# 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 .................................................................................................................... 20
   2.8. Numeric Representation and Computation ......................................................... 32
   2.9. Fixed-Point Data Conversions .............................................................................. 34
   2.10. Common Object Types ....................................................................................... 35

3. Initialization .................................................................................................................... 37
   3.1. Command Function Pointers ................................................................................. 37
   3.2. Instances ............................................................................................................... 40

4. Devices and Queues ....................................................................................................... 46
   4.1. Physical Devices ..................................................................................................... 46
   4.2. Devices .................................................................................................................. 67
   4.3. Queues .................................................................................................................. 77

5. Command Buffers .......................................................................................................... 84
   5.1. Command Buffer Lifecycle ................................................................................... 84
   5.2. Command Pools .................................................................................................... 86
   5.3. Command Buffer Allocation and Management ................................................... 92
   5.4. Command Buffer Recording ............................................................................... 96
   5.5. Command Buffer Submission .............................................................................. 102
   5.6. Queue Forward Progress ..................................................................................... 111
   5.7. Secondary Command Buffer Execution ................................................................ 112
   5.8. Command Buffer Device Mask ............................................................................ 115

6. Synchronization and Cache Control .............................................................................. 118
   6.1. Execution and Memory Dependencies ................................................................... 118
   6.2. Implicit Synchronization Guarantees ..................................................................... 132
   6.3. Fences ................................................................................................................... 134
   6.4. Semaphores .......................................................................................................... 144
   6.5. Events ................................................................................................................... 158
   6.6. Pipeline Barriers ................................................................................................... 171
   6.7. Memory Barriers ................................................................................................... 176
   6.8. Wait Idle Operations ............................................................................................. 185
6.9. Host Write Ordering Guarantees .................................................. 187
6.10. Synchronization and Multiple Physical Devices ......................... 187

7. Render Pass ................................................................. 188
  7.1. Render Pass Creation .................................................. 189
  7.2. Render Pass Compatibility ........................................... 234
  7.3. Framebuffers ......................................................... 234
  7.4. Render Pass Commands ............................................... 243

8. Shaders ................................................................. 262
  8.1. Shader Modules ..................................................... 262
  8.2. Shader Execution .................................................. 265
  8.3. Shader Memory Access Ordering .................................. 265
  8.4. Shader Inputs and Outputs ........................................ 266
  8.5. Vertex Shaders ...................................................... 266
  8.6. Tessellation Control Shaders ...................................... 267
  8.7. Tessellation Evaluation Shaders .................................. 267
  8.8. Geometry Shaders .................................................. 268
  8.9. Fragment Shaders .................................................. 268
  8.10. Compute Shaders .................................................. 269
  8.11. Interpolation Decorations .......................................... 269
  8.12. Static Use ........................................................ 270
  8.13. Scope ................................................................. 270
  8.15. Quad Group Operations ........................................... 275
  8.16. Derivative Operations ............................................. 275
  8.17. Helper Invocations ................................................. 276

9. Pipelines ................................................................. 277
  9.1. Compute Pipelines .................................................. 278
  9.2. Graphics Pipelines .................................................. 285
  9.3. Pipeline destruction ................................................ 296
  9.4. Multiple Pipeline Creation ...................................... 297
  9.5. Pipeline Derivatives ............................................... 297
  9.6. Pipeline Cache ...................................................... 298
  9.7. Specialization Constants ......................................... 305
  9.8. Pipeline Binding .................................................... 308
  9.9. Dynamic State ........................................................ 310

10. Memory Allocation ..................................................... 312
  10.1. Host Memory ........................................................ 312
  10.2. Device Memory ..................................................... 319

11. Resource Creation .................................................... 346
  11.1. Buffers ............................................................... 346
  11.2. Buffer Views ........................................................ 353
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.3. Images</td>
<td>357</td>
</tr>
<tr>
<td>11.4. Image Layouts</td>
<td>376</td>
</tr>
<tr>
<td>11.5. Image Views</td>
<td>379</td>
</tr>
<tr>
<td>11.6. Resource Memory Association</td>
<td>393</td>
</tr>
<tr>
<td>11.7. Resource Sharing Mode</td>
<td>417</td>
</tr>
<tr>
<td>11.8. Memory Aliasing</td>
<td>419</td>
</tr>
<tr>
<td>12. Samplers</td>
<td>422</td>
</tr>
<tr>
<td>12.1. Sampler Y’C’bC’r conversion</td>
<td>430</td>
</tr>
<tr>
<td>13. Resource Descriptors</td>
<td>439</td>
</tr>
<tr>
<td>13.1. Descriptor Types</td>
<td>439</td>
</tr>
<tr>
<td>13.2. Descriptor Sets</td>
<td>442</td>
</tr>
<tr>
<td>13.3. Physical Storage Buffer Access</td>
<td>499</td>
</tr>
<tr>
<td>14. Shader Interfaces</td>
<td>502</td>
</tr>
<tr>
<td>14.1. Shader Input and Output Interfaces</td>
<td>502</td>
</tr>
<tr>
<td>14.2. Vertex Input Interface</td>
<td>506</td>
</tr>
<tr>
<td>14.3. Fragment Output Interface</td>
<td>506</td>
</tr>
<tr>
<td>14.4. Fragment Input Attachment Interface</td>
<td>507</td>
</tr>
<tr>
<td>14.5. Shader Resource Interface</td>
<td>508</td>
</tr>
<tr>
<td>14.6. Built-In Variables</td>
<td>515</td>
</tr>
<tr>
<td>15. Image Operations</td>
<td>531</td>
</tr>
<tr>
<td>15.1. Image Operations Overview</td>
<td>531</td>
</tr>
<tr>
<td>15.2. Conversion Formulas</td>
<td>534</td>
</tr>
<tr>
<td>15.3. Texel Input Operations</td>
<td>536</td>
</tr>
<tr>
<td>15.4. Texel Output Operations</td>
<td>551</td>
</tr>
<tr>
<td>15.5. Normalized Texel Coordinate Operations</td>
<td>553</td>
</tr>
<tr>
<td>15.6. Unnormalized Texel Coordinate Operations</td>
<td>559</td>
</tr>
<tr>
<td>15.7. Integer Texel Coordinate Operations</td>
<td>560</td>
</tr>
<tr>
<td>15.8. Image Sample Operations</td>
<td>560</td>
</tr>
<tr>
<td>15.9. Image Operation Steps</td>
<td>563</td>
</tr>
<tr>
<td>16. Queries</td>
<td>565</td>
</tr>
<tr>
<td>16.1. Query Pools</td>
<td>565</td>
</tr>
<tr>
<td>16.2. Query Operation</td>
<td>568</td>
</tr>
<tr>
<td>16.3. Occlusion Queries</td>
<td>582</td>
</tr>
<tr>
<td>16.4. Pipeline Statistics Queries</td>
<td>582</td>
</tr>
<tr>
<td>16.5. Timestamp Queries</td>
<td>585</td>
</tr>
<tr>
<td>17. Clear Commands</td>
<td>588</td>
</tr>
<tr>
<td>17.1. Clearing Images Outside A Render Pass Instance</td>
<td>588</td>
</tr>
<tr>
<td>17.2. Clearing Images Inside A Render Pass Instance</td>
<td>593</td>
</tr>
<tr>
<td>17.3. Clear Values</td>
<td>597</td>
</tr>
<tr>
<td>17.4. Filling Buffers</td>
<td>598</td>
</tr>
<tr>
<td>17.5. Updating Buffers</td>
<td>600</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>18. Copy Commands</td>
<td>603</td>
</tr>
<tr>
<td>18.1. Common Operation</td>
<td>603</td>
</tr>
<tr>
<td>18.2. Copying Data Between Buffers</td>
<td>604</td>
</tr>
<tr>
<td>18.3. Copying Data Between Images</td>
<td>606</td>
</tr>
<tr>
<td>18.4. Copying Data Between Buffers and Images</td>
<td>614</td>
</tr>
<tr>
<td>18.5. Image Copies with Scaling</td>
<td>625</td>
</tr>
<tr>
<td>18.6. Resolving Multisample Images</td>
<td>633</td>
</tr>
<tr>
<td>19. Drawing Commands</td>
<td>637</td>
</tr>
<tr>
<td>19.1. Primitive Topologies</td>
<td>638</td>
</tr>
<tr>
<td>19.2. Primitive Order</td>
<td>644</td>
</tr>
<tr>
<td>19.3. Programmable Primitive Shading</td>
<td>645</td>
</tr>
<tr>
<td>20. Fixed-Function Vertex Processing</td>
<td>671</td>
</tr>
<tr>
<td>20.1. Vertex Attributes</td>
<td>671</td>
</tr>
<tr>
<td>20.2. Vertex Input Description</td>
<td>676</td>
</tr>
<tr>
<td>20.3. Example</td>
<td>681</td>
</tr>
<tr>
<td>21. Tessellation</td>
<td>683</td>
</tr>
<tr>
<td>21.1. Tessellator</td>
<td>683</td>
</tr>
<tr>
<td>21.2. Tessellator Patch Discard</td>
<td>685</td>
</tr>
<tr>
<td>21.3. Tessellator Spacing</td>
<td>685</td>
</tr>
<tr>
<td>21.4. Tessellation Primitive Ordering</td>
<td>686</td>
</tr>
<tr>
<td>21.5. Tessellator Vertex Winding Order</td>
<td>686</td>
</tr>
<tr>
<td>21.6. Triangle Tessellation</td>
<td>687</td>
</tr>
<tr>
<td>21.7. Quad Tessellation</td>
<td>688</td>
</tr>
<tr>
<td>21.8. Isoline Tessellation</td>
<td>690</td>
</tr>
<tr>
<td>21.9. Tessellation Point Mode</td>
<td>690</td>
</tr>
<tr>
<td>21.10. Tessellation Pipeline State</td>
<td>691</td>
</tr>
<tr>
<td>22. Geometry Shading</td>
<td>693</td>
</tr>
<tr>
<td>22.1. Geometry Shader Input Primitives</td>
<td>693</td>
</tr>
<tr>
<td>22.2. Geometry Shader Output Primitives</td>
<td>694</td>
</tr>
<tr>
<td>22.3. Multiple Invocations of Geometry Shaders</td>
<td>694</td>
</tr>
<tr>
<td>22.4. Geometry Shader Primitive Ordering</td>
<td>694</td>
</tr>
<tr>
<td>23. Fixed-Function Vertex Post-Processing</td>
<td>695</td>
</tr>
<tr>
<td>23.1. Flat Shading</td>
<td>695</td>
</tr>
<tr>
<td>23.2. Primitive Clipping</td>
<td>695</td>
</tr>
<tr>
<td>23.3. Clipping Shader Outputs</td>
<td>697</td>
</tr>
<tr>
<td>23.4. Coordinate Transformations</td>
<td>698</td>
</tr>
<tr>
<td>23.5. Controlling the Viewport</td>
<td>698</td>
</tr>
<tr>
<td>24. Rasterization</td>
<td>704</td>
</tr>
<tr>
<td>24.1. Discarding Primitives Before Rasterization</td>
<td>707</td>
</tr>
<tr>
<td>24.2. Rasterization Order</td>
<td>707</td>
</tr>
<tr>
<td>24.3. Multisampling</td>
<td>708</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>24.4. Sample Shading</td>
<td>710</td>
</tr>
<tr>
<td>24.5. Points</td>
<td>711</td>
</tr>
<tr>
<td>24.6. Line Segments</td>
<td>711</td>
</tr>
<tr>
<td>24.7. Polygons</td>
<td>714</td>
</tr>
<tr>
<td>25. Fragment Operations</td>
<td>720</td>
</tr>
<tr>
<td>25.1. Early Per-Fragment Tests</td>
<td>720</td>
</tr>
<tr>
<td>25.2. Scissor Test</td>
<td>720</td>
</tr>
<tr>
<td>25.3. Sample Mask</td>
<td>722</td>
</tr>
<tr>
<td>25.4. Early Fragment Test Mode</td>
<td>722</td>
</tr>
<tr>
<td>25.5. Late Per-Fragment Tests</td>
<td>723</td>
</tr>
<tr>
<td>25.6. Multisample Coverage</td>
<td>723</td>
</tr>
<tr>
<td>25.7. Depth and Stencil Operations</td>
<td>724</td>
</tr>
<tr>
<td>25.8. Depth Bounds Test</td>
<td>725</td>
</tr>
<tr>
<td>25.9. Stencil Test</td>
<td>727</td>
</tr>
<tr>
<td>25.10. Depth Test</td>
<td>733</td>
</tr>
<tr>
<td>25.11. Sample Counting</td>
<td>734</td>
</tr>
<tr>
<td>25.12. Coverage Reduction</td>
<td>734</td>
</tr>
<tr>
<td>26. The Framebuffer</td>
<td>735</td>
</tr>
<tr>
<td>26.1. Blending</td>
<td>735</td>
</tr>
<tr>
<td>26.2. Logical Operations</td>
<td>743</td>
</tr>
<tr>
<td>26.3. Color Write Mask</td>
<td>744</td>
</tr>
<tr>
<td>27. Dispatching Commands</td>
<td>746</td>
</tr>
<tr>
<td>28. Sparse Resources</td>
<td>756</td>
</tr>
<tr>
<td>28.1. Sparse Resource Features</td>
<td>756</td>
</tr>
<tr>
<td>28.2. Sparse Buffers and Fully-Resident Images</td>
<td>757</td>
</tr>
<tr>
<td>28.3. Sparse Partially-Resident Buffers</td>
<td>758</td>
</tr>
<tr>
<td>28.4. Sparse Partially-Resident Images</td>
<td>758</td>
</tr>
<tr>
<td>28.5. Sparse Memory Aliasing</td>
<td>766</td>
</tr>
<tr>
<td>28.7. Sparse Resource API</td>
<td>768</td>
</tr>
<tr>
<td>28.8. Examples</td>
<td>792</td>
</tr>
<tr>
<td>29. Extending Vulkan</td>
<td>798</td>
</tr>
<tr>
<td>29.1. Instance and Device Functionality</td>
<td>798</td>
</tr>
<tr>
<td>29.2. Core Versions</td>
<td>798</td>
</tr>
<tr>
<td>29.3. Layers</td>
<td>800</td>
</tr>
<tr>
<td>29.4. Extensions</td>
<td>804</td>
</tr>
<tr>
<td>29.5. Extension Dependencies</td>
<td>808</td>
</tr>
<tr>
<td>29.6. Compatibility Guarantees (Informative)</td>
<td>808</td>
</tr>
<tr>
<td>30. Features</td>
<td>813</td>
</tr>
<tr>
<td>30.1. Feature Requirements</td>
<td>847</td>
</tr>
<tr>
<td>31. Limits</td>
<td>849</td>
</tr>
</tbody>
</table>
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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.

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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.
Note

There is an important distinction between cannot and must not, as used in this Specification. Cannot means something the application literally is unable to express or accomplish through the API, while 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 Errors).

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

1.1.2. Technical Terminology

The Vulkan Specification makes use of common engineering and graphics terms such as Pipeline, Shader, and Host to identify and describe Vulkan API constructs and their attributes, states, and behaviors. The 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 Glossary definitions. When a term defined in the 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).

1.1.3. Normative References

References to external documents are considered normative references if the Specification uses any of the normative terms defined in 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 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).

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

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

- **VkQueue** objects **cannot** be explicitly destroyed. Instead, they are implicitly destroyed when the **VkDevice** object they are retrieved from is destroyed.

- Destroying a pool object implicitly frees all objects allocated from that pool. Specifically, destroying **VkCommandPool** frees all **VkCommandBuffer** objects that were allocated from it, and destroying **VkDescriptorPool** frees all **VkDescriptorSet** objects that were allocated from it.

- **VkDevice** objects **can** be destroyed when all **VkQueue** objects retrieved from them are idle, and all objects created from them have been destroyed. This includes the following objects:
  - **VkFence**
  - **VkSemaphore**
  - **VkEvent**
  - **VkQueryPool**
  - **VkBuffer**
  - **VkBufferView**
  - **VkImage**
  - **VkImageView**
  - **VkShaderModule**
  - **VkPipelineCache**
  - **VkPipeline**
  - **VkPipelineLayout**
  - **VkSampler**
  - **VkSamplerYcbcrConversion**
  - **VkDescriptorSetLayout**
  - **VkDescriptorPool**
  - **VkFramebuffer**
  - **VkRenderPass**
  - **VkCommandPool**
  - **VkCommandBuffer**
  - **VkDeviceMemory**

- **VkPhysicalDevice** objects **cannot** be explicitly destroyed. Instead, they are implicitly destroyed when the **VkInstance** object they are retrieved from is destroyed.

- **VkInstance** objects **can** be destroyed once all **VkDevice** objects created from any of its **VkPhysicalDevice** objects 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 `vkDestroy*`.

The last in-parameter to each command that creates or destroys a Vulkan object is `pAllocator`. The `pAllocator` parameter can be set to a non-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 `vkAllocate*`, and take `VkAllocateInfo` structures. These Vulkan objects are freed with commands of the form `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 `vkCmd*`. Each such command may have different restrictions on where it 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 duration of a Vulkan command refers to the interval between calling the command and its return to the caller.

### 2.5.1. Lifetime of Retrieved Results

Information is retrieved from the implementation with commands of the form `vkGet*` and `vkEnumerate*`.

Unless otherwise specified for an individual command, the results are 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.

### 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 externally synchronized. This means that the caller 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 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 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-\texttt{const} qualified memory at any point. Parameters referring to non-\texttt{const} qualified application-owned memory are not marked explicitly as \textit{externally synchronized} in the Specification.

Many object types are \textit{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`
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

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 `vkCmdBindDescriptorSets`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdBindIndexBuffer`
- The `VkCommandPool` that `commandBuffer` was allocated from, in `vkCmdBindVertexBuffers`
- 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 `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`
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.

