRangeSize, if bindingStride == 0; or

  • (vertexBufferRangeSize - (vertexBufferRangeSize % bindingStride))
  
  where vertexBufferRangeSize is the byte size of the memory range bound to the vertex buffer binding and bindingStride is the byte stride of the corresponding vertex input
binding. Further, if any vertex input attribute using a specific vertex input binding is out of bounds, then all vertex input attributes using that vertex input binding for that vertex shader invocation are considered out of bounds.

- If a vertex input attribute is out of bounds, it will be assigned one of the following values:
  - Values from anywhere within the memory range(s) bound to the buffer, converted according to the format of the attribute.
  - Zero values, format converted according to the format of the attribute.
  - Zero values, or (0,0,0,x) vectors, as described above.

- If robustBufferAccess is not enabled, applications must not perform out of bounds accesses.

- fullDrawIndexUint32 specifies the full 32-bit range of indices is supported for indexed draw calls when using a VkIndexType of VK_INDEX_TYPE_UINT32. maxDrawIndexedIndexValue is the maximum index value that may be used (aside from the primitive restart index, which is always 2^{32}-1 when the VkIndexType is VK_INDEX_TYPE_UINT32). If this feature is supported, maxDrawIndexedIndexValue must be 2^{32}-1; otherwise it must be no smaller than 2^{24}-1. See maxDrawIndexedIndexValue.

- imageCubeArray specifies whether image views with a VkImageViewType of VK_IMAGE_VIEW_TYPE_CUBE_ARRAY can be created, and that the corresponding SampledCubeArray and ImageCubeArray SPIR-V capabilities can be used in shader code.

- independentBlend specifies whether the VkPipelineColorBlendAttachmentState settings are controlled independently per-attachment. If this feature is not enabled, the VkPipelineColorBlendAttachmentState settings for all color attachments must be identical. Otherwise, a different VkPipelineColorBlendAttachmentState can be provided for each bound color attachment.

- geometryShader specifies whether geometry shaders are supported. If this feature is not enabled, the VK_SHADER_STAGE_GEOMETRY_BIT and VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT enum values must not be used. This also specifies whether shader modules can declare the Geometry capability.

- tessellationShader specifies whether tessellation control and evaluation shaders are supported. If this feature is not enabled, the VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT, VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT, VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT, and VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO enum values must not be used. This also specifies whether shader modules can declare the Tessellation capability.

- sampleRateShading specifies whether Sample Shading and multisample interpolation are supported. If this feature is not enabled, the sampleShadingEnable member of the VkPipelineMultisampleStateCreateInfo structure must be set to VK_FALSE and the minSampleShading member is ignored. This also specifies whether shader modules can declare the SampleRateShading capability.

- dualSrcBlend specifies whether blend operations which take two sources are supported. If this feature is not enabled, the VK_BLEND_FACTOR_SRC1_COLOR, VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR, VK_BLEND_FACTOR_SRC1_ALPHA, and VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA enum values must not be used as source or destination blending factors. See Dual-Source Blending.
• logicOp specifies whether logic operations are supported. If this feature is not enabled, the logicOpEnable member of the VkPipelineColorBlendStateCreateInfo structure must be set to VK_FALSE, and the logicOp member is ignored.

• multiDrawIndirect specifies whether multiple draw indirect is supported. If this feature is not enabled, the drawCount parameter to the vkCmdDrawIndirect and vkCmdDrawIndexedIndirect commands must be 0 or 1. The maxDrawIndirectCount member of the VkPhysicalDeviceIndirectLimits structure must also be 1 if this feature is not supported. See maxDrawIndirectCount.

• drawIndirectFirstInstance specifies whether indirect draw calls support the firstInstance parameter. If this feature is not enabled, the firstInstance member of all VkDrawIndirectCommand and VkDrawIndexedIndirectCommand structures that are provided to the vkCmdDrawIndirect and vkCmdDrawIndexedIndirect commands must be 0.

• depthClamp specifies whether depth clamping is supported. If this feature is not enabled, the depthClampEnable member of the VkPipelineRasterizationStateCreateInfo structure must be set to VK_FALSE. Otherwise, setting depthClampEnable to VK_TRUE will enable depth clamping.

• depthBiasClamp specifies whether depth bias clamping is supported. If this feature is not enabled, the depthBiasClamp member of the VkPipelineRasterizationStateCreateInfo structure must be set to 0.0 unless the VK_DYNAMIC_STATE_DEPTH_BIAS dynamic state is enabled, and the depthBiasClamp parameter to vkCmdSetDepthBias must be set to 0.0.

• fillModeNonSolid specifies whether point and wireframe fill modes are supported. If this feature is not enabled, the VK_POLYGON_MODE_POINT and VK_POLYGON_MODE_LINE enum values must not be used.

• depthBounds specifies whether depth bounds tests are supported. If this feature is not enabled, the depthBoundsTestEnable member of the VkPipelineDepthStencilStateCreateInfo structure must be set to VK_FALSE. When depthBoundsTestEnable is set to VK_FALSE, the minDepthBounds and maxDepthBounds members of the VkPipelineDepthStencilStateCreateInfo structure are ignored.

• wideLines specifies whether lines with width other than 1.0 are supported. If this feature is not enabled, the lineWidth member of the VkPipelineRasterizationStateCreateInfo structure must be set to 1.0 unless the VK_DYNAMIC_STATE_LINE_WIDTH dynamic state is enabled, and the lineWidth parameter to vkCmdSetLineWidth must be set to 1.0. When this feature is supported, the range and granularity of supported line widths are indicated by the lineWidthRange and lineWidthGranularity members of the VkPhysicalDeviceLimits structure, respectively.

• largePoints specifies whether points with size greater than 1.0 are supported. If this feature is not enabled, only a point size of 1.0 written by a shader is supported. The range and granularity of supported point sizes are indicated by the pointSizeRange and pointSizeGranularity members of the VkPhysicalDeviceLimits structure, respectively.

• alphaToOne specifies whether the implementation is able to replace the alpha value of the color fragment output from the fragment shader with the maximum representable alpha value for fixed-point colors or 1.0 for floating-point colors. If this feature is not enabled, then the alphaToOneEnable member of the VkPipelineMultisampleStateCreateInfo structure must be set to VK_FALSE. Otherwise setting alphaToOneEnable to VK_TRUE will enable alpha-to-one behavior.

• multiViewport specifies whether more than one viewport is supported. If this feature is not enabled:
  ◦ The viewportCount and scissorCount members of the VkPipelineViewportStateCreateInfo
structure **must** be set to 1.

- The firstViewport and viewportCount parameters to the vkCmdSetViewport command **must** be set to 0 and 1, respectively.
- The firstScissor and scissorCount parameters to the vkCmdSetScissor command **must** be set to 0 and 1, respectively.

**samplerAnisotropy** specifies whether anisotropic filtering is supported. If this feature is not enabled, the anisotropyEnable member of the VkSamplerCreateInfo structure **must** be VK_FALSE.

**textureCompressionETC2** specifies whether all of the ETC2 and EAC compressed texture formats are supported. If this feature is enabled, then the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, VK_FORMAT_FEATURE_BLIT_SRC_BIT and VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT features **must** be supported in optimalTilingFeatures for the following formats:

- VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK
- VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK
- VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK
- VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK
- VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK
- VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK
- VK_FORMAT_EAC_R11_UNORM_BLOCK
- VK_FORMAT_EAC_R11_SRGB_BLOCK
- VK_FORMAT_EAC_R11G11_UNORM_BLOCK
- VK_FORMAT_EAC_R11G11_SRGB_BLOCK

To query for additional properties, or if the feature is not enabled, vkGetPhysicalDeviceFormatProperties and vkGetPhysicalDeviceImageFormatProperties **can** be used to check for supported properties of individual formats as normal.

**textureCompressionASTC_LDR** specifies whether all of the ASTC LDR compressed texture formats are supported. If this feature is enabled, then the VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, VK_FORMAT_FEATURE_BLIT_SRC_BIT and VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT features **must** be supported in optimalTilingFeatures for the following formats:

- VK_FORMAT_ASTC_4x4_UNORM_BLOCK
- VK_FORMAT_ASTC_4x4_SRGB_BLOCK
- VK_FORMAT_ASTC_5x4_UNORM_BLOCK
- VK_FORMAT_ASTC_5x4_SRGB_BLOCK
- VK_FORMAT_ASTC_5x5_UNORM_BLOCK
- VK_FORMAT_ASTC_5x5_SRGB_BLOCK
- VK_FORMAT_ASTC_6x5_UNORM_BLOCK
- VK_FORMAT_ASTC_6x5_SRGB_BLOCK
- VK_FORMAT_ASTC_6x6_UNORM_BLOCK
- VK_FORMAT_ASTC_6x6_SRGB_BLOCK
- VK_FORMAT_ASTC_8x5_UNORM_BLOCK
- VK_FORMAT_ASTC_8x5_SRGB_BLOCK
- VK_FORMAT_ASTC_8x6_UNORM_BLOCK
- VK_FORMAT_ASTC_8x6_SRGB_BLOCK
- `VK_FORMAT_ASTC_8x6_SRGB_BLOCK`
- `VK_FORMAT_ASTC_8x8_UNORM_BLOCK`
- `VK_FORMAT_ASTC_8x8_SRGB_BLOCK`
- `VK_FORMAT_ASTC_10x5_UNORM_BLOCK`
- `VK_FORMAT_ASTC_10x5_SRGB_BLOCK`
- `VK_FORMAT_ASTC_10x6_UNORM_BLOCK`
- `VK_FORMAT_ASTC_10x6_SRGB_BLOCK`
- `VK_FORMAT_ASTC_10x8_UNORM_BLOCK`
- `VK_FORMAT_ASTC_10x8_SRGB_BLOCK`
- `VK_FORMAT_ASTC_10x10_UNORM_BLOCK`
- `VK_FORMAT_ASTC_10x10_SRGB_BLOCK`
- `VK_FORMAT_ASTC_12x10_UNORM_BLOCK`
- `VK_FORMAT_ASTC_12x10_SRGB_BLOCK`
- `VK_FORMAT_ASTC_12x12_UNORM_BLOCK`
- `VK_FORMAT_ASTC_12x12_SRGB_BLOCK`

To query for additional properties, or if the feature is not enabled, `vkGetPhysicalDeviceFormatProperties` and `vkGetPhysicalDeviceImageFormatProperties` can be used to check for supported properties of individual formats as normal.

- `textureCompressionBC` specifies whether all of the BC compressed texture formats are supported. If this feature is enabled, then the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`, `VK_FORMAT_FEATURE_BLIT_SRC_BIT` and `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT` features must be supported in `optimalTilingFeatures` for the following formats:
  - `VK_FORMAT_BC1_RGB_UNORM_BLOCK`
  - `VK_FORMAT_BC1_RGB_SRGB_BLOCK`
  - `VK_FORMAT_BC1_RGBA_UNORM_BLOCK`
  - `VK_FORMAT_BC1_RGBA_SRGB_BLOCK`
  - `VK_FORMAT_BC2_UNORM_BLOCK`
  - `VK_FORMAT_BC2_SRGB_BLOCK`
  - `VK_FORMAT_BC3_UNORM_BLOCK`
  - `VK_FORMAT_BC3_SRGB_BLOCK`
  - `VK_FORMAT_BC4_UNORM_BLOCK`
  - `VK_FORMAT_BC4_SNORM_BLOCK`
  - `VK_FORMAT_BC5_UNORM_BLOCK`
  - `VK_FORMAT_BC5_SNORM_BLOCK`
  - `VK_FORMAT_BC6H_UFLOAT_BLOCK`
  - `VK_FORMAT_BC6H_SFLOAT_BLOCK`
  - `VK_FORMAT_BC7_UNORM_BLOCK`
  - `VK_FORMAT_BC7_SRGB_BLOCK`

To query for additional properties, or if the feature is not enabled, `vkGetPhysicalDeviceFormatProperties` and `vkGetPhysicalDeviceImageFormatProperties` can be used to check for supported properties of individual formats as normal.
• **occlusionQueryPrecise** specifies whether occlusion queries returning actual sample counts are supported. Occlusion queries are created in a `VkQueryPool` by specifying the `queryType` of `VK_QUERY_TYPE_OCCLUSION` in the `VkQueryPoolCreateInfo` structure which is passed to `vkCreateQueryPool`. If this feature is enabled, queries of this type can enable `VK_QUERY_CONTROL_PRECISE_BIT` in the `flags` parameter to `vkCmdBeginQuery`. If this feature is not supported, the implementation supports only boolean occlusion queries. When any samples are passed, boolean queries will return a non-zero result value, otherwise a result value of zero is returned. When this feature is enabled and `VK_QUERY_CONTROL_PRECISE_BIT` is set, occlusion queries will report the actual number of samples passed.

• **pipelineStatisticsQuery** specifies whether the pipeline statistics queries are supported. If this feature is not enabled, queries of type `VK_QUERY_TYPE_PIPELINE_STATISTICS` cannot be created, and none of the `VkQueryPipelineStatisticFlagBits` bits can be set in the `pipelineStatistics` member of the `VkQueryPoolCreateInfo` structure.

• **vertexPipelineStoresAndAtomics** specifies whether storage buffers and images support stores and atomic operations in the vertex, tessellation, and geometry shader stages. If this feature is not enabled, all storage image, storage texel buffers, and storage buffer variables used by these stages in shader modules must be decorated with the `NonWritable` decoration (or the `readonly` memory qualifier in GLSL).

• **fragmentStoresAndAtomics** specifies whether storage buffers and images support stores and atomic operations in the fragment shader stage. If this feature is not enabled, all storage image, storage texel buffers, and storage buffer variables used by the fragment stage in shader modules must be decorated with the `NonWritable` decoration (or the `readonly` memory qualifier in GLSL).

• **shaderTessellationAndGeometryPointSize** specifies whether the `PointSize` built-in decoration is available in the tessellation control, tessellation evaluation, and geometry shader stages. If this feature is not enabled, members decorated with the `PointSize` built-in decoration must not be read from or written to and all points written from a tessellation or geometry shader will have a size of 1.0. This also specifies whether shader modules can declare the `TessellationPointSize` capability for tessellation control and evaluation shaders, or if the shader modules can declare the `GeometryPointSize` capability for geometry shaders. An implementation supporting this feature must also support one or both of the `tessellationShader` or `geometryShader` features.

• **shaderImageGatherExtended** specifies whether the extended set of image gather instructions are available in shader code. If this feature is not enabled, the `OpImage*Gather` instructions do not support the `Offset` and `ConstOffsets` operands. This also specifies whether shader modules can declare the `ImageGatherExtended` capability.

• **shaderStorageImageExtendedFormats** specifies whether all the “storage image extended formats” below are supported; if this feature is supported, then the `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT` must be supported in `optimalTilingFeatures` for the following formats:
  - `VK_FORMAT_R16G16_SFLOAT`
  - `VK_FORMAT_B10G11R11_UFLOAT_PACK32`
  - `VK_FORMAT_R16_SFLOAT`
  - `VK_FORMAT_R16G16B16A16_UNORM`
  - `VK_FORMAT_A2B10G10R10_UNORM_PACK32`
  - `VK_FORMAT_R16G16_UNORM`
• VK_FORMAT_R8G8_UNORM
• VK_FORMAT_R16_UNORM
• VK_FORMAT_R8_UNORM
• VK_FORMAT_R16G16B16A16_SNORM
• VK_FORMAT_R16G16_SNORM
• VK_FORMAT_R8G8_SNORM
• VK_FORMAT_R16_SINT
• VK_FORMAT_R8_SINT
• VK_FORMAT_A2B10G10R10_UINT_PACK32
• VK_FORMAT_R16G16_UINT
• VK_FORMAT_R8G8_UINT
• VK_FORMAT_R16_UINT
• VK_FORMAT_R8_UINT

Note
shaderStorageImageExtendedFormats feature only adds a guarantee of format support, which is specified for the whole physical device. Therefore enabling or disabling the feature via vkCreateDevice has no practical effect.

To query for additional properties, or if the feature is not supported, vkGetPhysicalDeviceFormatProperties and vkGetPhysicalDeviceImageFormatProperties can be used to check for supported properties of individual formats, as usual rules allow.

VK_FORMAT_R32G32_UINT, VK_FORMAT_R32G32_SINT, and VK_FORMAT_R32G32_SFLOAT from StorageImageExtendedFormats SPIR-V capability, are already covered by core Vulkan mandatory format support.

• shaderStorageImageMultisample specifies whether multisampled storage images are supported. If this feature is not enabled, images that are created with a usage that includes VK_IMAGE_USAGE_STORAGE_BIT must be created with samples equal to VK_SAMPLE_COUNT_1_BIT. This also specifies whether shader modules can declare the StorageImageMultisample capability.

• shaderStorageImageReadWithoutFormat specifies whether storage images require a format qualifier to be specified when reading from storage images. If this feature is not enabled, the OpImageRead instruction must not have an OpTypeImage of Unknown. This also specifies whether shader modules can declare the StorageImageReadWithoutFormat capability.

• shaderStorageImageWriteWithoutFormat specifies whether storage images require a format qualifier to be specified when writing to storage images. If this feature is not enabled, the OpImageWrite instruction must not have an OpTypeImage of Unknown. This also specifies whether shader modules can declare the StorageImageWriteWithoutFormat capability.

• shaderUniformBufferArrayDynamicIndexing specifies whether arrays of uniform buffers can be
indexed by \textit{dynamically uniform} integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of \texttt{VK\_DESCRIPTOR\_TYPE\_UNIFORM\_BUFFER} or \texttt{VK\_DESCRIPTOR\_TYPE\_UNIFORM\_BUFFER\_DYNAMIC} must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the UniformBufferArrayDynamicIndexing capability.

- \texttt{shaderSampledImageArrayDynamicIndexing} specifies whether arrays of samplers or sampled images can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of \texttt{VK\_DESCRIPTOR\_TYPE\_SAMPLER}, \texttt{VK\_DESCRIPTOR\_TYPE\_COMBINED\_IMAGE\_SAMPLER}, or \texttt{VK\_DESCRIPTOR\_TYPE\_SAMPLED\_IMAGE} must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the SampledImageArrayDynamicIndexing capability.

- \texttt{shaderStorageBufferArrayDynamicIndexing} specifies whether arrays of storage buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of \texttt{VK\_DESCRIPTOR\_TYPE\_STORAGE\_BUFFER} or \texttt{VK\_DESCRIPTOR\_TYPE\_STORAGE\_BUFFER\_DYNAMIC} must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the StorageBufferArrayDynamicIndexing capability.

- \texttt{shaderStorageImageArrayDynamicIndexing} specifies whether arrays of storage images can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of \texttt{VK\_DESCRIPTOR\_TYPE\_STORAGE\_IMAGE} must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also specifies whether shader modules can declare the StorageImageArrayDynamicIndexing capability.

- \texttt{shaderClipDistance} specifies whether clip distances are supported in shader code. If this feature is not enabled, any members decorated with the \texttt{ClipDistance} built-in decoration must not be read from or written to in shader modules. This also specifies whether shader modules can declare the ClipDistance capability.

- \texttt{shaderCullDistance} specifies whether cull distances are supported in shader code. If this feature is not enabled, any members decorated with the \texttt{CullDistance} built-in decoration must not be read from or written to in shader modules. This also specifies whether shader modules can declare the CullDistance capability.

- \texttt{shaderFloat64} specifies whether 64-bit floats (doubles) are supported in shader code. If this feature is not enabled, 64-bit floating-point types must not be used in shader code. This also specifies whether shader modules can declare the Float64 capability. Declaring and using 64-bit floats is enabled for all storage classes that SPIR-V allows with the Float64 capability.

- \texttt{shaderInt64} specifies whether 64-bit integers (signed and unsigned) are supported in shader code. If this feature is not enabled, 64-bit integer types must not be used in shader code. This also specifies whether shader modules can declare the Int64 capability. Declaring and using 64-bit integers is enabled for all storage classes that SPIR-V allows with the Int64 capability.

- \texttt{shaderInt16} specifies whether 16-bit integers (signed and unsigned) are supported in shader code. If this feature is not enabled, 16-bit integer types must not be used in shader code. This also specifies whether shader modules can declare the Int16 capability. However, this only enables a subset of the storage classes that SPIR-V allows for the Int16 SPIR-V capability: Declaring and using 16-bit integers in the Private, Workgroup, and Function storage classes is enabled, while declaring them in the interface storage classes (e.g., UniformConstant, Uniform,
StorageBuffer, Input, Output, and PushConstant) is not enabled.

- **shaderResourceResidency** specifies whether image operations that return resource residency information are supported in shader code. If this feature is not enabled, the OpImageSparse* instructions must not be used in shader code. This also specifies whether shader modules can declare the SparseResidency capability. The feature requires at least one of the sparseResidency* features to be supported.

- **shaderResourceMinLod** specifies whether image operations specifying the minimum resource LOD are supported in shader code. If this feature is not enabled, the MinLod image operand must not be used in shader code. This also specifies whether shader modules can declare the MinLod capability.

- **sparseBinding** specifies whether resource memory can be managed at opaque sparse block level instead of at the object level. If this feature is not enabled, resource memory must be bound only on a per-object basis using the vkBindBufferMemory and vkBindImageMemory commands. In this case, buffers and images must not be created with VK_BUFFER_CREATE_SPARSE_BINDING_BIT and VK_IMAGE_CREATE_SPARSE_BINDING_BIT set in the flags member of the VkBufferCreateInfo and VkImageCreateInfo structures, respectively. Otherwise resource memory can be managed as described in Sparse Resource Features.

- **sparseResidencyBuffer** specifies whether the device can access partially resident buffers. If this feature is not enabled, buffers must not be created with VK_BUFFER_CREATE_SPARSE_RESIDENCY_BIT set in the flags member of the VkBufferCreateInfo structure.

- **sparseResidencyImage2D** specifies whether the device can access partially resident 2D images with 1 sample per pixel. If this feature is not enabled, images with an imageType of VK_IMAGE_TYPE_2D and samples set to VK_SAMPLE_COUNT_1_BIT must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the flags member of the VkImageCreateInfo structure.

- **sparseResidencyImage3D** specifies whether the device can access partially resident 3D images. If this feature is not enabled, images with an imageType of VK_IMAGE_TYPE_3D must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the flags member of the VkImageCreateInfo structure.

- **sparseResidency2Samples** specifies whether the physical device can access partially resident 2D images with 2 samples per pixel. If this feature is not enabled, images with an imageType of VK_IMAGE_TYPE_2D and samples set to VK_SAMPLE_COUNT_2_BIT must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the flags member of the VkImageCreateInfo structure.

- **sparseResidency4Samples** specifies whether the physical device can access partially resident 2D images with 4 samples per pixel. If this feature is not enabled, images with an imageType of VK_IMAGE_TYPE_2D and samples set to VK_SAMPLE_COUNT_4_BIT must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the flags member of the VkImageCreateInfo structure.

- **sparseResidency8Samples** specifies whether the physical device can access partially resident 2D images with 8 samples per pixel. If this feature is not enabled, images with an imageType of VK_IMAGE_TYPE_2D and samples set to VK_SAMPLE_COUNT_8_BIT must not be created with VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT set in the flags member of the VkImageCreateInfo structure.
• **sparseResidency16Samples** specifies whether the physical device can access partially resident 2D images with 16 samples per pixel. If this feature is not enabled, images with an `imageType` of `VK_IMAGE_TYPE_2D` and `samples` set to `VK_SAMPLE_COUNT_16_BIT` must not be created with `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT` set in the `flags` member of the `VkImageCreateInfo` structure.

• **sparseResidencyAliased** specifies whether the physical device can correctly access data aliased into multiple locations. If this feature is not enabled, the `VK_BUFFER_CREATE_SPARSE_ALIASED_BIT` and `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT` enum values must not be used in `flags` members of the `VkBufferCreateInfo` and `VkImageCreateInfo` structures, respectively.

• **variableMultisampleRate** specifies whether all pipelines that will be bound to a command buffer during a subpass with no attachments must have the same value for `VkPipelineMultisampleStateCreateInfo::rasterizationSamples`. If set to `VK_TRUE`, the implementation supports variable multisample rates in a subpass with no attachments. If set to `VK_FALSE`, then all pipelines bound in such a subpass must have the same multisample rate. This has no effect in situations where a subpass uses any attachments.

• **inheritedQueries** specifies whether a secondary command buffer may be executed while a query is active.

The `VkPhysicalDeviceVariablePointersFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceVariablePointersFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           variablePointersStorageBuffer;
    VkBool32           variablePointers;
} VkPhysicalDeviceVariablePointersFeatures;
```

or the equivalent

```c
typedef VkPhysicalDeviceVariablePointersFeatures
    VkPhysicalDeviceVariablePointersFeaturesKHR;
```

The members of the `VkPhysicalDeviceVariablePointersFeatures` structure describe the following features:

• **variablePointersStorageBuffer** specifies whether the implementation supports the SPIR-V `VariablePointersStorageBuffer` capability. When this feature is not enabled, shader modules must not declare the `SPV_KHR_variable_pointers` extension or the `VariablePointersStorageBuffer` capability.

• **variablePointers** specifies whether the implementation supports the SPIR-V `VariablePointers` capability. When this feature is not enabled, shader modules must not declare the `VariablePointers` capability.

If the `VkPhysicalDeviceVariablePointersFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether each feature is supported.
VkPhysicalDeviceVariablePointersFeatures can also be included in the pNext chain of VkDeviceCreateInfo to enable the features.

Valid Usage

- If variablePointers is enabled then variablePointersStorageBuffer must also be enabled.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTERS_FEATURES

The VkPhysicalDeviceMultiviewFeatures structure is defined as:

```c
typedef struct VkPhysicalDeviceMultiviewFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           multiview;
    VkBool32           multiviewGeometryShader;
    VkBool32           multiviewTessellationShader;
} VkPhysicalDeviceMultiviewFeatures;
```

or the equivalent

```c
typedef VkPhysicalDeviceMultiviewFeatures VkPhysicalDeviceMultiviewFeaturesKHR;
```

The members of the VkPhysicalDeviceMultiviewFeatures structure describe the following features:

- multiview specifies whether the implementation supports multiview rendering within a render pass. If this feature is not enabled, the view mask of each subpass must always be zero.
- multiviewGeometryShader specifies whether the implementation supports multiview rendering within a render pass, with geometry shaders. If this feature is not enabled, then a pipeline compiled against a subpass with a non-zero view mask must not include a geometry shader.
- multiviewTessellationShader specifies whether the implementation supports multiview rendering within a render pass, with tessellation shaders. If this feature is not enabled, then a pipeline compiled against a subpass with a non-zero view mask must not include any tessellation shaders.

If the VkPhysicalDeviceMultiviewFeatures structure is included in the pNext chain of VkPhysicalDeviceFeatures2, it is filled with values indicating whether each feature is supported. VkPhysicalDeviceMultiviewFeatures can also be included in the pNext chain of VkDeviceCreateInfo to enable the features.
Valid Usage

- If `multiviewGeometryShader` is enabled then `multiview` must also be enabled.
- If `multiviewTessellationShader` is enabled then `multiview` must also be enabled.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_FEATURES`

To query 64-bit atomic support for signed and unsigned integers call `vkGetPhysicalDeviceFeatures2` with a `VkPhysicalDeviceShaderAtomicInt64Features` structure included in the `pNext` chain of its `pFeatures` parameter.

The `VkPhysicalDeviceShaderAtomicInt64Features` structure is defined as:

```c
typedef struct VkPhysicalDeviceShaderAtomicInt64Features {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           shaderBufferInt64Atomics;
    VkBool32           shaderSharedInt64Atomics;
} VkPhysicalDeviceShaderAtomicInt64Features;
```

or the equivalent

```c
typedef VkPhysicalDeviceShaderAtomicInt64Features
    VkPhysicalDeviceShaderAtomicInt64FeaturesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `shaderBufferInt64Atomics` indicates whether shaders can support 64-bit unsigned and signed integer atomic operations on buffers.
- `shaderSharedInt64Atomics` indicates whether shaders can support 64-bit unsigned and signed integer atomic operations on shared memory.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES`

To query 8-bit storage features additionally supported call `vkGetPhysicalDeviceFeatures2` with a `VkPhysicalDevice8BitStorageFeatures` structure included in the `pNext` chain of its `pFeatures` parameter. The `VkPhysicalDevice8BitStorageFeatures` structure can also be included in the `pNext` chain of a `VkDeviceCreateInfo` structure, in which case it controls which additional features are
enabled in the device.

The `VkPhysicalDevice8BitStorageFeatures` structure is defined as:

```c
typedef struct VkPhysicalDevice8BitStorageFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           storageBuffer8BitAccess;
    VkBool32           uniformAndStorageBuffer8BitAccess;
    VkBool32           storagePushConstant8;
} VkPhysicalDevice8BitStorageFeatures;
```

or the equivalent

```c
typedef VkPhysicalDevice8BitStorageFeatures VkPhysicalDevice8BitStorageFeaturesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.

- `storageBuffer8BitAccess` indicates whether objects in the `StorageBuffer` or `PhysicalStorageBuffer` storage class with the `Block` decoration can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the `StorageBuffer8BitAccess` capability.

- `uniformAndStorageBuffer8BitAccess` indicates whether objects in the `Uniform` storage class with the `Block` decoration and in the `StorageBuffer` or `PhysicalStorageBuffer` storage class with the same decoration can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the `UniformAndStorageBuffer8BitAccess` capability.

- `storagePushConstant8` indicates whether objects in the `PushConstant` storage class can have 8-bit integer members. If this feature is not enabled, 8-bit integer members must not be used in such objects. This also indicates whether shader modules can declare the `StoragePushConstant8` capability.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES`

To query 16-bit storage features additionally supported call `vkGetPhysicalDeviceFeatures2` with a `VkPhysicalDevice16BitStorageFeatures` structure included in the `pNext` chain of its `pFeatures` parameter. The `VkPhysicalDevice16BitStorageFeatures` structure can also be included in the `pNext` chain of a `VkDeviceCreateInfo` structure, in which case it controls which additional features are enabled in the device.

The `VkPhysicalDevice16BitStorageFeatures` structure is defined as:
typedef struct VkPhysicalDevice16BitStorageFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           storageBuffer16BitAccess;
    VkBool32           uniformAndStorageBuffer16BitAccess;
    VkBool32           storagePushConstant16;
    VkBool32           storageInputOutput16;
} VkPhysicalDevice16BitStorageFeatures;

or the equivalent

typedef VkPhysicalDevice16BitStorageFeatures VkPhysicalDevice16BitStorageFeaturesKHR;

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.

- **storageBuffer16BitAccess** specifies whether objects in the StorageBuffer or PhysicalStorageBuffer storage class with the Block decoration can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the StorageBuffer16BitAccess capability.

- **uniformAndStorageBuffer16BitAccess** specifies whether objects in the Uniform storage class with the Block decoration and in the StorageBuffer or PhysicalStorageBuffer storage class with the same decoration can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the UniformAndStorageBuffer16BitAccess capability.

- **storagePushConstant16** specifies whether objects in the PushConstant storage class can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or floating-point members must not be used in such objects. This also specifies whether shader modules can declare the StoragePushConstant16 capability.

- **storageInputOutput16** specifies whether objects in the Input and Output storage classes can have 16-bit integer and 16-bit floating-point members. If this feature is not enabled, 16-bit integer or 16-bit floating-point members must not be used in such objects. This also specifies whether shader modules can declare the StorageInputOutput16 capability.

**Valid Usage (Implicit)**

- **sType** must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES

To query features additionally supported by the VK_KHR_shader_float16_int8 extension, call vkGetPhysicalDeviceFeatures2KHR with a VkPhysicalDeviceShaderFloat16Int8Features structure included in the pNext chain. The VkPhysicalDeviceShaderFloat16Int8Features structure can also be included in the pNext chain of a VkDeviceCreateInfo structure, in which case it controls which
additional features are enabled in the device.

The VkPhysicalDeviceShaderFloat16Int8Features structure is defined as:

```c
typedef struct VkPhysicalDeviceShaderFloat16Int8Features {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           shaderFloat16;
    VkBool32           shaderInt8;
} VkPhysicalDeviceShaderFloat16Int8Features;
```

or the equivalent

```c
typedef VkPhysicalDeviceShaderFloat16Int8Features
VkPhysicalDeviceShaderFloat16Int8FeaturesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `shaderFloat16` indicates whether 16-bit floats (halves) are supported in shader code. This also indicates whether shader modules can declare the `Float16` capability. However, this only enables a subset of the storage classes that SPIR-V allows for the `Float16` SPIR-V capability: Declaring and using 16-bit floats in the `Private`, `Workgroup`, and `Function` storage classes is enabled, while declaring them in the interface storage classes (e.g., `UniformConstant`, `Uniform`, `StorageBuffer`, `Input`, `Output`, and `PushConstant`) is not enabled.
- `shaderInt8` indicates whether 8-bit integers (signed and unsigned) are supported in shader code. This also indicates whether shader modules can declare the `Int8` capability. However, this only enables a subset of the storage classes that SPIR-V allows for the `Int8` SPIR-V capability: Declaring and using 8-bit integers in the `Private`, `Workgroup`, and `Function` storage classes is enabled, while declaring them in the interface storage classes (e.g., `UniformConstant`, `Uniform`, `StorageBuffer`, `Input`, `Output`, and `PushConstant`) is not enabled.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES`

To query shader clock support, call `vkGetPhysicalDeviceFeatures2` with a `VkPhysicalDeviceShaderClockFeaturesKHR` structure included in the `pNext` chain of its `pFeatures` parameter.

The VkPhysicalDeviceShaderClockFeaturesKHR structure is defined as:
```c
typedef struct VkPhysicalDeviceShaderClockFeaturesKHR {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           shaderSubgroupClock;
    VkBool32           shaderDeviceClock;
} VkPhysicalDeviceShaderClockFeaturesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `shaderSubgroupClock` indicates whether shaders can support Subgroup scoped clock reads.
- `shaderDeviceClock` indicates whether shaders can support Device scoped clock reads.

If the `VkPhysicalDeviceShaderClockFeaturesKHR` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether each feature is supported. `VkPhysicalDeviceShaderClockFeaturesKHR` can also be included in the `pNext` chain of `VkDeviceCreateInfo` to enable the features.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_CLOCK_FEATURES_KHR`

The `VkPhysicalDeviceSamplerYcbcrConversionFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceSamplerYcbcrConversionFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           samplerYcbcrConversion;
} VkPhysicalDeviceSamplerYcbcrConversionFeatures;
```

or the equivalent

```c
typedefVkPhysicalDeviceSamplerYcbcrConversionFeatures
VkPhysicalDeviceSamplerYcbcrConversionFeaturesKHR;
```

The members of the `VkPhysicalDeviceSamplerYcbcrConversionFeatures` structure describe the following feature:

- `samplerYcbcrConversion` specifies whether the implementation supports sampler Y′C_b C_r conversion. If `samplerYcbcrConversion` is `VK_FALSE`, sampler Y′C_b C_r conversion is not supported, and samplers using sampler Y′C_b C_r conversion must not be used.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_YCBCR_CONVERSION_FEATURES`

The `VkPhysicalDeviceProtectedMemoryFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceProtectedMemoryFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           protectedMemory;
} VkPhysicalDeviceProtectedMemoryFeatures;
```

- **protectedMemory** specifies whether protected memory is supported.

If the `VkPhysicalDeviceProtectedMemoryFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with a value indicating whether the feature is supported.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_FEATURES`

The `VkPhysicalDeviceShaderDrawParametersFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceShaderDrawParametersFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           shaderDrawParameters;
} VkPhysicalDeviceShaderDrawParametersFeatures;
```

- **shaderDrawParameters** specifies whether shader draw parameters are supported.

If the `VkPhysicalDeviceShaderDrawParametersFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with a value indicating whether the feature is supported.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DRAW_PARAMETERS_FEATURES`

To query memory model features additionally supported call `vkGetPhysicalDeviceFeatures2` with a `VkPhysicalDeviceVulkanMemoryModelFeatures` structure included in the `pNext` chain of its `pFeatures` parameter. The `VkPhysicalDeviceVulkanMemoryModelFeatures` structure can also be included in the `pNext` chain of a `VkDeviceCreateInfo` structure, in which case it controls which additional features are enabled in the device.
The `VkPhysicalDeviceVulkanMemoryModelFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceVulkanMemoryModelFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           vulkanMemoryModel;
    VkBool32           vulkanMemoryModelDeviceScope;
    VkBool32           vulkanMemoryModelAvailabilityVisibilityChains;
} VkPhysicalDeviceVulkanMemoryModelFeatures;
```

or the equivalent

```c
typedef VkPhysicalDeviceVulkanMemoryModelFeatures
VkPhysicalDeviceVulkanMemoryModelFeaturesKHR;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `vulkanMemoryModel` indicates whether the Vulkan Memory Model is supported, as defined in Vulkan Memory Model. This also indicates whether shader modules can declare the `VulkanMemoryModel` capability.
- `vulkanMemoryModelDeviceScope` indicates whether the Vulkan Memory Model can use Device scope synchronization. This also indicates whether shader modules can declare the `VulkanMemoryModelDeviceScope` capability.
- `vulkanMemoryModelAvailabilityVisibilityChains` indicates whether the Vulkan Memory Model can use availability and visibility chains with more than one element.

**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_MEMORY_MODEL_FEATURES`

The `VkPhysicalDeviceUniformBufferStandardLayoutFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceUniformBufferStandardLayoutFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           uniformBufferStandardLayout;
} VkPhysicalDeviceUniformBufferStandardLayoutFeatures;
```

or the equivalent

```c
typedef VkPhysicalDeviceUniformBufferStandardLayoutFeatures
VkPhysicalDeviceUniformBufferStandardLayoutFeaturesKHR;
```
The members of the `VkPhysicalDeviceUniformBufferStandardLayoutFeatures` structure describe the following features:

- `uniformBufferStandardLayout` indicates that the implementation supports the same layouts for uniform buffers as for storage and other kinds of buffers. See Standard Buffer Layout.

If the `VkPhysicalDeviceUniformBufferStandardLayoutFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether the feature is supported. `VkPhysicalDeviceUniformBufferStandardLayoutFeatures` can also be included in the `pNext` chain of `VkDeviceCreateInfo` to enable this feature.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_UNIFORM_BUFFER_STANDARD_LAYOUT_FEATURES`.

The `VkPhysicalDeviceBufferDeviceAddressFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceBufferDeviceAddressFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           bufferDeviceAddress;
    VkBool32           bufferDeviceAddressCaptureReplay;
    VkBool32           bufferDeviceAddressMultiDevice;
} VkPhysicalDeviceBufferDeviceAddressFeatures;
```

or the equivalent

```c
typedef VkPhysicalDeviceBufferDeviceAddressFeatures
    VkPhysicalDeviceBufferDeviceAddressFeaturesKHR;
```

The members of the `VkPhysicalDeviceBufferDeviceAddressFeatures` structure describe the following features:

- `bufferDeviceAddress` indicates that the implementation supports accessing buffer memory in shaders as storage buffers via an address queried from `vkGetBufferDeviceAddress`.
- `bufferDeviceAddressCaptureReplay` indicates that the implementation supports saving and reusing buffer and device addresses, e.g. for trace capture and replay.
- `bufferDeviceAddressMultiDevice` indicates that the implementation supports the `bufferDeviceAddress` and `rayTracing` features for logical devices created with multiple physical devices. If this feature is not supported, buffer and acceleration structure addresses must not be queried on a logical device created with more than one physical device.
bufferDeviceAddressMultiDevice exists to allow certain legacy platforms to be able to support bufferDeviceAddress without needing to support shared GPU virtual addresses for multi-device configurations.

See \texttt{vkGetBufferDeviceAddress} for more information.

If the \texttt{VkPhysicalDeviceBufferDeviceAddressFeatures} structure is included in the \texttt{pNext} chain of \texttt{VkPhysicalDeviceFeatures2}, it is filled with values indicating whether the feature is supported. \texttt{VkPhysicalDeviceBufferDeviceAddressFeatures} can also be included in the \texttt{pNext} chain of \texttt{VkDeviceCreateInfo} to enable features.

### Valid Usage (Implicit)

- \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_BUFFER_DEVICE_ADDRESS features}

The \texttt{VkPhysicalDeviceImagelessFramebufferFeatures} structure is defined as:

```c
typedef struct VkPhysicalDeviceImagelessFramebufferFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 imagelessFramebuffer;
} VkPhysicalDeviceImagelessFramebufferFeatures;
```

or the equivalent

```c
typedef VkPhysicalDeviceImagelessFramebufferFeatures
VkPhysicalDeviceImagelessFramebufferFeaturesKHR;
```

The members of the \texttt{VkPhysicalDeviceImagelessFramebufferFeatures} structure describe the following features:

- \texttt{imagelessFramebuffer} indicates that the implementation supports specifying the image view for attachments at render pass begin time via \texttt{VkRenderPassAttachmentBeginInfo}.

If the \texttt{VkPhysicalDeviceImagelessFramebufferFeatures} structure is included in the \texttt{pNext} chain of \texttt{VkPhysicalDeviceFeatures2}, it is filled with values indicating whether the feature is supported. \texttt{VkPhysicalDeviceImagelessFramebufferFeatures} can also be included in the \texttt{pNext} chain of \texttt{VkDeviceCreateInfo} to enable this feature.

### Valid Usage (Implicit)

- \texttt{sType} must be \texttt{VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGELESS_FRAMEBUFFER features}

The \texttt{VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures} structure is defined as:
The members of the `VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures` structure describe the following features:

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `shaderSubgroupExtendedTypes` is a boolean that specifies whether subgroup operations can use 8-bit integer, 16-bit integer, 64-bit integer, 16-bit floating-point, and vectors of these types in group operations with subgroup scope if the implementation supports the types.

If the `VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether each feature is supported. `VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures` can also be included in the `pNext` chain of `VkDeviceCreateInfo` to enable features.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES`

The `VkPhysicalDeviceTimelineSemaphoreFeatures` structure is defined as:

```plaintext
typedef struct VkPhysicalDeviceTimelineSemaphoreFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           timelineSemaphore;
} VkPhysicalDeviceTimelineSemaphoreFeatures;
```

or the equivalent

```plaintext
typedef VkPhysicalDeviceTimelineSemaphoreFeatures
VkPhysicalDeviceTimelineSemaphoreFeaturesKHR;
```

The `VkPhysicalDeviceTimelineSemaphoreFeatures` structure is defined as:

```plaintext
typedef struct VkPhysicalDeviceTimelineSemaphoreFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           timelineSemaphore;
} VkPhysicalDeviceTimelineSemaphoreFeatures;
```

or the equivalent

```plaintext
typedef VkPhysicalDeviceTimelineSemaphoreFeatures
VkPhysicalDeviceTimelineSemaphoreFeaturesKHR;
```
The members of the `VkPhysicalDeviceTimelineSemaphoreFeatures` structure describe the following features:

- `timelineSemaphore` indicates whether semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` are supported.

If the `VkPhysicalDeviceTimelineSemaphoreFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether each feature is supported. `VkPhysicalDeviceTimelineSemaphoreFeatures` can also be included in the `pNext` chain of `VkDeviceCreateInfo` to enable features.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_FEATURES`

The `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           separateDepthStencilLayouts;
} VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures;
```

or the equivalent

```c
typedef VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures
    VkPhysicalDeviceSeparateDepthStencilLayoutsFeaturesKHR;
```

The members of the `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures` structure describe the following features:

- `separateDepthStencilLayouts` indicates whether the implementation supports a `VkImageMemoryBarrier` for a depth/stencil image with only one of `VK_IMAGE_ASPECT_DEPTH_BIT` or `VK_IMAGE_ASPECT_STENCIL_BIT` set, and whether `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL` can be used.

If the `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether the feature is supported. `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures` can also be included in the `pNext` chain of `VkDeviceCreateInfo` to enable the feature.
Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SEPARATE_DEPTH_STENCIL_LAYOUTS_FEATURES`.

The `VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR` structure is defined as:

```c
typedef struct VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR {
    VkStructureType sType;
    void* pNext;
    VkBool32 pipelineExecutableInfo;
} VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR;
```

The members of the `VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR` structure describe the following features:

- `pipelineExecutableInfo` indicates that the implementation supports reporting properties and statistics about the executables associated with a compiled pipeline.

If the `VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether the feature is supported. `VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR` can also be included in the `pNext` chain of `VkDeviceCreateInfo` to enable features.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PIPELINE_EXECUTABLE_PROPERTIES_FEATURES_KHR`.

The `VkPhysicalDeviceRayTracingFeaturesKHR` structure is defined as:

```c
typedef struct VkPhysicalDeviceRayTracingFeaturesKHR {
    VkStructureType sType;
    void* pNext;
    VkBool32 rayTracing;
    VkBool32 rayTracingShaderGroupHandleCaptureReplay;
    VkBool32 rayTracingShaderGroupHandleCaptureReplayMixed;
    VkBool32 rayTracingAccelerationStructureCaptureReplay;
    VkBool32 rayTracingIndirectTraceRays;
    VkBool32 rayTracingIndirectAccelerationStructureBuild;
    VkBool32 rayTracingHostAccelerationStructureCommands;
    VkBool32 rayQuery;
    VkBool32 rayTracingPrimitiveCulling;
} VkPhysicalDeviceRayTracingFeaturesKHR;
```

The members of the `VkPhysicalDeviceRayTracingFeaturesKHR` structure describe the following features:
features:

- `rayTracing` indicates whether the implementation supports ray tracing functionality. See Ray Tracing.

- `rayTracingShaderGroupHandleCaptureReplay` indicates whether the implementation supports saving and reusing shader group handles, e.g. for trace capture and replay.

- `rayTracingShaderGroupHandleCaptureReplayMixed` indicates whether the implementation supports reuse of shader group handles being arbitrarily mixed with creation of non-reused shader group handles. If this is `VK_FALSE`, all reused shader group handles must be specified before any non-reused handles may be created.

- `rayTracingAccelerationStructureCaptureReplay` indicates whether the implementation supports saving and reusing acceleration structure device addresses, e.g. for trace capture and replay.

- `rayTracingIndirectTraceRays` indicates whether the implementation supports indirect trace ray commands, e.g. `vkCmdTraceRaysIndirectKHR`.

- `rayTracingIndirectAccelerationStructureBuild` indicates whether the implementation supports indirect acceleration structure build commands, e.g. `vkCmdBuildAccelerationStructureIndirectKHR`.

- `rayTracingHostAccelerationStructureCommands` indicates whether the implementation supports host side acceleration structure commands, e.g. `vkBuildAccelerationStructureKHR`, `vkCopyAccelerationStructureKHR`, `vkCopyAccelerationStructureToMemoryKHR`, `vkCopyMemoryToAccelerationStructureKHR`, `vkWriteAccelerationStructuresPropertiesKHR`.

- `rayQuery` indicates whether the implementation supports ray query (`OpRayQueryProceedKHR`) functionality.

- `rayTracingPrimitiveCulling` indicates whether the implementation supports primitive culling during ray traversal.

If the `VkPhysicalDeviceRayTracingFeaturesKHR` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether the feature is supported. `VkPhysicalDeviceRayTracingFeaturesKHR` can also be used in the `pNext` chain of `VkDeviceCreateInfo` to enable the features.

### Valid Usage

- If `rayTracingShaderGroupHandleCaptureReplayMixed` is `VK_TRUE`, `rayTracingShaderGroupHandleCaptureReplay` must also be `VK_TRUE`.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_RAY_TRACING_FEATURES_KHR`
34.1. Feature Requirements

All Vulkan graphics implementations **must** support the following features:

- robustBufferAccess
- multiview, if Vulkan 1.1 is supported.
- uniformBufferStandardLayout, if Vulkan 1.2 or the `VK_KHR_uniform_buffer_standard_layout` extension is supported.
- variablePointersStorageBuffer, if the `VK_KHR_variable_pointers` extension is supported.
- storageBuffer8BitAccess, if the `VK_KHR_8bit_storage` extension is supported.
- timelineSemaphore, if Vulkan 1.2 or the `VK_KHR_timeline_semaphore` extension is supported.
- If the `VK_KHR_ray_tracing` extension is supported:
  - rayTracing
  - rayTracingIndirectTraceRays
  - All the features required by the `[VK_EXT_descriptor_indexing]` extension.
  - bufferDeviceAddress from the `VK_KHR_buffer_device_address` extension.
  - rayTracingPrimitiveCulling, if rayQuery is supported.

All other features defined in the Specification are **optional**.
Chapter 35. Limits

*Limits* are implementation-dependent minimums, maximums, and other device characteristics that an application *may* need to be aware of.

**Note**

Limits are reported via the basic `VkPhysicalDeviceLimits` structure, as well as the extensible structure `VkPhysicalDeviceProperties2`, which was added in `VK_KHR_get_physical_device_properties2` and included in Vulkan 1.1. When limits are added in future Vulkan versions or extensions, each extension *should* introduce one new limit structure, if needed. This structure *can* be added to the `pNext` chain of the `VkPhysicalDeviceProperties2` structure.

The `VkPhysicalDeviceLimits` structure is defined as:

```c
typedef struct VkPhysicalDeviceLimits {
    uint32_t maxImageDimension1D;
    uint32_t maxImageDimension2D;
    uint32_t maxImageDimension3D;
    uint32_t maxImageDimensionCube;
    uint32_t maxImageArrayLayers;
    uint32_t maxTexelBufferElements;
    uint32_t maxUniformBufferRange;
    uint32_t maxStorageBufferRange;
    uint32_t maxPushConstantsSize;
    uint32_t maxMemoryAllocationCount;
    uint32_t maxSamplerAllocationCount;
    VkDeviceSize bufferImageGranularity;
    VkDeviceSize sparseAddressSpaceSize;
    uint32_t maxBoundDescriptorSets;
    uint32_t maxPerStageDescriptorSamplers;
    uint32_t maxPerStageDescriptorUniformBuffers;
    uint32_t maxPerStageDescriptorStorageBuffers;
    uint32_t maxPerStageDescriptorSampledImages;
    uint32_t maxPerStageDescriptorStorageImages;
    uint32_t maxPerStageDescriptorInputAttachments;
    uint32_t maxPerStageResources;
    uint32_t maxDescriptorSetSamplers;
    uint32_t maxDescriptorSetUniformBuffers;
    uint32_t maxDescriptorSetUniformBuffersDynamic;
    uint32_t maxDescriptorSetStorageBuffers;
    uint32_t maxDescriptorSetStorageBuffersDynamic;
    uint32_t maxDescriptorSetSampledImages;
    uint32_t maxDescriptorSetStorageImages;
    uint32_t maxDescriptorSetInputAttachments;
    uint32_t maxVertexInputAttributes;
    uint32_t maxVertexInputBindings;
    uint32_t maxVertexInputAttributeOffset;
    uint32_t maxVertexInputBindingStride;
} VkPhysicalDeviceLimits;
```
The **VkPhysicalDeviceLimits** are properties of the physical device. These are available in the **limits** member of the **VkPhysicalDeviceProperties** structure which is returned from **vkGetPhysicalDeviceProperties**.

- **maxImageDimension1D** is the maximum dimension (width) supported for all images created with an **imageType** of **VK_IMAGE_TYPE_1D**.

- **maxImageDimension2D** is the maximum dimension (width or height) supported for all images created with an **imageType** of **VK_IMAGE_TYPE_2D** and without **VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT** set in **flags**.

- **maxImageDimension3D** is the maximum dimension (width, height, or depth) supported for all images created with an **imageType** of **VK_IMAGE_TYPE_3D**.

- **maxImageDimensionCube** is the maximum dimension (width or height) supported for all images created with an **imageType** of **VK_IMAGE_TYPE_2D** and with **VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT** set in **flags**.

- **maxImageArrayLayers** is the maximum number of layers (arrayLayers) for an image.

- **maxTexelBufferElements** is the maximum number of addressable texels for a buffer view created on a buffer which was created with the **VK_BUFFER_USAGE_UNIFORM_TEXEL_BUFFER_BIT** or **VK_BUFFER_USAGE_STORAGE_TEXEL_BUFFER_BIT** set in the **usage** member of the **VkBufferCreateInfo** structure.

- **maxUniformBufferRange** is the maximum value that **can** be specified in the **range** member of any **VkDescriptorBufferInfo** structures passed to a call to **vkUpdateDescriptorSets** for descriptors of type **VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER** or **VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC**.
• **maxStorageBufferRange** is the maximum value that can be specified in the range member of any `VkDescriptorBufferInfo` structures passed to a call to `vkUpdateDescriptorSets` for descriptors of type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`.

• **maxPushConstantsSize** is the maximum size, in bytes, of the pool of push constant memory. For each of the push constant ranges indicated by the `pPushConstantRanges` member of the `VkPipelineLayoutCreateInfo` structure, 
  
  (offset + size) **must** be less than or equal to this limit.

• **maxMemoryAllocationCount** is the maximum number of device memory allocations, as created by `vkAllocateMemory`, which can simultaneously exist.

• **maxSamplerAllocationCount** is the maximum number of sampler objects, as created by `vkCreateSampler`, which can simultaneously exist on a device.

• **bufferImageGranularity** is the granularity, in bytes, at which buffer or linear image resources, and optimal image resources can be bound to adjacent offsets in the same `VkDeviceMemory` object without aliasing. See Buffer-Image Granularity for more details.

• **sparseAddressSpaceSize** is the total amount of address space available, in bytes, for sparse memory resources. This is an upper bound on the sum of the size of all sparse resources, regardless of whether any memory is bound to them.

• **maxBoundDescriptorSets** is the maximum number of descriptor sets that can be simultaneously used by a pipeline. All `DescriptorSet` decorations in shader modules must have a value less than `maxBoundDescriptorSets`. See Descriptor Sets.

• **maxPerStageDescriptorSamplers** is the maximum number of samplers that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` count against this limit. A descriptor is accessible to a shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See Sampler and Combined Image Sampler.

• **maxPerStageDescriptorUniformBuffers** is the maximum number of uniform buffers that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` count against this limit. A descriptor is accessible to a shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See Uniform Buffer and Dynamic Uniform Buffer.

• **maxPerStageDescriptorStorageBuffers** is the maximum number of storage buffers that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See Storage Buffer and Dynamic Storage Buffer.

• **maxPerStageDescriptorSampledImages** is the maximum number of sampled images that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, or `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See Combined Image Sampler, Sampled Image, and Uniform Texel Buffer.
• `maxPerStageDescriptorStorageImages` is the maximum number of storage images that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, or `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. See Storage Image, and Storage Texel Buffer.

• `maxPerStageDescriptorInputAttachments` is the maximum number of input attachments that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` count against this limit. A descriptor is accessible to a pipeline shader stage when the `stageFlags` member of the `VkDescriptorSetLayoutBinding` structure has the bit for that shader stage set. These are only supported for the fragment stage. See Input Attachment.

• `maxPerStageResources` is the maximum number of resources that can be accessible to a single shader stage in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`, `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER`, `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER`, `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`, `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER`, `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER`, or `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` count against this limit. For the fragment shader stage the framebuffer color attachments also count against this limit.

• `maxDescriptorSetSamplers` is the maximum number of samplers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_SAMPLER` or `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` count against this limit. See Sampler and Combined Image Sampler.

• `maxDescriptorSetUniformBuffers` is the maximum number of uniform buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` count against this limit. See Uniform Buffer and Dynamic Uniform Buffer.

• `maxDescriptorSetUniformBuffersDynamic` is the maximum number of dynamic uniform buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` count against this limit. See Dynamic Uniform Buffer.

• `maxDescriptorSetStorageBuffers` is the maximum number of storage buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` count against this limit. See Storage Buffer and Dynamic Storage Buffer.

• `maxDescriptorSetStorageBuffersDynamic` is the maximum number of dynamic storage buffers that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` count against this limit. See Dynamic Storage Buffer.

• `maxDescriptorSetSampledImages` is the maximum number of sampled images that can be included in a pipeline layout. Descriptors with a type of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, or `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` count against this limit. See Combined Image Sampler, Sampled Image, and Uniform Texel Buffer.
• **maxDescriptorSetStorageImages** is the maximum number of storage images that can be included in a pipeline layout. Descriptors with a type of **VK_DESCRIPTOR_TYPE_STORAGE_IMAGE**, or **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER** count against this limit. See Storage Image, and Storage Texel Buffer.

• **maxDescriptorSetInputAttachments** is the maximum number of input attachments that can be included in a pipeline layout. Descriptors with a type of **VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT** count against this limit. See Input Attachment.

• **maxVertexInputAttributes** is the maximum number of vertex input attributes that can be specified for a graphics pipeline. These are described in the array of **VkVertexInputAttributeDescription** structures that are provided at graphics pipeline creation time via the pVertexAttributeDescriptions member of the **VkPipelineVertexInputStateCreateInfo** structure. See Vertex Attributes and Vertex Input Description.

• **maxVertexInputBindings** is the maximum number of vertex buffers that can be specified for providing vertex attributes to a graphics pipeline. These are described in the array of **VkVertexInputBindingDescription** structures that are provided at graphics pipeline creation time via the pVertexBindingDescriptions member of the **VkPipelineVertexInputStateCreateInfo** structure. The binding member of **VkVertexInputBindingDescription** must be less than this limit. See Vertex Input Description.

• **maxVertexInputAttributeOffset** is the maximum vertex input attribute offset that can be added to the vertex input binding stride. The offset member of the **VkVertexInputAttributeDescription** structure must be less than or equal to this limit. See Vertex Input Description.

• **maxVertexInputBindingStride** is the maximum vertex input binding stride that can be specified in a vertex input binding. The stride member of the **VkVertexInputBindingDescription** structure must be less than or equal to this limit. See Vertex Input Description.

• **maxVertexOutputComponents** is the maximum number of components of output variables which can be output by a vertex shader. See Vertex Shaders.

• **maxTessellationGenerationLevel** is the maximum tessellation generation level supported by the fixed-function tessellation primitive generator. See Tessellation.

• **maxTessellationPatchSize** is the maximum patch size, in vertices, of patches that can be processed by the tessellation control shader and tessellation primitive generator. The patchControlPoints member of the **VkPipelineTessellationStateCreateInfo** structure specified at pipeline creation time and the value provided in the OutputVertices execution mode of shader modules must be less than or equal to this limit. See Tessellation.

• **maxTessellationControlPerVertexInputComponents** is the maximum number of components of input variables which can be provided as per-vertex inputs to the tessellation control shader stage.

• **maxTessellationControlPerVertexOutputComponents** is the maximum number of components of per-vertex output variables which can be output from the tessellation control shader stage.

• **maxTessellationControlPerPatchOutputComponents** is the maximum number of components of per-patch output variables which can be output from the tessellation control shader stage.

• **maxTessellationControlTotalOutputComponents** is the maximum total number of components of per-vertex and per-patch output variables which can be output from the tessellation control shader stage.
• maxTessellationEvaluationInputComponents is the maximum number of components of input variables which can be provided as per-vertex inputs to the tessellation evaluation shader stage.

• maxTessellationEvaluationOutputComponents is the maximum number of components of per-vertex output variables which can be output from the tessellation evaluation shader stage.

• maxGeometryShaderInvocations is the maximum invocation count supported for instanced geometry shaders. The value provided in the Invocations execution mode of shader modules must be less than or equal to this limit. See Geometry Shading.

• maxGeometryInputComponents is the maximum number of components of input variables which can be provided as inputs to the geometry shader stage.

• maxGeometryOutputComponents is the maximum number of components of output variables which can be output from the geometry shader stage.

• maxGeometryOutputVertices is the maximum number of vertices which can be emitted by any geometry shader.

• maxGeometryTotalOutputComponents is the maximum total number of components of output, across all emitted vertices, which can be output from the geometry shader stage.

• maxFragmentInputComponents is the maximum number of components of input variables which can be provided as inputs to the fragment shader stage.

• maxFragmentOutputAttachments is the maximum number of output attachments which can be written to by the fragment shader stage.

• maxFragmentDualSrcAttachments is the maximum number of output attachments which can be written to by the fragment shader stage when blending is enabled and one of the dual source blend modes is in use. See Dual-Source Blending and dualSrcBlend.

• maxFragmentCombinedOutputResources is the total number of storage buffers, storage images, and output buffers which can be used in the fragment shader stage.

• maxComputeSharedMemorySize is the maximum total storage size, in bytes, available for variables declared with the Workgroup storage class in shader modules (or with the shared storage qualifier in GLSL) in the compute shader stage. The amount of storage consumed by the variables declared with the Workgroup storage class is implementation-dependent. However, the amount of storage consumed may not exceed the largest block size that would be obtained if all active variables declared with Workgroup storage class were assigned offsets in an arbitrary order by successively taking the smallest valid offset according to the Standard Storage Buffer Layout rules. (This is equivalent to using the GLSL std430 layout rules.)

• maxComputeWorkGroupCount[3] is the maximum number of local workgroups that can be dispatched by a single dispatch command. These three values represent the maximum number of local workgroups for the X, Y, and Z dimensions, respectively. The workgroup count parameters to the dispatch commands must be less than or equal to the corresponding limit. See Dispatching Commands.

• maxComputeWorkGroupInvocations is the maximum total number of compute shader invocations in a single local workgroup. The product of the X, Y, and Z sizes, as specified by the LocalSize execution mode in shader modules or by the object decorated by the WorkgroupSize decoration, must be less than or equal to this limit.
• `maxComputeWorkGroupSize[3]` is the maximum size of a local compute workgroup, per dimension. These three values represent the maximum local workgroup size in the X, Y, and Z dimensions, respectively. The x, y, and z sizes, as specified by the `LocalSize` execution mode or by the object decorated by the `WorkgroupSize` decoration in shader modules, must be less than or equal to the corresponding limit.

• `subPixelPrecisionBits` is the number of bits of subpixel precision in framebuffer coordinates x, and y. See Rasterization.

• `subTexelPrecisionBits` is the number of bits of precision in the division along an axis of an image used for minification and magnification filters. 2^{subTexelPrecisionBits} is the actual number of divisions along each axis of the image represented. Sub-texel values calculated during image sampling will snap to these locations when generating the filtered results.

• `mipmapPrecisionBits` is the number of bits of division that the LOD calculation for mipmap fetching get snapped to when determining the contribution from each mip level to the mip filtered results. 2^{mipmapPrecisionBits} is the actual number of divisions.

• `maxDrawIndexedIndexValue` is the maximum index value that can be used for indexed draw calls when using 32-bit indices. This excludes the primitive restart index value of 0xFFFFFFFF. See `fullDrawIndexUint32`.

• `maxDrawIndirectCount` is the maximum draw count that is supported for indirect draw calls. See `multiDrawIndirect`.

• `maxSamplerLodBias` is the maximum absolute sampler LOD bias. The sum of the `mipLodBias` member of the `VkSamplerCreateInfo` structure and the `Bias` operand of image sampling operations in shader modules (or 0 if no `Bias` operand is provided to an image sampling operation) are clamped to the range \([-maxSamplerLodBias, +maxSamplerLodBias]\). See [samplers-mipLodBias].

• `maxSamplerAnisotropy` is the maximum degree of sampler anisotropy. The maximum degree of anisotropic filtering used for an image sampling operation is the minimum of the `maxAnisotropy` member of the `VkSamplerCreateInfo` structure and this limit. See [samplers-maxAnisotropy].

• `maxViewports` is the maximum number of active viewports. The `viewportCount` member of the `VkPipelineViewportStateCreateInfo` structure that is provided at pipeline creation must be less than or equal to this limit.

• `maxViewportDimensions[2]` are the maximum viewport dimensions in the X (width) and Y (height) dimensions, respectively. The maximum viewport dimensions must be greater than or equal to the largest image which can be created and used as a framebuffer attachment. See Controlling the Viewport.

• `viewportBoundsRange[2]` is the [minimum, maximum] range that the corners of a viewport must be contained in. This range must be at least \([-2 \times size, 2 \times size - 1]\), where \(size = \max(maxViewportDimensions[0], maxViewportDimensions[1])\). See Controlling the Viewport.
The intent of the `viewportBoundsRange` limit is to allow a maximum sized viewport to be arbitrarily shifted relative to the output target as long as at least some portion intersects. This would give a bounds limit of \([-\text{size} + 1, 2 \times \text{size} - 1]\) which would allow all possible non-empty-set intersections of the output target and the viewport. Since these numbers are typically powers of two, picking the signed number range using the smallest possible number of bits ends up with the specified range.

- `viewportSubPixelBits` is the number of bits of subpixel precision for viewport bounds. The subpixel precision that floating-point viewport bounds are interpreted at is given by this limit.

- `minMemoryMapAlignment` is the minimum required alignment, in bytes, of host visible memory allocations within the host address space. When mapping a memory allocation with `vkMapMemory`, subtracting `offset` bytes from the returned pointer will always produce an integer multiple of this limit. See Host Access to Device Memory Objects.

- `minTexelBufferOffsetAlignment` is the minimum required alignment, in bytes, for the `offset` member of the `VkBufferViewCreateInfo` structure for texel buffers. `VkBufferViewCreateInfo::offset` must be a multiple of this value.

- `minUniformBufferOffsetAlignment` is the minimum required alignment, in bytes, for the `offset` member of the `VkDescriptorBufferInfo` structure for uniform buffers. When a descriptor of type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` is updated, the `offset` must be an integer multiple of this limit. Similarly, dynamic offsets for uniform buffers must be multiples of this limit.

- `minStorageBufferOffsetAlignment` is the minimum required alignment, in bytes, for the `offset` member of the `VkDescriptorBufferInfo` structure for storage buffers. When a descriptor of type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` is updated, the `offset` must be an integer multiple of this limit. Similarly, dynamic offsets for storage buffers must be multiples of this limit.

- `minTexelOffset` is the minimum offset value for the `ConstOffset` image operand of any of the `OpImageSample*` or `OpImageFetch*` image instructions.

- `maxTexelOffset` is the maximum offset value for the `ConstOffset` image operand of any of the `OpImageSample*` or `OpImageFetch*` image instructions.

- `minTexelGatherOffset` is the minimum offset value for the `Offset`, `ConstOffset`, or `ConstOffsets` image operands of any of the `OpImage*Gather` image instructions.

- `maxTexelGatherOffset` is the maximum offset value for the `Offset`, `ConstOffset`, or `ConstOffsets` image operands of any of the `OpImage*Gather` image instructions.

- `minInterpolationOffset` is the minimum negative offset value for the `offset` operand of the `InterpolateAtOffset` extended instruction.

- `maxInterpolationOffset` is the maximum positive offset value for the `offset` operand of the `InterpolateAtOffset` extended instruction.

- `subPixelInterpolationOffsetBits` is the number of subpixel fractional bits that the x and y offsets to the `InterpolateAtOffset` extended instruction may be rounded to as fixed-point values.

- `maxFramebufferWidth` is the maximum width for a framebuffer. The `width` member of the
VkFramebufferCreateInfo structure must be less than or equal to this limit.

- maxFramebufferHeight is the maximum height for a framebuffer. The height member of the VkFramebufferCreateInfo structure must be less than or equal to this limit.

- maxFramebufferLayers is the maximum layer count for a layered framebuffer. The layers member of the VkFramebufferCreateInfo structure must be less than or equal to this limit.

- framebufferColorSampleCounts is a bitmask of VkSampleCountFlagBits indicating the color sample counts that are supported for all framebuffer color attachments with floating- or fixed-point formats. There is no limit that specifies the color sample counts that are supported for all color attachments with integer formats.

- framebufferDepthSampleCounts is a bitmask of VkSampleCountFlagBits indicating the supported depth sample counts for all framebuffer depth/stencil attachments, when the format includes a depth component.

- framebufferStencilSampleCounts is a bitmask of VkSampleCountFlagBits indicating the supported stencil sample counts for all framebuffer depth/stencil attachments, when the format includes a stencil component.

- framebufferNoAttachmentsSampleCounts is a bitmask of VkSampleCountFlagBits indicating the supported sample counts for a framebuffer with no attachments.

- maxColorAttachments is the maximum number of color attachments that can be used by a subpass in a render pass. The colorAttachmentCount member of the VkSubpassDescription structure must be less than or equal to this limit.

- sampledImageColorSampleCounts is a bitmask of VkSampleCountFlagBits indicating the sample counts supported for all 2D images created with VK_IMAGE_TILING_OPTIMAL, usage containing VK_IMAGE_USAGE_SAMPLED_BIT, and a non-integer color format.

- sampledImageIntegerSampleCounts is a bitmask of VkSampleCountFlagBits indicating the sample counts supported for all 2D images created with VK_IMAGE_TILING_OPTIMAL, usage containing VK_IMAGE_USAGE_SAMPLED_BIT, and an integer color format.

- sampledImageDepthSampleCounts is a bitmask of VkSampleCountFlagBits indicating the sample counts supported for all 2D images created with VK_IMAGE_TILING_OPTIMAL, usage containing VK_IMAGE_USAGE_SAMPLED_BIT, and a depth format.

- sampledImageStencilSampleCounts is a bitmask of VkSampleCountFlagBits indicating the sample supported for all 2D images created with VK_IMAGE_TILING_OPTIMAL, usage containing VK_IMAGE_USAGE_SAMPLED_BIT, and a stencil format.

- storageImageSampleCounts is a bitmask of VkSampleCountFlagBits indicating the sample counts supported for all 2D images created with VK_IMAGE_TILING_OPTIMAL, and usage containing VK_IMAGE_USAGE_STORAGE_BIT.

- maxSampleMaskWords is the maximum number of array elements of a variable decorated with the SampleMask built-in decoration.

- timestampComputeAndGraphics specifies support for timestamps on all graphics and compute queues. If this limit is set to VK_TRUE, all queues that advertise the VK_QUEUE_GRAPHICS_BIT or VK_QUEUE_COMPUTE_BIT in the VkQueueFamilyProperties::queueFlags support VkQueueFamilyProperties::timestampValidBits of at least 36. See Timestamp Queries.

- timestampPeriod is the number of nanoseconds required for a timestamp query to be
incremented by 1. See Timestamp Queries.

- maxClipDistances is the maximum number of clip distances that can be used in a single shader stage. The size of any array declared with the ClipDistance built-in decoration in a shader module must be less than or equal to this limit.

- maxCullDistances is the maximum number of cull distances that can be used in a single shader stage. The size of any array declared with the CullDistance built-in decoration in a shader module must be less than or equal to this limit.

- maxCombinedClipAndCullDistances is the maximum combined number of clip and cull distances that can be used in a single shader stage. The sum of the sizes of any pair of arrays declared with the ClipDistance and CullDistance built-in decoration used by a single shader stage in a shader module must be less than or equal to this limit.

- discreteQueuePriorities is the number of discrete priorities that can be assigned to a queue based on the value of each member of VkDeviceQueueCreateInfo::pQueuePriorities. This must be at least 2, and levels must be spread evenly over the range, with at least one level at 1.0, and another at 0.0. See Queue Priority.

- pointSizeRange[2] is the range [minimum, maximum] of supported sizes for points. Values written to variables decorated with the PointSize built-in decoration are clamped to this range.

- lineWidthRange[2] is the range [minimum, maximum] of supported widths for lines. Values specified by the lineWidth member of the VkPipelineRasterizationStateCreateInfo or the lineWidth parameter to vkCmdSetLineWidth are clamped to this range.

- pointSizeGranularity is the granularity of supported point sizes. Not all point sizes in the range defined by pointSizeRange are supported. This limit specifies the granularity (or increment) between successive supported point sizes.

- lineWidthGranularity is the granularity of supported line widths. Not all line widths in the range defined by lineWidthRange are supported. This limit specifies the granularity (or increment) between successive supported line widths.

- strictLines specifies whether lines are rasterized according to the preferred method of rasterization. If set to VK_FALSE, lines may be rasterized under a relaxed set of rules. If set to VK_TRUE, lines are rasterized as per the strict definition. See Basic Line Segment Rasterization.

- standardSampleLocations specifies whether rasterization uses the standard sample locations as documented in Multisampling. If set to VK_TRUE, the implementation uses the documented sample locations. If set to VK_FALSE, the implementation may use different sample locations.

- optimalBufferCopyOffsetAlignment is the optimal buffer offset alignment in bytes for vkCmdCopyBufferToImage and vkCmdCopyImageToBuffer. The per texel alignment requirements are enforced, but applications should use the optimal alignment for optimal performance and power use.

- optimalBufferCopyRowPitchAlignment is the optimal buffer row pitch alignment in bytes for vkCmdCopyBufferToImage and vkCmdCopyImageToBuffer. Row pitch is the number of bytes between texels with the same X coordinate in adjacent rows (Y coordinates differ by one). The per texel alignment requirements are enforced, but applications should use the optimal alignment for optimal performance and power use.

- nonCoherentAtomSize is the size and alignment in bytes that bounds concurrent access to host-mapped device memory.
For all bitmasks of `VkSampleCountFlagBits`, the sample count limits defined above represent the minimum supported sample counts for each image type. Individual images may support additional sample counts, which are queried using `vkGetPhysicalDeviceImageFormatProperties` as described in Supported Sample Counts.

Bits which may be set in the sample count limits returned by `VkPhysicalDeviceLimits`, as well as in other queries and structures representing image sample counts, are:

```plaintext
typedef enum VkSampleCountFlagBits {
    VK_SAMPLE_COUNT_1_BIT = 0x00000001,
    VK_SAMPLE_COUNT_2_BIT = 0x00000002,
    VK_SAMPLE_COUNT_4_BIT = 0x00000004,
    VK_SAMPLE_COUNT_8_BIT = 0x00000008,
    VK_SAMPLE_COUNT_16_BIT = 0x00000010,
    VK_SAMPLE_COUNT_32_BIT = 0x00000020,
    VK_SAMPLE_COUNT_64_BIT = 0x00000040,
    VK_SAMPLE_COUNT_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSampleCountFlagBits;
```

- `VK_SAMPLE_COUNT_1_BIT` specifies an image with one sample per pixel.
- `VK_SAMPLE_COUNT_2_BIT` specifies an image with 2 samples per pixel.
- `VK_SAMPLE_COUNT_4_BIT` specifies an image with 4 samples per pixel.
- `VK_SAMPLE_COUNT_8_BIT` specifies an image with 8 samples per pixel.
- `VK_SAMPLE_COUNT_16_BIT` specifies an image with 16 samples per pixel.
- `VK_SAMPLE_COUNT_32_BIT` specifies an image with 32 samples per pixel.
- `VK_SAMPLE_COUNT_64_BIT` specifies an image with 64 samples per pixel.

```plaintext
typedef VkFlags VkSampleCountFlags;
```

`VkSampleCountFlags` is a bitmask type for setting a mask of zero or more `VkSampleCountFlagBits`.

The `VkPhysicalDevicePushDescriptorPropertiesKHR` structure is defined as:

```plaintext
typedef struct VkPhysicalDevicePushDescriptorPropertiesKHR {
    VkStructureType     sType;
    void*               pNext;
    uint32_t            maxPushDescriptors;
} VkPhysicalDevicePushDescriptorPropertiesKHR;
```

The members of the `VkPhysicalDevicePushDescriptorPropertiesKHR` structure describe the following implementation-dependent limits:

- `sType` is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.

• `maxPushDescriptors` is the maximum number of descriptors that **can** be used in a descriptor set created with `VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR` set.

If the `VkPhysicalDevicePushDescriptorPropertiesKHR` structure is included in the `pNext` chain of `VkPhysicalDeviceProperties2`, it is filled with the implementation-dependent limits.

### Valid Usage (Implicit)

• `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PUSH_DESCRIPTOR_PROPERTIES_KHR`

The `VkPhysicalDeviceMultiviewProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceMultiviewProperties {
    VkStructureType    sType;
    void*              pNext;
    uint32_t           maxMultiviewViewCount;
    uint32_t           maxMultiviewInstanceIndex;
} VkPhysicalDeviceMultiviewProperties;
```

or the equivalent

```c
typedef VkPhysicalDeviceMultiviewProperties VkPhysicalDeviceMultiviewPropertiesKHR;
```

The members of the `VkPhysicalDeviceMultiviewProperties` structure describe the following implementation-dependent limits:

• `sType` is the type of this structure.

• `pNext` is `NULL` or a pointer to an extension-specific structure.

• `maxMultiviewViewCount` is one greater than the maximum view index that **can** be used in a subpass.

• `maxMultiviewInstanceIndex` is the maximum valid value of instance index allowed to be generated by a drawing command recorded within a subpass of a multiview render pass instance.

If the `VkPhysicalDeviceMultiviewProperties` structure is included in the `pNext` chain of `VkPhysicalDeviceProperties2`, it is filled with the implementation-dependent limits.

### Valid Usage (Implicit)

• `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_PROPERTIES`

The `VkPhysicalDeviceFloatControlsProperties` structure is defined as:

```c
```
typedef struct VkPhysicalDeviceFloatControlsProperties {
    VkStructureType                      sType;
    void*                                pNext;
    VkShaderFloatControlsIndependence    denormBehaviorIndependence;
    VkShaderFloatControlsIndependence    roundingModeIndependence;
    VkBool32                             shaderSignedZeroInfNanPreserveFloat16;
    VkBool32                             shaderSignedZeroInfNanPreserveFloat32;
    VkBool32                             shaderSignedZeroInfNanPreserveFloat64;
    VkBool32                             shaderDenormPreserveFloat16;
    VkBool32                             shaderDenormPreserveFloat32;
    VkBool32                             shaderDenormPreserveFloat64;
    VkBool32                             shaderDenormFlushToZeroFloat16;
    VkBool32                             shaderDenormFlushToZeroFloat32;
    VkBool32                             shaderDenormFlushToZeroFloat64;
    VkBool32                             shaderRoundingModeRTEFloat16;
    VkBool32                             shaderRoundingModeRTEFloat32;
    VkBool32                             shaderRoundingModeRTEFloat64;
    VkBool32                             shaderRoundingModeRTZFloat16;
    VkBool32                             shaderRoundingModeRTZFloat32;
    VkBool32                             shaderRoundingModeRTZFloat64;
} VkPhysicalDeviceFloatControlsProperties;

or the equivalent

typedef VkPhysicalDeviceFloatControlsProperties
VkPhysicalDeviceFloatControlsPropertiesKHR;

The members of the VkPhysicalDeviceFloatControlsProperties structure describe the following implementation-dependent limits:

- **denormBehaviorIndependence** is a VkShaderFloatControlsIndependence value indicating whether, and how, denorm behavior can be set independently for different bit widths.

- **roundingModeIndependence** is a VkShaderFloatControlsIndependence value indicating whether, and how, rounding modes can be set independently for different bit widths.

- **shaderSignedZeroInfNanPreserveFloat16** is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 16-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 16-bit floating-point types.

- **shaderSignedZeroInfNanPreserveFloat32** is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 32-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 32-bit floating-point types.

- **shaderSignedZeroInfNanPreserveFloat64** is a boolean value indicating whether sign of a zero, Nans and ±∞ can be preserved in 64-bit floating-point computations. It also indicates whether the SignedZeroInfNanPreserve execution mode can be used for 64-bit floating-point types.

- **shaderDenormPreserveFloat16** is a boolean value indicating whether denormals can be preserved in 16-bit floating-point computations. It also indicates whether the DenormPreserve execution
mode can be used for 16-bit floating-point types.

- shaderDenormPreserveFloat32 is a boolean value indicating whether denormals can be preserved in 32-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 32-bit floating-point types.

- shaderDenormPreserveFloat64 is a boolean value indicating whether denormals can be preserved in 64-bit floating-point computations. It also indicates whether the DenormPreserve execution mode can be used for 64-bit floating-point types.

- shaderDenormFlushToZeroFloat16 is a boolean value indicating whether denormals can be flushed to zero in 16-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 16-bit floating-point types.

- shaderDenormFlushToZeroFloat32 is a boolean value indicating whether denormals can be flushed to zero in 32-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 32-bit floating-point types.

- shaderDenormFlushToZeroFloat64 is a boolean value indicating whether denormals can be flushed to zero in 64-bit floating-point computations. It also indicates whether the DenormFlushToZero execution mode can be used for 64-bit floating-point types.

- shaderRoundingModeRTEFloat16 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 16-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 16-bit floating-point types.

- shaderRoundingModeRTEFloat32 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 32-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 32-bit floating-point types.

- shaderRoundingModeRTEFloat64 is a boolean value indicating whether an implementation supports the round-to-nearest-even rounding mode for 64-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTE execution mode can be used for 64-bit floating-point types.

- shaderRoundingModeRTZFloat16 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 16-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 16-bit floating-point types.

- shaderRoundingModeRTZFloat32 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 32-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 32-bit floating-point types.

- shaderRoundingModeRTZFloat64 is a boolean value indicating whether an implementation supports the round-towards-zero rounding mode for 64-bit floating-point arithmetic and conversion instructions. It also indicates whether the RoundingModeRTZ execution mode can be used for 64-bit floating-point types.

If the VkPhysicalDeviceFloatControlsProperties structure is included in the pNext chain of VkPhysicalDeviceProperties2, it is filled with the implementation-dependent limits.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES`

Values which **may** be returned in the `denormBehaviorIndependence` and `roundingModeIndependence` fields of `VkPhysicalDeviceFloatControlsProperties` are:

```c
typedef enum VkShaderFloatControlsIndependence {
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY = 0,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_ALL = 1,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE = 2,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY_KHR =
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_ALL_KHR =
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_ALL,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE_KHR =
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE,
    VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_MAX_ENUM = 0x7FFFFFFF
} VkShaderFloatControlsIndependence;
```

- **VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY** specifies that shader float controls for 32-bit floating point can be set independently; other bit widths must be set identically to each other.
- **VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_ALL** specifies that shader float controls for all bit widths can be set independently.
- **VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE** specifies that shader float controls for all bit widths must be set identically.

The `VkPhysicalDevicePointClippingProperties` structure is defined as:

```c
typedef struct VkPhysicalDevicePointClippingProperties {
    VkStructureType            sType;
    void*                      pNext;
    VkPointClippingBehavior    pointClippingBehavior;
} VkPhysicalDevicePointClippingProperties;
```

or the equivalent

```c
typedef VkPhysicalDevicePointClippingProperties
    VkPhysicalDevicePointClippingPropertiesKHR;
```

The members of the `VkPhysicalDevicePointClippingProperties` structure describe the following implementation-dependent limit:

- **sType** is the type of this structure.
• **pNext** is NULL or a pointer to an extension-specific structure.

• **pointClippingBehavior** is a `VkPointClippingBehavior` value specifying the point clipping behavior supported by the implementation.

If the `VkPhysicalDevicePointClippingProperties` structure is included in the **pNext** chain of `VkPhysicalDeviceProperties2`, it is filled with the implementation-dependent limits.

### Valid Usage (Implicit)

• **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_POINT_CLIPPING_PROPERTIES`  

The `VkPhysicalDeviceSubgroupProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceSubgroupProperties {
    VkStructureType           sType;
    void*                     pNext;
    uint32_t                  subgroupSize;
    VkShaderStageFlags        supportedStages;
    VkSubgroupFeatureFlags    supportedOperations;
    VkBool32                  quadOperationsInAllStages;
} VkPhysicalDeviceSubgroupProperties;
```

The members of the `VkPhysicalDeviceSubgroupProperties` structure describe the following implementation-dependent limits:

• **sType** is the type of this structure.

• **pNext** is NULL or a pointer to an extension-specific structure.

• **subgroupSize** is the default number of invocations in each subgroup. **subgroupSize** is at least 1 if any of the physical device's queues support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`. **subgroupSize** is a power-of-two.

• **supportedStages** is a bitfield of `VkShaderStageFlagBits` describing the shader stages that group operations with subgroup scope are supported in. **supportedStages** will have the `VK_SHADER_STAGE_COMPUTE_BIT` bit set if any of the physical device's queues support `VK_QUEUE_COMPUTE_BIT`.

• **supportedOperations** is a bitmask of `VkSubgroupFeatureFlagBits` specifying the sets of group operations with subgroup scope supported on this device. **supportedOperations** will have the `VK_SUBGROUP_FEATURE_BASIC_BIT` bit set if any of the physical device's queues support `VK_QUEUE_GRAPHICS_BIT` or `VK_QUEUE_COMPUTE_BIT`.

• **quadOperationsInAllStages** is a boolean specifying whether quad group operations are available in all stages, or are restricted to fragment and compute stages.

If the `VkPhysicalDeviceSubgroupProperties` structure is included in the **pNext** chain of `VkPhysicalDeviceProperties2`, it is filled with the implementation-dependent limits.
If `supportedOperations` includes `VK_SUBGROUP_FEATURE_QUAD_BIT`, `subgroupSize` must be greater than or equal to 4.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_PROPERTIES`.

Bits which can be set in `VkPhysicalDeviceSubgroupProperties::supportedOperations` to specify supported group operations with subgroup scope are:

```c
typedef enum VkSubgroupFeatureFlagBits {
    VK_SUBGROUP_FEATURE_BASIC_BIT = 0x00000001,
    VK_SUBGROUP_FEATURE_VOTE_BIT = 0x00000002,
    VK_SUBGROUP_FEATURE_ARITHMETIC_BIT = 0x00000004,
    VK_SUBGROUP_FEATURE_BALLOT_BIT = 0x00000008,
    VK_SUBGROUP_FEATURE_SHUFFLE_BIT = 0x00000010,
    VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT = 0x00000020,
    VK_SUBGROUP_FEATURE_CLUSTERED_BIT = 0x00000040,
    VK_SUBGROUP_FEATURE_QUAD_BIT = 0x00000080,
    VK_SUBGROUP_FEATURE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSubgroupFeatureFlagBits;
```

- `VK_SUBGROUP_FEATURE_BASIC_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniform` capability.
- `VK_SUBGROUP_FEATURE_VOTE_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformVote` capability.
- `VK_SUBGROUP_FEATURE_ARITHMETIC_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformArithmetic` capability.
- `VK_SUBGROUP_FEATURE_BALLOT_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformBallot` capability.
- `VK_SUBGROUP_FEATURE_SHUFFLE_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformShuffle` capability.
- `VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformShuffleRelative` capability.
- `VK_SUBGROUP_FEATURE_CLUSTERED_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformClustered` capability.
- `VK_SUBGROUP_FEATURE_QUAD_BIT` specifies the device will accept SPIR-V shader modules containing the `GroupNonUniformQuad` capability.

```c
typedef VkFlags VkSubgroupFeatureFlags;
```

`VkSubgroupFeatureFlags` is a bitmask type for setting a mask of zero or more `VkSubgroupFeatureFlagBits`. 
The `VkPhysicalDeviceProtectedMemoryProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceProtectedMemoryProperties {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           protectedNoFault;
} VkPhysicalDeviceProtectedMemoryProperties;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `protectedNoFault` specifies the behavior of the implementation when protected memory access rules are broken. If `protectedNoFault` is `VK_TRUE`, breaking those rules will not result in process termination or device loss.

If the `VkPhysicalDeviceProtectedMemoryProperties` structure is included in the `pNext` chain of `VkPhysicalDeviceProperties2`, it is filled with a value indicating the implementation-dependent behavior.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_PROPERTIES`

The `VkPhysicalDeviceMaintenance3Properties` structure is defined as:

```c
typedef struct VkPhysicalDeviceMaintenance3Properties {
    VkStructureType    sType;
    void*              pNext;
    uint32_t           maxPerSetDescriptors;
    VkDeviceSize       maxMemoryAllocationSize;
} VkPhysicalDeviceMaintenance3Properties;
```

or the equivalent

```c
typedef VkPhysicalDeviceMaintenance3Properties
VkPhysicalDeviceMaintenance3PropertiesKHR;
```

The members of the `VkPhysicalDeviceMaintenance3Properties` structure describe the following implementation-dependent limits:

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `maxPerSetDescriptors` is a maximum number of descriptors (summed over all descriptor types) in a single descriptor set that is guaranteed to satisfy any implementation-dependent
constraints on the size of a descriptor set itself. Applications can query whether a descriptor set that goes beyond this limit is supported using vkGetDescriptorSetLayoutSupport.

- `maxMemoryAllocationSize` is the maximum size of a memory allocation that can be created, even if there is more space available in the heap.

If the `VkPhysicalDeviceMaintenance3Properties` structure is included in the `pNext` chain of `VkPhysicalDeviceProperties2`, it is filled with the implementation-dependent limits.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES`

The `VkPhysicalDeviceDepthStencilResolveProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceDepthStencilResolveProperties {
    VkStructureType sType;
    void* pNext;
    VkResolveModeFlags supportedDepthResolveModes;
    VkResolveModeFlags supportedStencilResolveModes;
    VkBool32 independentResolveNone;
    VkBool32 independentResolve;
} VkPhysicalDeviceDepthStencilResolveProperties;
```

or the equivalent

```c
typedef VkPhysicalDeviceDepthStencilResolveProperties
VkPhysicalDeviceDepthStencilResolvePropertiesKHR;
```

The members of the `VkPhysicalDeviceDepthStencilResolveProperties` structure describe the following implementation-dependent limits:

- `supportedDepthResolveModes` is a bitmask of `VkResolveModeFlagBits` indicating the set of supported depth resolve modes. `VK_RESOLVE_MODE_SAMPLE_ZERO_BIT` must be included in the set but implementations may support additional modes.

- `supportedStencilResolveModes` is a bitmask of `VkResolveModeFlagBits` indicating the set of supported stencil resolve modes. `VK_RESOLVE_MODE_SAMPLE_ZERO_BIT` must be included in the set but implementations may support additional modes. `VK_RESOLVE_MODE_AVERAGE_BIT` must not be included in the set.

- `independentResolveNone` is `VK_TRUE` if the implementation supports setting the depth and stencil resolve modes to different values when one of those modes is `VK_RESOLVE_MODE_NONE`. Otherwise the implementation only supports setting both modes to the same value.

- `independentResolve` is `VK_TRUE` if the implementation supports all combinations of the supported depth and stencil resolve modes, including setting either depth or stencil resolve mode to `VK_RESOLVE_MODE_NONE`. An implementation that supports `independentResolve` must also support `independentResolveNone`. 
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DEPTH_STENCIL_RESOLVE_PROPERTIES`

The `VkPhysicalDevicePerformanceQueryFeaturesKHR` structure is defined as:

```c
typedef struct VkPhysicalDevicePerformanceQueryFeaturesKHR {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           performanceCounterQueryPools;
    VkBool32           performanceCounterMultipleQueryPools;
} VkPhysicalDevicePerformanceQueryFeaturesKHR;
```

The members of the `VkPhysicalDevicePerformanceQueryFeaturesKHR` structure describe the following implementation-dependent features:

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **performanceCounterQueryPools** is `VK_TRUE` if the physical device supports performance counter query pools.
- **performanceCounterMultipleQueryPools** is `VK_TRUE` if the physical device supports using multiple performance query pools in a primary command buffer and secondary command buffers executed within it.

Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PERFORMANCE_QUERY_FEATURES_KHR`

To query supported performance counter query pool features, call `vkGetPhysicalDeviceFeatures2` with a `VkPhysicalDevicePerformanceQueryFeaturesKHR` structure included in the `pNext` chain of its `pFeatures` parameter. The `VkPhysicalDevicePerformanceQueryFeaturesKHR` structure can also be included in the `pNext` chain of a `VkDeviceCreateInfo` structure, in which case it controls which additional features are enabled in the device.

The `VkPhysicalDevicePerformanceQueryPropertiesKHR` structure is defined as:

```c
typedef struct VkPhysicalDevicePerformanceQueryPropertiesKHR {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           allowCommandBufferQueryCopies;
} VkPhysicalDevicePerformanceQueryPropertiesKHR;
```

The members of the `VkPhysicalDevicePerformanceQueryPropertiesKHR` structure describe the following implementation-dependent properties:
• `sType` is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.
• `allowCommandBufferQueryCopies` is `VK_TRUE` if the performance query pools are allowed to be used with `vkCmdCopyQueryPoolResults`.

Valid Usage (Implicit)

• `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PERFORMANCE_QUERY_PROPERTIES_KHR`

If the `VkPhysicalDevicePerformanceQueryPropertiesKHR` structure is included in the `pNext` chain of `VkPhysicalDeviceProperties2`, it is filled with the implementation-dependent properties.

The `VkPhysicalDeviceRayTracingPropertiesKHR` structure is defined as:

```c
typedef struct VkPhysicalDeviceRayTracingPropertiesKHR {
    VkStructureType    sType;
    void*              pNext;
    uint32_t           shaderGroupHandleSize;
    uint32_t           maxRecursionDepth;
    uint32_t           maxShaderGroupStride;
    uint32_t           shaderGroupBaseAlignment;
    uint64_t           maxGeometryCount;
    uint64_t           maxInstanceCount;
    uint64_t           maxPrimitiveCount;
    uint32_t           maxDescriptorSetAccelerationStructures;
    uint32_t           shaderGroupHandleCaptureReplaySize;
} VkPhysicalDeviceRayTracingPropertiesKHR;
```

• `sType` is the type of this structure.
• `pNext` is `NULL` or a pointer to an extension-specific structure.
• `shaderGroupHandleSize` size in bytes of the shader header.
• `maxRecursionDepth` is the maximum number of levels of recursion allowed in a trace command.
• `maxShaderGroupStride` is the maximum stride in bytes allowed between shader groups in the SBT.
• `shaderGroupBaseAlignment` is the required alignment in bytes for the base of the SBTs.
• `maxGeometryCount` is the maximum number of geometries in the bottom level acceleration structure.
• `maxInstanceCount` is the maximum number of instances in the top level acceleration structure.
• `maxPrimitiveCount` is the maximum number of triangles or AABBs in all geometries in the bottom level acceleration structure.
• `maxDescriptorSetAccelerationStructures` is the maximum number of acceleration structure descriptors that are allowed in a descriptor set.
• `shaderGroupHandleCaptureReplaySize` is the number of bytes for the information required to do
capture and replay for shader group handles.

If the VkPhysicalDeviceRayTracingPropertiesKHR structure is included in the pNext chain of VkPhysicalDeviceProperties2, it is filled with the implementation-dependent limits.

Valid Usage (Implicit)

- `sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_RAY_TRACING_PROPERTIES_KHR`

To query the timeline semaphore properties of a physical device, add a VkPhysicalDeviceTimelineSemaphoreProperties structure to the pNext chain of theVkPhysicalDeviceProperties2 structure. The VkPhysicalDeviceTimelineSemaphoreProperties structure is defined as:

```c
typedef struct VkPhysicalDeviceTimelineSemaphoreProperties {
    VkStructureType    sType;
    void*              pNext;
    uint64_t           maxTimelineSemaphoreValueDifference;
} VkPhysicalDeviceTimelineSemaphoreProperties;
```

or the equivalent

```c
typedef VkPhysicalDeviceTimelineSemaphoreProperties
    VkPhysicalDeviceTimelineSemaphorePropertiesKHR;
```

The members of the VkPhysicalDeviceTimelineSemaphoreProperties structure describe the following implementation-dependent limits:

- `maxTimelineSemaphoreValueDifference` indicates the maximum difference allowed by the implementation between the current value of a timeline semaphore and any pending signal or wait operations.

Valid Usage (Implicit)

- `sType must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_PROPERTIES`

35.1. Limit Requirements

The following table specifies the required minimum/maximum for all Vulkan graphics implementations. Where a limit corresponds to a fine-grained device feature which is optional, the feature name is listed with two required limits, one when the feature is supported and one when it is not supported. If an implementation supports a feature, the limits reported are the same whether or not the feature is enabled.

Table 35. Required Limit Types
<table>
<thead>
<tr>
<th>Type</th>
<th>Limit</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>uint32_t</td>
<td>maxImageDimension1D</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxImageDimension2D</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxImageDimension3D</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxImageDimensionCube</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxImageArrayLayers</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTexelBufferElements</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxUniformBufferRange</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxStorageBufferRange</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPushConstantsSize</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxMemoryAllocationCount</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxSamplerAllocationCount</td>
<td></td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>bufferImageGranularity</td>
<td></td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>sparseAddressSpaceSize</td>
<td>sparseBinding</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxBoundDescriptorSets</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPerStageDescriptorSamplers</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPerStageDescriptorUniformBuffers</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPerStageDescriptorStorageBuffers</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPerStageDescriptorSampledImages</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPerStageDescriptorStorageImages</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPerStageDescriptorInputAttachments</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPerStageResources</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetSamplers</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetUniformBuffers</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetUniformBuffersDynamic</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetStorageBuffers</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetStorageBuffersDynamic</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetSampledImages</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetInputAttachments</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxVertexInputAttributes</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxVertexInputBindings</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxVertexInputAttributeOffset</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxVertexInputBindingStride</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxVertexOutputComponents</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationGenerationLevel</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationPatchSize</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>Type</td>
<td>Limit</td>
<td>Feature</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationControlPerVertexInputComponents</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationControlPerVertexOutputComponents</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationControlPerPatchOutputComponents</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationControlTotalOutputComponents</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationEvaluationInputComponents</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTessellationEvaluationOutputComponents</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxGeometryShaderInvocations</td>
<td>geometryShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxGeometryInputComponents</td>
<td>geometryShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxGeometryOutputComponents</td>
<td>geometryShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxGeometryOutputVertices</td>
<td>geometryShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxGeometryTotalOutputComponents</td>
<td>geometryShader</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxFragmentInputComponents</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxFragmentOutputAttachments</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxFragmentDualSrcAttachments</td>
<td>dualSrcBlend</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxFragmentCombinedOutputResources</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxComputeSharedMemorySize</td>
<td>-</td>
</tr>
<tr>
<td>3 × uint32_t</td>
<td>maxComputeWorkGroupCount</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxComputeWorkGroupInvocations</td>
<td>-</td>
</tr>
<tr>
<td>3 × uint32_t</td>
<td>maxComputeWorkGroupSize</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>subPixelPrecisionBits</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>subTexelPrecisionBits</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>mipmapPrecisionBits</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDrawIndexedIndexValue</td>
<td>fullDrawIndexUint32</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDrawIndirectCount</td>
<td>multiDrawIndirect</td>
</tr>
<tr>
<td>float</td>
<td>maxSamplerLodBias</td>
<td>-</td>
</tr>
<tr>
<td>float</td>
<td>maxSamplerAnisotropy</td>
<td>samplerAnisotropy</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxViewports</td>
<td>multiViewport</td>
</tr>
<tr>
<td>2 × uint32_t</td>
<td>maxViewportDimensions</td>
<td>-</td>
</tr>
<tr>
<td>2 × float</td>
<td>viewportBoundsRange</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>viewportSubPixelBits</td>
<td>-</td>
</tr>
<tr>
<td>size_t</td>
<td>minMemoryMapAlignment</td>
<td>-</td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>minTexelBufferOffsetAlignment</td>
<td>-</td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>minUniformBufferOffsetAlignment</td>
<td>-</td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>minStorageBufferOffsetAlignment</td>
<td>-</td>
</tr>
<tr>
<td>int32_t</td>
<td>minTexelOffset</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTexelOffset</td>
<td>-</td>
</tr>
<tr>
<td>int32_t</td>
<td>minTexelGatherOffset</td>
<td>shaderImageGatherExtended</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxTexelGatherOffset</td>
<td>shaderImageGatherExtended</td>
</tr>
<tr>
<td>Type</td>
<td>Limit</td>
<td>Feature</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------------------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>float</td>
<td>minInterpolationOffset</td>
<td>sampleRateShading</td>
</tr>
<tr>
<td>float</td>
<td>maxInterpolationOffset</td>
<td>sampleRateShading</td>
</tr>
<tr>
<td>uint32_t</td>
<td>subPixelInterpolationOffsetBits</td>
<td>sampleRateShading</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxFramebufferWidth</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxFramebufferHeight</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxFramebufferLayers</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>framebufferColorSampleCounts</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>framebufferDepthSampleCounts</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>framebufferStencilSampleCounts</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>framebufferNoAttachmentsSampleCounts</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxColorAttachments</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>sampledImageColorSampleCounts</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>sampledImageIntegerSampleCounts</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>sampledImageDepthSampleCounts</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>sampledImageStencilSampleCounts</td>
<td></td>
</tr>
<tr>
<td>VkSampleCountFlags</td>
<td>storageImageSampleCounts</td>
<td>shaderStorageImageMultisample</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxSampleMaskWords</td>
<td></td>
</tr>
<tr>
<td>VkBool32</td>
<td>timestampComputeAndGraphics</td>
<td></td>
</tr>
<tr>
<td>float</td>
<td>timestampPeriod</td>
<td></td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxClipDistances</td>
<td>shaderClipDistance</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxCullDistances</td>
<td>shaderCullDistance</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxCombinedClipAndCullDistances</td>
<td>shaderCullDistance</td>
</tr>
<tr>
<td>uint32_t</td>
<td>discreteQueuePriorities</td>
<td></td>
</tr>
<tr>
<td>2 × float</td>
<td>pointSizeRange</td>
<td>largePoints</td>
</tr>
<tr>
<td>2 × float</td>
<td>lineWidthRange</td>
<td>wideLines</td>
</tr>
<tr>
<td>float</td>
<td>pointSizeGranularity</td>
<td>largePoints</td>
</tr>
<tr>
<td>float</td>
<td>lineWidthGranularity</td>
<td>wideLines</td>
</tr>
<tr>
<td>VkBool32</td>
<td>strictLines</td>
<td></td>
</tr>
<tr>
<td>VkBool32</td>
<td>standardSampleLocations</td>
<td></td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>optimalBufferCopyOffsetAlignment</td>
<td></td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>optimalBufferCopyRowPitchAlignment</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Limit</td>
<td>Feature</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------------------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>VkDeviceSize</td>
<td>nonCoherentAtomSize</td>
<td>-</td>
</tr>
<tr>
<td>uint32_t</td>
<td>shaderGroupHandleSize</td>
<td>[VK_NV_ray_tracing], VK_KHR_ray_tracing</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxRecursionDepth</td>
<td>[VK_NV_ray_tracing], VK_KHR_ray_tracing</td>
</tr>
<tr>
<td>uint32_t</td>
<td>shaderGroupBaseAlignment</td>
<td>[VK_NV_ray_tracing], VK_KHR_ray_tracing</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxGeometryCount</td>
<td>[VK_NV_ray_tracing], VK_KHR_ray_tracing</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxInstanceCount</td>
<td>[VK_NV_ray_tracing], VK_KHR_ray_tracing</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxPrimitiveCount</td>
<td>VK_KHR_ray_tracing</td>
</tr>
<tr>
<td>uint32_t</td>
<td>maxDescriptorSetAccelerationStructures</td>
<td>[VK_NV_ray_tracing], VK_KHR_ray_tracing</td>
</tr>
<tr>
<td>uint64_t</td>
<td>maxTimelineSemaphoreValueDifference</td>
<td>timelineSemaphore</td>
</tr>
</tbody>
</table>

Table 36. Required Limits

<table>
<thead>
<tr>
<th>Limit</th>
<th>Unsupported Limit</th>
<th>Supported Limit</th>
<th>Limit Type¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxImageDimension1D</td>
<td>-</td>
<td>4096</td>
<td>min</td>
</tr>
<tr>
<td>maxImageDimension2D</td>
<td>-</td>
<td>4096</td>
<td>min</td>
</tr>
<tr>
<td>maxImageDimension3D</td>
<td>-</td>
<td>256</td>
<td>min</td>
</tr>
<tr>
<td>maxImageDimensionCube</td>
<td>-</td>
<td>4096</td>
<td>min</td>
</tr>
<tr>
<td>maxImageArrayLayers</td>
<td>-</td>
<td>256</td>
<td>min</td>
</tr>
<tr>
<td>maxTexelBufferElements</td>
<td>-</td>
<td>65536</td>
<td>min</td>
</tr>
<tr>
<td>maxUniformBufferRange</td>
<td>-</td>
<td>16384</td>
<td>min</td>
</tr>
<tr>
<td>maxStorageBufferRange</td>
<td>-</td>
<td>2²⁷</td>
<td>min</td>
</tr>
<tr>
<td>maxPushConstantsSize</td>
<td>-</td>
<td>128</td>
<td>min</td>
</tr>
<tr>
<td>maxMemoryAllocationCount</td>
<td>-</td>
<td>4096</td>
<td>min</td>
</tr>
<tr>
<td>maxSamplerAllocationCount</td>
<td>-</td>
<td>4000</td>
<td>min</td>
</tr>
<tr>
<td>bufferImageGranularity</td>
<td>-</td>
<td>131072</td>
<td>max</td>
</tr>
<tr>
<td>sparseAddressSpaceSize</td>
<td>0</td>
<td>2³¹</td>
<td>min</td>
</tr>
<tr>
<td>maxBoundDescriptorSets</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorSamplers</td>
<td>-</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorUniformBuffers</td>
<td>-</td>
<td>12</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageBuffers</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorSampledImages</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorStorageImages</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageDescriptorInputAttachments</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxPerStageResources</td>
<td>-</td>
<td>128 ²</td>
<td>min</td>
</tr>
<tr>
<td>Limit</td>
<td>Unsupported Limit</td>
<td>Supported Limit</td>
<td>Limit Type¹</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>maxDescriptorSetSamplers</td>
<td>-</td>
<td>96 ⁸</td>
<td>min, n × PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetUniformBuffers</td>
<td>-</td>
<td>72 ⁸</td>
<td>min, n × PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetUniformBuffersDynamic</td>
<td>-</td>
<td>8</td>
<td>min</td>
</tr>
<tr>
<td>maxDescriptorSetStorageBuffers</td>
<td>-</td>
<td>24 ⁸</td>
<td>min, n × PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetStorageBuffersDynamic</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxDescriptorSetSampledImages</td>
<td>-</td>
<td>96 ⁸</td>
<td>min, n × PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetStorageImages</td>
<td>-</td>
<td>24 ⁸</td>
<td>min, n × PerStage</td>
</tr>
<tr>
<td>maxDescriptorSetInputAttachments</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxVertexInputAttributes</td>
<td>-</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td>maxVertexInputBindings</td>
<td>-</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td>maxVertexInputAttributeOffset</td>
<td>-</td>
<td>2047</td>
<td>min</td>
</tr>
<tr>
<td>maxVertexInputBindingStride</td>
<td>-</td>
<td>2048</td>
<td>min</td>
</tr>
<tr>
<td>maxVertexOutputComponents</td>
<td>-</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationGenerationLevel</td>
<td>0</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationPatchSize</td>
<td>0</td>
<td>32</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationControlPerVertexInputComponents</td>
<td>0</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationControlPerVertexOutputComponents</td>
<td>0</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationControlPerPatchOutputComponents</td>
<td>0</td>
<td>120</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationControlTotalOutputComponents</td>
<td>0</td>
<td>2048</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationEvaluationInputComponents</td>
<td>0</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxTessellationEvaluationOutputComponents</td>
<td>0</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxGeometryShaderInvocations</td>
<td>0</td>
<td>32</td>
<td>min</td>
</tr>
<tr>
<td>maxGeometryInputComponents</td>
<td>0</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxGeometryOutputComponents</td>
<td>0</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxGeometryOutputVertices</td>
<td>0</td>
<td>256</td>
<td>min</td>
</tr>
<tr>
<td>maxGeometryTotalOutputComponents</td>
<td>0</td>
<td>1024</td>
<td>min</td>
</tr>
<tr>
<td>maxFragmentInputComponents</td>
<td>-</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td>maxFragmentOutputAttachments</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxFragmentDualSrcAttachments</td>
<td>0</td>
<td>1</td>
<td>min</td>
</tr>
<tr>
<td>maxFragmentCombinedOutputResources</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>maxComputeSharedMemorySize</td>
<td>-</td>
<td>16384</td>
<td>min</td>
</tr>
<tr>
<td>Limit</td>
<td>Unsupported Limit</td>
<td>Supported Limit</td>
<td>Limit Type¹</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td><code>maxComputeWorkGroupCount</code></td>
<td>-</td>
<td>(65535,65535,65535)</td>
<td>min</td>
</tr>
<tr>
<td><code>maxComputeWorkGroupInvocations</code></td>
<td>-</td>
<td>128</td>
<td>min</td>
</tr>
<tr>
<td><code>maxComputeWorkGroupSize</code></td>
<td>-</td>
<td>(128,128,64)</td>
<td>min</td>
</tr>
<tr>
<td><code>subPixelPrecisionBits</code></td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td><code>subTexelPrecisionBits</code></td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td><code>mipmapPrecisionBits</code></td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td><code>maxDrawIndexedIndexValue</code></td>
<td>$2^{24}$-1</td>
<td>$2^{32}$-1</td>
<td>min</td>
</tr>
<tr>
<td><code>maxDrawIndirectCount</code></td>
<td>1</td>
<td>$2^{16}$-1</td>
<td>min</td>
</tr>
<tr>
<td><code>maxSamplerLodBias</code></td>
<td>-</td>
<td>2</td>
<td>min</td>
</tr>
<tr>
<td><code>maxSamplerAnisotropy</code></td>
<td>1</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td><code>maxViewports</code></td>
<td>1</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td><code>maxViewportDimensions</code></td>
<td>-</td>
<td>(4096,4096)³</td>
<td>min</td>
</tr>
<tr>
<td><code>viewportBoundsRange</code></td>
<td>-</td>
<td>(-8192,8191)⁴</td>
<td>(max,min)</td>
</tr>
<tr>
<td><code>viewportSubPixelBits</code></td>
<td>-</td>
<td>0</td>
<td>min</td>
</tr>
<tr>
<td><code>minMemoryMapAlignment</code></td>
<td>-</td>
<td>64</td>
<td>min</td>
</tr>
<tr>
<td><code>minTexelBufferOffsetAlignment</code></td>
<td>-</td>
<td>256</td>
<td>max</td>
</tr>
<tr>
<td><code>minUniformBufferOffsetAlignment</code></td>
<td>-</td>
<td>256</td>
<td>max</td>
</tr>
<tr>
<td><code>minStorageBufferOffsetAlignment</code></td>
<td>-</td>
<td>256</td>
<td>max</td>
</tr>
<tr>
<td><code>minTexelOffset</code></td>
<td>-</td>
<td>-8</td>
<td>max</td>
</tr>
<tr>
<td><code>maxTexelOffset</code></td>
<td>-</td>
<td>7</td>
<td>min</td>
</tr>
<tr>
<td><code>minTexelGatherOffset</code></td>
<td>0</td>
<td>-8</td>
<td>max</td>
</tr>
<tr>
<td><code>maxTexelGatherOffset</code></td>
<td>0</td>
<td>7</td>
<td>min</td>
</tr>
<tr>
<td><code>minInterpolationOffset</code></td>
<td>0.0</td>
<td>-0.5⁵</td>
<td>max</td>
</tr>
<tr>
<td><code>maxInterpolationOffset</code></td>
<td>0.0</td>
<td>0.5 - (1 ULP)⁵</td>
<td>min</td>
</tr>
<tr>
<td><code>subPixelInterpolationOffsetBits</code></td>
<td>0</td>
<td>4⁵</td>
<td>min</td>
</tr>
<tr>
<td><code>maxFramebufferWidth</code></td>
<td>-</td>
<td>4096</td>
<td>min</td>
</tr>
<tr>
<td><code>maxFramebufferHeight</code></td>
<td>-</td>
<td>4096</td>
<td>min</td>
</tr>
<tr>
<td><code>maxFramebufferLayers</code></td>
<td>-</td>
<td>256</td>
<td>min</td>
</tr>
<tr>
<td><code>framebufferColorSampleCounts</code></td>
<td>-</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td><code>framebufferDepthSampleCounts</code></td>
<td>-</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td>Limit</td>
<td>Unsupported Limit</td>
<td>Supported Limit</td>
<td>Limit Type</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>-------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>framebufferStencilSampleCounts</td>
<td>-</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td>framebufferNoAttachmentsSampleCounts</td>
<td>-</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td>maxColorAttachments</td>
<td>-</td>
<td>4</td>
<td>min</td>
</tr>
<tr>
<td>sampledImageColorSampleCounts</td>
<td>-</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td>sampledImageIntegerSampleCounts</td>
<td>-</td>
<td>VK_SAMPLE_COUNT_1_BIT</td>
<td>min</td>
</tr>
<tr>
<td>sampledImageDepthSampleCounts</td>
<td>-</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td>sampledImageStencilSampleCounts</td>
<td>-</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td>storageImageSampleCounts</td>
<td>VK_SAMPLE_COUNT_1_BIT</td>
<td>(VK_SAMPLE_COUNT_1_BIT</td>
<td>VK_SAMPLE_COUNT_4_BIT)</td>
</tr>
<tr>
<td>maxSampleMaskWords</td>
<td>-</td>
<td>1</td>
<td>min</td>
</tr>
<tr>
<td>timestampComputeAndGraphics</td>
<td>-</td>
<td>-</td>
<td>implementatio dependent</td>
</tr>
<tr>
<td>timestampPeriod</td>
<td>-</td>
<td>-</td>
<td>duration</td>
</tr>
<tr>
<td>maxClipDistances</td>
<td>0</td>
<td>8</td>
<td>min</td>
</tr>
<tr>
<td>maxCullDistances</td>
<td>0</td>
<td>8</td>
<td>min</td>
</tr>
<tr>
<td>maxCombinedClipAndCullDistances</td>
<td>0</td>
<td>8</td>
<td>min</td>
</tr>
<tr>
<td>discreteQueuePriorities</td>
<td>-</td>
<td>2</td>
<td>min</td>
</tr>
<tr>
<td>pointSizeRange</td>
<td>(1.0,1.0)</td>
<td>(1.0,64.0 - ULP)⁶</td>
<td>(max,min)</td>
</tr>
<tr>
<td>lineWidthRange</td>
<td>(1.0,1.0)</td>
<td>(1.0,8.0 - ULP)⁷</td>
<td>(max,min)</td>
</tr>
<tr>
<td>pointSizeGranularity</td>
<td>0.0</td>
<td>1.0⁶</td>
<td>max, fixed point increment</td>
</tr>
<tr>
<td>lineWidthGranularity</td>
<td>0.0</td>
<td>1.0⁷</td>
<td>max, fixed point increment</td>
</tr>
<tr>
<td>Limit</td>
<td>Unsupported Limit</td>
<td>Supported Limit</td>
<td>Limit Type (^1)</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>------------------</td>
<td>-----------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>strictLines</td>
<td>-</td>
<td>-</td>
<td>implementation dependent</td>
</tr>
<tr>
<td>standardSampleLocations</td>
<td>-</td>
<td>-</td>
<td>implementation dependent</td>
</tr>
<tr>
<td>optimalBufferCopyOffsetAlignment</td>
<td>-</td>
<td>-</td>
<td>recommendation</td>
</tr>
<tr>
<td>optimalBufferCopyRowPitchAlignment</td>
<td>-</td>
<td>-</td>
<td>recommendation</td>
</tr>
<tr>
<td>nonCoherentAtomSize</td>
<td>-</td>
<td>256</td>
<td>max</td>
</tr>
<tr>
<td>maxPushDescriptors</td>
<td>-</td>
<td>32</td>
<td>min</td>
</tr>
<tr>
<td>maxMultiviewViewCount</td>
<td>-</td>
<td>6</td>
<td>min</td>
</tr>
<tr>
<td>maxMultiviewInstanceIndex</td>
<td>-</td>
<td>(2^{27}-1)</td>
<td>min</td>
</tr>
<tr>
<td>maxPerSetDescriptors</td>
<td>-</td>
<td>1024</td>
<td>min</td>
</tr>
<tr>
<td>maxMemoryAllocationSize</td>
<td>-</td>
<td>(2^{30})</td>
<td>min</td>
</tr>
<tr>
<td>shaderGroupHandleSize</td>
<td>-</td>
<td>32</td>
<td>exact</td>
</tr>
<tr>
<td>maxRecursionDepth</td>
<td>-</td>
<td>1</td>
<td>min</td>
</tr>
<tr>
<td>shaderGroupBaseAlignment</td>
<td>-</td>
<td>64</td>
<td>max</td>
</tr>
<tr>
<td>maxGeometryCount</td>
<td>-</td>
<td>(2^{24}-1)</td>
<td>min</td>
</tr>
<tr>
<td>maxInstanceCount</td>
<td>-</td>
<td>(2^{24}-1)</td>
<td>min</td>
</tr>
<tr>
<td>maxPrimitiveCount</td>
<td>-</td>
<td>(2^{29}-1)</td>
<td>min</td>
</tr>
<tr>
<td>maxDescriptorSetAccelerationStructures</td>
<td>-</td>
<td>16</td>
<td>min</td>
</tr>
<tr>
<td>maxTimelineSemaphoreValueDifference</td>
<td>-</td>
<td>(2^{31}-1)</td>
<td>min</td>
</tr>
</tbody>
</table>

1. The **Limit Type** column specifies the limit is either the minimum limit all implementations **must** support, the maximum limit all implementations **must** support, or the exact value all implementations **must** support. For bitmasks a minimum limit is the least bits all implementations **must** set, but they **may** have additional bits set beyond this minimum.

2. The **maxPerStageResources** **must** be at least the smallest of the following:

   - the sum of the `maxPerStageDescriptorUniformBuffers`, `maxPerStageDescriptorStorageBuffers`, `maxPerStageDescriptorSampledImages`, `maxPerStageDescriptorStorageImages`, `maxPerStageDescriptorInputAttachments`, `maxColorAttachments` limits, or
   - \(128\).

   It **may** not be possible to reach this limit in every stage.

3. See `maxViewportDimensions` for the **required** relationship to other limits.
See `viewportBoundsRange` for the **required** relationship to other limits.

5

The values `minInterpolationOffset` and `maxInterpolationOffset` describe the closed interval of supported interpolation offsets: \([\text{minInterpolationOffset}, \text{maxInterpolationOffset}]\). The ULP is determined by `subPixelInterpolationOffsetBits`. If `subPixelInterpolationOffsetBits` is 4, this provides increments of \((1/2^4) = 0.0625\), and thus the range of supported interpolation offsets would be \([-0.5, 0.4375]\).

6

The point size ULP is determined by `pointSizeGranularity`. If the `pointSizeGranularity` is 0.125, the range of supported point sizes **must** be at least \([1.0, 63.875]\).

7

The line width ULP is determined by `lineWidthGranularity`. If the `lineWidthGranularity` is 0.0625, the range of supported line widths **must** be at least \([1.0, 7.9375]\).

8

The minimum `maxDescriptorSet*` limit is \(n\) times the corresponding *specification* minimum `maxPerStageDescriptor*` limit, where \(n\) is the number of shader stages supported by the `VkPhysicalDevice`. If all shader stages are supported, \(n = 6\) (vertex, tessellation control, tessellation evaluation, geometry, fragment, compute).
Chapter 36. Formats

Supported buffer and image formats may vary across implementations. A minimum set of format features are guaranteed, but others must be explicitly queried before use to ensure they are supported by the implementation.

The features for the set of formats (VkFormat) supported by the implementation are queried individually using the vkGetPhysicalDeviceFormatProperties command.

36.1. Format Definition

The following image formats can be passed to, and may be returned from Vulkan commands. The memory required to store each format is discussed with that format, and also summarized in the Representation and Texel Block Size section and the Compatible formats table.

```c
typedef enum VkFormat {
    VK_FORMAT_UNDEFINED = 0,
    VK_FORMAT_R4G4_UNORM_PACK8 = 1,
    VK_FORMAT_R4G4B4A4_UNORM_PACK16 = 2,
    VK_FORMAT_B4G4R4A4_UNORM_PACK16 = 3,
    VK_FORMAT_R5G6B5_UNORM_PACK16 = 4,
    VK_FORMAT_B5G6R5_UNORM_PACK16 = 5,
    VK_FORMAT_R5G5B5A1_UNORM_PACK16 = 6,
    VK_FORMAT_B5G5R5A1_UNORM_PACK16 = 7,
    VK_FORMAT_A1R5G5B5_UNORM_PACK16 = 8,
    VK_FORMAT_R8_UNORM = 9,
    VK_FORMAT_R8_SNORM = 10,
    VK_FORMAT_R8_USCALED = 11,
    VK_FORMAT_R8_SSCALED = 12,
    VK_FORMAT_R8_UINT = 13,
    VK_FORMAT_R8_SINT = 14,
    VK_FORMAT_R8_SRGB = 15,
    VK_FORMAT_R8G8_UNORM = 16,
    VK_FORMAT_R8G8_SNORM = 17,
    VK_FORMAT_R8G8_USCALED = 18,
    VK_FORMAT_R8G8_SSCALED = 19,
    VK_FORMAT_R8G8_UINT = 20,
    VK_FORMAT_R8G8_SINT = 21,
    VK_FORMAT_R8G8_SRGB = 22,
    VK_FORMAT_R8G8B8_UNORM = 23,
    VK_FORMAT_R8G8B8_SNORM = 24,
    VK_FORMAT_R8G8B8_USCALED = 25,
    VK_FORMAT_R8G8B8_SSCALED = 26,
    VK_FORMAT_R8G8B8_UINT = 27,
    VK_FORMAT_R8G8B8_SINT = 28,
    VK_FORMAT_R8G8B8_SRGB = 29,
    VK_FORMAT_B8G8R8_UNORM = 30,
    VK_FORMAT_B8G8R8_SNORM = 31,
    VK_FORMAT_B8G8R8_USCALED = 32,
    // More formats...
} VkFormat;
```
VK_FORMAT_B8G8R8_SSCALED = 33,
VK_FORMAT_B8G8R8_UINT = 34,
VK_FORMAT_B8G8R8_SINT = 35,
VK_FORMAT_B8G8R8_SRGB = 36,
VK_FORMAT_R8G8B8A8_UNORM = 37,
VK_FORMAT_R8G8B8A8_SNORM = 38,
VK_FORMAT_R8G8B8A8_USCALED = 39,
VK_FORMAT_R8G8B8A8_SSCALED = 40,
VK_FORMAT_R8G8B8A8_UINT = 41,
VK_FORMAT_R8G8B8A8_SINT = 42,
VK_FORMAT_R8G8B8A8_SRGB = 43,
VK_FORMAT_B8G8R8A8_UNORM = 44,
VK_FORMAT_B8G8R8A8_SNORM = 45,
VK_FORMAT_B8G8R8A8_USCALED = 46,
VK_FORMAT_B8G8R8A8_SSCALED = 47,
VK_FORMAT_B8G8R8A8_UINT = 48,
VK_FORMAT_B8G8R8A8_SINT = 49,
VK_FORMAT_B8G8R8A8_SRGB = 50,
VK_FORMAT_A8B8G8R8_UNORM_PACK32 = 51,
VK_FORMAT_A8B8G8R8_SNORM_PACK32 = 52,
VK_FORMAT_A8B8G8R8_USCALED_PACK32 = 53,
VK_FORMAT_A8B8G8R8_SSCALED_PACK32 = 54,
VK_FORMAT_A8B8G8R8_UINT_PACK32 = 55,
VK_FORMAT_A8B8G8R8_SINT_PACK32 = 56,
VK_FORMAT_A8B8G8R8_SRGB_PACK32 = 57,
VK_FORMAT_A2R10G10B10_UNORM_PACK32 = 58,
VK_FORMAT_A2R10G10B10_SNORM_PACK32 = 59,
VK_FORMAT_A2R10G10B10_USCALED_PACK32 = 60,
VK_FORMAT_A2R10G10B10_SSCALED_PACK32 = 61,
VK_FORMAT_A2R10G10B10_UINT_PACK32 = 62,
VK_FORMAT_A2R10G10B10_SINT_PACK32 = 63,
VK_FORMAT_A2B10G10R10_UNORM_PACK32 = 64,
VK_FORMAT_A2B10G10R10_SNORM_PACK32 = 65,
VK_FORMAT_A2B10G10R10_USCALED_PACK32 = 66,
VK_FORMAT_A2B10G10R10_SSCALED_PACK32 = 67,
VK_FORMAT_A2B10G10R10_UINT_PACK32 = 68,
VK_FORMAT_A2B10G10R10_SINT_PACK32 = 69,
VK_FORMAT_R16_UNORM = 70,
VK_FORMAT_R16_SNORM = 71,
VK_FORMAT_R16_USCALED = 72,
VK_FORMAT_R16_SSCALED = 73,
VK_FORMAT_R16_UINT = 74,
VK_FORMAT_R16_SINT = 75,
VK_FORMAT_R16_SFLOAT = 76,
VK_FORMAT_R16G16_UNORM = 77,
VK_FORMAT_R16G16_SNORM = 78,
VK_FORMAT_R16G16_USCALED = 79,
VK_FORMAT_R16G16_SSCALED = 80,
VK_FORMAT_R16G16_UINT = 81,
VK_FORMAT_R16G16_SINT = 82,
VK_FORMAT_R16G16_SFLOAT = 83,
VK_FORMAT_R16G16B16_UNORM = 84,
VK_FORMAT_R16G16B16_SNORM = 85,
VK_FORMAT_R16G16B16_USCALED = 86,
VK_FORMAT_R16G16B16_SSCALED = 87,
VK_FORMAT_R16G16B16_UINT = 88,
VK_FORMAT_R16G16B16_SINT = 89,
VK_FORMAT_R16G16B16_SFLOAT = 90,
VK_FORMAT_R16G16B16A16_UNORM = 91,
VK_FORMAT_R16G16B16A16_SNORM = 92,
VK_FORMAT_R16G16B16A16_USCALED = 93,
VK_FORMAT_R16G16B16A16_SSCALED = 94,
VK_FORMAT_R16G16B16A16_UINT = 95,
VK_FORMAT_R16G16B16A16_SINT = 96,
VK_FORMAT_R16G16B16A16_SFLOAT = 97,
VK_FORMAT_R32_UINT = 98,
VK_FORMAT_R32_SINT = 99,
VK_FORMAT_R32_SFLOAT = 100,
VK_FORMAT_R32G32_UINT = 101,
VK_FORMAT_R32G32_SINT = 102,
VK_FORMAT_R32G32_SFLOAT = 103,
VK_FORMAT_R32G32B32_UINT = 104,
VK_FORMAT_R32G32B32_SINT = 105,
VK_FORMAT_R32G32B32_SFLOAT = 106,
VK_FORMAT_R32G32B32A32_UINT = 107,
VK_FORMAT_R32G32B32A32_SINT = 108,
VK_FORMAT_R32G32B32A32_SFLOAT = 109,
VK_FORMAT_R64_UINT = 110,
VK_FORMAT_R64_SINT = 111,
VK_FORMAT_R64_SFLOAT = 112,
VK_FORMAT_R64G64_UINT = 113,
VK_FORMAT_R64G64_SINT = 114,
VK_FORMAT_R64G64_SFLOAT = 115,
VK_FORMAT_R64G64B64_UINT = 116,
VK_FORMAT_R64G64B64_SINT = 117,
VK_FORMAT_R64G64B64_SFLOAT = 118,
VK_FORMAT_R64G64B64A64_UINT = 119,
VK_FORMAT_R64G64B64A64_SINT = 120,
VK_FORMAT_R64G64B64A64_SFLOAT = 121,
VK_FORMAT_B10G11R11_UFLOAT_PACK32 = 122,
VK_FORMAT_E5B9G9R9_UFLOAT_PACK32 = 123,
VK_FORMAT_D16_UNORM = 124,
VK_FORMAT_X8_D24_UNORM_PACK32 = 125,
VK_FORMAT_D16_SFLOAT = 126,
VK_FORMAT_D32_SFLOAT = 127,
VK_FORMAT_D32_SFLOAT = 128,
VK_FORMAT_D24_UNORM_S8_UINT = 129,
VK_FORMAT_D32_SFLOAT_S8_UINT = 130,
VK_FORMAT_BC1_RGB_UNORM_BLOCK = 131,
VK_FORMAT_BC1_RGB_SRGB_BLOCK = 132,
VK_FORMAT_BC1_RGBA_UNORM_BLOCK = 133,
VK_FORMAT_BC1_RGBA_SRGB_BLOCK = 134,
<table>
<thead>
<tr>
<th>VK_FORMAT_BC2_UNORM_BLOCK</th>
<th>135</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_BC2_SRGB_BLOCK</td>
<td>136</td>
</tr>
<tr>
<td>VK_FORMAT_BC3_UNORM_BLOCK</td>
<td>137</td>
</tr>
<tr>
<td>VK_FORMAT_BC3_SRGB_BLOCK</td>
<td>138</td>
</tr>
<tr>
<td>VK_FORMAT_BC4_UNORM_BLOCK</td>
<td>139</td>
</tr>
<tr>
<td>VK_FORMAT_BC4_SNORM_BLOCK</td>
<td>140</td>
</tr>
<tr>
<td>VK_FORMAT_BC5_UNORM_BLOCK</td>
<td>141</td>
</tr>
<tr>
<td>VK_FORMAT_BC5_SNORM_BLOCK</td>
<td>142</td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_UFLOAT_BLOCK</td>
<td>143</td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
<td>144</td>
</tr>
<tr>
<td>VK_FORMAT_BC7_UNORM_BLOCK</td>
<td>145</td>
</tr>
<tr>
<td>VK_FORMAT_BC7_SRGB_BLOCK</td>
<td>146</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK</td>
<td>147</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK</td>
<td>148</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK</td>
<td>149</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK</td>
<td>150</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK</td>
<td>151</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK</td>
<td>152</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11_UNORM_BLOCK</td>
<td>153</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11_SNORM_BLOCK</td>
<td>154</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_UNORM_BLOCK</td>
<td>155</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_SNORM_BLOCK</td>
<td>156</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_4x4_UNORM_BLOCK</td>
<td>157</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_4x4_SRGB_BLOCK</td>
<td>158</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_UNORM_BLOCK</td>
<td>159</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_SRGB_BLOCK</td>
<td>160</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_UNORM_BLOCK</td>
<td>161</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_SRGB_BLOCK</td>
<td>162</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_UNORM_BLOCK</td>
<td>163</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_SRGB_BLOCK</td>
<td>164</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_UNORM_BLOCK</td>
<td>165</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_SRGB_BLOCK</td>
<td>166</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_UNORM_BLOCK</td>
<td>167</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_SRGB_BLOCK</td>
<td>168</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_UNORM_BLOCK</td>
<td>169</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_SRGB_BLOCK</td>
<td>170</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_UNORM_BLOCK</td>
<td>171</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_SRGB_BLOCK</td>
<td>172</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_UNORM_BLOCK</td>
<td>173</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_SRGB_BLOCK</td>
<td>174</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_UNORM_BLOCK</td>
<td>175</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_SRGB_BLOCK</td>
<td>176</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_UNORM_BLOCK</td>
<td>177</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_SRGB_BLOCK</td>
<td>178</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_UNORM_BLOCK</td>
<td>179</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_SRGB_BLOCK</td>
<td>180</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x10_UNORM_BLOCK</td>
<td>181</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x10_SRGB_BLOCK</td>
<td>182</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x12_UNORM_BLOCK</td>
<td>183</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x12_SRGB_BLOCK</td>
<td>184</td>
</tr>
<tr>
<td>VK_FORMAT_G8B8G8R8_422_UNORM</td>
<td>1000156000</td>
</tr>
</tbody>
</table>
VK_FORMAT_B8G8R8G8_422_UNORM = 1000156001,
VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM = 1000156002,
VK_FORMAT_G8_B8R8_2PLANE_420_UNORM = 1000156003,
VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM = 1000156004,
VK_FORMAT_G8_B8R8_2PLANE_422_UNORM = 1000156005,
VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM = 1000156006,
VK_FORMAT_R10X6_UNORM_PACK16 = 1000156007,
VK_FORMAT_R10X6G10X6_UNORM_2PACK16 = 1000156008,
VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16 = 1000156009,
VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16 = 1000156010,
VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16 = 1000156011,
VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16 = 1000156012,
VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16 = 1000156013,
VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16 = 1000156014,
VK_FORMAT_G10X6_B10X6R10X6_3PLANE_444_UNORM_3PACK16 = 1000156015,
VK_FORMAT_G10X6_B10X6R10X6_3PLANE_444_UNORM_3PACK16 = 1000156016,
VK_FORMAT_R12X4_UNORM_PACK16 = 1000156017,
VK_FORMAT_R12X4G12X4_UNORM_2PACK16 = 1000156018,
VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16 = 1000156019,
VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16 = 1000156020,
VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16 = 1000156021,
VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16 = 1000156022,
VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16 = 1000156023,
VK_FORMAT_G12X4_B12X4R12X4_3PLANE_422_UNORM_3PACK16 = 1000156024,
VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16 = 1000156025,
VK_FORMAT_G12X4_B12X4R12X4_3PLANE_444_UNORM_3PACK16 = 1000156026,
VK_FORMAT_G16B16G16R16_422_UNORM = 1000156027,
VK_FORMAT_B16G16R16G16_422_UNORM = 1000156028,
VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM = 1000156029,
VK_FORMAT_G16_B16R16_2PLANE_420_UNORM = 1000156030,
VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM = 1000156031,
VK_FORMAT_G16_B16R16_2PLANE_422_UNORM = 1000156032,
VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM = 1000156033,
VK_FORMAT_G8B8G8R8_422_UNORM_KHR = VK_FORMAT_G8B8G8R8_422_UNORM,
VK_FORMAT_B8G8R8G8_422_UNORM_KHR = VK_FORMAT_B8G8R8G8_422_UNORM,
VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM_KHR = VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM,
VK_FORMAT_G8_B8R8_2PLANE_420_UNORM_KHR = VK_FORMAT_G8_B8R8_2PLANE_420_UNORM,
VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM_KHR = VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM,
VK_FORMAT_G8_B8R8_2PLANE_422_UNORM_KHR = VK_FORMAT_G8_B8R8_2PLANE_422_UNORM,
VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM_KHR = VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM,
VK_FORMAT_R10X6_UNORM_PACK16_KHR = VK_FORMAT_R10X6_UNORM_PACK16,
VK_FORMAT_R10X6G10X6_UNORM_2PACK16_KHR = VK_FORMAT_R10X6G10X6_UNORM_2PACK16,
VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16_KHR = VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16,
VK_FORMAT_R10X6G10X6R10X6G10X6_422_UNORM_4PACK16_KHR = VK_FORMAT_R10X6G10X6R10X6G10X6_422_UNORM_4PACK16,
VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16_KHR = VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16,
VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16_KHR = VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16,
VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16_KHR = VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16,
VK_FORMAT_G10X6_B10X6R10X6_3PLANE_444_UNORM_3PACK16_KHR = VK_FORMAT_G10X6_B10X6R10X6_3PLANE_444_UNORM_3PACK16,
VK_FORMAT_R10X6G10X6R10X6G10X6_422_UNORM_4PACK16_KHR = VK_FORMAT_R10X6G10X6R10X6G10X6_422_UNORM_4PACK16,
VK_FORMAT_G10X6_B10X6R10X6_3PLANE_420_UNORM_3PACK16_KHR = VK_FORMAT_G10X6_B10X6R10X6_3PLANE_420_UNORM_3PACK16,
VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16_KHR = VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16,
• **VK_FORMAT_UNDEFINED** specifies that the format is not specified.

• **VK_FORMAT_R4G4_UNORM_PACK8** specifies a two-component, 8-bit packed unsigned normalized format that has a 4-bit R component in bits 4..7, and a 4-bit G component in bits 0..3.

• **VK_FORMAT_R4G4B4A4_UNORM_PACK16** specifies a four-component, 16-bit packed unsigned normalized format that has a 4-bit R component in bits 12..15, a 4-bit G component in bits 8..11, a 4-bit B component in bits 4..7, and a 4-bit A component in bits 0..3.

• **VK_FORMAT_B4G4R4A4_UNORM_PACK16** specifies a four-component, 16-bit packed unsigned normalized format that has a 4-bit B component in bits 12..15, a 4-bit G component in bits 8..11, a 4-bit R component in bits 4..7, and a 4-bit A component in bits 0..3.

• **VK_FORMAT_R5G6B5_UNORM_PACK16** specifies a three-component, 16-bit packed unsigned normalized
format that has a 5-bit R component in bits 11..15, a 6-bit G component in bits 5..10, and a 5-bit B component in bits 0..4.

- **VK_FORMAT_B5G6R5_UNORM_PACK16** specifies a three-component, 16-bit packed unsigned normalized format that has a 5-bit B component in bits 11..15, a 6-bit G component in bits 5..10, and a 5-bit R component in bits 0..4.

- **VK_FORMAT_R5G5B5A1_UNORM_PACK16** specifies a four-component, 16-bit packed unsigned normalized format that has a 5-bit R component in bits 11..15, a 5-bit G component in bits 6..10, a 5-bit B component in bits 1..5, and a 1-bit A component in bit 0.

- **VK_FORMAT_B5G5R5A1_UNORM_PACK16** specifies a four-component, 16-bit packed unsigned normalized format that has a 5-bit B component in bits 11..15, a 5-bit G component in bits 6..10, a 5-bit R component in bits 1..5, and a 1-bit A component in bit 0.

- **VK_FORMAT_A1R5G5B5_UNORM_PACK16** specifies a four-component, 16-bit packed unsigned normalized format that has a 1-bit A component in bit 15, a 5-bit R component in bits 10..14, a 5-bit G component in bits 5..9, and a 5-bit B component in bits 0..4.

- **VK_FORMAT_R8_UNORM** specifies a one-component, 8-bit unsigned normalized format that has a single 8-bit R component.

- **VK_FORMAT_R8_SNORM** specifies a one-component, 8-bit signed normalized format that has a single 8-bit R component.

- **VK_FORMAT_R8_USCALED** specifies a one-component, 8-bit unsigned scaled integer format that has a single 8-bit R component.

- **VK_FORMAT_R8_SSCALED** specifies a one-component, 8-bit signed scaled integer format that has a single 8-bit R component.

- **VK_FORMAT_R8_UINT** specifies a one-component, 8-bit unsigned integer format that has a single 8-bit R component.

- **VK_FORMAT_R8_SINT** specifies a one-component, 8-bit signed integer format that has a single 8-bit R component.

- **VK_FORMAT_R8_SRGB** specifies a one-component, 8-bit unsigned normalized format that has a single 8-bit R component stored with sRGB nonlinear encoding.

- **VK_FORMAT_R8G8_UNORM** specifies a two-component, 16-bit unsigned normalized format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.

- **VK_FORMAT_R8G8_SNORM** specifies a two-component, 16-bit signed normalized format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.

- **VK_FORMAT_R8G8_USCALED** specifies a two-component, 16-bit unsigned scaled integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.

- **VK_FORMAT_R8G8_SSCALED** specifies a two-component, 16-bit signed scaled integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.

- **VK_FORMAT_R8G8_UINT** specifies a two-component, 16-bit unsigned integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.

- **VK_FORMAT_R8G8_SINT** specifies a two-component, 16-bit signed integer format that has an 8-bit R component in byte 0, and an 8-bit G component in byte 1.
8-bit R component stored with sRGB nonlinear encoding in byte 0, and an 8-bit G component stored with sRGB nonlinear encoding in byte 1.

- **VK_FORMAT_R8G8B8_UNORM** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.

- **VK_FORMAT_R8G8B8_SNORM** specifies a three-component, 24-bit signed normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.

- **VK_FORMAT_R8G8B8_USCALED** specifies a three-component, 24-bit unsigned scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.

- **VK_FORMAT_R8G8B8_SSCALED** specifies a three-component, 24-bit signed scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.

- **VK_FORMAT_R8G8B8_UINT** specifies a three-component, 24-bit unsigned integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.

- **VK_FORMAT_R8G8B8_SINT** specifies a three-component, 24-bit signed integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, and an 8-bit B component in byte 2.

- **VK_FORMAT_R8G8B8_SRGB** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit R component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, and an 8-bit B component stored with sRGB nonlinear encoding in byte 2.

- **VK_FORMAT_B8G8R8_UNORM** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SNORM** specifies a three-component, 24-bit signed normalized format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_USCALED** specifies a three-component, 24-bit unsigned scaled format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SSCALED** specifies a three-component, 24-bit signed scaled format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_UINT** specifies a three-component, 24-bit unsigned integer format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SINT** specifies a three-component, 24-bit signed integer format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, and an 8-bit R component in byte 2.

- **VK_FORMAT_B8G8R8_SRGB** specifies a three-component, 24-bit unsigned normalized format that has an 8-bit B component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, and an 8-bit R component stored with sRGB nonlinear encoding in byte 2.

- **VK_FORMAT_R8G8B8A8_UNORM** specifies a four-component, 32-bit unsigned normalized format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

- **VK_FORMAT_R8G8B8A8_SNORM** specifies a four-component, 32-bit signed normalized format that has
• **VK_FORMAT_R8G8B8A8_USCALED** specifies a four-component, 32-bit unsigned scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

• **VK_FORMAT_R8G8B8A8_SSCALED** specifies a four-component, 32-bit signed scaled format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

• **VK_FORMAT_R8G8B8A8_UINT** specifies a four-component, 32-bit unsigned integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

• **VK_FORMAT_R8G8B8A8_SINT** specifies a four-component, 32-bit signed integer format that has an 8-bit R component in byte 0, an 8-bit G component in byte 1, an 8-bit B component in byte 2, and an 8-bit A component in byte 3.

• **VK_FORMAT_R8G8B8A8_SRGB** specifies a four-component, 32-bit unsigned normalized format that has an 8-bit R component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, an 8-bit B component stored with sRGB nonlinear encoding in byte 2, and an 8-bit A component in byte 3.

• **VK_FORMAT_B8G8R8A8_UNORM** specifies a four-component, 32-bit unsigned normalized format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

• **VK_FORMAT_B8G8R8A8_SNORM** specifies a four-component, 32-bit signed normalized format that has an 8-bit B component in byte 0, an 8-bit G component in byte 1, an 8-bit R component in byte 2, and an 8-bit A component in byte 3.

• **VK_FORMAT_B8G8R8A8_SRGB** specifies a four-component, 32-bit unsigned normalized format that has an 8-bit B component stored with sRGB nonlinear encoding in byte 0, an 8-bit G component stored with sRGB nonlinear encoding in byte 1, an 8-bit R component stored with sRGB nonlinear encoding in byte 2, and an 8-bit A component in byte 3.
• **VK_FORMAT_A8B8G8R8_SNORM_PACK32** specifies a four-component, 32-bit packed signed normalized format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

• **VK_FORMAT_A8B8G8R8_USCALED_PACK32** specifies a four-component, 32-bit packed unsigned scaled integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

• **VK_FORMAT_A8B8G8R8_SSCALED_PACK32** specifies a four-component, 32-bit packed signed scaled integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

• **VK_FORMAT_A8B8G8R8_UINT_PACK32** specifies a four-component, 32-bit packed unsigned integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

• **VK_FORMAT_A8B8G8R8_SINT_PACK32** specifies a four-component, 32-bit packed signed integer format that has an 8-bit A component in bits 24..31, an 8-bit B component in bits 16..23, an 8-bit G component in bits 8..15, and an 8-bit R component in bits 0..7.

• **VK_FORMAT_A8B8G8R8_SRGB_PACK32** specifies a four-component, 32-bit packed unsigned normalized format that has an 8-bit A component in bits 24..31, an 8-bit B component stored with sRGB nonlinear encoding in bits 16..23, an 8-bit G component stored with sRGB nonlinear encoding in bits 8..15, and an 8-bit R component stored with sRGB nonlinear encoding in bits 0..7.

• **VK_FORMAT_A2R10G10B10_UNORM_PACK32** specifies a four-component, 32-bit packed unsigned normalized format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

• **VK_FORMAT_A2R10G10B10_SNORM_PACK32** specifies a four-component, 32-bit packed signed normalized format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

• **VK_FORMAT_A2R10G10B10_USCALED_PACK32** specifies a four-component, 32-bit packed unsigned scaled integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

• **VK_FORMAT_A2R10G10B10_SSCALED_PACK32** specifies a four-component, 32-bit packed signed scaled integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

• **VK_FORMAT_A2R10G10B10_UINT_PACK32** specifies a four-component, 32-bit packed unsigned integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

• **VK_FORMAT_A2R10G10B10_SINT_PACK32** specifies a four-component, 32-bit packed signed integer format that has a 2-bit A component in bits 30..31, a 10-bit R component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit B component in bits 0..9.

• **VK_FORMAT_A2B10G10R10_UNORM_PACK32** specifies a four-component, 32-bit packed unsigned normalized format that has a 2-bit A component in bits 30..31, a 10-bit B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.

• **VK_FORMAT_A2B10G10R10_SNORM_PACK32** specifies a four-component, 32-bit packed signed normalized format that has a 2-bit A component in bits 30..31, a 10-bit B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.
• **VK_FORMAT_A2B10G10R10_USCALED_PACK32** specifies a four-component, 32-bit packed unsigned scaled integer format that has a 2-bit A component in bits 30..31, a 10-bit B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.

• **VK_FORMAT_A2B10G10R10_SSCALED_PACK32** specifies a four-component, 32-bit packed signed scaled integer format that has a 2-bit A component in bits 30..31, a 10-bit B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.

• **VK_FORMAT_A2B10G10R10_UINT_PACK32** specifies a four-component, 32-bit packed unsigned integer format that has a 2-bit A component in bits 30..31, a 10-bit B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.

• **VK_FORMAT_A2B10G10R10_SINT_PACK32** specifies a four-component, 32-bit packed signed integer format that has a 2-bit A component in bits 30..31, a 10-bit B component in bits 20..29, a 10-bit G component in bits 10..19, and a 10-bit R component in bits 0..9.

• **VK_FORMAT_R16_UNORM** specifies a one-component, 16-bit unsigned normalized format that has a single 16-bit R component.

• **VK_FORMAT_R16_SNORM** specifies a one-component, 16-bit signed normalized format that has a single 16-bit R component.

• **VK_FORMAT_R16_USCALED** specifies a one-component, 16-bit unsigned scaled integer format that has a single 16-bit R component.

• **VK_FORMAT_R16_SSCALED** specifies a one-component, 16-bit signed scaled integer format that has a single 16-bit R component.

• **VK_FORMAT_R16_UINT** specifies a one-component, 16-bit unsigned integer format that has a single 16-bit R component.

• **VK_FORMAT_R16_SINT** specifies a one-component, 16-bit signed integer format that has a single 16-bit R component.

• **VK_FORMAT_R16_SFLOAT** specifies a one-component, 16-bit signed floating-point format that has a single 16-bit R component.

• **VK_FORMAT_R16G16_UNORM** specifies a two-component, 32-bit unsigned normalized format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SNORM** specifies a two-component, 32-bit signed normalized format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_USCALED** specifies a two-component, 32-bit unsigned scaled integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SSCALED** specifies a two-component, 32-bit signed scaled integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_UINT** specifies a two-component, 32-bit unsigned integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SINT** specifies a two-component, 32-bit signed integer format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16_SFLOAT** specifies a two-component, 32-bit signed floating-point format that has a 16-bit R component in bytes 0..1, and a 16-bit G component in bytes 2..3.

• **VK_FORMAT_R16G16B16_UNORM** specifies a three-component, 48-bit unsigned normalized format that...
has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

- **VK_FORMAT_R16G16B16_SNORM** specifies a three-component, 48-bit signed normalized format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

- **VK_FORMAT_R16G16B16_USCALED** specifies a three-component, 48-bit unsigned scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

- **VK_FORMAT_R16G16B16_SSCALED** specifies a three-component, 48-bit signed scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

- **VK_FORMAT_R16G16B16_UINT** specifies a three-component, 48-bit unsigned integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

- **VK_FORMAT_R16G16B16_SINT** specifies a three-component, 48-bit signed integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

- **VK_FORMAT_R16G16B16_SFLOAT** specifies a three-component, 48-bit signed floating-point format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, and a 16-bit B component in bytes 4..5.

- **VK_FORMAT_R16G16B16A16_UNORM** specifies a four-component, 64-bit unsigned normalized format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

- **VK_FORMAT_R16G16B16A16_SNORM** specifies a four-component, 64-bit signed normalized format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

- **VK_FORMAT_R16G16B16A16_USCALED** specifies a four-component, 64-bit unsigned scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

- **VK_FORMAT_R16G16B16A16_SSCALED** specifies a four-component, 64-bit signed scaled integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

- **VK_FORMAT_R16G16B16A16_UINT** specifies a four-component, 64-bit unsigned integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

- **VK_FORMAT_R16G16B16A16_SINT** specifies a four-component, 64-bit signed integer format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

- **VK_FORMAT_R16G16B16A16_SFLOAT** specifies a four-component, 64-bit signed floating-point format that has a 16-bit R component in bytes 0..1, a 16-bit G component in bytes 2..3, a 16-bit B component in bytes 4..5, and a 16-bit A component in bytes 6..7.

- **VK_FORMAT_R32_UINT** specifies a one-component, 32-bit unsigned integer format that has a single
32-bit R component.

- **VK_FORMAT_R32_SINT** specifies a one-component, 32-bit signed integer format that has a single 32-bit R component.
- **VK_FORMAT_R32_SFLOAT** specifies a one-component, 32-bit signed floating-point format that has a single 32-bit R component.
- **VK_FORMAT_R32G32_UINT** specifies a two-component, 64-bit unsigned integer format that has a 32-bit R component in bytes 0..3, and a 32-bit G component in bytes 4..7.
- **VK_FORMAT_R32G32_SINT** specifies a two-component, 64-bit signed integer format that has a 32-bit R component in bytes 0..3, and a 32-bit G component in bytes 4..7.
- **VK_FORMAT_R32G32_SFLOAT** specifies a two-component, 64-bit signed floating-point format that has a 32-bit R component in bytes 0..3, and a 32-bit G component in bytes 4..7.
- **VK_FORMAT_R32G32B32_UINT** specifies a three-component, 96-bit unsigned integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, and a 32-bit B component in bytes 8..11.
- **VK_FORMAT_R32G32B32_SINT** specifies a three-component, 96-bit signed integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, and a 32-bit B component in bytes 8..11.
- **VK_FORMAT_R32G32B32_SFLOAT** specifies a three-component, 96-bit signed floating-point format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, and a 32-bit B component in bytes 8..11.
- **VK_FORMAT_R32G32B32A32_UINT** specifies a four-component, 128-bit unsigned integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, a 32-bit B component in bytes 8..11, and a 32-bit A component in bytes 12..15.
- **VK_FORMAT_R32G32B32A32_SINT** specifies a four-component, 128-bit signed integer format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, a 32-bit B component in bytes 8..11, and a 32-bit A component in bytes 12..15.
- **VK_FORMAT_R32G32B32A32_SFLOAT** specifies a four-component, 128-bit signed floating-point format that has a 32-bit R component in bytes 0..3, a 32-bit G component in bytes 4..7, a 32-bit B component in bytes 8..11, and a 32-bit A component in bytes 12..15.
- **VK_FORMAT_R64_UINT** specifies a one-component, 64-bit unsigned integer format that has a single 64-bit R component.
- **VK_FORMAT_R64_SINT** specifies a one-component, 64-bit signed integer format that has a single 64-bit R component.
- **VK_FORMAT_R64_SFLOAT** specifies a one-component, 64-bit signed floating-point format that has a single 64-bit R component.
- **VK_FORMAT_R64G64_UINT** specifies a two-component, 128-bit unsigned integer format that has a 64-bit R component in bytes 0..7, and a 64-bit G component in bytes 8..15.
- **VK_FORMAT_R64G64_SINT** specifies a two-component, 128-bit signed integer format that has a 64-bit R component in bytes 0..7, and a 64-bit G component in bytes 8..15.
- **VK_FORMAT_R64G64_SFLOAT** specifies a two-component, 128-bit signed floating-point format that has a 64-bit R component in bytes 0..7, and a 64-bit G component in bytes 8..15.
• **VK_FORMAT_R64G64B64_UINT** specifies a three-component, 192-bit unsigned integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, and a 64-bit B component in bytes 16..23.

• **VK_FORMAT_R64G64B64_SINT** specifies a three-component, 192-bit signed integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, and a 64-bit B component in bytes 16..23.

• **VK_FORMAT_R64G64B64_SFLOAT** specifies a three-component, 192-bit signed floating-point format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, and a 64-bit B component in bytes 16..23.

• **VK_FORMAT_R64G64B64A64_UINT** specifies a four-component, 256-bit unsigned integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, a 64-bit B component in bytes 16..23, and a 64-bit A component in bytes 24..31.

• **VK_FORMAT_R64G64B64A64_SINT** specifies a four-component, 256-bit signed integer format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, a 64-bit B component in bytes 16..23, and a 64-bit A component in bytes 24..31.

• **VK_FORMAT_R64G64B64A64_SFLOAT** specifies a four-component, 256-bit signed floating-point format that has a 64-bit R component in bytes 0..7, a 64-bit G component in bytes 8..15, a 64-bit B component in bytes 16..23, and a 64-bit A component in bytes 24..31.

• **VK_FORMAT_B10G11R11_UFLOAT_PACK32** specifies a three-component, 32-bit packed unsigned floating-point format that has a 10-bit B component in bits 22..31, an 11-bit G component in bits 11..21, an 11-bit R component in bits 0..10. See *Unsigned 10-Bit Floating-Point Numbers* and *Unsigned 11-Bit Floating-Point Numbers*.

• **VK_FORMAT_E5B9G9R9_UFLOAT_PACK32** specifies a three-component, 32-bit packed unsigned floating-point format that has a 5-bit shared exponent in bits 27..31, a 9-bit B component mantissa in bits 18..26, a 9-bit G component mantissa in bits 9..17, and a 9-bit R component mantissa in bits 0..8.

• **VK_FORMAT_D16_UNORM** specifies a one-component, 16-bit unsigned normalized format that has a single 16-bit depth component.

• **VK_FORMAT_X8_D24_UNORM_PACK32** specifies a two-component, 32-bit format that has 24 unsigned normalized bits in the depth component and, optionally, 8 bits that are unused.

• **VK_FORMAT_D32_SFLOAT** specifies a one-component, 32-bit signed floating-point format that has 32-bits in the depth component.

• **VK_FORMAT_S8_UINT** specifies a one-component, 8-bit unsigned integer format that has 8-bits in the stencil component.

• **VK_FORMAT_D16_UNORM_S8_UINT** specifies a two-component, 24-bit format that has 16 unsigned normalized bits in the depth component and 8 unsigned integer bits in the stencil component.

• **VK_FORMAT_D24_UNORM_S8_UINT** specifies a two-component, 32-bit packed format that has 8 unsigned integer bits in the stencil component, and 24 unsigned normalized bits in the depth component.

• **VK_FORMAT_D32_SFLOAT_S8_UINT** specifies a two-component format that has 32 signed float bits in the depth component and 8 unsigned integer bits in the stencil component. There are optionally: 24-bits that are unused.

• **VK_FORMAT_BC1_RGB_UNORM_BLOCK** specifies a three-component, block-compressed format where
each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data. This format has no alpha and is considered opaque.

- **VK_FORMAT_BC1_RGB_SRGB_BLOCK** specifies a three-component, block-compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding. This format has no alpha and is considered opaque.

- **VK_FORMAT_BC1_RGBA_UNORM_BLOCK** specifies a four-component, block-compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data, and provides 1 bit of alpha.

- **VK_FORMAT_BC1_RGBA_SRGB_BLOCK** specifies a four-component, block-compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding, and provides 1 bit of alpha.

- **VK_FORMAT_BC2_UNORM_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values.

- **VK_FORMAT_BC2_SRGB_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values with sRGB nonlinear encoding.

- **VK_FORMAT_BC3_UNORM_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values.

- **VK_FORMAT_BC3_SRGB_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values with sRGB nonlinear encoding.

- **VK_FORMAT_BC4_UNORM_BLOCK** specifies a one-component, block-compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized red texel data.

- **VK_FORMAT_BC4_SNORM_BLOCK** specifies a one-component, block-compressed format where each 64-bit compressed texel block encodes a $4 \times 4$ rectangle of signed normalized red texel data.

- **VK_FORMAT_BC5_UNORM_BLOCK** specifies a two-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

- **VK_FORMAT_BC5_SNORM_BLOCK** specifies a two-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of signed normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

- **VK_FORMAT_BC6H_UFLOAT_BLOCK** specifies a three-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned floating-point RGB texel data.

- **VK_FORMAT_BC6H_SFLOAT_BLOCK** specifies a three-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of signed floating-point RGB texel data.

- **VK_FORMAT_BC7_UNORM_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ rectangle of unsigned normalized RGBA texel data.
• **VK_FORMAT_BC7_SRGB_BLOCK** specifies a four-component, block-compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK** specifies a three-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data. This format has no alpha and is considered opaque.

• **VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK** specifies a three-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding. This format has no alpha and is considered opaque.

• **VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK** specifies a four-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data, and provides 1 bit of alpha.

• **VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK** specifies a four-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding and provides 1 bit of alpha.

• **VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK** specifies a four-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with the first 64 bits encoding alpha values followed by 64 bits encoding RGB values.

• **VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK** specifies a four-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied.

• **VK_FORMAT_EAC_R11_UNORM_BLOCK** specifies a one-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized red texel data.

• **VK_FORMAT_EAC_R11_SNORM_BLOCK** specifies a one-component, ETC2 compressed format where each 64-bit compressed texel block encodes a 4×4 rectangle of signed normalized red texel data.

• **VK_FORMAT_EAC_R11G11_UNORM_BLOCK** specifies a two-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

• **VK_FORMAT_EAC_R11G11_SNORM_BLOCK** specifies a two-component, ETC2 compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of signed normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

• **VK_FORMAT_ASTC_4x4_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_4x4_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 4×4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_5x4_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×4 rectangle of unsigned normalized RGBA texel data.
• **VK_FORMAT_ASTC_5x4_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×4 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_5x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×5 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_5x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 5×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_6x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×5 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_6x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_6x6_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×6 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_6x6_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 6×6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_8x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×5 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_8x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_8x6_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×6 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_8x6_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_8x8_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×8 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_8x8_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes an 8×8 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x5_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×5 rectangle of unsigned normalized RGBA
• **VK_FORMAT_ASTC_10x5_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×5 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x6_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×6 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_10x6_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×6 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x8_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×8 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_10x8_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×8 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_10x10_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×10 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_10x10_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 10×10 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_12x10_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×10 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_12x10_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×10 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_ASTC_12x12_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×12 rectangle of unsigned normalized RGBA texel data.

• **VK_FORMAT_ASTC_12x12_SRGB_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a 12×12 rectangle of unsigned normalized RGBA texel data with sRGB nonlinear encoding applied to the RGB components.

• **VK_FORMAT_G8B8G8R8_422_UNORM** specifies a four-component, 32-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each i coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has an 8-bit G component for the even i coordinate in byte 0, an 8-bit B component in byte 1, an 8-bit G component for the odd i coordinate in byte 2, and an 8-bit R component in byte 3. Images in this format must be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.
VK_FORMAT_B8G8R8G8_422_UNORM specifies a four-component, 32-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each \( i \) coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has an 8-bit B component in byte 0, an 8-bit G component for the even \( i \) coordinate in byte 1, an 8-bit R component in byte 2, and an 8-bit G component for the odd \( i \) coordinate in byte 3. Images in this format must be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

VK_FORMAT_G8_B8R8_2PLANE_420_UNORM specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, and a two-component, 16-bit BR plane 1 consisting of an 8-bit B component in byte 0 and an 8-bit R component in byte 1. The horizontal dimensions of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \( i_G \times 0.5J = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via vkGetImageSubresourceLayout, using VK_IMAGE_ASPECT_PLANE_0_BIT for the G plane, and VK_IMAGE_ASPECT_PLANE_1_BIT for the BR plane. Images in this format must be defined with a width that is a multiple of two.

VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, an 8-bit B component in plane 1, and an 8-bit R component in plane 2. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which \( i_G \times 0.5J = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via vkGetImageSubresourceLayout, using VK_IMAGE_ASPECT_PLANE_0_BIT for the G plane, VK_IMAGE_ASPECT_PLANE_1_BIT for the B plane, and VK_IMAGE_ASPECT_PLANE_2_BIT for the R plane. Images in this format must be defined with a width and height that is a multiple of two.

VK_FORMAT_G8_B8R8_2PLANE_422_UNORM specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, and a two-component, 16-bit BR plane 1 consisting of an 8-bit B component in byte 0 and an 8-bit R component in byte 1. The horizontal dimensions of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \( i_G \times 0.5J = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via vkGetImageSubresourceLayout, using VK_IMAGE_ASPECT_PLANE_0_BIT for the G plane, and VK_IMAGE_ASPECT_PLANE_1_BIT for the BR plane. Images in this format must be defined with a width that is a multiple of two.

VK_FORMAT_G8_B8R8_2PLANE_444_UNORM specifies an unsigned normalized multi-planar format that has an 8-bit G component in plane 0, an 8-bit B component in plane 1, and an 8-bit R component in plane 2. Each plane has the same dimensions and each R, G and B component contributes to a
single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane.

- **VK_FORMAT_R10X6_UNORM_PACK16** specifies a one-component, 16-bit unsigned normalized format that has a single 10-bit R component in the top 10 bits of a 16-bit word, with the bottom 6 bits unused.

- **VK_FORMAT_R10X6G10X6_UNORM_2PACK16** specifies a two-component, 32-bit unsigned normalized format that has a 10-bit R component in the top 10 bits of the word in bytes 0..1, and a 10-bit G component in the top 10 bits of the word in bytes 2..3, with the bottom 6 bits of each word unused.

- **VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16** specifies a four-component, 64-bit unsigned normalized format that has a 10-bit R component in the top 10 bits of the word in bytes 0..1, a 10-bit G component in the top 10 bits of the word in bytes 2..3, a 10-bit B component in the top 10 bits of the word in bytes 4..5, and a 10-bit A component in the top 10 bits of the word in bytes 6..7, with the bottom 6 bits of each word unused.

- **VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each $i$ coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 10-bit G component for the even $i$ coordinate in the top 10 bits of the word in bytes 0..1, a 10-bit B component in the top 10 bits of the word in bytes 2..3, a 10-bit G component for the odd $i$ coordinate in the top 10 bits of the word in bytes 4..5, and a 10-bit R component in the top 10 bits of the word in bytes 6..7, with the bottom 6 bits of each word unused. Images in this format **must** be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each $i$ coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 10-bit B component in the top 10 bits of the word in bytes 0..1, a 10-bit G component for the even $i$ coordinate in the top 10 bits of the word in bytes 2..3, a 10-bit R component in the top 10 bits of the word in bytes 4..5, and a 10-bit G component for the odd $i$ coordinate in the top 10 bits of the word in bytes 6..7, with the bottom 6 bits of each word unused. Images in this format **must** be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16** specifies an unsigned normalized **multi-planar format** that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, a 10-bit B component in the top 10 bits of each 16-bit word of plane 1, and a 10-bit R component in the top 10 bits of each 16-bit word of plane 2, with the bottom 6 bits of each word unused. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which $i_G \times 0.5 = i_B = i_R$ and $1_i G \times 0.5 i = j_B = j_R$. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using...
VK_IMAGE_ASPECT_PLANE_0_BIT for the G plane, VK_IMAGE_ASPECT_PLANE_1_BIT for the B plane, and VK_IMAGE_ASPECT_PLANE_2_BIT for the R plane. Images in this format must be defined with a width and height that is a multiple of two.

- **VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16** specifies an unsigned normalized *multiplanar format* that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 10-bit B component in the top 10 bits of the word in bytes 0..1, and a 10-bit R component in the top 10 bits of the word in bytes 2..3, the bottom 6 bits of each word unused. The horizontal and vertical dimensions of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which $|i_G \times 0.5| = i_B = i_R$ and $|j_G \times 0.5| = j_B = j_R$. The location of each plane when this image is in linear layout can be determined via vkGetImageSubresourceLayout, using VK_IMAGE_ASPECT_PLANE_0_BIT for the G plane, and VK_IMAGE_ASPECT_PLANE_1_BIT for the BR plane. Images in this format must be defined with a width and height that is a multiple of two.

- **VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16** specifies an unsigned normalized *multiplanar format* that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, a 10-bit B component in the top 10 bits of each 16-bit word of plane 1, and a 10-bit R component in the top 10 bits of each 16-bit word of plane 2, with the bottom 6 bits of each word unused. The horizontal dimension of the R and B plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which $|i_G \times 0.5| = i_B = i_R$. The location of each plane when this image is in linear layout can be determined via vkGetImageSubresourceLayout, using VK_IMAGE_ASPECT_PLANE_0_BIT for the G plane, VK_IMAGE_ASPECT_PLANE_1_BIT for the B plane, and VK_IMAGE_ASPECT_PLANE_2_BIT for the R plane. Images in this format must be defined with a width that is a multiple of two.

- **VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16** specifies an unsigned normalized *multiplanar format* that has a 10-bit G component in the top 10 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 10-bit B component in the top 10 bits of the word in bytes 0..1, and a 10-bit R component in the top 10 bits of the word in bytes 2..3, the bottom 6 bits of each word unused. The horizontal dimensions of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which $|i_G \times 0.5| = i_B = i_R$. The location of each plane when this image is in linear layout can be determined via vkGetImageSubresourceLayout, using VK_IMAGE_ASPECT_PLANE_0_BIT for the G plane, VK_IMAGE_ASPECT_PLANE_1_BIT for the B plane, and VK_IMAGE_ASPECT_PLANE_2_BIT for the R plane. Images in this format must be defined with a width that is a multiple of two.

- **VK_FORMAT_R12X4_UNORM_PACK16** specifies a one-component, 16-bit unsigned normalized format that has a single 12-bit R component in the top 12 bits of a 16-bit word, with the bottom 4 bits unused.

- **VK_FORMAT_R12X4G12X4_UNORM_2PACK16** specifies a two-component, 32-bit unsigned normalized
format that has a 12-bit R component in the top 12 bits of the word in bytes 0..1, and a 12-bit G component in the top 12 bits of the word in bytes 2..3, with the bottom 4 bits of each word unused.

- **VK_FORMAT_R12X4G12X4B12X4_UNORM_4PACK16** specifies a four-component, 64-bit unsigned normalized format that has a 12-bit R component in the top 12 bits of the word in bytes 0..1, a 12-bit G component in the top 12 bits of the word in bytes 2..3, a 12-bit B component in the top 12 bits of the word in bytes 4..5, and a 12-bit A component in the top 12 bits of the word in bytes 6..7, with the bottom 4 bits of each word unused.

- **VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each i coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 12-bit G component for the even i coordinate in the top 12 bits of the word in bytes 0..1, a 12-bit B component in the top 12 bits of the word in bytes 2..3, a 12-bit G component for the odd i coordinate in the top 12 bits of the word in bytes 4..5, and a 12-bit R component in the top 12 bits of the word in bytes 6..7, with the bottom 4 bits of each word unused. Images in this format must be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each i coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 12-bit B component in the top 12 bits of the word in bytes 0..1, a 12-bit G component for the even i coordinate in the top 12 bits of the word in bytes 2..3, a 12-bit R component in the top 12 bits of the word in bytes 4..5, and a 12-bit G component for the odd i coordinate in the top 12 bits of the word in bytes 6..7, with the bottom 4 bits of each word unused. Images in this format must be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, a 12-bit B component in the top 12 bits of each 16-bit word of plane 1, and a 12-bit R component in the top 12 bits of each 16-bit word of plane 2, with the bottom 4 bits of each word unused. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which \( i_G \times 0.5 = i_B = i_R \) and \( j_G \times 0.5 = j_B = j_R \). The location of each plane when this image is in linear layout can be determined via \( \text{vkGetImageSubresourceLayout} \), using \( \text{VK_IMAGE_ASPECT_PLANE_0_BIT} \) for the G plane, \( \text{VK_IMAGE_ASPECT_PLANE_1_BIT} \) for the B plane, and \( \text{VK_IMAGE_ASPECT_PLANE_2_BIT} \) for the R plane. Images in this format must be defined with a width and height that is a multiple of two.

- **VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 12-bit B component in the top 12 bits of the word in bytes 0..1, and a 12-bit R component in the top 12 bits of the word in bytes 2..3, the bottom 4 bits of each word unused. The horizontal and vertical dimensions of the BR plane is
halved relative to the image dimensions, and each R and B value is shared with the G components for which \( \lfloor i_G \times 0.5 \rfloor = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. Images in this format **must** be defined with a width and height that is a multiple of two.

- **VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_422_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, a 12-bit B component in the top 12 bits of each 16-bit word of plane 1, and a 12-bit R component in the top 12 bits of each 16-bit word of plane 2, with the bottom 4 bits of each word unused. The horizontal dimension of the R and B plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \( \lfloor i_G \times 0.5 \rfloor = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. Images in this format **must** be defined with a width that is a multiple of two.

- **VK_FORMAT_G12X4_B12X4_R12X4_2PLANE_422_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 12-bit B component in the top 12 bits of the word in bytes 0..1, and a 12-bit R component in the top 12 bits of the word in bytes 2..3, the bottom 4 bits of each word unused. The horizontal dimensions of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \( \lfloor i_G \times 0.5 \rfloor = i_B = i_R \). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. Images in this format **must** be defined with a width that is a multiple of two.

- **VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16** specifies an unsigned normalized multi-planar format that has a 12-bit G component in the top 12 bits of each 16-bit word of plane 0, a 12-bit B component in the top 12 bits of each 16-bit word of plane 1, and a 12-bit R component in the top 12 bits of each 16-bit word of plane 2, with the bottom 4 bits of each word unused. Each plane has the same dimensions and each R, G and B component contributes to a single texel. The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. Images in this format **must** be defined with a width that is a multiple of two.

- **VK_FORMAT_G16B16G16R16_422_UNORM** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each \( i \) coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image. This format has a 16-bit G component for the even \( i \) coordinate in the word in bytes 0..1, a 16-bit B component in the word in bytes 2..3, a 16-bit G component for the odd \( i \) coordinate in the word in bytes 4..5, and a 16-bit R component in the word in bytes 6..7. Images in this format **must** be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_B16G16R16G16_422_UNORM** specifies a four-component, 64-bit format containing a pair of G components, an R component, and a B component, collectively encoding a 2×1 rectangle of unsigned normalized RGB texel data. One G value is present at each \( i \) coordinate, with the B and R values shared across both G values and thus recorded at half the horizontal resolution of the image.
image. This format has a 16-bit B component in the word in bytes 0..1, a 16-bit G component for the even \(i\) coordinate in the word in bytes 2..3, a 16-bit R component in the word in bytes 4..5, and a 16-bit G component for the odd \(i\) coordinate in the word in bytes 6..7. Images in this format must be defined with a width that is a multiple of two. For the purposes of the constraints on copy extents, this format is treated as a compressed format with a 2×1 compressed texel block.

- **VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, a 16-bit B component in each 16-bit word of plane 1, and a 16-bit R component in each 16-bit word of plane 2. The horizontal and vertical dimensions of the R and B planes are halved relative to the image dimensions, and each R and B component is shared with the G components for which \(\lfloor c \times 0.5 \rfloor = j_B = j_R\) and \(\lceil c \times 0.5 \rceil = j_B = j_R\). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. Images in this format must be defined with a width and height that is a multiple of two.

- **VK_FORMAT_G16_B16R16_2PLANE_420_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 16-bit B component in the word in bytes 0..1, and a 16-bit R component in the word in bytes 2..3. The horizontal and vertical dimensions of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \(\lfloor c \times 0.5 \rfloor = i_B = i_R\) and \(\lceil c \times 0.5 \rceil = j_B = j_R\). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. Images in this format must be defined with a width and height that is a multiple of two.

- **VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, a 16-bit B component in each 16-bit word of plane 1, and a 16-bit R component in each 16-bit word of plane 2. The horizontal dimension of the R and B plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \(\lfloor c \times 0.5 \rfloor = j_B = j_R\). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane. Images in this format must be defined with a width that is a multiple of two.

- **VK_FORMAT_G16_B16R16_2PLANE_422_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, and a two-component, 32-bit BR plane 1 consisting of a 16-bit B component in the word in bytes 0..1, and a 16-bit R component in the word in bytes 2..3. The horizontal dimensions of the BR plane is halved relative to the image dimensions, and each R and B value is shared with the G components for which \(\lfloor c \times 0.5 \rfloor = i_B = i_R\). The location of each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, and `VK_IMAGE_ASPECT_PLANE_1_BIT` for the BR plane. Images in this format must be defined with a width that is a multiple of two.

- **VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM** specifies an unsigned normalized multi-planar format that has a 16-bit G component in each 16-bit word of plane 0, a 16-bit B component in each 16-bit word of plane 1, and a 16-bit R component in each 16-bit word of plane 2. Each plane has the same dimensions and each R, G and B component contributes to a single texel. The location of
each plane when this image is in linear layout can be determined via `vkGetImageSubresourceLayout`, using `VK_IMAGE_ASPECT_PLANE_0_BIT` for the G plane, `VK_IMAGE_ASPECT_PLANE_1_BIT` for the B plane, and `VK_IMAGE_ASPECT_PLANE_2_BIT` for the R plane.