Note

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_ENUM1.

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 valid VkStructureType value matching the type of the structure.

Structure types supported by the Vulkan API include:

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,
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_DEDICATED_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_MEMORYDEVICEGROUP_INFO = 1000060013,
VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORYDEVICEGROUP_INFO = 1000060014,
VK_STRUCTURE_TYPE_PHYSICALDEVICEGROUP_PROPERTIES = 1000070000,
VK_STRUCTURE_TYPE_DEVICEGROUP_DEVICE_CREATE_INFO = 1000070001,
VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2 = 1000146000,
VK_STRUCTURE_TYPE_IMAGEMEMORY_REQUIREMENTS_INFO_2 = 1000146001,
VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2 = 1000146002,
VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2 = 1000146003,
VK_STRUCTURE_TYPE_SPARSEIMAGE_MEMORY_REQUIREMENTS_2 = 1000146004,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_FEATURES_2 = 1000059000,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_PROPERTIES_2 = 1000059001,
VK_STRUCTURE_TYPE_FORMATPROPERTIES_2 = 1000059002,
VK_STRUCTURE_TYPE_IMAGEFORMATPROPERTIES_2 = 1000059003,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_IMAGEFORMAT_INFO_2 = 1000059004,
VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2 = 1000059005,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_MEMORYPROPERTIES_2 = 1000059006,
VK_STRUCTURE_TYPE_SPARSEIMAGEFORMAT_PROPERTIES_2 = 1000059007,
VK_STRUCTURE_TYPE_RENDER_PASS_MULTIVIEW_CREATE_INFO = 100053000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_FEATURES = 100053001,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_PROPERTIES = 100053002,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTERS_FEATURES = 1000120000,
VK_STRUCTURE_TYPE_PROTECTED_SUBMIT_INFO = 1000145000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_FEATURES = 1000145001,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_PROPERTIES = 1000145002,
VK_STRUCTURE_TYPE_DEVICE_QUEUE_INFO_2 = 1000145003,
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 = 1000085000,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_EXTERNAL_IMAGE_FORMAT_INFO = 1000071000,
VK_STRUCTURE_TYPE_EXTERNAL_IMAGE_FORMAT_PROPERTIES = 1000071001,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_BUFFER_INFO = 1000071002,
VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_PROPERTIES = 1000071003,
VK_STRUCTURE_TYPE_PHYSICALDEVICE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO = 1000072000,
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_BUFFER_CREATE_INFO = 1000072001,
VK_STRUCTURE_TYPE_EXTERNAL_MEMORY_ALLOCATE_INFO = 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 = 1000077000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_EXTERNAL_SEMAPHORE_INFO = 1000076000,
VK_STRUCTURE_TYPE_EXTERNAL_SEMAPHORE_PROPERTIES = 1000076001,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MAINTENANCE_3_PROPERTIES = 1000168000,
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_SUPPORT = 1000168001,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_DRAW_PARAMETERS_FEATURES = 1000063000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_FEATURES = 49,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_PROPERTIES = 50,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_FEATURES = 51,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_PROPERTIES = 52,
VK_STRUCTURE_TYPE_IMAGE_FORMAT_LIST_CREATE_INFO = 1000147000,
VK_STRUCTURE_TYPE_ATTACHMENT_DESCRIPTION_2 = 1000109000,
VK_STRUCTURE_TYPE_ATTACHMENT_REFERENCE_2 = 1000109001,
VK_STRUCTURE_TYPE_SUBPASS_DESCRIPTION_2 = 1000109002,
VK_STRUCTURE_TYPE_SUBPASS_DEPENDENCY_2 = 1000109003,
VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO_2 = 1000109004,
VK_STRUCTURE_TYPE_SUBPASS_BEGIN_INFO = 1000109005,
VK_STRUCTURE_TYPE_SUBPASS_END_INFO = 1000109006,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_8BIT_STORAGE_FEATURES = 1000177000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES = 1000196000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_ATOMIC_INT64_FEATURES = 1000180000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SHADER_FLOAT16_INT8_FEATURES = 1000082000,
VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FLOAT_CONTROLS_PROPERTIES = 1000197000,
VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_BINDING_FLAGS_CREATE_INFO = 1000161000.
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:

```cpp
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 = -1000009000,
    VK_ERROR_INVALID_EXTERNAL_HANDLE = -1000072003,
    VK_ERROR_FRAGMENTATION = -1000161000,
    VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS = -1000257000,
    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

**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_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_FRAGMENTATION** A descriptor pool creation has failed due to fragmentation.
- **VK_ERROR_INVALID_OPAQUE_CAPTURE_ADDRESS** A buffer creation or memory allocation failed because the requested address is not available.
- **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 (\text{vkCmd*}) run time errors are reported by \text{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 $2^{32}$.

$$x \times 0 = 0 \times x = 0$$

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 \( \text{Inf} \) and \(-\text{Inf} \) encode values with magnitudes too large to be represented; the special value \( \text{NaN} \) encodes “Not A Number” values resulting from undefined arithmetic operations such as \( 0 / 0 \). Implementations may support \( \text{Inf} \) and \( \text{NaN} \) 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

\[
f = \max\left(\frac{c}{2^b - 1}, -1.0\right)
\]

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 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 = convertFloatToInt(f \times (2^{b-1} - 1), b)

where 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 offsets is defined by the structure:

```c
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:

```c
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-
A two-dimensional extent is defined by the structure:

```c
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:

```c
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](image)

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><code>instance</code></th>
<th><code>pName</code></th>
<th><code>return value</code></th>
</tr>
</thead>
<tbody>
<tr>
<td><code>NULL</code></td>
<td><code>vkEnumerateInstanceVersion</code></td>
<td><code>fp</code></td>
</tr>
<tr>
<td>invalid non-<code>NULL</code> instance</td>
<td><code>NULL</code></td>
<td>undefined</td>
</tr>
<tr>
<td><code>*1</code></td>
<td><code>NULL</code></td>
<td>undefined</td>
</tr>
</tbody>
</table>

Table 1. `vkGetInstanceProcAddr` behavior
<table>
<thead>
<tr>
<th>instance</th>
<th>pName</th>
<th>return value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NULL</td>
<td>vkEnumerateInstanceExtensionProperties</td>
<td>fp</td>
</tr>
<tr>
<td>NULL</td>
<td>vkEnumerateInstanceLayerProperties</td>
<td>fp</td>
</tr>
<tr>
<td>instance</td>
<td>vkCreateInstance</td>
<td>fp</td>
</tr>
<tr>
<td>instance</td>
<td>core Vulkan command</td>
<td>fp(^2)</td>
</tr>
<tr>
<td>instance</td>
<td>enabled instance extension commands for instance</td>
<td>fp(^2)</td>
</tr>
<tr>
<td>instance</td>
<td>available device extension(^3) commands for instance</td>
<td>fp(^2)</td>
</tr>
<tr>
<td>any other case, not covered above</td>
<td>NULL</td>
<td></td>
</tr>
</tbody>
</table>

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 *instance* or a child of *instance*, e.g. *VkInstance*, *VkPhysicalDevice*, *VkDevice*, *VkQueue*, or *VkCommandBuffer*.

3

An “available device extension” is a device extension supported by any physical device enumerated by *instance*.

**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 \texttt{vkGetDeviceProcAddr} and expected return value for each case.

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

\begin{tabular}{|c|c|c|}
\hline
\texttt{device} & \texttt{pName} & \textbf{return value} \\
\hline
\texttt{NULL} & *1 & undefined \textbf{1} \\
\texttt{invalid device} & *1 & undefined \textbf{1} \\
\texttt{device} & \texttt{NULL} & undefined \textbf{2} \\
\texttt{device} & core device-level Vulkan command & \texttt{fp} \textbf{2} \\
\texttt{device} & enabled extension device-level commands & \texttt{fp} \textbf{2} \\
any other case, not covered above & & \texttt{NULL} \textbf{2} \\
\hline
\end{tabular}

\textbf{1} \\

"*" means any representable value for the parameter (including valid values, invalid values, and \texttt{NULL}).

\textbf{2} \\

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

\textbf{Valid Usage (Implicit)}

- \texttt{device} \textbf{must} be a valid \texttt{VkDevice} handle
- \texttt{pName} \textbf{must} be a null-terminated UTF-8 string

The definition of \texttt{PFN_vkVoidFunction} is:

\begin{verbatim}
typedef void (VKAPI_PTR *PFN_vkVoidFunction)(void);
\end{verbatim}

\subsection*{3.1.1. Extending Physical Device Core Functionality}

New core physical-device-level functionality \textbf{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 \textbf{can} be obtained by calling \texttt{vkGetPhysicalDeviceProperties}.

\subsection*{3.1.2. Extending Physical Device From Device Extensions}

When the \texttt{[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:

```c
VK_DEFINE_HANDLE(VkInstance)
```

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

```c
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:
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:

```c
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.

---

44 | Chapter 3. Initialization
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,
    uint32_t* pPhysicalDeviceCount,
    VkPhysicalDevice* pPhysicalDevices);
```

- `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 vendor ID 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 vendor ID 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 device ID. If the implementation is driven primarily by a PCI device with a PCI device ID, the low 16 bits of device ID 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.

Khrons vendor IDs which may be returned in VkPhysicalDeviceProperties::vendor ID are:

```cpp
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);
```

- `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;
```

• **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`, `VkPhysicalDeviceDescriptorIndexingProperties`, `VkPhysicalDeviceDriverProperties`, `VkPhysicalDeviceFloatControlsProperties`, `VkPhysicalDeviceIDProperties`, `VkPhysicalDeviceMaintenance3Properties`, `VkPhysicalDeviceMultiviewProperties`, `VkPhysicalDevicePointClippingProperties`, `VkPhysicalDeviceProtectedMemoryProperties`, `VkPhysicalDeviceSamplerFilterMinmaxProperties`, `VkPhysicalDeviceSubgroupProperties`, `VkPhysicalDeviceTimelineSemaphoreProperties`, `VkPhysicalDeviceVulkan11Properties`, or `VkPhysicalDeviceVulkan12Properties`

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

To query the properties of the driver corresponding to Vulkan 1.1 functionality, add `VkPhysicalDeviceVulkan11Properties` to the **pNext** chain of the `VkPhysicalDeviceProperties2` structure.

The **VkPhysicalDeviceVulkan11Properties** structure is defined as:
typedef struct VkPhysicalDeviceVulkan11Properties {
    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;
    uint32_t subgroupSize;
    VkShaderStageFlags subgroupSupportedStages;
    VkSubgroupFeatureFlags subgroupSupportedOperations;
    VkBool32 subgroupQuadOperationsInAllStages;
    VkPointClippingBehavior pointClippingBehavior;
    uint32_t maxMultiviewViewCount;
    uint32_t maxMultiviewInstanceIndex;
    VkBool32 protectedNoFault;
    uint32_t maxPerSetDescriptors;
    VkDeviceSize maxMemoryAllocationSize;
} VkPhysicalDeviceVulkan11Properties;

• 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 corresponding to the device.

• deviceLUIDValid is a boolean value that will be VK_TRUE if deviceLUID contains a valid LUID and deviceNodeMask contains a valid node mask, and VK_FALSE if they do not.

• 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.

• subgroupSupportedStages is a bitfield of VkShaderStageFlagBits describing the shader stages that subgroup operations are supported in. subgroupSupportedStages will have the VK_SHADER_STAGE_COMPUTE_BIT bit set if any of the physical device’s queues support VK_QUEUE_COMPUTE_BIT.

• subgroupSupportedOperations is a bitmask of VkSubgroupFeatureFlagBits specifying the sets of subgroup operations supported on this device. subgroupSupportedOperations 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.

• subgroupQuadOperationsInAllStages is a boolean specifying whether quad subgroup operations are available in all stages, or are restricted to fragment and compute stages.

• pointClippingBehavior is a VkPointClippingBehavior value specifying the point clipping
behavior supported by the implementation.

- **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.

- **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.

- **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.

The members of VkPhysicalDeviceVulkan11Properties must have the same values as the corresponding members of VkPhysicalDeviceIDProperties, VkPhysicalDeviceSubgroupProperties, VkPhysicalDevicePointClippingProperties, VkPhysicalDeviceMultiviewProperties, VkPhysicalDeviceProtectedMemoryProperties, and VkPhysicalDeviceMaintenance3Properties.

### Valid Usage (Implicit)

- **sType** must be VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_PROPERTIES
- **pointClippingBehavior** must be a valid VkPointClippingBehavior value

To query the properties of the driver corresponding to Vulkan 1.2 functionality, add VkPhysicalDeviceVulkan12Properties to the pNext chain of the VkPhysicalDeviceProperties2 structure.

The VkPhysicalDeviceVulkan12Properties structure is defined as:

```c
typedef struct VkPhysicalDeviceVulkan12Properties {
    VkStructureType                      sType;
    void*                                pNext;
    VkDriverId                           driverID;
    char                                 *driverName[VK_MAX_DRIVER_NAME_SIZE];
    char                                 *driverInfo[VK_MAX_DRIVER_INFO_SIZE];
    VkConformanceVersion                 conformanceVersion;
    VkShaderFloatControlsIndependence    denormBehaviorIndependence;
    VkShaderFloatControlsIndependence    roundingModeIndependence;
    VkBool32                             shaderSignedZeroInfNanPreserveFloat16;
    VkBool32                             shaderSignedZeroInfNanPreserveFloat32;
    VkBool32                             shaderSignedZeroInfNanPreserveFloat64;
    VkBool32                             shaderDenormPreserveFloat16;
} VkPhysicalDeviceVulkan12Properties;
```
VkBool32 shaderDenormPreserveFloat32;
VkBool32 shaderDenormPreserveFloat64;
VkBool32 shaderDenormFlushToZeroFloat16;
VkBool32 shaderDenormFlushToZeroFloat32;
VkBool32 shaderDenormFlushToZeroFloat64;
VkBool32 shaderRoundingModeRTEFloat16;
VkBool32 shaderRoundingModeRTEFloat32;
VkBool32 shaderRoundingModeRTEFloat64;
VkBool32 shaderRoundingModeRTZFloat16;
VkBool32 shaderRoundingModeRTZFloat32;
VkBool32 shaderRoundingModeRTZFloat64;
uint32_t maxUpdateAfterBindDescriptorsInAllPools;
VkBool32 shaderUniformBufferArrayNonUniformIndexingNative;
VkBool32 shaderSampledImageArrayNonUniformIndexingNative;
VkBool32 shaderStorageBufferArrayNonUniformIndexingNative;
VkBool32 shaderStorageImageArrayNonUniformIndexingNative;
VkBool32 shaderInputAttachmentArrayNonUniformIndexingNative;
VkBool32 robustBufferAccessUpdateAfterBind;
VkBool32 quadDivergentImplicitLod;
uint32_t maxPerStageDescriptorUpdateAfterBindSamplers;
uint32_t maxPerStageDescriptorUpdateAfterBindUniformBuffers;
uint32_t maxPerStageDescriptorUpdateAfterBindStorageBuffers;
uint32_t maxPerStageDescriptorUpdateAfterBindSampledImages;
uint32_t maxPerStageDescriptorUpdateAfterBindStorageImages;
uint32_t maxPerStageDescriptorUpdateAfterBindInputAttachments;
uint32_t maxPerStageUpdateAfterBindResources;
uint32_t maxDescriptorSetUpdateAfterBindSamplers;
uint32_t maxDescriptorSetUpdateAfterBindSamplersDynamic;
uint32_t maxDescriptorSetUpdateAfterBindUniformBuffers;
uint32_t maxDescriptorSetUpdateAfterBindUniformBuffersDynamic;
uint32_t maxDescriptorSetUpdateAfterBindStorageBuffers;
uint32_t maxDescriptorSetUpdateAfterBindStorageBuffersDynamic;
uint32_t maxDescriptorSetUpdateAfterBindSampledImages;
uint32_t maxDescriptorSetUpdateAfterBindStorageImages;
uint32_t maxDescriptorSetUpdateAfterBindInputAttachments;
VkResolveModeFlags supportedDepthResolveModes;
VkResolveModeFlags supportedStencilResolveModes;
VkBool32 independentResolveNone;
VkBool32 independentResolve;
VkBool32 filterMinMaxSingleComponentFormats;
VkBool32 filterMinMaxImageComponentMapping;
uint64_t maxTimelineSemaphoreValueDifference;
VkSampleCountFlags framebufferIntegerColorSampleCounts;

• **driverID** is a unique identifier for the driver of the physical device.

• **driverName** is an array of *VK_MAX_DRIVER_NAME_SIZE_KHR* char 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* char 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*).

• **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 beflushed 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.

• maxUpdateAfterBindDescriptorsInAllPools is the maximum number of descriptors (summed over all descriptor types) that can be created across all pools that are created with the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT bit set. Pool creation may fail when this limit is exceeded, or when the space this limit represents is unable to satisfy a pool creation due to fragmentation.

• shaderUniformBufferArrayNonUniformIndexingNative is a boolean value indicating whether uniform buffer descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of uniform buffers may execute multiple times in order to access all the descriptors.

• shaderSampledImageArrayNonUniformIndexingNative is a boolean value indicating whether sampler and image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of samplers or images may execute multiple times in order to access all the descriptors.

• shaderStorageBufferArrayNonUniformIndexingNative is a boolean value indicating whether storage buffer descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage buffers may execute multiple times in order to access all the descriptors.
shaderStorageImageArrayNonUniformIndexingNative is a boolean value indicating whether storage image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage images may execute multiple times in order to access all the descriptors.

shaderInputAttachmentArrayNonUniformIndexingNative is a boolean value indicating whether input attachment descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of input attachments may execute multiple times in order to access all the descriptors.

robustBufferAccessUpdateAfterBind is a boolean value indicating whether robustBufferAccess can be enabled in a device simultaneously with descriptorBindingUniformBufferUpdateAfterBind, descriptorBindingStorageBufferUpdateAfterBind, descriptorBindingUniformTexelBufferUpdateAfterBind, and/or descriptorBindingStorageTexelBufferUpdateAfterBind. If this is VK_FALSE, then either robustBufferAccess must be disabled or all of these update-after-bind features must be disabled.

quadDivergentImplicitLod is a boolean value indicating whether implicit level of detail calculations for image operations have well-defined results when the image and/or sampler objects used for the instruction are not uniform within a quad. See Derivative Image Operations.

maxPerStageDescriptorUpdateAfterBindSamplers is similar to maxPerStageDescriptorSamplers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxPerStageDescriptorUpdateAfterBindUniformBuffers is similar to maxPerStageDescriptorUniformBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxPerStageDescriptorUpdateAfterBindStorageBuffers is similar to maxPerStageDescriptorStorageBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxPerStageDescriptorUpdateAfterBindSampledImages is similar to maxPerStageDescriptorSampledImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxPerStageDescriptorUpdateAfterBindStorageImages is similar to maxPerStageDescriptorStorageImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxPerStageDescriptorUpdateAfterBindInputAttachments is similar to maxPerStageDescriptorInputAttachments but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxPerStageUpdateAfterBindResources is similar to maxPerStageResources but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxDescriptorSetUpdateAfterBindSamplers is similar to maxDescriptorSetSamplers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

maxDescriptorSetUpdateAfterBindUniformBuffers is similar to maxDescriptorSetUniformBuffers but
counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindUniformBuffersDynamic` is similar to `maxDescriptorSetUniformBuffersDynamic` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindStorageBuffers` is similar to `maxDescriptorSetStorageBuffers` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindStorageBuffersDynamic` is similar to `maxDescriptorSetStorageBuffersDynamic` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindSampledImages` is similar to `maxDescriptorSetSampledImages` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindStorageImages` is similar to `maxDescriptorSetStorageImages` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `maxDescriptorSetUpdateAfterBindInputAttachments` is similar to `maxDescriptorSetInputAttachments` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

- `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`.

- `filterMinmaxSingleComponentFormats` is a boolean value indicating whether a minimum set of required formats support min/max filtering.

- `filterMinmaxImageComponentMapping` is a boolean value indicating whether the implementation supports non-identity component mapping of the image when doing min/max filtering.

- `maxTimelineSemaphoreValueDifference` indicates the maximum difference allowed by the implementation between the current value of a timeline semaphore and any pending signal or wait operations.

- `framebufferIntegerColorSampleCounts` is a bitmask of `VkSampleCountFlagBits` indicating the color
sample counts that are supported for all framebuffer color attachments with integer formats.

The members of `VkPhysicalDeviceVulkan12Properties` must have the same values as the corresponding members of `VkPhysicalDeviceDriverProperties`, `VkPhysicalDeviceFloatControlsProperties`, `VkPhysicalDeviceDescriptorIndexingProperties`, `VkPhysicalDeviceDepthStencilResolveProperties`, `VkPhysicalDeviceSamplerFilterMinmaxProperties`, and `VkPhysicalDeviceTimelineSemaphoreProperties`.

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**Valid Usage (Implicit)**

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_PROPERTIES`
- `driverID` must be a valid `VkDriverId` value
- `driverName` must be a null-terminated UTF-8 string whose length is less than or equal to `VK_MAX_DRIVER_NAME_SIZE`
- `driverInfo` must be a null-terminated UTF-8 string whose length is less than or equal to `VK_MAX_DRIVER_INFO_SIZE`
- `denormBehaviorIndependence` must be a valid `VkShaderFloatControlsIndependence` value
- `roundingModeIndependence` must be a valid `VkShaderFloatControlsIndependence` value
- `supportedDepthResolveModes` must be a valid combination of `VkResolveModeFlagBits` values
- `supportedDepthResolveModes` must not be `0`
- `supportedStencilResolveModes` must be a valid combination of `VkResolveModeFlagBits` values
- `supportedStencilResolveModes` must not be `0`
- `framebufferIntegerColorSampleCounts` must be a valid combination of `VkSampleCountFlagBits` values

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:

```
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;
```

- `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 corresponding to the device.

• deviceLUIDValid is a boolean value that will be VK_TRUE if deviceLUID contains a valid LUID and deviceNodeMask contains a valid node mask, and VK_FALSE if they do not.

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.

Valid Usage (Implicit)

- `sType` must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_ID_PROPERTIES`

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;
```

- `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` `char` 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` `char` 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.
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DRIVER_PROPERTIES`.

Khronos driver IDs which *may* be returned in `VkPhysicalDeviceDriverProperties::driverID` are:

```c
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_MAX_ENUM = 0x7FFFFFFF
} VkDriverId;
```

**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:

```c
typedef struct VkConformanceVersion {
    uint8_t major;
    uint8_t minor;
    uint8_t subminor;
    uint8_t patch;
} VkConformanceVersion;
```

- **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:

```c
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 \(x + width\) **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 \(y + height\) **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 \(z + depth\) **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);
```

- **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.

**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` `VkQueueFamilyProperties2` structures

The `VkQueueFamilyProperties2` structure is defined as:

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

- **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`
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:

```
VkResult vkEnumeratePhysicalDeviceGroups(
    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 \texttt{pPhysicalDeviceGroupProperties} array, and on return the variable is overwritten with the number of structures actually written to \texttt{pPhysicalDeviceGroupProperties}. If \texttt{pPhysicalDeviceGroupCount} is less than the number of device groups available, at most \texttt{pPhysicalDeviceGroupCount} structures will be written. If \texttt{pPhysicalDeviceGroupCount} is smaller than the number of device groups available, \texttt{VK_INCOMPLETE} will be returned instead of \texttt{VK_SUCCESS}, to indicate that not all the available device groups were returned.

Every physical device \textbf{must} be in exactly one device group.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Valid Usage (Implicit)} &  \\
\hline
\textbullet \texttt{instance must} be a valid \texttt{VkInstance} handle &  \\
\hline
\textbullet \texttt{pPhysicalDeviceGroupCount must} be a valid pointer to a \texttt{uint32_t} value &  \\
\hline
\textbullet If the value referenced by \texttt{pPhysicalDeviceGroupCount} is not 0, and \texttt{pPhysicalDeviceGroupProperties} is not NULL, \texttt{pPhysicalDeviceGroupProperties must} be a valid pointer to an array of \texttt{pPhysicalDeviceGroupCount} \texttt{ VkPhysicalDeviceGroupProperties} structures &  \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Return Codes} &  \\
\hline
\textbf{Success} &  \\
\hline
\textbullet \texttt{VK_SUCCESS} &  \\
\hline
\textbullet \texttt{VK_INCOMPLETE} &  \\
\hline
\textbf{Failure} &  \\
\hline
\textbullet \texttt{VK_ERROR_OUT_OF_HOST_MEMORY} &  \\
\hline
\textbullet \texttt{VK_ERROR_OUT_OF_DEVICE_MEMORY} &  \\
\hline
\textbullet \texttt{VK_ERROR_INITIALIZATION_FAILED} &  \\
\hline
\end{tabular}
\end{table}

The \texttt{VkPhysicalDeviceGroupProperties} structure is defined as:

\begin{verbatim}
typedef struct VkPhysicalDeviceGroupProperties {
    VkStructureType     sType;
    void*               pNext;
    uint32_t            physicalDeviceCount;
    VkPhysicalDevice    physicalDevices[VK_MAX_DEVICE_GROUP_SIZE];
    VkBool32            subsetAllocation;
} VkPhysicalDeviceGroupProperties;
\end{verbatim}

\begin{itemize}
\item \texttt{sType} is the type of this structure.
\item \texttt{pNext} is \texttt{NULL} or a pointer to an extension-specific structure.
\item \texttt{physicalDeviceCount} is the number of physical devices in the group.
\end{itemize}
• `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:

```c
VK_DEFINE_HANDLE(VkDevice)
```

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

```c
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:
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`.

• If the `pNext` chain includes a `VkPhysicalDeviceVulkan11Features` structure, then it must not include one of the following structures:
  - `VkPhysicalDevice16BitStorageFeatures`
  - `VkPhysicalDeviceMultiviewFeatures`
  - `VkPhysicalDeviceVariablePointersFeatures`
  - `VkPhysicalDeviceProtectedMemoryFeatures`
  - `VkPhysicalDeviceSamplerYcbcrConversionFeatures`

• If the `pNext` chain includes a `VkPhysicalDeviceVulkan12Features` structure, then it must not include one of the following structures:
  - `VkPhysicalDevice8BitStorageFeatures`
  - `VkPhysicalDeviceShaderAtomicInt64Features`
  - `VkPhysicalDeviceShaderFloat16Int8Features`
  - `VkPhysicalDeviceDescriptorIndexingFeatures`
  - `VkPhysicalDeviceScalarBlockLayoutFeatures`
  - `VkPhysicalDeviceImagelessFramebufferFeatures`
  - `VkPhysicalDeviceUniformBufferStandardLayoutFeatures`
  - `VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures`
  - `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures`
  - `VkPhysicalDeviceHostQueryResetFeatures`
  - `VkPhysicalDeviceTimelineSemaphoreFeatures`
  - `VkPhysicalDeviceBufferDeviceAddressFeatures`
  - `VkPhysicalDeviceVulkanMemoryModelFeatures`
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`, `VkPhysicalDeviceBufferDeviceAddressFeatures`, `VkPhysicalDeviceDescriptorIndexingFeatures`, `VkPhysicalDeviceFeatures2`, `VkPhysicalDeviceHostQueryResetFeatures`, `VkPhysicalDeviceImagelessFramebufferFeatures`, `VkPhysicalDeviceMultiviewFeatures`, `VkPhysicalDeviceProtectedMemoryFeatures`, `VkPhysicalDeviceSamplerYcbcrConversionFeatures`, `VkPhysicalDeviceScalarBlockLayoutFeatures`, `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures`, `VkPhysicalDeviceShaderAtomicInt64Features`, `VkPhysicalDeviceShaderDrawParametersFeatures`, `VkPhysicalDeviceShaderFloat16Int8Features`, `VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures`, `VkPhysicalDeviceTimelineSemaphoreFeatures`, `VkPhysicalDeviceUniformBufferStandardLayoutFeatures`, `VkPhysicalDeviceVariablePointersFeatures`, `VkPhysicalDeviceVulkan11Features`, `VkPhysicalDeviceVulkan12Features`, 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 VkFlag 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;

• `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.

Note

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` 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:

```c
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 `VKDEVICE_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 {
    VKDEVICE_QUEUE_CREATE_PROTECTED_BIT = 0x00000001,
    VKDEVICE_QUEUE_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkDeviceQueueCreateFlagBits;
```

• `VKDEVICE_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`.

To retrieve a handle to a `VkQueue` object, call:
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 VkDeviceQueueCreateFlags 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:

```c
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, `vkCmd*` commands can be used to record to the command buffer.

**Executable**

`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 `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.

![Figure 1. Lifecycle of a command buffer](image)

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 `vkResetCommandBuffer` or `vkResetCommandPool`, or as part of `vkBeginCommandBuffer` (which additionally puts the command buffer in the **recording state**).

Secondary command buffers can be recorded to a primary command buffer via `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,                      // device
    const VkCommandPoolCreateInfo* pCreateInfo, // pCreateInfo
    const VkAllocationCallbacks* pAllocator,  // pAllocator
    VkCommandPool* pCommandPool);  // 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:

```cpp
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.

```cpp
typedef VkFlags VkCommandPoolCreateFlags;
```

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

To trim a command pool, call:

```cpp
void vkTrimCommandPool(
    VkDevice device,       // The logical device that owns the command pool.
    VkCommandPool commandPool,  // The command pool to trim.
    VkCommandPoolTrimFlags flags);  // 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 \texttt{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 \textbf{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 \textbf{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 \textbf{may} be an expensive operation, and \textbf{should} not be called frequently. Trimming \textbf{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)
- \texttt{device} \textbf{must} be a valid \texttt{VkDevice} handle
- \texttt{commandPool} \textbf{must} be a valid \texttt{VkCommandPool} handle
- \texttt{flags} \textbf{must} be 0
- \texttt{commandPool} \textbf{must} have been created, allocated, or retrieved from \texttt{device}

### Host Synchronization
- Host access to \texttt{commandPool} \textbf{must} be externally synchronized
typedef VkFlags VkCommandPoolTrimFlags;

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

To reset a command pool, call:

```
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:

```c
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.
5.3. Command Buffer Allocation and Management

To allocate command buffers, call:

```c
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.

For 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
buffer objects from this command, set all entries of the \texttt{pCommandBuffers} array to \texttt{NULL} and return the error.

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

### Valid Usage (Implicit)

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

### Host Synchronization

- Host access to \texttt{pAllocateInfo::commandPool} must be externally synchronized

### Return Codes

**Success**
- \texttt{VK_SUCCESS}

**Failure**
- \texttt{VK_ERROR_OUT_OF_HOST_MEMORY}
- \texttt{VK_ERROR_OUT_OF_DEVICE_MEMORY}

The \texttt{VkCommandBufferAllocateInfo} structure is defined as:

```c
typedef struct VkCommandBufferAllocateInfo {
    VkStructureType          sType;
    const void*              pNext;
    VkCommandPool            commandPool;
    VkCommandBufferLevel     level;
    uint32_t                 commandBufferCount;
} VkCommandBufferAllocateInfo;
```

- \texttt{sType} is the type of this structure.
- \texttt{pNext} is \texttt{NULL} or a pointer to an extension-specific structure.
- \texttt{commandPool} is the command pool from which the command buffers are allocated.
- \texttt{level} is a \texttt{VkCommandBufferLevel} value specifying the command buffer level.
- \texttt{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:

```cpp
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_LEVELPRIMARY` specifies a primary command buffer.
- `VK_COMMAND_BUFFER_LEVELSECONDARY` specifies a secondary command buffer.

To reset command buffers, call:

```cpp
VkResult vkResetCommandBuffer(
    VkCommandBuffer commandBuffer,           // 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.
    VkCommandBufferResetFlags flags);       // 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.

```c
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:
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:
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.

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:

```c
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.
- If calls to `vkCmdSetEvent`, `vkCmdResetEvent` or `vkCmdWaitEvents` 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` 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 `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

- 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 `VkDeviceGroupSubmitInfo`, `VkProtectedSubmitInfo`, 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 `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;
```

- **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** 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

---

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;
```

- **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

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,               commandBuffer,
    uint32_t commandBufferCount,                commandBufferCount,
    const VkCommandBuffer* pCommandBuffers);   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`
::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, Graphics, 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;
```

- `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.

<table>
<thead>
<tr>
<th>Valid Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>- deviceMask must be a valid device mask value</td>
</tr>
<tr>
<td>- deviceMask must not be zero</td>
</tr>
</tbody>
</table>
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,    // commandBuffer is command buffer whose current device mask is modified.
    uint32_t deviceMask);              // 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>
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<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 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_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_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.

```c
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 3. Supported pipeline stage flags

124 | Chapter 6. Synchronization and Cache Control
<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, 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>
</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.
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:
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_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.

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 4. Supported access types

<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_VERTEX_SHADER_BIT, VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT,</td>
</tr>
<tr>
<td></td>
<td>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT, VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT,</td>
</tr>
<tr>
<td></td>
<td>VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, or VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT</td>
</tr>
<tr>
<td>Access flag</td>
<td>Supported pipeline stages</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>VK_ACCESS_SHADER_READ_BIT</td>
<td>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_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>
</tbody>
</table>

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.
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, 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, layer, 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.