### 36.1.1. Compatible formats of planes of multi-planar formats

Individual planes of multi-planar formats are *compatible* with single-plane formats if they occupy the same number of bits per texel block. In the following table, individual planes of a *multi-planar* format are compatible with the format listed against the relevant plane index for that multi-planar format.

<table>
<thead>
<tr>
<th>Plane</th>
<th>Compatible format for plane</th>
<th>Width relative to the width (w) of the plane with the largest dimensions</th>
<th>Height relative to the height (h) of the plane with the largest dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>(w/2)</td>
<td>(h/2)</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>(w/2)</td>
<td>(h/2)</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8R8_2PLANE_420_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R8G8_UNORM</td>
<td>(w/2)</td>
<td>(h/2)</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R8G8_UNORM</td>
<td>(w/2)</td>
<td>(h)</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R8G8_UNORM</td>
<td>(w/2)</td>
<td>(h)</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8R8_2PLANE_422_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R8G8_UNORM</td>
<td>(w/2)</td>
<td>(h)</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R8G8_UNORM</td>
<td>(w/2)</td>
<td>(h)</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R8G8_UNORM</td>
<td>(w/2)</td>
<td>(h)</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>(w/2)</td>
<td>(h/2)</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>(w/2)</td>
<td>(h/2)</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R10X6G10X6_UNORM_2PACK16</td>
<td>(w/2)</td>
<td>(h/2)</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>(w)</td>
<td>(h)</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R10X6G10X6_UNORM_2PACK16</td>
<td>(w/2)</td>
<td>(h/2)</td>
</tr>
</tbody>
</table>

Table 37. Plane Format Compatibility Table
<table>
<thead>
<tr>
<th>Plane</th>
<th>Compatible format for plane</th>
<th>Width relative to the width $w$ of the plane with the largest dimensions</th>
<th>Height relative to the height $h$ of the plane with the largest dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R10X6G10X6_UNORM_2PACK16</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R12X4G12X4_UNORM_2PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R12X4R12X4_UNORM_2PACK16</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R12X4R12X4_UNORM_2PACK16</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_422_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R12X4G12X4_UNORM_2PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R12X4R12X4_UNORM_2PACK16</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R12X4R12X4_UNORM_2PACK16</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
<tr>
<td></td>
<td><strong>VK_FORMAT_G16_B16R16_2PLANE_420_UNORM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R16G16_UNORM</td>
<td>$w/2$</td>
<td>$h/2$</td>
</tr>
</tbody>
</table>

Chapter 36. Formats | 1151
<table>
<thead>
<tr>
<th>Plane</th>
<th>Compatible format for plane</th>
<th>Width relative to the width $w$ of the plane with the largest dimensions</th>
<th>Height relative to the height $h$ of the plane with the largest dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16R16_2PLANE_422_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R16G16_UNORM</td>
<td>$w/2$</td>
<td>$h$</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>1</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
<tr>
<td>2</td>
<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
</tbody>
</table>

### 36.1.2. Packed Formats

For the purposes of address alignment when accessing buffer memory containing vertex attribute or texel data, the following formats are considered *packed* - whole texels or attributes are stored in bitfields of a single 8-, 16-, or 32-bit fundamental data type.

- **Packed into 8-bit data types:**
  - VK_FORMAT_R4G4_UNORM_PACK8

- **Packed into 16-bit data types:**
  - VK_FORMAT_R4G4B4A4_UNORM_PACK16
  - VK_FORMAT_B4G4R4A4_UNORM_PACK16
  - VK_FORMAT_R5G6B5_UNORM_PACK16
  - VK_FORMAT_B5G6R5_UNORM_PACK16
  - VK_FORMAT_R5G5B5A1_UNORM_PACK16
  - VK_FORMAT_B5G5R5A1_UNORM_PACK16
  - VK_FORMAT_A1R5G5B5_UNORM_PACK16

- **Packed into 32-bit data types:**
  - VK_FORMAT_A8B8G8R8_UNORM_PACK32
  - VK_FORMAT_A8B8G8R8_SNORM_PACK32
  - VK_FORMAT_A8B8G8R8_USCALED_PACK32
  - VK_FORMAT_A8B8G8R8_SSCALED_PACK32
  - VK_FORMAT_A8B8G8R8_UINT_PACK32
  - VK_FORMAT_A8B8G8R8_SINT_PACK32
  - VK_FORMAT_A8B8G8R8_SRGB_PACK32
  - VK_FORMAT_A2R10G10B10_UNORM_PACK32
  - VK_FORMAT_A2R10G10B10_SNORM_PACK32
36.1.3. Identification of Formats

A “format” is represented by a single enum value. The name of a format is usually built up by using the following pattern:

\[
\text{VK_FORMAT}_{\text{component-format|compression-scheme}}_{\text{numeric-format}}
\]

The component-format indicates either the size of the R, G, B, and A components (if they are present) in the case of a color format, or the size of the depth (D) and stencil (S) components (if they are present) in the case of a depth/stencil format (see below). An X indicates a component that is unused, but may be present for padding.
### Table 38. Interpretation of Numeric Format

<table>
<thead>
<tr>
<th>Numeric format</th>
<th>SPIR-V Sampled Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNORM</td>
<td>OpTypeFloat</td>
<td>The components are unsigned normalized values in the range [0,1]</td>
</tr>
<tr>
<td>SNORM</td>
<td>OpTypeFloat</td>
<td>The components are signed normalized values in the range [-1,1]</td>
</tr>
<tr>
<td>USCALED</td>
<td>OpTypeFloat</td>
<td>The components are unsigned integer values that get converted to floating-point in the range ([0,2^n-1])</td>
</tr>
<tr>
<td>SSCALED</td>
<td>OpTypeFloat</td>
<td>The components are signed integer values that get converted to floating-point in the range ([-2^{n-1},2^{n-1}-1])</td>
</tr>
<tr>
<td>UINT</td>
<td>OpTypeInt</td>
<td>The components are unsigned integer values in the range ([0,2^n-1])</td>
</tr>
<tr>
<td>SINT</td>
<td>OpTypeInt</td>
<td>The components are signed integer values in the range ([-2^{n-1},2^{n-1}-1])</td>
</tr>
<tr>
<td>UFLOAT</td>
<td>OpTypeFloat</td>
<td>The components are unsigned floating-point numbers (used by packed, shared exponent, and some compressed formats)</td>
</tr>
<tr>
<td>SFLOAT</td>
<td>OpTypeFloat</td>
<td>The components are signed floating-point numbers</td>
</tr>
<tr>
<td>SRGB</td>
<td>OpTypeFloat</td>
<td>The R, G, and B components are unsigned normalized values that represent values using sRGB nonlinear encoding, while the A component (if one exists) is a regular unsigned normalized value</td>
</tr>
</tbody>
</table>

The suffix \_PACKnn indicates that the format is packed into an underlying type with \(nn\) bits. The suffix \_mPACKnn is a short-hand that indicates that the format has several components (which may or may not be stored in separate planes) that are each packed into an underlying type with \(nn\) bits.

The suffix \_BLOCK indicates that the format is a block-compressed format, with the representation of multiple pixels encoded interdependently within a region.

### Table 39. Interpretation of Compression Scheme

<table>
<thead>
<tr>
<th>Compression scheme</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>Block Compression. See Block-Compressed Image Formats.</td>
</tr>
<tr>
<td>ETC2</td>
<td>Ericsson Texture Compression. See ETC Compressed Image Formats.</td>
</tr>
<tr>
<td>EAC</td>
<td>ETC2 Alpha Compression. See ETC Compressed Image Formats.</td>
</tr>
<tr>
<td>ASTC</td>
<td>Adaptive Scalable Texture Compression (LDR Profile). See ASTC Compressed Image Formats.</td>
</tr>
</tbody>
</table>

For multi-planar images, the components in separate planes are separated by underscores, and the number of planes is indicated by the addition of a \_2PLANE or \_3PLANE suffix. Similarly, the separate aspects of depth-stencil formats are separated by underscores, although these are not considered separate planes. Formats are suffixed by \_422 to indicate that planes other than the first are reduced in size by a factor of two horizontally or that the R and B values appear at half the horizontal frequency of the G values, \_420 to indicate that planes other than the first are reduced in size by a factor of two vertically.

---

1154 | Chapter 36. Formats
size by a factor of two both horizontally and vertically, and _444 for consistency to indicate that all three planes of a three-planar image are the same size.

Note
No common format has a single plane containing both R and B channels but does not store these channels at reduced horizontal resolution.

36.1.4. Representation and Texel Block Size

Color formats **must** be represented in memory in exactly the form indicated by the format’s name. This means that promoting one format to another with more bits per component and/or additional components **must** not occur for color formats. Depth/stencil formats have more relaxed requirements as discussed below.

Each format has a *texel block size*, the number of bytes used to store one texel block (a single addressable element of an uncompressed image, or a single compressed block of a compressed image). The texel block size for each format is shown in the [Compatible formats](#) table.

The representation of non-packed formats is that the first component specified in the name of the format is in the lowest memory addresses and the last component specified is in the highest memory addresses. See [Byte mappings for non-packed/compressed color formats](#). The in-memory ordering of bytes within a component is determined by the host endianness.

<table>
<thead>
<tr>
<th>Value</th>
<th>Component Order</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>R</td>
<td>VK_FORMAT_R8_</td>
</tr>
<tr>
<td>0</td>
<td>G</td>
<td>VK_FORMAT_R8G8_</td>
</tr>
<tr>
<td>0</td>
<td>B</td>
<td>VK_FORMAT_R8G8B8_</td>
</tr>
<tr>
<td>0</td>
<td>R</td>
<td>VK_FORMAT_B8G8R8_</td>
</tr>
<tr>
<td>0</td>
<td>G</td>
<td>VK_FORMAT_B8G8B8_</td>
</tr>
<tr>
<td>0</td>
<td>B</td>
<td>VK_FORMAT_B8G8B8A8_</td>
</tr>
<tr>
<td>0</td>
<td>G</td>
<td>VK_FORMAT_B8G8B8R8_</td>
</tr>
<tr>
<td>0</td>
<td>B</td>
<td>VK_FORMAT_B8G8B8R8A8_</td>
</tr>
<tr>
<td>1</td>
<td>R</td>
<td>VK_FORMAT_R16_</td>
</tr>
<tr>
<td>1</td>
<td>G</td>
<td>VK_FORMAT_R16G16_</td>
</tr>
<tr>
<td>1</td>
<td>B</td>
<td>VK_FORMAT_R16G16B16_</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>VK_FORMAT_R16G16B16A16_</td>
</tr>
<tr>
<td>2</td>
<td>G</td>
<td>VK_FORMAT_G10X6B10X6G10X6R10X6_4PACK16_422_UNORM</td>
</tr>
<tr>
<td>3</td>
<td>R</td>
<td>VK_FORMAT_G12X4B12X4G12X4R12X4_4PACK16_422_UNORM</td>
</tr>
<tr>
<td>4</td>
<td>G</td>
<td>VK_FORMAT_G16B16G16R16_</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>VK_FORMAT_B10X6G10X6R10X6G10X6_4PACK16_422_UNORM</td>
</tr>
<tr>
<td>6</td>
<td>G</td>
<td>VK_FORMAT_B12X4G12X4R12X4G12X4_4PACK16_422_UNORM</td>
</tr>
<tr>
<td>7</td>
<td>R</td>
<td>VK_FORMAT_B16G16R16G16_</td>
</tr>
</tbody>
</table>

Table 40. Byte mappings for non-packed/compressed color formats

- Byte
Packed formats store multiple components within one underlying type. The bit representation is that the first component specified in the name of the format is in the most-significant bits and the last component specified is in the least-significant bits of the underlying type. The in-memory ordering of bytes comprising the underlying type is determined by the host endianness.

**Table 41. Bit mappings for packed 8-bit formats**

<table>
<thead>
<tr>
<th>Bit</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>R G</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 42. Bit mappings for packed 16-bit formats**

| Bit | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|-----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|---|
| R G B A | 3 | 2 | 1 | 0 | 3 | 2 | 1 | 0 | 3 | 2 | 1 | 0 | 3 | 2 | 1 | 0 |

| Bit | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|-----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|---|
| B G R A | 3 | 2 | 1 | 0 | 3 | 2 | 1 | 0 | 3 | 2 | 1 | 0 | 3 | 2 | 1 | 0 |

| Bit | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|-----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|---|
| R G B | 4 | 3 | 2 | 1 | 0 | 5 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 |

| Bit | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|-----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|---|
| B G R | 4 | 3 | 2 | 1 | 0 | 5 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 |

| Bit | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|-----|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|---|
| R G B A | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 | 4 | 3 | 2 | 1 | 0 | 0 |
### 36.1.5. Depth/Stencil Formats

Depth/stencil formats are considered opaque and need not be stored in the exact number of bits per texel or component ordering indicated by the format enum. However, implementations must not substitute a different depth or stencil precision than that described in the format (e.g. D16 must not be implemented as D24 or D32).

### 36.1.6. Format Compatibility Classes

Uncompressed color formats are compatible with each other if they occupy the same number of bits per texel block. Compressed color formats are compatible with each other if the only difference between them is the numerical type of the uncompressed pixels (e.g. signed vs. unsigned, or SRGB vs. UNORM encoding). Each depth/stencil format is only compatible with itself. In the following...
Table 44. Compatible Formats

<table>
<thead>
<tr>
<th>Class, Texel Block Size, # Texels/Block</th>
<th>Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-bit</td>
<td>VK_FORMAT_R4G4_UNORM_PACK8, VK_FORMAT_R8_UNORM, VK_FORMAT_R8_SNORM, VK_FORMAT_R8_USCALED, VK_FORMAT_R8_SSCALED, VK_FORMAT_R8_UINT, VK_FORMAT_R8_SINT, VK_FORMAT_R8_SRGB</td>
</tr>
<tr>
<td>16-bit</td>
<td>VK_FORMAT_R4G4B4A4_UNORM_PACK16, VK_FORMAT_B4G4R4A4_UNORM_PACK16, VK_FORMAT_R5G6B5_UNORM_PACK16, VK_FORMAT_B5G6R5_UNORM_PACK16, VK_FORMAT_R5G5B5A1_UNORM_PACK16, VK_FORMAT_B5G5R5A1_UNORM_PACK16, VK_FORMAT_A1R5G5B5_UNORM_PACK16, VK_FORMAT_R8G8_UNORM, VK_FORMAT_R8G8_SNORM, VK_FORMAT_R8G8_USCALED, VK_FORMAT_R8G8_SSCALED, VK_FORMAT_R8G8_UINT, VK_FORMAT_R8G8_SINT, VK_FORMAT_R8G8_SRGB, VK_FORMAT_R16_UNORM, VK_FORMAT_R16_SNORM, VK_FORMAT_R16_USCALED, VK_FORMAT_R16_SSCALED, VK_FORMAT_R16_UINT, VK_FORMAT_R16_SINT, VK_FORMAT_R16_SFLOAT, VK_FORMAT_R10X6_UNORM_PACK16, VK_FORMAT_R12X4_UNORM_PACK16</td>
</tr>
<tr>
<td>24-bit</td>
<td>VK_FORMAT_R8G8B8_UNORM, VK_FORMAT_R8G8B8_SNORM, VK_FORMAT_R8G8B8_USCALED, VK_FORMAT_R8G8B8_SSCALED, VK_FORMAT_R8G8B8_UINT, VK_FORMAT_R8G8B8_SINT, VK_FORMAT_R8G8B8_SRGB, VK_FORMAT_B8G8R8_UNORM, VK_FORMAT_B8G8R8_SNORM, VK_FORMAT_B8G8R8_USCALED, VK_FORMAT_B8G8R8_SSCALED, VK_FORMAT_B8G8R8_UINT, VK_FORMAT_B8G8R8_SINT, VK_FORMAT_B8G8R8_SRGB</td>
</tr>
</tbody>
</table>

all the formats in the same row are compatible.
<table>
<thead>
<tr>
<th>Class, Texel Block Size, # Texels/Block</th>
<th>Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td>32-bit Block size 4 bytes 1 texel/block</td>
<td>VK_FORMAT_R8G8B8A8_UNORM, VK_FORMAT_R8G8B8A8_SNORM, VK_FORMAT_R8G8B8A8_USCALED, VK_FORMAT_R8G8B8A8_SSCALED, VK_FORMAT_R8G8B8A8_UINT, VK_FORMAT_R8G8B8A8_SINT, VK_FORMAT_R8G8B8A8_SRGB, VK_FORMAT_B8G8R8A8_UNORM, VK_FORMAT_B8G8R8A8_SNORM, VK_FORMAT_B8G8R8A8_USCALED, VK_FORMAT_B8G8R8A8_SSCALED, VK_FORMAT_B8G8R8A8_UINT, VK_FORMAT_B8G8R8A8_SINT, VK_FORMAT_B8G8R8A8_SRGB, VK_FORMAT_A8B8G8R8_UNORM_PACK32, VK_FORMAT_A8B8G8R8_SNORM_PACK32, VK_FORMAT_A8B8G8R8_USCALED_PACK32, VK_FORMAT_A8B8G8R8_SSCALED_PACK32, VK_FORMAT_A8B8G8R8_UINT_PACK32, VK_FORMAT_A8B8G8R8_SINT_PACK32, VK_FORMAT_A8B8G8R8_SRGB_PACK32, VK_FORMAT_A2R10G10B10_UNORM_PACK32, VK_FORMAT_A2R10G10B10_SNORM_PACK32, VK_FORMAT_A2R10G10B10_USCALED_PACK32, VK_FORMAT_A2R10G10B10_SSCALED_PACK32, VK_FORMAT_A2R10G10B10_UINT_PACK32, VK_FORMAT_A2R10G10B10_SINT_PACK32, VK_FORMAT_A2B10G10R10_UNORM_PACK32, VK_FORMAT_A2B10G10R10_SNORM_PACK32, VK_FORMAT_A2B10G10R10_USCALED_PACK32, VK_FORMAT_A2B10G10R10_SSCALED_PACK32, VK_FORMAT_A2B10G10R10_UINT_PACK32, VK_FORMAT_A2B10G10R10_SINT_PACK32, VK_FORMAT_R16G16_UNORM, VK_FORMAT_R16G16_SNORM, VK_FORMAT_R16G16_USCALED, VK_FORMAT_R16G16_SSCALED, VK_FORMAT_R16G16_UINT, VK_FORMAT_R16G16_SINT, VK_FORMAT_R16G16_SFLOAT, VK_FORMAT_R32_UINT, VK_FORMAT_R32_SINT, VK_FORMAT_R32_SFLOAT, VK_FORMAT_B10G11R11_UFLOAT_PACK32, VK_FORMAT_E5B9G9R9_UFLOAT_PACK32, VK_FORMAT_R10X6G10X6_UNORM_2PACK16, VK_FORMAT_R12X4G12X4_UNORM_2PACK16</td>
</tr>
<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>32-bit G8B8G8R8 Block size 4 bytes 1 texel/block</td>
<td>VK_FORMAT_G8B8G8R8_422_UNORM</td>
</tr>
<tr>
<td>32-bit B8G8R8G8 Block size 4 bytes 1 texel/block</td>
<td>VK_FORMAT_B8G8R8G8_422_UNORM</td>
</tr>
<tr>
<td>64-bit R10G10B10A10 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit G10B10G10R10 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit B10G10R10G10 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit R12G12B12A12 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit G12B12G12R12 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>64-bit B12G12R12G12 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16</td>
</tr>
<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>64-bit G16B16G16R16 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_G16B16G16R16_422_UNORM</td>
</tr>
<tr>
<td>64-bit B16G16R16G16 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_B16G16R16G16_422_UNORM</td>
</tr>
<tr>
<td>96-bit Block size 12 bytes 1 texel/block</td>
<td>VK_FORMAT_R32G32B32A32_UINT, VK_FORMAT_R32G32B32A32_SINT, VK_FORMAT_R32G32B32A32_SFLOAT</td>
</tr>
<tr>
<td>128-bit Block size 16 bytes 1 texel/block</td>
<td>VK_FORMAT_R32G32B32A32_UINT, VK_FORMAT_R32G32B32A32_SINT, VK_FORMAT_R32G32B32A32_SFLOAT, VK_FORMAT_R64G64_UINT, VK_FORMAT_R64G64_SINT, VK_FORMAT_R64G64_SFLOAT</td>
</tr>
<tr>
<td>192-bit Block size 24 bytes 1 texel/block</td>
<td>VK_FORMAT_R64G64B64A64_UINT, VK_FORMAT_R64G64B64A64_SINT, VK_FORMAT_R64G64B64A64_SFLOAT</td>
</tr>
<tr>
<td>256-bit Block size 32 bytes 1 texel/block</td>
<td>VK_FORMAT_R64G64B64A64_UINT, VK_FORMAT_R64G64B64A64_SINT, VK_FORMAT_R64G64B64A64_SFLOAT</td>
</tr>
<tr>
<td>BC1_RGB (64 bit) Block size 8 bytes 16 texels/block</td>
<td>VK_FORMAT_BC1_RGB_UNORM_BLOCK, VK_FORMAT_BC1_RGB_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC1_RGBA (64 bit) Block size 8 bytes 16 texels/block</td>
<td>VK_FORMAT_BC1_RGBA_UNORM_BLOCK, VK_FORMAT_BC1_RGBA_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC2 (128 bit) Block size 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC2_UNORM_BLOCK, VK_FORMAT_BC2_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC3 (128 bit) Block size 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC3_UNORM_BLOCK, VK_FORMAT_BC3_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC4 (64 bit) Block size 8 bytes 16 texels/block</td>
<td>VK_FORMAT_BC4_UNORM_BLOCK, VK_FORMAT_BC4_SNORM_BLOCK</td>
</tr>
<tr>
<td>BC5 (128 bit) Block size 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC5_UNORM_BLOCK, VK_FORMAT_BC5_SNORM_BLOCK</td>
</tr>
<tr>
<td>BC6H (128 bit) Block size 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC6H_UFLOAT_BLOCK, VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
</tr>
<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>BC7 (128 bit) Block size 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC7_UNORM_BLOCK, VK_FORMAT_BC7_SRGB_BLOCK</td>
</tr>
<tr>
<td>ETC2_RGB (64 bit) Block size 8 bytes 16 texels/block</td>
<td>VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK</td>
</tr>
<tr>
<td>ETC2_RGBA (64 bit) Block size 8 bytes 16 texels/block</td>
<td>VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK</td>
</tr>
<tr>
<td>ETC2_EAC_RGBA (64 bit) Block size 8 bytes 16 texels/block</td>
<td>VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK, VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK</td>
</tr>
<tr>
<td>EAC_R (64 bit) Block size 8 bytes 16 texels/block</td>
<td>VK_FORMAT_EAC_R11_UNORM_BLOCK, VK_FORMAT_EAC_R11_SNORM_BLOCK</td>
</tr>
<tr>
<td>EAC_RG (128 bit) Block size 16 bytes 16 texels/block</td>
<td>VK_FORMAT_EAC_R11G11_UNORM_BLOCK, VK_FORMAT_EAC_R11G11_SNORM_BLOCK</td>
</tr>
<tr>
<td>ASTC_4x4 (128 bit) Block size 16 bytes 16 texels/block</td>
<td>VK_FORMAT_ASTC_4x4_UNORM_BLOCK, VK_FORMAT_ASTC_4x4_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_5x4 (128 bit) Block size 16 bytes 20 texels/block</td>
<td>VK_FORMAT_ASTC_5x4_UNORM_BLOCK, VK_FORMAT_ASTC_5x4_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_5x5 (128 bit) Block size 16 bytes 25 texels/block</td>
<td>VK_FORMAT_ASTC_5x5_UNORM_BLOCK, VK_FORMAT_ASTC_5x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_6x5 (128 bit) Block size 16 bytes 30 texels/block</td>
<td>VK_FORMAT_ASTC_6x5_UNORM_BLOCK, VK_FORMAT_ASTC_6x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_6x6 (128 bit) Block size 16 bytes 36 texels/block</td>
<td>VK_FORMAT_ASTC_6x6_UNORM_BLOCK, VK_FORMAT_ASTC_6x6_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_8x5 (128 bit) Block size 16 bytes 40 texels/block</td>
<td>VK_FORMAT_ASTC_8x5_UNORM_BLOCK, VK_FORMAT_ASTC_8x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_8x6 (128 bit) Block size 16 bytes 48 texels/block</td>
<td>VK_FORMAT_ASTC_8x6_UNORM_BLOCK, VK_FORMAT_ASTC_8x6_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_8x8 (128 bit) Block size 16 bytes 64 texels/block</td>
<td>VK_FORMAT_ASTC_8x8_UNORM_BLOCK, VK_FORMAT_ASTC_8x8_SRGB_BLOCK</td>
</tr>
<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>ASTC_10x5 (128 bit) Block size 16 bytes 50 texels/block</td>
<td>VK_FORMAT_ASTC_10x5_UNORM_BLOCK, VK_FORMAT_ASTC_10x5_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_10x6 (128 bit) Block size 16 bytes 60 texels/block</td>
<td>VK_FORMAT_ASTC_10x6_UNORM_BLOCK, VK_FORMAT_ASTC_10x6_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_10x8 (128 bit) Block size 16 bytes 80 texels/block</td>
<td>VK_FORMAT_ASTC_10x8_UNORM_BLOCK, VK_FORMAT_ASTC_10x8_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_10x10 (128 bit) Block size 16 bytes 100 texels/block</td>
<td>VK_FORMAT_ASTC_10x10_UNORM_BLOCK, VK_FORMAT_ASTC_10x10_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_12x10 (128 bit) Block size 16 bytes 120 texels/block</td>
<td>VK_FORMAT_ASTC_12x10_UNORM_BLOCK, VK_FORMAT_ASTC_12x10_SRGB_BLOCK</td>
</tr>
<tr>
<td>ASTC_12x12 (128 bit) Block size 16 bytes 144 texels/block</td>
<td>VK_FORMAT_ASTC_12x12_UNORM_BLOCK, VK_FORMAT_ASTC_12x12_SRGB_BLOCK</td>
</tr>
<tr>
<td>D16 (16 bit) Block size 2 bytes 1 texel/block</td>
<td>VK_FORMAT_D16_UNORM</td>
</tr>
<tr>
<td>D24 (32 bit) Block size 4 bytes 1 texel/block</td>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
</tr>
<tr>
<td>D32 (32 bit) Block size 4 bytes 1 texel/block</td>
<td>VK_FORMAT_D32_SFLOAT</td>
</tr>
<tr>
<td>S8 (8 bit) Block size 1 byte 1 texel/block</td>
<td>VK_FORMAT_S8_UINT</td>
</tr>
<tr>
<td>D16S8 (24 bit) Block size 3 bytes 1 texel/block</td>
<td>VK_FORMAT_D16_UNORM_S8_UINT</td>
</tr>
<tr>
<td>D24S8 (32 bit) Block size 4 bytes 1 texel/block</td>
<td>VK_FORMAT_D24_UNORM_S8_UINT</td>
</tr>
<tr>
<td>D32S8 (40 bit) Block size 5 bytes 1 texel/block</td>
<td>VK_FORMAT_D32_SFLOAT_S8_UINT</td>
</tr>
<tr>
<td>8-bit 3-plane 420 Block size (1,1,1) bytes 1 texel/block</td>
<td>VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM</td>
</tr>
<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>8-bit 2-plane 420 Block size (1,2) bytes 1 texel/block</td>
<td>VK_FORMAT_B8R8_2PLANE_420_UNORM</td>
</tr>
<tr>
<td>8-bit 3-plane 422 Block size (1,1,1) bytes 1 texel/block</td>
<td>VK_FORMAT_B8_R8_3PLANE_422_UNORM</td>
</tr>
<tr>
<td>8-bit 2-plane 422 Block size (1,2) bytes 1 texel/block</td>
<td>VK_FORMAT_B8R8_2PLANE_422_UNORM</td>
</tr>
<tr>
<td>8-bit 3-plane 444 Block size (1,1,1) bytes 1 texel/block</td>
<td>VK_FORMAT_B8_R8_3PLANE_444_UNORM</td>
</tr>
<tr>
<td>10-bit 3-plane 420 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 2-plane 420 Block size (2,4) bytes 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 3-plane 422 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 2-plane 422 Block size (2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>10-bit 3-plane 444 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 3-plane 420 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 2-plane 420 Block size (2,4) bytes 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 3-plane 422 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 2-plane 422 Block size (2,4) bytes 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16</td>
</tr>
<tr>
<td>12-bit 3-plane 444 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16</td>
</tr>
</tbody>
</table>
### Class, Texel Block Size, # Texels/Block

<table>
<thead>
<tr>
<th>Formats</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-bit 3-plane 420 Block size (2,2,2) bytes 1 texel/block</td>
</tr>
<tr>
<td>16-bit 2-plane 420 Block size (2,4) bytes 1 texel/block</td>
</tr>
<tr>
<td>16-bit 3-plane 422 Block size (2,2,2) bytes 1 texel/block</td>
</tr>
<tr>
<td>16-bit 2-plane 422 Block size (2,4) bytes 1 texel/block</td>
</tr>
<tr>
<td>16-bit 3-plane 444 Block size (2,2,2) bytes 1 texel/block</td>
</tr>
</tbody>
</table>

### 36.2. Format Properties

To query supported format features which are properties of the physical device, call:

```c
void vkGetPhysicalDeviceFormatProperties(
    VkPhysicalDevice physicalDevice,
    VkFormat format,
    VkFormatProperties* pFormatProperties);
```

- `physicalDevice` is the physical device from which to query the format properties.
- `format` is the format whose properties are queried.
- `pFormatProperties` is a pointer to a `VkFormatProperties` structure in which physical device properties for `format` are returned.

### Valid Usage (Implicit)

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `format` must be a valid `VkFormat` value
- `pFormatProperties` must be a valid pointer to a `VkFormatProperties` structure

The `VkFormatProperties` structure is defined as:
typedef struct VkFormatProperties {
    VkFormatFeatureFlags linearTilingFeatures;
    VkFormatFeatureFlags optimalTilingFeatures;
    VkFormatFeatureFlags bufferFeatures;
} VkFormatProperties;

- **linearTilingFeatures** is a bitmask of VkFormatFeatureFlagBits specifying features supported by images created with a tiling parameter of VK_IMAGE_TILING_LINEAR.
- **optimalTilingFeatures** is a bitmask of VkFormatFeatureFlagBits specifying features supported by images created with a tiling parameter of VK_IMAGE_TILING_OPTIMAL.
- **bufferFeatures** is a bitmask of VkFormatFeatureFlagBits specifying features supported by buffers.

**Note**
If no format feature flags are supported, the format itself is not supported, and images of that format cannot be created.

If format is a block-compressed format, then bufferFeatures must not support any features for the format.

If format is not a multi-plane format then linearTilingFeatures and optimalTilingFeatures must not contain VK_FORMAT_FEATURE_DISJOINT_BIT.

Bits which can be set in the VkFormatProperties features linearTilingFeatures, optimalTilingFeatures, and bufferFeatures are:

typedef enum VkFormatFeatureFlagBits {
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT = 0x00000001,
    VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT = 0x00000002,
    VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT = 0x00000004,
    VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT = 0x00000008,
    VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT = 0x00000010,
    VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT = 0x00000020,
    VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT = 0x00000040,
    VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT = 0x00000080,
    VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT = 0x00000100,
    VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT = 0x00000200,
    VK_FORMAT_FEATURE_BLIT_SRC_BIT = 0x00000400,
    VK_FORMAT_FEATURE_BLIT_DST_BIT = 0x00000800,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT = 0x00001000,
    VK_FORMAT_FEATURE_TRANSFER_SRC_BIT = 0x00004000,
    VK_FORMAT_FEATURE_TRANSFER_DST_BIT = 0x00008000,
    VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT = 0x00020000,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT = 0x00040000,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT = 0x00080000,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT = 0x00080000,
} VkFormatFeatureFlagBits;
The following bits may be set in `linearTilingFeatures` and `optimalTilingFeatures`, specifying that the features are supported by images or image views or sampler Y'CbCr conversion objects created with the queried `vkGetPhysicalDeviceFormatProperties::format`:

- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT` specifies that an image view can be sampled from.
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT` specifies that an image view can be used as a storage image.
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT` specifies that an image view can be used as storage image that supports atomic operations.
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT` specifies that an image view can be used as a framebuffer color attachment and as an input attachment.
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT` specifies that an image view can be used as a framebuffer color attachment that supports blending and as an input attachment.
- `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT` specifies that an image view can be used as a
framebuffer depth/stencil attachment and as an input attachment.

- **VK_FORMAT_FEATURE_BLIT_SRC_BIT** specifies that an image can be used as `srcImage` for the `vkCmdBlitImage` command.
- **VK_FORMAT_FEATURE_BLIT_DST_BIT** specifies that an image can be used as `dstImage` for the `vkCmdBlitImage` command.
- **VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT** specifies that if `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT` is also set, an image view can be used with a sampler that has either of `magFilter` or `minFilter` set to `VK_FILTER_LINEAR`, or `mipmapMode` set to `VK_SAMPLER_MIPMAP_MODE_LINEAR`. If `VK_FORMAT_FEATURE_BLIT_SRC_BIT` is also set, an image can be used as the `srcImage` to `vkCmdBlitImage` with a filter of `VK_FILTER_LINEAR`. This bit must only be exposed for formats that also support the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT` or `VK_FORMAT_FEATURE_BLIT_SRC_BIT`.

If the format being queried is a depth/stencil format, this bit only specifies that the depth aspect (not the stencil aspect) of an image of this format supports linear filtering, and that linear filtering of the depth aspect is supported whether depth compare is enabled in the sampler or not. If this bit is not present, linear filtering with depth compare disabled is unsupported and linear filtering with depth compare enabled is supported, but may compute the filtered value in an implementation-dependent manner which differs from the normal rules of linear filtering. The resulting value must be in the range [0,1] and should be proportional to, or a weighted average of, the number of comparison passes or failures.

- **VK_FORMAT_FEATURE_TRANSFER_SRC_BIT** specifies that an image can be used as a source image for copy commands.
- **VK_FORMAT_FEATURE_TRANSFER_DST_BIT** specifies that an image can be used as a destination image for copy commands and clear commands.
- **VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT** specifies that an application can define a sampler Y’CbCr conversion using this format as a source, and that an image of this format can be used with a `VkSamplerYcbcrConversionCreateInfo xChromaOffset` and/or `yChromaOffset` of `VK_CHROMA_LOCATION_MIDPOINT`. Otherwise both `xChromaOffset` and `yChromaOffset` must be `VK_CHROMA_LOCATION_COSITED_EVEN`. If a format does not incorporate chroma downsampling (it is not a “422” or “420” format) but the implementation supports sampler Y’CbCr conversion for this format, the implementation must set `VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT`.
- **VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT** specifies that an application can define a sampler Y’CbCr conversion using this format as a source, and that an image of this format can be used with a `VkSamplerYcbcrConversionCreateInfo xChromaOffset` and/or `yChromaOffset` of `VK_CHROMA_LOCATION_MIDPOINT`. Otherwise both `xChromaOffset` and `yChromaOffset` must be `VK_CHROMA_LOCATION_COSITED_EVEN`. If neither `VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT` nor `VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT` is set, the application must not define a sampler Y’CbCr conversion using this format as a source.
- **VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT** specifies that the format can do linear sampler filtering (min/magFilter) whilst sampler Y’CbCr conversion is enabled.
- **VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT** specifies that the format can have different chroma, min, and mag filters.
- **VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT**
specifies that reconstruction is explicit, as described in Chroma Reconstruction. If this bit is not present, reconstruction is implicit by default.

- **VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT** specifies that reconstruction can be forcibly made explicit by setting VkSamplerYcbcrConversionCreateInfo::forceExplicitReconstruction to VK_TRUE. If the format being queried supports VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT it must also support VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT.

- **VK_FORMAT_FEATURE_DISJOINT_BIT** specifies that a multi-planar image can have the VK_IMAGE_CREATE_DISJOINT_BIT set during image creation. An implementation must not set VK_FORMAT_FEATURE_DISJOINT_BIT for single-plane formats.

The following bits may be set in bufferFeatures, specifying that the features are supported by buffers or buffer views created with the queried vkGetPhysicalDeviceProperties::format:

- **VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT** specifies that the format can be used to create a buffer view that can be bound to a VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER descriptor.

- **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT** specifies that the format can be used to create a buffer view that can be bound to a VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER descriptor.

- **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT** specifies that atomic operations are supported on VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER with this format.

- **VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT** specifies that the format can be used as a vertex attribute format (VkVertexInputAttributeDescription::format).

```typedef VkFlags VkFormatFeatureFlags;
```

VkFormatFeatureFlags is a bitmask type for setting a mask of zero or more VkFormatFeatureFlagBits.

To query supported format features which are properties of the physical device, call:

```void vkGetPhysicalDeviceFormatProperties2(
    VkPhysicalDevice physicalDevice,
    VkFormat format,
    VkFormatProperties2* pFormatProperties);
```

or the equivalent command

```void vkGetPhysicalDeviceFormatProperties2KHR(
    VkPhysicalDevice physicalDevice,
    VkFormat format,
    VkFormatProperties2* pFormatProperties);
```

- **physicalDevice** is the physical device from which to query the format properties.
**format** is the format whose properties are queried.

**pFormatProperties** is a pointer to a `VkFormatProperties2` structure in which physical device properties for **format** are returned.

`vkGetPhysicalDeviceFormatProperties2` behaves similarly to `vkGetPhysicalDeviceFormatProperties`, with the ability to return extended information in a `pNext` chain of output structures.

### Valid Usage (Implicit)

- **physicalDevice** must be a valid `VkPhysicalDevice` handle
- **format** must be a valid `VkFormat` value
- **pFormatProperties** must be a valid pointer to a `VkFormatProperties2` structure

The `VkFormatProperties2` structure is defined as:

```c
typedef struct VkFormatProperties2 {
    VkStructureType sType;
    void* pNext;
    VkFormatProperties formatProperties;
} VkFormatProperties2;
```

or the equivalent

```c
typedef VkFormatProperties2 VkFormatProperties2KHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **formatProperties** is a `VkFormatProperties` structure describing features supported by the requested format.

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2`
- **pNext** must be `NULL`

## 36.3. Required Format Support

Implementations must support at least the following set of features on the listed formats. For images, these features must be supported for every `VkImageType` (including arrayed and cube variants) unless otherwise noted. These features are supported on existing formats without needing to advertise an extension or needing to explicitly enable them. Support for additional functionality beyond the requirements listed here is queried using the `vkGetPhysicalDeviceFormatProperties`
command.

**Note**

Unless otherwise excluded below, the required formats are supported for all `VkImageCreateFlags` values as long as those flag values are otherwise allowed.

The following tables show which feature bits must be supported for each format. Formats that are required to support `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT` must also support `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT` and `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`.

**Table 45. Key for format feature tables**

<table>
<thead>
<tr>
<th>✓</th>
<th>This feature <strong>must</strong> be supported on the named format</th>
</tr>
</thead>
<tbody>
<tr>
<td>†</td>
<td>This feature <strong>must</strong> be supported on at least some of the named formats, with more information in the table where the symbol appears</td>
</tr>
<tr>
<td>‡</td>
<td>This feature <strong>must</strong> be supported with some caveats or preconditions, with more information in the table where the symbol appears</td>
</tr>
</tbody>
</table>

**Table 46. Feature bits in `optimalTilingFeatures`**

- `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT`
- `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`
- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`
- `VK_FORMAT_FEATURE_BLIT_SRC_BIT`
- `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT`
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT`
- `VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT`
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT`
- `VK_FORMAT_FEATURE_BLIT_DST_BIT`
- `VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT`
- `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT`

**Table 47. Feature bits in `bufferFeatures`**

- `VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT`
- `VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT`
- `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT`
- `VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT`
### Table 48. Mandatory format support: sub-byte channels

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_UNDEFINED</th>
<th>VK_FORMAT_R4G4_UNORM_PACK8</th>
<th>VK_FORMAT_R4G4B4A4_UNORM_PACK16</th>
<th>VK_FORMAT_B4G4R4A4_UNORM_PACK16</th>
<th>VK_FORMAT_R5G6B5_UNORM_PACK16</th>
<th>VK_FORMAT_B5G6R5_UNORM_PACK16</th>
<th>VK_FORMAT_R5G5B5A1_UNORM_PACK16</th>
<th>VK_FORMAT_B5G5R5A1_UNORM_PACK16</th>
<th>VK_FORMAT_A1R5G5B5_UNORM_PACK16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Table 49. Mandatory format support: 1-3 byte-sized channels

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT</th>
<th>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT</th>
<th>VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT</th>
<th>VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
<th>VK_FORMAT_FEATURE_BARRIER_BIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_R8_UNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8_SNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8_USCALED</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8_SSCALED</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8_UINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8_SINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8_SRGB</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_UNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_SRGB</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_B8G8R8_UNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Chapter 36. Formats | 1173
<table>
<thead>
<tr>
<th>Format</th>
<th>Must be supported if ( \text{VkPhysicalDevice} ) supports the <code>shaderStorageImageExtendedFormats</code> feature.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_B8G8R8_SINT</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_B8G8R8_SRGB</td>
<td></td>
</tr>
<tr>
<td>Format</td>
<td>VK_FORMAT_R8G8B8A8_UNORM</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_BLIT_DST_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_BLIT_SRC_BIT</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT</td>
<td>✓</td>
</tr>
</tbody>
</table>
### Table 51. Mandatory format support: 10- and 12-bit channels

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_A2R10G10B10_UNORM_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_SNORM_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_USCALED_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_SSCALED_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_UINT_PACK32</th>
<th>VK_FORMAT_A2R10G10B10_SINT_PACK32</th>
<th>VK_FORMAT_A2B10G10R10_UNORM_PACK32</th>
<th>VK_FORMAT_A2B10G10R10_SNORM_PACK32</th>
<th>VK_FORMAT_A2B10G10R10_USCALED_PACK32</th>
<th>VK_FORMAT_A2B10G10R10_SSCALED_PACK32</th>
<th>VK_FORMAT_A2B10G10R10_UINT_PACK32</th>
<th>VK_FORMAT_A2B10G10R10_SINT_PACK32</th>
<th>VK_FORMAT_R10X6_UNORM_PACK16</th>
<th>VK_FORMAT_R10X6G10X6_UNORM_2PACK16</th>
<th>VK_FORMAT_R12X4_UNORM_PACK16</th>
<th>VK_FORMAT_R12X4G12X4_UNORM_2PACK16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✓</td>
<td>‡</td>
<td>‡</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Format features marked with ‡ must be supported for optimalTilingFeatures if the VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
### Table 52. Mandatory format support: 16-bit channels

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Format features marked with ‡ **must** be supported for `optimalTilingFeatures` if the `VkPhysicalDevice` supports the `shaderStorageImageExtendedFormats` feature.

<table>
<thead>
<tr>
<th>Format</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
<th>✓</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_R16G16B16A16_SINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R16G16B16A16_SFLOAT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Table 53. Mandatory format support: 32-bit channels

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_R32_UINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32_SINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32_SFLOAT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32_UINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32_SINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32_SFLOAT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32B32_UINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32B32_SINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32B32_SFLOAT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32B32A32_UINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32B32A32_SINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R32G32B32A32_SFLOAT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Format</td>
<td>VK_FORMAT_R64_UINT</td>
<td>VK_FORMAT_R64_SINT</td>
<td>VK_FORMAT_R64_SFLOAT</td>
<td>VK_FORMAT_R64G64_UINT</td>
<td>VK_FORMAT_R64G64_SINT</td>
<td>VK_FORMAT_R64G64_SFLOAT</td>
<td>VK_FORMAT_R64G64B64_UINT</td>
<td>VK_FORMAT_R64G64B64_SINT</td>
<td>VK_FORMAT_R64G64B64_SFLOAT</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>-----------------------</td>
<td>------------------------</td>
<td>------------------------</td>
<td>--------------------------</td>
<td>---------------------------</td>
<td>--------------------------</td>
<td>-----------------------------</td>
</tr>
</tbody>
</table>
| Format features marked with ‡ must be supported for optimalTilingFeatures if the VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
Table 55. Mandatory format support: depth/stencil with VkImageType VK_IMAGE_TYPE_2D

<table>
<thead>
<tr>
<th>Format</th>
<th>Feature Supported</th>
<th>Feature Supported</th>
<th>Feature Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_D16_UNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
<td></td>
<td></td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_D32_SFLOAT</td>
<td>✓</td>
<td>✓</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_S8_UINT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_D16_UNORM_S8_UINT</td>
<td></td>
<td></td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_D24_UNORM_S8_UINT</td>
<td></td>
<td></td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_D32_SFLOAT_S8_UINT</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The `VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT` feature must be supported for at least one of `VK_FORMAT_X8_D24_UNORM_PACK32` and `VK_FORMAT_D32_SFLOAT`, and must be supported for at least one of `VK_FORMAT_D24_UNORM_S8_UINT` and `VK_FORMAT_D32_SFLOAT_S8_UINT`. \[\]
### Table 56. Mandatory format support: BC compressed formats with VkImageType VK_IMAGE_TYPE_2D and VK_IMAGE_TYPE_3D

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT</th>
<th>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT</th>
<th>VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT</th>
<th>VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT</th>
<th>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</th>
<th>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT</th>
<th>VK_FORMAT_FEATURE_BLIT_DST_BIT</th>
<th>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT</th>
<th>VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT</th>
<th>VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT</th>
<th>VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT</th>
<th>VK_FORMAT_FEATURE_BLIT_SRC_BIT</th>
<th>VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_BC1_RGB_UNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGB_SRGB_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGBA_UNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGBA_SRGB_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC2_UNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC2_SRGB_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC3_UNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC3_SRGB_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC4_UNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC4_SNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC5_UNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC5_SNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_UFLOAT_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC7_UNORM_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC7_SRGB_BLOCK</td>
<td>† † †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, VK_FORMAT_FEATURE_BLIT_SRC_BIT and VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT features must be supported in optimalTilingFeatures for all the formats in at least one of: this table, Mandatory format support: ETC2 and EAC compressed formats with VkImageType VK_IMAGE_TYPE_2D, or Mandatory format support: ASTC LDR compressed formats with VkImageType VK_IMAGE_TYPE_2D.
<table>
<thead>
<tr>
<th>Format</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_EAC_R11_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11_SNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_SNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`, `VK_FORMAT_FEATURE_BLIT_SRC_BIT` and `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT` features must be supported in `optimalTilingFeatures` for all the formats in at least one of: this table, Mandatory format support: BC compressed formats with `VkImageType VK_IMAGE_TYPE_2D` and `VK_IMAGE_TYPE_3D`, or Mandatory format support: ASTC LDR compressed formats with `VkImageType VK_IMAGE_TYPE_2D`. 

Chapter 36. Formats | 1183
Table 58. Mandatory format support: ASTC LDR compressed formats with VkImageType VK_IMAGE_TYPE_2D

<table>
<thead>
<tr>
<th>Format</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_ASTC_4x4_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_4x4_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_SRGB_BLOCK</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
</tbody>
</table>

1184 | Chapter 36. Formats
The VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT, VK_FORMAT_FEATURE_BLIT_SRC_BIT and VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT features must be supported in optimalTilingFeatures for all the formats in at least one of: this table, Mandatory format support: BC compressed formats with VkImageType VK_IMAGE_TYPE_2D and VK_IMAGE_TYPE_3D, or Mandatory format support: ETC2 and EAC compressed formats with VkImageType VK_IMAGE_TYPE_2D.

To be used with VkImageView with subresourceRange.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT, sampler Y’C_bC_r conversion must be enabled for the following formats:

Table 59. Formats requiring sampler Y’C_bC_r conversion for VK_IMAGE_ASPECT_COLOR_BIT image views

<table>
<thead>
<tr>
<th>Format</th>
<th>Planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_G8B8G8R8_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_B8G8R8G8_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8R8_2PLANE_420_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8R8_2PLANE_422_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6_R10X6_2PLANE_420_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_422_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>Format</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_422_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_444_UNORM_3PACK16</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G16B16G16R16_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_B16G16R16G16_422_UNORM</td>
<td>1</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16R16_2PLANE_420_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16R16_2PLANE_422_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM</td>
<td>3</td>
</tr>
</tbody>
</table>

Format features marked ✓ **must** be supported only if `VkPhysicalDeviceSamplerYcbcrConversionFeatures` is enabled, and only with `VkImageType VK_IMAGE_TYPE_2D`.

Implementations are not required to support the `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`, `VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT`, or `VK_IMAGE_CREATE_SPARSE_ALIASED_BIT` `VkImageCreateFlags` for the above formats that require sampler Y'CbCr conversion. To determine whether the implementation supports sparse image creation flags with these formats use `vkGetPhysicalDeviceImageFormatProperties` or `vkGetPhysicalDeviceImageFormatProperties2`.

**VK_FORMAT_FEATURE_ACCELERATION_STRUCTURE_VERTEX_BUFFER_BIT_KHR** **must** be supported for the following formats if the ray tracing feature is enabled:

- `VK_FORMAT_R32G32_SFLOAT`
- `VK_FORMAT_R32G32B32_SFLOAT`
- `VK_FORMAT_R16G16_SFLOAT`
- `VK_FORMAT_R16G16B16A16_SFLOAT`
- `VK_FORMAT_R16G16_SNORM`
- `VK_FORMAT_R16G16B16A16_SNORM`
Chapter 37. Additional Capabilities

This chapter describes additional capabilities beyond the minimum capabilities described in the (Limits and Formats chapters, including:

- Additional Image Capabilities
- Additional Buffer Capabilities
- Optional Semaphore Capabilities
- Optional Fence Capabilities

37.1. Additional Image Capabilities

Additional image capabilities, such as larger dimensions or additional sample counts for certain image types, or additional capabilities for linear tiling format images, are described in this section.

To query additional capabilities specific to image types, call:

```c
VkResult vkGetPhysicalDeviceImageFormatProperties(
    VkPhysicalDevice                            physicalDevice,
    VkFormat                                    format,
    VkImageType                                 type,
    VkImageTiling                               tiling,
    VkImageUsageFlags                           usage,
    VkImageCreateFlags                          flags,
    VkImageFormatProperties*                    pImageFormatProperties);
```

- **physicalDevice** is the physical device from which to query the image capabilities.
- **format** is a VkFormat value specifying the image format, corresponding to VkImageCreateInfo::format.
- **type** is a VkImageType value specifying the image type, corresponding to VkImageCreateInfo::imageType.
- **tiling** is a VkImageTiling value specifying the image tiling, corresponding to VkImageCreateInfo::tiling.
- **usage** is a bitmask of VkImageUsageFlagBits specifying the intended usage of the image, corresponding to VkImageCreateInfo::usage.
- **flags** is a bitmask of VkImageCreateFlagBits specifying additional parameters of the image, corresponding to VkImageCreateInfo::flags.
- **pImageFormatProperties** is a pointer to a VkImageFormatProperties structure in which capabilities are returned.

The **format**, **type**, **tiling**, **usage**, and **flags** parameters correspond to parameters that would be consumed by vkCreateImage (as members of VkImageCreateInfo).

If **format** is not a supported image format, or if the combination of **format**, **type**, **tiling**, **usage**, and
flags is not supported for images, then `vkGetPhysicalDeviceImageFormatProperties` returns `VK_ERROR_FORMAT_NOT_SUPPORTED`.

The limitations on an image format that are reported by `vkGetPhysicalDeviceImageFormatProperties` have the following property: if `usage1` and `usage2` of type `VkImageUsageFlags` are such that the bits set in `usage1` are a subset of the bits set in `usage2`, and `flags1` and `flags2` of type `VkImageCreateFlags` are such that the bits set in `flags1` are a subset of the bits set in `flags2`, then the limitations for `usage1` and `flags1` must be no more strict than the limitations for `usage2` and `flags2`, for all values of `format`, `type`, and `tiling`.

### Valid Usage (Implicit)
- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `format` must be a valid `VkFormat` value
- `type` must be a valid `VkImageType` value
- `tiling` must be a valid `VkImageTiling` value
- `usage` must be a valid combination of `VkImageUsageFlagBits` values
- `usage` must not be `0`
- `flags` must be a valid combination of `VkImageCreateFlagBits` values
- `pImageFormatProperties` must be a valid pointer to a `VkImageFormatProperties` structure

### Return Codes

**Success**
- `VK_SUCCESS`

**Failure**
- `VK_ERROR_OUT_OF_HOST_MEMORY`
- `VK_ERROR_OUT_OF_DEVICE_MEMORY`
- `VK_ERROR_FORMAT_NOT_SUPPORTED`

The `VkImageFormatProperties` structure is defined as:

```c
typedef struct VkImageFormatProperties {
    VkExtent3D            maxExtent;
    uint32_t              maxMipLevels;
    uint32_t              maxArrayLayers;
    VkSampleCountFlags    sampleCounts;
    VkDeviceSize          maxResourceSize;
} VkImageFormatProperties;
```

- `maxExtent` are the maximum image dimensions. See the Allowed Extent Values section below for how these values are constrained by `type`. 
• `maxMipLevels` is the maximum number of mipmap levels. `maxMipLevels` must be equal to the number of levels in the complete mipmap chain based on the `maxExtent.width`, `maxExtent.height`, and `maxExtent.depth`, except when one of the following conditions is true, in which case it may instead be 1:
  ◦ `vkGetPhysicalDeviceImageFormatProperties::tiling` was `VK_IMAGE_TILING_LINEAR`
  ◦ the `VkPhysicalDeviceImageFormatInfo2::pNext` chain included a `VkPhysicalDeviceExternalImageFormatInfo` structure with a handle type included in the `handleTypes` member for which mipmap image support is not required
  ◦ image format is one of those listed in Formats requiring sampler Y’C₈C₈ conversion for `VK_IMAGE_ASPECT_COLOR_BIT` image views

• `maxArrayLayers` is the maximum number of array layers. `maxArrayLayers` must be no less than `VkPhysicalDeviceLimits::maxImageArrayLayers`, except when one of the following conditions is true, in which case it may instead be 1:
  ◦ tiling is `VK_IMAGE_TILING_LINEAR`
  ◦ tiling is `VK_IMAGE_TILING_OPTIMAL` and type is `VK_IMAGE_TYPE_3D`
  ◦ format is one of those listed in Formats requiring sampler Y’C₈C₈ conversion for `VK_IMAGE_ASPECT_COLOR_BIT` image views

• `sampleCounts` is a bitmask of `VkSampleCountFlagBits` specifying all the supported sample counts for this image as described below.

• `maxResourceSize` is an upper bound on the total image size in bytes, inclusive of all image subresources. Implementations may have an address space limit on total size of a resource, which is advertised by this property. `maxResourceSize` must be at least \(2^{31}\).

**Note**
There is no mechanism to query the size of an image before creating it, to compare that size against `maxResourceSize`. If an application attempts to create an image that exceeds this limit, the creation will fail and `vkCreateImage` will return `VK_ERROR_OUT_OF_DEVICE_MEMORY`. While the advertised limit must be at least \(2^{31}\), it may not be possible to create an image that approaches that size, particularly for `VK_IMAGE_TYPE_1D`.

If the combination of parameters to `vkGetPhysicalDeviceImageFormatProperties` is not supported by the implementation for use in `vkCreateImage`, then all members of `VkImageFormatProperties` will be filled with zero.

**Note**
Filling `VkImageFormatProperties` with zero for unsupported formats is an exception to the usual rule that output structures have undefined contents on error. This exception was unintentional, but is preserved for backwards compatibility.

To query additional capabilities specific to image types, call:
VkResult vkGetPhysicalDeviceImageFormatProperties2(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceImageFormatInfo2* pImageFormatInfo,
    VkImageFormatProperties2* pImageFormatProperties);

or the equivalent command

VkResult vkGetPhysicalDeviceImageFormatProperties2KHR(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceImageFormatInfo2* pImageFormatInfo,
    VkImageFormatProperties2* pImageFormatProperties);

- **physicalDevice** is the physical device from which to query the image capabilities.
- **pImageFormatInfo** is a pointer to a `VkPhysicalDeviceImageFormatInfo2` structure describing the parameters that would be consumed by `vkCreateImage`.
- **pImageFormatProperties** is a pointer to a `VkImageFormatProperties2` structure in which capabilities are returned.

`vkGetPhysicalDeviceImageFormatProperties2` behaves similarly to `vkGetPhysicalDeviceImageFormatProperties`, with the ability to return extended information in a `pNext` chain of output structures.

Valid Usage (Implicit)

- **physicalDevice** must be a valid `VkPhysicalDevice` handle
- **pImageFormatInfo** must be a valid pointer to a valid `VkPhysicalDeviceImageFormatInfo2` structure
- **pImageFormatProperties** must be a valid pointer to a `VkImageFormatProperties2` structure

Return Codes

**Success**

- VK_SUCCESS

**Failure**

- VK_ERROR_OUT_OF_HOST_MEMORY
- VK_ERROR_OUT_OF_DEVICE_MEMORY
- VK_ERROR_FORMAT_NOT_SUPPORTED

The `VkPhysicalDeviceImageFormatInfo2` structure is defined as:

---

1190 | Chapter 37. Additional Capabilities
typedef struct VkPhysicalDeviceImageFormatInfo2 {
    VkStructureType       sType;
    const void*           pNext;
    VkFormat              format;
    VkImageType           type;
    VkImageTiling         tiling;
    VkImageUsageFlags     usage;
    VkImageCreateFlags    flags;
} VkPhysicalDeviceImageFormatInfo2;

or the equivalent

typedef VkPhysicalDeviceImageFormatInfo2 VkPhysicalDeviceImageFormatInfo2KHR;

• **sType** is the type of this structure.
• **pNext** is **NULL** or a pointer to an extension-specific structure. The **pNext** chain of
  VkPhysicalDeviceImageFormatInfo2 is used to provide additional image parameters to
• **format** is a **VkFormat** value indicating the image format, corresponding to **VkImageCreateInfo::format**.
• **type** is a **VkImageType** value indicating the image type, corresponding to **VkImageCreateInfo::imageType**.
• **tiling** is a **VkImageTiling** value indicating the image tiling, corresponding to
  VkImageCreateInfo::tiling.
• **usage** is a bitmask of **VkImageUsageFlagBits** indicating the intended usage of the image,
  corresponding to **VkImageCreateInfo::usage**.
• **flags** is a bitmask of **VkImageCreateFlagBits** indicating additional parameters of the image,
  corresponding to **VkImageCreateInfo::flags**.

The members of VkPhysicalDeviceImageFormatInfo2 correspond to the arguments to
vkGetPhysicalDeviceImageFormatProperties, with **sType** and **pNext** added for extensibility.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_FORMAT_INFO_2`
- Each **pNext** member of any structure (including this one) in the **pNext** chain must be either **NULL** or a pointer to a valid instance of `VkImageFormatListCreateInfo` or `VkPhysicalDeviceExternalImageFormatInfo`
- The **sType** value of each struct in the **pNext** chain must be unique
- **format** must be a valid `VkFormat` value
- **type** must be a valid `VkImageType` value
- **tiling** must be a valid `VkImageTiling` value
- **usage** must be a valid combination of `VkImageUsageFlagBits` values
- **usage** must not be 0
- **flags** must be a valid combination of `VkImageCreateFlagBits` values

The `VkImageFormatProperties2` structure is defined as:

```c
typedef struct VkImageFormatProperties2 {
    VkStructureType            sType;
    void*                      pNext;
    VkImageFormatProperties    imageFormatProperties;
} VkImageFormatProperties2;
```

or the equivalent

```c
typedef VkImageFormatProperties2 VkImageFormatProperties2KHR;
```

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure. The **pNext** chain of `VkImageFormatProperties2` is used to allow the specification of additional capabilities to be returned from `vkGetPhysicalDeviceImageFormatProperties2`.
- **imageFormatProperties** is a `VkImageFormatProperties` structure in which capabilities are returned.

If the combination of parameters to `vkGetPhysicalDeviceImageFormatProperties2` is not supported by the implementation for use in `vkCreateImage`, then all members of **imageFormatProperties** will be filled with zero.
Note

Filling imageFormatProperties with zero for unsupported formats is an exception to the usual rule that output structures have undefined contents on error. This exception was unintentional, but is preserved for backwards compatibility. This exception only applies to imageFormatProperties, not sType, pNext, or any structures chained from pNext.

Valid Usage (Implicit)

- sType must be VK_STRUCTURE_TYPE_IMAGE_FORMAT_PROPERTIES_2
- Each pNext member of any structure (including this one) in the pNext chain must be either NULL or a pointer to a valid instance of VkExternalImageFormatProperties or VkSamplerYcbcrConversionImageFormatProperties
- The sType value of each struct in the pNext chain must be unique

To determine the image capabilities compatible with an external memory handle type, add a VkPhysicalDeviceExternalImageFormatInfo structure to the pNext chain of the VkPhysicalDeviceImageFormatInfo2 structure and a VkExternalImageFormatProperties structure to the pNext chain of the VkImageFormatProperties2 structure.

The VkPhysicalDeviceExternalImageFormatInfo structure is defined as:

```c
typedef struct VkPhysicalDeviceExternalImageFormatInfo {
    VkStructureType sType;
    const void*      pNext;
    VkExternalMemoryHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalImageFormatInfo;
```

or the equivalent

```c
typedef VkPhysicalDeviceExternalImageFormatInfo
VkPhysicalDeviceExternalImageFormatInfoKHR;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- handleType is a VkExternalMemoryHandleTypeFlagBits value specifying the memory handle type that will be used with the memory associated with the image.

If handleType is 0, vkGetPhysicalDeviceImageFormatProperties2 will behave as if VkPhysicalDeviceExternalImageFormatInfo was not present, and VkExternalImageFormatProperties will be ignored.

If handleType is not compatible with the format, type, tiling, usage, and flags specified in VkPhysicalDeviceImageFormatInfo2, then vkGetPhysicalDeviceImageFormatProperties2 returns
VK_ERROR_FORMAT_NOT_SUPPORTED.

Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_IMAGE_FORMAT_INFO**
- If **handleType** is not 0, **handleType** must be a valid **VkExternalMemoryHandleTypeFlagBits** value

Possible values of **VkPhysicalDeviceExternalImageFormatInfo::handleType**, specifying an external memory handle type, are:

```c
typedef enum VkExternalMemoryHandleTypeFlagBits {
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT = 0x00000001,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT = 0x00000002,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT = 0x00000004,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT = 0x00000008,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT = 0x00000010,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT = 0x00000020,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT = 0x00000040,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT_KHR = VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT_KHR = VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT_KHR = VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT_KHR = VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT_KHR = VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT_KHR = VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT_KHR = VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT,
    VK_EXTERNAL_MEMORY_HANDLE_TYPE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalMemoryHandleTypeFlagBits;
```

or the equivalent

```c
typedef VkExternalMemoryHandleTypeFlagBits VkExternalMemoryHandleTypeFlagBitsKHR;
```

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT** specifies a POSIX file descriptor handle that has only limited valid usage outside of Vulkan and other compatible APIs. It **must** be compatible with the POSIX system calls **dup**, **dup2**, **close**, and the non-standard system call **dup3**. Additionally, it **must** be transportable over a socket using an **SCM_RIGHTS** control message. It owns a reference to the underlying memory resource represented by its Vulkan memory object.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT** specifies an NT handle that has only limited valid usage outside of Vulkan and other compatible APIs. It **must** be compatible with the POSIX system calls **dup**, **dup2**, **close**, and the non-standard system call **dup3**. Additionally, it **must** be transportable over a socket using an **SCM_RIGHTS** control message. It owns a reference to the underlying memory resource represented by its Vulkan memory object.
valid usage outside of Vulkan and other compatible APIs. It **must** be compatible with the functions `DuplicateHandle`, `CloseHandle`, `CompareObjectHandles`, `GetHandleInformation`, and `SetHandleInformation`. It owns a reference to the underlying memory resource represented by its Vulkan memory object.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT** specifies a global share handle that has only limited valid usage outside of Vulkan and other compatible APIs. It is not compatible with any native APIs. It does not own a reference to the underlying memory resource represented its Vulkan memory object, and will therefore become invalid when all Vulkan memory objects associated with it are destroyed.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT** specifies an NT handle returned by `IDXGIResource1::CreateSharedHandle` referring to a Direct3D 10 or 11 texture resource. It owns a reference to the memory used by the Direct3D resource.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT** specifies a global share handle returned by `IDXGIResource::GetSharedHandle` referring to a Direct3D 10 or 11 texture resource. It does not own a reference to the underlying Direct3D resource, and will therefore become invalid when all Vulkan memory objects and Direct3D resources associated with it are destroyed.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT** specifies an NT handle returned by `ID3D12Device::CreateSharedHandle` referring to a Direct3D 12 heap resource. It owns a reference to the resources used by the Direct3D heap.

- **VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT** specifies an NT handle returned by `ID3D12Device::CreateSharedHandle` referring to a Direct3D 12 committed resource. It owns a reference to the memory used by the Direct3D resource.
Some external memory handle types can only be shared within the same underlying physical device and/or the same driver version, as defined in the following table:

**Table 60. External memory handle types compatibility**

<table>
<thead>
<tr>
<th>Handle type</th>
<th>VkPhysicalDeviceIDProperties::driverUUID</th>
<th>VkPhysicalDeviceIDProperties::deviceUUID</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_HEAP_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
</tbody>
</table>

typedef VkFlags VkExternalMemoryHandleTypeFlags;

or the equivalent

typedef VkExternalMemoryHandleTypeFlags VkExternalMemoryHandleTypeFlagsKHR;

**VkExternalMemoryHandleTypeFlags** is a bitmask type for setting a mask of zero or more **VkExternalMemoryHandleTypeFlagBits**.

The **VkExternalImageFormatProperties** structure is defined as:

```c
typedef struct VkExternalImageFormatProperties {
    VkStructureType           sType;
    void*                     pNext;
    VkExternalMemoryProperties externalMemoryProperties;
} VkExternalImageFormatProperties;
```

or the equivalent

typedef VkExternalImageFormatProperties VkExternalImageFormatPropertiesKHR;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **externalMemoryProperties** is a **VkExternalMemoryProperties** structure specifying various...
capabilities of the external handle type when used with the specified image creation parameters.

**Valid Usage (Implicit)**

- **sType** **must** be `VK_STRUCTURE_TYPE_EXTERNAL_IMAGE_FORMAT_PROPERTIES`

The `VkExternalMemoryProperties` structure is defined as:

```c
typedef struct VkExternalMemoryProperties {
    VkExternalMemoryFeatureFlags externalMemoryFeatures;
    VkExternalMemoryHandleTypeFlags exportFromImportedHandleTypes;
    VkExternalMemoryHandleTypeFlags compatibleHandleTypes;
} VkExternalMemoryProperties;
```

or the equivalent

```c
typedef VkExternalMemoryProperties VkExternalMemoryPropertiesKHR;
```

- **externalMemoryFeatures** is a bitmask of `VkExternalMemoryFeatureFlagBits` specifying the features of `handleType`.
- **exportFromImportedHandleTypes** is a bitmask of `VkExternalMemoryHandleTypeFlagBits` specifying which types of imported handle `handleType` can be exported from.
- **compatibleHandleTypes** is a bitmask of `VkExternalMemoryHandleTypeFlagBits` specifying handle types which can be specified at the same time as `handleType` when creating an image compatible with external memory.

`compatibleHandleTypes` **must** include at least `handleType`. Inclusion of a handle type in `compatibleHandleTypes` does not imply the values returned in `VkImageFormatProperties2` will be the same when `VkPhysicalDeviceExternalImageFormatInfo::handleType` is set to that type. The application is responsible for querying the capabilities of all handle types intended for concurrent use in a single image and intersecting them to obtain the compatible set of capabilities.

Bits which **may** be set in `VkExternalMemoryProperties::externalMemoryFeatures`, specifying features of an external memory handle type, are:
typedef enum VkExternalMemoryFeatureFlagBits {
    VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT = 0x00000001,
    VK_EXTERNAL_MEMORY_FEATURE_EXPORTABLE_BIT = 0x00000002,
    VK_EXTERNAL_MEMORY_FEATURE_IMPORTABLE_BIT = 0x00000004,
    VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT_KHR =
    VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT,
    VK_EXTERNAL_MEMORY_FEATURE_EXPORTABLE_BIT_KHR =
    VK_EXTERNAL_MEMORY_FEATURE_EXPORTABLE_BIT,
    VK_EXTERNAL_MEMORY_FEATURE_IMPORTABLE_BIT_KHR =
    VK_EXTERNAL_MEMORY_FEATURE_IMPORTABLE_BIT,
    VK_EXTERNAL_MEMORY_FEATURE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalMemoryFeatureFlagBits;

or the equivalent

typedef VkExternalMemoryFeatureFlagBits VkExternalMemoryFeatureFlagBitsKHR;

- VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT specifies that images or buffers created with the specified parameters and handle type must use the mechanisms defined by VkMemoryDedicatedRequirements and VkMemoryDedicatedAllocateInfo to create (or import) a dedicated allocation for the image or buffer.
- VK_EXTERNAL_MEMORY_FEATURE_EXPORTABLE_BIT specifies that handles of this type can be exported from Vulkan memory objects.
- VK_EXTERNAL_MEMORY_FEATURE_IMPORTABLE_BIT specifies that handles of this type can be imported as Vulkan memory objects.

Because their semantics in external APIs roughly align with that of an image or buffer with a dedicated allocation in Vulkan, implementations are required to report VK_EXTERNAL_MEMORY_FEATURE_DEDICATED_ONLY_BIT for the following external handle types:

- VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_BIT
- VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D11_TEXTURE_KHR_BIT
- VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT

typedef VkFlags VkExternalMemoryFeatureFlags;

or the equivalent

typedef VkExternalMemoryFeatureFlags VkExternalMemoryFeatureFlagsKHR;

VkExternalMemoryFeatureFlags is a bitmask type for setting a mask of zero or more VkExternalMemoryFeatureFlagBits.

To determine the number of combined image samplers required to support a multi-planar format, add VkSamplerYcbcrConversionImageFormatProperties to thepNext chain of the

The VkSamplerYcbcrConversionImageFormatProperties structure is defined as:

```c
typedef struct VkSamplerYcbcrConversionImageFormatProperties {
    VkStructureType sType;
    void* pNext;
    uint32_t combinedImageSamplerDescriptorCount;
} VkSamplerYcbcrConversionImageFormatProperties;
```

or the equivalent

```c
typedef VkSamplerYcbcrConversionImageFormatProperties
VkSamplerYcbcrConversionImageFormatPropertiesKHR;
```

- **sType** is the type of this structure.
- **pNext** is NULL or a pointer to an extension-specific structure.
- **combinedImageSamplerDescriptorCount** is the number of combined image sampler descriptors that the implementation uses to access the format.

**Valid Usage (Implicit)**

- **sType** must be `VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_IMAGE_FORMAT_PROPERTIES`

`combinedImageSamplerDescriptorCount` is a number between 1 and the number of planes in the format. A descriptor set layout binding with immutable Y’CbCr conversion samplers will have a maximum `combinedImageSamplerDescriptorCount` which is the maximum across all formats supported by its samplers of the `combinedImageSamplerDescriptorCount` for each format. Descriptor sets with that layout will internally use that maximum `combinedImageSamplerDescriptorCount` descriptors for each descriptor in the binding. This expanded number of descriptors will be consumed from the descriptor pool when a descriptor set is allocated, and counts towards the `maxDescriptorSetSamplers`, `maxDescriptorSetSampledImages`, `maxPerStageDescriptorSamplers`, and `maxPerStageDescriptorSampledImages` limits.
All descriptors in a binding use the same maximum combinedImageSamplerDescriptorCount descriptors to allow implementations to use a uniform stride for dynamic indexing of the descriptors in the binding.

For example, consider a descriptor set layout binding with two descriptors and immutable samplers for multi-planar formats that have VkSamplerYcbcrConversionImageFormatProperties::combinedImageSamplerDescriptorCount values of 2 and 3 respectively. There are two descriptors in the binding and the maximum combinedImageSamplerDescriptorCount is 3, so descriptor sets with this layout consume 6 descriptors from the descriptor pool. To create a descriptor pool that allows allocating four descriptor sets with this layout, descriptorCount must be at least 24.

37.1.1. Supported Sample Counts

vkGetPhysicalDeviceImageFormatProperties returns a bitmask of VkSampleCountFlagBits in sampleCounts specifying the supported sample counts for the image parameters.

sampleCounts will be set to VK_SAMPLE_COUNT_1_BIT if at least one of the following conditions is true:

- tiling is VK_IMAGE_TILING_LINEAR
- type is not VK_IMAGE_TYPE_2D
- flags contains VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT
- Neither the VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT flag nor the VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT flag in VkFormatProperties::optimalTilingFeatures returned by vkGetPhysicalDeviceFormatProperties is set
- VkPhysicalDeviceExternalImageFormatInfo::handleType is an external handle type for which multisampled image support is not required.
- format is one of those listed in Formats requiring sampler Y’C₉C₅ conversion for VK_IMAGE_ASPECT_COLOR_BIT image views

Otherwise, the bits set in sampleCounts will be the sample counts supported for the specified values of usage and format. For each bit set in usage, the supported sample counts relate to the limits in VkPhysicalDeviceLimits as follows:

- If usage includes VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT and format is a floating- or fixed-point color format, a superset of VkPhysicalDeviceLimits::framebufferColorSampleCounts
- If usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a depth aspect, a superset of VkPhysicalDeviceLimits::framebufferDepthSampleCounts
- If usage includes VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT, and format includes a stencil aspect, a superset of VkPhysicalDeviceLimits::framebufferStencilSampleCounts
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format includes a color aspect, a superset of VkPhysicalDeviceLimits::sampledImageColorSampleCounts
- If usage includes VK_IMAGE_USAGE_SAMPLED_BIT, and format includes a depth aspect, a superset of
If multiple bits are set in `usage`, `sampleCounts` will be the intersection of the per-usage values described above.

If none of the bits described above are set in `usage`, then there is no corresponding limit in `VkPhysicalDeviceLimits`. In this case, `sampleCounts` must include at least `VK_SAMPLE_COUNT_1_BIT`.

### 37.1.2. Allowed Extent Values Based On Image Type

Implementations may support extent values larger than the required minimum/maximum values for certain types of images subject to the constraints below.

**Note**
Implementations must support images with dimensions up to the required minimum/maximum values for all types of images. It follows that the query for additional capabilities must return extent values that are at least as large as the required values.

For `VK_IMAGE_TYPE_1D`:

- `maxExtent.width ≥ VkPhysicalDeviceLimits.maxImageDimension1D`
- `maxExtent.height = 1`
- `maxExtent.depth = 1`

For `VK_IMAGE_TYPE_2D` when flags does not contain `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT`:

- `maxExtent.width ≥ VkPhysicalDeviceLimits.maxImageDimension2D`
- `maxExtent.height ≥ VkPhysicalDeviceLimits.maxImageDimension2D`
- `maxExtent.depth = 1`

For `VK_IMAGE_TYPE_2D` when flags contains `VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT`:

- `maxExtent.width ≥ VkPhysicalDeviceLimits.maxImageDimensionCube`
- `maxExtent.height ≥ VkPhysicalDeviceLimits.maxImageDimensionCube`
- `maxExtent.depth = 1`

For `VK_IMAGE_TYPE_3D`:

- `maxExtent.width ≥ VkPhysicalDeviceLimits.maxImageDimension3D`
- `maxExtent.height ≥ VkPhysicalDeviceLimits.maxImageDimension3D`
- `maxExtent.depth ≥ VkPhysicalDeviceLimits.maxImageDimension3D`
37.2. Additional Buffer Capabilities

To query the external handle types supported by buffers, call:

```c
void vkGetPhysicalDeviceExternalBufferProperties(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceExternalBufferInfo* pExternalBufferInfo,
    VkExternalBufferProperties* pExternalBufferProperties);
```

or the equivalent command

```c
void vkGetPhysicalDeviceExternalBufferPropertiesKHR(
    VkPhysicalDevice physicalDevice,
    const VkPhysicalDeviceExternalBufferInfo* pExternalBufferInfo,
    VkExternalBufferProperties* pExternalBufferProperties);
```

- **physicalDevice** is the physical device from which to query the buffer capabilities.
- **pExternalBufferInfo** is a pointer to a `VkPhysicalDeviceExternalBufferInfo` structure describing the parameters that would be consumed by `vkCreateBuffer`.
- **pExternalBufferProperties** is a pointer to a `VkExternalBufferProperties` structure in which capabilities are returned.

### Valid Usage (Implicit)

- **physicalDevice** must be a valid `VkPhysicalDevice` handle
- **pExternalBufferInfo** must be a valid pointer to a valid `VkPhysicalDeviceExternalBufferInfo` structure
- **pExternalBufferProperties** must be a valid pointer to a `VkExternalBufferProperties` structure

The `VkPhysicalDeviceExternalBufferInfo` structure is defined as:

```c
typedef struct VkPhysicalDeviceExternalBufferInfo {
    VkStructureType sType;
    const void* pNext;
    VkBufferCreateFlags flags;
    VkBufferUsageFlags usage;
    VkExternalMemoryHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalBufferInfo;
```

or the equivalent
typedef VkPhysicalDeviceExternalBufferInfo VkPhysicalDeviceExternalBufferInfoKHR;

- **sType** is the type of this structure
- **pNext** is NULL or a pointer to an extension-specific structure.
- **flags** is a bitmask of `VkBufferCreateFlagBits` describing additional parameters of the buffer, corresponding to `VkBufferCreateInfo::flags`.
- **usage** is a bitmask of `VkBufferUsageFlagBits` describing the intended usage of the buffer, corresponding to `VkBufferCreateInfo::usage`.
- **handleType** is a `VkExternalMemoryHandleTypeFlagBits` value specifying the memory handle type that will be used with the memory associated with the buffer.

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_BUFFER_INFO`
- **pNext** must be NULL
- **flags** must be a valid combination of `VkBufferCreateFlagBits` values
- **usage** must be a valid combination of `VkBufferUsageFlagBits` values
- **usage** must not be 0
- **handleType** must be a valid `VkExternalMemoryHandleTypeFlagBits` value

The `VkExternalBufferProperties` structure is defined as:

```c
typedef struct VkExternalBufferProperties {
    VkStructureType               sType;
    void*                         pNext;
    VkExternalMemoryProperties    externalMemoryProperties;
} VkExternalBufferProperties;
```

or the equivalent

```c
typedef VkExternalBufferProperties VkExternalBufferPropertiesKHR;
```

- **sType** is the type of this structure
- **pNext** is NULL or a pointer to an extension-specific structure.
- **externalMemoryProperties** is a `VkExternalMemoryProperties` structure specifying various capabilities of the external handle type when used with the specified buffer creation parameters.
37.3. Optional Semaphore Capabilities

Semaphores may support import and export of their payload to external handles. To query the external handle types supported by semaphores, call:

```c
void vkGetPhysicalDeviceExternalSemaphoreProperties(
    VkPhysicalDevice                            physicalDevice,
    const VkPhysicalDeviceExternalSemaphoreInfo* pExternalSemaphoreInfo,
    VkExternalSemaphoreProperties*              pExternalSemaphoreProperties);
```

or the equivalent command

```c
void vkGetPhysicalDeviceExternalSemaphorePropertiesKHR(
    VkPhysicalDevice                            physicalDevice,
    const VkPhysicalDeviceExternalSemaphoreInfo* pExternalSemaphoreInfo,
    VkExternalSemaphoreProperties*              pExternalSemaphoreProperties);
```

• `physicalDevice` is the physical device from which to query the semaphore capabilities.
• `pExternalSemaphoreInfo` is a pointer to a `VkPhysicalDeviceExternalSemaphoreInfo` structure describing the parameters that would be consumed by `vkCreateSemaphore`.
• `pExternalSemaphoreProperties` is a pointer to a `VkExternalSemaphoreProperties` structure in which capabilities are returned.

Valid Usage (Implicit)

• `physicalDevice` must be a valid `VkPhysicalDevice` handle
• `pExternalSemaphoreInfo` must be a valid pointer to a valid `VkPhysicalDeviceExternalSemaphoreInfo` structure
• `pExternalSemaphoreProperties` must be a valid pointer to a `VkExternalSemaphoreProperties` structure

The `VkPhysicalDeviceExternalSemaphoreInfo` structure is defined as:
typedef struct VkPhysicalDeviceExternalSemaphoreInfo {
    VkStructureType     sType;
    const void*         pNext;
    VkExternalSemaphoreHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalSemaphoreInfo;

or the equivalent

typedef VkPhysicalDeviceExternalSemaphoreInfo
VkPhysicalDeviceExternalSemaphoreInfoKHR;

• **sType** is the type of this structure
• **pNext** is NULL or a pointer to an extension-specific structure.
• **handleType** is a `VkExternalSemaphoreHandleTypeFlagBits` value specifying the external semaphore handle type for which capabilities will be returned.

### Valid Usage (Implicit)

• **sType** **must** be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO`
• **pNext** **must** be NULL or a pointer to a valid instance of `VkSemaphoreTypeCreateInfo`
• The **sType** value of each struct in the **pNext** chain **must** be unique
• **handleType** **must** be a valid `VkExternalSemaphoreHandleTypeFlagBits` value

Bits which **may** be set in `VkPhysicalDeviceExternalSemaphoreInfo::handleType`, specifying an external semaphore handle type, are:
typedef enum VkExternalSemaphoreHandleTypeFlagBits {
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT = 0x00000001,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT = 0x00000002,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT = 0x00000004,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT = 0x00000008,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT = 0x00000010,
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT_KHR =
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT_KHR =
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT_KHR =
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT_KHR =
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT_KHR =
    VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalSemaphoreHandleTypeFlagBits;

or the equivalent

typedef VkExternalSemaphoreHandleTypeFlagBits
VkExternalSemaphoreHandleTypeFlagBitsKHR;

• VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT specifies a POSIX file descriptor handle that has only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the POSIX system calls dup, dup2, close, and the non-standard system call dup3. Additionally, it must be transportable over a socket using an SCM_RIGHTS control message. It owns a reference to the underlying synchronization primitive represented by its Vulkan semaphore object.

• VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT specifies an NT handle that has only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the functions DuplicateHandle, CloseHandle, CompareObjectHandles, GetHandleInformation, and SetHandleInformation. It owns a reference to the underlying synchronization primitive represented by its Vulkan semaphore object.

• VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT specifies a global share handle that has only limited valid usage outside of Vulkan and other compatible APIs. It is not compatible with any native APIs. It does not own a reference to the underlying synchronization primitive represented its Vulkan semaphore object, and will therefore become invalid when all Vulkan semaphore objects associated with it are destroyed.

• VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT specifies an NT handle returned by ID3D12Device::CreateSharedHandle referring to a Direct3D 12 fence. It owns a reference to the underlying synchronization primitive associated with the Direct3D fence.

• VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT specifies a POSIX file descriptor handle to a Linux Sync File or Android Fence object. It can be used with any native API accepting a valid sync file or fence as input. It owns a reference to the underlying synchronization primitive
associated with the file descriptor. Implementations which support importing this handle type must accept any type of sync or fence FD supported by the native system they are running on.

Note

Handles of type `VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT` generated by the implementation may represent either Linux Sync Files or Android Fences at the implementation’s discretion. Applications should only use operations defined for both types of file descriptors, unless they know via means external to Vulkan the type of the file descriptor, or are prepared to deal with the system-defined operation failures resulting from using the wrong type.
Some external semaphore handle types can only be shared within the same underlying physical device and/or the same driver version, as defined in the following table:

<table>
<thead>
<tr>
<th>Handle type</th>
<th>VkPhysicalDeviceIDProperties::driverUUID</th>
<th>VkPhysicalDeviceIDProperties::deviceUUID</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_D3D12_FENCE_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_SYNC_FD_BIT</td>
<td>No restriction</td>
<td>No restriction</td>
</tr>
</tbody>
</table>

```c
typedef VkFlags VkExternalSemaphoreHandleTypeFlags;
```

or the equivalent

```c
typedef VkExternalSemaphoreHandleTypeFlags VkExternalSemaphoreHandleTypeFlagsKHR;
```

`VkExternalSemaphoreHandleTypeFlags` is a bitmask type for setting a mask of zero or more `VkExternalSemaphoreHandleTypeFlagBits`.

The `VkExternalSemaphoreProperties` structure is defined as:

```c
typedef struct VkExternalSemaphoreProperties {
    VkStructureType                      sType;
    void*                                pNext;
    VkExternalSemaphoreHandleTypeFlags   exportFromImportedHandleTypes;
    VkExternalSemaphoreHandleTypeFlags   compatibleHandleTypes;
    VkExternalSemaphoreFeatureFlags      externalSemaphoreFeatures;
} VkExternalSemaphoreProperties;
```

or the equivalent

```c
typedef VkExternalSemaphoreProperties VkExternalSemaphorePropertiesKHR;
```

- `exportFromImportedHandleTypes` is a bitmask of `VkExternalSemaphoreHandleTypeFlagBits` specifying which types of imported handle `handleType` can be exported from.
- `compatibleHandleTypes` is a bitmask of `VkExternalSemaphoreHandleTypeFlagBits` specifying handle types which can be specified at the same time as `handleType` when creating a semaphore.
- `externalSemaphoreFeatures` is a bitmask of `VkExternalSemaphoreFeatureFlagBits` describing the
features of `handleType`.

If `handleType` is not supported by the implementation, then `VkExternalSemaphoreProperties::externalSemaphoreFeatures` will be set to zero.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES`
- `pNext` must be `NULL`

Possible values of `VkExternalSemaphoreProperties::externalSemaphoreFeatures`, specifying the features of an external semaphore handle type, are:

```c
typedef enum VkExternalSemaphoreFeatureFlagBits {
    VK_EXTERNAL_SEMAPHORE_FEATURE_EXPORTABLE_BIT = 0x00000001,
    VK_EXTERNAL_SEMAPHORE_FEATURE_IMPORTABLE_BIT = 0x00000002,
    VK_EXTERNAL_SEMAPHORE_FEATURE_EXPORTABLE_BIT_KHR =
    VK_EXTERNAL_SEMAPHORE_FEATURE_EXPORTABLE_BIT,
    VK_EXTERNAL_SEMAPHORE_FEATURE_IMPORTABLE_BIT_KHR =
    VK_EXTERNAL_SEMAPHORE_FEATURE_IMPORTABLE_BIT,
    VK_EXTERNAL_SEMAPHORE_FEATURE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalSemaphoreFeatureFlagBits;
```

or the equivalent

```c
typedef VkExternalSemaphoreFeatureFlagBits VkExternalSemaphoreFeatureFlagBitsKHR;
```

- `VK_EXTERNAL_SEMAPHORE_FEATURE_EXPORTABLE_BIT` specifies that handles of this type can be exported from Vulkan semaphore objects.
- `VK_EXTERNAL_SEMAPHORE_FEATURE_IMPORTABLE_BIT` specifies that handles of this type can be imported as Vulkan semaphore objects.

```c
typedef VkFlags VkExternalSemaphoreFeatureFlags;
```

or the equivalent

```c
typedef VkExternalSemaphoreFeatureFlags VkExternalSemaphoreFeatureFlagsKHR;
```

`VkExternalSemaphoreFeatureFlags` is a bitmask type for setting a mask of zero or more `VkExternalSemaphoreFeatureFlagBits`. 
37.4. Optional Fence Capabilities

Fences may support import and export of their payload to external handles. To query the external handle types supported by fences, call:

```c
void vkGetPhysicalDeviceExternalFenceProperties(
    VkPhysicalDevice                            physicalDevice,
    const VkPhysicalDeviceExternalFenceInfo*    pExternalFenceInfo,
    VkExternalFenceProperties*                  pExternalFenceProperties);
```

or the equivalent command

```c
void vkGetPhysicalDeviceExternalFencePropertiesKHR(
    VkPhysicalDevice                            physicalDevice,
    const VkPhysicalDeviceExternalFenceInfo*    pExternalFenceInfo,
    VkExternalFenceProperties*                  pExternalFenceProperties);
```

- `physicalDevice` is the physical device from which to query the fence capabilities.
- `pExternalFenceInfo` is a pointer to a `VkPhysicalDeviceExternalFenceInfo` structure describing the parameters that would be consumed by `vkCreateFence`.
- `pExternalFenceProperties` is a pointer to a `VkExternalFenceProperties` structure in which capabilities are returned.

**Valid Usage (Implicit)**

- `physicalDevice` must be a valid `VkPhysicalDevice` handle
- `pExternalFenceInfo` must be a valid pointer to a valid `VkPhysicalDeviceExternalFenceInfo` structure
- `pExternalFenceProperties` must be a valid pointer to a `VkExternalFenceProperties` structure

The `VkPhysicalDeviceExternalFenceInfo` structure is defined as:

```c
typedef struct VkPhysicalDeviceExternalFenceInfo {
    VkStructureType                      sType;
    const void*                          pNext;
    VkExternalFenceHandleTypeFlagBits    handleType;
} VkPhysicalDeviceExternalFenceInfo;
```

or the equivalent

```c
typedef VkPhysicalDeviceExternalFenceInfo VkPhysicalDeviceExternalFenceInfoKHR;
```
• **sType** is the type of this structure

• **pNext** is NULL or a pointer to an extension-specific structure.

• **handleType** is a [VkExternalFenceHandleTypeFlagBits](https://www.khronos.org/registry/vulkan/specs/1.2-extensions/man/html/vkVkPhysicalDeviceExternalFenceProperties.html) value indicating an external fence handle type for which capabilities will be returned.

*Note*

Handles of type `VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT` generated by the implementation may represent either Linux Sync Files or Android Fences at the implementation's discretion. Applications *should* only use operations defined for both types of file descriptors, unless they know via means external to Vulkan the type of the file descriptor, or are prepared to deal with the system-defined operation failures resulting from using the wrong type.

---

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_FENCE_INFO`
- **pNext** must be `NULL`
- **handleType** must be a valid [VkExternalFenceHandleTypeFlagBits](https://www.khronos.org/registry/vulkan/specs/1.2-extensions/man/html/vkVkPhysicalDeviceExternalFenceProperties.html) value

Bits which *may* be set in `VkPhysicalDeviceExternalFenceInfo::handleType`, and in the `exportFromImportedHandleTypes` and `compatibleHandleTypes` members of `VkExternalFenceProperties`, to indicate external fence handle types, are:

```c
typedef enum VkExternalFenceHandleTypeFlagBits {
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT = 0x00000001,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT = 0x00000002,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT = 0x00000004,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT = 0x00000008,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT_KHR =
        VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT_KHR =
        VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT_KHR =
        VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT_KHR =
        VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT,
    VK_EXTERNAL_FENCE_HANDLE_TYPE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalFenceHandleTypeFlagBits;
```

or the equivalent

```c
typedef VkExternalFenceHandleTypeFlagBits VkExternalFenceHandleTypeFlagBitsKHR;
```

- `VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT` specifies a POSIX file descriptor handle that has
only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the POSIX system calls `dup`, `dup2`, `close`, and the non-standard system call `dup3`. Additionally, it must be transportable over a socket using an `SCM_RIGHTS` control message. It owns a reference to the underlying synchronization primitive represented by its Vulkan fence object.

- **VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT** specifies an NT handle that has only limited valid usage outside of Vulkan and other compatible APIs. It must be compatible with the functions `DuplicateHandle`, `CloseHandle`, `CompareObjectHandles`, `GetHandleInformation`, and `SetHandleInformation`. It owns a reference to the underlying synchronization primitive represented by its Vulkan fence object.

- **VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT** specifies a global share handle that has only limited valid usage outside of Vulkan and other compatible APIs. It is not compatible with any native APIs. It does not own a reference to the underlying synchronization primitive represented by its Vulkan fence object, and will therefore become invalid when all Vulkan fence objects associated with it are destroyed.

- **VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT** specifies a POSIX file descriptor handle to a Linux Sync File or Android Fence. It can be used with any native API accepting a valid sync file or fence as input. It owns a reference to the underlying synchronization primitive associated with the file descriptor. Implementations which support importing this handle type must accept any type of sync or fence FD supported by the native system they are running on.
Some external fence handle types can only be shared within the same underlying physical device and/or the same driver version, as defined in the following table:

### Table 62. External fence handle types compatibility

<table>
<thead>
<tr>
<th>Handle type</th>
<th>VkPhysicalDeviceIDProperties::driverUUID</th>
<th>VkPhysicalDeviceIDProperties::deviceUUID</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCE_HANDLE_TYPE_SYNC_FD_BIT</td>
<td>No restriction</td>
<td>No restriction</td>
</tr>
</tbody>
</table>

```c
typedef VkFlags VkExternalFenceHandleTypeFlags;
```

or the equivalent

```c
typedef VkExternalFenceHandleTypeFlags VkExternalFenceHandleTypeFlagsKHR;
```

`VkExternalFenceHandleTypeFlags` is a bitmask type for setting a mask of zero or more `VkExternalFenceHandleTypeFlagBits`.

The `VkExternalFenceProperties` structure is defined as:

```c
typedef struct VkExternalFenceProperties {
    VkStructureType           sType;
    void*                     pNext;
    VkExternalFenceHandleTypeFlags exportFromImportedHandleTypes;
    VkExternalFenceHandleTypeFlags compatibleHandleTypes;
    VkExternalFenceFeatureFlags externalFenceFeatures;
} VkExternalFenceProperties;
```

or the equivalent

```c
typedef VkExternalFenceProperties VkExternalFencePropertiesKHR;
```

- `exportFromImportedHandleTypes` is a bitmask of `VkExternalFenceHandleTypeFlagBits` indicating which types of imported handle `handleType` can be exported from.
- `compatibleHandleTypes` is a bitmask of `VkExternalFenceHandleTypeFlagBits` specifying handle types which can be specified at the same time as `handleType` when creating a fence.
- `externalFenceFeatures` is a bitmask of `VkExternalFenceFeatureFlagBits` indicating the features of `handleType`. 

If `handleType` is not supported by the implementation, then `VkExternalFenceProperties::externalFenceFeatures` will be set to zero.

### Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_EXTERNAL_FENCE_PROPERTIES`
- `pNext` must be `NULL`

Bits which **may** be set in `VkExternalFenceProperties::externalFenceFeatures`, indicating features of a fence external handle type, are:

```c
typedef enum VkExternalFenceFeatureFlagBits {
    VK_EXTERNAL_FENCE_FEATURE_EXPORTABLE_BIT = 0x00000001,
    VK_EXTERNAL_FENCE_FEATURE_IMPORTABLE_BIT = 0x00000002,
    VK_EXTERNAL_FENCE_FEATURE_EXPORTABLE_BIT_KHR =
    VK_EXTERNAL_FENCE_FEATURE_IMPORTABLE_BIT_KHR =
    VK_EXTERNAL_FENCE_FEATURE_EXPORTABLE_BIT_KHR =
    VK_EXTERNAL_FENCE_FEATURE_FEATURE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalFenceFeatureFlagBits;
```

or the equivalent

```c
typedef VkExternalFenceFeatureFlagBits VkExternalFenceFeatureFlagBitsKHR;
```

- `VK_EXTERNAL_FENCE_FEATURE_EXPORTABLE_BIT` specifies handles of this type **can** be exported from Vulkan fence objects.
- `VK_EXTERNAL_FENCE_FEATURE_IMPORTABLE_BIT` specifies handles of this type **can** be imported to Vulkan fence objects.

```c
typedef VkFlags VkExternalFenceFeatureFlags;
```

or the equivalent

```c
typedef VkExternalFenceFeatureFlags VkExternalFenceFeatureFlagsKHR;
```

`VkExternalFenceFeatureFlags` is a bitmask type for setting a mask of zero or more `VkExternalFenceFeatureFlagBits`. 
Chapter 38. Debugging

To aid developers in tracking down errors in the application’s use of Vulkan, particularly in combination with an external debugger or profiler, *debugging extensions* may be available.

The `VkObjectType` enumeration defines values, each of which corresponds to a specific Vulkan handle type. These values can be used to associate debug information with a particular type of object through one or more extensions.
typedef enum VkObjectType {
    VK_OBJECT_TYPE_UNKNOWN = 0,
    VK_OBJECT_TYPE_INSTANCE = 1,
    VK_OBJECT_TYPE_PHYSICAL_DEVICE = 2,
    VK_OBJECT_TYPE_DEVICE = 3,
    VK_OBJECT_TYPE_QUEUE = 4,
    VK_OBJECT_TYPE_SEMAPHORE = 5,
    VK_OBJECT_TYPE_COMMAND_BUFFER = 6,
    VK_OBJECT_TYPE_FENCE = 7,
    VK_OBJECT_TYPE_DEVICE_MEMORY = 8,
    VK_OBJECT_TYPE_BUFFER = 9,
    VK_OBJECT_TYPE_IMAGE = 10,
    VK_OBJECT_TYPE_EVENT = 11,
    VK_OBJECT_TYPE_QUERY_POOL = 12,
    VK_OBJECT_TYPE_BUFFER_VIEW = 13,
    VK_OBJECT_TYPE_IMAGE_VIEW = 14,
    VK_OBJECT_TYPE_SHADER_MODULE = 15,
    VK_OBJECT_TYPE_PIPELINE_CACHE = 16,
    VK_OBJECT_TYPE_PIPELINE_LAYOUT = 17,
    VK_OBJECT_TYPE_RENDER_PASS = 18,
    VK_OBJECT_TYPE_PIPELINE = 19,
    VK_OBJECT_TYPE_DESCRIPTOR_SET_LAYOUT = 20,
    VK_OBJECT_TYPE_SAMPLER = 21,
    VK_OBJECT_TYPE_DESCRIPTOR_POOL = 22,
    VK_OBJECT_TYPE_DESCRIPTOR_SET = 23,
    VK_OBJECT_TYPE_FRAMEBUFFER = 24,
    VK_OBJECT_TYPE_COMMAND_POOL = 25,
    VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION = 1000156000,
    VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE = 1000085000,
    VK_OBJECT_TYPE_SURFACE_KHR = 1000000000,
    VK_OBJECT_TYPE_SWAPCHAIN_KHR = 1000001000,
    VK_OBJECT_TYPE_DISPLAY_KHR = 1000002000,
    VK_OBJECT_TYPE_DISPLAY_MODE_KHR = 1000002001,
    VK_OBJECT_TYPE_ACCELERATION_STRUCTURE_KHR = 1000165000,
    VK_OBJECT_TYPE_DEFERRED_OPERATION_KHR = 1000268000,
    VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_KHR = VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE,
    VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION_KHR = VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION,
    VK_OBJECT_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkObjectType;

<table>
<thead>
<tr>
<th>VkObjectType</th>
<th>Vulkan Handle Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_OBJECT_TYPE_UNKNOWN</td>
<td>Unknown/Undefined Handle</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_INSTANCE</td>
<td>VkInstance</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PHYSICAL_DEVICE</td>
<td>VkPhysicalDevice</td>
</tr>
</tbody>
</table>

Table 63. VkObjectType and Vulkan Handle Relationship
<table>
<thead>
<tr>
<th>VkObjectType</th>
<th>Vulkan Handle Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_OBJECT_TYPE_DEVICE</td>
<td>VkDevice</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_QUEUE</td>
<td>VkQueue</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SEMAPHORE</td>
<td>VkSemaphore</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_COMMAND_BUFFER</td>
<td>VkCommandBuffer</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_FENCE</td>
<td>VkFence</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DEVICE_MEMORY</td>
<td>VkDeviceMemory</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_BUFFER</td>
<td>VkBuffer</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_IMAGE</td>
<td>VkImage</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_EVENT</td>
<td>VkEvent</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_QUERY_POOL</td>
<td>VkQueryPool</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_BUFFER_VIEW</td>
<td>VkBufferView</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_IMAGE_VIEW</td>
<td>VkImageView</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SHADER_MODULE</td>
<td>VkShaderModule</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PIPELINE_CACHE</td>
<td>VkPipelineCache</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PIPELINE_LAYOUT</td>
<td>VkPipelineLayout</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_RENDER_PASS</td>
<td>VkRenderPass</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_PIPELINE</td>
<td>VkPipeline</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_SET_LAYOUT</td>
<td>VkDescriptorSetLayout</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SAMPLER</td>
<td>VkSampler</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_POOL</td>
<td>VkDescriptorPool</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_SET</td>
<td>VkDescriptorSet</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_FRAMEBUFFER</td>
<td>VkFramebuffer</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_COMMAND_POOL</td>
<td>VkCommandPool</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION</td>
<td>VkSamplerYcbcrConversion</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE</td>
<td>VkDescriptorUpdateTemplate</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SURFACE_KHR</td>
<td>VkSurfaceKHR</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_SWAPCHAIN_KHR</td>
<td>VkSwapchainKHR</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DISPLAY_KHR</td>
<td>VkDisplayKHR</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_DISPLAY_MODE_KHR</td>
<td>VkDisplayModeKHR</td>
</tr>
<tr>
<td>VK_OBJECT_TYPE_ACCELERATION_STRUCTURE_KHR</td>
<td>VkAccelerationStructureKHR</td>
</tr>
</tbody>
</table>

If this Specification was generated with any such extensions included, they will be described in the remainder of this chapter.
Appendix A: Vulkan Environment for SPIR-V

Shaders for Vulkan are defined by the Khronos SPIR-V Specification as well as the Khronos SPIR-V Extended Instructions for GLSL Specification. This appendix defines additional SPIR-V requirements applying to Vulkan shaders.

Versions and Formats

A Vulkan 1.1 implementation must support the 1.0, 1.1, 1.2, and 1.3 versions of SPIR-V and the 1.0 version of the SPIR-V Extended Instructions for GLSL. If the VK_KHR_spirv_1_4 extension is enabled, the implementation must additionally support the 1.4 version of SPIR-V.

A SPIR-V module passed into vkCreateShaderModule is interpreted as a series of 32-bit words in host endianness, with literal strings packed as described in section 2.2 of the SPIR-V Specification. The first few words of the SPIR-V module must be a magic number and a SPIR-V version number, as described in section 2.3 of the SPIR-V Specification.

Capabilities

The SPIR-V capabilities listed below must be supported if the corresponding feature or extension is enabled, or if no features or extensions are listed for that capability. Extensions are only listed when there is not also a feature bit associated with that capability.

<table>
<thead>
<tr>
<th>SPIR-V OpCapability</th>
<th>Vulkan feature or extension name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td></td>
</tr>
<tr>
<td>Shader</td>
<td></td>
</tr>
<tr>
<td>InputAttachment</td>
<td></td>
</tr>
<tr>
<td>Sampled1D</td>
<td></td>
</tr>
<tr>
<td>Image1D</td>
<td></td>
</tr>
<tr>
<td>SampledBuffer</td>
<td></td>
</tr>
<tr>
<td>ImageBuffer</td>
<td></td>
</tr>
<tr>
<td>ImageQuery</td>
<td></td>
</tr>
<tr>
<td>DerivativeControl</td>
<td></td>
</tr>
<tr>
<td>Geometry</td>
<td>geometryShader</td>
</tr>
<tr>
<td>Tessellation</td>
<td>tessellationShader</td>
</tr>
<tr>
<td>Float64</td>
<td>shaderFloat64</td>
</tr>
<tr>
<td>Int64</td>
<td>shaderInt64</td>
</tr>
<tr>
<td>Int64Atomics</td>
<td>shaderBufferInt64Atomics, shaderSharedInt64Atomics</td>
</tr>
<tr>
<td>Int16</td>
<td>shaderInt16</td>
</tr>
<tr>
<td>TessellationPointSize</td>
<td>shaderTessellationAndGeometryPointSize</td>
</tr>
<tr>
<td>GeometryPointSize</td>
<td>shaderTessellationAndGeometryPointSize</td>
</tr>
<tr>
<td>ImageGatherExtended</td>
<td>shaderImageGatherExtended</td>
</tr>
<tr>
<td>SPIR-V OpCapability</td>
<td>Vulkan feature or extension name</td>
</tr>
<tr>
<td>--------------------------------------------------------</td>
<td>------------------------------------------------------------------</td>
</tr>
<tr>
<td>StorageImageMultisample</td>
<td>shaderStorageImageMultisample</td>
</tr>
<tr>
<td>UniformBufferArrayDynamicIndexing</td>
<td>shaderUniformBufferArrayDynamicIndexing</td>
</tr>
<tr>
<td>SampledImageArrayDynamicIndexing</td>
<td>shaderSampledImageArrayDynamicIndexing</td>
</tr>
<tr>
<td>StorageBufferArrayDynamicIndexing</td>
<td>shaderStorageBufferArrayDynamicIndexing</td>
</tr>
<tr>
<td>StorageImageArrayDynamicIndexing</td>
<td>shaderStorageImageArrayDynamicIndexing</td>
</tr>
<tr>
<td>ClipDistance</td>
<td>shaderClipDistance</td>
</tr>
<tr>
<td>CullDistance</td>
<td>shaderCullDistance</td>
</tr>
<tr>
<td>ImageCubeArray</td>
<td>imageCubeArray</td>
</tr>
<tr>
<td>SampleRateShading</td>
<td>sampleRateShading</td>
</tr>
<tr>
<td>SparseResidency</td>
<td>shaderResourceResidency</td>
</tr>
<tr>
<td>MinLod</td>
<td>shaderResourceMinLod</td>
</tr>
<tr>
<td>SampledCubeArray</td>
<td>imageCubeArray</td>
</tr>
<tr>
<td>ImageMSArray</td>
<td>shaderStorageImageMultisample</td>
</tr>
<tr>
<td>StorageImageExtendedFormats</td>
<td></td>
</tr>
<tr>
<td>InterpolationFunction</td>
<td>sampleRateShading</td>
</tr>
<tr>
<td>StorageImageReadWithoutFormat</td>
<td>shaderStorageImageReadWithoutFormat</td>
</tr>
<tr>
<td>StorageImageWriteWithoutFormat</td>
<td>shaderStorageImageWriteWithoutFormat</td>
</tr>
<tr>
<td>MultiViewport</td>
<td>multiViewport</td>
</tr>
<tr>
<td>DrawParameters</td>
<td>shaderDrawParameters, VK_KHR_shader_draw_parameters</td>
</tr>
<tr>
<td>MultiView</td>
<td></td>
</tr>
<tr>
<td>DeviceGroup</td>
<td></td>
</tr>
<tr>
<td>VariablePointersStorageBuffer</td>
<td>variablePointersStorageBuffer</td>
</tr>
<tr>
<td>VariablePointers</td>
<td>variablePointers</td>
</tr>
<tr>
<td>ShaderClockKHR</td>
<td>VK_KHR_shader_clock</td>
</tr>
<tr>
<td>StorageBuffer16BitAccess</td>
<td>StorageBuffer16BitAccess</td>
</tr>
<tr>
<td>UniformAndStorageBuffer16BitAccess</td>
<td>UniformAndStorageBuffer16BitAccess</td>
</tr>
<tr>
<td>StoragePushConstant16</td>
<td>storagePushConstant16</td>
</tr>
<tr>
<td>StorageInputOutput16</td>
<td>storageInputOutput16</td>
</tr>
<tr>
<td>GroupNonUniform</td>
<td>VK_SUBGROUP_FEATURE_BASIC_BIT</td>
</tr>
<tr>
<td>GroupNonUniformVote</td>
<td>VK_SUBGROUP_FEATURE_VOTE_BIT</td>
</tr>
<tr>
<td>GroupNonUniformArithmetic</td>
<td>VK_SUBGROUP_FEATURE_ARITHMETIC_BIT</td>
</tr>
<tr>
<td>GroupNonUniformBallot</td>
<td>VK_SUBGROUP_FEATURE_BALLOT_BIT</td>
</tr>
<tr>
<td>GroupNonUniformShuffle</td>
<td>VK_SUBGROUP_FEATURE_SHUFFLE_BIT</td>
</tr>
<tr>
<td>GroupNonUniformShuffleRelative</td>
<td>VK_SUBGROUP_FEATURE_SHUFFLE_RELATIVE_BIT</td>
</tr>
<tr>
<td>GroupNonUniformClustered</td>
<td>VK_SUBGROUP_FEATURE_CLUSTERED_BIT</td>
</tr>
<tr>
<td>GroupNonUniformQuad</td>
<td>VK_SUBGROUP_FEATURE_QUAD_BIT</td>
</tr>
<tr>
<td>Float16</td>
<td>shaderFloat16</td>
</tr>
<tr>
<td>Int8</td>
<td>shaderInt8</td>
</tr>
<tr>
<td>StorageBuffer8BitAccess</td>
<td>StorageBuffer8BitAccess</td>
</tr>
<tr>
<td>UniformAndStorageBuffer8BitAccess</td>
<td>UniformAndStorageBuffer8BitAccess</td>
</tr>
</tbody>
</table>
The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_variable_pointers` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_shader_draw_parameters` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_8bit_storage` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_16bit_storage` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_shader_clock` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_float_controls` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_storage_buffer_storage_class` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_vulkan_memory_model` SPIR-V extension.
The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_ray_tracing` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_ray_query` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_physical_storage_buffer` SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the `SPV_KHR_non_semantic_info` SPIR-V extension.

The application must not pass a SPIR-V module containing any of the following to `vkCreateShaderModule`:

- any `OpCapability` not listed above,
- an unsupported capability, or
- a capability which corresponds to a Vulkan feature or extension which has not been enabled.

**Validation Rules within a Module**

A SPIR-V module passed to `vkCreateShaderModule` must conform to the following rules:

- Every entry point must have no return value and accept no arguments.
- Recursion: The static function-call graph for an entry point must not contain cycles.
- The Logical or PhysicalStorageBuffer64 addressing model must be selected.
- **Scope** for execution must be limited to:
  - **Workgroup**
    - The Workgroup scope must only be used in the tessellation control, and compute execution models.
  - **Subgroup**
- **Scope** for memory must be limited to:
  - **Device**
    - If `vulkanMemoryModel` is enabled and `vulkanMemoryModelDeviceScope` is not enabled, **Device** scope must not be used.
    - If `vulkanMemoryModel` is not enabled, **Device** scope only extends to the queue family, not the whole device.
  - **QueueFamily**
    - If `vulkanMemoryModel` is not enabled, **QueueFamily** must not be used.
  - **Workgroup**
    - The WorkGroup scope must only be used in the compute execution model(s).
  - **Subgroup**
Invocation

- Scope for Non Uniform Group Operations must be limited to:
  - Subgroup

- Storage Class must be limited to:
  - UniformConstant
  - Input
  - Uniform
  - Output
    - The Output storage class must not be used in the RayGenerationKHR, IntersectionKHR, AnyHitKHR, ClosestHitKHR, MissKHR, or CallableKHR execution models.

- Workgroup
  - The Workgroup storage class must only be used in the compute execution model(s).

- Private
- Function
- PushConstant
- Image
- StorageBuffer
- RayPayloadKHR
- IncomingRayPayloadKHR
- HitAttributeKHR
- CallableDataKHR
- IncomingCallableDataKHR
- ShaderRecordBufferKHR
- PhysicalStorageBuffer

- Memory semantics must obey the following rules:
  - Acquire must not be used with OpAtomicStore.
  - Release must not be used with OpAtomicLoad.
  - AcquireRelease must not be used with OpAtomicStore or OpAtomicLoad.
  - Sequentially consistent atomics and barriers are not supported and SequentiallyConsistent is treated as AcquireRelease. SequentiallyConsistent should not be used.
  - OpMemoryBarrier must use one of Acquire, Release, AcquireRelease, or SequentiallyConsistent and must include at least one storage class.
  - If the semantics for OpControlBarrier includes one of Acquire, Release, AcquireRelease, or SequentiallyConsistent, then it must include at least one storage class.
  - SubgroupMemory, CrossWorkgroupMemory, and AtomicCounterMemory are ignored.
• Any `OpVariable` with an `Initializer` operand **must** have one of the following as its `Storage Class` operand:
  • Output
  • Private
  • Function

• Scope for `OpReadClockKHR` must be limited to:
  • Subgroup
    • if `shaderSubgroupClock` is not enabled, the Subgroup scope **must** not be used.
  • Device
    • if `shaderDeviceClock` is not enabled, the Device scope **must** not be used.

• The `OriginLowerLeft` execution mode **must** not be used; fragment entry points **must** declare `OriginUpperLeft`.

• The `PixelCenterInteger` execution mode **must** not be used. Pixels are always centered at half-integer coordinates.

• Any variable in the `UniformConstant` storage class **must** be typed as either:
  • `OpTypeImage`
  • `OpTypeSampler`
  • `OpTypeSampledImage`
  • `OpTypeAccelerationStructureKHR`,
  • An array of one of these types.

• Images and Samplers
  • `OpTypeImage` **must** declare a scalar 32-bit float or 32-bit integer type for the “Sampled Type”. *(RelaxedPrecision can be applied to a sampling instruction and to the variable holding the result of a sampling instruction.)*
  • If the `Sampled Type` of an `OpTypeImage` declaration does not match the numeric format of the corresponding resource in type, as shown in the `SPIR-V Sampled Type` column of the `Interpretation of Numeric Format` table, the values obtained by reading or sampling from the image are undefined.
  • If the signedness of any read or sample operation does not match the signedness of the corresponding resource then the values obtained are undefined.
  • `OpTypeImage` **must** have a “Sampled” operand of 1 (sampled image) or 2 (storage image).
  • If `shaderStorageImageReadWithoutFormat` is not enabled and an `OpTypeImage` has “Image Format” operand of `Unknown`, any variables created with the given type must be decorated with `NonReadable`.
  • If `shaderStorageImageWriteWithoutFormat` is not enabled and an `OpTypeImage` has “Image Format” operand of `Unknown`, any variables created with the given type must be decorated with `NonWritable`.
  • `OpImageQuerySizeLod`, and `OpImageQueryLevels` **must** only consume an “Image” operand whose type has its “Sampled” operand set to 1.
• The (u,v) coordinates used for a SubpassData must be the <id> of a constant vector (0,0), or if a layer coordinate is used, must be a vector that was formed with constant 0 for the u and v components.

• The “Depth” operand of OpTypeImage is ignored.

• Objects of types OpTypeImage, OpTypeSampler, OpTypeSampledImage, and arrays of these types must not be stored to or modified.

• Any image operation must use at most one of the Offset, ConstOffset, and ConstOffsets image operands.

• Image operand Offset must only be used with OpImage*Gather instructions.

• The “Component” operand of OpImageGather, and OpImageSparseGather must be the <id> of a constant instruction.

• Acceleration Structures
  • Objects of types OpTypeAccelerationStructureKHR and arrays of this type must not be stored to or modified.

• The value of the “Hit Kind” operand of OpReportIntersectionKHR must be in the range [0,127].

• Structure types must not contain opaque types.

• Decorations
  • Any BuiltIn decoration not listed in Built-In Variables must not be used.

  • Any BuiltIn decoration that corresponds only to Vulkan features or extensions that have not been enabled must not be used.

  • The GLSLShared and GLSLPacked decorations must not be used.

  • The Flat, NoPerspective, Sample, and Centroid decorations must not be used on variables with storage class other than Input or on variables used in the interface of non-fragment shader entry points.

  • The Patch decoration must not be used on variables in the interface of a vertex, geometry, or fragment shader stage's entry point.

  • Only the round-to-nearest-even and the round-towards-zero rounding modes can be used for the FPRoundingMode decoration.

  • The FPRoundingMode decoration can only be used for the floating-point conversion instructions as described in the SPV_KHR_16bit_storage SPIR-V extension.

  • DescriptorSet and Binding decorations must obey the constraints on storage class, type, and descriptor type described in DescriptorSet and Binding Assignment

  • Variables decorated with Invariant and variables with structure types that have any members decorated with Invariant must be in the Output or Input storage class. Invariant used on an Input storage class variable or structure member has no effect.

• OpTypeRuntimeArray must only be used for:

  • the last member of an OpTypeStruct that is in the StorageBuffer storage class decorated as Block, or that is in the PhysicalStorageBuffer storage class decorated as Block, or that is in the Uniform storage class decorated as BufferBlock.
• Specialization constants:
  ◦ A type $T$ that is an array sized with a specialization constant can be, or be contained in, the type of a Variable $V$ only if:
    • $T$ is the (top-level) type of $V$, or
    • $V$ is declared in the Function, Private, or Workgroup storage classes, or
    • $V$ is an interface variable with an additional level of arrayness, as described in interface matching, in which case $T$ is allowed to be the element type of the (top-level) type of $V$.

• Linkage: See Shader Interfaces for additional linking and validation rules.

• If OpControlBarrier is used in ray generation, intersection, any-hit, closest hit, miss, fragment, vertex, tessellation evaluation, or geometry shaders, the execution Scope must be Subgroup.

• Compute Shaders
  ◦ For each compute shader entry point, either a LocalSize execution mode or an object decorated with the WorkgroupSize decoration must be specified.

  “Result Type” for Non Uniform Group Operations must be limited to 32-bit floating-point, 32-bit integer, boolean, or vectors of these types.

  ◦ If the Float64 capability is enabled, 64-bit floating-point and vector of 64-bit floating-point types are also permitted.
  ◦ If the Int8 capability is enabled and the shaderSubgroupExtendedTypes feature is VK_TRUE, 8-bit integer and vector of 8-bit integer types are also permitted.
  ◦ If the Int16 capability is enabled and the shaderSubgroupExtendedTypes feature is VK_TRUE, 16-bit integer and vector of 16-bit integer types are also permitted.
  ◦ If the Int64 capability is enabled and the shaderSubgroupExtendedTypes feature is VK_TRUE, 64-bit integer and vector of 64-bit integer types are also permitted.
  ◦ If the Float16 capability is enabled and the shaderSubgroupExtendedTypes feature is VK_TRUE, 16-bit floating-point and vector of 16-bit floating-point types are also permitted.

• If OpGroupNonUniformBallotBitCount is used, the group operation must be one of:
  ◦ Reduce
  ◦ InclusiveScan
  ◦ ExclusiveScan

• Atomic instructions must declare a scalar 32-bit integer type, or a scalar 64-bit integer type if the Int64Atomics capability is enabled, for the value pointed to by Pointer.

  ◦ shaderBufferInt64Atomics must be enabled for 64-bit integer atomic operations to be supported on a Pointer with a Storage Class of StorageBuffer or Uniform.
  ◦ shaderSharedInt64Atomics must be enabled for 64-bit integer atomic operations to be supported on a Pointer with a Storage Class of Workgroup.

• The Pointer operand of all atomic instructions must have a Storage Class limited to:
  ◦ Uniform
  ◦ Workgroup
• If `denormBehaviorIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY`, then the entry point **must** use the same denormals execution mode for both 16-bit and 64-bit floating-point types.

• If `denormBehaviorIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE`, then the entry point **must** use the same denormals execution mode for all floating-point types.

• If `roundingModeIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_32_BIT_ONLY`, then the entry point **must** use the same rounding execution mode for both 16-bit and 64-bit floating-point types.

• If `roundingModeIndependence` is `VK_SHADER_FLOAT_CONTROLS_INDEPENDENCE_NONE`, then the entry point **must** use the same rounding execution mode for all floating-point types.

• If `shaderSignedZeroInfNanPreserveFloat16` is `VK_FALSE`, then `SignedZeroInfNanPreserve` for 16-bit floating-point type **must** not be used.

• If `shaderSignedZeroInfNanPreserveFloat32` is `VK_FALSE`, then `SignedZeroInfNanPreserve` for 32-bit floating-point type **must** not be used.

• If `shaderSignedZeroInfNanPreserveFloat64` is `VK_FALSE`, then `SignedZeroInfNanPreserve` for 64-bit floating-point type **must** not be used.

• If `shaderDenormPreserveFloat16` is `VK_FALSE`, then `DenormPreserve` for 16-bit floating-point type **must** not be used.

• If `shaderDenormPreserveFloat32` is `VK_FALSE`, then `DenormPreserve` for 32-bit floating-point type **must** not be used.

• If `shaderDenormPreserveFloat64` is `VK_FALSE`, then `DenormPreserve` for 64-bit floating-point type **must** not be used.

• If `shaderDenormFlushToZeroFloat16` is `VK_FALSE`, then `DenormFlushToZero` for 16-bit floating-point type **must** not be used.

• If `shaderDenormFlushToZeroFloat32` is `VK_FALSE`, then `DenormFlushToZero` for 32-bit floating-point type **must** not be used.

• If `shaderDenormFlushToZeroFloat64` is `VK_FALSE`, then `DenormFlushToZero` for 64-bit floating-point type **must** not be used.

• If `shaderRoundingModeRTEFloat16` is `VK_FALSE`, then `RoundingModeRTE` for 16-bit floating-point type **must** not be used.

• If `shaderRoundingModeRTEFloat32` is `VK_FALSE`, then `RoundingModeRTE` for 32-bit floating-point type **must** not be used.

• If `shaderRoundingModeRTEFloat64` is `VK_FALSE`, then `RoundingModeRTE` for 64-bit floating-point type **must** not be used.

• If `shaderRoundingModeRTZFloat16` is `VK_FALSE`, then `RoundingModeRTZ` for 16-bit floating-point type **must** not be used.

• If `shaderRoundingModeRTZFloat32` is `VK_FALSE`, then `RoundingModeRTZ` for 32-bit floating-point type **must** not be used.
• If `shaderRoundingModeRtzFloat64` is `VK_FALSE`, then `RoundingModeRtz` for 64-bit floating-point type must not be used.

• `RayPayloadKHR` storage class must only be used in ray generation, any-hit, closest hit or miss shaders.

• `IncomingRayPayloadKHR` storage class must only be used in closest hit, any-hit, or miss shaders.

• `HitAttributeKHR` storage class must only be used in intersection, any-hit, or closest hit shaders.

• `CallableDataKHR` storage class must only be used in ray generation, closest hit, miss, and callable shaders.

• `IncomingCallableDataKHR` storage class must only be used in callable shaders.

• The Base operand of `OpPtrAccessChain` must point to one of the following storage classes:
  ○ `Workgroup`, if `VariablePointers` is enabled.
  ○ `StorageBuffer`, if `VariablePointers` or `VariablePointersStorageBuffer` is enabled.
  ○ `PhysicalStorageBuffer`, if the `PhysicalStorageBuffer64` addressing model is enabled.

• If the `PhysicalStorageBuffer64` addressing model is enabled:
  ◦ Any load or store through a physical pointer type must be aligned to a multiple of the size of the largest scalar type in the pointed-to type.
  ◦ All instructions that support memory access operands and that use a physical pointer must include the Aligned operand.
  ◦ The pointer value of a memory access instruction must be at least as aligned as specified by the Aligned memory access operand.
  ◦ Any access chain instruction that accesses into a RowMajor matrix must only be used as the Pointer operand to `OpLoad` or `OpStore`.
  ◦ `OpConvertUToPtr` and `OpConvertPtrToU` must use an integer type whose Width is 64.

### Precision and Operation of SPIR-V Instructions

The following rules apply to half, single, and double-precision floating point instructions:

• Positive and negative infinities and positive and negative zeros are generated as dictated by IEEE 754, but subject to the precisions allowed in the following table.

• Dividing a non-zero by a zero results in the appropriately signed IEEE 754 infinity.

• Signaling NaNs are not required to be generated and exceptions are never raised. Signaling NaN may be converted to quiet NaNs values by any floating point instruction.

• By default, the implementation may perform optimizations on half, single, or double-precision floating-point instructions that ignore sign of a zero, or assume that arguments and results are not NaNs or infinities. If the entry point is declared with the `SignedZeroInfNanPreserve` execution mode, then NaNs, infinities, and the sign of zero must not be ignored.

Operations described as “correctly rounded” will return the infinitely precise result, \( x \), rounded so that the magnitude of the error is less than or equal to half the unit in the last place (ULP). This execution mode must also be respected by OpLoad except for loads from the Input storage class in the fragment shader stage with the floating-point result type. Other SPIR-V instructions may also respect the SignedZeroInfNanPreserve execution mode.

The precision of operations is defined either in terms of rounding, as an error bound in ULP, or as inherited from a formula as follows.

**Correctly Rounded**

Operations described as “correctly rounded” will return the infinitely precise result, \( x \), rounded so that the magnitude of the error is less than or equal to half the unit in the last place (ULP). This execution mode must also be respected by OpLoad except for loads from the Input storage class in the fragment shader stage with the floating-point result type. Other SPIR-V instructions may also respect the SignedZeroInfNanPreserve execution mode.


- Denormalized values are supported.
  - By default, any half, single, or double-precision denormalized value input into a shader or potentially generated by any instruction (except those listed above) or any extended instructions for GLSL in a shader may be flushed to zero.
  - If the entry point is declared with the DenormFlushToZero execution mode then for the affected instructions the denormalized result must be flushed to zero and the denormalized operands may be flushed to zero. Denormalized values obtained via unpacking an integer into a vector of values with smaller bit width and interpreting those values as floating-point numbers must be flushed to zero.

The precision of double-precision instructions is at least that of single precision.

The precision of operations is defined either in terms of rounding, as an error bound in ULP, or as inherited from a formula as follows.
as to be representable in floating-point. The rounding mode is not specified, unless the entry point is declared with the RoundingModeRTE or the RoundingModeRTZ execution mode. These execution modes affect only correctly rounded SPIR-V instructions. These execution modes do not affect OpQuantizeToF16. If the rounding mode is not specified then this rounding is implementation specific, subject to the following rules. If x is exactly representable then x will be returned. Otherwise, either the floating-point value closest to and no less than x or the value closest to and no greater than x will be returned.

**ULP**

Where an error bound of n ULP (units in the last place) is given, for an operation with infinitely precise result x the value returned must be in the range \([x - n \times \text{ulp}(x), x + n \times \text{ulp}(x)]\). The function \text{ulp}(x) is defined as follows:

If there exist non-equal floating-point numbers a and b such that \(a \leq x \leq b\) then \(\text{ulp}(x) = \min_a |b - a|\). If such numbers do not exist then \(\text{ulp}(x)\) is defined to be the difference between the two finite floating-point numbers nearest to x.

Where the range of allowed return values includes any value of magnitude larger than that of the largest representable finite floating-point number, operations may, additionally, return either an infinity of the appropriate sign or the finite number with the largest magnitude of the appropriate sign. If the infinitely precise result of the operation is not mathematically defined then the value returned is undefined.

**Inherited From ...**

Where an operation’s precision is described as being inherited from a formula, the result returned must be at least as accurate as the result of computing an approximation to x using a formula equivalent to the given formula applied to the supplied inputs. Specifically, the formula given may be transformed using the mathematical associativity, commutativity and distributivity of the operators involved to yield an equivalent formula. The SPIR-V precision rules, when applied to each such formula and the given input values, define a range of permitted values. If NaN is one of the permitted values then the operation may return any result, otherwise let the largest permitted value in any of the ranges be \(F_{\text{max}}\) and the smallest be \(F_{\text{min}}\). The operation must return a value in the range \([x - E, x + E]\) where \(E = \max(|x - F_{\text{min}}|, |x - F_{\text{max}}|)\). If the entry point is declared with the DenormFlushToZero execution mode, then any intermediate denormal value(s) while evaluating the formula may be flushed to zero. Denormal final results must be flushed to zero. If the entry point is declared with the DenormPreserve execution mode, then denormals must be preserved throughout the formula.

For half- (16 bit) and single- (32 bit) precision instructions, precisions are required to be at least as follows:

**Table 65. Precision of core SPIR-V Instructions**

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Single precision, unless decorated with RelaxedPrecision</th>
<th>Half precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>OpFAdd</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>Instruction</td>
<td>Single precision, unless decorated with RelaxedPrecision</td>
<td>Half precision</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>OpFSub</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>OpDot(x, y)</td>
<td>Inherited from $\sum_{i=0}^{n-1} x_i \times y_i$.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdEqual, OpFUnordEqual</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdLessThan, OpFUnordLessThan</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdGreater Than, OpFUnordGreater Than</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdGreater ThanEqual, OpFUnordGreater ThanEqual</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFDiv(x,y)</td>
<td>2.5 ULP for $</td>
<td>y</td>
</tr>
<tr>
<td>OpFRem(x,y)</td>
<td>Inherited from $x - y \times \text{trunc}(x/y)$.</td>
<td></td>
</tr>
<tr>
<td>OpFMod(x,y)</td>
<td>Inherited from $x - y \times \text{floor}(x/y)$.</td>
<td></td>
</tr>
<tr>
<td>conversions between types</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
</tbody>
</table>

**Note**

The **OpFRem** and **OpFMod** instructions use cheap approximations of remainder, and the error can be large due to the discontinuity in \( \text{trunc()} \) and \( \text{floor()} \). This can produce mathematically unexpected results in some cases, such as FMod(x,x) computing x rather than 0, and can also cause the result to have a different sign than the infinitely precise result.

**Table 66. Precision of GLSL.std.450 Instructions**

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Single precision, unless decorated with RelaxedPrecision</th>
<th>Half precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>fma()</td>
<td>Inherited from <strong>OpFMul</strong> followed by <strong>OpFAdd</strong>.</td>
<td></td>
</tr>
<tr>
<td>exp(x), exp2(x)</td>
<td>3 + 2 ×</td>
<td>x</td>
</tr>
<tr>
<td>log(), log2()</td>
<td>3 ULP outside the range [0.5, 2.0]. Absolute error &lt; 2^{-21} inside the range [0.5, 2.0].</td>
<td>3 ULP outside the range [0.5, 2.0]. Absolute error &lt; 2^{-7} inside the range [0.5, 2.0].</td>
</tr>
<tr>
<td>pow(x, y)</td>
<td>Inherited from exp2(y × log2(x)).</td>
<td></td>
</tr>
<tr>
<td>sqrt()</td>
<td>Inherited from exp2(y × log2(x)).</td>
<td></td>
</tr>
<tr>
<td>inversesqrt()</td>
<td>2 ULP.</td>
<td></td>
</tr>
<tr>
<td>Instruction</td>
<td>Single precision, unless decorated with RelaxedPrecision</td>
<td>Half precision</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>radians(x)</td>
<td>Inherited from $x \times \frac{\pi}{180}$.</td>
<td></td>
</tr>
<tr>
<td>degrees(x)</td>
<td>Inherited from $x \times \frac{180}{\pi}$.</td>
<td></td>
</tr>
<tr>
<td>sin()</td>
<td>Absolute error $\leq 2^{-11}$ inside the range $[-n, n]$.</td>
<td>Absolute error $\leq 2^{-7}$ inside the range $[-n, n]$.</td>
</tr>
<tr>
<td>cos()</td>
<td>Absolute error $\leq 2^{-11}$ inside the range $[-n, n]$.</td>
<td>Absolute error $\leq 2^{-7}$ inside the range $[-n, n]$.</td>
</tr>
<tr>
<td>tan()</td>
<td>Inherited from $\frac{\sin(x)}{\cos(x)}$.</td>
<td></td>
</tr>
<tr>
<td>asin(x)</td>
<td>Inherited from $\arctan2(x, \sqrt{1.0 - x \times x})$.</td>
<td></td>
</tr>
<tr>
<td>acos(x)</td>
<td>Inherited from $\arctan2(\sqrt{1.0 - x \times x}, x)$.</td>
<td></td>
</tr>
<tr>
<td>atan(), atan2()</td>
<td>4096 ULP</td>
<td>5 ULP.</td>
</tr>
<tr>
<td>sinh(x)</td>
<td>Inherited from $(\exp(x) - \exp(-x)) \times 0.5$.</td>
<td></td>
</tr>
<tr>
<td>cosh(x)</td>
<td>Inherited from $(\exp(x) + \exp(-x)) \times 0.5$.</td>
<td></td>
</tr>
<tr>
<td>tanh()</td>
<td>Inherited from $\frac{\sinh(x)}{\cosh(x)}$.</td>
<td></td>
</tr>
<tr>
<td>asinh(x)</td>
<td>Inherited from $\log(x + \sqrt{x \times x + 1.0})$.</td>
<td></td>
</tr>
<tr>
<td>acosh(x)</td>
<td>Inherited from $\log(x + \sqrt{x \times x - 1.0})$.</td>
<td></td>
</tr>
<tr>
<td>atanh(x)</td>
<td>Inherited from $\log(\frac{1.0 + x}{1.0 - x}) \times 0.5$.</td>
<td></td>
</tr>
<tr>
<td>frexp()</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>ldexp()</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>length(x)</td>
<td>Inherited from $\sqrt{\text{dot}(x, x)}$.</td>
<td></td>
</tr>
<tr>
<td>distance(x, y)</td>
<td>Inherited from $\text{length}(x - y)$.</td>
<td></td>
</tr>
<tr>
<td>normalize(x)</td>
<td>Inherited from $\frac{x}{\text{length}(x)}$.</td>
<td></td>
</tr>
<tr>
<td>faceforward(N, I, NRef)</td>
<td>Inherited from $\text{dot}(NRef, I) \times 0.0 \ ? N : -N$.</td>
<td></td>
</tr>
<tr>
<td>reflect(x, y)</td>
<td>Inherited from $x - 2.0 \times \text{dot}(y, x) \times y$.</td>
<td></td>
</tr>
<tr>
<td>Instruction</td>
<td>Single precision, unless decorated with RelaxedPrecision</td>
<td>Half precision</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>refract(I, N, eta)</td>
<td>Inherited from k &lt; 0.0 ? 0.0 : eta × I - (eta × dot(N, I) + sqrt(k)) × N, where k = 1 - eta × eta × (1.0 - dot(N, I) × dot(N, I)).</td>
<td></td>
</tr>
<tr>
<td>round</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>roundEven</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>trunc</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fabs</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fsign</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>floor</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>ceil</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fract</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>modf</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fmin</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fmax</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fclamp</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>fmix(x, y, a)</td>
<td>Inherited from x × (1.0 - a) + y × a.</td>
<td></td>
</tr>
<tr>
<td>step</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>smoothStep(edge0, edge1, x)</td>
<td>Inherited from ( t \times t \times (3.0 - 2.0 \times t) ), where ( t = clamp(\frac{x - edge0}{edge1 - edge0}, 0.0, 1.0) ).</td>
<td></td>
</tr>
<tr>
<td>nmin</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>nmax</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
<tr>
<td>nclamp</td>
<td>Correctly rounded.</td>
<td></td>
</tr>
</tbody>
</table>

GLSL.std.450 extended instructions specifically defined in terms of the above instructions inherit the above errors. GLSL.std.450 extended instructions not listed above and not defined in terms of the above have undefined precision.

For the **OpSRem** and **OpSMod** instructions, if either operand is negative the result is undefined.

---

**Note**

While the **OpSRem** and **OpSMod** instructions are supported by the Vulkan environment, they require non-negative values and thus do not enable additional functionality beyond what **OpUMod** provides.
Images which are read from or written to by shaders must have SPIR-V image formats compatible with the Vulkan image formats backing the image under the circumstances described for texture image validation. The compatible formats are:

Table 67. SPIR-V and Vulkan Image Format Compatibility

<table>
<thead>
<tr>
<th>SPIR-V Image Format</th>
<th>Compatible Vulkan Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rgba32f</td>
<td>VK_FORMAT_R32G32B32A32_SFLOAT</td>
</tr>
<tr>
<td>Rgba16f</td>
<td>VK_FORMAT_R16G16B16A16_SFLOAT</td>
</tr>
<tr>
<td>R32f</td>
<td>VK_FORMAT_R32_SFLOAT</td>
</tr>
<tr>
<td>Rgba8</td>
<td>VK_FORMAT_R8G8B8B8_UNORM</td>
</tr>
<tr>
<td>Rgba8Snorm</td>
<td>VK_FORMAT_R8G8B8B8_SNORM</td>
</tr>
<tr>
<td>Rg32f</td>
<td>VK_FORMAT_R32G32_SFLOAT</td>
</tr>
<tr>
<td>Rg16f</td>
<td>VK_FORMAT_R16G16_SFLOAT</td>
</tr>
<tr>
<td>R11fG11fB10f</td>
<td>VK_FORMAT_B10G11R11_UFLOAT_PACK32</td>
</tr>
<tr>
<td>R16f</td>
<td>VK_FORMAT_R16_SFLOAT</td>
</tr>
<tr>
<td>Rgba16</td>
<td>VK_FORMAT_R16G16B16A16_UNORM</td>
</tr>
<tr>
<td>Rgb10A2</td>
<td>VK_FORMAT_A2B10G10R10_UNORM_PACK32</td>
</tr>
<tr>
<td>Rg16</td>
<td>VK_FORMAT_R16G16_UNORM</td>
</tr>
<tr>
<td>Rg8</td>
<td>VK_FORMAT_R8G8_UNORM</td>
</tr>
<tr>
<td>R16</td>
<td>VK_FORMAT_R16_UNORM</td>
</tr>
<tr>
<td>R8</td>
<td>VK_FORMAT_R8_UNORM</td>
</tr>
<tr>
<td>Rgba16Snorm</td>
<td>VK_FORMAT_R16G16B16A16_SNORM</td>
</tr>
<tr>
<td>Rg16Snorm</td>
<td>VK_FORMAT_R16G16_SNORM</td>
</tr>
<tr>
<td>Rg8Snorm</td>
<td>VK_FORMAT_R8G8_SNORM</td>
</tr>
<tr>
<td>R16Snorm</td>
<td>VK_FORMAT_R16_SNORM</td>
</tr>
<tr>
<td>R8Snorm</td>
<td>VK_FORMAT_R8_SNORM</td>
</tr>
<tr>
<td>Rgba32i</td>
<td>VK_FORMAT_R32G32B32A32_SINT</td>
</tr>
<tr>
<td>Rgba16i</td>
<td>VK_FORMAT_R16G16B16A16_SINT</td>
</tr>
<tr>
<td>Rgba8i</td>
<td>VK_FORMAT_R8G8B8B8_SINT</td>
</tr>
<tr>
<td>R32i</td>
<td>VK_FORMAT_R32_SINT</td>
</tr>
<tr>
<td>Rg32i</td>
<td>VK_FORMAT_R32G32_SINT</td>
</tr>
<tr>
<td>Rg16i</td>
<td>VK_FORMAT_R16G16_SINT</td>
</tr>
<tr>
<td>Rg8i</td>
<td>VK_FORMAT_R8G8_SINT</td>
</tr>
<tr>
<td>R16i</td>
<td>VK_FORMAT_R16_SINT</td>
</tr>
<tr>
<td>R8i</td>
<td>VK_FORMAT_R8_SINT</td>
</tr>
<tr>
<td>Rgba32ui</td>
<td>VK_FORMAT_R32G32B32A32_UINT</td>
</tr>
<tr>
<td>Rgba16ui</td>
<td>VK_FORMAT_R16G16B16A16_UINT</td>
</tr>
<tr>
<td>Rgba8ui</td>
<td>VK_FORMAT_R8G8B8B8_UINT</td>
</tr>
<tr>
<td>R32ui</td>
<td>VK_FORMAT_R32_UINT</td>
</tr>
<tr>
<td>Rgb10a2ui</td>
<td>VK_FORMAT_A2B10G10R10_UNORM_PACK32</td>
</tr>
<tr>
<td>SPIR-V Image Format</td>
<td>Compatible Vulkan Format</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Rg32ui</td>
<td>VK_FORMAT_R32G32_UINT</td>
</tr>
<tr>
<td>Rg16ui</td>
<td>VK_FORMAT_R16G16_UINT</td>
</tr>
<tr>
<td>Rg8ui</td>
<td>VK_FORMAT_R8G8_UINT</td>
</tr>
<tr>
<td>R16ui</td>
<td>VK_FORMAT_R16_UINT</td>
</tr>
<tr>
<td>R8ui</td>
<td>VK_FORMAT_R8_UINT</td>
</tr>
</tbody>
</table>
Appendix B: Memory Model

Agent

Operation is a general term for any task that is executed on the system.

An operation is by definition something that is executed, thus if an instruction is skipped due to flow control it does not constitute an operation.

Each operation is executed by a particular agent. Possible agents include each shader invocation, each host thread, and each fixed-function stage of the pipeline.

Memory Location

A memory location identifies unique storage for 8 bits of data. Memory operations access a set of memory locations consisting of one or more memory locations at a time, e.g., an operation accessing a 32-bit integer in memory would read/write a set of four memory locations. Memory operations that access whole aggregates may access any padding bytes between elements or members, but no padding bytes at the end of the aggregate. Two sets of memory locations overlap if the intersection of their sets of memory locations is non-empty. A memory operation must not affect memory at a memory location not within its set of memory locations.

Memory locations for buffers and images are explicitly allocated in VkDeviceMemory objects, and are implicitly allocated for SPIR-V variables in each shader invocation.

Allocation

The values stored in newly allocated memory locations are determined by a SPIR-V variable’s initializer, if present, or else are undefined. At the time an allocation is created there have been no memory operations to any of its memory locations. The initialization is not considered to be a memory operation.

For tessellation control shader output variables, a consequence of initialization not being considered a memory operation is that some implementations may need to insert a barrier between the initialization of the output variables and any reads of those variables.

Memory Operation

For an operation A and memory location M:

- A reads M if and only if the data stored in M is an input to A.
- A writes M if and only if the data output from A is stored to M.
- A accesses M if and only if it either reads or writes (or both) M.
A write whose value is the same as what was already in those memory locations is still considered to be a write and has all the same effects.

Reference

A reference is an object that a particular agent can use to access a set of memory locations. On the host, a reference is a host virtual address. On the device, a reference is:

- The descriptor that a variable is bound to, for variables in Image, Uniform, or StorageBuffer storage classes. If the variable is an array (or array of arrays, etc.) then each element of the array may be a unique reference.
- The address range for a buffer in PhysicalStorageBuffer storage class, where the base of the address range is queried with vkGetBufferDeviceAddress and the length of the range is the size of the buffer.
- The variable itself for variables in other storage classes.

Two memory accesses through distinct references may require availability and visibility operations as defined below.

Program-Order

A dynamic instance of an instruction is defined in SPIR-V (https://www.khronos.org/registry/spir-v/specs/unified1/SPIRV.html#DynamicInstance) as a way of referring to a particular execution of a static instruction. Program-order is an ordering on dynamic instances of instructions executed by a single shader invocation:

- (Basic block): If instructions A and B are in the same basic block, and A is listed in the module before B, then the n'th dynamic instance of A is program-ordered before the n'th dynamic instance of B.
- (Branch): The dynamic instance of a branch or switch instruction is program-ordered before the dynamic instance of the OpLabel instruction to which it transfers control.
- (Call entry): The dynamic instance of an OpFunctionCall instruction is program-ordered before the dynamic instances of the OpFunctionParameter instructions and the body of the called function.
- (Call exit): The dynamic instance of the instruction following an OpFunctionCall instruction is program-ordered after the dynamic instance of the return instruction executed by the called function.
- (Transitive Closure): If dynamic instance A of any instruction is program-ordered before dynamic instance B of any instruction and B is program-ordered before dynamic instance C of any instruction then A is program-ordered before C.
- (Complete definition): No other dynamic instances are program-ordered.

For instructions executed on the host, the source language defines the program-order relation (e.g. as “sequenced-before”).
Shader Call Related

Shader-call-related is an equivalence relation on invocations defined as the symmetric and transitive closure of:

- A is shader-call-related to B if A is created by an invocation repack instruction executed by B.

Shader Call Order

Shader-call-order is a partial order on dynamic instances of instructions executed by invocations that are shader-call-related:

- (Program order): If dynamic instance A is program-ordered before B, then A is shader-call-ordered before B.
- (Shader call entry): If A is a dynamic instance of an invocation repack instruction and B is a dynamic instance executed by an invocation that is created by A, then A is shader-call-ordered before B.
- (Shader call exit): If A is a dynamic instance of an invocation repack instruction, B is the next dynamic instance executed by the same invocation, and C is a dynamic instance executed by an invocation that is created by A, then C is shader-call-ordered before B.
- (Transitive closure): If A is shader-call-ordered-before B and B is shader-call-ordered-before C, then A is shader-call-ordered-before C.
- (Complete definition): No other dynamic instances are shader-call-ordered.

Scope

Atomic and barrier instructions include scopes which identify sets of shader invocations that must obey the requested ordering and atomicity rules of the operation, as defined below.

The various scopes are described in detail in the Shaders chapter.

Atomic Operation

An atomic operation on the device is any SPIR-V operation whose name begins with OpAtomic. An atomic operation on the host is any operation performed with an std::atomic typed object.

Each atomic operation has a memory scope and a semantics. Informally, the scope determines which other agents it is atomic with respect to, and the semantics constrains its ordering against other memory accesses. Device atomic operations have explicit scopes and semantics. Each host atomic operation implicitly uses the CrossDevice scope, and uses a memory semantics equivalent to a C++ std::memory_order value of relaxed, acquire, release, acq_rel, or seq_cst.

Two atomic operations A and B are potentially-mutually-ordered if and only if all of the following are true:

- They access the same set of memory locations.
They use the same reference.

A is in the instance of B's memory scope.

B is in the instance of A's memory scope.

A and B are not the same operation (irreflexive).

Two atomic operations A and B are mutually-ordered if and only if they are potentially-mutually-ordered and any of the following are true:

- A and B are both device operations.
- A and B are both host operations.
- A is a device operation, B is a host operation, and the implementation supports concurrent host- and device-atomics.

If two atomic operations are not mutually-ordered, and if their sets of memory locations overlap, then each must be synchronized against the other as if they were non-atomic operations.

Scoped Modification Order

For a given atomic write A, all atomic writes that are mutually-ordered with A occur in an order known as A's scoped modification order. A's scoped modification order relates no other operations.

Invocations outside the instance of A's memory scope may observe the values at A's set of memory locations becoming visible to it in an order that disagrees with the scoped modification order.

It is valid to have non-atomic operations or atomics in a different scope instance to the same set of memory locations, as long as they are synchronized against each other as if they were non-atomic (if they are not, it is treated as a data race). That means this definition of A's scoped modification order could include atomic operations that occur much later, after intervening non-atomics. That is a bit non-intuitive, but it helps to keep this definition simple and non-circular.

Memory Semantics

Non-atomic memory operations, by default, may be observed by one agent in a different order than they were written by another agent.

Atomics and some synchronization operations include memory semantics, which are flags that constrain the order in which other memory accesses (including non-atomic memory accesses and availability and visibility operations) performed by the same agent can be observed by other agents, or can observe accesses by other agents.

Device instructions that include semantics are OpAtomic, OpControlBarrier, OpMemoryBarrier, and OpMemoryNamedBarrier. Host instructions that include semantics are some std::atomic methods and
SPIR-V supports the following memory semantics:

- **Relaxed**: No constraints on order of other memory accesses.
- **Acquire**: A memory read with this semantic performs an *acquire operation*. A memory barrier with this semantic is an *acquire barrier*.
- **Release**: A memory write with this semantic performs a *release operation*. A memory barrier with this semantic is a *release barrier*.
- **AcquireRelease**: A memory read-modify-write operation with this semantic performs both an acquire operation and a release operation, and inherits the limitations on ordering from both of those operations. A memory barrier with this semantic is both a release and acquire barrier.

SPIR-V does not support “consume” semantics on the device.

The memory semantics operand also includes *storage class semantics* which indicate which storage classes are constrained by the synchronization. SPIR-V storage class semantics include:

- **UniformMemory**
- **WorkgroupMemory**
- **ImageMemory**
- **OutputMemory**

Each SPIR-V memory operation accesses a single storage class. Semantics in synchronization operations can include a combination of storage classes.

The UniformMemory storage class semantic applies to accesses to memory in the PhysicalStorageBuffer, ShaderRecordBufferKHR, Uniform and StorageBuffer storage classes. The WorkgroupMemory storage class semantic applies to accesses to memory in the Workgroup storage class. The ImageMemory storage class semantic applies to accesses to memory in the Image storage class. The OutputMemory storage class semantic applies to accesses to memory in the Output storage class.

Informally, these constraints limit how memory operations can be reordered, and these limits apply not only to the order of accesses as performed in the agent that executes the instruction, but also to the order the effects of writes become visible to all other agents within the same instance of the instruction’s memory scope.

Release and acquire operations in different threads can act as synchronization operations, to guarantee that writes that happened before the release are visible after the acquire. (This is not a formal definition, just an informative forward reference.)

The OutputMemory storage class semantic is only useful in tessellation control shaders, which is the only execution model where output variables are shared between invocations.
The memory semantics operand also optionally includes availability and visibility flags, which apply optional availability and visibility operations as described in availability and visibility. The availability/visibility flags are:

- **MakeAvailable**: Semantics **must** be Release or AcquireRelease. Performs an availability operation before the release operation or barrier.
- **MakeVisible**: Semantics **must** be Acquire or AcquireRelease. Performs a visibility operation after the acquire operation or barrier.

The specifics of these operations are defined in Availability and Visibility Semantics.

Host atomic operations **may** support a different list of memory semantics and synchronization operations, depending on the host architecture and source language.

**Release Sequence**

After an atomic operation A performs a release operation on a set of memory locations M, the **release sequence headed by A** is the longest continuous subsequence of A's scoped modification order that consists of:

- the atomic operation A as its first element
- atomic read-modify-write operations on M by any agent

The atomics in the last bullet **must** be mutually-ordered with A by virtue of being in A's scoped modification order.

This intentionally omits “atomic writes to M performed by the same agent that performed A”, which is present in the corresponding C++ definition.

**Synchronizes-With**

**Synchronizes-with** is a relation between operations, where each operation is either an atomic operation or a memory barrier (aka fence on the host).

If A and B are atomic operations, then A synchronizes-with B if and only if all of the following are true:

- A performs a release operation
- B performs an acquire operation
- A and B are mutually-ordered
- B reads a value written by A or by an operation in the release sequence headed by A

**OpControlBarrier**, **OpMemoryBarrier**, and **OpMemoryNamedBarrier** are memory barrier instructions in SPIR-V.

If A is a release barrier and B is an atomic operation that performs an acquire operation, then A
synchronizes-with B if and only if all of the following are true:

- there exists an atomic write X (with any memory semantics)
- A is program-ordered before X
- X and B are mutually-ordered
- B reads a value written by X or by an operation in the release sequence headed by X
  - If X is relaxed, it is still considered to head a hypothetical release sequence for this rule
- A and B are in the instance of each other’s memory scopes
- X’s storage class is in A’s semantics.

If A is an atomic operation that performs a release operation and B is an acquire barrier, then A synchronizes-with B if and only if all of the following are true:

- there exists an atomic read X (with any memory semantics)
- X is program-ordered before B
- X and A are mutually-ordered
- X reads a value written by A or by an operation in the release sequence headed by A
- A and B are in the instance of each other’s memory scopes
- X’s storage class is in B’s semantics.

If A is a release barrier and B is an acquire barrier, then A synchronizes-with B if all of the following are true:

- there exists an atomic write X (with any memory semantics)
- A is program-ordered before X
- there exists an atomic read Y (with any memory semantics)
- Y is program-ordered before B
- X and Y are mutually-ordered
- Y reads the value written by X or by an operation in the release sequence headed by X
  - If X is relaxed, it is still considered to head a hypothetical release sequence for this rule
- A and B are in the instance of each other’s memory scopes
- X’s and Y’s storage class is in A’s and B’s semantics.
  - NOTE: X and Y must have the same storage class, because they are mutually ordered.

If A is a release barrier and B is an acquire barrier and C is a control barrier (where A can optionally equal C and B can optionally equal C), then A synchronizes-with B if all of the following are true:

- A is program-ordered before (or equals) C
- C is program-ordered before (or equals) B
- A and B are in the instance of each other’s memory scopes
• A and B are in the instance of C’s execution scope

This is similar to the barrier-barrier synchronization above, but with a control barrier filling the role of the relaxed atomics.

If A is a release barrier and B is an acquire barrier, then A synchronizes-with B if all of the following are true:

• A is shader-call-ordered-before B
• A and B are in the instance of each other’s memory scopes

No other release and acquire barriers synchronize-with each other.

**System-Synchronizes-With**

System-synchronizes-with is a relation between arbitrary operations on the device or host. Certain operations system-synchronize-with each other, which informally means the first operation occurs before the second and that the synchronization is performed without using application-visible memory accesses.

If there is an execution dependency between two operations A and B, then the operation in the first synchronization scope system-synchronizes-with the operation in the second synchronization scope.

This covers all Vulkan synchronization primitives, including device operations executing before a synchronization primitive is signaled, wait operations happening before subsequent device operations, signal operations happening before host operations that wait on them, and host operations happening before `vkQueueSubmit`. The list is spread throughout the synchronization chapter, and is not repeated here.

System-synchronizes-with implicitly includes all storage class semantics and has CrossDevice scope.

If A system-synchronizes-with B, we also say A is system-synchronized-before B and B is system-synchronized-after A.

**Private vs. Non-Private**

By default, non-atomic memory operations are treated as private, meaning such a memory operation is not intended to be used for communication with other agents. Memory operations with the NonPrivatePointer/NonPrivateTexel bit set are treated as non-private, and are intended to be used for communication with other agents.

More precisely, for private memory operations to be Location-Ordered between distinct agents requires using system-synchronizes-with rather than shader-based synchronization. Non-private memory operations still obey program-order.

Atomic operations are always considered non-private.
Inter-Thread-Happens-Before

Let SC be a non-empty set of storage class semantics. Then (using template syntax) operation A 
\text{inter-thread-happens-before}^{SC} \text{ operation B if and only if any of the following is true:}

- A system-synchronizes-with B
- A synchronizes-with B, and both A and B have all of SC in their semantics
- A is an operation on memory in a storage class in SC or that has all of SC in its semantics, B is a release barrier or release atomic with all of SC in its semantics, and A is program-ordered before B
- A is an acquire barrier or acquire atomic with all of SC in its semantics, B is an operation on memory in a storage class in SC or that has all of SC in its semantics, and A is program-ordered before B
- A and B are both host operations and A inter-thread-happens-before B as defined in the host language spec
- A inter-thread-happens-before^{SC} some X and X inter-thread-happens-before^{SC} B

Happens-Before

Operation A \text{happens-before} \text{ operation B if and only if any of the following is true:}

- A is program-ordered before B
- A inter-thread-happens-before^{SC} B for some set of storage classes SC

\text{Happens-after} \text{ is defined similarly.}

Unlike C++, happens-before is not always sufficient for a write to be visible to a read. Additional \text{availability and visibility} operations may be required for writes to be \text{visible-to} other memory accesses.

Happens-before is not transitive, but each of program-order and inter-thread-happens-before^{SC} are transitive. These can be thought of as covering the “single-threaded” case and the “multi-threaded” case, and it is not necessary (and not valid) to form chains between the two.

Availability and Visibility

\text{Availability} and \text{visibility} are states of a write operation, which (informally) track how far the write has permeated the system, i.e. which agents and references are able to observe the write. \text{Availability} state is per \text{memory domain}. \text{Visibility} state is per (agent,reference) pair. \text{Availability} and \text{visibility} states are per-memory location for each write.

Memory domains are named according to the agents whose memory accesses use the domain. Domains used by shader invocations are organized hierarchically into multiple smaller memory domains which correspond to the different \text{scopes}. Each memory domain is considered the \text{dual} of
The memory domains defined in Vulkan include:

- **host** - accessible by host agents
- **device** - accessible by all device agents for a particular device
- **shader** - accessible by shader agents for a particular device, corresponding to the Device scope
- **queue family instance** - accessible by shader agents in a single queue family, corresponding to the QueueFamily scope.
- **shader call instance** - accessible by shader agents that are shader-call-related, corresponding to the ShaderCallKHR scope.
- **workgroup instance** - accessible by shader agents in the same workgroup, corresponding to the Workgroup scope.
- **subgroup instance** - accessible by shader agents in the same subgroup, corresponding to the Subgroup scope.

The memory domains are nested in the order listed above, except for shader call instance domain, with memory domains later in the list nested in the domains earlier in the list. The shader call instance domain is at an implementation-dependent location in the list, and is nested according to that location. The shader call instance domain is not broader than the queue family instance domain.

Memory domains do not correspond to storage classes or device-local and host-local VkDeviceMemory allocations, rather they indicate whether a write can be made visible only to agents in the same subgroup, same workgroup, shader-call-related ray tracing invocation, in any shader invocation, or anywhere on the device, or host. The shader, queue family instance, shader call instance, workgroup instance, and subgroup instance domains are only used for shader-based availability/visibility operations, in other cases writes can be made available from/visible to the shader via the device domain.

**Availability operations**, visibility operations, and memory domain operations alter the state of the write operations that happen-before them, and which are included in their source scope to be available or visible to their destination scope.

- For an availability operation, the source scope is a set of (agent,reference,memory location) tuples, and the destination scope is a set of memory domains.
- For a memory domain operation, the source scope is a memory domain and the destination scope is a memory domain.
- For a visibility operation, the source scope is a set of memory domains and the destination scope is a set of (agent,reference,memory location) tuples.

How the scopes are determined depends on the specific operation. Availability and memory domain operations expand the set of memory domains to which the write is available. Visibility operations expand the set of (agent,reference,memory location) tuples to which the write is visible.

Recall that availability and visibility states are per-memory location, and let W be a write operation to one or more locations performed by agent A via reference R. Let L be one of the locations...
written. \((W,L)\) (the write \(W\) to \(L\)), is initially not available to any memory domain and only visible to \((A,R,L)\). An availability operation \(AV\) that happens-after \(W\) and that includes \((A,R,L)\) in its source scope makes \((W,L)\) available to the memory domains in its destination scope.

A memory domain operation \(DOM\) that happens-after \(AV\) and for which \((W,L)\) is available in the source scope makes \((W,L)\) available in the destination memory domain.

A visibility operation \(VIS\) that happens-after \(AV\) (or \(DOM\)) and for which \((W,L)\) is available in any domain in the source scope makes \((W,L)\) visible to all \((agent,reference,L)\) tuples included in its destination scope.

If write \(W_2\) happens-after \(W\), and their sets of memory locations overlap, then \(W\) will not be available/visible to all agents/references for those memory locations that overlap (and future \(AV/DOM/VIS\) ops cannot revive \(W\)'s write to those locations).

Availability, memory domain, and visibility operations are treated like other non-atomic memory accesses for the purpose of memory semantics, meaning they can be ordered by release-acquire sequences or memory barriers.

An availability chain is a sequence of availability operations to increasingly broad memory domains, where element \(N+1\) of the chain is performed in the dual scope instance of the destination memory domain of element \(N\) and element \(N\) happens-before element \(N+1\). An example is an availability operation with destination scope of the workgroup instance domain that happens-before an availability operation to the shader domain performed by an invocation in the same workgroup. An availability chain \(AVC\) that happens-after \(W\) and that includes \((A,R,L)\) in the source scope makes \((W,L)\) available to the memory domains in its final destination scope. An availability chain with a single element is just the availability operation.

Similarly, a visibility chain is a sequence of visibility operations from increasingly narrow memory domains, where element \(N\) of the chain is performed in the dual scope instance of the source memory domain of element \(N+1\) and element \(N\) happens-before element \(N+1\). An example is a visibility operation with source scope of the shader domain that happens-before a visibility operation with source scope of the workgroup instance domain performance by an invocation in the same workgroup. A visibility chain \(VISC\) that happens-after \(AVC\) (or \(DOM\)) and for which \((W,L)\) is available in any domain in the source scope makes \((W,L)\) visible to all \((agent,reference,L)\) tuples included in its final destination scope. A visibility chain with a single element is just the visibility operation.

**Availability, Visibility, and Domain Operations**

The following operations generate availability, visibility, and domain operations. When multiple availability/visibility/domain operations are described, they are system-synchronized-with each other in the order listed.

An operation that performs a memory dependency generates:

- If the source access mask includes `VK_ACCESS_HOST_WRITE_BIT`, then the dependency includes a memory domain operation from host domain to device domain.
- An availability operation with source scope of all writes in the first access scope of the
dependency and a destination scope of the device domain.

- A visibility operation with source scope of the device domain and destination scope of the second access scope of the dependency.
- If the destination access mask includes `VK_ACCESS_HOST_READ_BIT` or `VK_ACCESS_HOST_WRITE_BIT`, then the dependency includes a memory domain operation from device domain to host domain.

`vkFlushMappedMemoryRanges` performs an availability operation, with a source scope of `(agents, references) = (all host threads, all mapped memory ranges passed to the command)`, and destination scope of the host domain.

`vkInvalidateMappedMemoryRanges` performs a visibility operation, with a source scope of the host domain and a destination scope of `(agents, references) = (all host threads, all mapped memory ranges passed to the command)`.

`vkQueueSubmit` performs a memory domain operation from host to device, and a visibility operation with source scope of the device domain and destination scope of all agents and references on the device.

### Availability and Visibility Semantics

A memory barrier or atomic operation via agent A that includes MakeAvailable in its semantics performs an availability operation whose source scope includes agent A and all references in the storage classes in that instruction’s storage class semantics, and all memory locations, and whose destination scope is a set of memory domains selected as specified below. The implicit availability operation is program-ordered between the barrier or atomic and all other operations program-ordered before the barrier or atomic.

A memory barrier or atomic operation via agent A that includes MakeVisible in its semantics performs a visibility operation whose source scope is a set of memory domains selected as specified below, and whose destination scope includes agent A and all references in the storage classes in that instruction’s storage class semantics, and all memory locations. The implicit visibility operation is program-ordered between the barrier or atomic and all other operations program-ordered after the barrier or atomic.

The memory domains are selected based on the memory scope of the instruction as follows:

- **Device** scope uses the shader domain
- **QueueFamily** scope uses the queue family instance domain
- **ShaderCallKHR** scope uses the shader call instance domain
- **Workgroup** scope uses the workgroup instance domain
- **Subgroup** uses the subgroup instance domain
- **Invocation** perform no availability/visibility operations.

When an availability operation performed by an agent A includes a memory domain D in its destination scope, where D corresponds to scope instance S, it also includes the memory domains that correspond to each smaller scope instance S’ that is a subset of S and that includes A. Similarly
Per-Instruction Availability and Visibility Semantics

A memory write instruction that includes MakePointerAvailable, or an image write instruction that includes MakeTexelAvailable, performs an availability operation whose source scope includes the agent and reference used to perform the write and the memory locations written by the instruction, and whose destination scope is a set of memory domains selected by the Scope operand specified in Availability and Visibility Semantics. The implicit availability operation is program-ordered between the write and all other operations program-ordered after the write.

A memory read instruction that includes MakePointerVisible, or an image read instruction that includes MakeTexelVisible, performs a visibility operation whose source scope is a set of memory domains selected by the Scope operand as specified in Availability and Visibility Semantics, and whose destination scope includes the agent and reference used to perform the read and the memory locations read by the instruction. The implicit visibility operation is program-ordered between read and all other operations program-ordered before the read.

Although reads with per-instruction visibility only perform visibility ops from the shader or shader call instance or workgroup instance or subgroup instance domain, they will also see writes that were made visible via the device domain, i.e. those writes previously performed by non-shader agents and made visible via API commands.

It is expected that all invocations in a subgroup execute on the same processor with the same path to memory, and thus availability and visibility operations with subgroup scope can be expected to be “free”.

Location-Ordered

Let X and Y be memory accesses to overlapping sets of memory locations M, where X != Y. Let (A_x,R_x) be the agent and reference used for X, and (A_y,R_y) be the agent and reference used for Y. For now, let “→” denote happens-before and “→rcpo” denote the reflexive closure of program-ordered before.

If D_1 and D_2 are different memory domains, then let DOM(D_1,D_2) be a memory domain operation from D_1 to D_2. Otherwise, let DOM(D,D) be a placeholder such that X → DOM(D,D) → Y if and only if X → Y.

X is location-ordered before Y for a location L in M if and only if any of the following is true:

- A_x == A_y and R_x == R_y and X → Y
  
  • NOTE: this case means no availability/visibility ops required when it is the same (agent,reference).
- X is a read, both X and Y are non-private, and X → Y
- X is a read, and X (transitively) system-synchronizes with Y
- If R_x == R_y and A_x and A_y access a common memory domain D (e.g. are in the same workgroup
instance if D is the workgroup instance domain), and both X and Y are non-private:

- X is a write, Y is a write, AVC(A_X, R_X, D, L) is an availability chain making (X,L) available to domain D, and X \rightarrow r^\text{cpo} AVC(A_X, R_X, D, L) \rightarrow Y

- X is a write, Y is a read, AVC(A_X, R_X, D, L) is an availability chain making (X,L) available to domain D, VISC(A_Y, R_Y, D, L) is a visibility chain making writes to L available in domain D visible to Y, and X \rightarrow r^\text{cpo} AVC(A_X, R_X, D, L) \rightarrow VISC(A_Y, R_Y, D, L) \rightarrow r^\text{cpo} Y

- If VkPhysicalDeviceVulkanMemoryModelFeatures
  ::vulkanMemoryModelAvailabilityVisibilityChains is VK_FALSE, then AVC and VISC must each only have a single element in the chain, in each sub-bullet above.

- Let D_X and D_Y each be either the device domain or the host domain, depending on whether A_X and A_Y execute on the device or host:

  - X is a write and Y is a write, and X \rightarrow AV(A_X, R_X, D_X, L) \rightarrow DOM(D_X, D_Y) \rightarrow Y

  - X is a write and Y is a read, and X \rightarrow AV(A_X, R_X, D_X, L) \rightarrow DOM(D_X, D_Y) \rightarrow VIS(A_Y, R_Y, D_Y, L) \rightarrow Y

The final bullet (synchronization through device/host domain) requires API-level synchronization operations, since the device/host domains are not accessible via shader instructions. And “device domain” is not to be confused with “device scope”, which synchronizes through the “shader domain”.

Data Race

Let X and Y be operations that access overlapping sets of memory locations M, where X \neq Y, and at least one of X and Y is a write, and X and Y are not mutually-ordered atomic operations. If there does not exist a location-ordered relation between X and Y for each location in M, then there is a data race.

Applications must ensure that no data races occur during the execution of their application.

Data races can only occur due to instructions that are actually executed, and for example an instruction skipped due to flow control must not contribute to a data race.

Visible-To

Let X be a write and Y be a read whose sets of memory locations overlap, and let M be the set of memory locations that overlap. Let M_2 be a non-empty subset of M. Then X is visible-to Y for memory locations M_2 if and only if all of the following are true:

- X is location-ordered before Y for each location L in M_2.
- There does not exist another write Z to any location L in M_2 such that X is location-ordered before Z for location L and Z is location-ordered before Y for location L.

If X is visible-to Y, then Y reads the value written by X for locations M_2.
It is possible for there to be a write between X and Y that overwrites a subset of the memory locations, but the remaining memory locations (M₂) will still be visible-to Y.

Acyclicity

*Reads-from* is a relation between operations, where the first operation is a write, the second operation is a read, and the second operation reads the value written by the first operation. *From-reads* is a relation between operations, where the first operation is a read, the second operation is a write, and the first operation reads a value written earlier than the second operation in the second operation's scoped modification order (or the first operation reads from the initial value, and the second operation is any write to the same locations).

Then the implementation must guarantee that no cycles exist in the union of the following relations:

- location-ordered
- scoped modification order (over all atomic writes)
- reads-from
- from-reads

This is a "consistency" axiom, which informally guarantees that sequences of operations can't violate causality.

Scoped Modification Order Coherence

Let A and B be mutually-ordered atomic operations, where A is location-ordered before B. Then the following rules are a consequence of acyclicity:

- If A and B are both reads and A does not read the initial value, then the write that A takes its value from must be earlier in its own scoped modification order than (or the same as) the write that B takes its value from (no cycles between location-order, reads-from, and from-reads).
- If A is a read and B is a write and A does not read the initial value, then A must take its value from a write earlier than B in B's scoped modification order (no cycles between location-order, scope modification order, and reads-from).
- If A is a write and B is a read, then B must take its value from A or a write later than A in A's scoped modification order (no cycles between location-order, scoped modification order, and from-reads).
- If A and B are both writes, then A must be earlier than B in A's scoped modification order (no cycles between location-order and scoped modification order).
- If A is a write and B is a read-modify-write and B reads the value written by A, then B comes immediately after A in A's scoped modification order (no cycles between scoped modification order and from-reads).
Shader I/O

If a shader invocation A in a shader stage other than Vertex performs a memory read operation X from an object in storage class CallableDataKHR, IncomingCallableDataKHR, RayPayloadKHR, HitAttributeKHR, IncomingRayPayloadKHR, or Input, then X is system-synchronized-after all writes to the corresponding CallableDataKHR, IncomingCallableDataKHR, RayPayloadKHR, HitAttributeKHR, IncomingRayPayloadKHR, or Output storage variable(s) in the shader invocation(s) that contribute to generating invocation A, and those writes are all visible-to X.

It is not necessary for the upstream shader invocations to have completed execution, they only need to have generated the output that is being read.

Deallocation

A call to vkFreeMemory must happen-after all memory operations on all memory locations in that VkDeviceMemory object.

Note

Normally, device memory operations in a given queue are synchronized with vkFreeMemory by having a host thread wait on a fence signalled by that queue, and the wait happens-before the call to vkFreeMemory on the host.

The deallocation of SPIR-V variables is managed by the system and happens-after all operations on those variables.

Informative Descriptions

This subsection is non-normative, and offers more easily understandable consequences of the memory model for app/compiler developers.

Let SC be the storage class(es) specified by a release or acquire operation or barrier.

- An atomic write with release semantics must not be reordered against any read or write to SC that is program-ordered before it (regardless of the storage class the atomic is in).
- An atomic read with acquire semantics must not be reordered against any read or write to SC that is program-ordered after it (regardless of the storage class the atomic is in).
- Any write to SC program-ordered after a release barrier must not be reordered against any read or write to SC program-ordered before that barrier.
- Any read from SC program-ordered before an acquire barrier must not be reordered against any read or write to SC program-ordered after the barrier.

A control barrier (even if it has no memory semantics) must not be reordered against any memory barriers.

This memory model allows memory accesses with and without availability and visibility operations, as well as atomic operations, all to be performed on the same memory location. This is
critical to allow it to reason about memory that is reused in multiple ways, e.g. across the lifetime of different shader invocations or draw calls. While GLSL (and legacy SPIR-V) applies the “coherent” decoration to variables (for historical reasons), this model treats each memory access instruction as having optional implicit availability/visibility operations. GLSL to SPIR-V compilers should map all (non-atomic) operations on a coherent variable to Make{Pointer,Texel}{Available}{Visible} flags in this model.

Atomic operations implicitly have availability/visibility operations, and the scope of those operations is taken from the atomic operation’s scope.

**Tessellation Output Ordering**

For SPIR-V that uses the Vulkan Memory Model, the **OutputMemory** storage class is used to synchronize accesses to tessellation control output variables. For legacy SPIR-V that does not enable the Vulkan Memory Model via **OpMemoryModel**, tessellation outputs can be ordered using a control barrier with no particular memory scope or semantics, as defined below.

Let X and Y be memory operations performed by shader invocations A_X and A_Y. Operation X is **tessellation-output-ordered** before operation Y if and only if all of the following are true:

- There is a dynamic instance of an **OpControlBarrier** instruction C such that X is program-ordered before C in A_X and C is program-ordered before Y in A_Y.
- A_X and A_Y are in the same instance of C’s execution scope.

If shader invocations A_X and A_Y in the **TessellationControl** execution model execute memory operations X and Y, respectively, on the **Output** storage class, and X is tessellation-output-ordered before Y with a scope of **Workgroup**, then X is location-ordered before Y, and if X is a write and Y is a read then X is visible-to Y.
Appendix C: Compressed Image Formats

The compressed texture formats used by Vulkan are described in the specifically identified sections of the Khronos Data Format Specification, version 1.3.

Unless otherwise described, the quantities encoded in these compressed formats are treated as normalized, unsigned values.

Those formats listed as sRGB-encoded have in-memory representations of R, G and B components which are nonlinearly-encoded as R', G', and B'; any alpha component is unchanged. As part of filtering, the nonlinear R', G', and B' values are converted to linear R, G, and B components; any alpha component is unchanged. The conversion between linear and nonlinear encoding is performed as described in the “KHR_DF_TRANSFER_SRGB” section of the Khronos Data Format Specification.
Block-Compressed Image Formats

BC1, BC2 and BC3 formats are described in “S3TC Compressed Texture Image Formats” chapter of the *Khronos Data Format Specification*. BC4 and BC5 are described in the “RGTC Compressed Texture Image Formats” chapter. BC6H and BC7 are described in the “BPTC Compressed Texture Image Formats” chapter.