**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.
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.

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.
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:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFence)
```

To create a fence, call:

```c
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**
• **pNext** **must** be **NULL** or a pointer to a valid instance of **VkExportFenceCreateInfo**
• 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.

typedefVkFlags 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;

• **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 destroy a fence, call:

```c
void vkDestroyFence(
    VkDevice device,  // device is the logical device that destroys the fence.
    VkFence fence,    // fence is the handle of the fence to destroy.
    const VkAllocationCallbacks* pAllocator);  // 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 5. Fence Object Status Codes**

<table>
<thead>
<tr>
<th>Status</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_SUCCESS</td>
<td>The fence specified by fence is signaled.</td>
</tr>
<tr>
<td>VK_NOT_READY</td>
<td>The fence specified by fence 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.

\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:

- 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.
- 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.
- 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.
- 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 \texttt{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.

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`.

### 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:
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** or **VkSemaphoreTypeCreateInfo**
- The **sType** value of each struct in the **pNext** chain must be unique
- **flags** must be 0

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:

typedef struct VkSemaphoreTypeCreateInfo {
    VkStructureType    sType;
    const void*        pNext;
    VkSemaphoreType    semaphoreType;
    uint64_t           initialValue;
} VkSemaphoreTypeCreateInfo;

- **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:

```c
typedef enum VkSemaphoreType {
    VK_SEMAPHORE_TYPE_BINARY = 0,
    VK_SEMAPHORE_TYPE_TIMELINE = 1,
    VK_SEMAPHORE_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkSemaphoreType;
```

- `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:

```c
typedef struct VkExportSemaphoreCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalSemaphoreHandleTypeFlags handleTypes;
} VkExportSemaphoreCreateInfo;
```

- `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_EXPORT_SEMAPHORE_CREATE_INFO`
- `handleTypes` must be a valid combination of `VkExternalSemaphoreHandleTypeFlagBits` values

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.

### 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
  executes.

### 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

To query the current counter value of a semaphore created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` from the host, call:

```c
VkResult vkGetSemaphoreCounterValue(
    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 vkWaitSemaphores(
    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;
```

- **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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSemaphoreWaitFlagBits;
```

- `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;
```

`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:

```c
VkResult vkSignalSemaphore(
    VkDevice device,                  // device
    const VkSemaphoreSignalInfo* pSignalInfo);    // 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;
```

- `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.

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.

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`.

### 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, 
    const VkEventCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkEvent* 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.
- `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.
Valid Usage (Implicit)

- **device** must be a valid `VkDevice` handle
- **pCreateInfo** must be a valid pointer to a valid `VkEventCreateInfo` structure
- If **pAllocator** is not `NULL`, **pAllocator** must be a valid pointer to a valid `VkAllocationCallbacks` structure
- **pEvent** must be a valid pointer to a `VkEvent` handle

Return Codes

Success

- **VK_SUCCESS**

Failure

- **VK_ERROR_OUT_OF_HOST_MEMORY**
- **VK_ERROR_OUT_OF_DEVICE_MEMORY**

The `VkEventCreateInfo` structure is defined as:

```c
typedef struct VkEventCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkEventCreateFlags flags;
} VkEventCreateInfo;
```

- **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_EVENT_CREATE_INFO`
- **pNext** must be `NULL`
- **flags** must be `0`

```c
typedef VkFlags VkEventCreateFlags;
```

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

To destroy an event, call:
**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:

**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 6. Event Object Status Codes**
Status | Meaning
---|---
VK_EVENT_SET | The event specified by event is signaled.
VK_EVENT_RESET | The event specified by event is unsignaled.

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,
    VkEvent event);
```

• `device` is the logical device that owns the 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,    // commandBuffer is the command buffer into which the command is recorded.
    VkEvent event,                    // event is the event that will be signaled.
    VkPipelineStageFlags stageMask); // 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...
vkCmdSetEvent has no effect, no event signal 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`
- **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 unsignaled 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**

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<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
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</tr>
<tr>
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<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);
```

166 | Chapter 6. Synchronization and Cache Control
- **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.
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.

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 `dstStageMask`, as specified in the table of supported access types

- The `srcAccessMask` member of each element of `pImageMemoryBarriers` 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 any element of `pImageMemoryBarriers` 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

---

**Valid Usage (Implicit)**

- `commandBuffer` must be a valid `VkCommandBuffer` handle
- `pEvents` must be a valid pointer to an array of `eventCount` valid `VkEvent` handles
- `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
- 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 graphics, or compute operations
- `eventCount` must be greater than 0
- Both of `commandBuffer`, and the elements of `pEvents` 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
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, commandBuffer,
    VkPipelineStageFlags srcStageMask, srcStageMask,
    VkPipelineStageFlags dstStageMask, dstStageMask,
    VkDependencyFlags dependencyFlags, dependencyFlags,
    uint32_t memoryBarrierCount, memoryBarrierCount,
    const VkMemoryBarrier* pMemoryBarriers, pMemoryBarriers,
    uint32_t bufferMemoryBarrierCount, bufferMemoryBarrierCount,
    const VkBufferMemoryBarrier* pBufferMemoryBarriers, pBufferMemoryBarriers,
    uint32_t imageMemoryBarrierCount, imageMemoryBarrierCount,
    const VkImageMemoryBarrier* pImageMemoryBarriers, 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

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<td>Transfer</td>
<td></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>

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_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_DEPENDENCYDEVICE_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 \texttt{srcAccessMask} was 0.

If \texttt{oldLayout} is not equal to \texttt{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 \texttt{image} has a multi-planar format and the image is disjoint, then including \texttt{VK\_IMAGE\_ASPECT\_COLOR\_BIT} in the \texttt{aspectMask} member of \texttt{subresourceRange} is equivalent to including \texttt{VK\_IMAGE\_ASPECT\_PLANE\_0\_BIT}, \texttt{VK\_IMAGE\_ASPECT\_PLANE\_1\_BIT}, and (for three-plane formats only) \texttt{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` 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 \texttt{VkSharingMode} of \texttt{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 \texttt{VkSharingMode} specified when creating them. The special queue family index \texttt{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 \texttt{VkDevice}, as indicated by \texttt{VkPhysicalDeviceIDProperties::deviceUUID} and \texttt{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.

\textbf{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 \textit{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 \textit{buffer memory barrier} (for a buffer range) or an \textit{image memory barrier} (for an image subresource range) using \texttt{vkCmdPipelineBarrier}, on a queue from the source queue family. The \texttt{srcQueueFamilyIndex} parameter of the barrier must be set to the source queue family index, and the \texttt{dstQueueFamilyIndex} parameter to the destination queue family index. \texttt{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 \textit{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 \textit{buffer memory barrier} (for a buffer range) or an \textit{image memory barrier} (for an image subresource range) using \texttt{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 \texttt{srcQueueFamilyIndex} parameter of the barrier must be set to the source queue family index, and the \texttt{dstQueueFamilyIndex} parameter to the destination queue family index. \texttt{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:

```c
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:

```
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;  // sType is the type of this structure.
    const void*                       pNext;  // pNext is NULL or a pointer to an extension-specific structure.
    VkRenderPassCreateFlags           flags;  // flags is reserved for future use.
    uint32_t                          attachmentCount;  // attachmentCount is the number of attachments used by this render pass.
    const VkAttachmentDescription*    pAttachments;  // pAttachments is a pointer to an array of attachmentCount VkAttachmentDescription structures describing the attachments used by the render pass.
    uint32_t                          subpassCount;  // subpassCount is the number of subpasses to create.
    const VkSubpassDescription*       pSubpasses;  // pSubpasses is a pointer to an array of subpassCount VkSubpassDescription structures describing each subpass.
    uint32_t                          dependencyCount;  // dependencyCount is the number of memory dependencies between pairs of subpasses.
} VkRenderPassCreateInfo;
```
• 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`.

- 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_DEPTH_ATTACHMENT_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_DEPTH_ATTACHMENT_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;
```

- **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 pCorrelation Masks 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 pCorrelation Masks

Valid Usage (Implicit)

• sType must be VK_STRUCTURE_TYPE_RENDER_PASS_MULTIVIEW_CREATE_INFO
• If subpassCount is not 0, pView Masks must be a valid pointer to an array of subpassCount uint32_t values
• If dependencyCount is not 0, pView Offsets must be a valid pointer to an array of dependencyCount int32_t values
• If correlationMask Count is not 0, pCorrelation Masks must be a valid pointer to an array of correlationMask Count uint32_t values

The VkAttachment Description 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 \texttt{VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT} pipeline stage. Store operations for attachments with a color format execute in the \texttt{VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT} pipeline stage.

If an attachment is not used by any subpass, then \texttt{loadOp}, \texttt{storeOp}, \texttt{stencilStoreOp}, and \texttt{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 \texttt{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 \texttt{storeOp}. Conversions occur as described in \texttt{Numeric Representation and Computation} and \texttt{Fixed-Point Data Conversions}.

If \texttt{flags} includes \texttt{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 \texttt{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 \texttt{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.

\begin{sidenote}{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 \texttt{VK_DEPENDENCY_BY_REGION_BIT} if the aliases are views of distinct image subresources which overlap in memory.
\end{sidenote}
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`,
  - `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, **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, **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 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)

• `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:

```c
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.

```c
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;
```

- `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]
```

```c
typedef struct VkInputAttachmentAspectReference {
    uint32_t subpass;
    uint32_t inputAttachmentIndex;
    VkImageAspectFlags aspectMask;
} VkInputAttachmentAspectReference;
```

- `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:

```c
typedef struct VkSubpassDescription {
    VkSubpassDescriptionFlags flags;
    VkPipelineBindPoint pipelineBindPoint;
    uint32_t inputAttachmentCount;
    const VkAttachmentReference* pInputAttachments;
    uint32_t colorAttachmentCount;
    const VkAttachmentReference* pColorAttachments;
    const VkAttachmentReference* pResolveAttachments;
    const VkAttachmentReference* pDepthStencilAttachment;
    uint32_t preserveAttachmentCount;
    const uint32_t* pPreserveAttachments;
} 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 $S_1$ that uses or preserves the attachment, and a subpass dependency from $S_1$ 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 $S_1$ 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`.
- `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:

```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.

```typedef VkFlags VkSubpassDescriptionFlags;
```

VkSubpassDescriptionFlags is a bitmask type for setting a mask of zero or more VkSubpassDescriptionFlagBits.

The VkAttachmentReference structure is defined as:

```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*.

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_OFPIPE_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 \((x, y, \text{layer}, \text{sample})\) 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_GENERAL` layout. An attachment used as an input attachment and depth/stencil attachment must be in the `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. 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 vkCreateRenderPass2(
    VkDevice device,                     // device is the logical device that creates the render pass.
    const VkRenderPassCreateInfo2* pCreateInfo, // pCreateInfo is a pointer to a VkRenderPassCreateInfo2 structure describing the parameters of the render pass.
    const VkAllocationCallbacks* pAllocator, // pAllocator controls host memory allocation as described in the Memory Allocation chapter.
    VkRenderPass* pRenderPass);            // 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 sub-structures 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;
```

- **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 0, correlatedViewMaskCount must be 0.

• The VkSubpassDescription2::viewMask member of all elements of pSubpasses must either all be 0, or all not be 0.

• If the VkSubpassDescription2::viewMask member of all elements of pSubpasses is 0, 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:

```c
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;
```
• **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`,
  or
  `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`,
  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`,
  `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`,
  `VK_IMAGE_LAYOUT_STENCIL_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`,
  `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_OPTIMAL`,
  `VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_OPTIMAL` or
  `VK_IMAGE_LAYOUT_STENCIL_READ_ONLY_OPTIMAL`

- 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`,
  or
  `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_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 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`
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;

• 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_ATTACHMENT_STENCIL_READ_ONLY_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_ATTACHMENT_STENCIL_READ_ONLY_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;
    uint32_t                 preserveAttachmentCount;
    const uint32_t*          pPreserveAttachments;
    const VkAttachmentReference2* pResolveAttachments;
    const VkAttachmentReference2* pDepthStencilAttachment;
    const uint32_t*          pResolveAttachmentCount;
    const uint32_t*          pPreserveAttachmentCount;
} VkSubpassDescription2;
```

- `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;
```

- 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`.
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:

```c
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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkResolveModeFlagBits;
```

- **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.

```c
typedef VkFlags VkResolveModeFlags;
```

**VkResolveModeFlags** is a bitmask type for setting a mask of zero or more **VkResolveModeFlagBits**.

The **VkAttachmentReference2** structure is defined as:
```c
typedef struct VkAttachmentReference2 {
    VkStructureType       sType;
    const void*           pNext;
    uint32_t              attachment;
    VkImageLayout         layout;
    VkImageAspectFlags    aspectMask;
} VkAttachmentReference2;
```

- **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 separateDepthStencilLayers 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 VK_IMAGE_ASPECT_COLOR_BIT, 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_DEPTH_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_STENCIL_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;

- **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_STENCIL_ATTACHMENT_OPTIMAL**, **VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL**, **VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL**, or **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;

- **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_SUBPASSDEPENDENCY_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,            // device
    VkRenderPass renderPass,    // renderPass
    const VkAllocationCallbacks* pAllocator); // 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 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkFramebuffer)
```

To create a framebuffer, call:

```
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 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`
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_ATTACHMENTS_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;
```

- `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;
```

- `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_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,
    VkFramebuffer framebuffer,
    const VkAllocationCallbacks* 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_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
- 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);
```

- `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_ATTACHMENT_STENCIL_READ_ONLY_OPTIMAL`, `VK_IMAGE_LAYOUT_DEPTH_READ_ONLY_STENCIL_ATTACHMENT_OPTIMAL`, or `VK_IMAGE_LAYOUT_DEPTH_STENCIL_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_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`.
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 VkClearValue* 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` `VkClearValue` 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
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.

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>There <strong>may</strong> be a performance cost for using a render area smaller than the framebuffer, unless it matches the render area granularity for the render pass.</td>
</tr>
</tbody>
</table>
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 with a width equal to the width 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 with a height equal to the height 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 with a width equal to the width 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 with a height equal to the height 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 with a width equal to the width 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 with a height equal to the height 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 VkClearColorValue 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;
```

- 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;
```

- **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;
```

- `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, 
    VkRenderPass renderPass, 
    VkExtent2D* pGranularity);
```

- **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 render area 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:
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);
```

- `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.

`vkCmdNextSubpass2` is semantically identical to `vkCmdNextSubpass`, except that it is extensible, and that `contents` is provided as part of an extensible structure instead of as a flat parameter.

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
- `pSubpassBeginInfo` must be a valid pointer to a valid `VkSubpassBeginInfo` structure
- `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>
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<tbody>
<tr>
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<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);
```

- `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

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</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);
```

- `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

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<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;
```

- `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`
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:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkShaderModule)
```

To create a shader module, call:

```c
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 vertexPipeline StoresAndAtomics).

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
defined in Sample Shading.

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. 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.

**8.13. 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.
8.13.1. 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.

8.13.2. 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.

8.13.3. 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.

8.13.4. 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.

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).
8.13.5. 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.

8.13.6. 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).

8.13.7. 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.

8.13.8. 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 `quadOperationsInAllStages` limit is supported, any shader stages that support subgroup operations also have defined quad scope instances.

**8.13.9. 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**.


**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.


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.

8.14.2. 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.

8.14.3. 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.


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.

8.14.5. Shuffle Group Operations

The shuffle group operations allow invocations to read values from other invocations within a group.


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.
8.14.7. 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.

8.15. 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.

8.16. 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) are calculated as

\[
DPdx(P) = DPdx(P_i) = P_i - P_0
\]
DPdx(P₂) = DPdx(P₃) = P₃ - P₂
and the values of DPdy(Pᵢ) are calculated as

DPdy(P₀) = DPdy(P₂) = P₂ - P₀
DPdy(P₁) = DPdy(P₃) = P₃ - P₁

where i is the index of each invocation as described in Quad.

Coarse derivative operations (OpDPdxCoarse and OpDPdyCoarse), calculate their results in roughly the same manner, but 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 should use the fine derivative calculations described for P₀.

The results for OpDPdx and OpDPdy may be calculated as either fine or coarse derivatives, with implementations favouring the most efficient approach. Implementations must choose coarse or fine consistently between the two.

Executing OpFwidthFine, OpFwidthCoarse, or OpFwidth is equivalent to executing the corresponding OpDPdx* and OpDPdy* instructions, taking the absolute value of the results, and summing them.

Executing a OpImage*Sample*ImplicitLod instruction is equivalent to executing OpDPdx(Coordinate) and OpDPdy(Coordinate), and passing the results as the Grad operands dx and dy.

Note
It is expected that using the ImplicitLod variants of sampling functions will be substantially more efficient than using the ExplicitLod variants with explicitly generated derivatives.

8.17. Helper Invocations

When performing derivative or quad group operations in a fragment shader, additional invocations may be spawned in order to ensure correct results. These additional invocations are known as helper invocations and can be identified by a non-zero value in the HelperInvocation built-in. 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.

Helper invocations 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 must be active for derivative and 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, 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, 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 [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`.

### 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:
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

```c
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:

```c
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:

```c
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
} 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.

**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.

```c
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,                                  // device,
    VkPipelineCache pipelineCache,                   // pipelineCache,
    uint32_t createInfoCount,                        // createInfoCount,
    const VkGraphicsPipelineCreateInfo* pCreateInfos, // pCreateInfos,
    const VkAllocationCallbacks* pAllocator,        // pAllocator,
    VkPipeline* pPipelines);                        // pPipelines);
```

- **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 VkPipelineDepthStencilStateCreateInfo* pDepthStencilState;
    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 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 rasterization 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 rasterization 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 rasterization 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 rasterization 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 `pDynamicState` 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...
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.
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`, and `VkComputePipelineCreateInfo`, specifying how a pipeline is created, are:

```c
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_DISPATCH_BASE = VK_PIPELINE_CREATE_DISPATCH_BASE_BIT,
    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.
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;  // sType is the type of this structure.
    const void*                          pNext;  // pNext is NULL or a pointer to an extension-specific structure.
    VkPipelineDynamicStateCreateFlags    flags;  // flags is reserved for future use.
    uint32_t                             dynamicStateCount;  // dynamicStateCount is the number of elements in the pDynamicStates array.
    const VkDynamicState*                pDynamicStates;  // 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.
} VkPipelineDynamicStateCreateInfo;
```

- Valid Usage
  - Each element of `pDynamicStates` must be unique

- Valid Usage (Implicit)
  - `sType` must be `VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO`
  - `pNext` must be `NULL`
  - `flags` must be `0`
  - If `dynamicStateCount` is not `0`, `pDynamicStates` must be a valid pointer to an array of `dynamicStateCount` valid `VkDynamicState` values

```c
typedef VkFlags VkPipelineDynamicStateCreateFlags;
```
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 VkPipelineDynamicStateCreateInfo::pDynamicStates property of the currently active pipeline, each of whose elements must be one of the values:

```c
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;
```

- **VK_DYNAMIC_STATE_VIEWPORT** specifies that the pViewports state in VkPipelineViewportStateCreateInfo will be ignored and must be set dynamically with vkCmdSetViewport before any draw commands. The number of viewports used by a pipeline is still specified by the viewportCount member of VkPipelineViewportStateCreateInfo.

- **VK_DYNAMIC_STATE_SCISSOR** specifies that the pScissors state in VkPipelineViewportStateCreateInfo will be ignored and must be set dynamically with vkCmdSetScissor before any draw commands. The number of scissor rectangles used by a pipeline is still specified by the scissorCount member of VkPipelineViewportStateCreateInfo.

- **VK_DYNAMIC_STATE_LINE_WIDTH** specifies that the 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
- VkPipelineMultisampleStateCreateInfo
- VkPipelineDepthStencilStateCreateInfo
- VkPipelineColorBlendStateCreateInfo

9.3. Pipeline destruction

To destroy a graphics or compute pipeline, call:

```c
void vkDestroyPipeline(
    VkDevice device,         // device
    VkPipeline pipeline,     // pipeline
    const VkAllocationCallbacks* pAllocator);
```

- `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 `VkPipelineCreateInfo` 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:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipelineCache)
```

To create pipeline cache objects, call:

```c
class 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.
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.

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:
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,                  // device
    VkPipelineCache pipelineCache,    // pipelineCache
    size_t* pDataSize,               // pDataSize
    void* pData);                     // 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 7. Layout for pipeline cache header version VK_PIPELINE_CACHE_HEADER_VERSION_ONE
<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 <code>VkPipelineCacheHeaderVersion</code> 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 <code>VkPhysicalDeviceProperties::vendorID</code> 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 <code>VkPhysicalDeviceProperties::deviceID</code> 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 <code>VkPhysicalDeviceProperties::pipelineCacheUUID</code></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 \texttt{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;
```

- \texttt{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);
```

- \texttt{device} is the logical device that destroys the pipeline cache object.
- \texttt{pipelineCache} is the handle of the pipeline cache to destroy.
- \texttt{pAllocator} controls host memory allocation as described in the \textit{Memory Allocation} chapter.

### Valid Usage

- If \texttt{VkAllocationCallbacks} were provided when \texttt{pipelineCache} was created, a compatible set of callbacks \textbf{must} be provided here.
- If no \texttt{VkAllocationCallbacks} were provided when \texttt{pipelineCache} was created, \texttt{pAllocator} \textbf{must} be \texttt{NULL}.

### Valid Usage (Implicit)

- \texttt{device} \textbf{must} be a valid \texttt{VkDevice} handle.
- If \texttt{pipelineCache} is not \texttt{VK_NULL_HANDLE}, \texttt{pipelineCache} \textbf{must} be a valid \texttt{VkPipelineCache} handle.
- If \texttt{pAllocator} is not \texttt{NULL}, \texttt{pAllocator} \textbf{must} be a valid pointer to a valid \texttt{VkAllocationCallbacks} structure.
- If \texttt{pipelineCache} is a valid handle, it \textbf{must} have been created, allocated, or retrieved from \texttt{device}.

### Host Synchronization

- Host access to \texttt{pipelineCache} \textbf{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:
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:

```
OpDecorate %x SpecId 13 ; decorate .x component of WorkgroupSize with ID 13
OpDecorate %y SpecId 42 ; decorate .y component of WorkgroupSize with ID 42
OpDecorate %z SpecId 3 ; decorate .z component of WorkgroupSize with ID 3
OpDecorate %wgsize BuiltIn WorkgroupSize ; decorate WorkgroupSize onto constant
%32 = OpTypeInt 32 0 ; declare an unsigned 32-bit type
%uvec3 = OpTypeVector %i32 3 ; declare a 3 element vector type of unsigned 32-bit
%x = OpSpecConstant %i32 1 ; declare the .x component of WorkgroupSize
%y = OpSpecConstant %i32 1 ; declare the .y component of WorkgroupSize
%z = OpSpecConstant %i32 1 ; declare the .z component of WorkgroupSize
%wgsize = OpSpecConstantComposite %uvec3 %x %y %z ; declare WorkgroupSize
```

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:
const VkSpecializationMapEntry entries[] = {
    {
        13,              // constantID
        0 * sizeof(uint32_t),  // offset
        sizeof(uint32_t)      // size
    },
    {
        42,              // constantID
        1 * sizeof(uint32_t),  // offset
        sizeof(uint32_t)      // size
    },
    {
        3,               // constantID
        2 * sizeof(uint32_t),  // offset
        sizeof(uint32_t)      // size
    }
};

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
%i1 = 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:

```c
struct SpecializationData {
    int32_t data0;
    float data1;
};

const VkSpecializationMapEntry entries[] = {
    {0, offsetof(SpecializationData, data0), sizeof(SpecializationData::data0)},
    {12, offsetof(SpecializationData, data1), sizeof(SpecializationData::data1)}
};

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 Binding

Once a pipeline has been created, it can be bound to the command buffer using the command:
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. 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.

### 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`.

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Chapter 9. Pipelines | 309
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_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.

9.9. 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.

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
</tr>
</tbody>
</table>
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 `PFN_vkReallocationFunction` 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 `PFN_vkReallocationFunction` or `PFN_vkAllocationFunction` 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](#).

`PFN_vkReallocationFunction` 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 `PFN_vkReallocationFunction` **must** behave equivalently to a call to `PFN_vkAllocationFunction` with the same parameter values (without `pOriginal`).

If `size` is zero, then `PFN_vkReallocationFunction` **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.

`PFN_vkReallocationFunction` **must** follow the same rules for return values as `PFN_vkAllocationFunction`.

The type of `PFN_vkFreeFunction` 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 \textit{may} fail object creation and/or generate a `VK_ERROR_OUT_OF_HOST_MEMORY` error, as appropriate.

Allocation callbacks \textbf{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` \textbf{may} be called in the following situations:

- Allocations scoped to a \texttt{VkDevice} or \texttt{VkInstance} \textbf{may} be allocated from any API command.
- Allocations scoped to a command \textbf{may} be allocated from any API command.
- Allocations scoped to a \texttt{VkPipelineCache} \textbf{may} only be allocated from:
  - `vkCreatePipelineCache`
  - `vkMergePipelineCaches` for `dstCache`
  - `vkCreateGraphicsPipelines` for `pipelineCache`
  - `vkCreateComputePipelines` for `pipelineCache`
- Allocations scoped to a \texttt{VkDescriptorPool} \textbf{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 \texttt{VkCommandPool} \textbf{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 \textbf{may} only be allocated in that object’s `vkCreate*` command.

`pfnFree`, or `pfnReallocation` with zero size, \textbf{may} be called in the following situations:

- Allocations scoped to a \texttt{VkDevice} or \texttt{VkInstance} \textbf{may} be freed from any API command.
- Allocations scoped to a command \textbf{must} be freed by any API command which allocates such memory.
- Allocations scoped to a \texttt{VkPipelineCache} \textbf{may} be freed from `vkDestroyPipelineCache`.
- Allocations scoped to a \texttt{VkDescriptorPool} \textbf{may} be freed from:
  - any command that takes the pool as a direct argument
- Allocations scoped to a \texttt{VkCommandPool} \textbf{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 \textbf{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_PROPERTY_DEVICE_LOCAL_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_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT
- VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT | VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT
- VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT | VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT
- VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT | VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_CACHED_BIT | VK_MEMORY_PROPERTY_HOST_COHERENT_BIT | VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT
- VK_MEMORY_PROPERTY_PROTECTED_BIT
- VK_MEMORY_PROPERTY_PROTECTED_BIT | VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT
There **must** be at least one memory type with both the `VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT` and `VK_MEMORYPROPERTY_HOST_COHERENT_BIT` bits set in its propertyFlags. There **must** be at least one memory type with the `VK_MEMORYPROPERTYDEVICE_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_MEMORYPROPERTYDEVICE_LOCAL_BIT` was before `VK_MEMORYPROPERTYHOST_VISIBLE_BIT | VK_MEMORYPROPERTYHOST_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:
```c
int32_t findProperties(const VkPhysicalDeviceMemoryProperties* pMemoryProperties,
                        uint32_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;
}
```

To query memory properties, call:

```c
void vkGetPhysicalDeviceMemoryProperties2(
    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. 
vkGetPhysicalDeviceMemoryProperties2 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;
```

- 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:

```c
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_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.

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.

```c
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:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDeviceMemory)
```

To allocate memory objects, call:

```c
VkResult vkAllocateMemory(
    VkDevice device,           // device,
    const VkMemoryAllocateInfo* pAllocateInfo,  // pAllocateInfo,
    const VkAllocationCallbacks* pAllocator,    // pAllocator,
    VkDeviceMemory* pMemory);  // 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.

### 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

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

Valid Usage

• allocationSize must be greater than 0

• 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`, `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;
```

- **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.
- **buffer** is `VK_NULL_HANDLE` or a handle of a buffer 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`, **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 inVkImageCreateInfo::flags
- If **buffer** is not `VK_NULL_HANDLE`, **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

328 | Chapter 10. Memory Allocation
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_MEMORY_DEDICATED_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;
```

- **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

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:
```c
typedef struct VkMemoryAllocateFlagsInfo {
    VkStructureType sType;
    const void* pNext;
    VkMemoryAllocateFlags flags;
    uint32_t deviceMask;
} VkMemoryAllocateFlagsInfo;
```

- `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:
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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkMemoryAllocateFlagBits;

- **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;
```

**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 `VkMemoryOpaqueCaptureAddressAllocateInfo` structure 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;
```

- **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.
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:

```c
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,      // device
    VkDeviceMemory memory,   // memory
    VkDeviceSize offset,     // offset
    VkDeviceSize size,       // size
    VkMemoryMapFlags flags,  // flags
    void** ppData);         // 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

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

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.
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,                        // device
    uint32_t memoryRangeCount,              // memoryRangeCount
    const VkMappedMemoryRange* pMemoryRanges); // 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.

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,                  // device
    uint32_t memoryRangeCount,        // memoryRangeCount
    const VkMappedMemoryRange* pMemoryRanges);  // 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**
Host Synchronization

- Host access to memory must be externally synchronized

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);
```

- `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:

```c
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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkPeerMemoryFeatureFlagBits;
```

- **`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;
```

**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 vkGetDeviceMemoryOpaqueCaptureAddress(
    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;
```

- `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_TYPEDEVICE_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:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkBuffer)
```

To create buffers, call:

```c
VkResult vkCreateBuffer(
    VkDevice device, 
    const VkBufferCreateInfo* pCreateInfo, 
    const VkAllocationCallbacks* pAllocator, 
    VkBuffer* pBuffer);
```

- **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

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_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_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_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.
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;
```

**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;
```

- **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:
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:

```c
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

```c
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
define vkDestroyBufferView(
    VkDevice device,
    VkBufferView bufferView,
    const VkAllocationCallbacks* pAllocator);
```

- `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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImage)
```

To create images, call:

```
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:

```c
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 levels 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 \( Y'C_bC_r \) 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 \( Y'C_bC_r \) 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 the 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 vkGetPhysicalDeviceExternalImageFormatProperties2 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`, `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` or `VK_IMAGE_CREATE_SPARSE_BINDING_BIT`, it must also contain `VK_IMAGE_CREATE_SPARSE_RESIDENCY_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 Y'CbCr 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 Y'CbCr 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 Y'CbCr 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 Y'CbCr 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 `VkImageStencilUsageCreateInfo`

• 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;
```

### 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** 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;
```

- **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:

```c
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_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:
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:

// (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.

// (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`. 

Chapter 11. Resource Creation | 373
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,                     /* device is the logical device that destroys the image. */
    VkImage image,                       /* image is the image 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 `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 miplevels, from the largest miplevel provided, down to the minimum mipmap size.

Conventional Images

For conventional images, the dimensions of each successive miplevel, n+1, are:

\[
\text{width}_{n+1} = \max( \text{width}_n/2', 1) \\
\text{height}_{n+1} = \max( \text{height}_n/2', 1) \\
\text{depth}_{n+1} = \max( \text{depth}_n/2', 1)
\]

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:

\[
\log_2(\max(\text{width}_0, \text{height}_0, \text{depth}_0))' + 1
\]

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_READ_ONLY_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_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_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_MAX_ENUM** 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_READ_ONLY_OPTIMAL and VK_IMAGE_LAYOUT_STENCIL_ATTACHMENT_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 depth aspect as a depth attachment, and read only access to the stencil aspect as a stencil 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 the depth aspect of a depth/stencil format image allowing read and write access as a depth attachment.

- **VK_IMAGE_LAYOUT_DEPTH_ATTACHMENT_STENCIL_READ_ONLY_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_DEPTH_ATTACHMENT_STENCIL_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_DEPTH_ATTACHMENT_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.

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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkImageView)
```

The types of image views that can be created are:

```c
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.

<table>
<thead>
<tr>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
</tr>
</tbody>
</table>

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 **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\_plane, v\_plane) unnormalized coordinates of the reduced-resolution plane, and these coordinates access the same memory locations as the (u\_color, v\_color) unnormalized coordinates of the color aspect for which chroma reconstruction operations operate on the same (i\_plane, j\_plane) coordinates.

Table 8. 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>imageSize = ci.imageType width = ci.extent.width height = ci.extent.height depth = ci.extent.depth arrayLayers = ci.arrayLayers samples = ci.samples flags = ci.flags where ci is the VkImageCreateInfo used to create image.</td>
<td>baseArrayLayer, layerCount, and levelCount are members of the subresourceRange member.</td>
</tr>
<tr>
<td>1D, 0, 0</td>
<td>imageSize = VK_IMAGE_TYPE_1D width ≥ 1 height = 1 depth = 1 arrayLayers ≥ 1 samples = 1</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_1D baseArrayLayer ≥ 0 layerCount ≥ 0</td>
</tr>
<tr>
<td>1D, 1, 0</td>
<td>imageSize = VK_IMAGE_TYPE_1D width ≥ 1 height = 1 depth = 1 arrayLayers ≥ 1 samples = 1</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_1D_ARRAY baseArrayLayer ≥ 0 layerCount ≥ 1</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>
<tr>
<td>2D, 0, 0</td>
<td>imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples = 1</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_2D baseArrayLayer ≥ 0 layerCount = 1</td>
</tr>
<tr>
<td>2D, 1, 0</td>
<td>imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples = 1</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_2D ARRAY baseArrayLayer ≥ 0 layerCount ≥ 1</td>
</tr>
<tr>
<td>2D, 0, 1</td>
<td>imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples &gt; 1</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_2D baseArrayLayer ≥ 0 layerCount = 1</td>
</tr>
<tr>
<td>2D, 1, 1</td>
<td>imageType = VK_IMAGE_TYPE_2D width ≥ 1 height ≥ 1 depth = 1 arrayLayers ≥ 1 samples &gt; 1</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_2D ARRAY baseArrayLayer ≥ 0 layerCount ≥ 1</td>
</tr>
<tr>
<td>CUBE, 0, 0</td>
<td>imageType = VK_IMAGE_TYPE_2D width ≥ 1 height = width depth = 1 arrayLayers ≥ 6 samples = 1 flags includes VK_IMAGE_CREATE_CUBE_COMPATIBLE_BIT</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_CUBE baseArrayLayer ≥ 0 layerCount = 6</td>
</tr>
<tr>
<td>CUBE, 1, 0</td>
<td>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</td>
<td>viewType = VK_IMAGE_VIEW_TYPE_CUBE ARRAY baseArrayLayer ≥ 0 layerCount = 6 × N, N ≥ 1</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>
| 3D, 0, 0        | `imageType = VK_IMAGE_TYPE_3D`<br>`width ≥ 1`
|                 | `height ≥ 1`<br>`depth ≥ 1`<br>`arrayLayers = 1`<br>`samples = 1` | `viewType = VK_IMAGE_VIEW_TYPE_3D`<br>`baseArrayLayer = 0`<br>`layerCount = 1` |
| 3D, 0, 0        | `imageType = VK_IMAGE_TYPE_3D`<br>`width ≥ 1`<br>`height ≥ 1`<br>`depth ≥ 1`<br>`arrayLayers = 1`<br>`samples = 1`<br>`flags includes VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT`<br>`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`<br>`levelCount = 1`<br>`baseArrayLayer ≥ 0`<br>`layerCount = 1` |
| 3D, 0, 0        | `imageType = VK_IMAGE_TYPE_3D`<br>`width ≥ 1`<br>`height ≥ 1`<br>`depth ≥ 1`<br>`arrayLayers = 1`<br>`samples = 1`<br>`flags includes VK_IMAGE_CREATE_2D_ARRAY_COMPATIBLE_BIT`<br>`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_ARRAY`<br>`levelCount = 1`<br>`baseArrayLayer ≥ 0`<br>`layerCount ≥ 1` |
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:
typedef struct VkImageViewUsageCreateInfo {
    VkStructureType      sType;
    const void*          pNext;
    VkImageUsageFlags    usage;
} VkImageViewUsageCreateInfo;

- **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:

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 mipmap 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 mipmap 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 $VK_IMAGE_ASPECT_DEPTH_BIT$ 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_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 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:
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:

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_SWIZZE_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><code>VK_COMPONENT_SWIZZLE_R</code></td>
</tr>
<tr>
<td>components.g</td>
<td><code>VK_COMPONENT_SWIZZLE_G</code></td>
</tr>
<tr>
<td>components.b</td>
<td><code>VK_COMPONENT_SWIZZLE_B</code></td>
</tr>
<tr>
<td>components.a</td>
<td><code>VK_COMPONENT_SWIZZLE_A</code></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.

**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,  // Logical device that owns the buffer.
    VkBuffer buffer,  // Buffer to query.
    VkMemoryRequirements* pMemoryRequirements);  // Pointer to VkMemoryRequirements structure.
```

- **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,  // Logical device that owns the image.
    VkImage image,  // Image to query.
    VkMemoryRequirements* pMemoryRequirements);  // Pointer to VkMemoryRequirements structure.
```

- **device** is the logical device that owns the image.
- **image** is the image to query.
• `pMemoryRequirements` 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` 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 a power of two.