Table 68. Mapping of Vulkan BC formats to descriptions

<table>
<thead>
<tr>
<th>VkFormat</th>
<th>Khronos Data Format Specification description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Formats described in the “S3TC Compressed Texture Image Formats” chapter</strong></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGB_UNORM_BLOCK</td>
<td>BC1 with no alpha</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGB_SRGB_BLOCK</td>
<td>BC1 with no alpha, sRGB-encoded</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGBA_UNORM_BLOCK</td>
<td>BC1 with alpha</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGBA_SRGB_BLOCK</td>
<td>BC1 with alpha, sRGB-encoded</td>
</tr>
<tr>
<td>VK_FORMAT_BC2_UNORM_BLOCK</td>
<td>BC2</td>
</tr>
<tr>
<td>VK_FORMAT_BC2_SRGB_BLOCK</td>
<td>BC2, sRGB-encoded</td>
</tr>
<tr>
<td>VK_FORMAT_BC3_UNORM_BLOCK</td>
<td>BC3</td>
</tr>
<tr>
<td>VK_FORMAT_BC3_SRGB_BLOCK</td>
<td>BC3, sRGB-encoded</td>
</tr>
<tr>
<td><strong>Formats described in the “RGTC Compressed Texture Image Formats” chapter</strong></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC4_UNORM_BLOCK</td>
<td>BC4 unsigned</td>
</tr>
<tr>
<td>VK_FORMAT_BC4_SNORM_BLOCK</td>
<td>BC4 signed</td>
</tr>
<tr>
<td>VK_FORMAT_BC5_UNORM_BLOCK</td>
<td>BC5 unsigned</td>
</tr>
<tr>
<td>VK_FORMAT_BC5_SNORM_BLOCK</td>
<td>BC5 signed</td>
</tr>
<tr>
<td><strong>Formats described in the “BPTC Compressed Texture Image Formats” chapter</strong></td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_UFLOAT_BLOCK</td>
<td>BC6H (unsigned version)</td>
</tr>
<tr>
<td>VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
<td>BC6H (signed version)</td>
</tr>
<tr>
<td>VK_FORMAT_BC7_UNORM_BLOCK</td>
<td>BC7</td>
</tr>
<tr>
<td>VK_FORMAT_BC7_SRGB_BLOCK</td>
<td>BC7, sRGB-encoded</td>
</tr>
</tbody>
</table>
ETC Compressed Image Formats

The following formats are described in the “ETC2 Compressed Texture Image Formats” chapter of the [Khronos Data Format Specification](#).

### Table 69. Mapping of Vulkan ETC formats to descriptions

<table>
<thead>
<tr>
<th>VkFormat</th>
<th>Khronos Data Format Specification description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK</td>
<td>RGB ETC2</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK</td>
<td>RGB ETC2 with sRGB encoding</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK</td>
<td>RGB ETC2 with punch-through alpha</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK</td>
<td>RGB ETC2 with punch-through alpha and sRGB</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK</td>
<td>RGBA ETC2</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK</td>
<td>RGBA ETC2 with sRGB encoding</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11_UNORM_BLOCK</td>
<td>Unsigned R11 EAC</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11_SNORM_BLOCK</td>
<td>Signed R11 EAC</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_UNORM_BLOCK</td>
<td>Unsigned RG11 EAC</td>
</tr>
<tr>
<td>VK_FORMAT_EAC_R11G11_SNORM_BLOCK</td>
<td>Signed RG11 EAC</td>
</tr>
</tbody>
</table>
### ASTC Compressed Image Formats

ASTC formats are described in the “ASTC Compressed Texture Image Formats” chapter of the Khronos Data Format Specification.

**Table 70. Mapping of Vulkan ASTC formats to descriptions**

<table>
<thead>
<tr>
<th>VkFormat</th>
<th>Compressed texel block dimensions</th>
<th>sRGB-encoded</th>
<th>Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_ASTC_4x4_UNORM_BLOCK</td>
<td>4 × 4</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_4x4_SRGB_BLOCK</td>
<td>4 × 4</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_UNORM_BLOCK</td>
<td>5 × 4</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x4_SRGB_BLOCK</td>
<td>5 × 4</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_UNORM_BLOCK</td>
<td>5 × 5</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_5x5_SRGB_BLOCK</td>
<td>5 × 5</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_UNORM_BLOCK</td>
<td>6 × 5</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x5_SRGB_BLOCK</td>
<td>6 × 5</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_UNORM_BLOCK</td>
<td>6 × 6</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_6x6_SRGB_BLOCK</td>
<td>6 × 6</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_UNORM_BLOCK</td>
<td>8 × 5</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x5_SRGB_BLOCK</td>
<td>8 × 5</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_UNORM_BLOCK</td>
<td>8 × 6</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x6_SRGB_BLOCK</td>
<td>8 × 6</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_UNORM_BLOCK</td>
<td>8 × 8</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_8x8_SRGB_BLOCK</td>
<td>8 × 8</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_UNORM_BLOCK</td>
<td>10 × 5</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x5_SRGB_BLOCK</td>
<td>10 × 5</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_UNORM_BLOCK</td>
<td>10 × 6</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x6_SRGB_BLOCK</td>
<td>10 × 6</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_UNORM_BLOCK</td>
<td>10 × 8</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x8_SRGB_BLOCK</td>
<td>10 × 8</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_UNORM_BLOCK</td>
<td>10 × 10</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_10x10_SRGB_BLOCK</td>
<td>10 × 10</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x10_UNORM_BLOCK</td>
<td>12 × 10</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x10_SRGB_BLOCK</td>
<td>12 × 10</td>
<td>Yes</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x12_UNORM_BLOCK</td>
<td>12 × 12</td>
<td>No</td>
<td>LDR</td>
</tr>
<tr>
<td>VK_FORMAT_ASTC_12x12_SRGB_BLOCK</td>
<td>12 × 12</td>
<td>Yes</td>
<td>LDR</td>
</tr>
</tbody>
</table>

The ASTC decode mode is decode_float16.
Appendix D: Core Revisions (Informative)

New minor versions of the Vulkan API are defined periodically by the Khronos Vulkan Working Group. These consist of some amount of additional functionality added to the core API, potentially including both new functionality and functionality promoted from extensions.

It is possible to build the specification for earlier versions, but to aid readability of the latest versions, this appendix gives an overview of the changes as compared to earlier versions.

Version 1.1

Vulkan Version 1.1 promoted a number of key extensions into the core API:

- VK_KHR_16bit_storage
- VK_KHR_bind_memory2
- VK_KHR_dedicated_allocation
- VK_KHR_descriptor_update_template
- VK_KHR_device_group
- VK_KHR_device_group_creation
- VK_KHR_external_fence
- VK_KHR_external_fence_capabilities
- VK_KHR_external_memory
- VK_KHR_external_memory_capabilities
- VK_KHR_external_semaphore
- VK_KHR_external_semaphore_capabilities
- VK_KHR_get_memory_requirements2
- VK_KHR_get_physical_device_properties2
VK_KHR_maintenance1

- VK_KHR_maintenance2
- VK_KHR_maintenance3
- VK_KHR_multiview
- VK_KHR_relaxed_block_layout
- VK_KHR_sampler_ycbcr_conversion
- VK_KHR_shader_draw_parameters
- VK_KHR_storage_buffer_storage_class
- VK_KHR_variable_pointers

The only changes to the functionality added by these extensions were to `VK_KHR_shader_draw_parameters`, which had the `shaderDrawParameters` feature bit added to determine support in the core API, and `variablePointersStorageBuffer` from `VK_KHR_variable_pointers` was made optional.

Additionally, Vulkan 1.1 added support for group operations with subgroup scope, protected memory, and a new command to enumerate the instance version.

New Object Types

- VkDescriptorUpdateTemplate
- VkSamplerYcbcrConversion

New Defines

- `VK_API_VERSION_1_1`

New Enum Constants

- Extending `VkBufferCreateFlagBits`:
  - `VK_BUFFER_CREATE_PROTECTED_BIT`
- Extending `VkCommandPoolCreateFlagBits`:
  - `VK_COMMAND_POOL_CREATE_PROTECTED_BIT`
- Extending `VkDependencyFlagBits`:
  - `VK_DEPENDENCY_DEVICE_GROUP_BIT`
• Extending *VkDeviceQueueCreateFlagBits*:
  
  - VK_DEVICE_QUEUE_CREATE_PROTECTED_BIT

• Extending *VkFormat*:
  
  - VK_FORMAT_G8B8G8R8_422_UNORM
  - VK_FORMAT_B8G8R8G8_422_UNORM
  - VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM
  - VK_FORMAT_G8_B8R8_2PLANE_420_UNORM
  - VK_FORMAT_G8_B8_R8_3PLANE_422_UNORM
  - VK_FORMAT_G8_B8R8_2PLANE_422_UNORM
  - VK_FORMAT_G8_B8_R8_3PLANE_444_UNORM
  - VK_FORMAT_R10X6_UNORM_PACK16
  - VK_FORMAT_R10X6G10X6_2PACK16
  - VK_FORMAT_G10X6B10X6G10X6R10X6_4PACK16
  - VK_FORMAT_B10X6G10X6R10X6G10X6_4PACK16
  - VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_444_UNORM_3PACK16
  - VK_FORMAT_R12X4_UNORM_PACK16
  - VK_FORMAT_R12X4G12X4_2PACK16
  - VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16
  - VK_FORMAT_G12X4B12X4G12X4R12X4_4PACK16
  - VK_FORMAT_B12X4G12X4R12X4G12X4_4PACK16
  - VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4R12X4_3PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16
  - VK_FORMAT_G12X4_B12X4R12X4_3PLANE_444_UNORM_3PACK16
  - VK_FORMAT_B16G16B16G16_422_UNORM
  - VK_FORMAT_B16G16R16G16_422_UNORM
  - VK_FORMAT_B16B16G16B16_422_UNORM
  - VK_FORMAT_B16B16G16B16R16_3PLANE_420_UNORM
  - VK_FORMAT_B16B16R16_2PLANE_420_UNORM
  - VK_FORMAT_B16B16R16_3PLANE_422_UNORM
  - VK_FORMAT_G16B16R16_2PLANE_422_UNORM

• Extending *VkFormatFeatureFlagBits*:

  - VK_FORMAT_FEATURE_TRANSFER_SRC_BIT
  - VK_FORMAT_FEATURE_TRANSFER_DST_BIT
• Extending VkImageAspectFlagBits:
  ◦ VK_IMAGE_ASPECT_PLANE_0_BIT
  ◦ VK_IMAGE_ASPECT_PLANE_1_BIT
  ◦ VK_IMAGE_ASPECT_PLANE_2_BIT
• Extending VkImageCreateFlagBits:
  ◦ VK_IMAGE_CREATE_ALIAS_BIT
  ◦ VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT
  ◦ VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT
  ◦ VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT
  ◦ VK_IMAGE_CREATE_EXTENDED_USAGE_BIT
  ◦ VK_IMAGE_CREATE_PROTECTED_BIT
  ◦ VK_IMAGE_CREATE_DISJOINT_BIT
• Extending VkImageCreateFlagBits:
  ◦ VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL
  ◦ VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL
• Extending VkMemoryHeapFlagBits:
  ◦ VK_MEMORY_HEAP_MULTI_INSTANCE_BIT
• Extending VkMemoryPropertyFlagBits:
  ◦ VK_MEMORY_PROPERTY_PROTECTED_BIT
• Extending VkObjectType:
  ◦ VK_OBJECT_TYPE_SAMPLER_YCBCR_CONVERSION
  ◦ VK_OBJECT_TYPE_DESCRIPTOR_UPDATE_TEMPLATE
• Extending VkPipelineCreateFlagBits:
  ◦ VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT
  ◦ VK_PIPELINE_CREATE_DISPATCH_BASE
• Extending VkQueueFlagBits:
  ◦ VK_QUEUE_PROTECTED_BIT
• Extending VkResult:
  ◦ VK_ERROR_OUT_OF_POOL_MEMORY
  ◦ VK_ERROR_INVALID_EXTERNAL_HANDLE
• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SUBGROUP_PROPERTIES
New Enums

- VkChromaLocation
- VkDescriptorUpdateTemplateType
- VkExternalFenceFeatureFlagBits
- VkExternalFenceHandleTypeFlagBits
- VkExternalMemoryFeatureFlagBits
- VkExternalMemoryHandleTypeFlagBits
- VkExternalSemaphoreFeatureFlagBits
- VkExternalSemaphoreHandleTypeFlagBits
- VkFenceImportFlagBits
- VkMemoryAllocateFlagBits
- VkPeerMemoryFeatureFlagBits
- VkPointClippingBehavior
- VkSamplerYcbcrModelConversion
- VkSamplerYcbcrRange
- VkSemaphoreImportFlagBits
• VkSubgroupFeatureFlagBits
• VkTessellationDomainOrigin
• VkCommandPoolTrimFlags
• VkDescriptorUpdateTemplateCreateFlags
• VkExternalFenceFeatureFlags
• VkExternalFenceHandleTypeFlags
• VkExternalMemoryFeatureFlags
• VkExternalMemoryHandleTypeFlags
• VkExternalSemaphoreFeatureFlags
• VkExternalSemaphoreHandleTypeFlags
• VkFenceImportFlags
• VkMemoryAllocateFlags
• VkPeerMemoryFeatureFlags
• VkSemaphoreImportFlags
• VkSubgroupFeatureFlags

New Structures

• VkBindBufferMemoryDeviceGroupInfo
• VkBindBufferMemoryInfo
• VkBindImageMemoryDeviceGroupInfo
• VkBindImageMemoryInfo
• VkBindImagePlaneMemoryInfo
• VkBufferMemoryRequirementsInfo2
• VkDescriptorSetLayoutSupport
• VkDescriptorUpdateTemplateCreateInfo
• VkDescriptorUpdateTemplateEntry
• VkDeviceGroupBindSparseInfo
• VkDeviceGroupCommandBufferBeginInfo
• VkDeviceGroupDeviceCreateInfo
• VkDeviceGroupRenderPassBeginInfo
• VkDeviceGroupSubmitInfo
• VkDeviceQueueInfo2
• VkExportFenceCreateInfo
• VkExportMemoryAllocateInfo
• VkExportSemaphoreCreateInfo
• VkExternalBufferProperties
• VkExternalFenceProperties
• VkExternalImageFormatProperties
• VkExternalMemoryBufferCreateInfo
• VkExternalMemoryImageCreateInfo
• VkExternalMemoryProperties
• VkExternalSemaphoreProperties
• VkFormatProperties2
• VkImageFormatProperties2
• VkImageMemoryRequirementsInfo2
• VkImagePlaneMemoryRequirementsInfo
• VkImageSparseMemoryRequirementsInfo2
• VkImageViewUsageCreateInfo
• VkInputAttachmentAspectReference
• VkMemoryAllocateFlagsInfo
• VkMemoryDedicatedAllocateInfo
• VkMemoryDedicatedRequirements
• VkMemoryRequirements2
• VkPhysicalDevice16BitStorageFeatures
• VkPhysicalDeviceExternalBufferInfo
• VkPhysicalDeviceExternalFenceInfo
• VkPhysicalDeviceExternalImageFormatInfo
• VkPhysicalDeviceExternalSemaphoreInfo
• VkPhysicalDeviceFeatures2
• VkPhysicalDeviceGroupProperties
• VkPhysicalDeviceIDProperties
• VkPhysicalDeviceImageFormatInfo2
• VkPhysicalDeviceMaintenance3Properties
• VkPhysicalDeviceMemoryProperties2
• VkPhysicalDeviceMultiviewFeatures
• VkPhysicalDeviceMultiviewProperties
• VkPhysicalDevicePointClippingProperties
• VkPhysicalDeviceProperties2
• VkPhysicalDeviceProtectedMemoryFeatures
• VkPhysicalDeviceProtectedMemoryProperties
• VkPhysicalDeviceSamplerYcbcrConversionFeatures
• VkPhysicalDeviceShaderDrawParametersFeatures
• VkPhysicalDeviceSparseImageFormatInfo2
• VkPhysicalDeviceSubgroupProperties
• VkPhysicalDeviceVariablePointersFeatures
• VkPipelineTessellationDomainOriginStateCreateInfo
• VkProtectedSubmitInfo
• VkQueueFamilyProperties2
• VkRenderPassInputAttachmentAspectCreateInfo
• VkRenderPassMultiviewCreateInfo
• VkSamplerYcbcrConversionCreateInfo
• VkSamplerYcbcrConversionImageFormatProperties
• VkSamplerYcbcrConversionInfo
• VkSparseImageFormatProperties2
• VkSparseImageMemoryRequirements2

New Functions

• vkBindBufferMemory2
• vkBindImageMemory2
• vkCmdDispatchBase
• vkCmdSetDeviceMask
• vkCreateDescriptorUpdateTemplate
• vkCreateSamplerYcbcrConversion
• vkDestroyDescriptorUpdateTemplate
• vkDestroySamplerYcbcrConversion
• vkEnumerateInstanceVersion
• vkEnumeratePhysicalDeviceGroups
• vkGetBufferMemoryRequirements2
• vkGetDescriptorSetLayoutSupport
• vkGetDeviceGroupPeerMemoryFeatures
• vkGetDeviceQueue2
• vkGetImageMemoryRequirements2
• vkGetImageSparseMemoryRequirements2
• vkGetPhysicalDeviceExternalBufferProperties
• vkGetPhysicalDeviceExternalFenceProperties
- vkGetPhysicalDeviceExternalSemaphoreProperties
- vkGetPhysicalDeviceFeatures2
- vkGetPhysicalDeviceFormatProperties2
- vkGetPhysicalDeviceImageFormatProperties2
- vkGetPhysicalDeviceMemoryProperties2
- vkGetPhysicalDeviceProperties2
- vkGetPhysicalDeviceQueueFamilyProperties2
- vkGetPhysicalDeviceSparseImageFormatProperties2
- vkTrimCommandPool
- vkUpdateDescriptorSetWithTemplate
Appendix E: Layers & Extensions (Informative)

Extensions to the Vulkan API can be defined by authors, groups of authors, and the Khronos Vulkan Working Group. In order not to compromise the readability of the Vulkan Specification, the core Specification does not incorporate most extensions. The online Registry of extensions is available at URL

https://www.khronos.org/registry/vulkan/

and allows generating versions of the Specification incorporating different extensions.

Most of the content previously in this appendix does not specify use of specific Vulkan extensions and layers, but rather specifies the processes by which extensions and layers are created. As of version 1.0.21 of the Vulkan Specification, this content has been migrated to the Vulkan Documentation and Extensions document. Authors creating extensions and layers must follow the mandatory procedures in that document.

The remainder of this appendix documents a set of extensions chosen when this document was built. Versions of the Specification published in the Registry include:

- Core API + mandatory extensions required of all Vulkan implementations.
- Core API + all registered and published Khronos (KHR) extensions.
- Core API + all registered and published extensions.

Extensions are grouped as Khronos KHR, multivendor EXT, and then alphabetically by author ID. Within each group, extensions are listed in alphabetical order by their name.

Note

As of the initial Vulkan 1.1 public release, the KHX author ID is no longer used. All KHX extensions have been promoted to KHR status. Previously, this author ID was used to indicate that an extension was experimental, and is being considered for standardization in future KHR or core Vulkan API versions. We no longer use this mechanism for exposing experimental functionality.

Some vendors may use an alternate author ID ending in X for some of their extensions. The exact meaning of such an author ID is defined by each vendor, and may not be equivalent to KHX, but it is likely to indicate a lesser degree of interface stability than a non-X extension from the same vendor.

List of Current Extensions

- VK_KHR_8bit_storage
- VK_KHR_android_surface
- VK_KHR_buffer_device_address
- VK_KHR_create_renderpass2
• VK_KHR_depth_stencil_resolve
• VK_KHR_display
• VK_KHR_display_swapchain
• VK_KHR_draw_indirect_count
• VK_KHR_driver_properties
• VK_KHR_external_fence_fd
• VK_KHR_external_fence_win32
• VK_KHR_external_memory_fd
• VK_KHR_external_memory_win32
• VK_KHR_external_semaphore_fd
• VK_KHR_external_semaphore_win32
• VK_KHR_get_display_properties2
• VK_KHR_get_surface_capabilities2
• VK_KHR_image_format_list
• VK_KHR_imageless_framebuffer
• VK_KHR_incremental_present
• VK_KHR_performance_query
• VK_KHR_pipeline_executable_properties
• VK_KHR_push_descriptor
• VK_KHR_sampler_mirror_clamp_to_edge
• VK_KHR_separate_depth_stencil_layouts
• VK_KHR_shader_atomic_int64
• VK_KHR_shader_clock
• VK_KHR_shader_float16_int8
• VK_KHR_shader_float_controls
• VK_KHR_shader_non_semantic_info
• VK_KHR_shader_subgroup_extended_types
• VK_KHR_shared_presentable_image
• VK_KHR_spirv_1_4
• VK_KHR_surface
• VK_KHR_surface_protected_capabilities
• VK_KHR_swapchain
• VK_KHR_swapchain Mutable_format
• VK_KHR_timeline_semaphore
• VK_KHR_uniform_buffer_standard_layout
• VK_KHR_vulkan_memory_model
• VK_KHR_wayland_surface
• VK_KHR_win32_keyed_mutex
• VK_KHR_win32_surface
• VK_KHR_xcb_surface
• VK_KHR_xlib_surface
**VK_KHR_8bit_storage**

**Name String**

VK_KHR_8bit_storage

**Extension Type**

Device extension

**Registered Extension Number**

178

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2
- Requires VK_KHR_storage_buffer_storage_class

**Deprecation state**

- *Promoted* to Vulkan 1.2

**Contact**

- Alexander Galazin ♦alegal-arm

**Other Extension Metadata**

**Last Modified Date**

2018-02-05

**Interactions and External Dependencies**

- Promoted to Vulkan 1.2 Core

**IP Status**

No known IP claims.

**Interactions and External Dependencies**

- This extension requires SPV_KHR_8bit_storage

**Contributors**

- Alexander Galazin, Arm

**Description**

The **VK_KHR_8bit_storage** extension allows use of 8-bit types in uniform and storage buffers, and push constant blocks. This extension introduces several new optional features which map to SPIR-V capabilities and allow access to 8-bit data in **Block**-decorated objects in the **Uniform** and the **StorageBuffer** storage classes, and objects in the **PushConstant** storage class.
The **StorageBuffer8BitAccess** capability **must** be supported by all implementations of this extension. The other capabilities are optional.

**New Enum Constants**

- Extending **VkStructureType**:
  - **VK_STRUCTURE_TYPE_PHYSICALDEVICE8BITSTORAGEFEATURESKHR**

**New Structures**

- **VkPhysicalDevice8BitStorageFeaturesKHR**

**New SPIR-V Capabilities**

- **StorageBuffer8BitAccess**
- **UniformAndStorageBuffer8BitAccess**
- **StoragePushConstant8**

**Promotion to Vulkan 1.2**

Functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. However, if Vulkan 1.2 is supported and this extension is not, the **StorageBuffer8BitAccess** capability is optional. The original type, enum and command names are still available as aliases of the core functionality.

**Issues**

**Version History**

- Revision 1, 2018-02-05 (Alexander Galazin)
  - Initial draft

**VK_KHR_android_surface**

**Name String**

`VK_KHR_android_surface`

**Extension Type**

Instance extension

**Registered Extension Number**

9

**Revision**

6

**Extension and Version Dependencies**

- Requires Vulkan 1.0
The **VK_KHR_android_surface** extension is an instance extension. It provides a mechanism to create a `VkSurfaceKHR` object (defined by the **VK_KHR_surface** extension) that refers to an `ANativeWindow`, Android's native surface type. The `ANativeWindow` represents the producer endpoint of any buffer queue, regardless of consumer endpoint. Common consumer endpoints for `ANativeWindows` are the system window compositor, video encoders, and application-specific compositors importing the images through a `SurfaceTexture`.
New Object Types
None

New Enum Constants

• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_ANDROID_SURFACE_CREATE_INFO_KHR

New Enums
None

New Structures

• VkAndroidSurfaceCreateInfoKHR

New Functions

• vkCreateAndroidSurfaceKHR

Issues

1) Does Android need a way to query for compatibility between a particular physical device (and queue family?) and a specific Android display?

RESOLVED: No. Currently on Android, any physical device is expected to be able to present to the system compositor, and all queue families must support the necessary image layout transitions and synchronization operations.

Version History

• Revision 1, 2015-09-23 (Jesse Hall)
  ◦ Initial draft.

• Revision 2, 2015-10-26 (Ian Elliott)
  ◦ Renamed from VK_EXT_KHR_android_surface to VK_KHR_android_surface.

• Revision 3, 2015-11-03 (Daniel Rakos)
  ◦ Added allocation callbacks to surface creation function.

• Revision 4, 2015-11-10 (Jesse Hall)
  ◦ Removed VK_ERROR_INVALID_ANDROID_WINDOW_KHR.

• Revision 5, 2015-11-28 (Daniel Rakos)
  ◦ Updated the surface create function to take a pCreateInfo structure.

• Revision 6, 2016-01-14 (James Jones)
  ◦ Moved VK_ERROR_NATIVE_WINDOW_IN_USE_KHR from the VK_KHR_android_surface to
the VK_KHR_surface extension.

**VK_KHR_buffer_device_address**

**Name String**  
VK_KHR_buffer_device_address

**Extension Type**  
Device extension

**Registered Extension Number**  
258

**Revision**  
1

**Extension and Version Dependencies**  
- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

**Deprecation state**  
- Promoted to Vulkan 1.2

**Contact**  
- Jeff Bolz [jeffbolznv](mailto:jeffbolznv)

**Other Extension Metadata**

**Last Modified Date**  
2019-06-24

**IP Status**  
No known IP claims.

**Interactions and External Dependencies**  
- Promoted to Vulkan 1.2 Core

**Contributors**  
- Jeff Bolz, NVIDIA
- Neil Henning, AMD
- Tobias Hector, AMD
- Jason Ekstran, Intel
- Baldur Karlsson, Valve
- Jan-Harald Fredriksen, Arm
Description

This extension allows the application to query a 64-bit buffer device address value for a buffer, which can be used to access the buffer memory via the PhysicalStorageBuffer storage class in the GL_EXT_buffer_reference GLSL extension and SPV_KHR_physical_storage_buffer SPIR-V extension.

This extension also allows opaque addresses for buffers and memory objects to be queried and later supplied by a trace capture and replay tool, so that addresses used at replay time match the addresses used when the trace was captured. To enable tools to insert these queries, new memory allocation flags must be specified for memory objects that will be bound to buffers accessed via the PhysicalStorageBuffer storage class.

New Object Types

None

New Enum Constants

• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_BUFFER_DEVICE_ADDRESS_FEATURES_KHR
  ◦ VK_STRUCTURE_TYPE_BUFFER_DEVICE_ADDRESS_INFO_KHR
  ◦ VK_STRUCTURE_TYPE_BUFFER_OPAQUE_CAPTURE_ADDRESS_CREATE_INFO_KHR
  ◦ VK_STRUCTURE_TYPE_MEMORY_OPAQUE_CAPTURE_ADDRESS_ALLOCATE_INFO_KHR
  ◦ VK_STRUCTURE_TYPE_DEVICE_MEMORY_OPAQUE_CAPTURE_ADDRESS_INFO_KHR

• Extending VkBufferUsageFlagBits:
  ◦ VK_BUFFER_USAGE_SHADER_DEVICE_ADDRESS_BIT_KHR

• Extending VkBufferCreateFlagBits:
  ◦ VK_BUFFER_CREATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT_KHR

• Extending VkMemoryAllocateFlagBits:
  ◦ VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_BIT_KHR
  ◦ VK_MEMORY_ALLOCATE_DEVICE_ADDRESS_CAPTURE_REPLAY_BIT_KHR

• Extending VkResult:
  ◦ VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS_KHR

New Enums

None

New Structures

• VkPhysicalDeviceBufferDeviceAddressFeaturesKHR
• VkBufferDeviceAddressInfoKHR
• VkBufferOpaqueCaptureAddressCreateInfoKHR
• VkMemoryOpaqueCaptureAddressAllocateInfoKHR
New Functions

- vkGetBufferDeviceAddressKHR
- vkGetBufferOpaqueCaptureAddressKHR
- vkGetDeviceMemoryOpaqueCaptureAddressKHR

New Built-In Variables

None

New SPIR-V Capabilities

- PhysicalStorageBufferAddresses

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None

Version History

- Revision 1, 2019-06-24 (Jan-Harald Fredriksen)
  - Internal revisions based on VK_EXT_buffer_device_address

VK_KHR_create_renderpass2

Name String

VK_KHR_create_renderpass2

Extension Type

Device extension

Registered Extension Number

110

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_multiview
• Requires VK_KHR_maintenance2

Deprecation state
• Promoted to Vulkan 1.2

Contact
• Tobias Hector

Other Extension Metadata

Last Modified Date
2018-02-07

Interactions and External Dependencies
• Promoted to Vulkan 1.2 Core

Contributors
• Tobias Hector
• Jeff Bolz

Description
This extension provides a new entry point to create render passes in a way that can be easily extended by other extensions through the substructures of render pass creation. The Vulkan 1.0 render pass creation sub-structures do not include sType/pNext members. Additionally, the renderpass begin/next/end commands have been augmented with new extensible structures for passing additional subpass information.

The VkRenderPassMultiviewCreateInfo and VkInputAttachmentAspectReference structures that extended the original VkRenderPassCreateInfo are not accepted into the new creation functions, and instead their parameters are folded into this extension as follows:

• Elements of VkRenderPassMultiviewCreateInfo::pViewMasks are now specified in VkSubpassDescription2KHR::viewMask.

• Elements of VkRenderPassMultiviewCreateInfo::pViewOffsets are now specified in VkSubpassDependency2KHR::viewOffset.

• VkRenderPassMultiviewCreateInfo::correlationMaskCount and VkRenderPassMultiviewCreateInfo::pCorrelationMasks are directly specified in VkRenderPassCreateInfo2KHR.

• VkInputAttachmentAspectReference::aspectMask is now specified in the relevant input attachment description in VkAttachmentDescription2KHR::aspectMask

The details of these mappings are explained fully in the new structures.

New Enum Constants
• Extending VkStructureType:
New Structures

- VkAttachmentDescription2KHR
- VkAttachmentReference2KHR
- VkSubpassDescription2KHR
- VkSubpassDependency2KHR
- VkRenderPassCreateInfo2KHR
- VkSubpassBeginInfoKHR
- VkSubpassEndInfoKHR

New Functions

- vkCreateRenderPass2KHR
- vkCmdBeginRenderPass2KHR
- vkCmdNextSubpass2KHR
- vkCmdEndRenderPass2KHR

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

- Revision 1, 2018-02-07 (Tobias Hector)
  - Internal revisions

VK_KHR_depth_stencil_resolve

Name String

VK_KHR_depth_stencil_resolve

Extension Type

Device extension

Registered Extension Number
Revision
1

Extension and Version Dependencies
• Requires Vulkan 1.0
• Requires VK_KHR_create_renderpass2

Deprecation state
• Promoted to Vulkan 1.2

Contact
• Jan-Harald Fredriksen janharald

Other Extension Metadata

Last Modified Date
2018-04-09

Interactions and External Dependencies
• Promoted to Vulkan 1.2 Core

Contributors
• Jan-Harald Fredriksen, Arm
• Andrew Garrard, Samsung Electronics
• Soowan Park, Samsung Electronics
• Jeff Bolz, NVIDIA
• Daniel Rakos, AMD

Description
This extension adds support for automatically resolving multisampled depth/stencil attachments in a subpass in a similar manner as for color attachments.

New Enum Constants
• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_DEPTH_STENCIL_RESOLVE_KHR
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DEPTH_STENCIL_RESOLVE_PROPERTIES_KHR

New Enums
• VkResolveModeFlagBitsKHR
New Structures

- VkPhysicalDeviceDepthStencilResolvePropertiesKHR
- VkSubpassDescriptionDepthStencilResolveKHR

New Functions

None.

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

- Revision 1, 2018-04-09 (Jan-Harald Fredriksen)
  - Initial revision

VK_KHR_display

Name String

VK_KHR_display

Extension Type

Instance extension

Registered Extension Number

3

Revision

23

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_surface

Contact

- James Jones @cubanismo
- Norbert Nopper @FslNopper

Other Extension Metadata

Last Modified Date

2017-03-13

IP Status
No known IP claims.

Contributors
• James Jones, NVIDIA
• Norbert Nopper, Freescale
• Jeff Vigil, Qualcomm
• Daniel Rakos, AMD

Description
This extension provides the API to enumerate displays and available modes on a given device.

New Object Types
• VkDisplayKHR
• VkDisplayModeKHR

New Enum Constants
• Extending VkStructureType:
  o VK_STRUCTURE_TYPE_DISPLAY_MODE_CREATE_INFO_KHR
  o VK_STRUCTURE_TYPE_DISPLAY_SURFACE_CREATE_INFO_KHR

New Enums
• VkDisplayPlaneAlphaFlagBitsKHR

New Structures
• VkDisplayPropertiesKHR
• VkDisplayModeParametersKHR
• VkDisplayModePropertiesKHR
• VkDisplayModeCreateInfoKHR
• VkDisplayPlanePropertiesKHR
• VkDisplayPlaneCapabilitiesKHR
• VkDisplaySurfaceCreateInfoKHR

New Functions
• vkGetPhysicalDeviceDisplayPropertiesKHR
• vkGetPhysicalDeviceDisplayPlanePropertiesKHR
• vkGetDisplayPlaneSupportedDisplaysKHR
• vkGetDisplayModePropertiesKHR
• vkCreateDisplayModeKHR
• vkGetDisplayPlaneCapabilitiesKHR
• vkCreateDisplayPlaneSurfaceKHR

Issues

1) Which properties of a mode should be fixed in the mode info vs. settable in some other function when setting the mode? E.g., do we need to double the size of the mode pool to include both stereo and non-stereo modes? YUV and RGB scanout even if they both take RGB input images? BGR vs. RGB input? etc.

**PROPOSED RESOLUTION:** Many modern displays support at most a handful of resolutions and timings natively. Other “modes” are expected to be supported using scaling hardware on the display engine or GPU. Other properties, such as rotation and mirroring should not require duplicating hardware modes just to express all combinations. Further, these properties may be implemented on a per-display or per-overlay granularity.

To avoid the exponential growth of modes as mutable properties are added, as was the case with EGLConfig/WGL pixel formats/GLXFBConfig, this specification should separate out hardware properties and configurable state into separate objects. Modes and overlay planes will express capabilities of the hardware, while a separate structure will allow applications to configure scaling, rotation, mirroring, color keys, LUT values, alpha masks, etc. for a given swapchain independent of the mode in use. Constraints on these settings will be established by properties of the immutable objects.

Note the resolution of this issue may affect issue 5 as well.

2) What properties of a display itself are useful?

**PROPOSED RESOLUTION:** This issue is too broad. It was meant to prompt general discussion, but resolving this issue amounts to completing this specification. All interesting properties should be included. The issue will remain as a placeholder since removing it would make it hard to parse existing discussion notes that refer to issues by number.

3) How are multiple overlay planes within a display or mode enumerated?

**PROPOSED RESOLUTION:** They are referred to by an index. Each display will report the number of overlay planes it contains.

4) Should swapchains be created relative to a mode or a display?

**PROPOSED RESOLUTION:** When using this extension, swapchains are created relative to a mode and a plane. The mode implies the display object the swapchain will present to. If the specified mode is not the display's current mode, the new mode will be applied when the first image is presented to the swapchain, and the default operating system mode, if any, will be restored when the swapchain is destroyed.

5) Should users query generic ranges from displays and construct their own modes explicitly using those constraints rather than querying a fixed set of modes (Most monitors only have one real...
“mode” these days, even though many support relatively arbitrary scaling, either on the monitor side or in the GPU display engine, making “modes” something of a relic/compatibility construct).

**PROPOSED RESOLUTION:** Expose both. Display info structures will expose a set of predefined modes, as well as any attributes necessary to construct a customized mode.

6) Is it fine if we return the display and display mode handles in the structure used to query their properties?

**PROPOSED RESOLUTION:** Yes.

7) Is there a possibility that not all displays of a device work with all of the present queues of a device? If yes, how do we determine which displays work with which present queues?

**PROPOSED RESOLUTION:** No known hardware has such limitations, but determining such limitations is supported automatically using the existing `VK_KHR_surface` and `VK_KHR_swapchain` query mechanisms.

8) Should all presentation need to be done relative to an overlay plane, or can a display mode + display be used alone to target an output?

**PROPOSED RESOLUTION:** Require specifying a plane explicitly.

9) Should displays have an associated window system display, such as an `HDC` or `Display`?

**PROPOSED RESOLUTION:** No. Displays are independent of any windowing system in use on the system. Further, neither `HDC` nor `Display` refer to a physical display object.

10) Are displays queried from a physical GPU or from a device instance?

**PROPOSED RESOLUTION:** Developers prefer to query modes directly from the physical GPU so they can use display information as an input to their device selection algorithms prior to device creation. This avoids the need to create dummy device instances to enumerate displays.

This preference must be weighed against the extra initialization that must be done by driver vendors prior to device instance creation to support this usage.

11) Should displays and/or modes be dispatchable objects? If functions are to take displays, overlays, or modes as their first parameter, they must be dispatchable objects as defined in Khronos bug 13529. If they are not added to the list of dispatchable objects, functions operating on them must take some higher-level object as their first parameter. There is no performance case against making them dispatchable objects, but they would be the first extension objects to be dispatchable.

**PROPOSED RESOLUTION:** Do not make displays or modes dispatchable. They will dispatch based on their associated physical device.

12) Should hardware cursor capabilities be exposed?

**PROPOSED RESOLUTION:** Defer. This could be a separate extension on top of the base WSI specs.

if they are one physical display device to an end user, but may internally be implemented as two
side-by-side displays using the same display engine (and sometimes cabling) resources as two physically separate display devices.

**RESOLVED:** Tiled displays will appear as a single display object in this API.

14) Should the raw EDID data be included in the display information?

**RESOLVED:** No. A future extension could be added which reports the EDID if necessary. This may be complicated by the outcome of issue 13.

15) Should min and max scaling factor capabilities of overlays be exposed?

**RESOLVED:** Yes. This is exposed indirectly by allowing applications to query the min/max position and extent of the source and destination regions from which image contents are fetched by the display engine when using a particular mode and overlay pair.

16) Should devices be able to expose planes that can be moved between displays? If so, how?

**RESOLVED:** Yes. Applications can determine which displays a given plane supports using `vkGetDisplayPlaneSupportedDisplaysKHR`.

17) Should there be a way to destroy display modes? If so, does it support destroying “built in” modes?

**RESOLVED:** Not in this extension. A future extension could add this functionality.

18) What should the lifetime of display and built-in display mode objects be?

**RESOLVED:** The lifetime of the instance. These objects cannot be destroyed. A future extension may be added to expose a way to destroy these objects and/or support display hotplug.

19) Should persistent mode for smart panels be enabled/disabled at swapchain creation time, or on a per-present basis?

**RESOLVED:** On a per-present basis.

**Examples**

The example code for the `VK_KHR_display` and `VK_KHR_display_swapchain` extensions was removed from the appendix after revision 1.0.43. The display enumeration example code was ported to the cube demo that is shipped with the official Khronos SDK, and is being kept up-to-date in that location (see: [https://github.com/KhronosGroup/Vulkan-Tools/blob/master/cube/cube.c](https://github.com/KhronosGroup/Vulkan-Tools/blob/master/cube/cube.c)).

**Version History**

- Revision 1, 2015-02-24 (James Jones)
  - Initial draft
- Revision 2, 2015-03-12 (Norbert Nopper)
• Added overlay enumeration for a display.

• Revision 3, 2015-03-17 (Norbert Nopper)
  ◦ Fixed typos and namings as discussed in Bugzilla.
  ◦ Reordered and grouped functions.
  ◦ Added functions to query count of display, mode and overlay.
  ◦ Added native display handle, which is maybe needed on some platforms to create a native Window.

• Revision 4, 2015-03-18 (Norbert Nopper)
  ◦ Removed primary and virtualPosition members (see comment of James Jones in Bugzilla).
  ◦ Added native overlay handle to info structure.
  ◦ Replaced , with ; in struct.

• Revision 6, 2015-03-18 (Daniel Rakos)
  ◦ Added WSI extension suffix to all items.
  ◦ Made the whole API more "Vulkanish".
  ◦ Replaced all functions with a single vkGetDisplayInfoKHR function to better match the rest of the API.
  ◦ Made the display, display mode, and overlay objects be first class objects, not subclasses of VkBaseObject as they do not support the common functions anyways.
  ◦ Renamed *Info structures to *Properties.
  ◦ Removed overlayIndex field from VkOverlayProperties as there is an implicit index already as a result of moving to a "Vulkanish" API.
  ◦ Displays are not get through device, but through physical GPU to match the rest of the Vulkan API. Also this is something ISVs explicitly requested.
  ◦ Added issue (6) and (7).

• Revision 7, 2015-03-25 (James Jones)
  ◦ Added an issues section
  ◦ Added rotation and mirroring flags

• Revision 8, 2015-03-25 (James Jones)
  ◦ Combined the duplicate issues sections introduced in last change.
  ◦ Added proposed resolutions to several issues.

• Revision 9, 2015-04-01 (Daniel Rakos)
  ◦ Rebased extension against Vulkan 0.82.0

• Revision 10, 2015-04-01 (James Jones)
  ◦ Added issues (10) and (11).
  ◦ Added more straw-man issue resolutions, and cleaned up the proposed resolution for issue (4).
Updated the rotation and mirroring enums to have proper bitmask semantics.

- Revision 11, 2015-04-15 (James Jones)
  - Added proposed resolution for issues (1) and (2).
  - Added issues (12), (13), (14), and (15)
  - Removed pNativeHandle field from overlay structure.
  - Fixed small compilation errors in example code.

- Revision 12, 2015-07-29 (James Jones)
  - Rewrote the guts of the extension against the latest WSI swapchain specifications and the latest Vulkan API.
  - Address overlay planes by their index rather than an object handle and refer to them as "planes" rather than "overlays" to make it slightly clearer that even a display with no "overlays" still has at least one base "plane" that images can be displayed on.
  - Updated most of the issues.
  - Added an "extension type" section to the specification header.
  - Re-used the VK_EXT_KHR_surface surface transform enumerations rather than redefining them here.
  - Updated the example code to use the new semantics.

- Revision 13, 2015-08-21 (Ian Elliott)
  - Renamed this extension and all of its enumerations, types, functions, etc. This makes it compliant with the proposed standard for Vulkan extensions.
  - Switched from "revision" to "version", including use of the VK_MAKE_VERSION macro in the header file.

- Revision 14, 2015-09-01 (James Jones)
  - Restore single-field revision number.

- Revision 15, 2015-09-08 (James Jones)
  - Added alpha flags enum.
  - Added premultiplied alpha support.

- Revision 16, 2015-09-08 (James Jones)
  - Added description section to the spec.
  - Added issues 16 - 18.

- Revision 17, 2015-10-02 (James Jones)
  - Planes are now a property of the entire device rather than individual displays. This allows planes to be moved between multiple displays on devices that support it.
  - Added a function to create a VkSurfaceKHR object describing a display plane and mode to align with the new per-platform surface creation conventions.
  - Removed detailed mode timing data. It was agreed that the mode extents and refresh rate are sufficient for current use cases. Other information could be added back in as an
extension if it is needed in the future.
• Added support for smart/persistent/buffered display devices.

• Revision 18, 2015-10-26 (Ian Elliott)
  • Renamed from VK_EXT_KHR_display to VK_KHR_display.

• Revision 19, 2015-11-02 (James Jones)
  • Updated example code to match revision 17 changes.

• Revision 20, 2015-11-03 (Daniel Rakos)
  • Added allocation callbacks to creation functions.

• Revision 21, 2015-11-10 (Jesse Hall)
  • Added VK_DISPLAY_PLANE_ALPHA_OPAQUE_BIT_KHR, and use
    VkDisplayPlaneAlphaFlagBitsKHR for VkDisplayPlanePropertiesKHR::alphaMode instead of
    VkDisplayPlaneAlphaFlagsKHR, since it only represents one mode.
  • Added reserved flags bitmask to VkDisplayPlanePropertiesKHR.
  • Use VkSurfaceTransformFlagBitsKHR instead of obsolete VkSurfaceTransformKHR.
  • Renamed vkGetDisplayPlaneSupportedDisplaysKHR parameters for clarity.

• Revision 22, 2015-12-18 (James Jones)
  • Added missing "planeIndex" parameter to vkGetDisplayPlaneSupportedDisplaysKHR()

• Revision 23, 2017-03-13 (James Jones)
  • Closed all remaining issues. The specification and implementations have been shipping with
    the proposed resolutions for some time now.
  • Removed the sample code and noted it has been integrated into the official Vulkan SDK cube
    demo.

**VK_KHR_display_swapchain**

**Name String**

VK_KHR_display_swapchain

**Extension Type**

Device extension

**Registered Extension Number**

4

**Revision**

10

**Extension and Version Dependencies**

• Requires Vulkan 1.0

• Requires VK_KHR_swapchain

• Requires VK_KHR_display
Description
This extension provides an API to create a swapchain directly on a device's display without any underlying window system.

New Object Types
None

New Enum Constants
• Extending VkStructureType:
  ○ VK_STRUCTURE_TYPE_DISPLAY_PRESENT_INFO_KHR
• Extending VkResult:
  ○ VK_ERROR_INCOMPATIBLE_DISPLAY_KHR

New Enums
None

New Structures
• VkDisplayPresentInfoKHR

New Functions
• vkCreateSharedSwapchainsKHR

Issues
1) Should swapchains sharing images each hold a reference to the images, or should it be up to the
application to destroy the swapchains and images in an order that avoids the need for reference counting?

**RESOLVED**: Take a reference. The lifetime of presentable images is already complex enough.

2) Should the `srcRect` and `dstRect` parameters be specified as part of the present command, or at swapchain creation time?

**RESOLVED**: As part of the presentation command. This allows moving and scaling the image on the screen without the need to respecify the mode or create a new swapchain and presentable images.

3) Should `srcRect` and `dstRect` be specified as rects, or separate offset/extent values?

**RESOLVED**: As rects. Specifying them separately might make it easier for hardware to expose support for one but not the other, but in such cases applications must just take care to obey the reported capabilities and not use non-zero offsets or extents that require scaling, as appropriate.

4) How can applications create multiple swapchains that use the same images?

**RESOLVED**: By calling `vkCreateSharedSwapchainsKHR`.

An earlier resolution used `vkCreateSwapchainKHR`, chaining multiple `VkSwapchainCreateInfoKHR` structures through `pNext`. In order to allow each swapchain to also allow other extension structs, a level of indirection was used: `VkSwapchainCreateInfoKHR::pNext` pointed to a different structure, which had both `sType` and `pNext` members for additional extensions, and also had a pointer to the next `VkSwapchainCreateInfoKHR` structure. The number of swapchains to be created could only be found by walking this linked list of alternating structures, and the `pSwapchains` out parameter was reinterpreted to be an array of `VkSwapchainKHR` handles.

Another option considered was a method to specify a “shared” swapchain when creating a new swapchain, such that groups of swapchains using the same images could be built up one at a time. This was deemed unusable because drivers need to know all of the displays an image will be used on when determining which internal formats and layouts to use for that image.

**Examples**

```
Note
The example code for the VK_KHR_display and VK_KHR_display_swapchain extensions was removed from the appendix after revision 1.0.43. The display swapchain creation example code was ported to the cube demo that is shipped with the official Khronos SDK, and is being kept up-to-date in that location (see: https://github.com/KhronosGroup/Vulkan-Tools/blob/master/cube/cube.c).
```

**Version History**

- Revision 1, 2015-07-29 (James Jones)
  - Initial draft
- Revision 2, 2015-08-21 (Ian Elliott)
Renamed this extension and all of its enumerations, types, functions, etc. This makes it compliant with the proposed standard for Vulkan extensions.

Switched from "revision" to "version", including use of the VK_MAKE_VERSION macro in the header file.

- Revision 3, 2015-09-01 (James Jones)
  - Restore single-field revision number.

- Revision 4, 2015-09-08 (James Jones)
  - Allow creating multiple swap chains that share the same images using a single call to vkCreateSwapChainKHR().

- Revision 5, 2015-09-10 (Alon Or-bach)
  - Removed underscores from SWAP_CHAIN in two enums.

- Revision 6, 2015-10-02 (James Jones)
  - Added support for smart panels/buffered displays.

- Revision 7, 2015-10-26 (Ian Elliott)
  - Renamed from VK_EXT_KHR_display_swapchain to VK_KHR_display_swapchain.

- Revision 8, 2015-11-03 (Daniel Rakos)
  - Updated sample code based on the changes to VK_KHR_swapchain.

- Revision 9, 2015-11-10 (Jesse Hall)
  - Replaced VkDisplaySwapchainCreateInfoKHR with vkCreateSharedSwapchainsKHR, changing resolution of issue #4.

- Revision 10, 2017-03-13 (James Jones)
  - Closed all remaining issues. The specification and implementations have been shipping with the proposed resolutions for some time now.
  - Removed the sample code and noted it has been integrated into the official Vulkan SDK cube demo.

**VK_KHR_draw_indirect_count**

**Name String**

VK_KHR_draw_indirect_count

**Extension Type**

Device extension

**Registered Extension Number**

170

**Revision**

1

**Extension and Version Dependencies**
• Requires Vulkan 1.0

**Deprecation state**

• *Promoted to Vulkan 1.2*

**Contact**

• Piers Daniell [pdaniell-nv](#)

**Other Extension Metadata**

**Last Modified Date**

2017-08-25

**Interactions and External Dependencies**

• Promoted to Vulkan 1.2 Core

**IP Status**

No known IP claims.

**Contributors**

• Matthaeus G. Chajdas, AMD
• Derrick Owens, AMD
• Graham Sellers, AMD
• Daniel Rakos, AMD
• Dominik Witczak, AMD
• Piers Daniell, NVIDIA

**Description**

This extension is based off the [VK_AMD_draw_indirect_count] extension. This extension allows an application to source the number of draw calls for indirect draw calls from a buffer. This enables applications to generate arbitrary amounts of draw commands and execute them without host intervention.

**New Functions**

• `vkCmdDrawIndirectCountKHR`
• `vkCmdDrawIndexedIndirectCountKHR`

**Promotion to Vulkan 1.2**

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. However, if Vulkan 1.2 is supported and this extension is not, the entry points `vkCmdDrawIndirectCount` and `vkCmdDrawIndexedIndirectCount` are optional. The original type, enum and command names are still available as aliases of the core functionality.
Version History

- Revision 1, 2017-08-25 (Piers Daniell)
  - Initial draft based off VK_AMD_draw_indirect_count

VK_KHR_driver_properties

Name String
VK_KHR_driver_properties

Extension Type
Device extension

Registered Extension Number
197

Revision
1

Extension and Version Dependencies
- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

Deprecation state
- Promoted to Vulkan 1.2

Contact
- Daniel Rakos drakos-amd

Other Extension Metadata

Last Modified Date
2018-04-11

Interactions and External Dependencies
- Promoted to Vulkan 1.2 Core

IP Status
- No known IP claims.

Contributors
- Baldur Karlsson
- Matthaeus G. Chajdas, AMD
- Piers Daniell, NVIDIA
- Alexander Galazin, Arm
- Jesse Hall, Google
Description

This extension provides a new physical device query which allows retrieving information about the driver implementation, allowing applications to determine which physical device corresponds to which particular vendor’s driver, and which conformance test suite version the driver implementation is compliant with.

New Object Types

None.

New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES_KHR
  - VK_MAX_DRIVER_NAME_SIZE_KHR
  - VK_MAX_DRIVER_INFO_SIZE_KHR

New Enums

None.

New Structures

- VkConformanceVersionKHR
- VkPhysicalDeviceDriverPropertiesKHR

New Functions

None.

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None.

Examples

None.
**Version History**

- Revision 1, 2018-04-11 (Daniel Rakos)
  - Internal revisions

**VK_KHR_external_fence_fd**

**Name String**

`VK_KHR_external_fence_fd`

**Extension Type**

Device extension

**Registered Extension Number**

116

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires `VK_KHR_external_fence`

**Contact**

- Jesse Hall [critsec](https://critsec.com)

**Other Extension Metadata**

**Last Modified Date**

2017-05-08

**IP Status**

No known IP claims.

**Contributors**

- Jesse Hall, Google
- James Jones, NVIDIA
- Jeff Juliano, NVIDIA
- Cass Everitt, Oculus
- Contributors to `VK_KHR_external_semaphore_fd`

**Description**

An application using external memory may wish to synchronize access to that memory using fences. This extension enables an application to export fence payload to and import fence payload from POSIX file descriptors.
New Object Types

None.

New Enum Constants

- VK_STRUCTURE_TYPE_IMPORT_FENCE_FD_INFO_KHR
- VK_STRUCTURE_TYPE_FENCE_GET_FD_INFO_KHR

New Enums

None.

New Structs

- VkImportFenceFdInfoKHR
- VkFenceGetFdInfoKHR

New Functions

- vkImportFenceFdKHR
- vkGetFenceFdKHR

Issues

This extension borrows concepts, semantics, and language from VK_KHR_external_semaphore_fd. That extension's issues apply equally to this extension.

Version History

- Revision 1, 2017-05-08 (Jesse Hall)
  - Initial revision

VK_KHR_external_fence_win32

Name String

VK_KHR_external_fence_win32

Extension Type

Device extension

Registered Extension Number

115

Revision

1
Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_external_fence

Contact

- Jesse Hall @critsec

Other Extension Metadata

Last Modified Date
2017-05-08

IP Status
No known IP claims.

Contributors

- Jesse Hall, Google
- James Jones, NVIDIA
- Jeff Juliano, NVIDIA
- Cass Everitt, Oculus
- Contributors to VK_KHR_external_semaphore_win32

Description

An application using external memory may wish to synchronize access to that memory using fences. This extension enables an application to export fence payload to and import fence payload from Windows handles.

New Object Types

None.

New Enum Constants

- VK_STRUCTURE_TYPE_IMPORT_FENCE_WIN32_HANDLE_INFO_KHR
- VK_STRUCTURE_TYPE_EXPORT_FENCE_WIN32_HANDLE_INFO_KHR
- VK_STRUCTURE_TYPE_FENCE_GET_WIN32_HANDLE_INFO_KHR

New Enums

None.

New Structs

- VkImportFenceWin32HandleInfoKHR
- VkExportFenceWin32HandleInfoKHR
New Functions

- VkFenceGetWin32HandleInfoKHR
- VkImportFenceWin32HandleKHR
- VkGetFenceWin32HandleKHR

Issues

This extension borrows concepts, semantics, and language from VK_KHR_external_semaphore_win32. That extension’s issues apply equally to this extension.

1) Should D3D12 fence handle types be supported, like they are for semaphores?

**RESOLVED**: No. Doing so would require extending the fence signal and wait operations to provide values to signal / wait for, like VkD3D12FenceSubmitInfoKHR does. A D3D12 fence can be signaled by importing it into a VkSemaphore instead of a VkFence, and applications can check status or wait on the D3D12 fence using non-Vulkan APIs. The convenience of being able to do these operations on VkFence objects doesn’t justify the extra API complexity.

Version History

- Revision 1, 2017-05-08 (Jesse Hall)
  - Initial revision

**VK_KHR_external_memory_fd**

Name String

VK_KHR_external_memory_fd

Extension Type

Device extension

Registered Extension Number

75

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_external_memory

Contact

- James Jones Cubanismo
Other Extension Metadata

Last Modified Date
2016-10-21

IP Status
No known IP claims.

Contributors
• James Jones, NVIDIA
• Jeff Juliano, NVIDIA

Description
An application may wish to reference device memory in multiple Vulkan logical devices or instances, in multiple processes, and/or in multiple APIs. This extension enables an application to export POSIX file descriptor handles from Vulkan memory objects and to import Vulkan memory objects from POSIX file descriptor handles exported from other Vulkan memory objects or from similar resources in other APIs.

New Object Types
None.

New Enum Constants
• VK_STRUCTURE_TYPE_IMPORT_MEMORY_FD_INFO_KHR
• VK_STRUCTURE_TYPE_MEMORY_FD_PROPERTIES_KHR
• VK_STRUCTURE_TYPE_MEMORY_GET_FD_INFO_KHR

New Enums
None.

New Structs
• VkImportMemoryFdInfoKHR
• VkMemoryFdPropertiesKHR
• VkMemoryGetFdInfoKHR

New Functions
• vkGetMemoryFdKHR
• vkGetMemoryFdPropertiesKHR
Issues

1) Does the application need to close the file descriptor returned by `vkGetMemoryFdKHR`?

**RESOLVED:** Yes, unless it is passed back in to a driver instance to import the memory. A successful get call transfers ownership of the file descriptor to the application, and a successful import transfers it back to the driver. Destroying the original memory object will not close the file descriptor or remove its reference to the underlying memory resource associated with it.

2) Do drivers ever need to expose multiple file descriptors per memory object?

**RESOLVED:** No. This would indicate there are actually multiple memory objects, rather than a single memory object.

3) How should the valid size and memory type for POSIX file descriptor memory handles created outside of Vulkan be specified?

**RESOLVED:** The valid memory types are queried directly from the external handle. The size will be specified by future extensions that introduce such external memory handle types.

Version History

- Revision 1, 2016-10-21 (James Jones)
  - Initial revision

**VK_KHR_external_memory_win32**

Name String

`VK_KHR_external_memory_win32`

Extension Type

Device extension

Registered Extension Number

74

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires `VK_KHR_external_memory`  

Contact

- James Jones Cubanismo

Other Extension Metadata
Description

An application may wish to reference device memory in multiple Vulkan logical devices or instances, in multiple processes, and/or in multiple APIs. This extension enables an application to export Windows handles from Vulkan memory objects and to import Vulkan memory objects from Windows handles exported from other Vulkan memory objects or from similar resources in other APIs.

New Object Types

None.

New Enum Constants

- VK_STRUCTURE_TYPE_IMPORT_MEMORY_WIN32_HANDLE_INFO_KHR
- VK_STRUCTURE_TYPE_EXPORT_MEMORY_WIN32_HANDLE_INFO_KHR
- VK_STRUCTURE_TYPE_MEMORY_WIN32_HANDLE_PROPERTIES_KHR
- VK_STRUCTURE_TYPE_MEMORY_GET_WIN32_HANDLE_INFO_KHR

New Enums

None.

New Structs

- VkImportMemoryWin32HandleInfoKHR
- VkExportMemoryWin32HandleInfoKHR
- VkMemoryWin32HandlePropertiesKHR
- VkMemoryGetWin32HandleInfoKHR

New Functions

- vkGetMemoryWin32HandleKHR
- vkGetMemoryWin32HandlePropertiesKHR
Issues

1) Do applications need to call `CloseHandle()` on the values returned from `vkGetMemoryWin32HandleKHR` when `handleType` is `VK_EXTERNAL_MEMORY_HANDLE_TYPE_OPAQUE_WIN32_BIT_KHR`?

**RESOLVED:** Yes, unless it is passed back in to another driver instance to import the object. A successful get call transfers ownership of the handle to the application. Destroying the memory object will not destroy the handle or the handle’s reference to the underlying memory resource.

2) Should the language regarding KMT/Windows 7 handles be moved to a separate extension so that it can be deprecated over time?

**RESOLVED:** No. Support for them can be deprecated by drivers if they choose, by no longer returning them in the supported handle types of the instance level queries.

3) How should the valid size and memory type for windows memory handles created outside of Vulkan be specified?

**RESOLVED:** The valid memory types are queried directly from the external handle. The size is determined by the associated image or buffer memory requirements for external handle types that require dedicated allocations, and by the size specified when creating the object from which the handle was exported for other external handle types.

Version History

- Revision 1, 2016-10-21 (James Jones)
  - Initial revision

VK_KHR_external_semaphore_fd

Name String

VK_KHR_external_semaphore_fd

Extension Type

Device extension

Registered Extension Number

80

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_external_semaphore

Contact

- James Jones cubanismo
Other Extension Metadata

Last Modified Date
2016-10-21

IP Status
No known IP claims.

Contributors
• Jesse Hall, Google
• James Jones, NVIDIA
• Jeff Juliano, NVIDIA
• Carsten Rohde, NVIDIA

Description
An application using external memory may wish to synchronize access to that memory using semaphores. This extension enables an application to export semaphore payload to and import semaphore payload from POSIX file descriptors.

New Object Types
None.

New Enum Constants

- VK_STRUCTURE_TYPE_IMPORT_SEMAPHORE_FD_INFO_KHR
- VK_STRUCTURE_TYPE_SEMAPHORE_GET_FD_INFO_KHR

New Enums
None.

New Structs

- VkImportSemaphoreFdInfoKHR
- VkSemaphoreGetFdInfoKHR

New Functions

- vkImportSemaphoreFdKHR
- vkGetSemaphoreFdKHR

Issues

1) Does the application need to close the file descriptor returned by vkGetSemaphoreFdKHR?
RESOLVED: Yes, unless it is passed back in to a driver instance to import the semaphore. A successful get call transfers ownership of the file descriptor to the application, and a successful import transfers it back to the driver. Destroying the original semaphore object will not close the file descriptor or remove its reference to the underlying semaphore resource associated with it.

Version History

• Revision 1, 2016-10-21 (Jesse Hall)
  ◦ Initial revision

VK_KHR_external_semaphore_win32

Name String

VK_KHR_external_semaphore_win32

Extension Type

Device extension

Registered Extension Number

79

Revision

1

Extension and Version Dependencies

• Requires Vulkan 1.0
• Requires VK_KHR_external_semaphore

Contact

• James Jones @cubanismo

Other Extension Metadata

Last Modified Date

2016-10-21

IP Status

No known IP claims.

Contributors

• James Jones, NVIDIA
• Jeff Juliano, NVIDIA
• Carsten Rohde, NVIDIA

Description

An application using external memory may wish to synchronize access to that memory using
semaphores. This extension enables an application to export semaphore payload to and import semaphore payload from Windows handles.

**New Object Types**

None.

**New Enum Constants**

- VK_STRUCTURE_TYPE_IMPORT_SEMAPHORE_WIN32_HANDLE_INFO_KHR
- VK_STRUCTURE_TYPE_EXPORT_SEMAPHORE_WIN32_HANDLE_INFO_KHR
- VK_STRUCTURE_TYPE_D3D12_FENCE_SUBMIT_INFO_KHR
- VK_STRUCTURE_TYPE_SEMAPHORE_GET_WIN32_HANDLE_INFO_KHR

**New Enums**

None.

**New Structs**

- VkImportSemaphoreWin32HandleInfoKHR
- VkExportSemaphoreWin32HandleInfoKHR
- VkD3D12FenceSubmitInfoKHR
- VkSemaphoreGetWin32HandleInfoKHR

**New Functions**

- vkImportSemaphoreWin32HandleKHR
- vkGetSemaphoreWin32HandleKHR

**Issues**

1) Do applications need to call `CloseHandle()` on the values returned from `vkGetSemaphoreWin32HandleKHR` when `handleType` is `VK_EXTERNAL_SEMAPHORE_HANDLE_TYPE_OPAQUE_WIN32_BIT_KHR`?

**RESOLVED:** Yes, unless it is passed back in to another driver instance to import the object. A successful get call transfers ownership of the handle to the application. Destroying the semaphore object will not destroy the handle or the handle’s reference to the underlying semaphore resource.

2) Should the language regarding KMT/Windows 7 handles be moved to a separate extension so that it can be deprecated over time?

**RESOLVED:** No. Support for them can be deprecated by drivers if they choose, by no longer returning them in the supported handle types of the instance level queries.

3) Should applications be allowed to specify additional object attributes for shared handles?
RESOLVED: Yes. Applications will be allowed to provide similar attributes to those they would to any other handle creation API.

4) How do applications communicate the desired fence values to use with D3D12_FENCE-based Vulkan semaphores?

RESOLVED: There are a couple of options. The values for the signaled and reset states could be communicated up front when creating the object and remain static for the life of the Vulkan semaphore, or they could be specified using auxiliary structures when submitting semaphore signal and wait operations, similar to what is done with the keyed mutex extensions. The latter is more flexible and consistent with the keyed mutex usage, but the former is a much simpler API.

Since Vulkan tends to favor flexibility and consistency over simplicity, a new structure specifying D3D12 fence acquire and release values is added to the `vkQueueSubmit` function.

Version History

- Revision 1, 2016-10-21 (James Jones)
  - Initial revision

VK_KHR_get_display_properties2

Name String

- VK_KHR_get_display_properties2

Extension Type

- Instance extension

Registered Extension Number

- 122

Revision

- 1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_display

Contact

- James Jones Cubanismo

Other Extension Metadata

Last Modified Date

- 2017-02-21

IP Status

- No known IP claims.
Contributors

- Ian Elliott, Google
- James Jones, NVIDIA

Description

This extension provides new entry points to query device display properties and capabilities in a way that can be easily extended by other extensions, without introducing any further entry points. This extension can be considered the `VK_KHR_display` equivalent of the `VK_KHR_get_physical_device_properties2` extension.

New Object Types

None.

New Enum Constants

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_DISPLAY_PROPERTIES_2_KHR`
  - `VK_STRUCTURE_TYPE_DISPLAY_PLANE_PROPERTIES_2_KHR`
  - `VK_STRUCTURE_TYPE_DISPLAY_MODE_PROPERTIES_2_KHR`
  - `VK_STRUCTURE_TYPE_DISPLAY_PLANE_INFO_2_KHR`
  - `VK_STRUCTURE_TYPE_DISPLAY_PLANE_CAPABILITIES_2_KHR`

New Enums

None.

New Structures

- `VkDisplayProperties2KHR`
- `VkDisplayPlaneProperties2KHR`
- `VkDisplayModeProperties2KHR`
- `VkDisplayPlaneInfo2KHR`
- `VkDisplayPlaneCapabilities2KHR`

New Functions

- `vkGetPhysicalDeviceDisplayProperties2KHR`
- `vkGetPhysicalDeviceDisplayPlaneProperties2KHR`
- `vkGetDisplayModeProperties2KHR`
- `vkGetDisplayPlaneCapabilities2KHR`
Issues

1) What should this extension be named?

RESOLVED: VK_KHR_get_display_properties2. Other alternatives:

- VK_KHR_display2
- One extension, combined with VK_KHR_surface_capabilities2.

2) Should extensible input structs be added for these new functions:

RESOLVED:

- vkGetPhysicalDeviceDisplayProperties2KHR: No. The only current input is a VkPhysicalDevice. Other inputs wouldn't make sense.
- vkGetPhysicalDeviceDisplayPlaneProperties2KHR: No. The only current input is a VkPhysicalDevice. Other inputs wouldn't make sense.
- vkGetDisplayModeProperties2KHR: No. The only current inputs are a VkPhysicalDevice and a VkDisplayModeKHR. Other inputs wouldn't make sense.

3) Should additional display query functions be extended?

RESOLVED:

- vkGetDisplayPlaneSupportedDisplaysKHR: No. Extensions should instead extend vkGetDisplayPlaneCapabilitiesKHR().

Version History

- Revision 1, 2017-02-21 (James Jones)

  Initial draft.

VK_KHR_get_surface_capabilities2

Name String

VK_KHR_get_surface_capabilities2

Extension Type

Instance extension

Registered Extension Number

120

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_surface
Description

This extension provides new entry points to query device surface capabilities in a way that can be
easily extended by other extensions, without introducing any further entry points. This extension
can be considered the VK_KHR_surface equivalent of the VK_KHR_get_physical_device_properties2
extension.

New Object Types

None.

New Enum Constants

• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SURFACE_INFO_2_KHR
  ◦ VK_STRUCTURE_TYPE_SURFACE_CAPABILITIES_2_KHR
  ◦ VK_STRUCTURE_TYPE_SURFACE_FORMAT_2_KHR

New Enums

None.

New Structures

• VkPhysicalDeviceSurfaceInfo2KHR
• VkSurfaceCapabilities2KHR
• VkSurfaceFormat2KHR
New Functions

- vkGetPhysicalDeviceSurfaceCapabilities2KHR
- vkGetPhysicalDeviceSurfaceFormats2KHR

Issues

1) What should this extension be named?

**RESOLVED:** VK_KHR_get_surface_capabilities2. Other alternatives:

- VK_KHR_surface2
- One extension, combining a separate display-specific query extension.

2) Should additional WSI query functions be extended?

**RESOLVED:**

- vkGetPhysicalDeviceSurfaceCapabilitiesKHR: Yes. The need for this motivated the extension.
- vkGetPhysicalDeviceSurfaceSupportKHR: No. Currently only has boolean output. Extensions should instead extend vkGetPhysicalDeviceSurfaceCapabilities2KHR.
- vkGetPhysicalDeviceSurfaceFormatsKHR: Yes.
- vkGetPhysicalDeviceSurfacePresentModesKHR: No. Recent discussion concluded this introduced too much variability for applications to deal with. Extensions should instead extend vkGetPhysicalDeviceSurfaceCapabilities2KHR.
- vkGetPhysicalDeviceXlibPresentationSupportKHR: Not in this extension.
- vkGetPhysicalDeviceXcbPresentationSupportKHR: Not in this extension.
- vkGetPhysicalDeviceWaylandPresentationSupportKHR: Not in this extension.
- vkGetPhysicalDeviceWin32PresentationSupportKHR: Not in this extension.

Version History

- Revision 1, 2017-02-27 (James Jones)
  - Initial draft.

**VK_KHR_image_format_list**

Name String

VK_KHR_image_format_list

Extension Type

Device extension

Registered Extension Number

148
Revision
1

Extension and Version Dependencies
• Requires Vulkan 1.0

Deprecation state
• Promoted to Vulkan 1.2

Contact
• Jason Ekstrand @jekstrand

Other Extension Metadata

Last Modified Date
2017-03-20

Interactions and External Dependencies
• Promoted to Vulkan 1.2 Core

IP Status
No known IP claims.

Contributors
• Jason Ekstrand, Intel
• Jan-Harald Fredriksen, ARM
• Jeff Bolz, NVIDIA
• Jeff Leger, Qualcomm
• Neil Henning, Codeplay

Description
On some implementations, setting the `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT` on image creation can cause access to that image to perform worse than an equivalent image created without `VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT` because the implementation does not know what view formats will be paired with the image.

This extension allows an application to provide the list of all formats that can be used with an image when it is created. The implementation may then be able to create a more efficient image that supports the subset of formats required by the application without having to support all formats in the format compatibility class of the image format.

New Object Types
None.
New Enum Constants

- VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO_KHR

New Enums

None.

New Structs

- VkImageFormatListCreateInfoKHR

New Functions

None.

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

Version History

- Revision 1, 2017-03-20 (Jason Ekstrand)
  - Initial revision

VK_KHR_imageless_framebuffer

Name String

VK_KHR_imageless_framebuffer

Extension Type

Device extension

Registered Extension Number

109

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_maintenance2
- Requires VK_KHR_image_format_list
Deprecation state

• Promoted to Vulkan 1.2

Contact

• Tobias Hector ⟨tobias

Other Extension Metadata

Last Modified Date

2018-12-14

Interactions and External Dependencies

• Promoted to Vulkan 1.2 Core

Contributors

• Tobias Hector
• Graham Wihlidal

Description

This extension allows framebuffers to be created without the need for creating images first, allowing more flexibility in how they are used, and avoiding the need for many of the confusing compatibility rules.

Framebuffers are now created with a small amount of additional metadata about the image views that will be used in VkFramebufferAttachmentsCreateInfoKHR, and the actual image views are provided at render pass begin time via VkRenderPassAttachmentBeginInfoKHR.

New Enum Constants

• Extending VkStructureType:
  • VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGELESS_FRAMEBUFFER_FEATURES_KHR
  • VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENTS_CREATE_INFO_KHR
  • VK_STRUCTURE_TYPE_FRAMEBUFFER_ATTACHMENT_IMAGE_INFO_KHR
  • VK_STRUCTURE_TYPE_RENDER_PASS_ATTACHMENT_BEGIN_INFO_KHR

• Extending VkFramebufferCreateFlagBits:
  • VK_FRAMEBUFFER_CREATE_IMAGELESS_BIT_KHR

New Structures

• VkPhysicalDeviceImagelessFramebufferFeaturesKHR
• VkFramebufferAttachmentsCreateInfoKHR
• VkFramebufferAttachmentImageInfoKHR
• VkRenderPassAttachmentBeginInfoKHR
Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

• Revision 1, 2018-12-14 (Tobias Hector)
  ◦ Internal revisions

VK_KHR_incremental_present

Name String

VK_KHR_incremental_present

Extension Type

Device extension

Registered Extension Number

85

Revision

1

Extension and Version Dependencies

• Requires Vulkan 1.0
  • Requires VK_KHR_swapchain

Contact

• Ian Elliott @ianelliottus

Other Extension Metadata

Last Modified Date

2016-11-02

IP Status

No known IP claims.

Contributors

• Ian Elliott, Google
• Jesse Hall, Google
• Alon Or-bach, Samsung
• James Jones, NVIDIA
• Daniel Rakos, AMD
• Ray Smith, ARM
Description

This device extension extends `vkQueuePresentKHR`, from the `VK_KHR_swapchain` extension, allowing an application to specify a list of rectangular, modified regions of each image to present. This should be used in situations where an application is only changing a small portion of the presentable images within a swapchain, since it enables the presentation engine to avoid wasting time presenting parts of the surface that have not changed.

This extension is leveraged from the `EGL_KHR_swap_buffers_with_damage` extension.

New Object Types

None.

New Enum Constants

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_PRESENT_REGIONS_KHR`

New Enums

None.

New Structures

- `VkRectLayerKHR`
- `VkPresentRegionKHR`
- `VkPresentRegionsKHR`

New Functions

None.

Examples

None.

Issues

1) How should we handle steroescopic-3D swapchains? We need to add a layer for each rectangle. One approach is to create another struct containing the `VkRect2D` plus layer, and have `VkPresentRegionsKHR` point to an array of that struct. Another approach is to have two parallel arrays, `pRectangles` and `pLayers`, where `pRectangles[i]` and `pLayers[i]` must be used together. Which
approach should we use, and if the array of a new structure, what should that be called?

**RESOLVED:** Create a new structure, which is a `VkRect2D` plus a layer, and will be called `VkRectLayerKHR`.

2) Where is the origin of the `VkRectLayerKHR`?

**RESOLVED:** The upper left corner of the presentable image(s) of the swapchain, per the definition of framebuffer coordinates.

3) Does the rectangular region, `VkRectLayerKHR`, specify pixels of the swapchain's image(s), or of the surface?

**RESOLVED:** Of the image(s). Some presentation engines may scale the pixels of a swapchain's image(s) to the size of the surface. The size of the swapchain's image(s) will be consistent, where the size of the surface may vary over time.

4) What if all of the rectangles for a given swapchain contain a width and/or height of zero?

**RESOLVED:** The application is indicating that no pixels changed since the last present. The presentation engine may use such a hint and not update any pixels for the swapchain. However, all other semantics of `vkQueuePresentKHR` must still be honored, including waiting for semaphores to signal.

**Version History**

- Revision 1, 2016-11-02 (Ian Elliott)
  - Internal revisions

**VK_KHR_performance_query**

**Name String**

`VK_KHR_performance_query`

**Extension Type**

Device extension

**Registered Extension Number**

117

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires `VK_KHR_get_physical_device_properties2`

**Contact**

- Alon Or-bach [alonorbach](mailto:alonorbach)
The **VK_KHR_performance_query** extension adds a mechanism to allow querying of performance counters for use in applications and by profiling tools.

Each queue family may expose counters that can be enabled on a queue of that family. We extend **VkQueryType** to add a new query type for performance queries, and chain a structure on **VkQueryPoolCreateInfo** to specify the performance queries to enable.

**New Object Types**

None.

**New Enum Constants**

- Extending **VkStructureType**:
  - **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PERFORMANCE_QUERY_FEATURES_KHR**
  - **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PERFORMANCE_QUERY_PROPERTIES_KHR**
  - **VK_STRUCTURE_TYPE_PERFORMANCE_COUNTER_KHR**
• Extending VkQueryType:
  ◦ VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR

New Enums

• VkPerformanceCounterScopeKHR
• VkPerformanceCounterStorageKHR
• VkPerformanceCounterUnitKHR
• VkPerformanceCounterDescriptionFlagBitsKHR
• VkAcquireProfilingLockFlagBitsKHR

New Structures

• VkPhysicalDevicePerformanceQueryFeaturesKHR
• VkPhysicalDevicePerformanceQueryPropertiesKHR
• VkPerformanceCounterKHR
• VkPerformanceCounterDescriptionKHR
• VkPerformanceCounterDescriptionFlagsKHR
• VkQueryPoolPerformanceCreateInfoKHR
• VkPerformanceCounterResultKHR
• VkAcquireProfilingLockInfoKHR
• VkAcquireProfilingLockFlagsKHR
• VkPerformanceQuerySubmitInfoKHR

New Functions

• vkEnumeratePhysicalDeviceQueueFamilyPerformanceQueryCountersKHR
• vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR
• vkAcquireProfilingLockKHR
• vkReleaseProfilingLockKHR

Issues

1) Should this extension include a mechanism to begin a query in command buffer A and end the query in command buffer B?

RESOLVED No - queries are tied to command buffer creation and thus have to be encapsulated within a single command buffer.
2) Should this extension include a mechanism to begin and end queries globally on the queue, not using the existing command buffer commands?

RESOLVED No - for the same reasoning as the resolution of 1).

3) Should this extension expose counters that require multiple passes?

RESOLVED Yes - users should re-submit a command buffer with the same commands in it multiple times, specifying the pass to count as the query parameter in VkPerformanceQuerySubmitInfoKHR.

4) How to handle counters across parallel workloads?

RESOLVED In the spirit of Vulkan, a counter description flag VK_PERFORMANCE_COUNTER_DESCRIPTION_CONCURRENTLY_IMPACTED_KHR denotes that the accuracy of a counter result is affected by parallel workloads.

5) How to handle secondary command buffers?

RESOLVED Secondary command buffers inherit any counter pass index specified in the parent primary command buffer. Note: this is no longer an issue after change from issue 10 resolution.

6) What commands does the profiling lock have to be held for?

RESOLVED For any command buffer that is being queried with a performance query pool, the profiling lock must be held while that command buffer is in the recording, executable, or pending state.

7) Should we support vkCmdCopyQueryPoolResults?

RESOLVED Yes.

8) Should we allow performance queries to interact with multiview?

RESOLVED Yes, but the performance queries must be performed once for each pass per view.

9) Should a queryCount > 1 be usable for performance queries?

RESOLVED Yes. Some vendors will have costly performance counter query pool creation, and would rather if a certain set of counters were to be used multiple times that a queryCount > 1 can be used to amortize the instantiation cost.

10) Should we introduce an indirect mechanism to set the counter pass index?

RESOLVED Specify the counter pass index at submit time instead to avoid requiring re-recording of command buffers when multiple counter passes needed.

Examples

The following example shows how to find what performance counters a queue family supports, setup a query pool to record these performance counters, how to add the query pool to the command buffer to record information, and how to get the results from the query pool.
// A previously created physical device
VkPhysicalDevice physicalDevice;

// One of the queue families our device supports
uint32_t queueFamilyIndex;

uint32_t counterCount;

// Get the count of counters supported
vkEnumeratePhysicalDeviceQueueFamilyPerformanceQueryCountersKHR(
    physicalDevice,
    queueFamilyIndex,
    &counterCount,
    NULL,
    NULL);

VkPerformanceCounterKHR* counters =
    malloc(sizeof(VkPerformanceCounterKHR) * counterCount);
VkPerformanceCounterDescriptionKHR* counterDescriptions =
    malloc(sizeof(VkPerformanceCounterDescriptionKHR) * counterCount);

// Get the counters supported
vkEnumeratePhysicalDeviceQueueFamilyPerformanceQueryCountersKHR(
    physicalDevice,
    queueFamilyIndex,
    &counterCount,
    counters,
    counterDescriptions);

// Try to enable the first 8 counters
uint32_t enabledCounters[8];

const uint32_t enabledCounterCount = min(counterCount, 8));

for (uint32_t i = 0; i < enabledCounterCount; i++) {
    enabledCounters[i] = i;
}

// A previously created device that had the performanceCounterQueryPools feature
// set to VK_TRUE
VkDevice device;

VkQueryPoolPerformanceCreateInfoKHR performanceQueryCreateInfo = {
    VK_STRUCTURE_TYPE_QUERY_POOL_PERFORMANCE_CREATE_INFO_KHR,
    NULL,
    // Specify the queue family that this performance query is performed on
    queueFamilyIndex,
    // The number of counters to enable
    enabledCounterCount,
}
// The array of indices of counters to enable
enabledCounters
};

// Get the number of passes our counters will require.
uint32_t numPasses;

vkGetPhysicalDeviceQueueFamilyPerformanceQueryPassesKHR(
    physicalDevice,
    &performanceQueryCreateInfo,
    &numPasses);

VkQueryPoolCreateInfo queryPoolCreateInfo = {
    VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO,
    &performanceQueryCreateInfo,
    0,
    // Using our new query type here
    VK_QUERY_TYPE_PERFORMANCE_QUERY_KHR,
    1,
    0
};

VkQueryPool queryPool;

VkResult result = vkCreateQueryPool(
    device,
    &queryPoolCreateInfo,
    NULL,
    &queryPool);

assert(VK_SUCCESS == result);

// A queue from queueFamilyIndex
VkQueue queue;

// A command buffer we want to record counters on
VkCommandBuffer commandBuffer;

VkCommandBufferBeginInfo commandBufferBeginInfo = {
    VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO,
    NULL,
    0,
    NULL
};

VkAcquireProfilingLockInfoKHR lockInfo = {
VK_STRUCTURE_TYPE_ACQUIRE_PROFILING_LOCK_INFO_KHR,
    NULL,
    0,
    UINT64_MAX // Wait forever for the lock
};

// Acquire the profiling lock before we record command buffers
// that will use performance queries

result = vkAcquireProfilingLockKHR(device, &lockInfo);

assert(VK_SUCCESS == result);

result = vkBeginCommandBuffer(commandBuffer, &commandBufferBeginInfo);

assert(VK_SUCCESS == result);

vkCmdResetQueryPool(
    commandBuffer,
    queryPool,
    0,
    1);

vkCmdBeginQuery(
    commandBuffer,
    queryPool,
    0,
    0);

// Perform the commands you want to get performance information on
// ...

// Perform a barrier to ensure all previous commands were complete before
// ending the query
vkCmdPipelineBarrier(commandBuffer,
    VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT,
    VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT,
    0,
    0,
    NULL,
    0,
    NULL,
    0,
    NULL);

vkCmdEndQuery(
    commandBuffer,
    queryPool,
    0);

result = vkEndCommandBuffer(commandBuffer);
assert(VK_SUCCESS == result);

for (uint32_t counterPass = 0; counterPass < numPasses; counterPass++) {

VkPerformanceQuerySubmitInfoKHR performanceQuerySubmitInfo = {
    VK_STRUCTURE_TYPE_PERFORMANCE_QUERY_SUBMIT_INFO_KHR,
    NULL,
    counterPass
};

// Submit the command buffer and wait for its completion
// ...
}

// Release the profiling lock after the command buffer is no longer in the
// pending state.
vkReleaseProfilingLockKHR(device);

result = vkResetCommandBuffer(commandBuffer, 0);
assert(VK_SUCCESS == result);

// Create an array to hold the results of all counters
VkPerformanceCounterResultKHR* recordedCounters = malloc(
    sizeof(VkPerformanceCounterResultKHR) * enabledCounterCount);

result = vkGetQueryPoolResults(
    device,
    queryPool,
    0,
    1,
    sizeof(VkPerformanceCounterResultKHR) * enabledCounterCount,
    recordedCounters,
    sizeof(VkPerformanceCounterResultKHR),
    NULL);

// recordedCounters is filled with our counters, we'll look at one for posterity
switch (counters[0].storage) {
    case VK_PERFORMANCE_COUNTER_STORAGE_INT32:
        // use recordCounters[0].int32 to get at the counter result!
        break;
    case VK_PERFORMANCE_COUNTER_STORAGE_INT64:
        // use recordCounters[0].int64 to get at the counter result!
        break;
    case VK_PERFORMANCE_COUNTER_STORAGE_UINT32:
        // use recordCounters[0].uint32 to get at the counter result!
        break;
    case VK_PERFORMANCE_COUNTER_STORAGE_UINT64:
        // use recordCounters[0].uint64 to get at the counter result!
        break;
}
break;
case VK_PERFORMANCE_COUNTER_STORAGE_FLOAT32:
    // use recordCounters[0].float32 to get at the counter result!
    break;
case VK_PERFORMANCE_COUNTER_STORAGE_FLOAT64:
    // use recordCounters[0].float64 to get at the counter result!
    break;
}

Version History

• Revision 1, 2019-10-08

VK_KHR_pipeline_executable_properties

Name String
    VK_KHR_pipeline_executable_properties

Extension Type
    Device extension

Registered Extension Number
    270

Revision
    1

Extension and Version Dependencies
    • Requires Vulkan 1.0

Contact
    • Jason Ekstrand @jekstrand

Other Extension Metadata

Last Modified Date
    2019-05-28

IP Status
    No known IP claims.

Interactions and External Dependencies

Contributors
    • Jason Ekstrand, Intel
    • Ian Romanick, Intel
    • Kenneth Graunke, Intel
    • Baldur Karlsson, Valve
Description

When a pipeline is created, its state and shaders are compiled into zero or more device-specific executables, which are used when executing commands against that pipeline. This extension adds a mechanism to query properties and statistics about the different executables produced by the pipeline compilation process. This is intended to be used by debugging and performance tools to allow them to provide more detailed information to the user. Certain compile-time shader statistics provided through this extension may be useful to developers for debugging or performance analysis.

New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PIPELINE_EXECUTABLE_PROPERTIES_FEATURES_KHR
  - VK_STRUCTURE_TYPE_PIPELINE_INFO_KHR
  - VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_PROPERTIES_KHR
  - VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_INFO_KHR
  - VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_STATISTIC_KHR
  - VK_STRUCTURE_TYPE_PIPELINE_EXECUTABLE_INTERNAL_REPRESENTATION_KHR

- Extending VkPipelineCreateFlagBits:
  - VK_PIPELINE_CREATE_CAPTURE_STATISTICS_BIT_KHR
  - VK_PIPELINE_CREATE_CAPTURE_INTERNAL_REPRESENTATIONS_BIT_KHR

New Enums

- VkPipelineExecutableStatisticFormatKHR

New Structures

- VkPhysicalDevicePipelineExecutablePropertiesFeaturesKHR
- VkPipelineInfoKHR
- VkPipelineExecutablePropertiesKHR
- VkPipelineExecutableInfoKHR
• VkPipelineExecutableStatisticValueKHR
• VkPipelineExecutableStatisticKHR
• VkPipelineExecutableInternalRepresentationKHR

New Functions

• vkGetPipelineExecutablePropertiesKHR
• vkGetPipelineExecutableStatisticsKHR
• vkGetPipelineExecutableInternalRepresentationsKHR

Issues

1) What should we call the pieces of the pipeline which are produced by the compilation process and about which you can query properties and statistics?

RESOLVED: Call them "executables". The name "binary" was used in early drafts of the extension but it was determined that "pipeline binary" could have a fairly broad meaning (such as a binary serialized form of an entire pipeline) and was too big of a namespace for the very specific needs of this extension.

Version History

• Revision 1, 2019-05-28 (Jason Ekstrand)
  ◦ Initial draft

VK_KHR_push_descriptor

Name String
VK_KHR_push_descriptor

Extension Type
Device extension

Registered Extension Number
81

Revision
2

Extension and Version Dependencies
• Requires Vulkan 1.0
• Requires VK_KHR_get_physical_device_properties2

Contact
• Jeff Bolz ⌁jeffbolz
Other Extension Metadata

Last Modified Date
2017-09-12

IP Status
No known IP claims.

Contributors
• Jeff Bolz, NVIDIA
• Michael Worcester, Imagination Technologies

Description
This extension allows descriptors to be written into the command buffer, while the implementation is responsible for managing their memory. Push descriptors may enable easier porting from older APIs and in some cases can be more efficient than writing descriptors into descriptor sets.

New Object Types
None.

New Enum Constants
• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PUSH_DESCRIPTOR_PROPERTIES_KHR
• Extending VkDescriptorSetLayoutCreateFlagBits
  ◦ VK_DESCRIPTOR_SET_LAYOUT_CREATE_PUSH_DESCRIPTOR_BIT_KHR
• Extending VkDescriptorUpdateTemplateType
  ◦ VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_PUSH_DESCRIPTORS_KHR

New Enums
None.

New Structures
• VkPhysicalDevicePushDescriptorPropertiesKHR

New Functions
• vkCmdPushDescriptorSetKHR
• vkCmdPushDescriptorSetWithTemplateKHR
**Issues**
None.

**Examples**
None.

**Version History**
- Revision 1, 2016-10-15 (Jeff Bolz)
  - Internal revisions
- Revision 2, 2017-09-12 (Tobias Hector)
  - Added interactions with Vulkan 1.1

**VK_KHR_sampler_mirror_clamp_to_edge**

**Name String**
VK_KHR_sampler_mirror_clamp_to_edge

**Extension Type**
Device extension

**Registered Extension Number**
15

**Revision**
3

**Extension and Version Dependencies**
- Requires Vulkan 1.0

**Deprecation state**
- Promoted to Vulkan 1.2

**Contact**
- Tobias Hector @tobski

**Other Extension Metadata**

**Last Modified Date**
2019-08-17

**Interactions and External Dependencies**
- Promoted to Vulkan 1.2 Core

**Contributors**
Description

VK_KHR_sampler_mirror_clamp_to_edge extends the set of sampler address modes to include an additional mode (VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE) that effectively uses a texture map twice as large as the original image in which the additional half of the new image is a mirror image of the original image.

This new mode relaxes the need to generate images whose opposite edges match by using the original image to generate a matching “mirror image”. This mode allows the texture to be mirrored only once in the negative s, t, and r directions.

New Enum Constants

- Extending VkSamplerAddressMode:
  - VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2. However, if Vulkan 1.2 is supported and this extension is not, the VkSamplerAddressMode VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE is optional. Since the original extension did not use an author suffix on the enum VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE, it is used by both core and extension implementations.

Example

Creating a sampler with the new address mode in each dimension

```c
VkSamplerCreateInfo createInfo =
{
    VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO // sType
    // Other members set to application-desired values
};

createInfo.addressModeU = VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE;
createInfo.addressModeV = VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE;
createInfo.addressModeW = VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE;

VkSampler sampler;
VkResult result = vkCreateSampler(
    device,
    &createInfo,
    &sampler);
```
Issues

1) Why are both KHR and core versions of the `VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE` token present?

**RESOLVED:** This functionality was intended to be required in Vulkan 1.0. We realized shortly before public release that not all implementations could support it, and moved the functionality into an optional extension, but did not apply the KHR extension suffix. Adding a KHR-suffixed alias of the non-suffixed enum has been done to comply with our own naming rules.

In a related change, before spec revision 1.1.121 this extension was hardwiring into the spec Makefile so it was always included with the Specification, even in the core-only versions. This has now been reverted, and it is treated as any other extension.

Version History

- Revision 1, 2016-02-16 (Tobias Hector)
  - Initial draft
- Revision 2, 2019-08-14 (Jon Leech)
  - Add KHR-suffixed alias of non-suffixed enum.
- Revision 3, 2019-08-17 (Jon Leech)
  - Add an issue explaining the reason for the extension API not being suffixed with KHR.

**VK_KHR_separate_depth_stencil_layouts**

**Name String**

VK_KHR_separate_depth_stencil_layouts

**Extension Type**

Device extension

**Registered Extension Number**

242

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires `VK_KHR_get_physical_device_properties2`
- Requires `VK_KHR_create_renderpass2`

**Deprecation state**

- Promoted to Vulkan 1.2

**Contact**
Other Extension Metadata

Last Modified Date
2019-06-25

Interactions and External Dependencies
• Promoted to Vulkan 1.2 Core

Contributors
• Daniel Koch, NVIDIA
• Jeff Bolz, NVIDIA
• Jesse Barker, Unity
• Tobias Hector, AMD

Description
This extension allows image memory barriers for depth/stencil images to have just one of the
VK_IMAGE_ASPECT_DEPTH_BIT or VK_IMAGE_ASPECT_STENCIL_BIT aspect bits set, rather than require both.
This allows their layouts to be set independently. To support depth/stencil images with different
layouts for the depth and stencil aspects, the depth/stencil attachment interface has been updated
to support a separate layout for stencil.

New Object Types
None.

New Enum Constants

• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SEPARATE_DEPTH_STENCIL_LAYOUTS_FEATURES_KHR
  ◦ VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_STENCIL_LAYOUT_KHR
  ◦ VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_STENCIL_LAYOUT_KHR

• Extending VkImageLayout:
  ◦ VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_OPTIMAL_KHR
  ◦ VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL_KHR
  ◦ VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL_KHR
  ◦ VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL_KHR

New Enums
None.
New Structures

- Extending `VkPhysicalDeviceFeatures2`:
  - `VkPhysicalDeviceSeparateDepthStencilLayoutsFeaturesKHR`

- Extending `VkAttachmentReference2KHR`:
  - `VkAttachmentReferenceStencilLayoutKHR`

- Extending `VkAttachmentDescription2KHR`:
  - `VkAttachmentDescriptionStencilLayoutKHR`

New Functions

None.

New SPIR-V Capabilities

None.

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None.

Version History

- Revision 1, 2019-06-25 (Piers Daniell)
  - Internal revisions

VK_KHR_shader_atomic_int64

Name String

`VK_KHR_shader_atomic_int64`

Extension Type

Device extension

Registered Extension Number

181

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
Requires `VK_KHR_get_physical_device_properties2`

**Deprecation state**
- *Promoted* to Vulkan 1.2

**Contact**
- Aaron Hagan @ahagan

**Other Extension Metadata**

**Last Modified Date**
2018-07-05

**Interactions and External Dependencies**
- Promoted to Vulkan 1.2 Core

**Interactions and External Dependencies**
- This extension requires the `GL_ARB_gpu_shader_int64` and `GL_EXT_shader_atomic_int64` extensions for GLSL source languages.

**Contributors**
- Aaron Hagan, AMD
- Daniel Rakos, AMD
- Jeff Bolz, NVIDIA
- Neil Henning, Codeplay

**Description**

This extension advertises the SPIR-V **Int64Atomics** capability for Vulkan, which allows a shader to contain 64-bit atomic operations on signed and unsigned integers. The supported operations include OpAtomicMin, OpAtomicMax, OpAtomicAnd, OpAtomicOr, OpAtomicXor, OpAtomicAdd, OpAtomicExchange, and OpAtomicCompareExchange.

**New Enum Constants**
- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES_KHR`

**New SPIR-V Capabilities**
- Int64Atomics

**New Structures**
- `VkPhysicalDeviceShaderAtomicInt64FeaturesKHR`
Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

- Revision 1, 2018-07-05 (Aaron Hagan)
  - Internal revisions

VK_KHR_shader_clock

Name String

VK_KHR_shader_clock

Extension Type

Device extension

Registered Extension Number

182

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

Contact

- Aaron Hagan 🧮ahagan

Other Extension Metadata

Last Modified Date

2019-4-25

IP Status

No known IP claims.

Interactions and External Dependencies

- This extension requires SPV_KHR_shader_clock.
- This extension enables ARB_shader_clock for GLSL source languages.
- This extension enables EXT_shader_realtime_clock for GLSL source languages.

Contributors

- Aaron Hagan, AMD
- Daniel Koch, NVIDIA
Description

This extension advertises the SPIR-V ShaderClockKHR capability for Vulkan, which allows a shader to query a real-time or monotonically incrementing counter at the subgroup level or across the device level. The two valid SPIR-V scopes for OpReadClockKHR are Subgroup and Device.

When using GLSL source-based shading languages, the clockRealtime*EXT() timing functions map to the OpReadClockKHR instruction with a scope of Device, and the clock*ARB() timing functions map to the OpReadClockKHR instruction with a scope of Subgroup.

New Object Types

None.

New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_CLOCK_FEATURES_KHR

New SPIR-V Capabilities

- ShaderClockKHR

New Structures

- VkPhysicalDeviceShaderClockFeaturesKHR

Version History

- Revision 1, 2019-4-25 (Aaron Hagan)
  - Initial revision

VK_KHR_shader_float16_int8

Name String

VK_KHR_shader_float16_int8

Extension Type

Device extension

Registered Extension Number

83

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
• Requires `VK_KHR_get_physical_device_properties2`

**Deprecation state**

• *Promoted* to Vulkan 1.2

**Contact**

• Alexander Galazin [alegal-arm](mailto:alegal-arm)

**Other Extension Metadata**

**Last Modified Date**

2018-03-07

**Interactions and External Dependencies**

• Promoted to Vulkan 1.2 Core

**IP Status**

No known IP claims.

**Interactions and External Dependencies**

• This extension interacts with `VK_KHR_8bit_storage`

• This extension interacts with `VK_KHR_16bit_storage`

• This extension interacts with `VK_KHR_shader_float_controls`

**Contributors**

• Alexander Galazin, Arm

• Jan-Harald Fredriksen, Arm

• Jeff Bolz, NVIDIA

• Graeme Leese, Broadcom

• Daniel Rakos, AMD

**Description**

The `VK_KHR_shader_float16_int8` extension allows use of 16-bit floating-point types and 8-bit integer types in shaders for arithmetic operations.

It introduces two new optional features `shaderFloat16` and `shaderInt8` which directly map to the `Float16` and the `Int8` SPIR-V capabilities. The `VK_KHR_shader_float16_int8` extension also specifies precision requirements for half-precision floating-point SPIR-V operations. This extension does not enable use of 8-bit integer types or 16-bit floating-point types in any shader input and output interfaces and therefore does not supersede the `VK_KHR_8bit_storage` or `VK_KHR_16bit_storage` extensions.

**New Enum Constants**

• Extending `VkStructureType`:
New Structures

- VkPhysicalDeviceShaderFloat16Int8FeaturesKHR

New Functions

- None

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

- Revision 1, 2018-03-07 (Alexander Galazin)
  - Initial draft

VK_KHR_shader_float_controls

Name String

- VK_KHR_shader_float_controls

Extension Type

- Device extension

Registered Extension Number

- 198

Revision

- 4

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

Deprecation state

- Promoted to Vulkan 1.2

Contact

- Alexander Galazin @alegal-arm

Other Extension Metadata

Last Modified Date

- 2018-09-11
Interactions and External Dependencies

• Promoted to Vulkan 1.2 Core

IP Status

No known IP claims.

Interactions and External Dependencies

• This extension requires SPV_KHR_float_controls

Contributors

• Alexander Galazin, Arm
• Jan-Harald Fredriksen, Arm
• Jeff Bolz, NVIDIA
• Graeme Leese, Broadcom
• Daniel Rakos, AMD

Description

The VK_KHR_shader_float_controls extension enables efficient use of floating-point computations through the ability to query and override the implementation’s default behavior for rounding modes, denormals, signed zero, and infinity.

New Enum Constants

• Extending VkStructureType:
  • VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES_KHR

New Enums

• None

New Structures

• VkPhysicalDeviceFloatControlsPropertiesKHR

New Functions

• None

New SPIR-V Capabilities

• DenormPreserve
• DenormFlushToZero
• SignedZeroInfNaNPreserve
• RoundingModeRTE
• RoundingModeRTZ
Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

1) Which instructions must flush denorms?

**RESOLVED:** Only floating-point conversion, floating-point arithmetic, floating-point relational (except `OpIsNaN`, `OpIsInf`), and floating-point GLSL.std.450 extended instructions must flush denormals.

2) What is the denorm behavior for intermediate results?

**RESOLVED:** When a SPIR-V instruction is implemented as a sequence of other instructions: - in the `DenormFlushToZero` execution mode the intermediate instructions may flush denormals, the final result of the sequence **must** not be denormal. - in the `DenormPreserve` execution mode denormals must be preserved throughout the whole sequence.

3) Do denorm and rounding mode controls apply to `OpSpecConstantOp`?

**RESOLVED:** Yes, except when the opcode is `OpQuantizeToF16`.

4) The SPIR-V specification says that `OpConvertFToF16` and `OpConvertFToS` unconditionally round towards zero. Do the rounding mode controls specified through the execution modes apply to them?

**RESOLVED:** No, these instructions unconditionally round towards zero.

5) Do any of the "Pack" GLSL.std.450 instructions count as conversion instructions and have the rounding mode apply?

**RESOLVED:** No, only instructions listed in the section "3.32.11. Conversion Instructions" of the SPIR-V specification count as conversion instructions.

6) When using inf/nan-ignore mode, what is expected of `OpIsNan` and `OpIsInf`?

**RESOLVED:** These instructions must always accurately detect inf/nan if it is passed to them.

Version 4 API incompatibility

The original versions of `VK_KHR_shader_float_controls` shipped with booleans named “separateDenormSettings” and “separateRoundingModeSettings”, which at first glance could have indicated “they can all independently set, or not”. However the spec language as written indicated that the 32-bit value could always be set independently, and only the 16- and 64-bit controls needed to be the same if these values were `VK_FALSE`.

As a result of this slight disparity, and lack of test coverage for this facet of the extension, we ended up with two different behaviors in the wild, where some implementations worked as written, and others worked based on the naming. As these are hard limits in hardware with reasons for
exposure as written, it was not possible to standardise on a single way to make this work within the existing API.

No known users of this part of the extension exist in the wild, and as such the Vulkan WG took the unusual step of retroactively changing the once boolean value into a tri-state enum, breaking source compatibility. This was however done in such a way as to retain ABI compatibility, in case any code using this did exist; with the numerical values 0 and 1 retaining their original specified meaning, and a new value signifying the additional “all need to be set together” state. If any applications exist today, compiled binaries will continue to work as written in most cases, but will need changes before the code can be recompiled.

Version History

• Revision 4, 2019-06-18 (Tobias Hector)
  ◦ Modified settings restrictions, see Version 4 API incompatibility
• Revision 3, 2018-09-11 (Alexander Galazin)
  ◦ Minor restructuring
• Revision 2, 2018-04-17 (Alexander Galazin)
  ◦ Added issues and resolutions
• Revision 1, 2018-04-11 (Alexander Galazin)
  ◦ Initial draft

VK_KHR_shader_non_semantic_info

Name String

VK_KHR_shader_non_semantic_info

Extension Type

Device extension

Registered Extension Number

294

Revision

1

Extension and Version Dependencies

• Requires Vulkan 1.0

Contact

• Baldur Karlsson @baldurk

Other Extension Metadata

Last Modified Date

2019-10-16
IP Status
No known IP claims.

Interactions and External Dependencies
• This extension requires the SPV_KHR_non_semantic_info SPIR-V extension.

Contributors
• Baldur Karlsson, Valve

Description
This extension allows the use of the SPV_KHR_non_semantic_info extension in SPIR-V shader modules.

New Object Types
None.

New Enum Constants
None.

New SPIR-V Capabilities
None.

New Structures
None.

Version History
• Revision 1, 2019-10-16 (Baldur Karlsson)
  ◦ Initial revision

VK_KHR_shader_subgroup_extended_types

Name String
VK_KHR_shader_subgroup_extended_types

Extension Type
Device extension

Registered Extension Number
176

Revision
1
Extension and Version Dependencies
• Requires Vulkan 1.1

Deprecation state
• Promoted to Vulkan 1.2

Contact
• Neil Henning @sheredom

Other Extension Metadata

Last Modified Date
2019-01-08

IP Status
No known IP claims.

Interactions and External Dependencies
• Promoted to Vulkan 1.2 Core

Contributors
• Jeff Bolz, NVIDIA
• Jan-Harald Fredriksen, Arm
• Neil Henning, AMD
• Daniel Koch, NVIDIA
• Jeff Leger, Qualcomm
• Graeme Leese, Broadcom
• David Neto, Google
• Daniel Rakos, AMD

Description
This extension enables the Non Uniform Group Operations in SPIR-V to support 8-bit integer, 16-bit integer, 64-bit integer, 16-bit floating-point, and vectors of these types.

New Object Types
None.

New Enum Constants
• Extending VkStructureType:
  ○ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_SUBGROUP_EXTENDED_TYPES_FEATURES_KHR
New Enums
None.

New Structures
• VkPhysicalDeviceShaderSubgroupExtendedTypesFeaturesKHR

New Functions
None.

New Built-In Variables
None.

New SPIR-V Capabilities
None.

Promotion to Vulkan 1.2
All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues
None.

Version History
• Revision 1, 2019-01-08 (Neil Henning)
  ◦ Initial draft

VK_KHR_shared_presentable_image
Name String
  VK_KHR_shared_presentable_image

Extension Type
  Device extension

Registered Extension Number
  112

Revision
  1
Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_swapchain
- Requires VK_KHR_get_physical_device_properties2
- Requires VK_KHR_get_surface_capabilities2

Contact

- Alon Or-bach @alonorbach

Other Extension Metadata

Last Modified Date
2017-03-20

IP Status
No known IP claims.

Contributors

- Alon Or-bach, Samsung Electronics
- Ian Elliott, Google
- Jesse Hall, Google
- Pablo Ceballos, Google
- Chris Forbes, Google
- Jeff Juliano, NVIDIA
- James Jones, NVIDIA
- Daniel Rakos, AMD
- Tobias Hector, Imagination Technologies
- Graham Connor, Imagination Technologies
- Michael Worcester, Imagination Technologies
- Cass Everitt, Oculus
- Johannes Van Waveren, Oculus

Description

This extension extends VK_KHR_swapchain to enable creation of a shared presentable image. This allows the application to use the image while the presentation engine is accessing it, in order to reduce the latency between rendering and presentation.

New Object Types

None.
New Enum Constants

- Extending `VkPresentModeKHR`:
  - `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR`
  - `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`
- Extending `VkImageLayout`:
  - `VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR`
- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_SHARED_PRESENT_SURFACE_CAPABILITIES_KHR`

New Enums

None.

New Structures

- `VkSharedPresentSurfaceCapabilitiesKHR`

New Functions

- `vkGetSwapchainStatusKHR`

Issues

1) Should we allow a Vulkan WSI swapchain to toggle between normal usage and shared presentation usage?

**RESOLVED**: No. WSI swapchains are typically recreated with new properties instead of having their properties changed. This can also save resources, assuming that fewer images are needed for shared presentation, and assuming that most VR applications do not need to switch between normal and shared usage.

2) Should we have a query for determining how the presentation engine refresh is triggered?

**RESOLVED**: Yes. This is done via which presentation modes a surface supports.

3) Should the object representing a shared presentable image be an extension of a `VkSwapchainKHR` or a separate object?

**RESOLVED**: Extension of a swapchain due to overlap in creation properties and to allow common functionality between shared and normal presentable images and swapchains.

4) What should we call the extension and the new structures it creates?

**RESOLVED**: Shared presentable image / shared present.

5) Should the `minImageCount` and `presentMode` values of the `VkSwapchainCreateInfoKHR` be ignored, or required to be compatible values?
**RESOLVED:** minImageCount must be set to 1, and presentMode should be set to either VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR or VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR.

6) What should the layout of the shared presentable image be?

**RESOLVED:** After acquiring the shared presentable image, the application must transition it to the VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR layout prior to it being used. After this initial transition, any image usage that was requested during swapchain creation can be performed on the image without layout transitions being performed.

7) Do we need a new API for the trigger to refresh new content?

**RESOLVED:** vkQueuePresentKHR to act as API to trigger a refresh, as will allow combination with other compatible extensions to vkQueuePresentKHR.

8) How should an application detect a VK_ERROR_OUT_OF_DATE_KHR error on a swapchain using the VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR present mode?

**RESOLVED:** Introduce vkGetSwapchainStatusKHR to allow applications to query the status of a swapchain using a shared presentation mode.

9) What should subsequent calls to vkQueuePresentKHR for VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR swapchains be defined to do?

**RESOLVED:** State that implementations may use it as a hint for updated content.

10) Can the ownership of a shared presentable image be transferred to a different queue?

**RESOLVED:** No. It is not possible to transfer ownership of a shared presentable image obtained from a swapchain created using VK_SHARING_MODE_EXCLUSIVE after it has been presented.

11) How should vkQueueSubmit behave if a command buffer uses an image from a VK_ERROR_OUT_OF_DATE_KHR swapchain?

**RESOLVED:** vkQueueSubmit is expected to return the VK_ERROR_DEVICE_LOST error.

12) Can Vulkan provide any guarantee on the order of rendering, to enable beam chasing?

**RESOLVED:** This could be achieved via use of render passes to ensure strip rendering.

**Version History**

- Revision 1, 2017-03-20 (Alon Or-bach)
  - Internal revisions

**VK_KHR_spirv_1_4**

**Name String**

- VK_KHR_spirv_1_4

**Extension Type**
Device extension

Registered Extension Number
237

Revision
1

Extension and Version Dependencies
- Requires Vulkan 1.1
- Requires VK_KHR_shader_float_controls

Deprecation state
- Promoted to Vulkan 1.2

Contact
- Jesse Hall @critsec

Other Extension Metadata

Last Modified Date
2019-04-01

IP Status
No known IP claims.

Interactions and External Dependencies
- Requires SPIR-V 1.4.
- Promoted to Vulkan 1.2 Core

Contributors
- Alexander Galazin, Arm
- David Neto, Google
- Jesse Hall, Google
- John Kessenich, Google
- Neil Henning, AMD
- Tom Olson, Arm

Description
This extension allows the use of SPIR-V 1.4 shader modules. SPIR-V 1.4’s new features primarily make it an easier target for compilers from high-level languages, rather than exposing new hardware functionality.

SPIR-V 1.4 incorporates features that are also available separately as extensions. SPIR-V 1.4 shader modules do not need to enable those extensions with the OpExtension opcode, since they are integral
SPIR-V 1.4 introduces new floating point execution mode capabilities, also available via SPV_KHR_float_controls. Implementations are not required to support all of these new capabilities; support can be queried using VkPhysicalDeviceFloatControlsPropertiesKHR from the VK_KHR_shader_float_controls extension.

**New Object Types**

None.

**New Enum Constants**

None.

**New Enums**

None.

**New Structures**

None.

**New Functions**

None.

**Promotion to Vulkan 1.2**

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

**Issues**

1. Should we have an extension specific to this SPIR-V version, or add a version-generic query for SPIR-V version? SPIR-V 1.4 doesn't need any other API changes.

RESOLVED: Just expose SPIR-V 1.4.

Most new SPIR-V versions introduce optionally-required capabilities or have implementation-defined limits, and would need more API and specification changes specific to that version to make them available in Vulkan. For example, to support the subgroup capabilities added in SPIR-V 1.3 required introducing VkPhysicalDeviceSubgroupProperties to allow querying the supported group operation categories, maximum supported subgroup size, etc. While we could expose the parts of a new SPIR-V version that don’t need accompanying changes generically, we’ll still end up writing extensions specific to each version for the remaining parts. Thus the generic mechanism won’t reduce future spec-writing effort. In addition, making it clear which parts of a future version are supported by the generic mechanism and which can’t be used without specific support would be difficult to get right ahead of time.
2. Can different stages of the same pipeline use shaders with different SPIR-V versions?

RESOLVED: Yes.

Mixing SPIR-V versions 1.0-1.3 in the same pipeline has not been disallowed, so it would be inconsistent to disallow mixing 1.4 with previous versions. SPIR-V 1.4 does not introduce anything that should cause new difficulties here.

3. Must Vulkan extensions corresponding to SPIR-V extensions that were promoted to core in 1.4 be enabled in order to use that functionality in a SPIR-V 1.4 module?

RESOLVED: No, with caveats.

The SPIR-V 1.4 module does not need to declare the SPIR-V extensions, since the functionality is now part of core, so there is no need to enable the Vulkan extension that allows SPIR-V modules to declare the SPIR-V extension. However, when the functionality that is now core in SPIR-V 1.4 is optionally supported, the query for support is provided by a Vulkan extension, and that query can only be used if the extension is enabled.

This applies to any SPIR-V version; specifically for SPIR-V 1.4 this only applies to the functionality from SPV_KHR_float_controls, which was made available in Vulkan by VK_KHR_shader_float_controls. Even though the extension was promoted in SPIR-V 1.4, the capabilities are still optional in implementations that support VK_KHR_spirv_1_4.

A SPIR-V 1.4 module doesn’t need to enable SPV_KHR_float_controls in order to use the capabilities, so if the application has a priori knowledge that the implementation supports the capabilities, it doesn’t need to enable VK_KHR_shader_float_controls. However, if it doesn’t have this knowledge and has to query for support at runtime, it must enable VK_KHR_shader_float_controls in order to use VkPhysicalDeviceFloatControlsPropertiesKHR.

Version History

- Revision 1, 2019-04-01 (Jesse Hall)
  - Internal draft versions

VK_KHR_surface

Name String

VK_KHR_surface

Extension Type

Instance extension

Registered Extension Number

1

Revision

25
Extension and Version Dependencies

- Requires Vulkan 1.0

Contact

- James Jones @cubanismo
- Ian Elliott @ianelliottus

Other Extension Metadata

Last Modified Date

2016-08-25

IP Status

No known IP claims.

Contributors

- Patrick Doane, Blizzard
- Ian Elliott, LunarG
- Jesse Hall, Google
- James Jones, NVIDIA
- David Mao, AMD
- Norbert Nopper, Freescale
- Alon Or-bach, Samsung
- Daniel Rakos, AMD
- Graham Sellers, AMD
- Jeff Vigil, Qualcomm
- Chia-I Wu, LunarG
- Jason Ekstrand, Intel

Description

The VK_KHR_surface extension is an instance extension. It introduces VkSurfaceKHR objects, which abstract native platform surface or window objects for use with Vulkan. It also provides a way to determine whether a queue family in a physical device supports presenting to particular surface.

Separate extensions for each platform provide the mechanisms for creating VkSurfaceKHR objects, but once created they may be used in this and other platform-independent extensions, in particular the VK_KHR_swapchain extension.

New Object Types

- VkSurfaceKHR
New Enum Constants

- Extending VkResult:
  - VK_ERROR_SURFACE_LOST_KHR
  - VK_ERROR_NATIVE_WINDOW_IN_USE_KHR

New Enums

- VkSurfaceTransformFlagBitsKHR
- VkPresentModeKHR
- VkColorSpaceKHR
- VkCompositeAlphaFlagBitsKHR

New Structures

- VkSurfaceCapabilitiesKHR
- VkSurfaceFormatKHR

New Functions

- vkDestroySurfaceKHR
- vkGetPhysicalDeviceSurfaceSupportKHR
- vkGetPhysicalDeviceSurfaceCapabilitiesKHR
- vkGetPhysicalDeviceSurfaceFormatsKHR
- vkGetPhysicalDeviceSurfacePresentModesKHR

Examples

```
Note
The example code for the VK_KHR_surface and VK_KHR_swapchain extensions was removed from the appendix after revision 1.0.29. This WSI example code was ported to the cube demo that is shipped with the official Khronos SDK, and is being kept up-to-date in that location (see: https://github.com/KhronosGroup/Vulkan-Tools/blob/master/cube/cube.c).
```

Issues

1) Should this extension include a method to query whether a physical device supports presenting to a specific window or native surface on a given platform?

RESOLVED: Yes. Without this, applications would need to create a device instance to determine whether a particular window can be presented to. Knowing that a device supports presentation to a platform in general is not sufficient, as a single machine might support multiple seats, or instances of the platform that each use different underlying physical devices. Additionally, on some platforms, such as the X Window System, different drivers and devices might be used for different
windows depending on which section of the desktop they exist on.

2) Should the `vkGetPhysicalDeviceSurfaceCapabilitiesKHR`, `vkGetPhysicalDeviceSurfaceFormatsKHR`, and `vkGetPhysicalDeviceSurfacePresentModesKHR` functions be in this extension and operate on physical devices, rather than being in `VK_KHR_swapchain` (i.e. device extension) and being dependent on `VkDevice`?

**RESOLVED**: Yes. While it might be useful to depend on `VkDevice` (and therefore on enabled extensions and features) for the queries, Vulkan was released only with the `VkPhysicalDevice` versions. Many cases can be resolved by a Valid Usage. And/or by a separate `pNext` chain version of the query struct specific to a given extension or parameters, via extensible versions of the queries: `vkGetPhysicalDeviceSurfaceCapabilities2KHR`, `vkGetPhysicalDeviceSurfaceFormats2KHR`, and `vkGetPhysicalDeviceSurfacePresentModes2EXT`.

3) Should Vulkan include support Xlib or XCB as the API for accessing the X Window System platform?

**RESOLVED**: Both. XCB is a more modern and efficient API, but Xlib usage is deeply ingrained in many applications and likely will remain in use for the foreseeable future. Not all drivers necessarily need to support both, but including both as options in the core specification will probably encourage support, which should in turn ease adoption of the Vulkan API in older codebases. Additionally, the performance improvements possible with XCB likely will not have a measurable impact on the performance of Vulkan presentation and other minimal window system interactions defined here.

4) Should the GBM platform be included in the list of platform enums?

**RESOLVED**: Deferred, and will be addressed with a platform-specific extension to be written in the future.

**Version History**

- **Revision 1, 2015-05-20** (James Jones)
  - Initial draft, based on LunarG KHR spec, other KHR specs, patches attached to bugs.
- **Revision 2, 2015-05-22** (Ian Elliott)
  - Created initial Description section.
  - Removed query for whether a platform requires the use of a queue for presentation, since it was decided that presentation will always be modeled as being part of the queue.
  - Fixed typos and other minor mistakes.
- **Revision 3, 2015-05-26** (Ian Elliott)
  - Improved the Description section.
- **Revision 4, 2015-05-27** (James Jones)
  - Fixed compilation errors in example code.
- **Revision 5, 2015-06-01** (James Jones)
  - Added issues 1 and 2 and made related spec updates.
• Revision 6, 2015-06-01 (James Jones)
  ◦ Merged the platform type mappings table previously removed from VK_KHR_swapchain with the platform description table in this spec.
  ◦ Added issues 3 and 4 documenting choices made when building the initial list of native platforms supported.

• Revision 7, 2015-06-11 (Ian Elliott)
  ◦ Updated table 1 per input from the KHR TSG.
  ◦ Updated issue 4 (GBM) per discussion with Daniel Stone. He will create a platform-specific extension sometime in the future.

• Revision 8, 2015-06-17 (James Jones)
  ◦ Updated enum-extending values using new convention.
  ◦ Fixed the value of VK_SURFACE_PLATFORM_INFO_TYPE_SUPPORTED_KHR.

• Revision 9, 2015-06-17 (James Jones)
  ◦ Rebased on Vulkan API version 126.

• Revision 10, 2015-06-18 (James Jones)
  ◦ Marked issues 2 and 3 resolved.

• Revision 11, 2015-06-23 (Ian Elliott)
  ◦ Examples now show use of function pointers for extension functions.
  ◦ Eliminated extraneous whitespace.

• Revision 12, 2015-07-07 (Daniel Rakos)
  ◦ Added error section describing when each error is expected to be reported.
  ◦ Replaced the term “queue node index” with “queue family index” in the spec as that is the agreed term to be used in the latest version of the core header and spec.
  ◦ Replaced bool32_t with VkBool32.

• Revision 13, 2015-08-06 (Daniel Rakos)
  ◦ Updated spec against latest core API header version.

• Revision 14, 2015-08-20 (Ian Elliott)
  ◦ Renamed this extension and all of its enumerations, types, functions, etc. This makes it compliant with the proposed standard for Vulkan extensions.
  ◦ Switched from “revision” to “version”, including use of the VK_MAKE_VERSION macro in the header file.
  ◦ Did miscellaneous cleanup, etc.

• Revision 15, 2015-08-20 (Ian Elliott—porting a 2015-07-29 change from James Jones)
  ◦ Moved the surface transform enums here from VK_WSI_swapchain so they could be re-used by VK_WSI_display.

• Revision 16, 2015-09-01 (James Jones)
  ◦ Restore single-field revision number.
• Revision 17, 2015-09-01 (James Jones)
  ◦ Fix example code compilation errors.

• Revision 18, 2015-09-26 (Jesse Hall)
  ◦ Replaced VkSurfaceDescriptionKHR with the VkSurfaceKHR object, which is created via layered extensions. Added VkDestroySurfaceKHR.

• Revision 19, 2015-09-28 (Jesse Hall)
  ◦ Renamed from VK_EXT_KHR_swapchain to VK_EXT_KHR_surface.

• Revision 20, 2015-09-30 (Jeff Vigil)
  ◦ Add error result VK_ERROR_SURFACE_LOST_KHR.

• Revision 21, 2015-10-15 (Daniel Rakos)
  ◦ Updated the resolution of issue #2 and include the surface capability queries in this extension.
  ◦ Renamed SurfaceProperties to SurfaceCapabilities as it better reflects that the values returned are the capabilities of the surface on a particular device.
  ◦ Other minor cleanup and consistency changes.

• Revision 22, 2015-10-26 (Ian Elliott)
  ◦ Renamed from VK_EXT_KHR_surface to VK_KHR_surface.

• Revision 23, 2015-11-03 (Daniel Rakos)
  ◦ Added allocation callbacks to vkDestroySurfaceKHR.

• Revision 24, 2015-11-10 (Jesse Hall)
  ◦ Removed VkSurfaceTransformKHR. Use VkSurfaceTransformFlagBitsKHR instead.
  ◦ Rename VkSurfaceCapabilitiesKHR member maxImageArraySize to maxImageArrayLayers.

• Revision 25, 2016-01-14 (James Jones)
  ◦ Moved VK_ERROR_NATIVE_WINDOW_IN_USE_KHR from the VK_KHR_android_surface to the VK_KHR_surface extension.

• 2016-08-23 (Ian Elliott)
  ◦ Update the example code, to not have so many characters per line, and to split out a new example to show how to obtain function pointers.

• 2016-08-25 (Ian Elliott)
  ◦ A note was added at the beginning of the example code, stating that it will be removed from future versions of the appendix.

**VK_KHR_surface_protected_capabilities**

**Name String**

```
VK_KHR_surface_protected_capabilities
```

**Extension Type**

Instance extension
Description

This extension extends `VkSurfaceCapabilities2KHR`, providing applications a way to query whether swapchains can be created with the `VK_SWAPCHAIN_CREATE_PROTECTED_BIT_KHR` flag set.

Vulkan 1.1 added (optional) support for protect memory and protected resources including buffers (`VK_BUFFER_CREATE_PROTECTED_BIT`), images (`VK_IMAGE_CREATE_PROTECTED_BIT`), and swapchains (`VK_SWAPCHAIN_CREATE_PROTECTED_BIT_KHR`). However, on implementations which support multiple windowing systems, not all window systems may be able to provide a protected display path.

This extension provides a way to query if a protected swapchain created for a surface (and thus a specific windowing system) can be displayed on screen. It extends the existing `VkSurfaceCapabilities2KHR` structure with a new `VkSurfaceProtectedCapabilitiesKHR` structure from which the application can obtain information about support for protected swapchain creation through `vkGetPhysicalDeviceSurfaceCapabilities2KHR`.

New Object Types

None.
New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_SURFACE_PROTECTED_CAPABILITIES_KHR

New Enums

None.

New Structures

- VkSurfaceProtectedCapabilitiesKHR

New Functions

None.

Issues

None.

Version History

- Revision 1, 2018-12-18 (Sandeep Shinde, Daniel Koch)
  - Internal revisions.

VK_KHR_swapchain

Name String

VK_KHR_swapchain

Extension Type

Device extension

Registered Extension Number

2

Revision

70

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_surface

Contact

- James Jones @cubanismo
- Ian Elliott @ianelliottus
Other Extension Metadata

Last Modified Date
2017-10-06

IP Status
No known IP claims.

Interactions and External Dependencies
• Interacts with Vulkan 1.1

Contributors
• Patrick Doane, Blizzard
• Ian Elliott, LunarG
• Jesse Hall, Google
• Mathias Heyer, NVIDIA
• James Jones, NVIDIA
• David Mao, AMD
• Norbert Nopper, Freescale
• Alon Or-bach, Samsung
• Daniel Rakos, AMD
• Graham Sellers, AMD
• Jeff Vigil, Qualcomm
• Chia-I Wu, LunarG
• Jason Ekstrand, Intel
• Matthaeus G. Chajdas, AMD
• Ray Smith, ARM

Description
The VK_KHR_swapchain extension is the device-level companion to the VK_KHR_surface extension. It introduces VkSwapchainKHR objects, which provide the ability to present rendering results to a surface.

New Object Types
• VkSwapchainKHR

New Enum Constants
• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO_KHR
Extending `VkImageLayout`:
- `VK_IMAGE_LAYOUT_PRESENT_SRC_KHR`

Extending `VkResult`:
- `VK_SUBOPTIMAL_KHR`
- `VK_ERROR_OUT_OF_DATE_KHR`

**New Enums**
- `VkDeviceGroupPresentModeFlagBitsKHR`
- `VkSwapchainCreateFlagBitsKHR`

**New Structures**
- `VkSwapchainCreateInfoKHR`
- `VkPresentInfoKHR`
- `VkDeviceGroupPresentCapabilitiesKHR`
- `VkImageSwapchainCreateInfoKHR`
- `VkBindImageMemorySwapchainInfoKHR`
- `VkAcquireNextImageInfoKHR`
- `VkDeviceGroupPresentInfoKHR`
- `VkDeviceGroupSwapchainCreateInfoKHR`

**New Functions**
- `vkCreateSwapchainKHR`
- `vkDestroySwapchainKHR`
- `vkGetSwapchainImagesKHR`
- `vkAcquireNextImageKHR`
- `vkQueuePresentKHR`
- `vkGetDeviceGroupPresentCapabilitiesKHR`
- `vkGetDeviceGroupSurfacePresentModesKHR`
- `vkGetPhysicalDevicePresentRectanglesKHR`
- `vkAcquireNextImage2KHR`
Issues

1) Does this extension allow the application to specify the memory backing of the presentable images?

**RESOLVED:** No. Unlike standard images, the implementation will allocate the memory backing of the presentable image.

2) What operations are allowed on presentable images?

**RESOLVED:** This is determined by the image usage flags specified when creating the presentable image's swapchain.

3) Does this extension support MSAA presentable images?

**RESOLVED:** No. Presentable images are always single-sampled. Multi-sampled rendering must use regular images. To present the rendering results the application must manually resolve the multi-sampled image to a single-sampled presentable image prior to presentation.

4) Does this extension support stereo/multi-view presentable images?

**RESOLVED:** Yes. The number of views associated with a presentable image is determined by the `imageArrayLayers` specified when creating a swapchain. All presentable images in a given swapchain use the same array size.

5) Are the layers of stereo presentable images half-sized?

**RESOLVED:** No. The image extents always match those requested by the application.

6) Do the “present” and “acquire next image” commands operate on a queue? If not, do they need to include explicit semaphore objects to interlock them with queue operations?

**RESOLVED:** The present command operates on a queue. The image ownership operation it represents happens in order with other operations on the queue, so no explicit semaphore object is required to synchronize its actions.

Applications may want to acquire the next image in separate threads from those in which they manage their queue, or in multiple threads. To make such usage easier, the acquire next image command takes a semaphore to signal as a method of explicit synchronization. The application must later queue a wait for this semaphore before queuing execution of any commands using the image.

7) Does `vkAcquireNextImageKHR` block if no images are available?

**RESOLVED:** The command takes a timeout parameter. Special values for the timeout are 0, which makes the call a non-blocking operation, and `UINT64_MAX`, which blocks indefinitely. Values in between will block for up to the specified time. The call will return when an image becomes available or an error occurs. It may, but is not required to, return before the specified timeout expires if the swapchain becomes out of date.

8) Can multiple presents be queued using one `vkQueuePresentKHR` call?

1356 | Appendix E: Layers & Extensions (Informative)
**RESOLVED:** Yes. `VkPresentInfoKHR` contains a list of swapchains and corresponding image indices that will be presented. When supported, all presentations queued with a single `vkQueuePresentKHR` call will be applied atomically as one operation. The same swapchain must not appear in the list more than once. Later extensions may provide applications stronger guarantees of atomicity for such present operations, and/or allow them to query whether atomic presentation of a particular group of swapchains is possible.

9) How do the presentation and acquire next image functions notify the application the targeted surface has changed?

**RESOLVED:** Two new result codes are introduced for this purpose:

- **VK_SUBOPTIMAL_KHR** - Presentation will still succeed, subject to the window resize behavior, but the swapchain is no longer configured optimally for the surface it targets. Applications should query updated surface information and recreate their swapchain at the next convenient opportunity.

- **VK_ERROR_OUT_OF_DATE_KHR** - Failure. The swapchain is no longer compatible with the surface it targets. The application must query updated surface information and recreate the swapchain before presentation will succeed.

These can be returned by both `vkAcquireNextImageKHR` and `vkQueuePresentKHR`.

10) Does the `vkAcquireNextImageKHR` command return a semaphore to the application via an output parameter, or accept a semaphore to signal from the application as an object handle parameter?

**RESOLVED:** Accept a semaphore to signal as an object handle. This avoids the need to specify whether the application must destroy the semaphore or whether it is owned by the swapchain, and if the latter, what its lifetime is and whether it can be re-used for other operations once it is received from `vkAcquireNextImageKHR`.

11) What types of swapchain queuing behavior should be exposed? Options include swap interval specification, mailbox/most recent vs. FIFO queue management, targeting specific vertical blank intervals or absolute times for a given present operation, and probably others. For some of these, whether they are specified at swapchain creation time or as per-present parameters needs to be decided as well.

**RESOLVED:** The base swapchain extension will expose 3 possible behaviors (of which, FIFO will always be supported):

- **Immediate present:** Does not wait for vertical blanking period to update the current image, likely resulting in visible tearing. No internal queue is used. Present requests are applied immediately.

- **Mailbox queue:** Waits for the next vertical blanking period to update the current image. No tearing should be observed. An internal single-entry queue is used to hold pending presentation requests. If the queue is full when a new presentation request is received, the new request replaces the existing entry, and any images associated with the prior entry become available for re-use by the application.

- **FIFO queue:** Waits for the next vertical blanking period to update the current image. No tearing
should be observed. An internal queue containing $\text{numSwapchainImages} - 1$ entries is used to hold pending presentation requests. New requests are appended to the end of the queue, and one request is removed from the beginning of the queue and processed during each vertical blanking period in which the queue is non-empty.

Not all surfaces will support all of these modes, so the modes supported will be returned using a surface info query. All surfaces must support the FIFO queue mode. Applications must choose one of these modes up front when creating a swapchain. Switching modes can be accomplished by recreating the swapchain.

12) Can $\text{VK_PRESENT_MODE_MAILBOX_KHR}$ provide non-blocking guarantees for $\text{vkAcquireNextImageKHR}$? If so, what is the proper criteria?

**RESOLVED:** Yes. The difficulty is not immediately obvious here. Naively, if at least 3 images are requested, mailbox mode should always have an image available for the application if the application does not own any images when the call to $\text{vkAcquireNextImageKHR}$ was made. However, some presentation engines may have more than one “current” image, and would still need to block in some cases. The right requirement appears to be that if the application allocates the surface’s minimum number of images + 1 then it is guaranteed non-blocking behavior when it does not currently own any images.

13) Is there a way to create and initialize a new swapchain for a surface that has generated a $\text{VK_SUBOPTIMAL_KHR}$ return code while still using the old swapchain?

**RESOLVED:** Not as part of this specification. This could be useful to allow the application to create an “optimal” replacement swapchain and rebuild all its command buffers using it in a background thread at a low priority while continuing to use the “suboptimal” swapchain in the main thread. It could probably use the same “atomic replace” semantics proposed for recreating direct-to-device swapchains without incurring a mode switch. However, after discussion, it was determined some platforms probably could not support concurrent swapchains for the same surface though, so this will be left out of the base KHR extensions. A future extension could add this for platforms where it is supported.

14) Should there be a special value for $\text{VkSurfaceCapabilitiesKHR::maxImageCount}$ to indicate there are no practical limits on the number of images in a swapchain?

**RESOLVED:** Yes. There where often be cases where there is no practical limit to the number of images in a swapchain other than the amount of available resources (i.e., memory) in the system. Trying to derive a hard limit from things like memory size is prone to failure. It is better in such cases to leave it to applications to figure such soft limits out via trial/failure iterations.

15) Should there be a special value for $\text{VkSurfaceCapabilitiesKHR::currentExtent}$ to indicate the size of the platform surface is undefined?

**RESOLVED:** Yes. On some platforms (Wayland, for example), the surface size is defined by the images presented to it rather than the other way around.

16) Should there be a special value for $\text{VkSurfaceCapabilitiesKHR::maxImageExtent}$ to indicate there is no practical limit on the surface size?

1358 | Appendix E: Layers & Extensions (Informative)
**RESOLVED:** No. It seems unlikely such a system would exist. 0 could be used to indicate the platform places no limits on the extents beyond those imposed by Vulkan for normal images, but this query could just as easily return those same limits, so a special “unlimited” value does not seem useful for this field.

17) How should surface rotation and mirroring be exposed to applications? How do they specify rotation and mirroring transforms applied prior to presentation?

**RESOLVED:** Applications can query both the supported and current transforms of a surface. Both are specified relative to the device’s “natural” display rotation and direction. The supported transforms indicates which orientations the presentation engine accepts images in. For example, a presentation engine that does not support transforming surfaces as part of presentation, and which is presenting to a surface that is displayed with a 90-degree rotation, would return only one supported transform bit: `VK_SURFACE_TRANSFORM_ROTATE_90_BIT_KHR`. Applications must transform their rendering by the transform they specify when creating the swapchain in `preTransform` field.

18) Can surfaces ever not support `VK_MIRROR_NONE`? Can they support vertical and horizontal mirroring simultaneously? Relatedly, should `VK_MIRROR_NONE`[_BIT] be zero, or bit one, and should applications be allowed to specify multiple pre and current mirror transform bits, or exactly one?

**RESOLVED:** Since some platforms may not support presenting with a transform other than the native window’s current transform, and prerotation/mirroring are specified relative to the device’s natural rotation and direction, rather than relative to the surface’s current rotation and direction, it is necessary to express lack of support for no mirroring. To allow this, the `MIRROR_NONE` enum must occupy a bit in the flags. Since `MIRROR_NONE` must be a bit in the bitmask rather than a bitmask with no values set, allowing more than one bit to be set in the bitmask would make it possible to describe undefined transforms such as `VK_MIRROR_NONE_BIT | VK_MIRROR_HORIZONTAL_BIT`, or a transform that includes both “no mirroring” and “horizontal mirroring” simultaneously. Therefore, it is desirable to allow specifying all supported mirroring transforms using only one bit. The question then becomes, should there be a `VK_MIRROR_HORIZONTAL_AND_VERTICAL_BIT` to represent a simultaneous horizontal and vertical mirror transform? However, such a transform is equivalent to a 180 degree rotation, so presentation engines and applications that wish to support or use such a transform can express it through rotation instead. Therefore, 3 exclusive bits are sufficient to express all needed mirroring transforms.

19) Should support for sRGB be required?

**RESOLVED:** In the advent of UHD and HDR display devices, proper color space information is vital to the display pipeline represented by the swapchain. The app can discover the supported format/color-space pairs and select a pair most suited to its rendering needs. Currently only the sRGB color space is supported, future extensions may provide support for more color spaces. See issues 23 and 24.

20) Is there a mechanism to modify or replace an existing swapchain with one targeting the same surface?

**RESOLVED:** Yes. This is described above in the text.

21) Should there be a way to set prerotation and mirroring using native APIs when presenting using a Vulkan swapchain?
RESOLVED: Yes. The transforms that can be expressed in this extension are a subset of those possible on native platforms. If a platform exposes a method to specify the transform of presented images for a given surface using native methods and exposes more transforms or other properties for surfaces than Vulkan supports, it might be impossible, difficult, or inconvenient to set some of those properties using Vulkan KHR extensions and some using the native interfaces. To avoid overwriting properties set using native commands when presenting using a Vulkan swapchain, the application can set the pretransform to “inherit”, in which case the current native properties will be used, or if none are available, a platform-specific default will be used. Platforms that do not specify a reasonable default or do not provide native mechanisms to specify such transforms should not include the inherit bits in the `supportedTransforms` bitmask they return in `VkSurfaceCapabilitiesKHR`.

22) Should the content of presentable images be clipped by objects obscuring their target surface?

RESOLVED: Applications can choose which behavior they prefer. Allowing the content to be clipped could enable more optimal presentation methods on some platforms, but some applications might rely on the content of presentable images to perform techniques such as partial updates or motion blurs.

23) What is the purpose of specifying a `VkColorSpaceKHR` along with `VkFormat` when creating a swapchain?

RESOLVED: While Vulkan itself is color space agnostic (e.g. even the meaning of R, G, B and A can be freely defined by the rendering application), the swapchain eventually will have to present the images on a display device with specific color reproduction characteristics. If any color space transformations are necessary before an image can be displayed, the color space of the presented image must be known to the swapchain. A swapchain will only support a restricted set of color format and -space pairs. This set can be discovered via `vkGetPhysicalDeviceSurfaceFormatsKHR`. As it can be expected that most display devices support the sRGB color space, at least one format/color-space pair has to be exposed, where the color space is `VK_COLOR_SPACE_SRGB_NONLINEAR_KHR`.

24) How are sRGB formats and the sRGB color space related?

RESOLVED: While Vulkan exposes a number of SRGB texture formats, using such formats does not guarantee working in a specific color space. It merely means that the hardware can directly support applying the non-linear transfer functions defined by the sRGB standard color space when reading from or writing to images of that these formats. Still, it is unlikely that a swapchain will expose a `*_SRGB` format along with any color space other than `VK_COLOR_SPACE_SRGB_NONLINEAR_KHR`.

On the other hand, non-`*_SRGB` formats will be very likely exposed in pair with a SRGB color space. This means, the hardware will not apply any transfer function when reading from or writing to such images, yet they will still be presented on a device with SRGB display characteristics. In this case the application is responsible for applying the transfer function, for instance by using shader math.

25) How are the lifetime of surfaces and swapchains targeting them related?

RESOLVED: A surface must outlive any swapchains targeting it. A `VkSurfaceKHR` owns the binding of the native window to the Vulkan driver.
26) How can the client control the way the alpha channel of swapchain images is treated by the presentation engine during compositing?

**RESOLVED:** We should add new enum values to allow the client to negotiate with the presentation engine on how to treat image alpha values during the compositing process. Since not all platforms can practically control this through the Vulkan driver, a value of `VK_COMPOSITE_ALPHA_INHERIT_BIT_KHR` is provided like for surface transforms.

27) Is `vkCreateSwapchainKHR` the right function to return `VK_ERROR_NATIVE_WINDOW_IN_USE_KHR`, or should the various platform-specific `VkSurfaceKHR` factory functions catch this error earlier?

**RESOLVED:** For most platforms, the `VkSurfaceKHR` structure is a simple container holding the data that identifies a native window or other object representing a surface on a particular platform. For the surface factory functions to return this error, they would likely need to register a reference on the native objects with the native display server somehow, and ensure no other such references exist. Surfaces were not intended to be that heavyweight.

Swapchains are intended to be the objects that directly manipulate native windows and communicate with the native presentation mechanisms. Swapchains will already need to communicate with the native display server to negotiate allocation and/or presentation of presentable images for a native surface. Therefore, it makes more sense for swapchain creation to be the point at which native object exclusivity is enforced. Platforms may choose to enforce further restrictions on the number of `VkSurfaceKHR` objects that may be created for the same native window if such a requirement makes sense on a particular platform, but a global requirement is only sensible at the swapchain level.

**Examples**

*Note*

The example code for the `VK_KHR_surface` and `VK_KHR_swapchain` extensions was removed from the appendix after revision 1.0.29. This WSI example code was ported to the cube demo that is shipped with the official Khronos SDK, and is being kept up-to-date in that location (see: [https://github.com/KhronosGroup/Vulkan-Tools/blob/master/cube/cube.c](https://github.com/KhronosGroup/Vulkan-Tools/blob/master/cube/cube.c)).

**Version History**

- **Revision 1, 2015-05-20** (James Jones)
  - Initial draft, based on LunarG KHR spec, other KHR specs, patches attached to bugs.
- **Revision 2, 2015-05-22** (Ian Elliott)
  - Made many agreed-upon changes from 2015-05-21 KHR TSG meeting. This includes using only a queue for presentation, and having an explicit function to acquire the next image.
  - Fixed typos and other minor mistakes.
- **Revision 3, 2015-05-26** (Ian Elliott)
  - Improved the Description section.
• Added or resolved issues that were found in improving the Description. For example, pSurfaceDescription is used consistently, instead of sometimes using pSurface.

• Revision 4, 2015-05-27 (James Jones)
  ◦ Fixed some grammatical errors and typos
  ◦ Filled in the description of imageUseFlags when creating a swapchain.
  ◦ Added a description of swapInterval.
  ◦ Replaced the paragraph describing the order of operations on a queue for image ownership and presentation.

• Revision 5, 2015-05-27 (James Jones)
  ◦ Imported relevant issues from the (abandoned) vk_wsi_persistent_swapchain_images extension.
  ◦ Added issues 6 and 7, regarding behavior of the acquire next image and present commands with respect to queues.
  ◦ Updated spec language and examples to align with proposed resolutions to issues 6 and 7.

• Revision 6, 2015-05-27 (James Jones)
  ◦ Added issue 8, regarding atomic presentation of multiple swapchains
  ◦ Updated spec language and examples to align with proposed resolution to issue 8.

• Revision 7, 2015-05-27 (James Jones)
  ◦ Fixed compilation errors in example code, and made related spec fixes.

• Revision 8, 2015-05-27 (James Jones)
  ◦ Added issue 9, and the related VK_SUBOPTIMAL_KHR result code.
  ◦ Renamed VK_OUT_OF_DATE_KHR to VK_ERROR_OUT_OF_DATE_KHR.

• Revision 9, 2015-05-27 (James Jones)
  ◦ Added inline proposed resolutions (marked with [JRJ]) to some XXX questions/issues. These should be moved to the issues section in a subsequent update if the proposals are adopted.

• Revision 10, 2015-05-28 (James Jones)
  ◦ Converted vkAcquireNextImageKHR back to a non-queue operation that uses a VkSemaphore object for explicit synchronization.
  ◦ Added issue 10 to determine whether vkAcquireNextImageKHR generates or returns semaphores, or whether it operates on a semaphore provided by the application.

• Revision 11, 2015-05-28 (James Jones)
  ◦ Marked issues 6, 7, and 8 resolved.
  ◦ Renamed VkSurfaceCapabilityPropertiesKHR to VkSurfacePropertiesKHR to better convey the mutable nature of the info it contains.

• Revision 12, 2015-05-28 (James Jones)
  ◦ Added issue 11 with a proposed resolution, and the related issue 12.
  ◦ Updated various sections of the spec to match the proposed resolution to issue 11.
• Revision 13, 2015-06-01 (James Jones)
  ◦ Moved some structures to VK_EXT_KHR_swap_chain to resolve the spec's issues 1 and 2.

• Revision 14, 2015-06-01 (James Jones)
  ◦ Added code for example 4 demonstrating how an application might make use of the two different present and acquire next image KHR result codes.
  ◦ Added issue 13.

• Revision 15, 2015-06-01 (James Jones)
  ◦ Added issues 14 - 16 and related spec language.
  ◦ Fixed some spelling errors.
  ◦ Added language describing the meaningful return values for vkAcquireNextImageKHR and vkQueuePresentKHR.

• Revision 16, 2015-06-02 (James Jones)
  ◦ Added issues 17 and 18, as well as related spec language.
  ◦ Removed some erroneous text added by mistake in the last update.

• Revision 17, 2015-06-15 (Ian Elliott)
  ◦ Changed special value from "-1" to "0" so that the data types can be unsigned.

• Revision 18, 2015-06-15 (Ian Elliott)
  ◦ Clarified the values of VkSurfacePropertiesKHR::minImageCount and the timeout parameter of the vkAcquireNextImageKHR function.

• Revision 19, 2015-06-17 (James Jones)
  ◦ Misc. cleanup. Removed resolved inline issues and fixed typos.
  ◦ Fixed clarification of VkSurfacePropertiesKHR::minImageCount made in version 18.
  ◦ Added a brief "Image Ownership" definition to the list of terms used in the spec.

• Revision 20, 2015-06-17 (James Jones)
  ◦ Updated enum-extending values using new convention.

• Revision 21, 2015-06-17 (James Jones)
  ◦ Added language describing how to use VK_IMAGE_LAYOUT_PRESENT_SOURCE_KHR.
  ◦ Cleaned up an XXX comment regarding the description of which queues vkQueuePresentKHR can be used on.

• Revision 22, 2015-06-17 (James Jones)
  ◦ Rebased on Vulkan API version 126.

• Revision 23, 2015-06-18 (James Jones)
  ◦ Updated language for issue 12 to read as a proposed resolution.
  ◦ Marked issues 11, 12, 13, 16, and 17 resolved.
  ◦ Temporarily added links to the relevant bugs under the remaining unresolved issues.
  ◦ Added issues 19 and 20 as well as proposed resolutions.
• Revision 24, 2015-06-19 (Ian Elliott)
  ◦ Changed special value for VkSurfacePropertiesKHR::currentExtent back to "-1" from "0". This value will never need to be unsigned, and "0" is actually a legal value.

• Revision 25, 2015-06-23 (Ian Elliott)
  ◦ Examples now show use of function pointers for extension functions.
  ◦ Eliminated extraneous whitespace.

• Revision 26, 2015-06-25 (Ian Elliott)
  ◦ Resolved Issues 9 & 10 per KHR TSG meeting.

• Revision 27, 2015-06-25 (James Jones)
  ◦ Added oldSwapchain member to VkSwapchainCreateInfoKHR.

• Revision 28, 2015-06-25 (James Jones)
  ◦ Added the "inherit" bits to the rotation and mirroring flags and the associated issue 21.

• Revision 29, 2015-06-25 (James Jones)
  ◦ Added the "clipped" flag to VkSwapchainCreateInfoKHR, and the associated issue 22.
  ◦ Specified that presenting an image does not modify it.

• Revision 30, 2015-06-25 (James Jones)
  ◦ Added language to the spec that clarifies the behavior of vkCreateSwapchainKHR() when the oldSwapchain field of VkSwapchainCreateInfoKHR is not NULL.

• Revision 31, 2015-06-26 (Ian Elliott)
  ◦ Example of new VkSwapchainCreateInfoKHR members, "oldSwapchain" and "clipped".
  ◦ Example of using VkSurfacePropertiesKHR::{min|max}ImageCount to set VkSwapchainCreateInfoKHR::minImageCount.
  ◦ Rename vkGetSurfaceInfoKHR()'s 4th parameter to "pDataSize", for consistency with other functions.
  ◦ Add macro with C-string name of extension (just to header file).

• Revision 32, 2015-06-26 (James Jones)
  ◦ Minor adjustments to the language describing the behavior of "oldSwapchain"
  ◦ Fixed the version date on my previous two updates.

• Revision 33, 2015-06-26 (Jesse Hall)
  ◦ Add usage flags to VkSwapchainCreateInfoKHR

• Revision 34, 2015-06-26 (Ian Elliott)
  ◦ Rename vkQueuePresentKHR()'s 2nd parameter to "pPresentInfo", for consistency with other functions.

• Revision 35, 2015-06-26 (Jason Ekstrand)
  ◦ Merged the VkRotationFlagBitsKHR and VkMirrorFlagBitsKHR enums into a single VkSurfaceTransformFlagBitsKHR enum.
• Revision 36, 2015-06-26 (Jason Ekstrand)
  ◦ Added a VkSurfaceTransformKHR enum that is not a bitmask. Each value in
    VkSurfaceTransformKHR corresponds directly to one of the bits in
    VkSurfaceTransformFlagBitsKHR so transforming from one to the other is easy. Having a
    separate enum means that currentTransform and preTransform are now unambiguous by
    definition.

• Revision 37, 2015-06-29 (Ian Elliott)
  ◦ Corrected one of the signatures of vkAcquireNextImageKHR, which had the last two
    parameters switched from what it is elsewhere in the specification and header files.

• Revision 38, 2015-06-30 (Ian Elliott)
  ◦ Corrected a typo in description of the vkGetSwapchainInfoKHR() function.
  ◦ Corrected a typo in header file comment for VkPresentInfoKHR::sType.

• Revision 39, 2015-07-07 (Daniel Rakos)
  ◦ Added error section describing when each error is expected to be reported.
  ◦ Replaced bool32_t with VkBool32.

• Revision 40, 2015-07-10 (Ian Elliott)
  ◦ Updated to work with version 138 of the "vulkan.h" header. This includes declaring the
    VkSwapchainKHR type using the new VK_DEFINE_NONDISP_HANDLE macro, and no longer
    extending VkObjectType (which was eliminated).

• Revision 41 2015-07-09 (Mathias Heyer)
  ◦ Added color space language.

• Revision 42, 2015-07-10 (Daniel Rakos)
  ◦ Updated query mechanism to reflect the convention changes done in the core spec.
  ◦ Removed "queue" from the name of VK_STRUCTURE_TYPE_QUEUE_PRESENT_INFO_KHR to
    be consistent with the established naming convention.
  ◦ Removed reference to the no longer existing VkObjectType enum.

• Revision 43, 2015-07-17 (Daniel Rakos)
  ◦ Added support for concurrent sharing of swapchain images across queue families.
  ◦ Updated sample code based on recent changes

• Revision 44, 2015-07-27 (Ian Elliott)
  ◦ Noted that support for VK_PRESENT_MODE_FIFO_KHR is required. That is ICDs may
    optionally support IMMEDIATE and MAILBOX, but must support FIFO.

• Revision 45, 2015-08-07 (Ian Elliott)
  ◦ Corrected a typo in spec file (type and variable name had wrong case for the
    imageColorSpace member of the VkSwapchainCreateInfoKHR struct).
  ◦ Corrected a typo in header file (last parameter in PFN_vkGetSurfacePropertiesKHR was
    missing "KHR" at the end of type: VkSurfacePropertiesKHR).

• Revision 46, 2015-08-20 (Ian Elliott)
Renamed this extension and all of its enumerations, types, functions, etc. This makes it compliant with the proposed standard for Vulkan extensions.

Switched from "revision" to "version", including use of the VK_MAKE_VERSION macro in the header file.

Made improvements to several descriptions.

Changed the status of several issues from PROPOSED to RESOLVED, leaving no unresolved issues.

Resolved several TODOs, did miscellaneous cleanup, etc.

- Revision 47, 2015-08-20 (Ian Elliott—porting a 2015-07-29 change from James Jones)
  - Moved the surface transform enums to VK_WSI_swapchain so they could be re-used by VK_WSI_display.

- Revision 48, 2015-09-01 (James Jones)
  - Various minor cleanups.

- Revision 49, 2015-09-01 (James Jones)
  - Restore single-field revision number.

- Revision 50, 2015-09-01 (James Jones)
  - Update Example #4 to include code that illustrates how to use the oldSwapchain field.

- Revision 51, 2015-09-01 (James Jones)
  - Fix example code compilation errors.

- Revision 52, 2015-09-08 (Matthaeus G. Chajdas)
  - Corrected a typo.

- Revision 53, 2015-09-10 (Alon Or-bach)
  - Removed underscore from SWAP_CHAIN left in VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO_KHR.

- Revision 54, 2015-09-11 (Jesse Hall)
  - Described the execution and memory coherence requirements for image transitions to and from VK_IMAGE_LAYOUT_PRESENT_SOURCE_KHR.

- Revision 55, 2015-09-11 (Ray Smith)
  - Added errors for destroying and binding memory to presentable images.

- Revision 56, 2015-09-18 (James Jones)
  - Added fence argument to vkAcquireNextImageKHR
  - Added example of how to meter a host thread based on presentation rate.

- Revision 57, 2015-09-26 (Jesse Hall)
  - Replace VkSurfaceDescriptionKHR with VkSurfaceKHR.
  - Added issue 25 with agreed resolution.

- Revision 58, 2015-09-28 (Jesse Hall)
• Renamed from VK_EXT_KHR_device_swapchain to VK_EXT_KHR_swapchain.

• Revision 59, 2015-09-29 (Ian Elliott)
  • Changed vkDestroySwapchainKHR() to return void.

• Revision 60, 2015-10-01 (Jeff Vigil)
  • Added error result VK_ERROR_SURFACE_LOST_KHR.

• Revision 61, 2015-10-05 (Jason Ekstrand)
  • Added the VkCompositeAlpha enum and corresponding structure fields.

• Revision 62, 2015-10-12 (Daniel Rakos)
  • Added VK_PRESENT_MODE_FIFO_RELAXED_KHR.

• Revision 63, 2015-10-15 (Daniel Rakos)
  • Moved surface capability queries to VK_EXT_KHR_surface.

• Revision 64, 2015-10-26 (Ian Elliott)
  • Renamed from VK_EXT_KHR_swapchain to VK_KHR_swapchain.

• Revision 65, 2015-10-28 (Ian Elliott)
  • Added optional pResult member to VkPresentInfoKHR, so that per-swapchain results can be obtained from vkQueuePresentKHR().

• Revision 66, 2015-11-03 (Daniel Rakos)
  • Added allocation callbacks to create and destroy functions.
  • Updated resource transition language.
  • Updated sample code.

• Revision 67, 2015-11-10 (Jesse Hall)
  • Add reserved flags bitmask to VkSwapchainCreateInfoKHR.
  • Modify naming and member ordering to match API style conventions, and so the VkSwapchainCreateInfoKHR image property members mirror corresponding VkImageCreateInfo members but with an 'image' prefix.
  • Make VkPresentInfoKHR::pResults non-const; it is an output array parameter.
  • Make pPresentInfo parameter to vkQueuePresentKHR const.

• Revision 68, 2016-04-05 (Ian Elliott)
  • Moved the "validity" include for vkAcquireNextImage to be in its proper place, after the prototype and list of parameters.
  • Clarified language about presentable images, including how they are acquired, when applications can and cannot use them, etc. As part of this, removed language about "ownership" of presentable images, and replaced it with more-consistent language about presentable images being "acquired" by the application.

• 2016-08-23 (Ian Elliott)
  • Update the example code, to use the final API command names, to not have so many characters per line, and to split out a new example to show how to obtain function pointers.
This code is more similar to the LunarG "cube" demo program.

- 2016-08-25 (Ian Elliott)
  - A note was added at the beginning of the example code, stating that it will be removed from future versions of the appendix.

- Revision 69, 2017-09-07 (Tobias Hector)
  - Added interactions with Vulkan 1.1

- Revision 70, 2017-10-06 (Ian Elliott)
  - Corrected interactions with Vulkan 1.1

**VK_KHR_swapchain Mutable Format**

**Name String**

VK_KHR_swapchain Mutable Format

**Extension Type**

Device extension

**Registered Extension Number**

201

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires VK_KHR_swapchain
- Requires VK_KHR_maintenance2
- Requires VK_KHR_image_format_list

**Contact**

- Daniel Rakos (drakos-arm)

**Other Extension Metadata**

**Last Modified Date**

2018-03-28

**IP Status**

No known IP claims.

**Contributors**

- Jason Ekstrand, Intel
- Jan-Harald Fredriksen, ARM
- Jesse Hall, Google
Description

This extension allows processing of swapchain images as different formats to that used by the window system, which is particularly useful for switching between sRGB and linear RGB formats.

It adds a new swapchain creation flag that enables creating image views from presentable images with a different format than the one used to create the swapchain.

New Object Types

None.

New Enum Constants

- Extending VkSwapchainCreateFlagBitsKHR:
  - VK_SWAPCHAIN_CREATE_MUTABLE_FORMAT_BIT_KHR

New Enums

None.

New Structures

None.

New Functions

None.

Issues

1) Are there any new capabilities needed?

**RESOLVED:** No. It is expected that all implementations exposing this extension support swapchain image format mutability.

2) Do we need a separate VK_SWAPCHAIN_CREATE_EXTENDED_USAGE_BIT_KHR?

**RESOLVED:** No. This extension requires VK_KHR_maintenance2 and presentable images of swapchains created with VK_SWAPCHAIN_CREATE_MUTABLE_FORMAT_BIT_KHR are created internally in a way equivalent to specifying both VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT and VK_IMAGE_CREATE_EXTENDED_USAGE_BIT_KHR.

3) Do we need a separate structure to allow specifying an image format list for swapchains?

**RESOLVED:** No. We simply use the same VkImageFormatListCreateInfoKHR structure introduced by VK_KHR_image_format_list. The structure is required to be included in the pNext chain of
VkSwapchainCreateInfoKHR for swapchains created with VK_SWAPCHAIN_CREATE_MUTABLE_FORMAT_BIT_KHR.

Version History

- Revision 1, 2018-03-28 (Daniel Rakos)
  - Internal revisions.

VK_KHR_timeline_semaphore

Name String

VK_KHR_timeline_semaphore

Extension Type

Device extension

Registered Extension Number

208

Revision

2

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

Deprecation state

- Promoted to Vulkan 1.2

Contact

- Jason Ekstrand 🌐jekstrand

Other Extension Metadata

Last Modified Date

2019-06-12

IP Status

No known IP claims.

Interactions and External Dependencies

- This extension interacts with VK_KHR_external_semaphore_capabilities
- This extension interacts with VK_KHR_external_semaphore
- This extension interacts with VK_KHR_external_semaphore_win32
- Promoted to Vulkan 1.2 Core
Description

This extension introduces a new type of semaphore that has an integer payload identifying a point in a timeline. Such timeline semaphores support the following operations:

- Host query - A host operation that allows querying the payload of the timeline semaphore.
- Host wait - A host operation that allows a blocking wait for a timeline semaphore to reach a specified value.
- Host signal - A host operation that allows advancing the timeline semaphore to a specified value.
- Device wait - A device operation that allows waiting for a timeline semaphore to reach a specified value.
- Device signal - A device operation that allows advancing the timeline semaphore to a specified value.

New Object Types

None

New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_FEATURES_KHR
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_TIMELINE_SEMAPHORE_PROPERTIES_KHR
  - VK_STRUCTURE_TYPE_SEMAPHORE_TYPE_CREATE_INFO_KHR
  - VK_STRUCTURE_TYPE_TIMELINE_SEMAPHORE_SUBMIT_INFO_KHR
  - VK_STRUCTURE_TYPE_SEMAPHORE_WAIT_INFO_KHR
  - VK_STRUCTURE_TYPE_SEMAPHORE_SIGNAL_INFO_KHR

New Enums

- VkSemaphoreTypeKHR
New Structs

- VkPhysicalDeviceTimelineSemaphoreFeaturesKHR
- VkPhysicalDeviceTimelineSemaphorePropertiesKHR
- VkSemaphoreTypeCreateInfoKHR
- VkTimelineSemaphoreSubmitInfoKHR
- VkSemaphoreWaitInfoKHR
- VkSemaphoreSignalInfoKHR

New Functions

- vkGetSemaphoreCounterValueKHR
- vkWaitSemaphoresKHR
- vkSignalSemaphoreKHR

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

1) Do we need a new object type for this?

**RESOLVED:** No, we just introduce a new type of semaphore object, as VK_KHR_external_semaphore_win32 already uses semaphores as the destination for importing D3D12 fence objects, which are semantically close/identical to the proposed synchronization primitive.

2) What type of payload the new synchronization primitive has?

**RESOLVED:** A 64-bit unsigned integer that can only be set to monotonically increasing values by signal operations and is not changed by wait operations.

3) Does the new synchronization primitive have the same signal-before-wait requirement as the existing semaphores do?

**RESOLVED:** No. Timeline semaphores support signaling and waiting entirely asynchronously. It is the responsibility of the client to avoid deadlock.

4) Does the new synchronization primitive allow resetting its payload?

**RESOLVED:** No, allowing the payload value to "go backwards" is problematic. Applications looking for reset behavior should create a new instance of the synchronization primitive instead.

5) How do we enable host waits on the synchronization primitive?

**RESOLVED:** Both a non-blocking query of the current payload value of the synchronization primitive, and a blocking wait operation are provided.
6) How do we enable device waits and signals on the synchronization primitive?

**RESOLVED:** Similar to `VK_KHR_external_semaphore_win32`, this extension introduces a new structure that can be chained to `VkSubmitInfo` to specify the values signaled semaphores should be set to, and the values waited semaphores need to reach.

7) Can the new synchronization primitive be used to synchronize presentation and swapchain image acquisition operations?

**RESOLVED:** Some implementations may have problems with supporting that directly, thus it's not allowed in this extension.

8) Do we want to support external sharing of the new synchronization primitive type?

**RESOLVED:** Yes. Timeline semaphore specific external sharing capabilities can be queried using `vkGetPhysicalDeviceExternalSemaphoreProperties` by chaining the new `VkSemaphoreTypeCreateInfoKHR` structure to its `pExternalSemaphoreInfo` structure. This allows having a different set of external semaphore handle types supported for timeline semaphores vs binary semaphores.

9) Do we need to add a host signal operation for the new synchronization primitive type?

**RESOLVED:** Yes. This helps in situations where one host thread submits a workload but another host thread has the information on when the workload is ready to be executed.

10) How should the new synchronization primitive interact with the ordering requirements of the original `VkSemaphore`?

**RESOLVED:** Prior to calling any command which may cause a wait operation on a binary semaphore, the client must ensure that the semaphore signal operation that has been submitted for execution and any semaphore signal operations on which it depends (if any) must have also been submitted for execution.

11) Should we have separate feature bits for different sub-features of timeline semaphores?

**RESOLVED:** No. The only feature which cannot be supported universally is timeline semaphore import/export. For import/export, the client is already required to query available external handle types via `vkGetPhysicalDeviceExternalSemaphoreProperties` and provide the semaphore type by adding a `VkSemaphoreTypeCreateInfoKHR` structure to the `pNext` chain of `VkPhysicalDeviceExternalSemaphoreInfo` so no new feature bit is required.

**Version History**

- Revision 1, 2018-05-10 (Jason Ekstrand)
  - Initial version
- Revision 2, 2019-06-12 (Jason Ekstrand)
  - Added an initialValue parameter to timeline semaphore creation
VK_KHR_uniform_buffer_standard_layout

Name String
VK_KHR_uniform_buffer_standard_layout

Extension Type
Device extension

Registered Extension Number
254

Revision
1

Extension and Version Dependencies
• Requires Vulkan 1.0
• Requires VK_KHR_get_physical_device_properties2

Deprecation state
• Promoted to Vulkan 1.2

Contact
• Graeme Leese @gnl21

Other Extension Metadata

Last Modified Date
2019-01-25

Interactions and External Dependencies
• Promoted to Vulkan 1.2 Core

Contributors
• Graeme Leese, Broadcom
• Jeff Bolz, NVIDIA
• Tobias Hector, AMD
• Jason Ekstrand, Intel
• Neil Henning, AMD

Description

This extension enables tighter array and struct packing to be used with uniform buffers.

It modifies the alignment rules for uniform buffers, allowing for tighter packing of arrays and structures. This allows, for example, the std430 layout, as defined in GLSL to be supported in uniform buffers.
New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_UNIFORM_BUFFER_STANDARD_LAYOUT_FEATURES_KHR

New Structures

- VkPhysicalDeviceUniformBufferStandardLayoutFeaturesKHR

Issues

None.

Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

- Revision 1, 2019-01-25 (Graeme Leese)
  - Initial draft

VK_KHR_vulkan_memory_model

Name String

VK_KHR_vulkan_memory_model

Extension Type

Device extension

Registered Extension Number

212

Revision

3

Extension and Version Dependencies

- Requires Vulkan 1.0

Deprecation state

- Promoted to Vulkan 1.2

Contact

- Jeff Bolz jeffbolznv
Other Extension Metadata

Last Modified Date
2018-12-10

IP Status
No known IP claims.

Interactions and External Dependencies

• Promoted to Vulkan 1.2 Core
• This extension requires SPV_KHR_vulkan_memory_model

Contributors

• Jeff Bolz, NVIDIA
• Alan Baker, Google
• Tobias Hector, AMD
• David Neto, Google
• Robert Simpson, Qualcomm Technologies, Inc.
• Brian Sumner, AMD

Description

The VK_KHR_vulkan_memory_model extension allows use of the Vulkan Memory Model, which formally defines how to synchronize memory accesses to the same memory locations performed by multiple shader invocations.

New Enum Constants

• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_PHYSICALDEVICE_VULKAN_MEMORY_MODEL_FEATURES_KHR

New Structures

• VkPhysicalDeviceVulkanMemoryModelFeaturesKHR

Note
Version 3 of the spec added a member (vulkanMemoryModelAvailabilityVisibilityChains) to VkPhysicalDeviceVulkanMemoryModelFeaturesKHR, which is an incompatible change from version 2.

New SPIR-V Capabilities

• VulkanMemoryModelKHR
Promotion to Vulkan 1.2

All functionality in this extension is included in core Vulkan 1.2, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

Version History

• Revision 1, 2018-06-24 (Jeff Bolz)
  ◦ Initial draft
• Revision 3, 2018-12-10 (Jeff Bolz)
  ◦ Add `vulkanMemoryModelAvailabilityVisibilityChains` member to the `VkPhysicalDeviceVulkanMemoryModelFeaturesKHR` structure.

VK_KHR_wayland_surface

Name String

`VK_KHR_wayland_surface`

Extension Type

Instance extension

Registered Extension Number

7

Revision

6

Extension and Version Dependencies

• Requires Vulkan 1.0
• Requires `VK_KHR_surface`

Contact

• Jesse Hall @critsec
• Ian Elliott @ianelliottus

Other Extension Metadata

Last Modified Date

2015-11-28

IP Status

No known IP claims.

Contributors
Description

The `VK_KHR_wayland_surface` extension is an instance extension. It provides a mechanism to create a `VkSurfaceKHR` object (defined by the `VK_KHR_surface` extension) that refers to a Wayland `wl_surface`, as well as a query to determine support for rendering to a Wayland compositor.

New Object Types

None

New Enum Constants

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_WAYLAND_SURFACE_CREATE_INFO_KHR`

New Enums

None

New Structures

- `VkWaylandSurfaceCreateInfoKHR`
New Functions

- `vkCreateWaylandSurfaceKHR`
- `vkGetPhysicalDeviceWaylandPresentationSupportKHR`

Issues

1) Does Wayland need a way to query for compatibility between a particular physical device and a specific Wayland display? This would be a more general query than `vkGetPhysicalDeviceSurfaceSupportKHR`: if the Wayland-specific query returned `VK_TRUE` for a (`VkPhysicalDevice`, `struct wl_display*`) pair, then the physical device could be assumed to support presentation to any `VkSurfaceKHR` for surfaces on the display.

RESOLVED: Yes. `vkGetPhysicalDeviceWaylandPresentationSupportKHR` was added to address this issue.

2) Should we require surfaces created with `vkCreateWaylandSurfaceKHR` to support the `VK_PRESENT_MODE_MAILBOX_KHR` present mode?

RESOLVED: Yes. Wayland is an inherently mailbox window system and mailbox support is required for some Wayland compositor interactions to work as expected. While handling these interactions may be possible with `VK_PRESENT_MODE_FIFO_KHR`, it is much more difficult to do without deadlock and requiring all Wayland applications to be able to support implementations which only support `VK_PRESENT_MODE_FIFO_KHR` would be an onerous restriction on application developers.

Version History

- Revision 1, 2015-09-23 (Jesse Hall)
  - Initial draft, based on the previous contents of VK_EXT_KHR_swapchain (later renamed VK_EXT_KHR_surface).
- Revision 2, 2015-10-02 (James Jones)
  - Added `vkGetPhysicalDeviceWaylandPresentationSupportKHR()` to resolve issue #1.
  - Adjusted wording of issue #1 to match the agreed-upon solution.
  - Renamed "window" parameters to "surface" to match Wayland conventions.
- Revision 3, 2015-10-26 (Ian Elliott)
  - Renamed from VK_EXT_KHR_wayland_surface to VK_KHR_wayland_surface.
- Revision 4, 2015-11-03 (Daniel Rakos)
  - Added allocation callbacks to `vkCreateWaylandSurfaceKHR`.
- Revision 5, 2015-11-28 (Daniel Rakos)
  - Updated the surface create function to take a `pCreateInfo` structure.
- Revision 6, 2017-02-08 (Jason Ekstrand)
  - Added the requirement that implementations support `VK_PRESENT_MODE_MAILBOX_KHR`.
  - Added wording about interactions between `vkQueuePresentKHR` and the Wayland requests...
VK_KHR_win32_keyed_mutex

Name String
VK_KHR_win32_keyed_mutex

Extension Type
Device extension

Registered Extension Number
76

Revision
1

Extension and Version Dependencies
• Requires Vulkan 1.0
• Requires VK_KHR_external_memory_win32

Contact
• Carsten Rohde @crohde

Other Extension Metadata

Last Modified Date
2016-10-21

IP Status
No known IP claims.

Contributors
• James Jones, NVIDIA
• Jeff Juliano, NVIDIA
• Carsten Rohde, NVIDIA

Description
Applications that wish to import Direct3D 11 memory objects into the Vulkan API may wish to use the native keyed mutex mechanism to synchronize access to the memory between Vulkan and Direct3D. This extension provides a way for an application to access the keyed mutex associated with an imported Vulkan memory object when submitting command buffers to a queue.

New Object Types
None.
New Enum Constants

- VK_STRUCTURE_TYPE_WIN32_KEYED_MUTEX_ACQUIRE_RELEASE_INFO_KHR

New Enums

None.

New Structs

- VkWin32KeyedMutexAcquireReleaseInfoKHR

New Functions

None.

Issues

None.

Version History

- Revision 1, 2016-10-21 (James Jones)
  - Initial revision

VK_KHR_win32_surface

Name String

VK_KHR_win32_surface

Extension Type

Instance extension

Registered Extension Number

10

Revision

6

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_surface

Contact

- Jesse Hall @critsec
- Ian Elliott @ianelliottus
Other Extension Metadata

Last Modified Date
2017-04-24

IP Status
No known IP claims.

Contributors
- Patrick Doane, Blizzard
- Jason Ekstrand, Intel
- Ian Elliott, LunarG
- Courtney Goeltzenleuchter, LunarG
- Jesse Hall, Google
- James Jones, NVIDIA
- Antoine Labour, Google
- Jon Leech, Khronos
- David Mao, AMD
- Norbert Nopper, Freescale
- Alon Or-bach, Samsung
- Daniel Rakos, AMD
- Graham Sellers, AMD
- Ray Smith, ARM
- Jeff Vigil, Qualcomm
- Chia-I Wu, LunarG

Description
The VK_KHR_win32_surface extension is an instance extension. It provides a mechanism to create a VkSurfaceKHR object (defined by the VK_KHR_surface extension) that refers to a Win32 HWND, as well as a query to determine support for rendering to the windows desktop.

New Object Types
None

New Enum Constants
- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_WIN32_SURFACE_CREATE_INFO_KHR
New Enums

None

New Structures

- VkWin32SurfaceCreateInfoKHR

New Functions

- vkCreateWin32SurfaceKHR
- vkGetPhysicalDeviceWin32PresentationSupportKHR

Issues

1) Does Win32 need a way to query for compatibility between a particular physical device and a specific screen? Compatibility between a physical device and a window generally only depends on what screen the window is on. However, there is not an obvious way to identify a screen without already having a window on the screen.

**RESOLVED:** No. While it may be useful, there is not a clear way to do this on Win32. However, a method was added to query support for presenting to the windows desktop as a whole.

2) If a native window object (HWND) is used by one graphics API, and then is later used by a different graphics API (one of which is Vulkan), can these uses interfere with each other?

**RESOLVED:** Yes.

Uses of a window object by multiple graphics APIs results in undefined behavior. Such behavior may succeed when using one Vulkan implementation but fail when using a different Vulkan implementation. Potential failures include:

- Creating then destroying a flip presentation model DXGI swapchain on a window object can prevent `vkCreateSwapchainKHR` from succeeding on the same window object.
- Creating then destroying a `VkSwapchainKHR` on a window object can prevent creation of a bitblt model DXGI swapchain on the same window object.
- Creating then destroying a `VkSwapchainKHR` on a window object can effectively `SetPixelFormat` to a different format than the format chosen by an OpenGL application.
- Creating then destroying a `VkSwapchainKHR` on a window object on one `VkPhysicalDevice` can prevent `vkCreateSwapchainKHR` from succeeding on the same window object, but on a different `VkPhysicalDevice` that is associated with a different Vulkan ICD.

In all cases the problem can be worked around by creating a new window object.

Technical details include:

- Creating a DXGI swapchain over a window object can alter the object for the remainder of its lifetime. The alteration persists even after the DXGI swapchain has been destroyed. This alteration can make it impossible for a conformant Vulkan implementation to create a
**VkSwapchainKHR** over the same window object. Mention of this alteration can be found in the remarks section of the MSDN documentation for **DXGI_SWAP_EFFECT**.

- Calling GDI's **SetPixelFormat** (needed by OpenGL's WGL layer) on a window object alters the object for the remainder of its lifetime. The MSDN documentation for **SetPixelFormat** explains that a window object's pixel format can be set only one time.

- Creating a **VkSwapchainKHR** over a window object can alter the object for the remaining life of its lifetime. Either of the above alterations may occur as a side-effect of **VkSwapchainKHR**.