• 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 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);
```

- `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
typedef struct VkBufferMemoryRequirementsInfo2 {
    VkStructureType sType;
    const void* pNext;
    VkBuffer buffer;
} VkBufferMemoryRequirementsInfo2;
```

- `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);
```

- **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 valid `VkImageMemoryRequirementsInfo2` structure
- **pMemoryRequirements** must be a valid pointer to a `VkMemoryRequirements2` structure

The `VkImageMemoryRequirementsInfo2` structure is defined as:

```c
typedef struct VkImageMemoryRequirementsInfo2 {
    VkStructureType             sType;
    const void*                  pNext;
    VkImage                      image;
} VkImageMemoryRequirementsInfo2;
```

- **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:

```c
typedef struct VkImagePlaneMemoryRequirementsInfo {
    VkStructureType            sType;
    const void*                pNext;
    VkImageAspectFlagBits      planeAspect;
} VkImagePlaneMemoryRequirementsInfo;
```

- `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:

```c
typedef struct VkMemoryRequirements2 {
    VkStructureType     sType;
    void*               pNext;
    VkMemoryRequirements memoryRequirements;
} VkMemoryRequirements2;
```

- `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 a `VkMemoryDedicatedRequirements` 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;

- **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`

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);
```

- **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**

`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;
```

- **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
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;
```

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:

```cpp
VkResult vkBindImageMemory(
    VkDevice device,              // device
    VkImage image,               // image
    VkDeviceMemory memory,       // memory
    VkDeviceSize memoryOffset); // 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` 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);
```

- **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 command.

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;
```

- **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.

memory must be a valid VkDeviceMemory handle

- 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 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 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
typedef struct VkBindImageMemoryDeviceGroupInfo {
    VkStructureType sType;
    const void* pNext;
    uint32_t deviceIndexCount;
    const uint32_t* pDeviceIndices;
    uint32_t splitInstanceBindRegionCount;
    const VkRect2D* pSplitInstanceBindRegions;
} VkBindImageMemoryDeviceGroupInfo;

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 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 image, and the block at (0,0) corresponds to memory starting at memoryOffset.

If splitInstanceBindRegionCount and 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 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 splitInstanceBindRegionCount and 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 pDeviceIndices contains an array of zeros. In other words, by default each physical device attaches to instance zero.
Valid Usage

- At least one of `deviceIndexCount` and `splitInstanceBindRegions` must be zero.
- `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.
- `splitInstanceBindRegionCount` must either be zero or equal to the number of physical devices in the logical device squared.
- Elements of `pSplitInstanceBindRegions` that correspond to the same instance of an image must not overlap.
- The `offset.x` member of any element of `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 `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 `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 `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.

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;
```
• **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:

```plaintext
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:

```plaintext
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.
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`, 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\textsubscript{A} and resource\textsubscript{B}, bound respectively to memory range\textsubscript{A} and range\textsubscript{B}. Let paddedRange\textsubscript{A} and paddedRange\textsubscript{B} be, respectively, range\textsubscript{A} and range\textsubscript{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\textsubscript{A} and range\textsubscript{B}. If one resource is linear and the other is non-linear, then the resources alias the memory in the intersection of paddedRange\textsubscript{A} and paddedRange\textsubscript{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 alias 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.
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’C_bC_R conversion is enabled and the sampler Y’C_bC_R 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’C_bC_R 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, addressModeU and addressModeV must each be either VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE or VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER
- 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’C_bC_R 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
- The sampler reduction mode must be set to VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE if sampler Y’C_bC_R conversion is enabled
- If samplerMirrorClampToEdge is not enabled, and 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
- If compareEnable is VK_TRUE, the reductionMode member of VkSamplerReductionModeCreateInfo must be
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_SAMPLER_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 `VkSamplerReductionModeCreateInfo` or `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:

```plaintext
typedef enum VkSamplerCreateFlagBits {
    VK_SAMPLER_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkSamplerCreateFlagBits;
```

```plaintext
typedef VkFlags VkSamplerCreateFlags;
```

`VkSamplerCreateFlags` is a bitmask type for setting a mask of zero or more `VkSamplerCreateFlagBits`.

The `VkSamplerReductionModeCreateInfo` structure is defined as:

```plaintext
typedef struct VkSamplerReductionModeCreateInfo {
    VkStructureType           sType;
    const void*               pNext;
    VkSamplerReductionMode    reductionMode;
} VkSamplerReductionModeCreateInfo;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **reductionMode** is a `VkSamplerReductionMode` value controlling how texture filtering combines texel values.

If the **pNext** chain of `VkSamplerCreateInfo` includes a `VkSamplerReductionModeCreateInfo` structure,
then that structure includes a mode that controls how texture filtering combines texel values.

If this structure is not present, \(\text{reductionMode}\) is considered to be \text{VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE}.

### Valid Usage (Implicit)

- \text{sType} must be \text{VK_STRUCTURE_TYPE_SAMPLER_REDUCTION_MODE_CREATE_INFO}
- \text{reductionMode} must be a valid \text{VkSamplerReductionMode} value

Reduction modes are specified by \text{VkSamplerReductionMode}, which takes values:

```c
typedef enum VkSamplerReductionMode {
    VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE = 0,
    VK_SAMPLER_REDUCTION_MODE_MIN = 1,
    VK_SAMPLER_REDUCTION_MODE_MAX = 2,
    VK_SAMPLER_REDUCTION_MODE_MAX_ENUM = 0x7FFFFFFF
} VkSamplerReductionMode;
```

- \text{VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE} specifies that texel values are combined by computing a weighted average of values in the footprint, using weights as specified in the image operations chapter.
- \text{VK_SAMPLER_REDUCTION_MODE_MIN} specifies that texel values are combined by taking the component-wise minimum of values in the footprint with non-zero weights.
- \text{VK_SAMPLER_REDUCTION_MODE_MAX} specifies that texel values are combined by taking the component-wise maximum of values in the footprint with non-zero weights.

Possible values of the \text{VkSamplerCreateInfo}::\text{magFilter} and \text{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;
```

- \text{VK_FILTER_NEAREST} specifies nearest filtering.
- \text{VK_FILTER_LINEAR} specifies linear filtering.

These filters are described in detail in Texel Filtering.

Possible values of the \text{VkSamplerCreateInfo}::\text{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:

define 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_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 `samplerMirrorClampToEdge` is enabled, or 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,
    VkSampler sampler,
    const VkAllocationCallbacks* pAllocator);
```

- `device` is the logical device that destroys the sampler.
- `sampler` is the sampler to destroy.
- `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`. 
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;
```

- **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_bC_r conversion is an opaque representation of a device-specific sampler Y’C_bC_r conversion description, represented as a `VkSamplerYcbcrConversion` handle:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkSamplerYcbcrConversion)
```

To create a `VkSamplerYcbcrConversion`, call:

```c
VkResult vkCreateSamplerYcbcrConversion(
    VkDevice                                    device,
    const VkSamplerYcbcrConversionCreateInfo*   pCreateInfo,
    const VkAllocationCallbacks*               pAllocator,
    VkSamplerYcbcrConversion*                   pYcbcrConversion);
```

- `device` is the logical device that creates the sampler Y’C_bC_r conversion.
- `pCreateInfo` is a pointer to a `VkSamplerYcbcrConversionCreateInfo` structure specifying the requested sampler Y’C_bC_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_bC_r conversion is returned.

The interpretation of the configured sampler Y’C_bC_r conversion is described in more detail in the description of sampler Y’C_bC_r conversion in the Image Operations chapter.

Valid Usage

- The sampler Y’C_bC_r 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:

```plaintext
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;
```

- `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 the 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’C₈C₆ 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’C_bC_r** conversion’s features **must** support
  - VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT
  - VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT

- If the **sampler Y’C_bC_r** 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’C_bC_r** 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’C_bC_r** conversion’s features do not support
  - VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT forceExplicitReconstruction **must** be VK_FALSE

- If the **sampler Y’C_bC_r** 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:

```cpp
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_MAX_ENUM = 0x7FFFFFFF
} VkSamplerYcbcrModelConversion;
```

- **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 $Y'CbCr$ range expansion and model conversion:

- the $Y$ (Y' luma) channel corresponds to the $G$ channel of an RGB image.
- the $C_b$ (or “$U$” blue color difference) channel corresponds to the $B$ channel of an RGB image.
- the $C_r$ (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:

```c
typedef enum VkSamplerYcbcrRange {
    VK_SAMPLER_YCBCR_RANGE_ITU_FULL = 0,
    VK_SAMPLER_YCBCR_RANGE_ITU_NARROW = 1,
    VK_SAMPLER_YCBCR_RANGE_MAX_ENUM = 0x7FFFFFFF
} VkSamplerYcbcrRange;
```

- `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 $Y'CbCr$ 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_MAX_ENUM = 0x7FFFFFFF
} VkChromaLocation;

• **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 halfway between each even luma sample and the nearest higher odd luma sample.

To destroy a sampler Y’C₉C₈ conversion, call:

```c
void vkDestroySamplerYcbcrConversion(
    VkDevice device,
    VkSamplerYcbcrConversion ycbcrConversion,
    const VkAllocationCallbacks* pAllocator);
```

• **device** is the logical device that destroys the Y’C₉C₈ 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_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_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_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.

**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_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.

13.2. 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:
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 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 any binding has the `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` bit set, `flags` **must** include `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT`.
- If any binding has the `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` bit set, then all bindings **must** not have `descriptorType` of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`.

### Valid Usage (Implicit)

- `sType` **must** be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO`.
- `pNext` **must** be `NULL` or a pointer to a valid instance of `VkDescriptorsetLayoutBindingFlagsCreateInfo`.
- The `sType` value of each struct in the `pNext` chain **must** be unique.
- `flags` **must** be a valid combination of `VkDescriptorsetLayoutCreateFlagBits` values.
- If `bindingCount` is not 0, `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_UPDATE_AFTER_BIND_POOL_BIT = 0x00000002,
    VK_DESCRIPTOR_SET_LAYOUT_CREATE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkDescriptorSetLayoutCreateFlagBits;

• **VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT** specifies that descriptor sets using this layout **must** be allocated from a descriptor pool created with the **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** bit set. Descriptor set layouts created with this bit set have alternate limits for the maximum number of descriptors per-stage and per-pipeline layout. The non-UpdateAfterBind limits only count descriptors in sets created without this flag. The UpdateAfterBind limits count all descriptors, but the limits **may** be higher than the non-UpdateAfterBind limits.

  *Note*
  All bits for this type are defined by extensions, and none of those extensions are enabled in this build of the specification.

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

If the pNext chain of a VkDescriptorSetLayoutCreateInfo structure includes a VkDescriptorSetLayoutBindingFlagsCreateInfo structure, then that structure includes an array of flags, one for each descriptor set layout binding.

The VkDescriptorSetLayoutBindingFlagsCreateInfo structure is defined as:

```c
typedef struct VkDescriptorSetLayoutBindingFlagsCreateInfo {
    VkStructureType                    sType;
    const void*                        pNext;
    uint32_t                           bindingCount;
    const VkDescriptorBindingFlags*    pBindingFlags;
} VkDescriptorSetLayoutBindingFlagsCreateInfo;
```

- sType is the type of this structure.
- pNext is NULL or a pointer to an extension-specific structure.
- bindingCount is zero or the number of elements in pBindingFlags.
- pBindingFlags is a pointer to an array of VkDescriptorBindingFlags bitfields, one for each descriptor set layout binding.

If bindingCount is zero or if this structure is not included in the pNext chain, the VkDescriptorBindingFlags for each descriptor set layout binding is considered to be zero. Otherwise, the descriptor set layout binding at VkDescriptorSetLayoutCreateInfo::pBindings[i] uses the flags in pBindingFlags[i].
Valid Usage

- If `bindingCount` is not zero, `bindingCount` must equal `VkDescriptorSetLayoutCreateInfo::bindingCount`.
- If an element of `pBindingFlags` includes `VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT`, then all other elements of `VkDescriptorSetLayoutCreateInfo::pBindings` must have a smaller value of `binding`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingUniformBufferUpdateAfterBind` is not enabled, all bindings with descriptor type `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` must not use `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingSampledImageUpdateAfterBind` is not enabled, all bindings with descriptor type `VK_DESCRIPTOR_TYPE_SAMPLER`, `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, or `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` must not use `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingStorageImageUpdateAfterBind` is not enabled, all bindings with descriptor type `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE` must not use `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingStorageBufferUpdateAfterBind` is not enabled, all bindings with descriptor type `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` must not use `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingUniformTexelBufferUpdateAfterBind` is not enabled, all bindings with descriptor type `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` must not use `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingStorageTexelBufferUpdateAfterBind` is not enabled, all bindings with descriptor type `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` must not use `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.
- All bindings with descriptor type `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT`, `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`, or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` must not use `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingUpdateUnusedWhilePending` is not enabled, all elements of `pBindingFlags` must not include `VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingPartiallyBound` is not enabled, all elements of `pBindingFlags` must not include `VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT`.
- If `VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingVariableDescriptorCount` is not enabled, all elements of `pBindingFlags` must not include `VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT`.

448 | Chapter 13. Resource Descriptors
• If an element of `pBindingFlags` includes `VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT`, that element's `descriptorType` **must** not be `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC`

---

**Valid Usage (Implicit)**

• `sType` **must** be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_BINDING_FLAGS_CREATE_INFO`

• If `bindingCount` is not 0, and `pBindingFlags` is not NULL, `pBindingFlags` **must** be a valid pointer to an array of `bindingCount` valid combinations of `VkDescriptorBindingFlagBits` values

Bits which **can** be set in each element of `VkDescriptorSetLayoutBindingFlagsCreateInfo::pBindingFlags` to specify options for the corresponding descriptor set layout binding are:

```c
typedef enum VkDescriptorBindingFlagBits {
    VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT = 0x00000001,
    VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT = 0x00000002,
    VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT = 0x00000004,
    VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT = 0x00000008,
    VK_DESCRIPTOR_BINDING_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkDescriptorBindingFlagBits;
```

• **`VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT`** indicates that if descriptors in this binding are updated between when the descriptor set is bound in a command buffer and when that command buffer is submitted to a queue, then the submission will use the most recently set descriptors for this binding and the updates do not invalidate the command buffer. Descriptor bindings created with this flag are also partially exempt from the external synchronization requirement in `vkUpdateDescriptorSets`. Multiple descriptors with this flag set **can** be updated concurrently in different threads, though the same descriptor **must** not be updated concurrently by two threads. Descriptors with this flag set **can** be updated concurrently with the set being bound to a command buffer in another thread, but not concurrently with the set being reset or freed.

• **`VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT`** indicates that descriptors in this binding that are not dynamically used need not contain valid descriptors at the time the descriptors are consumed. A descriptor is dynamically used if any shader invocation executes an instruction that performs any memory access using the descriptor.

• **`VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT`** indicates that descriptors in this binding **can** be updated after a command buffer has bound this descriptor set, or while a command buffer that uses this descriptor set is pending execution, as long as the descriptors that are updated are not used by those command buffers. If `VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT` is also set, then descriptors **can** be updated as long as they are not dynamically used by any shader invocations. If `VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT` is not set, then descriptors **can** be updated as long as they are not statically used by any shader invocations.
**VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT** indicates that this descriptor binding has a variable size that will be specified when a descriptor set is allocated using this layout. The value of `descriptorCount` is treated as an upper bound on the size of the binding. This must only be used for the last binding in the descriptor set layout (i.e. the binding with the largest value of `binding`). For the purposes of counting against limits such as `maxDescriptorSet`* and `maxPerStageDescriptor`*, the full value of `descriptorCount` is counted.

**Note**

Note that while `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` and `VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT` both involve updates to descriptor sets after they are bound, `VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT` is a weaker requirement since it is only about descriptors that are not used, whereas `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` requires the implementation to observe updates to descriptors that are used.

```typedef VkFlags VkDescriptorBindingFlags;
```

`VkDescriptorBindingFlags` is a bitmask type for setting a mask of zero or more `VkDescriptorBindingFlagBits`.

To query information about whether a descriptor set layout can be created, call:

```void vkGetDescriptorSetLayoutSupport(
    VkDevice                                    device,  // the logical device that would create the descriptor set layout.
    const VkDescriptorSetLayoutCreateInfo*      pCreateInfo,  // a pointer to a VkDescriptorSetLayoutCreateInfo structure specifying the state of the descriptor set layout object.
    VkDescriptorSetLayoutSupport*               pSupport);  // a pointer to a VkDescriptorSetLayoutSupport structure, in which information about support for the descriptor set layout object is returned.
```

- `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:

```c
typedef struct VkDescriptorSetLayoutSupport {
    VkStructureType sType;
    void* pNext;
    VkBool32 supported;
} VkDescriptorSetLayoutSupport;
```

- **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` or a pointer to a valid instance of `VkDescriptorSetVariableDescriptorCountLayoutSupport`
- The **sType** value of each struct in the **pNext** chain must be unique

If the **pNext** chain of a `VkDescriptorSetLayoutSupport` structure includes a `VkDescriptorSetVariableDescriptorCountLayoutSupport` structure, then that structure returns additional information about whether the descriptor set layout is supported.
typedef struct VkDescriptorSetVariableDescriptorCountLayoutSupport {
    VkStructureType sType;
    void* pNext;
    uint32_t maxVariableDescriptorCount;
} VkDescriptorSetVariableDescriptorCountLayoutSupport;

- **sType** is the type of this structure.
- **pNext** is **NULL** or a pointer to an extension-specific structure.
- **maxVariableDescriptorCount** indicates the maximum number of descriptors supported in the highest numbered binding of the layout, if that binding is variable-sized.

If the create info includes a variable-sized descriptor, then **supported** is determined assuming the requested size of the variable-sized descriptor, and **maxVariableDescriptorCount** is set to the maximum size of that descriptor that **can** be successfully created (which is greater than or equal to the requested size passed in). If the create info does not include a variable-sized descriptor or if the **VkPhysicalDeviceDescriptorIndexingFeatures::descriptorBindingVariableDescriptorCount** feature is not enabled, then **maxVariableDescriptorCount** is set to zero. For the purposes of this command, a variable-sized descriptor binding with a **descriptorCount** of zero is treated as if the **descriptorCount** is one, and thus the binding is not ignored and the maximum descriptor count will be returned. If the layout is not supported, then the value written to **maxVariableDescriptorCount** is undefined.

**Valid Usage (Implicit)**

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

  `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_LAYOUT_SUPPORT`

The following examples show a shader snippet using two descriptor sets, and application code that creates corresponding descriptor set layouts.
// 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**

```c
VkResult myResult;

const VkDescriptorSetLayoutBinding myDescriptorSetLayoutBinding[] =
{
    // binding to a single image descriptor
    { 0,
        VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE, // descriptorType
        1, // descriptorCount
        VK_SHADER_STAGE_FRAGMENT_BIT, // stageFlags
    }
};
```
// 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],
        NULL
    );
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**.
Host Synchronization

- Host access to descriptorSetLayout must be externally synchronized

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:

```c
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkPipelineLayout)
```

To create a pipeline layout, call:

```c
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 in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_SAMPLER` and `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorSamplers`

- The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` and `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorUniformBuffers`

- The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` and `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorStorageBuffers`

- The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, and `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorSampledImages`

- The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, and `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimits::maxPerStageDescriptorStorageImages`

- The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a `descriptorType` of `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 with a `descriptorType` of `VK_DESCRIPTOR_TYPE_SAMPLER` and `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindSamplers`

- The total number of descriptors with a `descriptorType` of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` and `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindSamplers`
- The total number of descriptors with a descriptorType of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` and `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindUniformBuffers`

- The total number of descriptors with a descriptorType of `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`, and `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindSampledImages`

- The total number of descriptors with a descriptorType of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`, and `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceDescriptorIndexingProperties::maxPerStageDescriptorUpdateAfterBindStorageImages`

- The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a descriptorType of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` accessible to any given shader stage across all elements of `pSetLayouts` must be less than or equal to `VkPhysicalDeviceLimit::maxDescriptorSetInputAttachments`

- The total number of descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a descriptorType of `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 in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a descriptorType of `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 in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a descriptorType of `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 in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set with a descriptorType of `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`
across all elements of $pSetLayouts$ must be less than or equal to $VkPhysicalDeviceLimits::maxDescriptorSetStorageBuffersDynamic$

- The total number of descriptors in descriptor set layouts created without the $VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT$ bit set with a $descriptorType$ of $VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER$, $VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE$, 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 in descriptor set layouts created without the $VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT$ bit set with a $descriptorType$ of $VK_DESCRIPTOR_TYPE_STORAGE_IMAGE$, 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 $VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindInputAttachments$

- 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 $VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindSamplers$

- 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 $VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindUniformBuffers$

- 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 $VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindUniformBuffersDynamic$

- 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 $VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindStorageBuffers$

- 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 $VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindStorageBuffersDynamic$

- 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 $VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindSampledImages$

- The total number of descriptors of the type $VK_DESCRIPTOR_TYPE_STORAGE_IMAGE$ and $Chapter 13. Resource Descriptors | 461$
VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER accessible across all shader stages and across all elements of pSetLayouts must be less than or equal to VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindStorageImages

- 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 VkPhysicalDeviceDescriptorIndexingProperties::maxDescriptorSetUpdateAfterBindInputAttachments

- Any two elements of pPushConstantRanges must not include the same stage in stageFlags

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 10. Pipeline Layout Resource Limits
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].
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

```cpp
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:

```
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:

```c
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.

If flags has the VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT bit set, descriptor pool creation may fail with the error VK_ERROR_FRAGMENTATION if the total number of descriptors across all pools (including this one) created with this bit set exceeds maxUpdateAfterBindDescriptorsInAllPools, or if fragmentation of the underlying hardware resources occurs.

### Valid Usage

- **maxSets** must be greater than 0

### 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_UPDATE_AFTER_BIND_BIT = 0x00000002,
    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.

- **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** specifies that descriptor sets allocated from this pool can include bindings with the VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT bit set. It is valid to allocate descriptor sets that have bindings that do not set the VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT bit from a pool that has VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT set.

```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.

**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:

VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorSet)

To allocate descriptor sets from a descriptor pool, call:

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:

- For descriptor set bindings created with the `VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT` bit set, all descriptors in that binding that are dynamically used must have been populated before the descriptor set is consumed.

- For descriptor set bindings created without the `VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT` bit set, all descriptors in that binding 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:

```c
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

- If any element of `pSetLayouts` was created with the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set, `descriptorPool` must have been created with the `VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT` flag set
Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO`
- **pNext** must be `NULL` or a pointer to a valid instance of `VkDescriptorSetVariableDescriptorCountAllocateInfo`
- The **sType** value of each struct in the **pNext** chain must be unique
- **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`

If the **pNext** chain of a `VkDescriptorSetAllocateInfo` structure includes a `VkDescriptorSetVariableDescriptorCountAllocateInfo` structure, then that structure includes an array of descriptor counts for variable descriptor count bindings, one for each descriptor set being allocated.

The `VkDescriptorSetVariableDescriptorCountAllocateInfo` structure is defined as:

```c
typedef struct VkDescriptorSetVariableDescriptorCountAllocateInfo {
    VkStructureType    sType;
    const void*        pNext;
    uint32_t           descriptorSetCount;
    const uint32_t*    pDescriptorCounts;
} VkDescriptorSetVariableDescriptorCountAllocateInfo;
```

- **sType** is the type of this structure.
- **pNext** is `NULL` or a pointer to an extension-specific structure.
- **descriptorSetCount** is zero or the number of elements in **pDescriptorCounts**.
- **pDescriptorCounts** is a pointer to an array of descriptor counts, with each member specifying the number of descriptors in a variable descriptor count binding in the corresponding descriptor set being allocated.

If **descriptorSetCount** is zero or this structure is not included in the **pNext** chain, then the variable lengths are considered to be zero. Otherwise, **pDescriptorCounts[i]** is the number of descriptors in the variable count descriptor binding in the corresponding descriptor set layout. If `VkDescriptorSetAllocateInfo::pSetLayouts[i]` does not include a variable count descriptor binding, then **pDescriptorCounts[i]** is ignored.
Valid Usage

• If \( \text{descriptorSetCount} \) is not zero, \( \text{descriptorSetCount} \) must equal \( \text{VkDescriptorSetAllocateInfo}::\text{descriptorSetCount} \)

• If \( \text{VkDescriptorSetAllocateInfo}::\text{pSetLayouts}[i] \) has a variable descriptor count binding, then \( \text{pDescriptorCounts}[i] \) must be less than or equal to the descriptor count specified for that binding when the descriptor set layout was created.

Valid Usage (Implicit)

• \( \text{sType} \) must be \( \text{VK_STRUCTURE_TYPE_DESCRIPTOR_SET_VARIABLE_DESCRIPTOR_COUNT_ALLOCATE_INFO} \)

• If \( \text{descriptorSetCount} \) is not 0, \( \text{pDescriptorCounts} \) must be a valid pointer to an array of \( \text{descriptorSetCount} \) \text{uint32_t} \) values

To free allocated descriptor sets, call:

```c
VkResult vkFreeDescriptorSets(
    VkDevice device,
    VkDescriptorPool descriptorPool,
    uint32_t descriptorSetCount,
    const VkDescriptorSet* pDescriptorSets);
```

• \( \text{device} \) is the logical device that owns the descriptor pool.

• \( \text{descriptorPool} \) is the descriptor pool from which the descriptor sets were allocated.

• \( \text{descriptorSetCount} \) is the number of elements in the \( \text{pDescriptorSets} \) array.

• \( \text{pDescriptorSets} \) is a pointer to an array of handles to \( \text{VkDescriptorSet} \) objects.

After calling \( \text{vkFreeDescriptorSets} \), all descriptor sets in \( \text{pDescriptorSets} \) are invalid.

Valid Usage

• All submitted commands that refer to any element of \( \text{pDescriptorSets} \) must have completed execution

• \( \text{pDescriptorSets} \) must be a valid pointer to an array of \( \text{descriptorSetCount} \) \( \text{VkDescriptorSet} \) handles, each element of which must either be a valid handle or \( \text{VK_NULL_HANDLE} \)

• Each valid handle in \( \text{pDescriptorSets} \) must have been allocated from \( \text{descriptorPool} \)

• \( \text{descriptorPool} \) must have been created with the \( \text{VK_DESCRIPTOR_POOL_CREATE_FREE_DESCRIPTOR_SET_BIT} \) 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:

```c
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**

```c
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,
    uint32_t descriptorWriteCount,
    const VkWriteDescriptorSet* pDescriptorWrites,
    uint32_t descriptorCopyCount,
    const VkCopyDescriptorSet* pDescriptorCopies);
```

- **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, and any of the descriptor bindings that are updated were not created with the VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT or VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT bits set, that command buffer becomes invalid.

---

**Valid Usage**

- Descriptor bindings updated by this command which were created without the VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT or VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT bits set 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:
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**).
- **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, 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`, `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC`, 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_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`.
• 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::minUniformBufferOffsetAlignment`.

• 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` or `VK_DESCRIPTOR_TYPE_UNIFORM_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_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.

• All consecutive bindings updated via a single `VkWriteDescriptorSet` structure, except those with a `descriptorCount` of zero, must have identical `VkDescriptorBindingFlagBits`.

• 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`
- `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:

```c
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_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.
- `VK_DESCRIPTOR_TYPE_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.

The `VkDescriptorBufferInfo` structure is defined as:

```c
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.

- `imageView` 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 `VkCopyDescriptorSet` structure is defined as:

```c
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 **srcSet’s** layout was created with the **VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT** flag set, then **dstSet’s** layout must also have been created with the **VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT** flag set

- If **srcSet’s** layout was created without the **VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT** flag set, then **dstSet’s** layout must also have been created without the **VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT** flag set

- If the descriptor pool from which **srcSet** was allocated was created with the **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** flag set, then the descriptor pool from which **dstSet** was allocated must also have been created with the **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** flag set

- If the descriptor pool from which **srcSet** was allocated was created without the **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** flag set, then the descriptor pool from which **dstSet** was allocated must also have been created without the **VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT** flag set

- 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:

```
VK_DEFINE_NON_DISPATCHABLE_HANDLE(VkDescriptorUpdateTemplate)
```

### 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`, can be more efficient compared to calling `vkUpdateDescriptorSets`. 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`. 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:

```c
VkResult vkCreateDescriptorUpdateTemplate(
    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 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_OFDEVICE_MEMORY

The VkDescriptorUpdateTemplateCreateInfo structure is defined as:

```c
typedef struct VkDescriptorUpdateTemplateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkDescriptorUpdateTemplateCreateFlags flags;
    uint32_t descriptorUpdateEntryCount;
    const VkDescriptorUpdateTemplateEntry* pDescriptorUpdateEntries;
    VkDescriptorUpdateTemplateType templateType;
    VkDescriptorSetLayout descriptorSetLayout;
    VkPipelineBindPoint pipelineBindPoint;
    VkPipelineLayout pipelineLayout;
    uint32_t set;
} VkDescriptorUpdateTemplateCreateInfo;
```

• 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`.

• **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 reserved for future use and is ignored

• **pipelineLayout** is reserved for future use and is ignored

• **set** is reserved for future use and is ignored

### Valid Usage

- If `templateType` is `VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET`, `descriptorSetLayout` must be a valid `VkDescriptorSetLayout` handle

### 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`

```c
typedef VkFlags VkDescriptorUpdateTemplateCreateFlags;
```

`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:

```c
typedef enum VkDescriptorUpdateTemplateType {
    VK_DESCRIPTOR_UPDATE_TEMPLATE_TYPE_DESCRIPTOR_SET = 0,
    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.

The `VkDescriptorUpdateTemplateEntry` structure is defined as:

```c
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:

```c
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);
```

- **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);
```

- `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, offsetof(AppDataStructure, imageInfo), 0 },
    // stride is not required if descriptorCount is 1
    // binding to an array of buffer descriptors
    { 1, 0, 3, VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER, offsetof(AppDataStructure, bufferInfoArray), sizeof(VkDescriptorBufferInfo) },
    // stride, descriptor buffer infos are compact
    // binding to an array of buffer views
    { 2, 0, 2, VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, offsetof(AppDataStructure, bufferView) + offsetof(AppBufferView, bufferView), sizeof(AppBufferView) },
    // stride, bufferViews do not have to be compact
};

// 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_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,
  &createInfo,
  NULL,
  &myDescriptorUpdateTemplate);
}

AppDataStructure appData;

// fill appData here or cache it in your engine
vkUpdateDescriptorSetWithTemplate(myDevice, myDescriptorSet,
  myDescriptorUpdateTemplate, &appData);
```

### 13.2.7. Descriptor Set Binding

To bind one or more descriptor sets to a command buffer, call:

```c
void vkCmdBindDescriptorSets(
  VkCommandBuffer commandBuffer,
  VkPipelineBindPoint pipelineBindPoint,
  VkPipelineLayout layout,
  uint32_t firstSet,
  uint32_t descriptorSetCount,
  const VkDescriptorSet* pDescriptorSets,
  uint32_t dynamicOffsetCount,
  const uint32_t* 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 `[firstSet.. 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:

- For descriptor bindings created with the `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` bit set,
  the contents **may** be consumed when the command buffer is submitted to a queue, or during
  shader execution of the resulting draws and dispatches, or any time in between. Otherwise,
• 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.

<table>
<thead>
<tr>
<th>Valid Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 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</td>
</tr>
<tr>
<td>• dynamicOffsetCount must be equal to the total number of dynamic descriptors in pDescriptorSets</td>
</tr>
<tr>
<td>• The sum of firstSet and descriptorSetCount must be less than or equal to VkPipelineLayoutCreateInfo::setLayoutCount provided when layout was created</td>
</tr>
<tr>
<td>• pipelineBindPoint must be supported by the commandBuffer’s parent VkCommandPool’s queue family</td>
</tr>
<tr>
<td>• 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</td>
</tr>
<tr>
<td>• 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</td>
</tr>
<tr>
<td>• 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</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
- `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`

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 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

Command Properties

<table>
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<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

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 vkGetBufferDeviceAddress(
    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 or the equivalent 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` or 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;
```

- `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 vkGetBufferOpaqueCaptureAddress(
    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 `Vk*PipelineCreateInfo` 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>maxTessellationControlPerVertexInputComponents / 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 \( \text{pColorAttachments}[i] \), 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**
- Non-uniform: \texttt{shaderStorageImageArrayNonUniformIndexing} and \\
  \texttt{StorageImageArrayNonUniformIndexing}

**Storage texel buffers:**

- Dynamically uniform: \texttt{shaderStorageTexelBufferArrayDynamicIndexing} and \\
  \texttt{StorageTexelBufferArrayDynamicIndexing}

- Non-uniform: \texttt{shaderStorageTexelBufferArrayNonUniformIndexing} and \\
  \texttt{StorageTexelBufferArrayNonUniformIndexing}

**Input attachments:**

- Dynamically uniform: \texttt{shaderInputAttachmentArrayDynamicIndexing} and \\
  \texttt{InputAttachmentArrayDynamicIndexing}

- Non-uniform: \texttt{shaderInputAttachmentArrayNonUniformIndexing} and \\
  \texttt{InputAttachmentArrayNonUniformIndexing}

**Sampled images (except uniform texel buffers), samplers and combined image samplers:**

- Dynamically uniform: \texttt{shaderSampledImageArrayDynamicIndexing} and \\
  \texttt{SampledImageArrayDynamicIndexing}

- Non-uniform: \texttt{shaderSampledImageArrayNonUniformIndexing} and \\
  \texttt{SampledImageArrayNonUniformIndexing}

**Uniform texel buffers:**

- Dynamically uniform: \texttt{shaderUniformTexelBufferArrayDynamicIndexing} and \\
  \texttt{UniformTexelBufferArrayDynamicIndexing}

- Non-uniform: \texttt{shaderUniformTexelBufferArrayNonUniformIndexing} and \\
  \texttt{UniformTexelBufferArrayNonUniformIndexing}

**Uniform buffers:**

- Dynamically uniform: \texttt{shaderUniformBufferArrayDynamicIndexing} and \\
  \texttt{UniformBufferArrayDynamicIndexing}

- Non-uniform: \texttt{shaderUniformBufferArrayNonUniformIndexing} and \\
  \texttt{UniformBufferArrayNonUniformIndexing}

**Storage buffers:**

- Dynamically uniform: \texttt{shaderStorageBufferArrayDynamicIndexing} and \\
  \texttt{StorageBufferArrayDynamicIndexing}

- Non-uniform: \texttt{shaderStorageBufferArrayNonUniformIndexing} and \\
  \texttt{StorageBufferArrayNonUniformIndexing}

If an instruction loads from or stores to a resource (including atomics and image instructions) and 
the resource descriptor being accessed is not dynamically uniform, then the corresponding non-
uniform indexing feature \textbf{must} be enabled and the capability \textbf{must} be declared. 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 or non-uniform 
feature \textbf{must} be enabled and the capability \textbf{must} be declared.

If the combined image sampler enables sampler $Y'CbCr$ conversion, it \textbf{must} be indexed only by 
constant integral expressions when aggregated into arrays in shader code, irrespective of the 
\texttt{shaderSampledImageArrayDynamicIndexing} feature.

\textit{Table 12. Shader Resource and Descriptor Type Correspondence}
### Table 13. Shader Resource and Storage Class Correspondence

<table>
<thead>
<tr>
<th>Resource type</th>
<th>Descriptor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>sampler</td>
<td>VK_DESCRIPTOR_TYPE_SAMPLER or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER</td>
</tr>
<tr>
<td>sampled image</td>
<td>VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE or VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER</td>
</tr>
<tr>
<td>storage image</td>
<td>VK_DESCRIPTOR_TYPE_STORAGE_IMAGE</td>
</tr>
<tr>
<td>combined image sampler</td>
<td>VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER</td>
</tr>
<tr>
<td>uniform texel buffer</td>
<td>VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER</td>
</tr>
<tr>
<td>storage texel buffer</td>
<td>VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER</td>
</tr>
<tr>
<td>uniform buffer</td>
<td>VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC</td>
</tr>
<tr>
<td>storage buffer</td>
<td>VK_DESCRIPTOR_TYPE_STORAGE_BUFFER or VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC</td>
</tr>
<tr>
<td>input attachment</td>
<td>VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT</td>
</tr>
</tbody>
</table>

The table above shows the correspondence between shader resources and their storage classes and types, along with their associated decorations.