**Version History**

- Revision 1, 2015-09-23 (Jesse Hall)
  - Initial draft, based on the previous contents of VK_EXT_KHR_swapchain (later renamed VK_EXT_KHR_surface).

- Revision 2, 2015-10-02 (James Jones)
  - Added presentation support query for win32 desktops.

- Revision 3, 2015-10-26 (Ian Elliott)
  - Renamed from VK_EXT_KHR_win32_surface to VK_KHR_win32_surface.

- Revision 4, 2015-11-03 (Daniel Rakos)
  - Added allocation callbacks to vkCreateWin32SurfaceKHR.

- Revision 5, 2015-11-28 (Daniel Rakos)
  - Updated the surface create function to take a pCreateInfo structure.

- Revision 6, 2017-04-24 (Jeff Juliano)
  - Add issue 2 addressing reuse of a native window object in a different Graphics API, or by a different Vulkan ICD.

**VK_KHR_xcb_surface**

**Name String**

VK_KHR_xcb_surface

**Extension Type**

Instance extension

**Registered Extension Number**

6

**Revision**

6

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires **VK_KHR_surface**
**Contact**
- Jesse Hall ● critsec
- Ian Elliott ● ianelliottus

**Other Extension Metadata**

**Last Modified Date**
2015-11-28

**IP Status**
No known IP claims.

**Contributors**
- Patrick Doane, Blizzard
- Jason Ekstrand, Intel
- Ian Elliott, LunarG
- Courtney Goeltzeleuchter, LunarG
- Jesse Hall, Google
- James Jones, NVIDIA
- Antoine Labour, Google
- Jon Leech, Khronos
- David Mao, AMD
- Norbert Nopper, Freescale
- Alon Or-bach, Samsung
- Daniel Rakos, AMD
- Graham Sellers, AMD
- Ray Smith, ARM
- Jeff Vigil, Qualcomm
- Chia-I Wu, LunarG

**Description**
The **VK_KHR_xcb_surface** extension is an instance extension. It provides a mechanism to create a **VkSurfaceKHR** object (defined by the **VK_KHR_surface** extension) that refers to an X11 **Window**, using the XCB client-side library, as well as a query to determine support for rendering via XCB.

**New Object Types**
None
New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_XCB_SURFACE_CREATE_INFO_KHR

New Enums

None

New Structures

- VkXcbSurfaceCreateInfoKHR

New Functions

- vkCreateXcbSurfaceKHR
- vkGetPhysicalDeviceXcbPresentationSupportKHR

Issues

1) Does XCB need a way to query for compatibility between a particular physical device and a specific screen? This would be a more general query than vkGetPhysicalDeviceSurfaceSupportKHR: If it returned VK_TRUE, then the physical device could be assumed to support presentation to any window on that screen.

RESOLVED: Yes, this is needed for toolkits that want to create a VkDevice before creating a window. To ensure the query is reliable, it must be made against a particular X visual rather than the screen in general.

Version History

- Revision 1, 2015-09-23 (Jesse Hall)
  - Initial draft, based on the previous contents of VK_EXT_KHR_swapchain (later renamed VK_EXT_KHR_surface).
- Revision 2, 2015-10-02 (James Jones)
  - Added presentation support query for an (xcb_connection_t*, xcb_visualid_t) pair.
  - Removed "root" parameter from CreateXcbSurfaceKHR(), as it is redundant when a window on the same screen is specified as well.
  - Adjusted wording of issue #1 and added agreed upon resolution.
- Revision 3, 2015-10-14 (Ian Elliott)
  - Removed "root" parameter from CreateXcbSurfaceKHR() in one more place.
- Revision 4, 2015-10-26 (Ian Elliott)
  - Renamed from VK_EXT_KHR_xcb_surface to VK_KHR_xcb_surface.
- Revision 5, 2015-10-23 (Daniel Rakos)
- Added allocation callbacks to vkCreateXcbSurfaceKHR.
- Revision 6, 2015-11-28 (Daniel Rakos)
  - Updated the surface create function to take a pCreateInfo structure.

**VK_KHR_xlib_surface**

<table>
<thead>
<tr>
<th>Name String</th>
<th>VK_KHR_xlib_surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extension Type</strong></td>
<td>Instance extension</td>
</tr>
<tr>
<td><strong>Registered Extension Number</strong></td>
<td>5</td>
</tr>
<tr>
<td><strong>Revision</strong></td>
<td>6</td>
</tr>
<tr>
<td><strong>Extension and Version Dependencies</strong></td>
<td>Requires Vulkan 1.0</td>
</tr>
<tr>
<td></td>
<td>Requires VK_KHR_surface</td>
</tr>
</tbody>
</table>

**Contact**

- Jesse Hall @critsec
- Ian Elliott @ianelliottus

**Other Extension Metadata**

**Last Modified Date**

2015-11-28

**IP Status**

No known IP claims.

**Contributors**

- Patrick Doane, Blizzard
- Jason Ekstrand, Intel
- Ian Elliott, LunarG
- Courtney Goeltzenleuchter, LunarG
- Jesse Hall, Google
- James Jones, NVIDIA
- Antoine Labour, Google
- Jon Leech, Khronos
**Description**

The `VK_KHR_xlib_surface` extension is an instance extension. It provides a mechanism to create a `VkSurfaceKHR` object (defined by the `VK_KHR_surface` extension) that refers to an X11 Window, using the Xlib client-side library, as well as a query to determine support for rendering via Xlib.

**New Object Types**

None

**New Enum Constants**

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_XLIB_SURFACE_CREATE_INFO_KHR`

**New Enums**

None

**New Structures**

- `VkXlibSurfaceCreateInfoKHR`

**New Functions**

- `vkCreateXlibSurfaceKHR`
- `vkGetPhysicalDeviceXlibPresentationSupportKHR`

**Issues**

1) Does X11 need a way to query for compatibility between a particular physical device and a specific screen? This would be a more general query than `vkGetPhysicalDeviceSurfaceSupportKHR`; if it returned `VK_TRUE`, then the physical device could be assumed to support presentation to any window on that screen.

**RESOLVED**: Yes, this is needed for toolkits that want to create a `VkDevice` before creating a window. To ensure the query is reliable, it must be made against a particular X visual rather than the screen.
in general.

Version History

- Revision 1, 2015-09-23 (Jesse Hall)
  - Initial draft, based on the previous contents of VK_EXT_KHR_swapchain (later renamed VK_EXT_KHR_surface).
- Revision 2, 2015-10-02 (James Jones)
  - Added presentation support query for (Display*, VisualID) pair.
  - Removed "root" parameter from CreateXlibSurfaceKHR(), as it is redundant when a window on the same screen is specified as well.
  - Added appropriate X errors.
  - Adjusted wording of issue #1 and added agreed upon resolution.
- Revision 3, 2015-10-14 (Ian Elliott)
  - Renamed this extension from VK_EXT_KHR_x11_surface to VK_EXT_KHR_xlib_surface.
- Revision 4, 2015-10-26 (Ian Elliott)
  - Renamed from VK_EXT_KHR_xlib_surface to VK_KHR_xlib_surface.
- Revision 5, 2015-11-03 (Daniel Rakos)
  - Added allocation callbacks to vkCreateXlibSurfaceKHR.
- Revision 6, 2015-11-28 (Daniel Rakos)
  - Updated the surface create function to take a pCreateInfo structure.

List of Provisional Extensions

- VK_KHR_deferred_host_operations
- VK_KHR_pipeline_library
- VK_KHR_ray_tracing
VK_KHR_deferred_host_operations

Name String
VK_KHR_deferred_host_operations

Extension Type
Device extension

Registered Extension Number
269

Revision
2

Extension and Version Dependencies
• Requires Vulkan 1.0
• This is a provisional extension and must be used with caution. See the description of provisional header files for enablement and stability details.

Contact
• Josh Barczak @jbarczak

Other Extension Metadata

Last Modified Date
2020-03-06

IP Status
No known IP claims.

Contributors
• Joshua Barczak, Intel
• Jeff Bolz, NVIDIA
• Daniel Koch, NVIDIA
• Slawek Grajewski, Intel
• Tobias Hector, AMD
• Yuriy O'Donnell, Epic
• Eric Werness, NVIDIA
• Baldur Karlsson, Valve
• Jesse Barker, Unity
• Contributors to VK_KHR_ray_tracing
Description

The VK_KHR_deferred_host_operations extension defines the infrastructure and usage patterns for
deferrable commands, but does not specify any commands as deferrable. This is left to additional
dependent extensions. Commands must not be deferred unless the deferral is specifically allowed
by another extension which depends on VK_KHR_deferred_host_operations.

New Object Types

• VkDeferredOperationKHR

New Enum Constants

• Extending VkResult:
  ◦ VK_THREAD_IDLE_KHR
  ◦ VK_THREAD_DONE_KHR
  ◦ VK_OPERATION_DEFERRED_KHR
  ◦ VK_OPERATION_NOT_DEFERRED_KHR

• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_DEFERRED_OPERATION_INFO_KHR

• Extending VkObjectType:
  ◦ VK_OBJECT_TYPE_DEFERRED_OPERATION_KHR

New Enums

None

New Structures

• VkDeferredOperationInfoKHR

New Functions

• vkCreateDeferredOperationKHR
• vkDestroyDeferredOperationKHR
• vkGetDeferredOperationMaxConcurrencyKHR
• vkGetDeferredOperationResultKHR
• vkDeferredOperationJoinKHR

Code Examples

The following examples will illustrate the concept of deferrable operations using a hypothetical
example. The command vkDoSomethingExpensiveEXT denotes a deferrable command. The structure
VkExpensiveOperationArgsEXT represents the arguments which it would normally accept.

The following example illustrates how a vulkan application might request deferral of an expensive
The following example shows a subroutine which guarantees completion of a deferred operation, in the presence of multiple worker threads, and returns the result of the operation.
VkResult FinishDeferredOperation(VkDeferredOperationKHR hOp) {
  // Attempt to join the operation until the implementation indicates that we should stop
  VkResult result = vkDeferredOperationJoinKHR(device, hOp);
  while (result == VK_THREAD_IDLE_KHR) {
    std::this_thread::yield();
    result = vkDeferredOperationJoinKHR(device, hOp);
  }
  switch (result) {
    case VK_SUCCESS:
    {
      // deferred operation has finished. Query its result
      result = vkGetDeferredOperationResultKHR(device, hOp);
    }
    break;
    case VK_THREAD_DONE_KHR:
    {
      // deferred operation is being wrapped up by another thread
      // wait for that thread to finish
      do {
        std::this_thread::yield();
        result = vkGetDeferredOperationResultKHR(device, hOp);
      } while (result == VK_NOT_READY);
    }
    break;
    default:
    {
      assert(false); // other conditions are illegal.
      break;
    }
    return result;
  }
}

**Issues**

1. Should this extension have a VkPhysicalDevice*FeaturesKHR structure?

**RESOLVED:** No. This extension does not add any functionality on its own and requires a dependent extension to actually enable functionality and thus there is no value in adding a feature structure. If necessary, any dependent extension could add a feature boolean if it wanted to indicate that it is adding optional deferral support.
**Version History**

- Revision 1, 2019-12-05 (Josh Barczak, Daniel Koch)
  - Initial draft.
- Revision 2, 2020-03-06 (Daniel Koch, Tobias Hector)
  - Add missing VK_OBJECT_TYPE_DEFERRED_OPERATION_KHR enum
  - fix sample code
  - Clarified deferred operation parameter lifetimes (#2018,!3647)

**VK_KHR_pipeline_library**

**Name String**

- VK_KHR_pipeline_library

**Extension Type**

- Device extension

**Registered Extension Number**

- 291

**Revision**

- 1

**Extension and Version Dependencies**

- Requires Vulkan 1.0

- This is a *provisional* extension and must be used with caution. See the description of provisional header files for enablement and stability details.

**Contact**

- Christoph Kubisch [pixeljetstream](http://pixeljetstream)

**Other Extension Metadata**

**Last Modified Date**

- 2020-01-08

**IP Status**

- No known IP claims.

**Contributors**

- See contributors to [VK_KHR_ray_tracing](http://VK_KHR_ray_tracing)

**Description**

A pipeline library is a special pipeline that cannot be bound, instead it defines a set of shaders and shader groups which can be linked into other pipelines. This extension defines the infrastructure
for pipeline libraries, but does not specify the creation or usage of pipeline libraries. This is left to additional dependent extensions.

**New Object Types**
None

**New Enum Constants**
- Extending `VkPipelineCreateFlagBits`:
  - `VK_PIPELINE_CREATE_LIBRARY_BIT_KHR`
- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_PIPELINE_LIBRARY_CREATE_INFO_KHR`

**New Enums**
None

**New Structures**
- `VkPipelineLibraryCreateInfoKHR`

**New Functions**
None

**Version History**
- Revision 1, 2020-01-08 (Christoph Kubisch)
  - Initial draft.

**VK_KHR_ray_tracing**

**Name String**
`VK_KHR_ray_tracing`

**Extension Type**
Device extension

**Registered Extension Number**
151

**Revision**
8

**Extension and Version Dependencies**
- Requires Vulkan 1.0
• Requires VK_KHR_get_physical_device_properties2
• Requires VK_KHR_get_memory_requirements2
• Requires VK_EXT_descriptor_indexing
• Requires VK_KHR_buffer_device_address
• Requires VK_KHR_deferred_host_operations
• Requires VK_KHR_pipeline_library

• This is a provisional extension and must be used with caution. See the description of provisional header files for enablement and stability details.

Contact
• Daniel Koch 🌐dgkoch

Other Extension Metadata

Last Modified Date
2020-02-28

Interactions and External Dependencies
• This extension requires the SPV_KHR_ray_tracing and SPV_KHR_ray_query SPIR-V extensions.
• This extension requires the GLSL_EXT_ray_tracing and GLSL_EXT_ray_query extensions for GLSL source languages.

Contributors
• Matthäus Chajdas, AMD
• Greg Grebe, AMD
• Nicolai Hähnle, AMD
• Tobias Hector, AMD
• Dave Oldcorn, AMD
• Skyler Saleh, AMD
• Mathieu Robart, Arm
• Marius Bjorge, Arm
• Tom Olson, Arm
• Sebastian Tafuri, EA
• Henrik Rydgard, Embark
• Juan Cañada, Epic Games
• Patrick Kelly, Epic Games
• Yuriy O'Donnell, Epic Games
• Michael Doggett, Facebook/Oculus
• Don Scorgie, Imagination
Description

Rasterization has been the dominant method to produce interactive graphics, but increasing performance of graphics hardware has made ray tracing a viable option for interactive rendering. Being able to integrate ray tracing with traditional rasterization makes it easier for applications to incrementally add ray traced effects to existing applications or to do hybrid approaches with rasterization for primary visibility and ray tracing for secondary queries.

To enable ray tracing, this extension adds a few different categories of new functionality:

- Acceleration structure objects and build commands
- A new pipeline type with new shader domains
- An indirection table to link shader groups with acceleration structure items
Additionally, ray queries are available to other shader types outside of the dedicated ray tracing pipeline. Unlike OpTraceRayKHR, ray queries are not able to launch additional shaders, instead returning traversal results to the calling shader.

This extension adds support for the following SPIR-V extension in Vulkan:

- SPV_KHR_ray_tracing
- SPV_KHR_ray_query

**New Object Types**

- VkAccelerationStructureKHR

**New Enum Constants**

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_RAY_TRACING_PIPELINE_CREATE_INFO_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_BUILD_GEOMETRY_INFO_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_CREATE_INFO_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_INFO_KHR
  - VK_STRUCTURE_TYPE_BIND_ACCELERATION_STRUCTURE_MEMORY_INFO_KHR
  - VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET_ACCELERATION_STRUCTURE_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_MEMORY_REQUIREMENTS_INFO_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_CREATE_GEOMETRY_TYPE_INFO_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_TRIANGLES_DATA_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_AABBS_DATA_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_INSTANCES_DATA_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_GEOMETRY_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_DEVICE_ADDRESS_INFO_KHR
  - VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_VERSION_KHR
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_RAY_TRACING_PROPERTIES_KHR
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_RAY_TRACING_FEATURES_KHR
  - VK_STRUCTURE_TYPE_RAY_TRACING_PIPELINE_INTERFACE_CREATE_INFO_KHR
  - VK_STRUCTURE_TYPE_RAY_TRACING_SHADER_GROUP_CREATE_INFO_KHR
  - VK_STRUCTURE_TYPE_COPY_ACCELERATION_STRUCTURE_INFO_KHR
  - VK_STRUCTURE_TYPE_COPY_ACCELERATION_STRUCTURE_TO_MEMORY_INFO_KHR
  - VK_STRUCTURE_TYPE_COPY_MEMORY_TO_ACCELERATION_STRUCTURE_INFO_KHR

- Extending VkShaderStageFlagBits:
  - VK_SHADER_STAGE_RAYGEN_BIT_KHR
  - VK_SHADER_STAGE_ANY_HIT_BIT_KHR
  - VK_SHADER_STAGE_CLOSEST_HIT_BIT_KHR
  - VK_SHADER_STAGE_MISS_BIT_KHR
  - VK_SHADER_STAGE_INTERSECTION_BIT_KHR
  - VK_SHADER_STAGE_CALLABLE_BIT_KHR
• Extending VkPipelineStageFlagBits:
  ◦ VK_PIPELINE_STAGE_RAY_TRACING_SHADER_BIT_KHR
  ◦ VK_PIPELINE_STAGE_ACCELERATION_STRUCTURE_BUILD_BIT_KHR

• Extending VkBufferUsageFlagBits:
  ◦ VK_BUFFER_USAGE_RAY_TRACING_BIT_KHR

• Extending VkPipelineBindPoint:
  ◦ VK_PIPELINE_BIND_POINT_RAY_TRACING_KHR

• Extending VkDescriptorType:
  ◦ VK_DESCRIPTOR_TYPE_ACCELERATION_STRUCTURE_KHR

• Extending VkAccessFlagBits:
  ◦ VK_ACCESS_ACCELERATION_STRUCTURE_READ_BIT_KHR
  ◦ VK_ACCESS_ACCELERATION_STRUCTURE_WRITE_BIT_KHR

• Extending VkQueryType:
  ◦ VK_QUERY_TYPE_ACCELERATION_STRUCTURE_COMPACTED_SIZE_KHR
  ◦ VK_QUERY_TYPE_ACCELERATION_STRUCTURE_SERIALIZATION_SIZE_KHR

• Extending VkObjectType:
  ◦ VK_OBJECT_TYPE_ACCELERATION_STRUCTURE_KHR

• Extending VkDebugReportObjectTypeEXT:
  ◦ VK_DEBUG_REPORT_OBJECT_TYPE_ACCELERATION_STRUCTURE_KHR_EXT

• Extending VkIndexType:
  ◦ VK_INDEX_TYPE_NONE_KHR

• Extending VkResult:
  ◦ VK_ERROR_INCOMPATIBLE_VERSION_KHR

• Extending VkPipelineCreateFlagBits:
  ◦ VK_PIPELINE_CREATE_RAY_TRACING_SKIP_TRIANGLES_BIT_KHR
  ◦ VK_PIPELINE_CREATE_RAY_TRACING_SKIP_AABBS_BIT_KHR

**New Enums**

- VkAccelerationStructureMemoryRequirementsTypeKHR
- VkAccelerationStructureBuildTypeKHR
- VkAccelerationStructureTypeKHR
- VkBuildAccelerationStructureFlagBitsKHR
- VkCopyAccelerationStructureModeKHR
- VkGeometryFlagBitsKHR
- VkGeometryInstanceFlagBitsKHR
- VkGeometryTypeKHR
- VkRayTracingShaderGroupTypeKHR
New Structures

- VkAabbPositionsKHR
- VkAccelerationStructureBuildGeometryInfoKHR
- VkAccelerationStructureBuildOffsetInfoKHR
- VkAccelerationStructureCreateGeometryTypeInfoKHR
- VkAccelerationStructureCreateInfoKHR
- VkAccelerationStructureDeviceAddressInfoKHR
- VkAccelerationStructureGeometryAabbsDataKHR
- VkAccelerationStructureGeometryDataKHR
- VkAccelerationStructureGeometryInstancesDataKHR
- VkAccelerationStructureGeometryKHR
- VkAccelerationStructureGeometryTrianglesDataKHR
- VkAccelerationStructureInstanceKHR
- VkAccelerationStructureMemoryRequirementsInfoKHR
- VkAccelerationStructureVersionKHR
- VkBindAccelerationStructureMemoryInfoKHR
- VkTraceRaysIndirectCommandKHR
- VkCopyAccelerationStructureInfoKHR
- VkCopyAccelerationStructureToMemoryInfoKHR
- VkCopyMemoryToAccelerationStructureInfoKHR
- VkDeviceOrHostAddressKHR
- VkDeviceOrHostAddressConstKHR
- VkPhysicalDeviceRayTracingFeaturesKHR
- VkPhysicalDeviceRayTracingPropertiesKHR
- VkRayTracingPipelineCreateInfoKHR
- VkRayTracingShaderGroupCreateInfoKHR
- VkStridedBufferRegionKHR
- VkTransformMatrixKHR
- VkWriteDescriptorSetAccelerationStructureKHR

New Functions

- vkBindAccelerationStructureMemoryKHR
- vkBuildAccelerationStructureKHR
- vkCmdBuildAccelerationStructureIndirectKHR
• vkCmdBuildAccelerationStructureKHR
• vkCmdCopyAccelerationStructureKHR
• vkCmdCopyAccelerationStructureToMemoryKHR
• vkCmdCopyMemoryToAccelerationStructureKHR
• vkCmdTraceRaysIndirectKHR
• vkCmdTraceRaysKHR
• vkCmdWriteAccelerationStructuresPropertiesKHR
• vkCreateAccelerationStructureKHR
• vkCreateRayTracingPipelinesKHR
• vkCopyAccelerationStructureKHR
• vkCopyAccelerationStructureToMemoryKHR
• vkCopyMemoryToAccelerationStructureKHR
• vkDestroyAccelerationStructureKHR
• vkGetAccelerationStructureDeviceAddressKHR
• vkGetAccelerationStructureMemoryRequirementsKHR
• vkGetDeviceAccelerationStructureCompatibilityKHR
• vkGetRayTracingCaptureReplayShaderGroupHandlesKHR
• vkGetRayTracingShaderGroupHandlesKHR
• vkWriteAccelerationStructuresPropertiesKHR

New or Modified Built-In Variables

• LaunchIDKHR
• LaunchSizeKHR
• WorldRayOriginKHR
• WorldRayDirectionKHR
• ObjectRayOriginKHR
• ObjectRayDirectionKHR
• RayTminKHR
• RayTmaxKHR
• InstanceCustomIndexKHR
• InstanceId
• ObjectToWorldKHR
• WorldToObjectKHR
• HitKindKHR
• IncomingRayFlagsKHR
• (modified)PrimitiveId
New SPIR-V Capabilities

- RayTracingProvisionalKHR
- RayQueryProvisionalKHR
- RayTraversalPrimitiveCullingProvisionalKHR

Issues

(1) How does this extension differ from VK_NV_ray_tracing?

DISCUSSION:

The following is a summary of the main functional differences between VK_KHR_ray_tracing and VK_NV_ray_tracing:

- added support for indirect ray tracing (vkCmdTraceRaysIndirectKHR)
- uses SPV_KHR_ray_tracing instead of SPV_NV_ray_tracing
  - refer to KHR SPIR-V enums instead of NV SPIR-V enums (which are functionally equivalent and aliased to the same values).
  - added RayGeometryIndexKHR built-in
- added acceleration structure serialization / deserialization
  (VK_COPY_ACCELERATION_STRUCTURE_MODE_SERIALIZE_KHR,
  VK_COPY_ACCELERATION_STRUCTURE_MODE_DESERIALIZE_KHR,
  vkCmdCopyAccelerationStructureToMemoryKHR,
  vkCmdCopyMemoryToAccelerationStructureKHR)
- removed vkCompileDeferredNV compilation functionality and replaced with deferred host operations interactions for ray tracing
- document inactive primitives and instances
- added VkPhysicalDeviceRayTracingFeaturesKHR structure
- extended VkPhysicalDeviceRayTracingPropertiesKHR
  - maxRecursionDepth has a minimum of 1 instead of 31
  - require shaderGroupHandleSize to be 32 bytes
- added indirect and batched acceleration structure builds (vkCmdBuildAccelerationStructureIndirectKHR)
- added host acceleration structure commands
- reworked geometry structures so they could be better shared between device, host, and indirect builds
  - added geometryArrayOfPointers and made instances more like triangles and AABBs.
  - changed SBT parameters to a structure and added size (VkStridedBufferRegionKHR)
  - explicitly made VkAccelerationStructureKHR use device addresses
- added ability to capture and replay shader group handles and acceleration structures
• added acceleration structure compatibility check function
  (vkGetDeviceAccelerationStructureCompatibilityKHR)

• add parameter for requesting memory requirements for host and/or device build

• added pipeline library support for ray tracing

• added watertightness guarantees

• added format feature for acceleration structure build vertex formats
  (VK_FORMAT_FEATURE_ACCELERATION_STRUCTURE_VERTEX_BUFFER_BIT_KHR)

• added no-null-shader pipeline flags (VK_PIPELINE_CREATE_RAY_TRACING_NO_NULL_*_SHADERS_BIT_KHR)

• added memory model interactions with ray tracing and define how subgroups work and can be repacked

• added ray query and SPV_KHR_ray_query support

**Sample Code**

Example ray generation GLSL shader

```glsl
#version 450 core
#extension GL_EXT_ray_tracing : require
layout(set = 0, binding = 0, rgba8) uniform image2D image;
layout(set = 0, binding = 1) uniform accelerationStructureEXT as;
layout(location = 0) rayPayloadEXT float payload;

void main()
{
    vec4 col = vec4(0, 0, 0, 1);

    vec3 origin = vec3(float(gl_LaunchIDEXT.x)/float(gl_LaunchSizeEXT.x), float(gl_LaunchIDEXT.y)/float(gl_LaunchSizeEXT.y), 1.0);
    vec3 dir = vec3(0.0, 0.0, -1.0);

    traceRayEXT(as, 0, 0xff, 0, 1, 0, origin, 0.0, dir, 1000.0, 0);

    col.y = payload;

    imageStore(image, ivec2(gl_LaunchIDEXT.xy), col);
}
```

**Version History**

• Revision 1, 2019-12-05 (Members of the Vulkan Ray Tracing TSG)
  ◦ Internal revisions (forked from NV_ray_tracing)

• Revision 2, 2019-12-20 (Daniel Koch, Eric Werness)
  ◦ Add const version of DeviceOrHostAddress (!3515)
  ◦ Add VU to clarify that only handles in the current pipeline are valid (!3518)
- Restore some missing VUs and add in-place update language (#1902, !3522)
- rename VkAccelerationStructureInstanceKHR member from accelerationStructure to accelerationStructureReference to better match its type (!3523)
- Allow VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS for pipeline creation if shader group handles cannot be re-used. (!3523)
- update documentation for the VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS error code and add missing documentation for new return codes from VK_KHR_deferred_host_operations (!3523)
- list new query types for VK_KHR_ray_tracing (!3523)
- Fix VU statements for VkAccelerationStructureGeometryKHR referring to correct union members and update to use more current wording (!3523)

- Revision 3, 2020-01-10 (Daniel Koch, Jon Leech, Christoph Kubisch)
  - Fix `instance of` and `that/which contains/defines` markup issues (!3528)
  - factor out VK_KHR_pipeline_library as stand-alone extension (!3540)
  - Resolve Vulkan-hpp issues (!3543)
  - add missing require for VkGeometryInstanceFlagsKHR
  - de-alias VK_STRUCTURE_TYPE_ACCELERATION_STRUCTURE_CREATE_INFO_NV since the KHR structure is no longer equivalent
  - add len to pDataSize attribute for vkWriteAccelerationStructuresPropertiesKHR

- Revision 4, 2020-01-23 (Daniel Koch, Eric Werness)
  - Improve vkWriteAccelerationStructuresPropertiesKHR, add return value and VUs (#1947)
  - Clarify language to allow multiple raygen shaders (#1959)
  - Various editorial feedback (!3556)
  - Add language to help deal with looped self-intersecting fans (#1901)
  - Change vkCmdTraceRays{Indirect}KHR args to pointers (!3559)
  - Add scratch address validation language (#1941, !3551)
  - Fix definition and add hierarchy information for shader call scope (#1977, !3571)

- Revision 5, 2020-02-04 (Eric Werness, Jeff Bolz, Daniel Koch)
  - remove vestigial accelerationStructureUUID (!3582)
  - update definition of repack instructions and improve memory model interactions (#1910, #1913, !3584)
  - Fix wrong sType for VkPhysicalDeviceRayTracingFeaturesKHR (#1988)
  - Use provisional SPIR-V capabilities (#1987)
  - require rayTracingPrimitiveCulling if rayQuery is supported (#1927)
  - Miss shaders do not have object parameters (!3592)
  - Fix missing required types in XML (!3592)
  - clarify matching conditions for update (!3592)
• add goal that host and device builds be similar (!3592)
• clarify that maxPrimitiveCount limit should apply to triangles and AABBs (!3592)
• Require alignment for instance arrayOfPointers (!3592)
• Zero is a valid value for instance flags (!3592)
• Add some alignment VUs that got lost in refactoring (!3592)
• Recommend TMin epsilon rather than culling (!3592)
• Get angle from dot product not cross product (!3592)
• Clarify that AH can access the payload and attributes (!3592)
• Match DXR behavior for inactive primitive definition (!3592)
• Use a more generic term than degenerate for inactive to avoid confusion (!3592)

• Revision 6, 2020-02-20 (Daniel Koch)
  • fix some dangling NV references (#1996)
  • rename VkCmdTraceRaysIndirectCommandKHR to VkTraceRaysIndirectCommandKHR (!3607)
  • update contributor list (!3611)
  • use uint64_t instead of VkAccelerationStructureReferenceKHR in VkAccelerationStructureInstanceKHR (#2004)

• Revision 7, 2020-02-28 (Tobias Hector)
  • remove HitTKHR SPIR-V builtin (spirv/spirv-extensions#7)

• Revision 8, 2020-03-06 (Tobias Hector, Dae Kim, Daniel Koch, Jeff Bolz, Eric Werness)
  • explicitly state that Tmax is updated when new closest intersection is accepted (#2020,#3536)
  • Made references to min and max t values consistent (#3644)
  • finish enumerating differences relative to NV_ray_tracing in issues (1) and (2) (#1974,#3642)
  • fix formatting in some math equations (#3642)
  • Restrict the Hit Kind operand of OpReportIntersectionKHR to 7-bits (spirv/spirv-extensions#8,#3646)
  • Say raytracing 'should' be watertight (#2008,#3631)
  • Clarify memory requirements for ray tracing buffers (#2005,#3649)
  • Add callable size limits (#1997,#3652)

List of Deprecated Extensions

• VK_KHR_16bit_storage
• VK_KHR_bind_memory2
• VK_KHR_dedicated_allocation
• VK_KHR_descriptor_update_template
• VK_KHR_device_group
VK_KHR_device_group_creation
VK_KHR_external_fence
VK_KHR_external_fence_capabilities
VK_KHR_external_memory
VK_KHR_external_memory_capabilities
VK_KHR_external_semaphore
VK_KHR_external_semaphore_capabilities
VK_KHR_get_memory_requirements2
VK_KHR_get_physical_device_properties2
VK_KHR_maintenance1
VK_KHR_maintenance2
VK_KHR_maintenance3
VK_KHR_multiview
VK_KHR_relaxed_block_layout
VK_KHR_sampler_ycbcr_conversion
VK_KHR_shader_draw_parameters
VK_KHR_storage_buffer_storage_class
VK_KHR_variable_pointers
VK_KHR_16bit_storage

Name String

    VK_KHR_16bit_storage

Extension Type

    Device extension

Registered Extension Number

    84

Revision

    1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2
- Requires VK_KHR_storage_buffer_storage_class

Deprecation state

- Promoted to Vulkan 1.1

Contact

- Jan-Harald Fredriksen @janharaldfredriksen-arm

Other Extension Metadata

Last Modified Date

    2017-09-05

IP Status

    No known IP claims.

Interactions and External Dependencies

- This extension requires SPV_KHR_16bit_storage
- Promoted to Vulkan 1.1 Core

Contributors

- Alexander Galazin, ARM
- Jan-Harald Fredriksen, ARM
- Joerg Wagner, ARM
- Neil Henning, Codeplay
- Jeff Bolz, Nvidia
- Daniel Koch, Nvidia
- David Neto, Google
Description

The `VK_KHR_16bit_storage` extension allows use of 16-bit types in shader input and output interfaces, and push constant blocks. This extension introduces several new optional features which map to SPIR-V capabilities and allow access to 16-bit data in `Block`-decorated objects in the `Uniform` and the `StorageBuffer` storage classes, and objects in the `PushConstant` storage class. This extension allows 16-bit variables to be declared and used as user-defined shader inputs and outputs but does not change location assignment and component assignment rules.

New Enum Constants

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES_KHR`

New Structures

- `VkPhysicalDevice16BitStorageFeaturesKHR`

New SPIR-V Capabilities

- `StorageBuffer16BitAccess`
- `UniformAndStorageBuffer16BitAccess`
- `StoragePushConstant16`
- `StorageInputOutput16`

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

Version History

- Revision 1, 2017-03-23 (Alexander Galazin)
  - Initial draft

VK_KHR_bind_memory2

Name String

- `VK_KHR_bind_memory2`

Extension Type

- Device extension
This extension provides versions of `vkBindBufferMemory` and `vkBindImageMemory` that allow multiple bindings to be performed at once, and are extensible.

This extension also introduces `VK_IMAGE_CREATE_ALIAS_BIT_KHR`, which allows “identical” images that alias the same memory to interpret the contents consistently, even across image layout changes.
• Extending VkImageCreateFlagBits:
  ◦ VK_IMAGE_CREATE_ALIAS_BIT_KHR

New Enums
None.

New Structures
• VkBindBufferMemoryInfoKHR
• VkBindImageMemoryInfoKHR

New Functions
• vkBindBufferMemory2KHR
• vkBindImageMemory2KHR

New Built-In Variables
None.

New SPIR-V Capabilities
None.

Promotion to Vulkan 1.1
All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues
None.

Version History
• Revision 1, 2017-05-19 (Tobias Hector)
  ◦ Pulled bind memory functions into their own extension

VK_KHR_dedicated_allocation

Name String
VK_KHR_dedicated_allocation

Extension Type
Device extension
Description

This extension enables resources to be bound to a dedicated allocation, rather than suballocated. For any particular resource, applications can query whether a dedicated allocation is recommended, in which case using a dedicated allocation may improve the performance of access to that resource. Normal device memory allocations must support multiple resources per allocation, memory aliasing and sparse binding, which could interfere with some optimizations. Applications should query the implementation for when a dedicated allocation may be beneficial by adding a VkMemoryDedicatedRequirementsKHR structure to the pNext chain of the VkMemoryRequirements2 structure passed as the pMemoryRequirements parameter of a call to vkGetBufferMemoryRequirements2 or vkGetImageMemoryRequirements2. Certain external handle types and external images or buffers may also depend on dedicated allocations on implementations that associate image or buffer metadata with OS-level memory objects.

This extension adds a two small structures to memory requirements querying and memory allocation: a new structure that flags whether an image/buffer should have a dedicated allocation,
and a structure indicating the image or buffer that an allocation will be bound to.

New Object Types
None.

New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS_KHR
  - VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO_KHR

New Enums
None.

New Structures

- VkMemoryDedicatedRequirementsKHR
- VkMemoryDedicatedAllocateInfoKHR

New Functions
None.

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues
None.

Examples

```c
// Create an image with a dedicated allocation based on the
// implementation's preference

VkImageCreateInfo imageCreateInfo =
{
    // Image creation parameters
};

VkImage image;
VkResult result = vkCreateImage(
    device,
    @imageCreateInfo,
```
VkMemoryDedicatedRequirementsKHR dedicatedRequirements =
{
    VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS_KHR,
    NULL,  // pNext
};

VkMemoryRequirements2 memoryRequirements =
{
    VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2,
    &dedicatedRequirements,  // pNext
};

const VkImageMemoryRequirementsInfo2 imageRequirementsInfo =
{
    VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2,
    NULL,  // pNext
    image
};

vkGetImageMemoryRequirements2(
    device,
    &imageRequirementsInfo,
    &memoryRequirements);

if (dedicatedRequirements.prefersDedicatedAllocation) {
    // Allocate memory with VkMemoryDedicatedAllocateInfoKHR::image
    // pointing to the image we are allocating the memory for

    VkMemoryDedicatedAllocateInfoKHR dedicatedInfo =
    {
        VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO_KHR,  // sType
        NULL,  // pNext
        image,  // image
        VK_NULL_HANDLE,  // buffer
    };

    VkMemoryAllocateInfo memoryAllocateInfo =
    {
        VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO,  // sType
        &dedicatedInfo,  // pNext
        memoryRequirements.size,  // allocationSize
        FindMemoryTypeIndex(memoryRequirements.memoryTypeBits),  // memoryTypeIndex
    };

    VkDeviceMemory memory;
    vkAllocateMemory(
        device,
        &memoryAllocateInfo,
        &memory);
NULL, // pAllocator
&mmemory);

// Bind the image to the memory

vkBindImageMemory(
        device,
        image,
        memory,
        0);
} else {
    // Take the normal memory sub-allocation path
}

Version History

- Revision 1, 2017-02-27 (James Jones)
  ◦ Copy content from VK_NV_dedicated_allocation
  ◦ Add some references to external object interactions to the overview.
- Revision 2, 2017-03-27 (Jason Ekstrand)
  ◦ Rework the extension to be query-based
- Revision 3, 2017-07-31 (Jason Ekstrand)
  ◦ Clarify that memory objects created with VkMemoryDedicatedAllocateInfoKHR can only
    have the specified resource bound and no others.

VK_KHR_descriptor_update_template

Name String
VK_KHR_descriptor_update_template

Extension Type
Device extension

Registered Extension Number
86

Revision
1

Extension and Version Dependencies
- Requires Vulkan 1.0

Deprecation state
- Promoted to Vulkan 1.1

Contact
Other Extension Metadata

Last Modified Date
2017-09-05

IP Status
No known IP claims.

Interactions and External Dependencies
• Interacts with VK_KHR_push_descriptor
• Promoted to Vulkan 1.1 Core

Contributors
• Jeff Bolz, NVIDIA
• Michael Worcester, Imagination Technologies

Description
Applications may wish to update a fixed set of descriptors in a large number of descriptor sets very frequently, i.e. during initializaton phase or if it is required to rebuild descriptor sets for each frame. For those cases it is also not unlikely that all information required to update a single descriptor set is stored in a single struct. This extension provides a way to update a fixed set of descriptors in a single VkDescriptorSet with a pointer to a user defined data structure describing the new descriptors.

New Object Types
• VkDescriptorUpdateTemplateKHR

New Enum Constants
Extending VkStructureType:
• VK_STRUCTURE_TYPE_DESCRIPTOR_UPDATE_TEMPLATE_CREATE_INFO_KHR

New Enums
• VkDescriptorUpdateTemplateCreateFlagsKHR
• VkDescriptorUpdateTemplateTypeKHR

New Structures
• VkDescriptorUpdateTemplateEntryKHR
• VkDescriptorUpdateTemplateCreateInfoKHR
New Functions

- `vkCreateDescriptorUpdateTemplateKHR`
- `vkDestroyDescriptorUpdateTemplateKHR`
- `vkUpdateDescriptorSetWithTemplateKHR`
- `vkCmdPushDescriptorSetWithTemplateKHR`

Promotion to Vulkan 1.1

`vkCmdPushDescriptorSetWithTemplateKHR` is included as an interaction with `VK_KHR_push_descriptor`. If Vulkan 1.1 and `VK_KHR_push_descriptor` are supported, this is included by `VK_KHR_push_descriptor`.

The base functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

- Revision 1, 2016-01-11 (Markus Tavenrath)
  - Initial draft

VK_KHR_device_group

Name String

- `VK_KHR_device_group`

Extension Type

- Device extension

Registered Extension Number

- 61

Revision

- 4

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires `VK_KHR_device_group_creation`

Deprecation state

- *Promoted* to Vulkan 1.1

Contact

- Jeff Bolz [jeffbolznv](mailto:jeffbolznv)
Other Extension Metadata

Last Modified Date
2017-10-10

IP Status
No known IP claims.

Interactions and External Dependencies
• Promoted to Vulkan 1.1 Core

Contributors
• Jeff Bolz, NVIDIA
• Tobias Hector, Imagination Technologies

Description
This extension provides functionality to use a logical device that consists of multiple physical devices, as created with the `VK_KHR_device_group_creation` extension. A device group can allocate memory across the subdevices, bind memory from one subdevice to a resource on another subdevice, record command buffers where some work executes on an arbitrary subset of the subdevices, and potentially present a swapchain image from one or more subdevices.

New Object Types
None.

New Enum Constants
• Extending `VkStructureType`:
  o `VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO_KHR`
  o `VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO_KHR`
  o `VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO_KHR`
  o `VK_STRUCTURE_TYPE_DEVICE_GROUP_SUBMIT_INFO_KHR`
  o `VK_STRUCTURE_TYPEDEVICE_GROUP_BIND_SPARSE_INFO_KHR`
  o `VK_STRUCTURE_TYPE_DEVICE_GROUP_PRESENT_CAPABILITIES_KHR`
  o `VK_STRUCTURE_TYPE_IMAGE_SWAPCHAIN_CREATE_INFO_KHR`
  o `VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_SWAPCHAIN_INFO_KHR`
  o `VK_STRUCTURE_TYPE_ACQUIRE_NEXT_IMAGE_INFO_KHR`
  o `VK_STRUCTURE_TYPE_DEVICE_GROUP_PRESENT_INFO_KHR`
  o `VK_STRUCTURE_TYPE_DEVICE_GROUP_SWAPCHAIN_CREATE_INFO_KHR`
  o `VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO_KHR`
  o `VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORYDEVICE_GROUP_INFO_KHR`
• Extending `VkImageCreateFlagBits`
  o `VK_IMAGE_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR`
• Extending VkPipelineCreateFlagBits
  ◦ VK_PIPELINE_CREATE_VIEW_INDEX_FROM_DEVICE_INDEX_BIT_KHR
  ◦ VK_PIPELINE_CREATE_DISPATCH_BASE_KHR
• Extending VkDependencyFlagBits
  ◦ VK_DEPENDENCY_DEVICE_GROUP_BIT_KHR
• Extending VkSwapchainCreateFlagBitsKHR
  ◦ VK_SWAPCHAIN_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR

New Enums

• VkPeerMemoryFeatureFlagBitsKHR
• VkMemoryAllocateFlagBitsKHR
• VkDeviceGroupPresentModeFlagBitsKHR

New Structures

• VkMemoryAllocateFlagsInfoKHR
• VkDeviceGroupRenderPassBeginInfoKHR
• VkDeviceGroupCommandBufferBeginInfoKHR
• VkDeviceGroupSubmitInfoKHR
• VkDeviceGroupBindSparseInfoKHR
• VkBindBufferMemoryDeviceGroupInfoKHR
• VkBindImageMemoryDeviceGroupInfoKHR
• VkDeviceGroupPresentCapabilitiesKHR
• VkImageSwapchainCreateInfoKHR
• VkBindImageMemorySwapchainInfoKHR
• VkAcquireNextImageInfoKHR
• VkDeviceGroupPresentInfoKHR
• VkDeviceGroupSwapchainCreateInfoKHR

New Functions

• vkGetDeviceGroupPeerMemoryFeaturesKHR
• vkCmdSetDeviceMaskKHR
• vkCmdDispatchBaseKHR
• vkGetDeviceGroupPresentCapabilitiesKHR
• vkGetDeviceGroupSurfacePresentModesKHR
• vkGetPhysicalDevicePresentRectanglesKHR
• vkAcquireNextImage2KHR
New Built-In Variables

- DeviceIndex

New SPIR-V Capabilities

- DeviceGroup

Promotion to Vulkan 1.1

The following enums, types and commands are included as interactions with VK_KHR_swapchain:

- VK_STRUCTURE_TYPE_DEVICE_GROUP_PRESENT_CAPABILITIES_KHR
- VK_STRUCTURE_TYPE_IMAGE_SWAPCHAIN_CREATE_INFO_KHR
- VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_SWAPCHAIN_INFO_KHR
- VK_STRUCTURE_TYPE_ACQUIRE_NEXT_IMAGE_INFO_KHR
- VK_STRUCTURE_TYPE_DEVICE_GROUP_PRESENT_INFO_KHR
- VK_STRUCTURE_TYPE_DEVICE_GROUP_SWAPCHAIN_CREATE_INFO_KHR
- VK_SWAPCHAIN_CREATE_SPLIT_INSTANCE_BIND_REGIONS_BIT_KHR
- VkDeviceGroupPresentModeFlagBitsKHR
- VkDeviceGroupPresentCapabilitiesKHR
- VkImageSwapchainCreateInfoKHR
- VkBindImageMemorySwapchainInfoKHR
- VkAcquireNextImageInfoKHR
- VkDeviceGroupPresentInfoKHR
- VkDeviceGroupSwapchainCreateInfoKHR
- vkGetDeviceGroupPresentCapabilitiesKHR
- vkGetDeviceGroupSurfacePresentModesKHR
- vkGetPhysicalDevicePresentRectanglesKHR
- vkAcquireNextImage2KHR

If Vulkan 1.1 and VK_KHR_swapchain are supported, these are included by VK_KHR_swapchain.

The base functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None.

Examples

TODO
Version History

- Revision 1, 2016-10-19 (Jeff Bolz)
  - Internal revisions

- Revision 2, 2017-05-19 (Tobias Hector)
  - Removed extended memory bind functions to VK_KHR_bind_memory2, added dependency on that extension, and device-group-specific structs for those functions.

- Revision 3, 2017-10-06 (Ian Elliott)
  - Corrected Vulkan 1.1 interactions with the WSI extensions. All Vulkan 1.1 WSI interactions are with the VK_KHR_swapchain extension.

- Revision 4, 2017-10-10 (Jeff Bolz)
  - Rename "SFR" bits and structure members to use the phrase "split instance bind regions".

VK_KHR_device_group_creation

Name String

VK_KHR_device_group_creation

Extension Type

Instance extension

Registered Extension Number

71

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0

Deprecation state

- Promoted to Vulkan 1.1

Contact

- Jeff Bolz ♦️jeffbolznv

Other Extension Metadata

Last Modified Date

2016-10-19

IP Status

No known IP claims.

Interactions and External Dependencies

- Promoted to Vulkan 1.1 Core
Contributors

• Jeff Bolz, NVIDIA

Description

This extension provides instance-level commands to enumerate groups of physical devices, and to create a logical device from a subset of one of those groups. Such a logical device can then be used with new features in the VK_KHR_device_group extension.

New Object Types

None.

New Enum Constants

- Extending VkStructureType:
  - VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_PROPERTIES_KHR
  - VK_STRUCTURE_TYPE_DEVICE_GROUP_DEVICE_CREATE_INFO_KHR
- Extending VkMemoryHeapFlagBits
  - VK_MEMORY_HEAP_MULTI_INSTANCE_BIT_KHR

New Enums

None.

New Structures

- VkPhysicalDeviceGroupPropertiesKHR
- VkDeviceGroupDeviceCreateInfoKHR

New Functions

- vkEnumeratePhysicalDeviceGroupsKHR

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None.

Examples
VkDeviceCreateInfo devCreateInfo = { VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO};
// (not shown) fill out devCreateInfo as usual.
uint32_t deviceGroupCount = 0;
VkPhysicalDeviceGroupPropertiesKHR *props = NULL;

// Query the number of device groups
vkEnumeratePhysicalDeviceGroupsKHR(g_vkInstance, &deviceGroupCount, NULL);

// Allocate and initialize structures to query the device groups
props = (VkPhysicalDeviceGroupPropertiesKHR *)malloc(deviceGroupCount*sizeof(VkPhysicalDeviceGroupPropertiesKHR));
for (i = 0; i < deviceGroupCount; ++i) {
    props[i].sType = VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_GROUP_PROPERTIES_KHR;
    props[i].pNext = NULL;
}
vkEnumeratePhysicalDeviceGroupsKHR(g_vkInstance, &deviceGroupCount, props);

// If the first device group has more than one physical device. create a logical device using all of the physical devices.
VkDeviceGroupDeviceCreateInfoKHR deviceGroupInfo = {
    VK_STRUCTURE_TYPE_DEVICE_GROUP_DEVICE_CREATE_INFO_KHR
};
if (props[0].physicalDeviceCount > 1) {
    deviceGroupInfo.physicalDeviceCount = props[0].physicalDeviceCount;
    deviceGroupInfo.pPhysicalDevices = props[0].pPhysicalDevices;
    devCreateInfo.pNext = &deviceGroupInfo;
}

vkCreateDevice(props[0].pPhysicalDevices[0], &devCreateInfo, NULL, &g_vkDevice);
free(props);

Version History

- Revision 1, 2016-10-19 (Jeff Bolz)
  - Internal revisions

VK_KHR_external_fence

Name String

VK_KHR_external_fence

Extension Type

Device extension

Registered Extension Number

114

Revision

1
Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires `VK_KHR_external_fence_capabilities`

Deprecation state

- Promoted to Vulkan 1.1

Contact

- Jesse Hall @critsec

Other Extension Metadata

Last Modified Date

2017-05-08

IP Status

No known IP claims.

Interactions and External Dependencies

- Promoted to Vulkan 1.1 Core

Contributors

- Jesse Hall, Google
- James Jones, NVIDIA
- Jeff Juliano, NVIDIA
- Cass Everitt, Oculus
- Contributors to `VK_KHR_external_semaphore`

Description

An application using external memory may wish to synchronize access to that memory using fences. This extension enables an application to create fences from which non-Vulkan handles that reference the underlying synchronization primitive can be exported.

New Object Types

None.

New Enum Constants

- `VK_STRUCTURE_TYPE_EXPORT_FENCE_CREATE_INFO_KHR`

New Enums

- `VkFenceImportFlagBitsKHR`
New Structs

- VkExportFenceCreateInfoKHR

New Functions

None.

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

This extension borrows concepts, semantics, and language from VK_KHR_external_semaphore. That extension’s issues apply equally to this extension.

Version History

- Revision 1, 2017-05-08 (Jesse Hall)
  - Initial revision

VK_KHR_external_fence_capabilities

Name String

VK_KHR_external_fence_capabilities

Extension Type

Instance extension

Registered Extension Number

113

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

Deprecation state

- Promoted to Vulkan 1.1

Contact

- Jesse Hall @critsec
Other Extension Metadata

Last Modified Date
2017-05-08

IP Status
No known IP claims.

Interactions and External Dependencies
• Promoted to Vulkan 1.1 Core

Contributors
• Jesse Hall, Google
• James Jones, NVIDIA
• Jeff Juliano, NVIDIA
• Cass Everitt, Oculus
• Contributors to VK_KHR_external_semaphore_capabilities

Description
An application may wish to reference device fences in multiple Vulkan logical devices or instances, in multiple processes, and/or in multiple APIs. This extension provides a set of capability queries and handle definitions that allow an application to determine what types of “external” fence handles an implementation supports for a given set of use cases.

New Object Types
None.

New Enum Constants
• VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_FENCE_INFO_KHR
• VK_STRUCTURE_TYPE_EXTERNAL_FENCE_PROPERTIES_KHR
• VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ID_PROPERTIES_KHR
• VK_LUID_SIZE_KHR

New Enums
• VkExternalFenceHandleTypeFlagBitsKHR
• VkExternalFenceFeatureFlagBitsKHR

New Structs
• VkPhysicalDeviceExternalFenceInfoKHR
• VkExternalFencePropertiesKHR
• VkPhysicalDeviceIDPropertiesKHR
New Functions

• *vkGetPhysicalDeviceExternalFencePropertiesKHR*

**Promotion to Vulkan 1.1**

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

**Issues**

None.

**Version History**

• Revision 1, 2017-05-08 (Jesse Hall)
  ◦ Initial version

**VK_KHR_external_memory**

**Name String**

`VK_KHR_external_memory`

**Extension Type**

Device extension

**Registered Extension Number**

73

**Revision**

1

**Extension and Version Dependencies**

• Requires Vulkan 1.0
  
  • Requires `VK_KHR_external_memory_capabilities`

**Deprecation state**

• *Promoted to Vulkan 1.1*

**Contact**

• James Jones 🌱cubanismo

**Other Extension Metadata**

**Last Modified Date**

2016-10-20
IP Status
No known IP claims.

Interactions and External Dependencies
- Interacts with VK_KHR_dedicated_allocation.
- Interacts with [VK_NV_dedicated_allocation].
- Promoted to Vulkan 1.1 Core

Contributors
- Jason Ekstrand, Intel
- Ian Elliot, Google
- Jesse Hall, Google
- Tobias Hector, Imagination Technologies
- James Jones, NVIDIA
- Jeff Juliano, NVIDIA
- Matthew Netsch, Qualcomm Technologies, Inc.
- Daniel Rakos, AMD
- Carsten Rohde, NVIDIA
- Ray Smith, ARM
- Chad Versace, Google

Description
An application may wish to reference device memory in multiple Vulkan logical devices or instances, in multiple processes, and/or in multiple APIs. This extension enables an application to export non-Vulkan handles from Vulkan memory objects such that the underlying resources can be referenced outside the scope of the Vulkan logical device that created them.

New Object Types
None.

New Enum Constants
- VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO_KHR
- VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_IMAGE_CREATE_INFO_KHR
- VK_STRUCTURE_TYPE_EXPORT_MEMORY_ALLOCATE_INFO_KHR
- VK_QUEUE_FAMILY_EXTERNAL_KHR
- VK_ERROR_INVALID_EXTERNAL_HANDLE_KHR

New Enums
None.
New Structs

- VkExternalMemoryImageCreateInfoKHR
- VkExternalMemoryBufferCreateInfoKHR
- VkExportMemoryAllocateInfoKHR

New Functions

None.

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

1) How do applications correlate two physical devices across process or Vulkan instance boundaries?

**RESOLVED:** New device ID fields have been introduced by `VK_KHR_external_memory_capabilities`. These fields, combined with the existing `VkPhysicalDeviceProperties::driverVersion` field can be used to identify compatible devices across processes, drivers, and APIs. `VkPhysicalDeviceProperties::pipelineCacheUUID` is not sufficient for this purpose because despite its description in the specification, it need only identify a unique pipeline cache format in practice. Multiple devices may be able to use the same pipeline cache data, and hence it would be desirable for all of them to have the same pipeline cache UUID. However, only the same concrete physical device can be used when sharing memory, so an actual unique device ID was introduced. Further, the pipeline cache UUID was specific to Vulkan, but correlation with other, non-extensible APIs is required to enable interoperation with those APIs.

2) If memory objects are shared between processes and APIs, is this considered aliasing according to the rules outlined in the Memory Aliasing section?

**RESOLVED:** Yes. Applications must take care to obey all restrictions imposed on aliased resources when using memory across multiple Vulkan instances or other APIs.

3) Are new image layouts or metadata required to specify image layouts and layout transitions compatible with non-Vulkan APIs, or with other instances of the same Vulkan driver?

**RESOLVED:** Separate instances of the same Vulkan driver running on the same GPU should have identical internal layout semantics, so applications have the tools they need to ensure views of images are consistent between the two instances. Other APIs will fall into two categories: Those that are Vulkan-compatible, and those that are Vulkan-incompatible. Vulkan-incompatible APIs will require the image to be in the GENERAL layout whenever they are accessing them.

Note this does not attempt to address cross-device transitions, nor transitions to engines on the same device which are not visible within the Vulkan API. Both of these are beyond the scope of this extension.
4) Is a new barrier flag or operation of some type needed to prepare external memory for handoff to another Vulkan instance or API and/or receive it from another instance or API?

**RESOLVED:** Yes. Some implementations need to perform additional cache management when transitioning memory between address spaces, and other APIs, instances, or processes may operate in a separate address space. Options for defining this transition include:

- A new structure that can be added to the `pNext` list in `VkMemoryBarrier`, `VkBufferMemoryBarrier`, and `VkImageMemoryBarrier`.
- A new bit in `VkAccessFlags` that can be set to indicate an “external” access.
- A new bit in `VkDependencyFlags`.
- A new special queue family that represents an “external” queue.

A new structure has the advantage that the type of external transition can be described in as much detail as necessary. However, there is not currently a known need for anything beyond differentiating external vs. internal accesses, so this is likely an over-engineered solution. The access flag bit has the advantage that it can be applied at buffer, image, or global granularity, and semantically it maps pretty well to the operation being described. Additionally, the API already includes `VK_ACCESS_MEMORY_READ_BIT` and `VK_ACCESS_MEMORY_WRITE_BIT` which appear to be intended for this purpose. However, there is no obvious pipeline stage that would correspond to an external access, and therefore no clear way to use `VK_ACCESS_MEMORY_READ_BIT` or `VK_ACCESS_MEMORY_WRITE_BIT`. `VkDependencyFlags` and `VkPipelineStageFlags` operate at command granularity rather than image or buffer granularity, which would make an entire pipeline barrier an internal → external or external → internal barrier. This may not be a problem in practice, but seems like the wrong scope. Another downside of `VkDependencyFlags` is that it lacks inherent directionality: There are not `src` and `dst` variants of it in the barrier or dependency description semantics, so two bits might need to be added to describe both internal → external and external → internal transitions. Transitioning a resource to a special queue family corresponds well with the operation of transitioning to a separate Vulkan instance, in that both operations ideally include scheduling a barrier on both sides of the transition: Both the releasing and the acquiring queue or process. Using a special queue family requires adding an additional reserved queue family index. Re-using `VK_QUEUE_FAMILY_IGNORED` would have left it unclear how to transition a concurrent usage resource from one process to another, since the semantics would have likely been equivalent to the currently-ignored transition of `VK_QUEUE_FAMILY_IGNORED` → `VK_QUEUE_FAMILY_IGNORED`. Fortunately, creating a new reserved queue family index is not invasive.

Based on the above analysis, the approach of transitioning to a special “external” queue family was chosen.

5) Do internal driver memory arrangements and/or other internal driver image properties need to be exported and imported when sharing images across processes or APIs?

**RESOLVED:** Some vendors claim this is necessary on their implementations, but it was determined that the security risks of allowing opaque meta data to be passed from applications to the driver were too high. Therefore, implementations which require metadata will need to associate it with the objects represented by the external handles, and rely on the dedicated allocation mechanism to associate the exported and imported memory objects with a single image or buffer.
6) Most prior interoperation and cross-process sharing APIs have been based on image-level sharing. Should Vulkan sharing be based on memory-object sharing or image sharing?

**RESOLVED:** These extensions have assumed memory-level sharing is the correct granularity. Vulkan is a lower-level API than most prior APIs, and as such attempts to closely align with to the underlying primitives of the hardware and system-level drivers it abstracts. In general, the resource that holds the backing store for both images and buffers of various types is memory. Images and buffers are merely metadata containing brief descriptions of the layout of bits within that memory.

Because memory object-based sharing is aligned with the overall Vulkan API design, it exposes the full power of Vulkan on external objects. External memory can be used as backing for sparse images, for example, whereas such usage would be awkward at best with a sharing mechanism based on higher-level primitives such as images. Further, aligning the mechanism with the API in this way provides some hope of trivial compatibility with future API enhancements. If new objects backed by memory objects are added to the API, they too can be used across processes with minimal additions to the base external memory APIs.

Earlier APIs implemented interop at a higher level, and this necessitated entirely separate sharing APIs for images and buffers. To co-exist and interoperate with those APIs, the Vulkan external sharing mechanism must accommodate their model. However, if it can be agreed that memory-based sharing is the more desirable and forward-looking design, legacy interoperation considerations can be considered another reason to favor memory-based sharing: While native and legacy driver primitives that may be used to implement sharing may not be as low-level as the API here suggests, raw memory is still the least common denominator among the types. Image-based sharing can be cleanly derived from a set of base memory-object sharing APIs with minimal effort, whereas image-based sharing does not generalize well to buffer or raw-memory sharing. Therefore, following the general Vulkan design principle of minimalism, it is better to expose even interoperability with image-based native and external primitives via the memory sharing API, and place sufficient limits on their usage to ensure they can be used only as backing for equivalent Vulkan images. This provides a consistent API for applications regardless of which platform or external API they are targeting, which makes development of multi-API and multi-platform applications simpler.

7) Should Vulkan define a common external handle type and provide Vulkan functions to facilitate cross-process sharing of such handles rather than relying on native handles to define the external objects?

**RESOLVED:** No. Cross-process sharing of resources is best left to native platforms. There are myriad security and extensibility issues with such a mechanism, and attempting to re-solve all those issues within Vulkan does not align with Vulkan’s purpose as a graphics API. If desired, such a mechanism could be built as a layer or helper library on top of the opaque native handle defined in this family of extensions.

8) Must implementations provide additional guarantees about state implicitly included in memory objects for those memory objects that may be exported?

**RESOLVED:** Implementations must ensure that sharing memory objects does not transfer any information between the exporting and importing instances and APIs other than that required to
share the data contained in the memory objects explicitly shared. As specific examples, data from previously freed memory objects that used the same underlying physical memory, and data from memory objects using adjacent physical memory must not be visible to applications importing an exported memory object.

9) Must implementations validate external handles the application provides as input to memory import operations?

**RESOLVED:** Implementations must return an error to the application if the provided memory handle cannot be used to complete the requested import operation. However, implementations need not validate handles are of the exact type specified by the application.

**Version History**

- Revision 1, 2016-10-20 (James Jones)
  - Initial version

**VK_KHR_external_memory_capabilities**

**Name String**

VK_KHR_external_memory_capabilities

**Extension Type**

Instance extension

**Registered Extension Number**

72

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

**Deprecation state**

- Promoted to Vulkan 1.1

**Contact**

- James Jones cubanismo

**Other Extension Metadata**

**Last Modified Date**

2016-10-17

**IP Status**

No known IP claims.
Interactions and External Dependencies

- Interacts with `VK_KHR_dedicated_allocation`.
- Interacts with `[VK_NV_dedicated_allocation]`.
- Promoted to Vulkan 1.1 Core

Contributors

- Ian Elliot, Google
- Jesse Hall, Google
- James Jones, NVIDIA

Description

An application may wish to reference device memory in multiple Vulkan logical devices or instances, in multiple processes, and/or in multiple APIs. This extension provides a set of capability queries and handle definitions that allow an application to determine what types of “external” memory handles an implementation supports for a given set of use cases.

New Object Types

None.

New Enum Constants

- `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_IMAGE_FORMAT_INFO_KHR`
- `VK_STRUCTURE_TYPE_EXTERNAL_IMAGE_FORMAT_PROPERTIES_KHR`
- `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_BUFFER_INFO_KHR`
- `VK_STRUCTURE_TYPE_EXTERNALBUFFER_PROPERTIES_KHR`
- `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ID_PROPERTIES_KHR`
- `VK_LUID_SIZE_KHR`

New Enums

- `VkExternalMemoryHandleTypeFlagBitsKHR`
- `VkExternalMemoryFeatureFlagBitsKHR`

New Structs

- `VkExternalMemoryPropertiesKHR`
- `VkPhysicalDeviceExternalImageFormatInfoKHR`
- `VkExternalImageFormatPropertiesKHR`
- `VkPhysicalDeviceExternalBufferInfoKHR`
- `VkExternalBufferPropertiesKHR`
- `VkPhysicalDeviceIDPropertiesKHR`
New Functions

• vkGetPhysicalDeviceExternalBufferPropertiesKHR

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

1) Why do so many external memory capabilities need to be queried on a per-memory-handle-type basis?

PROPOSED RESOLUTION: This is because some handle types are based on OS-native objects that have far more limited capabilities than the very generic Vulkan memory objects. Not all memory handle types can name memory objects that support 3D images, for example. Some handle types cannot even support the deferred image and memory binding behavior of Vulkan and require specifying the image when allocating or importing the memory object.

2) Do the VkExternalImageFormatPropertiesKHR and VkExternalBufferPropertiesKHR structs need to include a list of memory type bits that support the given handle type?

PROPOSED RESOLUTION: No. The memory types that don’t support the handle types will simply be filtered out of the results returned by vkGetImageMemoryRequirements and vkGetBufferMemoryRequirements when a set of handle types was specified at image or buffer creation time.

3) Should the non-opaque handle types be moved to their own extension?

PROPOSED RESOLUTION: Perhaps. However, defining the handle type bits does very little and does not require any platform-specific types on its own, and it’s easier to maintain the bitfield values in a single extension for now. Presumably more handle types could be added by separate extensions though, and it would be midly weird to have some platform-specific ones defined in the core spec and some in extensions.

4) Do we need a D3D11_TILEPOOL type?

PROPOSED RESOLUTION: No. This is technically possible, but the synchronization is awkward. D3D11 surfaces must be synchronized using shared mutexes, and these synchronization primitives are shared by the entire memory object, so D3D11 shared allocations divided among multiple buffer and image bindings may be difficult to synchronize.

5) Should the Windows 7-compatible handle types be named “KMT” handles or “GLOBAL_SHARE” handles?

PROPOSED RESOLUTION: KMT, simply because it is more concise.

6) How do applications identify compatible devices and drivers across instance, process, and API boundaries when sharing memory?
PROPOSED RESOLUTION: New device properties are exposed that allow applications to correctly correlate devices and drivers. A device and driver UUID that must both match to ensure sharing compatibility between two Vulkan instances, or a Vulkan instance and an extensible external API are added. To allow correlating with Direct3D devices, a device LUID is added that corresponds to a DXGI adapter LUID. A driver ID is not needed for Direct3D because mismatched driver component versions are not a currently supported configuration on the Windows OS. Should support for such configurations be introduced at the OS level, further Vulkan extensions would be needed to correlate userspace component builds.

Version History

• Revision 1, 2016-10-17 (James Jones)
  ◦ Initial version

VK_KHR_external_semaphore

Name String
  VK_KHR_external_semaphore

Extension Type
  Device extension

Registered Extension Number
  78

Revision
  1

Extension and Version Dependencies
  • Requires Vulkan 1.0
    • Requires VK_KHR_external_semaphore_capabilities

Deprecation state
  • Promoted to Vulkan 1.1

Contact
  • James Jones cubanismo

Other Extension Metadata

Last Modified Date
  2016-10-21

IP Status
  No known IP claims.

Interactions and External Dependencies
• Promoted to Vulkan 1.1 Core

Contributors
• Jason Ekstrand, Intel
• Jesse Hall, Google
• Tobias Hector, Imagination Technologies
• James Jones, NVIDIA
• Jeff Juliano, NVIDIA
• Matthew Netsch, Qualcomm Technologies, Inc.
• Ray Smith, ARM
• Chad Versace, Google

Description
An application using external memory may wish to synchronize access to that memory using semaphores. This extension enables an application to create semaphores from which non-Vulkan handles that reference the underlying synchronization primitive can be exported.

New Object Types
None.

New Enum Constants
• VK_STRUCTURE_TYPE_EXPORT_SEMAPHORE_CREATE_INFO_KHR
• VK_ERROR_INVALID_EXTERNAL_HANDLE_KHR

New Enums
• VkSemaphoreImportFlagBitsKHR

New Structs
• VkExportSemaphoreCreateInfoKHR

New Functions
None.

Promotion to Vulkan 1.1
All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.
Issues

1) Should there be restrictions on what side effects can occur when waiting on imported semaphores that are in an invalid state?

RESOLVED: Yes. Normally, validating such state would be the responsibility of the application, and the implementation would be free to enter an undefined state if valid usage rules were violated. However, this could cause security concerns when using imported semaphores, as it would require the importing application to trust the exporting application to ensure the state is valid. Requiring this level of trust is undesirable for many potential use cases.

2) Must implementations validate external handles the application provides as input to semaphore state import operations?

RESOLVED: Implementations must return an error to the application if the provided semaphore state handle cannot be used to complete the requested import operation. However, implementations need not validate handles are of the exact type specified by the application.

Version History

• Revision 1, 2016-10-21 (James Jones)
  ◦ Initial revision

VK_KHR_external_semaphore_capabilities

Name String

VK_KHR_external_semaphore_capabilities

Extension Type

Instance extension

Registered Extension Number

77

Revision

1

Extension and Version Dependencies

• Requires Vulkan 1.0
• Requires VK_KHR_get_physical_device_properties2

Deprecation state

• Promoted to Vulkan 1.1

Contact

• James Jones cubanismo
Other Extension Metadata

Last Modified Date
2016-10-20

IP Status
No known IP claims.

Interactions and External Dependencies
- Promoted to Vulkan 1.1 Core

Contributors
- Jesse Hall, Google
- James Jones, NVIDIA
- Jeff Juliano, NVIDIA

Description
An application may wish to reference device semaphores in multiple Vulkan logical devices or instances, in multiple processes, and/or in multiple APIs. This extension provides a set of capability queries and handle definitions that allow an application to determine what types of “external” semaphore handles an implementation supports for a given set of use cases.

New Object Types
None.

New Enum Constants
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO_KHR
- VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES_KHR
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ID_PROPERTIES_KHR
- VK_LUID_SIZE_KHR

New Enums
- VkExternalSemaphoreHandleTypeFlagBitsKHR
- VkExternalSemaphoreFeatureFlagBitsKHR

New Structs
- VkPhysicalDeviceExternalSemaphoreInfoKHR
- VkExternalSemaphorePropertiesKHR
- VkPhysicalDeviceIDPropertiesKHR
New Functions

• `vkGetPhysicalDeviceExternalSemaphorePropertiesKHR`

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

Version History

• Revision 1, 2016-10-20 (James Jones)
  ◦ Initial revision

VK_KHR_get_memory_requirements2

Name String
  `VK_KHR_get_memory_requirements2`

Extension Type
  Device extension

Registered Extension Number
  147

Revision
  1

Extension and Version Dependencies
  • Requires Vulkan 1.0

Deprecation state
  • Promoted to Vulkan 1.1

Contact
  • Jason Ekstrand @jekstrand

Other Extension Metadata

Last Modified Date
  2017-09-05

IP Status
  No known IP claims.

Interactions and External Dependencies
• Promoted to Vulkan 1.1 Core

Contributors
• Jason Ekstrand, Intel
• Jeff Bolz, NVIDIA
• Jesse Hall, Google

Description
This extension provides new entry points to query memory requirements of images and buffers in a way that can be easily extended by other extensions, without introducing any further entry points. The Vulkan 1.0 VkMemoryRequirements and VkSparseImageMemoryRequirements structures do not include sType and pNext members. This extension wraps them in new structures with these members, so an application can query a chain of memory requirements structures by constructing the chain and letting the implementation fill them in. A new command is added for each vkGet*MemoryRequirements command in core Vulkan 1.0.

New Object Types
None.

New Enum Constants
• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2_KHR
  ◦ VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2_KHR
  ◦ VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2_KHR
  ◦ VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2_KHR
  ◦ VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2_KHR

New Enums
None.

New Structures
• VkBufferMemoryRequirementsInfo2KHR
• VkImageMemoryRequirementsInfo2KHR
• VkImageSparseMemoryRequirementsInfo2KHR
• VkMemoryRequirements2KHR
• VkSparseImageMemoryRequirements2KHR

New Functions
• vkGetImageMemoryRequirements2KHR
Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None.

Version History

- Revision 1, 2017-03-23 (Jason Ekstrand)
  - Internal revisions

VK_KHR_get_physical_device_properties2

Name String

VK_KHR_get_physical_device_properties2

Extension Type

Instance extension

Registered Extension Number

60

Revision

2

Extension and Version Dependencies

- Requires Vulkan 1.0

Deprecation state

- Promoted to Vulkan 1.1

Contact

- Jeff Bolz jeffbolz

Other Extension Metadata

Last Modified Date

2017-09-05

IP Status

No known IP claims.
Interactions and External Dependencies

• Promoted to Vulkan 1.1 Core

Contributors

• Jeff Bolz, NVIDIA
• Ian Elliott, Google

Description

This extension provides new entry points to query device features, device properties, and format properties in a way that can be easily extended by other extensions, without introducing any further entry points. The Vulkan 1.0 feature/limit/formatproperty structures do not include sType/pNext members. This extension wraps them in new structures with sType/pNext members, so an application can query a chain of feature/limit/formatproperty structures by constructing the chain and letting the implementation fill them in. A new command is added for each vkGetPhysicalDevice* command in core Vulkan 1.0. The new feature structure (and a chain of extension structures) can also be passed in to device creation to enable features.

This extension also allows applications to use the physical-device components of device extensions before vkCreateDevice is called.

New Object Types

None.

New Enum Constants

• Extending VkStructureType:
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2_KHR
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROPERTIES_2_KHR
  ◦ VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2_KHR
  ◦ VK_STRUCTURE_TYPE_IMAGE_FORMAT_PROPERTIES_2_KHR
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_FORMAT_INFO_2_KHR
  ◦ VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2_KHR
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MEMORY_PROPERTIES_2_KHR
  ◦ VK_STRUCTURE_TYPE_SPARSE_IMAGE_FORMAT_PROPERTIES_2_KHR
  ◦ VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SPARSE_IMAGE_FORMAT_INFO_2_KHR

New Enums

None.

New Structures

• VkPhysicalDeviceFeatures2KHR
• VkPhysicalDeviceProperties2KHR
• VkFormatProperties2KHR
• VkImageFormatProperties2KHR
• VkPhysicalDeviceImageFormatInfo2KHR
• VkQueueFamilyProperties2KHR
• VkPhysicalDeviceMemoryProperties2KHR
• VkSparseImageFormatProperties2KHR
• VkPhysicalDeviceSparseImageFormatInfo2KHR

New Functions

• vkGetPhysicalDeviceFeatures2KHR
• vkGetPhysicalDeviceProperties2KHR
• vkGetPhysicalDeviceFormatProperties2KHR
• vkGetPhysicalDeviceImageFormatProperties2KHR
• vkGetPhysicalDeviceQueueFamilyProperties2KHR
• vkGetPhysicalDeviceMemoryProperties2KHR
• vkGetPhysicalDeviceSparseImageFormatProperties2KHR

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None.

Examples

```c
// Get features with a hypothetical future extension.
VkHypotheticalExtensionFeaturesKHR hypotheticalFeatures =
{
    .sType = VK_STRUCTURE_TYPE_HYPOTHETICAL_FEATURES_KHR,
    .pNext = NULL,
};

VkPhysicalDeviceFeatures2KHR features =
{
    .sType = VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2_KHR,
    .pNext = &hypotheticalFeatures,
};
```
vkGetPhysicalDeviceFeatures2KHR(physicalDevice, &features);

// Properties/limits can be chained and queried similarly.

// Enable some features:
VkHypotheticalExtensionFeaturesKHR enabledHypotheticalFeatures = {
    VK_STRUCTURE_TYPE_HYPOTHETICAL_FEATURES_KHR,
    NULL,
    NULL,
};

VkPhysicalDeviceFeatures2KHR enabledFeatures = {
    VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2_KHR,
    &enabledHypotheticalFeatures,
    NULL,
};

enabledFeatures.features.xyz = VK_TRUE;
enabledHypotheticalFeatures.abc = VK_TRUE;

VkDeviceCreateInfo deviceCreateInfo = {
    VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO,
    &enabledFeatures,
    NULL,
    ...,
    NULL,
};

VkDevice device;
vkCreateDevice(physicalDevice, &deviceCreateInfo, NULL, &device);

Version History

• Revision 1, 2016-09-12 (Jeff Bolz)
  ◦ Internal revisions
• Revision 2, 2016-11-02 (Ian Elliott)
  ◦ Added ability for applications to use the physical-device components of device extensions before vkCreateDevice is called.
VK_KHR_maintenance1

Name String
VK_KHR_maintenance1

Extension Type
Device extension

Registered Extension Number
70

Revision
2

Extension and Version Dependencies
• Requires Vulkan 1.0

Deprecation state
• Promoted to Vulkan 1.1

Contact
• Piers Daniell @pdaniell-nv

Other Extension Metadata

Last Modified Date
2018-03-13

Interactions and External Dependencies
• Promoted to Vulkan 1.1 Core

Contributors
• Dan Ginsburg, Valve
• Daniel Koch, NVIDIA
• Daniel Rakos, AMD
• Jan-Harald Fredriksen, ARM
• Jason Ekstrand, Intel
• Jeff Bolz, NVIDIA
• Jesse Hall, Google
• John Kessenich, Google
• Michael Worcester, Imagination Technologies
• Neil Henning, Codeplay Software Ltd.
• Piers Daniell, NVIDIA
• Slawomir Grajewski, Intel
**Description**

VK_KHR_maintenance1 adds a collection of minor features that were intentionally left out or overlooked from the original Vulkan 1.0 release.

The new features are as follows:

- Allow 2D and 2D array image views to be created from 3D images, which can then be used as color framebuffer attachments. This allows applications to render to slices of a 3D image.

- Support `vkCmdCopyImage` between 2D array layers and 3D slices. This extension allows copying from layers of a 2D array image to slices of a 3D image and vice versa.

- Allow negative height to be specified in the `VkViewport::height` field to perform y-inversion of the clip-space to framebuffer-space transform. This allows apps to avoid having to use `gl_Position.y = -gl_Position.y` in shaders also targeting other APIs.

- Allow implementations to express support for doing just transfers and clears of image formats that they otherwise support no other format features for. This is done by adding new format feature flags `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT_KHR` and `VK_FORMAT_FEATURE_TRANSFER_DST_BIT_KHR`.

- Support `vkCmdFillBuffer` on transfer-only queues. Previously `vkCmdFillBuffer` was defined to only work on command buffers allocated from command pools which support graphics or compute queues. It is now allowed on queues that just support transfer operations.

- Fix the inconsistency of how error conditions are returned between the `vkCreateGraphicsPipelines` and `vkCreateComputePipelines` functions and the `vkAllocateDescriptorSets` and `vkAllocateCommandBuffers` functions.

- Add new `VK_ERROR_OUT_OF_POOL_MEMORY_KHR` error so implementations can give a more precise reason for `vkAllocateDescriptorSets` failures.

- Add a new command `vkTrimCommandPoolKHR` which gives the implementation an opportunity to release any unused command pool memory back to the system.

**New Object Types**

None.

**New Enum Constants**

- `VK_ERROR_OUT_OF_POOL_MEMORY_KHR`
- `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT_KHR`
- `VK_FORMAT_FEATURE_TRANSFER_DST_BIT_KHR`
- `VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT_KHR`
New Enums
None.

New Structures
None.

New Functions
• vkTrimCommandPoolKHR

Promotion to Vulkan 1.1
All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues
1. Are viewports with zero height allowed?

  RESOLVED: Yes, although they have low utility.

Version History
• Revision 1, 2016-10-26 (Piers Daniell)
  ◦ Internal revisions
• Revision 2, 2018-03-13 (Jon Leech)
  ◦ Add issue for zero-height viewports

VK_KHR_maintenance2

Name String
VK_KHR_maintenance2

Extension Type
Device extension

Registered Extension Number
118

Revision
1

Extension and Version Dependencies
• Requires Vulkan 1.0
Description

`VK_KHR_maintenance2` adds a collection of minor features that were intentionally left out or overlooked from the original Vulkan 1.0 release.

The new features are as follows:

- Allow the application to specify which aspect of an input attachment might be read for a given subpass.
- Allow implementations to express the clipping behavior of points.
- Allow creating images with usage flags that may not be supported for the base image's format, but are supported for image views of the image that have a different but compatible format.
- Allow creating uncompressed image views of compressed images.
- Allow the application to select between an upper-left and lower-left origin for the tessellation domain space.
- Adds two new image layouts for depth stencil images to allow either the depth or stencil aspect to be read-only while the other aspect is writable.
Input Attachment Specification

Input attachment specification allows an application to specify which aspect of a multi-aspect image (e.g. a combined depth stencil format) will be accessed via a `subpassLoad` operation.

On some implementations there may be a performance penalty if the implementation does not know (at `vkCreateRenderPass` time) which aspect(s) of multi-aspect images can be accessed as input attachments.

New Object Types

None.

New Enum Constants

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT_ASPECT_CREATE_INFO_KHR`
  - `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_POINT_CLIPPING_PROPERTIES_KHR`
  - `VK_STRUCTURE_TYPE_IMAGE_VIEW_USAGE_CREATE_INFO_KHR`
  - `VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_DOMAIN_ORIGIN_STATE_CREATE_INFO_KHR`

- Extending `VkImageCreateFlagBits`:
  - `VK_IMAGE_CREATE_BLOCK_TEXEL_VIEW_COMPATIBLE_BIT_KHR`
  - `VK_IMAGE_CREATE_EXTENDED_USAGE_BIT_KHR`

- Extending `VkImageLayout`
  - `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL_KHR`
  - `VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL_KHR`
  - `VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIP_PLANES_KHR`
  - `VK_POINT_CLIPPING_BEHAVIOR_USER_CLIP_PLANES_ONLY_KHR`

New Enums

- `VkPointClippingBehaviorKHR`
- `VkTessellationDomainOriginKHR`

New Structures

- `VkPhysicalDevicePointClippingPropertiesKHR`
- `VkRenderPassInputAttachmentAspectCreateInfoKHR`
- `VkInputAttachmentAspectReferenceKHR`
- `VkImageViewUsageCreateInfoKHR`
- `VkPipelineTessellationDomainOriginStateCreateInfoKHR`
New Functions

None.

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Input Attachment Specification Example

Consider the case where a render pass has two subpasses and two attachments.

Attachment 0 has the format VK_FORMAT_D24_UNORM_S8_UINT, attachment 1 has some color format.

Subpass 0 writes to attachment 0, subpass 1 reads only the depth information from attachment 0 (using inputAttachmentRead) and writes to attachment 1.

```c
VkInputAttachmentAspectReferenceKHR references[] = {
    {
        .subpass = 1,
        .inputAttachmentIndex = 0,
        .aspectMask = VK_IMAGE_ASPECT_DEPTH_BIT
    }
};

VkRenderPassInputAttachmentAspectCreateInfoKHR specifyAspects = {
    .sType = VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT_ASPECT_CREATE_INFO_KHR,
    .pNext = NULL,
    .aspectReferenceCount = 1,
    .pAspectReferences = references
};

VkRenderPassCreateInfo createInfo = {
    ...
    .pNext = &specifyAspects,
    ...
}

vkCreateRenderPass(...);
```

Issues

1) What is the default tessellation domain origin?

RESOLVED: Vulkan 1.0 originally inadvertently documented a lower-left origin, but the conformance tests and all implementations implemented an upper-left origin. This extension adds
a control to select between lower-left (for compatibility with OpenGL) and upper-left, and we retroactively fix unextended Vulkan to have a default of an upper-left origin.

**Version History**

- Revision 1, 2017-04-28

**VK_KHR_maintenance3**

**Name String**

VK_KHR_maintenance3

**Extension Type**

Device extension

**Registered Extension Number**

169

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2

**Deprecation state**

- Promoted to Vulkan 1.1

**Contact**

- Jeff Bolz @jeffbolznv

**Other Extension Metadata**

**Last Modified Date**

2017-09-05

**Interactions and External Dependencies**

- Promoted to Vulkan 1.1 Core

**Contributors**

- Jeff Bolz, NVIDIA

**Description**

VK_KHR_maintenance3 adds a collection of minor features that were intentionally left out or overlooked from the original Vulkan 1.0 release.

The new features are as follows:
• A limit on the maximum number of descriptors that are supported in a single descriptor set layout. Some implementations have a limit on the total size of descriptors in a set, which cannot be expressed in terms of the limits in Vulkan 1.0.

• A limit on the maximum size of a single memory allocation. Some platforms have kernel interfaces that limit the maximum size of an allocation.

**New Object Types**
None.

**New Enum Constants**

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES_KHR`
  - `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT_KHR`

**New Enums**
None.

**New Structures**

- `VkPhysicalDeviceMaintenance3PropertiesKHR`
- `VkDescriptorSetLayoutSupportKHR`

**New Functions**

- `vkGetDescriptorSetLayoutSupportKHR`

**Promotion to Vulkan 1.1**

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

**Issues**
None.

**Version History**

- Revision 1, 2017-08-22

**VK_KHR_multiview**

**Name String**

`VK_KHR_multiview`
Extension Type
Device extension

Registered Extension Number
54

Revision
1

Extension and Version Dependencies
• Requires Vulkan 1.0
• Requires VK_KHR_get_physical_device_properties2

Deprecation state
• Promoted to Vulkan 1.1

Contact
• Jeff Bolz @jeffbolznv

Other Extension Metadata

Last Modified Date
2016-10-28

IP Status
No known IP claims.

Interactions and External Dependencies
• Promoted to Vulkan 1.1 Core
• Requires the SPV_KHR_multiview SPIR-V extension.
• Requires GL_EXT_multiview for GLSL source languages.

Contributors
• Jeff Bolz, NVIDIA

Description
This extension has the same goal as the OpenGL ES GL_OVR_multiview extension - it enables rendering to multiple “views” by recording a single set of commands to be executed with slightly different behavior for each view. It includes a concise way to declare a render pass with multiple views, and gives implementations freedom to render the views in the most efficient way possible.

New Object Types
None.
New Enum Constants

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_RENDER_PASS_MULTIVIEW_CREATE_INFO_KHR`
  - `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_FEATURES_KHR`
  - `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_PROPERTIES_KHR`

- Extending `VkDependencyFlagBits`
  - `VK_DEPENDENCY_VIEW_LOCAL_BIT_KHR`

New Enums

None.

New Structures

- `VkPhysicalDeviceMultiviewFeaturesKHR`
- `VkPhysicalDeviceMultiviewPropertiesKHR`
- `VkRenderPassMultiviewCreateInfoKHR`

New Functions

None.

New Built-In Variables

- `ViewIndex`

New SPIR-V Capabilities

- `MultiView`

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Issues

None.

Examples

None.

Version History

- Revision 1, 2016-10-28 (Jeff Bolz)
VK_KHR_relaxed_block_layout

**Name String**

VK_KHR_relaxed_block_layout

**Extension Type**

Device extension

**Registered Extension Number**

145

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0

**Deprecation state**

- Promoted to Vulkan 1.1

**Contact**

- John Kessenich 📧johnkslang

**Other Extension Metadata**

**Last Modified Date**

2017-03-26

**IP Status**

No known IP claims.

**Interactions and External Dependencies**

- Promoted to Vulkan 1.1 Core

**Contributors**

- John Kessenich, Google

**Description**

The `VK_KHR_relaxed_block_layout` extension allows implementations to indicate they can support more variation in block Offset decorations. For example, placing a vector of three floats at an offset of $16 \times N + 4$.

See Offset and Stride Assignment for details.
Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

• Revision 1, 2017-03-26 (JohnK)

VK_KHR_sampler_ycbcr_conversion

Name String

VK_KHR_sampler_ycbcr_conversion

Extension Type

Device extension

Registered Extension Number

157

Revision

14

Extension and Version Dependencies

• Requires Vulkan 1.0
• Requires VK_KHR_maintenance1
• Requires VK_KHR_bind_memory2
• Requires VK_KHR_get_memory_requirements2
• Requires VK_KHR_get_physical_device_properties2

Deprecation state

• Promoted to Vulkan 1.1

Contact

• Andrew Garrard @fluppeteer

Other Extension Metadata

Last Modified Date

2017-08-11

IP Status

No known IP claims.

Interactions and External Dependencies

• Promoted to Vulkan 1.1 Core
Contributors

• Andrew Garrard, Samsung Electronics
• Tobias Hector, Imagination Technologies
• James Jones, NVIDIA
• Daniel Koch, NVIDIA
• Daniel Rakos, AMD
• Romain Guy, Google
• Jesse Hall, Google
• Tom Cooksey, ARM Ltd
• Jeff Leger, Qualcomm Technologies, Inc
• Jan-Harald Fredriksen, ARM Ltd
• Jan Outters, Samsung Electronics
• Alon Or-bach, Samsung Electronics
• Michael Worcester, Imagination Technologies
• Jeff Bolz, NVIDIA
• Tony Zlatinski, NVIDIA
• Matthew Netsch, Qualcomm Technologies, Inc

Description

This extension provides the ability to perform specified color space conversions during texture sampling operations. It also adds a selection of multi-planar formats, including the ability to bind memory to the planes of an image collectively or separately.

New Enum Constants

• Extending VkStructureType:
  o VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO_KHR
  o VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO_KHR
  o VK_STRUCTURE_TYPE_BIND_IMAGE_PLANE_MEMORY_INFO_KHR
  o VK_STRUCTURE_TYPE_IMAGE_PLANE_MEMORY_REQUIREMENTS_INFO_KHR
  o VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_YCBCR_CONVERSION_FEATURES_KHR

• Extending VkFormat:
  o VK_FORMAT_G8B8G8R8_422_UNORM_KHR
  o VK_FORMAT_B8G8R8B8_422_UNORM_KHR
  o VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM_KHR
  o VK_FORMAT_G8_B8R8_2PLANE_420_UNORM_KHR
  o VK_FORMAT_G8_B8R8_3PLANE_444_UNORM_KHR
- VK_FORMAT_R10X6_UNORM_PACK16_KHR
- VK_FORMAT_R10X6G10X6_UNORM_2PACK16_KHR
- VK_FORMAT_R10X6G10X6B10X6A10X6_UNORM_4PACK16_KHR
- VK_FORMAT_G10X6B10X6G10X6R10X6_422_UNORM_4PACK16_KHR
- VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16_KHR
- VK_FORMAT_G10X6_B10X6_R10X6_3PLANE_420_UNORM_3PACK16_KHR
- VK_FORMAT_G10X6_B10X6R10X6_2PLANE_420_UNORM_3PACK16_KHR
- VK_FORMAT_G10X6_B10X6R10X6_3PLANE_422_UNORM_3PACK16_KHR
- VK_FORMAT_G10X6_B10X6R10X6_2PLANE_422_UNORM_3PACK16_KHR
- VK_FORMAT_G10X6_B10X6R10X6_3PLANE_444_UNORM_3PACK16_KHR
- VK_FORMAT_R12X4_UNORM_PACK16_KHR
- VK_FORMAT_R12X4G12X4_UNORM_2PACK16_KHR
- VK_FORMAT_R12X4G12X4B12X4A12X4_UNORM_4PACK16_KHR
- VK_FORMAT_G12X4B12X4G12X4R12X4_422_UNORM_4PACK16_KHR
- VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16_KHR
- VK_FORMAT_G12X4_B12X4_R12X4_3PLANE_420_UNORM_3PACK16_KHR
- VK_FORMAT_G12X4_B12X4R12X4_2PLANE_420_UNORM_3PACK16_KHR
- VK_FORMAT_G12X4_B12X4R12X4_3PLANE_422_UNORM_3PACK16_KHR
- VK_FORMAT_G12X4_B12X4R12X4_2PLANE_422_UNORM_3PACK16_KHR
- VK_FORMAT_G12X4_B12X4R12X4_3PLANE_444_UNORM_3PACK16_KHR

- **Extending VkImageAspectFlagBits:**
  - VK_IMAGE_ASPECT_PLANE_0_BIT_KHR
  - VK_IMAGE_ASPECT_PLANE_1_BIT_KHR
  - VK_IMAGE_ASPECT_PLANE_2_BIT_KHR

- **Extending VkImageCreateFlagBits:**
  - VK_IMAGE_CREATE_DISJOINT_BIT_KHR

- **Extending VkFormatFeatureFlagBits:**
  - VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT_KHR
  - VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT_KHR
  - VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT_KHR
  - VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT_KHR
  - VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT_KHR
  - VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT_KHR
New Enums

- VkSamplerYcbcrModelConversionKHR
- VkSamplerYcbcrRangeKHR
- VkChromaLocationKHR

New Structures

- VkSamplerYcbcrConversionInfoKHR
- VkSamplerYcbcrConversionCreateInfoKHR
- VkBindImagePlaneMemoryInfoKHR
- VkImagePlaneMemoryRequirementsInfoKHR
- VkPhysicalDeviceSamplerYcbcrConversionFeaturesKHR
- VkSamplerYcbcrConversionImageFormatPropertiesKHR

New Functions

- vkCreateSamplerYcbcrConversionKHR
- vkDestroySamplerYcbcrConversionKHR

New Objects

- VkSamplerYcbcrConversionKHR

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted. The original type, enum and command names are still available as aliases of the core functionality.

Version History

- Revision 1, 2017-01-24 (Andrew Garrard)
  - Initial draft
- Revision 2, 2017-01-25 (Andrew Garrard)
  - After initial feedback
- Revision 3, 2017-01-27 (Andrew Garrard)
  - Higher bit depth formats, renaming, swizzle
- Revision 4, 2017-02-22 (Andrew Garrard)
  - Added query function, formats as RGB, clarifications
- Revision 5, 2017-04 (Andrew Garrard)
- Simplified query and removed output conversions

- Revision 6, 2017-4-24 (Andrew Garrard)
  - Tidying, incorporated new image query, restored transfer functions

- Revision 7, 2017-04-25 (Andrew Garrard)
  - Added cosited option/midpoint requirement for formats, "bypassConversion"

- Revision 8, 2017-04-25 (Andrew Garrard)
  - Simplified further

- Revision 9, 2017-04-27 (Andrew Garrard)
  - Disjoint no more

- Revision 10, 2017-04-28 (Andrew Garrard)
  - Restored disjoint

- Revision 11, 2017-04-29 (Andrew Garrard)
  - Now Ycbcr conversion, and KHR

- Revision 12, 2017-06-06 (Andrew Garrard)
  - Added conversion to image view creation

- Revision 13, 2017-07-13 (Andrew Garrard)
  - Allowed cosited-only chroma samples for formats

- Revision 14, 2017-08-11 (Andrew Garrard)
  - Reflected quantization changes in BT.2100-1

**VK_KHR_shader_draw_parameters**

**Name String**

VK_KHR_shader_draw_parameters

**Extension Type**

Device extension

**Registered Extension Number**

64

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0

**Deprecation state**

- Promoted to Vulkan 1.1

**Contact**
Other Extension Metadata

Last Modified Date
2017-09-05

IP Status
No known IP claims.

Interactions and External Dependencies
• Requires the `SPV_KHR_shader_draw_parameters` SPIR-V extension.
• Requires `GL_ARB_shader_draw_parameters` for GLSL source languages.
• Promoted to Vulkan 1.1 Core

Contributors
• Daniel Koch, NVIDIA Corporation
• Jeff Bolz, NVIDIA
• Daniel Rakos, AMD
• Jan-Harald Fredriksen, ARM
• John Kessenich, Google
• Stuart Smith, IMG

Description
This extension adds support for the following SPIR-V extension in Vulkan:
• `SPV_KHR_shader_draw_parameters`

The extension provides access to three additional built-in shader variables in Vulkan:
• `BaseInstance`, which contains the `firstInstance` parameter passed to draw commands,
• `BaseVertex`, which contains the `firstVertex` or `vertexOffset` parameter passed to draw commands, and
• `DrawIndex`, which contains the index of the draw call currently being processed from an indirect draw call.

When using GLSL source-based shader languages, the following variables from `GL_ARB_shader_draw_parameters` can map to these SPIR-V built-in decorations:
• `in int gl_BaseInstanceARB; → BaseInstance`,
• `in int gl_BaseVertexARB; → BaseVertex`, and
• `in int gl_DrawIDARB; → DrawIndex`. 
New Object Types

None.

New Enum Constants

None.

New Enums

None.

New Structures

None.

New Functions

None.

New Built-In Variables

- BaseInstance
- BaseVertex
- DrawIndex

New SPIR-V Capabilities

- DrawParameters

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, however a feature bit was added to distinguish whether it is actually available or not.

Issues

1) Is this the same functionality as GL_ARB_shader_draw_parameters?

RESOLVED: It’s actually a superset as it also adds in support for arrayed drawing commands.

In GL for GL_ARB_shader_draw_parameters, gl_BaseVertexARB holds the integer value passed to the parameter to the command that resulted in the current shader invocation. In the case where the command has no baseVertex parameter, the value of gl_BaseVertexARB is zero. This means that gl_BaseVertexARB = baseVertex (for glDrawElements commands with baseVertex) or 0. In particular there are no glDrawArrays commands that take a baseVertex parameter.

Now in Vulkan, we have BaseVertex = vertexOffset (for indexed drawing commands) or firstVertex (for arrayed drawing commands), and so Vulkan’s version is really a superset of GL functionality.
Version History

- Revision 1, 2016-10-05 (Daniel Koch)
  - Internal revisions

VK_KHR_storage_buffer_storage_class

Name String

VK_KHR_storage_buffer_storage_class

Extension Type

Device extension

Registered Extension Number

132

Revision

1

Extension and Version Dependencies

- Requires Vulkan 1.0

Deprecation state

- Promoted to Vulkan 1.1

Contact

- Alexander Galazin @alegal-arm

Other Extension Metadata

Last Modified Date

2017-09-05

IP Status

No known IP claims.

Interactions and External Dependencies

- This extension requires the SPV_KHR_storage_buffer_storage_class SPIR-V extension.
- Promoted to Vulkan 1.1 Core

Contributors

- Alexander Galazin, ARM
- David Neto, Google

Description

This extension adds support for the following SPIR-V extension in Vulkan:
This extension provides a new SPIR-V StorageBuffer storage class. A Block-decorated object in this class is equivalent to a BufferBlock-decorated object in the Uniform storage class.

**New Enum Constants**

None.

**New Structures**

None.

**Promotion to Vulkan 1.1**

All functionality in this extension is included in core Vulkan 1.1.

**Issues**

None.

**Version History**

- Revision 1, 2017-03-23 (Alexander Galazin)
  - Initial draft

**VK_KHR_variable_pointers**

**Name String**

VK_KHR_variable_pointers

**Extension Type**

Device extension

**Registered Extension Number**

121

**Revision**

1

**Extension and Version Dependencies**

- Requires Vulkan 1.0
- Requires VK_KHR_get_physical_device_properties2
- Requires VK_KHR_storage_buffer_storage_class

**Deprecation state**

- Promoted to Vulkan 1.1
Description

The `VK_KHR_variable_pointers` extension allows implementations to indicate their level of support for the `SPV_KHR_variable_pointers` SPIR-V extension. The SPIR-V extension allows shader modules to use invocation-private pointers into uniform and/or storage buffers, where the pointer values can be dynamic and non-uniform.

The `SPV_KHR_variable_pointers` extension introduces two capabilities. The first, `VariablePointersStorageBuffer`, must be supported by all implementations of this extension. The second, `VariablePointers`, is optional.

New Enum Constants

- Extending `VkStructureType`:
  - `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTER_FEATURES_KHR`
New Structures

- VkPhysicalDeviceVariablePointersFeaturesKHR

New SPIR-V Capabilities

- VariablePointersStorageBuffer
- VariablePointers

Promotion to Vulkan 1.1

All functionality in this extension is included in core Vulkan 1.1, with the KHR suffix omitted, however support for the `variablePointersStorageBuffer` feature is made optional. The original type, enum and command names are still available as aliases of the core functionality.

Issues

1) Do we need an optional property for the SPIR-V `VariablePointersStorageBuffer` capability or should it be mandatory when this extension is advertised?

**RESOLVED**: Add it as a distinct feature, but make support mandatory. Adding it as a feature makes the extension easier to include in a future core API version. In the extension, the feature is mandatory, so that presence of the extension guarantees some functionality. When included in a core API version, the feature would be optional.

2) Can support for these capabilities vary between shader stages?

**RESOLVED**: No, if the capability is supported in any stage it must be supported in all stages.

3) Should the capabilities be features or limits?

**RESOLVED**: Features, primarily for consistency with other similar extensions.

Version History

- Revision 1, 2017-03-14 (Jesse Hall and John Kessenich)
  - Internal revisions
Appendix F: API Boilerplate

This appendix defines Vulkan API features that are infrastructure required for a complete functional description of Vulkan, but do not logically belong elsewhere in the Specification.

Vulkan Header Files

Vulkan is defined as an API in the C99 language. Khronos provides a corresponding set of header files for applications using the API, which may be used in either C or C++ code. The interface descriptions in the specification are the same as the interfaces defined in these header files, and both are derived from the vk.xml XML API Registry, which is the canonical machine-readable description of the Vulkan API. The Registry, scripts used for processing it into various forms, and documentation of the registry schema are available as described at https://www.khronos.org/registry/vulkan/#apiregistry.

Language bindings for other languages can be defined using the information in the Specification and the Registry. Khronos does not provide any such bindings, but third-party developers have created some additional bindings.

Vulkan Combined API Header vulkan.h (Informative)

Applications normally will include the header vulkan.h. In turn, vulkan.h always includes the following headers:

• vk_platform.h, defining platform-specific macros and headers.
• vulkan_core.h, defining APIs for the Vulkan core and all registered extensions other than window system-specific and provisional extensions, which are included in separate header files.

In addition, specific preprocessor macros defined at the time vulkan.h is included cause header files for the corresponding window system-specific and provisional interfaces to be included, as described below.

Vulkan Platform-Specific Header vk_platform.h (Informative)

Platform-specific macros and interfaces are defined in vk_platform.h. These macros are used to control platform-dependent behavior, and their exact definitions are under the control of specific platforms and Vulkan implementations.

Platform-Specific Calling Conventions

On many platforms the following macros are empty strings, causing platform- and compiler-specific default calling conventions to be used.

VKAPI_ATTR is a macro placed before the return type in Vulkan API function declarations. This macro controls calling conventions for C++11 and GCC/Clang-style compilers.

VKAPI_CALL is a macro placed after the return type in Vulkan API function declarations. This macro controls calling conventions for MSVC-style compilers.
VKAPI_PTR is a macro placed between the '(' and '*-' in Vulkan API function pointer declarations. This macro also controls calling conventions, and typically has the same definition as VKAPI_ATTR or VKAPI_CALL, depending on the compiler.

With these macros, a Vulkan function declaration takes the form of:

```
VKAPI_ATTR <return_type> VKAPI_CALL <command_name>(<command_parameters>);
```

Additionally, a Vulkan function pointer type declaration takes the form of:

```
typedef <return_type> (VKAPI_PTR *PFN_<command_name>)(<command_parameters>);
```

Platform-Specific Header Control

If the VK_NO_STDINT_H macro is defined by the application at compile time, extended integer types used by the Vulkan API, such as uint8_t, must also be defined by the application. Otherwise, the Vulkan headers will not compile. If VK_NO_STDINT_H is not defined, the system <stdint.h> is used to define these types. There is a fallback path when Microsoft Visual Studio version 2008 and earlier versions are detected at compile time.

Vulkan Core API Header vulkan_core.h

Applications that do not make use of window system-specific extensions may simply include vulkan_core.h instead of vulkan.h, although there is usually no reason to do so. In addition to the Vulkan API, vulkan_core.h also defines a small number of C preprocessor macros that are described below.

Vulkan Header File Version Number

VK_HEADER_VERSION is the version number of the vulkan_core.h header. This value is kept synchronized with the patch version of the released Specification.

```
// Version of this file
#define VK_HEADER_VERSION 136
```

VK_HEADER_VERSION_COMPLETE is the complete version number of the vulkan_core.h header, comprising the major, minor, and patch versions. The major/minor values are kept synchronized with the complete version of the released Specification. This value is intended for use by automated tools to identify exactly which version of the header was used during their generation.

Applications should not use this value as their VkApplicationInfo::apiVersion. Instead applications should explicitly select a specific fixed major/minor API version using, for example, one of the VK_API_VERSION_*_* values.
// Complete version of this file
#define VK_HEADER_VERSION_COMPLETE VK_MAKE_VERSION(1, 2, VK_HEADER_VERSION)

**VK_API_VERSION** is now commented out of **vulkan_core.h** and cannot be used.

// DEPRECATED: This define has been removed. Specific version defines (e.g. VK_API_VERSION_1_0), or the VK_MAKE_VERSION macro, should be used instead.
// #define VK_API_VERSION VK_MAKE_VERSION(1, 0, 0) // Patch version should always be set to 0

**Vulkan Handle Macros**

**VK_DEFINE_HANDLE** defines a **dispatchable handle** type.

```c
#define VK_DEFINE_HANDLE(object) typedef struct object##_T* object;
```

- **object** is the name of the resulting C type.

The only dispatchable handle types are those related to device and instance management, such as **VkDevice**.

**VK_DEFINE_NON_DISPATCHABLE_HANDLE** defines a **non-dispatchable handle** type.

```c
#if !defined(VK_DEFINE_NON_DISPATCHABLE_HANDLE)
#if defined(__LP64__) || defined(_WIN64) || (defined(__x86_64__) && !defined(__ILP32__)) || defined(_M_X64) || defined(__ia64) || defined(_M_IA64) || defined(__aarch64__) || defined(__powerpc64__)
    #define VK_DEFINE_NON_DISPATCHABLE_HANDLE(object) typedef struct object##_T* object;
#else
    #define VK_DEFINE_NON_DISPATCHABLE_HANDLE(object) typedef uint64_t object;
#endif
#endif
```

- **object** is the name of the resulting C type.

Most Vulkan handle types, such as **VkBuffer**, are non-dispatchable.
Note

The `vulkan_core.h` header allows the `VK_DEFINE_NON_DISPATCHABLE_HANDLE` definition to be overridden by the application. If `VK_DEFINE_NON_DISPATCHABLE_HANDLE` is already defined when `vulkan_core.h` is compiled, the default definition is skipped. This allows the application to define a binary-compatible custom handle which may provide more type-safety or other features needed by the application. Applications must not define handles in a way that is not binary compatible - where binary compatibility is platform dependent.

`VK_NULL_HANDLE` is a reserved value representing a non-valid object handle. It may be passed to and returned from Vulkan commands only when specifically allowed.

```c
#define VK_NULL_HANDLE 0
```

Window System-Specific Header Control (Informative)

To use a Vulkan extension supporting a platform-specific window system, header files for that window systems must be included at compile time, or platform-specific types must be forward-declared. The Vulkan header files cannot determine whether or not an external header is available at compile time, so platform-specific extensions are provided in separate headers from the core API and platform-independent extensions, allowing applications to decide which ones should be defined and how the external headers are included.

Extensions dependent on particular sets of platform headers, or that forward-declare platform-specific types, are declared in a header named for that platform. Before including these platform-specific Vulkan headers, applications must include both `vulkan_core.h` and any external native headers the platform extensions depend on.

As a convenience for applications that do not need the flexibility of separate platform-specific Vulkan headers, `vulkan.h` includes `vulkan_core.h`, and then conditionally includes platform-specific Vulkan headers and the external headers they depend on. Applications control which platform-specific headers are included by defining macros before including `vulkan.h`.

The correspondence between platform-specific extensions, external headers they require, the platform-specific header which declares them, and the preprocessor macros which enable inclusion by `vulkan.h` are shown in the following table.

Table 71. Window System Extensions and Headers

<table>
<thead>
<tr>
<th>Extension Name</th>
<th>Window System Name</th>
<th>Platform-specific Header</th>
<th>Required External Headers</th>
<th>Controlling <code>vulkan.h</code> Macro</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_KHR_android_surface</td>
<td>Android</td>
<td><code>vulkan_android.h</code></td>
<td>None</td>
<td><code>VK_USE_PLATFORM_ANDROID_KHR</code></td>
</tr>
<tr>
<td>VK_KHR_wayland_surface</td>
<td>Wayland</td>
<td><code>vulkan_wayland.h</code></td>
<td><code>&lt;wayland-client.h&gt;</code></td>
<td><code>VK_USE_PLATFORM_WAYLAND_KHR</code></td>
</tr>
<tr>
<td>Extension Name</td>
<td>Window System Name</td>
<td>Platform-specific Header</td>
<td>Required External Headers</td>
<td>Controlling vulkan.h Macro</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>--------------------</td>
<td>--------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>VK_KHR xcb_surface</td>
<td>X11 Xcb</td>
<td>vulkan xcb.h</td>
<td>&lt;xcb/xcb.h&gt;</td>
<td>VK_USE_PLATFORM_XCB_KHR</td>
</tr>
<tr>
<td>VK_KHR xlib_surface</td>
<td>X11 Xlib</td>
<td>vulkan xlib.h</td>
<td>&lt;X11/Xlib.h&gt;</td>
<td>VK_USE_PLATFORM_XLIB_KHR</td>
</tr>
</tbody>
</table>

Note
This section describes the purpose of the headers independently of the specific underlying functionality of the window system extensions themselves. Each extension name will only link to a description of that extension when viewing a specification built with that extension included.

Provisional Extension Header Control (Informative)

Provisional extensions should not be used in production applications. The functionality defined by such extensions may change in ways that break backwards compatibility between revisions, and before final release of a non-provisional version of that extension.

Provisional extensions are defined in a separate provisional header, vulkan_beta.h, allowing applications to decide whether or not to include them. The mechanism is similar to window system-specific headers: before including vulkan_beta.h, applications must include vulkan_core.h.

Note
Sometimes a provisional extension will include a subset of its interfaces in vulkan_core.h. This may occur if the provisional extension is promoted from an existing vendor or EXT extension and some of the existing interfaces are defined as aliases of the provisional extension interfaces. All other interfaces of that provisional extension which are not aliased will be included in vulkan_beta.h.

As a convenience for applications, vulkan.h conditionally includes vulkan_beta.h. Applications can control inclusion of vulkan_beta.h by defining the macro VK_ENABLE_BETA_EXTENSIONS before including vulkan.h.
Note

This section describes the purpose of the provisional header independently of the specific provisional extensions which are contained in that header at any given time. The extension appendices for provisional extensions note their provisional status, and link back to this section for more information. Provisional extensions are intended to provide early access for bleeding-edge developers, with the understanding that extension interfaces may change in response to developer feedback. Provisional extensions are very likely to eventually be updated and released as non-provisional extensions, but there is no guarantee this will happen, or how long it will take if it does happen.
Appendix G: Invariance

The Vulkan specification is not pixel exact. It therefore does not guarantee an exact match between images produced by different Vulkan implementations. However, the specification does specify exact matches, in some cases, for images produced by the same implementation. The purpose of this appendix is to identify and provide justification for those cases that require exact matches.

Repeatability

The obvious and most fundamental case is repeated issuance of a series of Vulkan commands. For any given Vulkan and framebuffer state vector, and for any Vulkan command, the resulting Vulkan and framebuffer state must be identical whenever the command is executed on that initial Vulkan and framebuffer state. This repeatability requirement does not apply when using shaders containing side effects (image and buffer variable stores and atomic operations), because these memory operations are not guaranteed to be processed in a defined order.

One purpose of repeatability is avoidance of visual artifacts when a double-buffered scene is redrawn. If rendering is not repeatable, swapping between two buffers rendered with the same command sequence may result in visible changes in the image. Such false motion is distracting to the viewer. Another reason for repeatability is testability.

Repeatability, while important, is a weak requirement. Given only repeatability as a requirement, two scenes rendered with one (small) polygon changed in position might differ at every pixel. Such a difference, while within the law of repeatability, is certainly not within its spirit. Additional invariance rules are desirable to ensure useful operation.

Multi-pass Algorithms

Invariance is necessary for a whole set of useful multi-pass algorithms. Such algorithms render multiple times, each time with a different Vulkan mode vector, to eventually produce a result in the framebuffer. Examples of these algorithms include:

- “Erasing” a primitive from the framebuffer by redrawing it, either in a different color or using the XOR logical operation.
- Using stencil operations to compute capping planes.

Invariance Rules

For a given Vulkan device:

Rule 1 For any given Vulkan and framebuffer state vector, and for any given Vulkan command, the resulting Vulkan and framebuffer state must be identical each time the command is executed on that initial Vulkan and framebuffer state.

Rule 2 Changes to the following state values have no side effects (the use of any other state value is not affected by the change):
Required:

- Color and depth/stencil attachment contents
- Scissor parameters (other than enable)
- Write masks (color, depth, stencil)
- Clear values (color, depth, stencil)

Strongly suggested:

- Stencil parameters (other than enable)
- Depth test parameters (other than enable)
- Blend parameters (other than enable)
- Logical operation parameters (other than enable)

Corollary 1 Fragment generation is invariant with respect to the state values listed in Rule 2.

Rule 3 The arithmetic of each per-fragment operation is invariant except with respect to parameters that directly control it.

Corollary 2 Images rendered into different color attachments of the same framebuffer, either simultaneously or separately using the same command sequence, are pixel identical.

Rule 4 Identical pipelines will produce the same result when run multiple times with the same input. The wording “Identical pipelines” means VkPipeline objects that have been created with identical SPIR-V binaries and identical state, which are then used by commands executed using the same Vulkan state vector. Invariance is relaxed for shaders with side effects, such as performing stores or atomics.

Rule 5 All fragment shaders that either conditionally or unconditionally assign FragCoord.z to FragDepth are depth-invariant with respect to each other, for those fragments where the assignment to FragDepth actually is done.

If a sequence of Vulkan commands specifies primitives to be rendered with shaders containing side effects (image and buffer variable stores and atomic operations), invariance rules are relaxed. In particular, rule 1, corollary 2, and rule 4 do not apply in the presence of shader side effects.

The following weaker versions of rules 1 and 4 apply to Vulkan commands involving shader side effects:

Rule 6 For any given Vulkan and framebuffer state vector, and for any given Vulkan command, the contents of any framebuffer state not directly or indirectly affected by results of shader image or buffer variable stores or atomic operations must be identical each time the command is executed on that initial Vulkan and framebuffer state.

Rule 7 Identical pipelines will produce the same result when run multiple times with the same input as long as:

- shader invocations do not use image atomic operations;
• no framebuffer memory is written to more than once by image stores, unless all such stores write the same value; and

• no shader invocation, or other operation performed to process the sequence of commands, reads memory written to by an image store.

**Note**

The OpenGL spec has the following invariance rule: Consider a primitive \( p' \) obtained by translating a primitive \( p \) through an offset \((x, y)\) in window coordinates, where \( x \) and \( y \) are integers. As long as neither \( p' \) nor \( p \) is clipped, it **must** be the case that each fragment \( f' \) produced from \( p' \) is identical to a corresponding fragment \( f \) from \( p \) except that the center of \( f' \) is offset by \((x, y)\) from the center of \( f \).

This rule does not apply to Vulkan and is an intentional difference from OpenGL.

When any sequence of Vulkan commands triggers shader invocations that perform image stores or atomic operations, and subsequent Vulkan commands read the memory written by those shader invocations, these operations **must** be explicitly synchronized.

**Tessellation Invariance**

When using a pipeline containing tessellation evaluation shaders, the fixed-function tessellation primitive generator consumes the input patch specified by an application and emits a new set of primitives. The following invariance rules are intended to provide repeatability guarantees. Additionally, they are intended to allow an application with a carefully crafted tessellation evaluation shader to ensure that the sets of triangles generated for two adjacent patches have identical vertices along shared patch edges, avoiding “cracks” caused by minor differences in the positions of vertices along shared edges.

**Rule 1** When processing two patches with identical outer and inner tessellation levels, the tessellation primitive generator will emit an identical set of point, line, or triangle primitives as long as the pipeline used to process the patch primitives has tessellation evaluation shaders specifying the same tessellation mode, spacing, vertex order, and point mode decorations. Two sets of primitives are considered identical if and only if they contain the same number and type of primitives and the generated tessellation coordinates for the vertex numbered \( m \) of the primitive numbered \( n \) are identical for all values of \( m \) and \( n \).

**Rule 2** The set of vertices generated along the outer edge of the subdivided primitive in triangle and quad tessellation, and the tessellation coordinates of each, depends only on the corresponding outer tessellation level and the spacing decorations in the tessellation shaders of the pipeline.

**Rule 3** The set of vertices generated when subdividing any outer primitive edge is always symmetric. For triangle tessellation, if the subdivision generates a vertex with tessellation coordinates of the form \((0, x, 1-x)\), \((x, 0, 1-x)\), or \((x, 1-x, 0)\), it will also generate a vertex with coordinates of exactly \((0, 1-x, x)\), \((1-x, 0, x)\), or \((1-x, x, 0)\), respectively. For quad tessellation, if the subdivision generates a vertex with coordinates of \((x, 0)\) or \((0, x)\), it will also generate a vertex with coordinates of exactly \((1-x, 0)\) or \((0, 1-x)\), respectively. For isoline tessellation, if it generates vertices at \((0, x)\) and \((1, x)\) where \( x \) is not zero, it will also generate vertices at exactly \((0, 1-x)\) and \((1, 1-x)\), respectively.
Rule 4 The set of vertices generated when subdividing outer edges in triangular and quad tessellation must be independent of the specific edge subdivided, given identical outer tessellation levels and spacing. For example, if vertices at \((x, 1-x, 0)\) and \((1-x, x, 0)\) are generated when subdividing the \(w = 0\) edge in triangular tessellation, vertices must be generated at \((x, 0, 1-x)\) and \((1-x, 0, x)\) when subdividing an otherwise identical \(v = 0\) edge. For quad tessellation, if vertices at \((x, 0)\) and \((1-x, 0)\) are generated when subdividing the \(v = 0\) edge, vertices must be generated at \((0, x)\) and \((0, 1-x)\) when subdividing an otherwise identical \(u = 0\) edge.

Rule 5 When processing two patches that are identical in all respects enumerated in rule 1 except for vertex order, the set of triangles generated for triangle and quad tessellation must be identical except for vertex and triangle order. For each triangle \(n_1\) produced by processing the first patch, there must be a triangle \(n_2\) produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in \(n_1\).

Rule 6 When processing two patches that are identical in all respects enumerated in rule 1 other than matching outer tessellation levels and/or vertex order, the set of interior triangles generated for triangle and quad tessellation must be identical in all respects except for vertex and triangle order. For each interior triangle \(n_1\) produced by processing the first patch, there must be a triangle \(n_2\) produced when processing the second patch each of whose vertices has the same tessellation coordinates as one of the vertices in \(n_1\). A triangle produced by the tessellator is considered an interior triangle if none of its vertices lie on an outer edge of the subdivided primitive.

Rule 7 For quad and triangle tessellation, the set of triangles connecting an inner and outer edge depends only on the inner and outer tessellation levels corresponding to that edge and the spacing decorations.

Rule 8 The value of all defined components of \(\text{TessCoord}\) will be in the range \([0, 1]\). Additionally, for any defined component \(x\) of \(\text{TessCoord}\), the results of computing \(1.0-x\) in a tessellation evaluation shader will be exact. If any floating-point values in the range \([0, 1]\) fail to satisfy this property, such values must not be used as tessellation coordinate components.
Glossary

The terms defined in this section are used consistently throughout this Specification and may be used with or without capitalization.

**Accessible (Descriptor Binding)**

A descriptor binding is accessible to a shader stage if that stage is included in the `stageFlags` of the descriptor binding. Descriptors using that binding can only be used by stages in which they are accessible.

**Acquire Operation (Resource)**

An operation that acquires ownership of an image subresource or buffer range.

**Adjacent Vertex**

A vertex in an adjacency primitive topology that is not part of a given primitive, but is accessible in geometry shaders.

**Active Object (Ray Tracing)**

A primitive or instance in a ray tracing acceleration structure which has a corresponding ID, and is not `inactive` (meaning that it is visible to rays).

**Alias (API type/command)**

An identical definition of another API type/command with the same behavior but a different name.

**Aliased Range (Memory)**

A range of a device memory allocation that is bound to multiple resources simultaneously.

**Allocation Scope**

An association of a host memory allocation to a parent object or command, where the allocation's lifetime ends before or at the same time as the parent object is freed or destroyed, or during the parent command.

**Aspect (Image)**

An image may contain multiple kinds, or aspects, of data for each pixel, where each aspect is used in a particular way by the pipeline and may be stored differently or separately from other aspects. For example, the color components of an image format make up the color aspect of the image, and may be used as a framebuffer color attachment. Some operations, like depth testing, operate only on specific aspects of an image. Others operations, like image/buffer copies, only operate on one aspect at a time.

**Attachment (Render Pass)**

A zero-based integer index name used in render pass creation to refer to a framebuffer attachment that is accessed by one or more subpasses. The index also refers to an attachment description which includes information about the properties of the image view that will later be attached.
**Availability Operation**
An operation that causes the values generated by specified memory write accesses to become available for future access.

**Available**
A state of values written to memory that allows them to be made visible.

**Axis-aligned Bounding Box**
A box bounding a region in space defined by extents along each axis and thus representing a box where each edge is aligned to one of the major axes.

**Back-Facing**
See Facingness.

**Batch**
A single structure submitted to a queue as part of a queue submission command, describing a set of queue operations to execute.

**Backwards Compatibility**
A given version of the API is backwards compatible with an earlier version if an application, relying only on valid behavior and functionality defined by the earlier specification, is able to correctly run against each version without any modification. This assumes no active attempt by that application to not run when it detects a different version.

**Binary Semaphore**
A semaphore with a boolean payload indicating whether the semaphore is signaled or unsigned. Represented by a VkSemaphore object created with a semaphore type of VK_SEMAPHORE_TYPE_BINARY.

**Full Compatibility**
A given version of the API is fully compatible with another version if an application, relying only on valid behavior and functionality defined by either of those specifications, is able to correctly run against each version without any modification. This assumes no active attempt by that application to not run when it detects a different version.

**Binding (Memory)**
An association established between a range of a resource object and a range of a memory object. These associations determine the memory locations affected by operations performed on elements of a resource object. Memory bindings are established using the vkBindBufferMemory command for non-sparse buffer objects, using the vkBindImageMemory command for non-sparse image objects, and using the vkQueueBindSparse command for sparse resources.

**Blend Constant**
Four floating point (RGBA) values used as an input to blending.

**Blending**
Arithmetic operations between a fragment color value and a value in a color attachment that produce a final color value to be written to the attachment.
Buffer
A resource that represents a linear array of data in device memory. Represented by a VkBuffer object.

Buffer Device Address
A 64-bit value used in a shader to access buffer memory through the PhysicalStorageBuffer storage class.

Buffer View
An object that represents a range of a specific buffer, and state that controls how the contents are interpreted. Represented by a VkBufferView object.

Built-In Variable
A variable decorated in a shader, where the decoration makes the variable take values provided by the execution environment or values that are generated by fixed-function pipeline stages.

Built-In Interface Block
A block defined in a shader that contains only variables decorated with built-in decorations, and is used to match against other shader stages.

Clip Coordinates
The homogeneous coordinate space that vertex positions (Position decoration) are written in by vertex processing stages.

Clip Distance
A built-in output from vertex processing stages that defines a clip half-space against which the primitive is clipped.

Clip Volume
The intersection of the view volume with all clip half-spaces.

Color Attachment
A subpass attachment point, or image view, that is the target of fragment color outputs and blending.

Color Renderable Format
A VkFormat where VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT is set in one of the following, depending on the image's tiling:

• VkImageFormatProperties::linearTilingFeatures
• VkImageFormatProperties::optimalTilingFeatures

Color Sample Mask
A bitfield associated with a fragment, with one bit for each sample in the color attachment(s). Samples are considered to be covered based on the result of the Coverage Reduction stage. Uncovered samples do not write to color attachments.
**Combined Image Sampler**
A descriptor type that includes both a sampled image and a sampler.

**Command Buffer**
An object that records commands to be submitted to a queue. Represented by a `VkCommandBuffer` object.

**Command Pool**
An object that command buffer memory is allocated from, and that owns that memory. Command pools aid multithreaded performance by enabling different threads to use different allocators, without internal synchronization on each use. Represented by a `VkCommandPool` object.

**Compatible Allocator**
When allocators are compatible, allocations from each allocator can be freed by the other allocator.

**Compatible Image Formats**
When formats are compatible, images created with one of the formats can have image views created from it using any of the compatible formats. Also see Size-Compatible Image Formats.

**Compatible Queues**
Queues within a queue family. Compatible queues have identical properties.

**Complete Mipmap Chain**
The entire set of mipmap levels that can be provided for an image, from the largest application specified mipmap level size down to the minimum mipmap level size. See Image Mipmap Sizing.

**Completed Operation**
A deferred operation whose corresponding command has been executed to completion. See Deferred Host Operations

**Component (Format)**
A distinct part of a format. Depth, stencil, and color channels (e.g. R, G, B, A), are all separate components.

**Compressed Texel Block**
An element of an image having a block-compressed format, comprising a rectangular block of texel values that are encoded as a single value in memory. Compressed texel blocks of a particular block-compressed format have a corresponding width, height, and depth that define the dimensions of these elements in units of texels, and a size in bytes of the encoding in memory.

**Constant Integral Expressions**
A SPIR-V constant instruction whose type is `OpTypeInt`. See Constant Instruction in section 2.2.1 “Instructions” of the Khronos SPIR-V Specification.

**Coverage**
A bitfield associated with a fragment, where each bit is associated to a rasterization sample. Samples are initially considered to be covered based on the result of rasterization, and then coverage can subsequently be turned on or off by other fragment operations or the fragment shader. Uncovered samples do not write to framebuffer attachments.

Cull Distance
A built-in output from vertex processing stages that defines a cull half-space where the primitive is rejected if all vertices have a negative value for the same cull distance.

Cull Volume
The intersection of the view volume with all cull half-spaces.

Decoration (SPIR-V)
Auxiliary information such as built-in variables, stream numbers, invariance, interpolation type, relaxed precision, etc., added to variables or structure-type members through decorations.

Deferrable Command
A command which allows deferred execution of host-side work. See Deferred Host Operations.

Deferrable Operation
A single logical item of host-side work which can be deferred. Represented by the VkDeferredOperationKHR object. See Deferred Host Operations.

Deprecated (feature)
A feature is deprecated if it is no longer recommended as the correct or best way to achieve its intended purpose.

Depth/Stencil Attachment
A subpass attachment point, or image view, that is the target of depth and/or stencil test operations and writes.

Depth/Stencil Format
A VkFormat that includes depth and/or stencil components.

Depth/Stencil Image (or ImageView)
A VkImage (or VkImageView) with a depth/stencil format.

Depth/Stencil Resolve Attachment
A subpass attachment point, or image view, that is the target of a multisample resolve operation from the corresponding depth/stencil attachment at the end of the subpass.

Derivative Group
A set of fragment shader invocations that cooperate to compute derivatives, including implicit derivatives for sampled image operations.

Descriptor
Information about a resource or resource view written into a descriptor set that is used to access the resource or view from a shader.
**Descriptor Binding**

An entry in a descriptor set layout corresponding to zero or more descriptors of a single descriptor type in a set. Defined by a `VkDescriptorSetLayoutBinding` structure.

**Descriptor Pool**

An object that descriptor sets are allocated from, and that owns the storage of those descriptor sets. Descriptor pools aid multithreaded performance by enabling different threads to use different allocators, without internal synchronization on each use. Represented by a `VkDescriptorPool` object.

**Descriptor Set**

An object that resource descriptors are written into via the API, and that can be bound to a command buffer such that the descriptors contained within it can be accessed from shaders. Represented by a `VkDescriptorSet` object.

**Descriptor Set Layout**

An object that defines the set of resources (types and counts) and their relative arrangement (in the binding namespace) within a descriptor set. Used when allocating descriptor sets and when creating pipeline layouts. Represented by a `VkDescriptorSetLayout` object.

**Device**

The processor(s) and execution environment that perform tasks requested by the application via the Vulkan API.

**Device Group**

A set of physical devices that support accessing each other's memory and recording a single command buffer that can be executed on all the physical devices.

**Device Index**

A zero-based integer that identifies one physical device from a logical device. A device index is valid if it is less than the number of physical devices in the logical device.

**Device Mask**

A bitmask where each bit represents one device index. A device mask value is valid if every bit that is set in the mask is at a bit position that is less than the number of physical devices in the logical device.

**Device Memory**

Memory accessible to the device. Represented by a `VkDeviceMemory` object.

**Device-Level Command**

Any command that is dispatched from a logical device, or from a child object of a logical device.

**Device-Level Functionality**

All device-level commands and objects, and their structures, enumerated types, and enumerants.

**Device-Level Object**

Logical device objects and their child objects. For example, `VkDevice`, `VkQueue`, and
VkCommandBuffer objects are device-level objects.

**Device-Local Memory**

Memory that is connected to the device, and may be more performant for device access than host-local memory.

**Direct Drawing Commands**

*Drawing commands* that take all their parameters as direct arguments to the command (and not sourced via structures in buffer memory as the *indirect drawing commands*). Includes `vkCmdDraw`, and `vkCmdDrawIndexed`.

**Disjoint**

*Disjoint planes* are *image planes* to which memory is bound independently.

A *disjoint image* consists of multiple *disjoint planes*, and is created with the `VK_IMAGE_CREATE_DISJOINT_BIT` bit set.

**Dispatchable Handle**

A handle of a pointer handle type which may be used by layers as part of intercepting API commands. The first argument to each Vulkan command is a dispatchable handle type.

**Dispatching Commands**

Commands that provoke work using a compute pipeline. Includes `vkCmdDispatch` and `vkCmdDispatchIndirect`.

**Drawing Commands**

Commands that provoke work using a graphics pipeline. Includes `vkCmdDraw`, `vkCmdDrawIndexed`, `vkCmdDrawIndirectCountKHR`, `vkCmdDrawIndexedIndirectCountKHR`, `vkCmdDrawIndirect`, and `vkCmdDrawIndexedIndirect`.

**Duration (Command)**

The *duration* of a Vulkan command refers to the interval between calling the command and its return to the caller.

**Dynamic Storage Buffer**

A storage buffer whose offset is specified each time the storage buffer is bound to a command buffer via a descriptor set.

**Dynamic Uniform Buffer**

A uniform buffer whose offset is specified each time the uniform buffer is bound to a command buffer via a descriptor set.

**Dynamically Uniform**

See *Dynamically Uniform* in section 2.2 “Terms” of the Khronos SPIR-V Specification.

**Element**

Arrays are composed of multiple elements, where each element exists at a unique index within that array. Used primarily to describe data passed to or returned from the Vulkan API.
**Explicitly-Enabled Layer**
A layer enabled by the application by adding it to the enabled layer list in `vkCreateInstance` or `vkCreateDevice`.

**Event**
A synchronization primitive that is signaled when execution of previous commands complete through a specified set of pipeline stages. Events can be waited on by the device and polled by the host. Represented by a `VkEvent` object.

**Executable State (Command Buffer)**
A command buffer that has ended recording commands and can be executed. See also Initial State and Recording State.

**Execution Dependency**
A dependency that guarantees that certain pipeline stages' work for a first set of commands has completed execution before certain pipeline stages' work for a second set of commands begins execution. This is accomplished via pipeline barriers, subpass dependencies, events, or implicit ordering operations.

**Execution Dependency Chain**
A sequence of execution dependencies that transitively act as a single execution dependency.

**Explicit chroma reconstruction**
An implementation of sampler $Y'{{C}_b}{C}_r$ conversion which reconstructs reduced-resolution chroma samples to luma resolution and then separately performs texture sample interpolation. This is distinct from an implicit implementation, which incorporates chroma sample reconstruction into texture sample interpolation.

**Extension Scope**
The set of objects and commands that can be affected by an extension. Extensions are either device scope or instance scope.

**External Handle**
A resource handle which has meaning outside of a specific Vulkan device or its parent instance. External handles may be used to share resources between multiple Vulkan devices in different instances, or between Vulkan and other APIs. Some external handle types correspond to platform-defined handles, in which case the resource may outlive any particular Vulkan device or instance and may be transferred between processes, or otherwise manipulated via functionality defined by the platform for that handle type.

**External synchronization**
A type of synchronization required of the application, where parameters defined to be externally synchronized must not be used simultaneously in multiple threads.

**Facingness (Polygon)**
A classification of a polygon as either front-facing or back-facing, depending on the orientation (winding order) of its vertices.
Facingness (Fragment)

A fragment is either front-facing or back-facing, depending on the primitive it was generated from. If the primitive was a polygon (regardless of polygon mode), the fragment inherits the facingness of the polygon. All other fragments are front-facing.

Fence

A synchronization primitive that is signaled when a set of batches or sparse binding operations complete execution on a queue. Fences can be waited on by the host. Represented by a VkFence object.

Flat Shading

A property of a vertex attribute that causes the value from a single vertex (the provoking vertex) to be used for all vertices in a primitive, and for interpolation of that attribute to return that single value unaltered.

Fragment

A rectangular framebuffer region with associated data produced by rasterization and processed by fragment operations including the fragment shader.

Fragment Area

The width and height, in pixels, of a fragment.

Fragment Input Attachment Interface

Variables with UniformConstant storage class and a decoration of InputAttachmentIndex that are statically used by a fragment shader's entry point, which receive values from input attachments.

Fragment Output Interface

A fragment shader entry point’s variables with Output storage class, which output to color and/or depth/stencil attachments.

Framebuffer

A collection of image views and a set of dimensions that, in conjunction with a render pass, define the inputs and outputs used by drawing commands. Represented by a VkFramebuffer object.

Framebuffer Attachment

One of the image views used in a framebuffer.

Framebuffer Coordinates

A coordinate system in which adjacent pixels’ coordinates differ by 1 in x and/or y, with (0,0) in the upper left corner and pixel centers at half-integers.

Framebuffer-Space

Operating with respect to framebuffer coordinates.

Framebuffer-Local

A framebuffer-local dependency guarantees that only for a single framebuffer region, the first set of operations happens-before the second set of operations.
Framebuffer-Global
A framebuffer-global dependency guarantees that for all framebuffer regions, the first set of operations happens-before the second set of operations.

Framebuffer Region
A framebuffer region is a set of sample (x, y, layer, sample) coordinates that is a subset of the entire framebuffer.

Front-Facing
See Facingness.

Global Workgroup
A collection of local workgroups dispatched by a single dispatch command.

Handle
An opaque integer or pointer value used to refer to a Vulkan object. Each object type has a unique handle type.

Happen-after, happens-after
A transitive, irreflexive and antisymmetric ordering relation between operations. An execution dependency with a source of A and a destination of B enforces that B happens-after A. The inverse relation of happens-before.

Happen-before, happens-before
A transitive, irreflexive and antisymmetric ordering relation between operations. An execution dependency with a source of A and a destination of B enforces that A happens-before B. The inverse relation of happens-after.

Helper Invocation
A fragment shader invocation that is created solely for the purposes of evaluating derivatives for use in non-helper fragment shader invocations, and which does not have side effects.

Host
The processor(s) and execution environment that the application runs on, and that the Vulkan API is exposed on.

Host Mapped Device Memory
Device memory that is mapped for host access using vkMapMemory.

Host Memory
Memory not accessible to the device, used to store implementation data structures.

Host-Accessible Subresource
A buffer, or a linear image subresource in either the VK_IMAGE_LAYOUT_PREINITIALIZED or VK_IMAGE_LAYOUT_GENERAL layout. Host-accessible subresources have a well-defined addressing scheme which can be used by the host.

Host-Local Memory
Memory that is not local to the device, and **may** be less performant for device access than device-local memory.

**Host-Visible Memory**
Device memory that **can** be mapped on the host and **can** be read and written by the host.

**Identically Defined Objects**
Objects of the same type where all arguments to their creation or allocation functions, with the exception of `pAllocator`, are

1. Vulkan handles which refer to the same object or
2. identical scalar or enumeration values or
3. Host pointers which point to an array of values or structures which also satisfy these three constraints.

**Image**
A resource that represents a multi-dimensional formatted interpretation of device memory. Represented by a `VkImage` object.

**Image Subresource**
A specific mipmap level and layer of an image.

**Image Subresource Range**
A set of image subresources that are contiguous mipmap levels and layers.

**Image View**
An object that represents an image subresource range of a specific image, and state that controls how the contents are interpreted. Represented by a `VkImageView` object.

**Immutable Sampler**
A sampler descriptor provided at descriptor set layout creation time, and that is used for that binding in all descriptor sets allocated from the layout, and cannot be changed.

**Implicit chroma reconstruction**
An implementation of sampler $Y'$ChCr conversion which reconstructs the reduced-resolution chroma samples directly at the sample point, as part of the normal texture sampling operation. This is distinct from an *explicit chroma reconstruction* implementation, which reconstructs the reduced-resolution chroma samples to the resolution of the luma samples, then filters the result as part of texture sample interpolation.

**Implicitly-Enabled Layer**
A layer enabled by a loader-defined mechanism outside the Vulkan API, rather than explicitly by the application during instance or device creation.

**Inactive Object (Ray Tracing)**
A primitive or instance in a ray tracing acceleration structure which has a corresponding ID, but which will never report an intersection with any ray.
Index Buffer
A buffer bound via `vkCmdBindIndexBuffer` which is the source of index values used to fetch vertex attributes for a `vkCmdDrawIndexed` or `vkCmdDrawIndexedIndirect` command.

Indexed Drawing Commands
*Drawing commands* which use an *index buffer* as the source of index values used to fetch vertex attributes for a *drawing command*. Includes `vkCmdDrawIndexed`, `vkCmdDrawIndexedIndirectCountKHR`, and `vkCmdDrawIndexedIndirect`.

Indirect Commands
Drawing or dispatching commands that source some of their parameters from structures in buffer memory. Includes `vkCmdDrawIndirect`, `vkCmdDrawIndexedIndirect`, `vkCmdDrawIndexedIndirectCountKHR`, `vkCmdDrawIndexedIndirectCountKHR`, and `vkCmdDispatchIndirect`.

Indirect Drawing Commands
*Drawing commands* that source some of their parameters from structures in buffer memory. Includes `vkCmdDrawIndirect`, `vkCmdDrawIndexedIndirectCountKHR`, `vkCmdDrawIndexedIndirectCountKHR`, and `vkCmdDrawIndexedIndirect`.

Initial State (Command Buffer)
A command buffer that has not begun recording commands. See also Recorded State and Executable State.

Input Attachment
A descriptor type that represents an image view, and supports unfiltered read-only access in a shader, only at the fragment's location in the view.

Instance
The top-level Vulkan object, which represents the application's connection to the implementation. Represented by a `VkInstance` object.

Instance-Level Command
Any command that is dispatched from an instance, or from a child object of an instance, except for physical devices and their children.

Instance-Level Functionality
All instance-level commands and objects, and their structures, enumerated types, and enumerants.

Instance-Level Object
High-level Vulkan objects, which are not physical devices, nor children of physical devices. For example, `VkInstance` is an instance-level object.

Instance (Memory)
In a logical device representing more than one physical device, some device memory allocations have the requested amount of memory allocated multiple times, once for each physical device in a device mask. Each such replicated allocation is an instance of the device memory.
Instance (Resource)
In a logical device representing more than one physical device, buffer and image resources exist on all physical devices but can be bound to memory differently on each. Each such replicated resource is an instance of the resource.

Internal Synchronization
A type of synchronization required of the implementation, where parameters not defined to be externally synchronized may require internal mutexing to avoid multithreaded race conditions.

Invocation (Shader)
A single execution of an entry point in a SPIR-V module. For example, a single vertex’s execution of a vertex shader or a single fragment’s execution of a fragment shader.

Invocation Group
A set of shader invocations that are executed in parallel and that must execute the same control flow path in order for control flow to be considered dynamically uniform.

Invocation Repack Instruction
A ray tracing shader call where the implementation may change the set of invocations that are executing.

Join (Deferred Host Operations)
The act of instructing a thread to participate in the execution of a deferred operation. See Deferred Host Operations.

Linear Resource
A resource is linear if it is one of the following:

- a VkBuffer
- a VkImage created with VK_IMAGE_TILING_LINEAR

A resource is non-linear if it is one of the following:

- a VkImage created with VK_IMAGE_TILING_OPTIMAL

Local Workgroup
A collection of compute shader invocations invoked by a single dispatch command, which share data via WorkgroupLocal variables and can synchronize with each other.

Logical Device
An object that represents the application’s interface to the physical device. The logical device is the parent of most Vulkan objects. Represented by a VkDevice object.

Logical Operation
Bitwise operations between a fragment color value and a value in a color attachment, that produce a final color value to be written to the attachment.

Lost Device
A state that a logical device **may** be in as a result of unrecoverable implementation errors, or other exceptional conditions.

**Mappable**
See Host-Visible Memory.

**Memory Dependency**
A memory dependency is an execution dependency which includes availability and visibility operations such that:

- The first set of operations happens-before the availability operation
- The availability operation happens-before the visibility operation
- The visibility operation happens-before the second set of operations

**Memory Domain**
A memory domain is an abstract place to which memory writes are made available by availability operations and memory domain operations. The memory domains correspond to the set of agents that the write **can** then be made visible to. The memory domains are **host**, **device**, **shader**, **workgroup instance** (for workgroup instance there is a unique domain for each compute workgroup) and **subgroup instance** (for subgroup instance there is a unique domain for each subgroup).

**Memory Domain Operation**
An operation that makes the writes that are available to one memory domain available to another memory domain.

**Memory Heap**
A region of memory from which device memory allocations **can** be made.

**Memory Type**
An index used to select a set of memory properties (e.g. mappable, cached) for a device memory allocation.

**Minimum Mipmap Size**
The smallest size that is permitted for a mipmap level. For conventional images this is 1x1x1. See Image Mipmap Sizing.

**Mip Tail Region**
The set of mipmap levels of a sparse residency texture that are too small to fill a sparse block, and that **must** all be bound to memory collectively andopaquely.

**Multi-planar**
A **multi-planar format** (or “planar format”) is an image format consisting of more than one **plane**, identifiable with a **_2PLANE** or **_3PLANE** component to the format name and listed in Formats requiring sampler Y′C₆C₈ conversion for **VK_IMAGE_ASPECT_COLOR_BIT** image views. A **multi-planar image** (or “planar image”) is an image of a multi-planar format.
Non-Dispatchable Handle
A handle of an integer handle type. Handle values may not be unique, even for two objects of the same type.

Non-Indexed Drawing Commands
Drawing commands for which the vertex attributes are sourced in linear order from the vertex input attributes for a drawing command (i.e. they do not use an index buffer). Includes vkCmdDraw, vkCmdDrawIndirectCountKHR, and vkCmdDrawIndirect.

Normalized
A value that is interpreted as being in the range [0,1] as a result of being implicitly divided by some other value.

Normalized Device Coordinates
A coordinate space after perspective division is applied to clip coordinates, and before the viewport transformation converts to framebuffer coordinates.

Obsoleted (feature)
A feature is obsolete if it can no longer be used.

Opaque Capture Address
A 64-bit value representing the device address of a buffer or memory object that is expected to be used by trace capture/replay tools in combination with the bufferDeviceAddress feature.

Overlapped Range (Aliased Range)
The aliased range of a device memory allocation that intersects a given image subresource of an image or range of a buffer.

Ownership (Resource)
If an entity (e.g. a queue family) has ownership of a resource, access to that resource is well-defined for access by that entity.

Packed Format
A format whose components are stored as a single texel block in memory, with their relative locations defined within that element.

Payload
Importable or exportable reference to the internal data of an object in Vulkan.

Peer Memory
An instance of memory corresponding to a different physical device than the physical device performing the memory access, in a logical device that represents multiple physical devices.

Physical Device
An object that represents a single device in the system. Represented by a VkPhysicalDevice object.

Physical-Device-Level Command
Any command that is dispatched from a physical device.

**Physical-Device-Level Functionality**

All physical-device-level commands and objects, and their structures, enumerated types, and enumerants.

**Physical-Device-Level Object**

Physical device objects. For example, `VkPhysicalDevice` is a physical-device-level object.

**Pipeline**

An object that controls how graphics or compute work is executed on the device. A pipeline includes one or more shaders, as well as state controlling any non-programmable stages of the pipeline. Represented by a `VkPipeline` object.

**Pipeline Barrier**

An execution and/or memory dependency recorded as an explicit command in a command buffer, that forms a dependency between the previous and subsequent commands.

**Pipeline Cache**

An object that can be used to collect and retrieve information from pipelines as they are created, and can be populated with previously retrieved information in order to accelerate pipeline creation. Represented by a `VkPipelineCache` object.

**Pipeline Layout**

An object that defines the set of resources (via a collection of descriptor set layouts) and push constants used by pipelines that are created using the layout. Used when creating a pipeline and when binding descriptor sets and setting push constant values. Represented by a `VkPipelineLayout` object.

**Pipeline Library**

A pipeline that cannot be directly used, instead defining a set of shaders and shader groups which will be linked into other pipelines.

**Pipeline Stage**

A logically independent execution unit that performs some of the operations defined by an action command.

**pNext Chain**

A set of structures chained together through their `pNext` members.

**Planar**

See *multi-planar*.

**Plane**

An *image plane* is part of the representation of an image, containing a subset of the color channels required to represent the texels in the image and with a contiguous mapping of coordinates to bound memory. Most images consist only of a single plane, but some formats spread the channels across multiple image planes. The host-accessible properties of each image
plane are accessed in a linear layout using `vkGetImageSubresourceLayout`. If a multi-planar image is created with the `VK_IMAGE_CREATE_DISJOINT_BIT` bit set, the image is described as *disjoint*, and its planes are therefore are bound to memory independently.

**Point Sampling (Rasterization)**

A rule that determines whether a fragment sample location is covered by a polygon primitive by testing whether the sample location is in the interior of the polygon in framebuffer-space, or on the boundary of the polygon according to the tie-breaking rules.

**Presentable image**

A `VkImage` object obtained from a `VkSwapchainKHR` used to present to a `VkSurfaceKHR` object.

**Preserve Attachment**

One of a list of attachments in a subpass description that is not read or written by the subpass, but that is read or written on earlier and later subpasses and whose contents **must** be preserved through this subpass.

**Primary Command Buffer**

A command buffer that **can** execute secondary command buffers, and **can** be submitted directly to a queue.

**Primitive Topology**

State that controls how vertices are assembled into primitives, e.g. as lists of triangles, strips of lines, etc..

**Promoted (feature)**

A feature from an older extension is considered promoted if it is made available as part of a new core version or newer extension with wider support.

**Protected Buffer**

A buffer to which protected device memory **can** be bound.

**Protected-capable Device Queue**

A device queue to which protected command buffers **can** be submitted.

**Protected Command Buffer**

A command buffer which **can** be submitted to a protected-capable device queue.

**Protected Device Memory**

Device memory which **can** be visible to the device but **must** not be visible to the host.

**Protected Image**

An image to which protected device memory **can** be bound.

**Provisional**

A feature is released provisionally in order to get wider feedback on the functionality before it is finalized. Provisional features may change in ways that break backwards compatibility, and thus are not recommended for use in production applications.
Proving Vertex
The vertex in a primitive from which flat shaded attribute values are taken. This is generally the “first” vertex in the primitive, and depends on the primitive topology.

Push Constants
A small bank of values writable via the API and accessible in shaders. Push constants allow the application to set values used in shaders without creating buffers or modifying and binding descriptor sets for each update.

Push Constant Interface
The set of variables with PushConstant storage class that are statically used by a shader entry point, and which receive values from push constant commands.

Push Descriptors
Descriptors that are written directly into a command buffer rather than into a descriptor set. Push descriptors allow the application to set descriptors used in shaders without allocating or modifying descriptor sets for each update.

Descriptor Update Template
An object that specifies a mapping from descriptor update information in host memory to elements in a descriptor set, which helps enable more efficient descriptor set updates.

Query Pool
An object containing a number of query entries and their associated state and results. Represented by a VkQueryPool object.

Queue
An object that executes command buffers and sparse binding operations on a device. Represented by a VkQueue object.

Queue Family
A set of queues that have common properties and support the same functionality, as advertised in VkQueueFamilyProperties.

Queue Operation
A unit of work to be executed by a specific queue on a device, submitted via a queue submission command. Each queue submission command details the specific queue operations that occur as a result of calling that command. Queue operations typically include work that is specific to each command, and synchronization tasks.

Queue Submission
Zero or more batches and an optional fence to be signaled, passed to a command for execution on a queue. See the Devices and Queues chapter for more information.

Recording State (Command Buffer)
A command buffer that is ready to record commands. See also Initial State and Executable State.

Release Operation (Resource)
An operation that releases ownership of an image subresource or buffer range.

**Render Pass**
An object that represents a set of framebuffer attachments and phases of rendering using those attachments. Represented by a `VkRenderPass` object.

**Render Pass Instance**
A use of a render pass in a command buffer.

**Required Extensions**
Extensions that must be enabled alongside extensions dependent on them (see Extension Dependencies).

**Reset (Command Buffer)**
Resetting a command buffer discards any previously recorded commands and puts a command buffer in the initial state.

**Residency Code**
An integer value returned by sparse image instructions, indicating whether any sparse unbound texels were accessed.

**Resolve Attachment**
A subpass attachment point, or image view, that is the target of a multisample resolve operation from the corresponding color attachment at the end of the subpass.

**Retired Swapchain**
A swapchain that has been used as the `oldSwapchain` parameter to `vkCreateSwapchainKHR`. Images cannot be acquired from a retired swapchain, however images that were acquired (but not presented) before the swapchain was retired can be presented.

**Sample Shading**
Invoking the fragment shader multiple times per fragment, with the covered samples partitioned among the invocations.

**Sampled Image**
A descriptor type that represents an image view, and supports filtered (sampled) and unfiltered read-only access in a shader.

**Sampler**
An object containing state that controls how sampled image data is sampled (or filtered) when accessed in a shader. Also a descriptor type describing the object. Represented by a `VkSampler` object.

**Secondary Command Buffer**
A command buffer that can be executed by a primary command buffer, and must not be submitted directly to a queue.

**Self-Dependency**
A subpass dependency from a subpass to itself, i.e. with `srcSubpass` equal to `dstSubpass`. A self-dependency is not automatically performed during a render pass instance, rather a subset of it can be performed via `vkCmdPipelineBarrier` during the subpass.

**Semaphore**

A synchronization primitive that supports signal and wait operations, and can be used to synchronize operations within a queue or across queues. Represented by a `VkSemaphore` object.

**Shader**

Instructions selected (via an entry point) from a shader module, which are executed in a shader stage.

**Shader Call**

An instruction which may cause execution to continue in a different shader stage.

**Shader Code**

A stream of instructions used to describe the operation of a shader.

**Shader Group**

A set of Shader Stages that are part of a `slink::VkPipeline` which contains multiple of such sets. This allows the device to make use of all the shader groups from the bound pipeline independently.

**Shader Module**

A collection of shader code, potentially including several functions and entry points, that is used to create shaders in pipelines. Represented by a `VkShaderModule` object.

**Shader Stage**

A stage of the graphics or compute pipeline that executes shader code.

**Shared presentable image**

A presentable image created from a swapchain with `VkPresentModeKHR` set to either `VK_PRESENT_MODE_SHARED_DEMAND_REFRESH_KHR` or `VK_PRESENT_MODE_SHARED_CONTINUOUS_REFRESH_KHR`.

**Side Effect**

A store to memory or atomic operation on memory from a shader invocation.

**Single-plane format**

A format that is not multi-planar.

**Size-Compatible Image Formats**

When a compressed image format and an uncompressed image format are size-compatible, it means that the texel block size of the uncompressed format must equal the texel block size of the compressed format.

**Sparse Block**

An element of a sparse resource that can be independently bound to memory. Sparse blocks of a particular sparse resource have a corresponding size in bytes that they use in the bound
memory.

**Sparse Image Block**
A sparse block in a sparse partially-resident image. In addition to the sparse block size in bytes, sparse image blocks have a corresponding width, height, and depth that define the dimensions of these elements in units of texels or compressed texel blocks, the latter being used in case of sparse images having a block-compressed format.

**Sparse Unbound Texel**
A texel read from a region of a sparse texture that does not have memory bound to it.

**Static Use**
An object in a shader is statically used by a shader entry point if any function in the entry point’s call tree contains an instruction using the object. Static use is used to constrain the set of descriptors used by a shader entry point.

**Storage Buffer**
A descriptor type that represents a buffer, and supports reads, writes, and atomics in a shader.

**Storage Image**
A descriptor type that represents an image view, and supports unfiltered loads, stores, and atomics in a shader.

**Storage Texel Buffer**
A descriptor type that represents a buffer view, and supports unfiltered, formatted reads, writes, and atomics in a shader.

**Subgroup**
A set of shader invocations that can synchronize and share data with each other efficiently. In compute shaders, the local workgroup is a superset of the subgroup.

**Subgroup Mask**
A bitmask for all invocations in the current subgroup with one bit per invocation, starting with the least significant bit in the first vector component, continuing to the last bit (less than SubgroupSize) in the last required vector component.

**Subpass**
A phase of rendering within a render pass, that reads and writes a subset of the attachments.

**Subpass Dependency**
An execution and/or memory dependency between two subpasses described as part of render pass creation, and automatically performed between subpasses in a render pass instance. A subpass dependency limits the overlap of execution of the pair of subpasses, and can provide guarantees of memory coherence between accesses in the subpasses.

**Subpass Description**
Lists of attachment indices for input attachments, color attachments, depth/stencil attachment, resolve attachments, depth/stencil resolve, and preserve attachments used by the subpass in a
render pass.

**Subset (Self-Dependency)**

A subset of a self-dependency is a pipeline barrier performed during the subpass of the self-dependency, and whose stage masks and access masks each contain a subset of the bits set in the identically named mask in the self-dependency.

**Texel Block**

A single addressable element of an image with an uncompressed `VkFormat`, or a single compressed block of an image with a compressed `VkFormat`.

**Texel Block Size**

The size (in bytes) used to store a texel block of a compressed or uncompressed image.

**Texel Coordinate System**

One of three coordinate systems (normalized, unnormalized, integer) that define how texel coordinates are interpreted in an image or a specific mipmap level of an image.

**Timeline Semaphore**

A semaphore with a monotonically increasing 64-bit unsigned integer payload indicating whether the semaphore is signaled with respect to a particular reference value. Represented by a `VkSemaphore` object created with a semaphore type of `VK_SEMAPHORE_TYPE_TIMELINE`.

**Uniform Texel Buffer**

A descriptor type that represents a buffer view, and supports unfiltered, formatted, read-only access in a shader.

**Uniform Buffer**

A descriptor type that represents a buffer, and supports read-only access in a shader.

**Units in the Last Place (ULP)**

A measure of floating-point error loosely defined as the smallest representable step in a floating-point format near a given value. For the precise definition see Precision and Operation of SPIR-V instructions or Jean-Michel Muller, “On the definition of ulp(x)”, RR-5504, INRIA. Other sources may also use the term “unit of least precision”.

**Unnormalized**

A value that is interpreted according to its conventional interpretation, and is not normalized.

**Unprotected Buffer**

A buffer to which unprotected device memory can be bound.

**Unprotected Command Buffer**

A command buffer which can be submitted to an unprotected device queue or a protected-capable device queue.

**Unprotected Device Memory**

Device memory which can be visible to the device and can be visible to the host.
Unprotected Image
An image to which unprotected device memory can be bound.

User-Defined Variable Interface
A shader entry point’s variables with Input or Output storage class that are not built-in variables.

Vertex Input Attribute
A graphics pipeline resource that produces input values for the vertex shader by reading data from a vertex input binding and converting it to the attribute’s format.

Vertex Input Binding
A graphics pipeline resource that is bound to a buffer and includes state that affects addressing calculations within that buffer.

Vertex Input Interface
A vertex shader entry point’s variables with Input storage class, which receive values from vertex input attributes.

Vertex Processing Stages
A set of shader stages that comprises the vertex shader, tessellation control shader, tessellation evaluation shader, and geometry shader stages.

View Mask
When multiview is enabled, a view mask is a property of a subpass controlling which views the rendering commands are broadcast to.

View Volume
A subspace in homogeneous coordinates, corresponding to post-projection x and y values between -1 and +1, and z values between 0 and +1.

Viewport Transformation
A transformation from normalized device coordinates to framebuffer coordinates, based on a viewport rectangle and depth range.

Visibility Operation
An operation that causes available values to become visible to specified memory accesses.

Visible
A state of values written to memory that allows them to be accessed by a set of operations.
Common Abbreviations

Abbreviations and acronyms are sometimes used in the Specification and the API where they are considered clear and commonplace, and are defined here:

**Src**
Source

**Dst**
Destination

**Min**
Minimum

**Max**
Maximum

**Rect**
Rectangle

**Info**
Information

**LOD**
Level of Detail

**ID**
Identifier

**UUID**
Universally Unique Identifier

**Op**
Operation

**R**
Red color component

**G**
Green color component

**B**
Blue color component

**A**
Alpha color component
**RTZ**
- Round towards zero

**RTE**
- Round to nearest even
Prefixes

Prefixes are used in the API to denote specific semantic meaning of Vulkan names, or as a label to avoid name clashes, and are explained here:

**VK/Vk/vk**

Vulkan namespace
All types, commands, enumerants and defines in this specification are prefixed with these two characters.

**PFN/pfn**

Function Pointer
Denotes that a type is a function pointer, or that a variable is of a pointer type.

**p**

Pointer
Variable is a pointer.

**vkCmd**

Commands that record commands in command buffers
These API commands do not result in immediate processing on the device. Instead, they record the requested action in a command buffer for execution when the command buffer is submitted to a queue.

**s**

Structure
Used to denote the VK_STRUCTURE_TYPE* member of each structure in sType
Appendix H: Credits (Informative)

Vulkan 1.2 is the result of contributions from many people and companies participating in the Khronos Vulkan Working Group, as well as input from the Vulkan Advisory Panel.

Members of the Working Group, including the company that they represented at the time of their most recent contribution, are listed in the following section. Some specific contributions made by individuals are listed together with their name.

Working Group Contributors to Vulkan

- Aaron Greig, Codeplay Software Ltd. (version 1.1)
- Aaron Hagan, AMD (version 1.1)
- Adam Jackson, Red Hat (versions 1.0, 1.1)
- Adam Śmigielski, Mobica (version 1.0)
- Aidan Fabius, Core Avionics & Industrial Inc. (version 1.2)
- Alan Baker, Google (versions 1.1, 1.2)
- Alan Ward, Google (versions 1.1, 1.2)
- Alejandro Piñeiro, Igalia (version 1.1)
- Alex Bourd, Qualcomm Technologies, Inc. (versions 1.0, 1.1)
- Alex Crabb, Caster Communications (version 1.2)
- Alex Walters, Imagination Technologies (version 1.2)
- Alexander Galazin, Arm (versions 1.0, 1.1, 1.2)
- Allen Hux, Intel (version 1.0)
- Alon Or-bach, Samsung Electronics (versions 1.0, 1.1, 1.2) (WSI technical sub-group chair)
- Anastasia Stulova, Arm (version 1.2)
- Andreas Vasilakis, Think Silicon (version 1.2)
- Andres Gomez, Igalia (version 1.1)
- Andrew Cox, Samsung Electronics (version 1.0)
- Andrew Garrard, Samsung Electronics (versions 1.0, 1.1, 1.2) (format wrangler)
- Andrew Poole, Samsung Electronics (version 1.0)
- Andrew Rafter, Samsung Electronics (version 1.0)
- Andrew Richards, Codeplay Software Ltd. (version 1.0)
- Andrew Woloszyn, Google (versions 1.0, 1.1)
- Ann Thorsnes, Khronos (version 1.2)
- Antoine Labour, Google (versions 1.0, 1.1)
- Aras Pranckevičius, Unity Technologies (version 1.0)
• Ashwin Kolhe, NVIDIA (version 1.0)
• Baldur Karlsson, Independent (versions 1.1, 1.2)
• Barthold Lichtenbelt, NVIDIA (version 1.1)
• Bas Nieuwenhuizen, Google (versions 1.1, 1.2)
• Ben Bowman, Imagination Technologies (version 1.0)
• Benj Lipchak, Unknown (version 1.0)
• Bill Hollings, Brenwill (versions 1.0, 1.1, 1.2)
• Bill Licea-Kane, Qualcomm Technologies, Inc. (versions 1.0, 1.1)
• Blaine Kohl, Khronos (version 1.2)
• Boris Zanin, Mobica (version 1.2)
• Brent E. Insko, Intel (version 1.0)
• Brian Ellis, Qualcomm Technologies, Inc. (version 1.0)
• Brian Paul, VMware (version 1.2)
• Caio Marcelo de Oliveira Filho, Intel (version 1.2)
• Cass Everitt, Oculus VR (versions 1.0, 1.1)
• Cemil Azizoglu, Canonical (version 1.0)
• Chad Versace, Google (versions 1.0, 1.1, 1.2)
• Chang-Hyo Yu, Samsung Electronics (version 1.0)
• Chia-I Wu, LunarG (version 1.0)
• Chris Frascati, Qualcomm Technologies, Inc. (version 1.0)
• Christophe Riccio, Unity Technologies (versions 1.0, 1.1)
• Cody Northrop, LunarG (version 1.0)
• Colin Riley, AMD (version 1.1)
• Cort Stratton, Google (versions 1.1, 1.2)
• Courtney Goeltzenleuchter, Google (versions 1.0, 1.1)
• Craig Davies, Huawei (version 1.2)
• Dae Kim, Imagination Technologies (version 1.1)
• Damien Leone, NVIDIA (version 1.0)
• Dan Baker, Oxide Games (versions 1.0, 1.1)
• Dan Ginsburg, Valve Software (versions 1.0, 1.1, 1.2)
• Daniel Johnston, Intel (versions 1.0, 1.1)
• Daniel Koch, NVIDIA (versions 1.0, 1.1, 1.2)
• Daniel Rakos, AMD (versions 1.0, 1.1, 1.2)
• Daniel Stone, Collabora (versions 1.1, 1.2)
• Daniel Vetter, Intel (version 1.2)
• David Airlie, Red Hat (versions 1.0, 1.1, 1.2)
• David Mao, AMD (versions 1.0, 1.2)
• David Miller, Miller & Mattson (versions 1.0, 1.1) (Vulkan reference card)
• David Neto, Google (versions 1.0, 1.1, 1.2)
• David Wilkinson, AMD (version 1.2)
• David Yu, Pixar (version 1.0)
• Dejan Mircevski, Google (version 1.1)
• Dominik Witzczak, AMD (versions 1.0, 1.1)
• Donald Scorgie, Imagination Technologies (version 1.2)
• Dzmitry Malyshau, Mozilla (versions 1.1, 1.2)
• Ed Hutchins, Oculus (version 1.2)
• Emily Stearns, Khronos (version 1.2)
• Frank (LingJun) Chen, Qualcomm Technologies, Inc. (version 1.0)
• Fred Liao, Mediatek (version 1.0)
• Gabe Dagani, Freescale (version 1.0)
• Gabor Sines, AMD (version 1.2)
• Graeme Leese, Broadcom (versions 1.0, 1.1, 1.2)
• Graham Connor, Imagination Technologies (version 1.0)
• Graham Sellers, AMD (versions 1.0, 1.1)
• Greg Fischer, LunarG (version 1.1)
• Hai Nguyen, Google (version 1.2)
• Hans-Kristian Arntzen, Arm (versions 1.1, 1.2)
• Henri Verbeet, Codeweavers (version 1.2)
• Hwanyong Lee, Kyungpook National University (version 1.0)
• Iago Toral, Igalia (versions 1.1, 1.2)
• Ian Elliott, Google (versions 1.0, 1.1, 1.2)
• Ian Romanick, Intel (versions 1.0, 1.1)
• James Hughes, Oculus VR (version 1.0)
• James Jones, NVIDIA (versions 1.0, 1.1, 1.2)
• James Riordon, Khronos (version 1.2)
• Jan Hermes, Continental Corporation (versions 1.0, 1.1)
• Jan-Harald Fredriksen, Arm (versions 1.0, 1.1, 1.2)
• Jason Ekstrand, Intel (versions 1.0, 1.1, 1.2)
• Jean-François Roy, Google (versions 1.1, 1.2)
• Jeff Bolz, NVIDIA (versions 1.0, 1.1, 1.2)
• Jeff Juliano, NVIDIA (versions 1.0, 1.1, 1.2)
• Jeff Leger, Qualcomm Technologies, Inc. (version 1.1)
• Jeff Vigil, Samsung Electronics (versions 1.0, 1.1, 1.2)
• Jens Owen, Google (versions 1.0, 1.1)
• Jeremy Hayes, LunarG (version 1.0)
• Jesse Barker, Unity Technologies (versions 1.0, 1.1, 1.2)
• Jesse Hall, Google (versions 1.0, 1.1, 1.2)
• Joe Davis, Samsung Electronics (version 1.1)
• Johannes van Waveren, Oculus VR (versions 1.0, 1.1)
• John Kessenich, Google (versions 1.0, 1.1, 1.2) (SPIR-V and GLSL for Vulkan spec author)
• John McDonald, Valve Software (versions 1.0, 1.1, 1.2)
• John Zulauf, LunarG (versions 1.1, 1.2)
• Jon Ashburn, LunarG (version 1.0)
• Jon Leech, Independent (versions 1.0, 1.1, 1.2) (XML toolchain, normative language, release wrangler)
• Jonas Gustavsson, Samsung Electronics (versions 1.0, 1.1)
• Jonas Meyer, Epic Games (version 1.2)
• Jonathan Hamilton, Imagination Technologies (version 1.0)
• Jordan Justen, Intel (version 1.1)
• Jungwoo Kim, Samsung Electronics (versions 1.0, 1.1)
• Jörg Wagner, Arm (version 1.1)
• Kalle Raita, Google (version 1.1)
• Karen Ghavam, LunarG (versions 1.1, 1.2)
• Karl Schultz, LunarG (versions 1.1, 1.2)
• Kathleen Mattson, Khronos (versions 1.0, 1.1, 1.2)
• Kaye Mason, Google (version 1.2)
• Keith Packard, Valve (version 1.2)
• Kenneth Benzie, Codeplay Software Ltd. (versions 1.0, 1.1)
• Kenneth Russell, Google (version 1.1)
• Kerch Holt, NVIDIA (versions 1.0, 1.1)
• Kevin O'Neil, AMD (version 1.1)
• Kris Rose, Khronos (version 1.2)
• Kristian Kristensen, Intel (versions 1.0, 1.1)
• Krzysztof Iwanicki, Samsung Electronics (version 1.0)
• Larry Seiler, Intel (version 1.0)
• Lauri Ilola, Nokia (version 1.1)
• Lei Zhang, Google (version 1.2)
• Lenny Komow, LunarG (versions 1.1, 1.2)
• Lionel Landwerlin, Intel (versions 1.1, 1.2)
• Liz Maitral, Khronos (version 1.2)
• Lutz Latta, Lucasfilm (version 1.0)
• Maciej Jesionowski, AMD (version 1.1)
• Mais Alnasser, AMD (version 1.1)
• Marcin Rogucki, Mobica (version 1.1)
• Maria Rovatsou, Codeplay Software Ltd. (version 1.0)
• Mark Callow, Independent (versions 1.0, 1.1, 1.2)
• Mark Kilgard, NVIDIA (versions 1.1, 1.2)
• Mark Lobodzinski, LunarG (versions 1.0, 1.1, 1.2)
• Mark Young, LunarG (version 1.1)
• Markus Tavenrath, NVIDIA (version 1.1)
• Mateusz Przybylski, Intel (version 1.0)
• Mathias Heyer, NVIDIA (versions 1.0, 1.1)
• Mathias Schott, NVIDIA (versions 1.0, 1.1)
• Matt Netsch, Qualcomm Technologies, Inc. (version 1.1)
• Matthäus Chajdas, AMD (versions 1.1, 1.2)
• Maurice Ribble, Qualcomm Technologies, Inc. (versions 1.0, 1.1)
• Maxim Lukyanov, Samsung Electronics (version 1.0)
• Michael Lentine, Google (version 1.0)
• Michael O'Hara, AMD (version 1.1)
• Michael Phillip, Samsung Electronics (version 1.2)
• Michael Wong, Codeplay Software Ltd. (version 1.1)
• Michael Worcester, Imagination Technologies (versions 1.0, 1.1)
• Michal Pietrasniuk, Intel (version 1.0)
• Mika Isojarvi, Google (versions 1.0, 1.1)
• Mike Schuchardt, LunarG (versions 1.1, 1.2)
• Mike Stroyan, LunarG (version 1.0)
• Mike Weiblen, LunarG (versions 1.1, 1.2)
• Minyoung Son, Samsung Electronics (version 1.0)
• Mitch Singer, AMD (versions 1.0, 1.1, 1.2)
• Mythri Venugopal, Samsung Electronics (version 1.0)
• Naveen Leekha, Google (version 1.0)
• Neil Henning, AMD (versions 1.0, 1.1, 1.2)
• Neil Hickey, Arm (version 1.2)
• Neil Trevett, NVIDIA (versions 1.0, 1.1, 1.2)
• Nick Penwarden, Epic Games (version 1.0)
• Nicolai Hähnle, AMD (version 1.1)
• Niklas Smedberg, Unity Technologies (version 1.0)
• Norbert Nopper, Independent (versions 1.0, 1.1)
• Nuno Subtil, NVIDIA (versions 1.1, 1.2)
• Pat Brown, NVIDIA (version 1.0)
• Patrick Cozzi, Independent (version 1.1)
• Patrick Doane, Blizzard Entertainment (version 1.0)
• Peter Lohrmann, AMD (versions 1.0, 1.2)
• Petros Bantolas, Imagination Technologies (version 1.1)
• Pierre Boudier, NVIDIA (versions 1.0, 1.1, 1.2)
• Pierre-Loup Griffais, Valve Software (versions 1.0, 1.1, 1.2)
• Piers Daniell, NVIDIA (versions 1.0, 1.1, 1.2)
• Piotr Bialecki, Intel (version 1.0)
• Prabindh Sundareson, Samsung Electronics (version 1.0)
• Pyry Haulos, Google (versions 1.0, 1.1) (Vulkan conformance test subcommittee chair)
• Rajeev Rao, Qualcomm (version 1.2)
• Ralph Potter, Codeplay Software Ltd. (versions 1.1, 1.2)
• Ray Smith, Arm (versions 1.0, 1.1, 1.2)
• Richard Huddy, Samsung Electronics (version 1.2)
• Rob Barris, NVIDIA (version 1.1)
• Rob Stepinski, Transgaming (version 1.0)
• Robert Simpson, Qualcomm Technologies, Inc. (versions 1.0, 1.1)
• Rolando Caloca Olivares, Epic Games (versions 1.0, 1.1, 1.2)
• Roy Ju, Mediatek (version 1.0)
• Rufus Hamade, Imagination Technologies (version 1.0)
• Ruihao Zhang, Qualcomm Technologies, Inc. (versions 1.1, 1.2)
• Sean Ellis, Arm (version 1.0)
• Sean Harmer, KDAB Group (versions 1.0, 1.1)
• Shannon Woods, Google (versions 1.0, 1.1, 1.2)
• Slawomir Cygan, Intel (versions 1.0, 1.1)
• Slawomir Grajewski, Intel (versions 1.0, 1.1)
• Sorel Bosan, AMD (version 1.1)
• Spencer Fricke, Samsung Electronics (version 1.2)
• Stefanus Du Toit, Google (version 1.0)
• Stephen Huang, Mediatek (version 1.1)
• Steve Hill, Broadcom (versions 1.0, 1.2)
• Steve Viggers, Core Avionics & Industrial Inc. (versions 1.0, 1.2)
• Stuart Smith, Imagination Technologies (versions 1.0, 1.1, 1.2)
• Tilmann Scheller, Samsung Electronics (version 1.1)
• Tim Foley, Intel (version 1.0)
• Timo Suoranta, AMD (version 1.0)
• Timothy Lottes, AMD (versions 1.0, 1.1)
• Tobias Hector, AMD (versions 1.0, 1.1, 1.2) (validity language and toolchain)
• Tobin Ehlis, LunarG (version 1.0)
• Tom Olson, Arm (versions 1.0, 1.1, 1.2) (Working Group chair)
• Tomasz Bednarz, Independent (version 1.1)
• Tomasz Kubale, Intel (version 1.0)
• Tony Barbour, LunarG (versions 1.0, 1.1, 1.2)
• Victor Eruhimov, Unknown (version 1.1)
• Vincent Hindriksen, StreamHPC (version 1.2)
• Wayne Lister, Imagination Technologies (version 1.0)
• Wolfgang Engel, Unknown (version 1.1)
• Yanjun Zhang, VeriSilicon (versions 1.0, 1.1, 1.2)

Other Credits

The Vulkan Advisory Panel members provided important real-world usage information and advice that helped guide design decisions.

The wider Vulkan community have provided useful feedback, questions and spec changes that have helped improve the quality of the Specification via GitHub.

Administrative support to the Working Group for Vulkan 1.1 and 1.2 was provided by Khronos staff including Angela Cheng, Ann Thorsnes, Blaine Kohl, Dominic Agoro-Ombaka, Emily Stearns, Jeff Phillips, Lisie Aartsen, and Liz Maitral; and by Alex Crabb of Caster Communications.

Administrative support for Vulkan 1.0 was provided by Andrew Riegel, Elizabeth Riegel, Glenn Fredericks, Kathleen Mattson and Michelle Clark of Gold Standard Group.

Technical support was provided by James Riordon, webmaster of Khronos.org and OpenGL.org.