### 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`. In addition to `DescriptorSet` and `Binding`, the variable is also associated with the index of the input attachment.
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. If the array is runtime-sized, then array elements greater than or equal to the size of that binding in the bound descriptor set must not be used. If the array is runtime-sized, the runtimeDescriptorArray feature must be enabled and the RuntimeDescriptorArray capability must be declared. 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 14. Shader Resource Limits

<table>
<thead>
<tr>
<th>Resources per Stage</th>
<th>Resource Types</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>maxPerStageDescriptorSamplers</code> or <code>maxPerStageDescriptorUpdateAfterBindSamplers</code></td>
<td>sampler</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorSampledImages</code> or <code>maxPerStageDescriptorUpdateAfterBindSampledImages</code></td>
<td>combined image sampler</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorStorageImages</code> or <code>maxPerStageDescriptorUpdateAfterBindStorageImages</code></td>
<td>sampled image</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorUniformBuffers</code> or <code>maxPerStageDescriptorUpdateAfterBindUniformBuffers</code></td>
<td>combined image sampler</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorStorageBuffers</code> or <code>maxPerStageDescriptorUpdateAfterBindStorageBuffers</code></td>
<td>uniform texel buffer</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorStorageImages</code> or <code>maxPerStageDescriptorUpdateAfterBindStorageImages</code></td>
<td>storage image</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorUniformBuffers</code> or <code>maxPerStageDescriptorUpdateAfterBindUniformBuffers</code></td>
<td>storage texel buffer</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorStorageBuffers</code> or <code>maxPerStageDescriptorUpdateAfterBindStorageBuffers</code></td>
<td>uniform buffer</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorInputAttachments</code> or <code>maxPerStageDescriptorUpdateAfterBindInputAttachments</code></td>
<td>uniform buffer dynamic</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorStorageBuffers</code> or <code>maxPerStageDescriptorUpdateAfterBindStorageBuffers</code></td>
<td>storage buffer</td>
</tr>
<tr>
<td><code>maxPerStageDescriptorInputAttachments</code> or <code>maxPerStageDescriptorUpdateAfterBindInputAttachments</code></td>
<td>storage buffer dynamic</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 floor(F / 16) != 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. If the `scalarBlockLayout` feature is enabled on the device then every member must be aligned according to its scalar alignment.
2. All vectors must be aligned according to their scalar alignment.
3. 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.
4. Every other member must be aligned according to its base alignment.

**Note**

Even if scalar alignment is supported, it is generally more performant to use the 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.

Unless the `scalarBlockLayout` feature is enabled on the device:

- 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.
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 \( i^{th} \) 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.
Note
The array variable decorated with `ClipDistance` is explicitly sized by the shader.

Note
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.

Note
In fragment shaders, the values of the `CullDistance` array are linearly interpolated
across each primitive.

Note
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 `DeviceIndex` **must** be declared as a scalar 32-bit integer.

**DrawIndex**
Decorating a variable with the `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 **indirect drawing commands**, `DrawIndex` begins at zero and increments by one for each draw command executed. The number of draw commands is given by the `drawCount` parameter. For **direct drawing commands**, `DrawIndex` is always zero. `DrawIndex` is dynamically uniform.

The `DrawIndex` decoration **must** be used only within vertex shaders.

The variable decorated with `DrawIndex` **must** be declared using the input storage class.

The variable decorated with `DrawIndex` **must** be declared as a scalar 32-bit integer.

**FragCoord**
Decorating a variable with the `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 **Sample Shading** is enabled, the \(x\) and \(y\) components of `FragCoord` reflect the location of one of the samples corresponding to the shader invocation.

Otherwise, the \(x\) and \(y\) components of `FragCoord` reflect the location of the center of the fragment.

The \(z\) component of `FragCoord` is the interpolated depth value of the primitive.

The \(w\) component is the interpolated \(\frac{1}{w}\).

The `FragCoord` decoration **must** be used only within fragment shaders.

The variable decorated with `FragCoord` **must** be declared using the Input storage class.

The `Centroid` interpolation decoration is ignored, but allowed, on `FragCoord`.

The variable decorated with `FragCoord` **must** be declared as a four-component vector of 32-bit floating-point values.

**FragDepth**
To have a shader supply a fragment-depth value, the shader **must** declare the DepthReplacing execution mode. Such a shader’s fragment-depth value will come from the variable decorated with the `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 `FragDepth` decoration **must** be used only within fragment shaders.

The variable decorated with `FragDepth` **must** be declared using the Output storage class.
The variable decorated with `FragDepth` must be declared as a scalar 32-bit floating-point value.

**FrontFacing**

Decorating a variable with the `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 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 `FrontFacing` decoration must be used only within fragment shaders.

The variable decorated with `FrontFacing` must be declared using the `Input` storage class.

The variable decorated with `FrontFacing` must be declared as a boolean.

**GlobalInvocationId**

Decorating a variable with the `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 `LocalInvocationId`.

The `GlobalInvocationId` decoration must be used only within compute shaders.

The variable decorated with `GlobalInvocationId` must be declared using the `Input` storage class.

The variable decorated with `GlobalInvocationId` must be declared as a three-component vector of 32-bit integers.

**HelperInvocation**

Decorating a variable with the `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 `HelperInvocation` decoration must be used only within fragment shaders.

The variable decorated with `HelperInvocation` must be declared using the `Input` storage class.

The variable decorated with `HelperInvocation` must be declared as a boolean.

**Note**

It is very likely that a helper invocation will have a value of `SampleMask` fragment shader input value that is zero.

**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.

**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 vertex, tessellation evaluation, or 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.

The last active vertex processing stage (in pipeline order) controls the `Layer` that is used. Outputs in previous shader stages are not used, even if the last stage fails to write the `Layer`.

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 vertex, tessellation evaluation, geometry, and fragment shaders. If the `shaderOutputLayer` feature is not enabled then the `Layer` decoration **must** be used only with geometry, and fragment shaders.

In a vertex, tessellation evaluation, or 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.

**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.

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 fragment, tessellation control, tessellation evaluation, and geometry shaders.

In 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.

**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 (\(\text{SampleMask}[M]\)) 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 \([0, \text{NumSubgroups}-1]\).

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.

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 vertex, tessellation evaluation, or 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.

The last active **vertex processing stage** (in pipeline order) controls the **ViewportIndex** that is used.
Outputs in previous shader stages are not used, even if the last stage fails to write the ViewportIndex.

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 vertex, tessellation evaluation, geometry, and fragment shaders. If the shaderOutputViewportIndex feature is not enabled then the ViewportIndex decoration must be used only with geometry, and fragment shaders.

In a vertex, tessellation evaluation, or 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.
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.
- OpImageGather and OpImageSparseGather 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 \texttt{Dim} of the image, and \(l\) conditionally present based on the \texttt{Arrayed} property of the image. \(n\) is conditionally present and is taken from the \texttt{Sample} image operand.

For all coordinate types, unused coordinates are assigned a value of zero.

![Diagram of Texel Coordinate Systems, Linear Filtering](image)

**Figure 3. Texel Coordinate Systems, Linear Filtering**

The Texel Coordinate Systems - For the example shown of an 8×4 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 \(i_{0j0}, i_{1j0}, i_{0j1},\) and \(i_{1j1}\).
  - 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.

Figure 4. Texel Coordinate Systems, Nearest Filtering

The Texel Coordinate Systems - For the example shown of an $8 \times 4$ 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 ($\text{red}_{\text{shared}}$, $\text{green}_{\text{shared}}$, $\text{blue}_{\text{shared}}$, $\text{exp}_{\text{shared}}$) as follows:

First, the components (red, green, blue) are clamped to ($\text{red}_{\text{clamped}}$, $\text{green}_{\text{clamped}}$, $\text{blue}_{\text{clamped}}$) as:

\[
\text{red}_{\text{clamped}} = \max(0, \min(\text{sharedexp}_{\text{max}}, \text{red}))
\]
\[
\text{green}_{\text{clamped}} = \max(0, \min(\text{sharedexp}_{\text{max}}, \text{green}))
\]
\[
\text{blue}_{\text{clamped}} = \max(0, \min(\text{sharedexp}_{\text{max}}, \text{blue}))
\]

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:

\[
\exp' = \begin{cases} 
\log_2(\text{max}_{\text{clamped}}) + (B + 1) & \text{for } \text{max}_{\text{clamped}} > 2^{-(B + 1)} \\
0 & \text{for } \text{max}_{\text{clamped}} \leq 2^{-(B + 1)}
\end{cases}
\]

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:

\[
\begin{align*}
\text{red}_{\text{shared}} &= \left\lfloor \frac{\text{red}_{\text{clamped}}}{2^{(\exp_{\text{shared}} - B - N)}} + \frac{1}{2} \right\rfloor \\
\text{green}_{\text{shared}} &= \left\lfloor \frac{\text{green}_{\text{clamped}}}{2^{(\exp_{\text{shared}} - B - N)}} + \frac{1}{2} \right\rfloor \\
\text{blue}_{\text{shared}} &= \left\lfloor \frac{\text{blue}_{\text{clamped}}}{2^{(\exp_{\text{shared}} - B - N)}} + \frac{1}{2} \right\rfloor
\end{align*}
\]

### 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 (red, green, 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:

\[N = 9\] (number of mantissa bits per component)
B = 15 (exponent bias)

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′CrC_{x} 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_{x}C_{x} 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′C_bC_r conversion.

`OpImageFetch`, `OpImageSparseFetch`, `OpImage*Gather`, and `OpImageSparse*Gather` must not be used with a sampler that enables sampler Y′C_bC_r conversion.
The ConstOffset and Offset operands must not be used with a sampler that enables sampler Y’C_aC_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

\[
0 \leq i < w_s \\
0 \leq j < h_s \\
0 \leq k < d_s \\
0 \leq l < \text{layers} \\
0 \leq n < \text{samples}
\]

where:

\[
w_s = \text{width of the image level} \\
h_s = \text{height of the image level} \\
d_s = \text{depth of the image level} \\
\text{layers} = \text{number of layers in the image} \\
\text{samples} = \text{number of samples per texel in the image}
\]

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'CbCr 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 15. 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></td>
<td>[B_r, B_g, B_b, B_a] = [0.0, 0.0, 0.0, 0.0]</td>
</tr>
<tr>
<td>VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK</td>
<td></td>
<td>[B_r, B_g, B_b, B_a] = [0.0, 0.0, 0.0, 1.0]</td>
</tr>
<tr>
<td>VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE</td>
<td></td>
<td>[B_r, B_g, B_b, B_a] = [1.0, 1.0, 1.0, 1.0]</td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_TRANSPARENT_BLACK</td>
<td></td>
<td>[B_r, B_g, B_b, B_a] = [0, 0, 0, 0]</td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_OPAQUE_BLACK</td>
<td></td>
<td>[B_r, B_g, B_b, B_a] = [0, 0, 0, 1]</td>
</tr>
<tr>
<td>VK_BORDER_COLOR_INT_OPAQUE_WHITE</td>
<td></td>
<td>[B_r, B_g, B_b, B_a] = [1, 1, 1, 1]</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.
Table 16. 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>Color_r = B_r</td>
</tr>
<tr>
<td>Two component color format</td>
<td>[Color_r,Color_g] = [B_r,B_g]</td>
</tr>
<tr>
<td>Three component color format</td>
<td>[Color_r,Color_g,Color_b] = [B_r,B_g,B_b]</td>
</tr>
<tr>
<td>Four component color format</td>
<td>[Color_r,Color_g,Color_b,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.

\[
\begin{align*}
D &= 1.0 & D_{\text{ref}} \leq D & \text{for LEQUAL} \\
D &= 1.0 & D_{\text{ref}} \geq D & \text{for GEQUAL} \\
D &= 1.0 & D_{\text{ref}} < D & \text{for LESS} \\
D &= 1.0 & D_{\text{ref}} > D & \text{for GREATER} \\
D &= 1.0 & D_{\text{ref}} = D & \text{for EQUAL} \\
D &= 1.0 & D_{\text{ref}} \neq D & \text{for NOTEQUAL} \\
D &= 0.0 & \text{true} & \text{for ALWAYS} \\
D &= 0.0 & \text{false} & \text{for NEVER}
\end{align*}
\]

where, in the depth comparison:

\[D_{\text{ref}} = \text{shaderOp.D}_{\text{ref}}\text{ (from optional SPIR-V operand)}\]

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>
<thead>
<tr>
<th>Texel Aspect or Format</th>
<th>RGBA Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth aspect</td>
<td>([\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{Color}_a] = [D, 0, 0, \text{one}])</td>
</tr>
<tr>
<td>Stencil aspect</td>
<td>([\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{Color}_a] = [S, 0, 0, \text{one}])</td>
</tr>
<tr>
<td>One component color format</td>
<td>([\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{Color}_a] = [\text{Color}_r, 0, 0, \text{one}])</td>
</tr>
<tr>
<td>Two component color format</td>
<td>([\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{Color}_a] = [\text{Color}_r, \text{Color}_g, 0, \text{one}])</td>
</tr>
<tr>
<td>Three component color format</td>
<td>([\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{Color}_a] = [\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{one}])</td>
</tr>
<tr>
<td>Four component color format</td>
<td>([\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{Color}_a] = [\text{Color}_r, \text{Color}_g, \text{Color}_b, \text{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_bC_r 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:

\[
\text{Color}^{\text{component}} = \begin{cases} 
\text{Color}_r & \text{for RED swizzle} \\
\text{Color}_g & \text{for GREEN swizzle} \\
\text{Color}_b & \text{for BLUE swizzle} \\
\text{Color}_a & \text{for ALPHA swizzle} \\
0 & \text{for ZERO swizzle} \\
\text{one} & \text{for ONE swizzle} \\
\text{identity} & \text{for IDENTITY swizzle}
\end{cases}
\]

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’C₆C₈ 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.
Figure 5. 422 downsampling, xChromaOffset=COSITED_EVEN

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 \( \text{VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT} \) and if the \( \text{VkSamplerYcbcrConversionCreateInfo} \)’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 \( \text{VkSamplerYcbcrConversionCreateInfo} \) 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 \( \tau_{ijk}[\text{level}] \) values accessed by texel filtering are reconstructed as follows:
    
    \[
    \begin{align*}
    \tau_R'(i, j) &= \tau_R([i \times 0.5], j)[\text{level}] \\
    \tau_B'(i, j) &= \tau_B([i \times 0.5], j)[\text{level}]
    \end{align*}
    \]

  - 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 \( \tau_{ijk}[\text{level}] \) values accessed by texel filtering are reconstructed as follows:
    
    \[
    \begin{align*}
    \tau_R'(i, j) &= \tau_R([i \times 0.5], [j \times 0.5])[\text{level}] \\
    \tau_B'(i, j) &= \tau_B([i \times 0.5], [j \times 0.5])[\text{level}]
    \end{align*}
    \]

  *Note*

  `xChromaOffset` and `yChromaOffset` have no effect if `chromaFilter` is `VK_FILTER_NEAREST` for explicit reconstruction.

- If the `chromaFilter` member of the \( \text{VkSamplerYcbcrConversionCreateInfo} \) 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`:
      
      \[
      \begin{align*}
      \tau_{RB}'(i, j) &= \begin{cases} 
      \tau_{RB}([i \times 0.5], j)[\text{level}], & 0.5 \times i = [0.5 \times i] \\
      0.5 \times \tau_{RB}([i \times 0.5], j)[\text{level}] + 0.5 \times \tau_{RB}([i \times 0.5] + 1, j)[\text{level}], & 0.5 \times i \neq [0.5 \times i]
      \end{cases}
      \end{align*}
      \]

    - If `xChromaOffset` is `VK_CHROMA_LOCATION_MIDPOINT`:
      
      \[
      \begin{align*}
      \tau_{RB}'(i, j) &= \begin{cases} 
      0.25 \times \tau_{RB}([i \times 0.5] - 1, j)[\text{level}] + 0.75 \times \tau_{RB}([i \times 0.5], j)[\text{level}], & 0.5 \times i = [0.5 \times i] \\
      0.75 \times \tau_{RB}([i \times 0.5] - 1, j)[\text{level}] + 0.25 \times \tau_{RB}([i \times 0.5], j)[\text{level}], & 0.5 \times i \neq [0.5 \times i]
      \end{cases}
      \end{align*}
      \]

  - 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:
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 \texttt{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 \texttt{chromaFilter} takes precedence for the chroma samples.

If \texttt{chromaFilter} is \texttt{VK FILTER_NEAREST}, an implementation \textbf{may} behave as if \texttt{xChromaOffset} and \texttt{yChromaOffset} were both \texttt{VK CHROMALOCATION_MIDPOINT}, irrespective of the values set.

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):

\[
\begin{align*}
\tau_{RB}^{(i, j)}(u, v) &= \tau_{RB}(\text{floor}, \text{floor})[\text{level}] \\
\tau_{RB}(1 + \text{floor}, \text{floor})[\text{level}] \\
\tau_{RB}(\text{floor}, 1 + \text{floor})[\text{level}] \\
\tau_{RB}(1 + \text{floor}, 1 + \text{floor})[\text{level}]
\end{align*}
\]

\[
\begin{align*}
\tau_{RB}^{(i, j)} &= \tau_{RB}^{(i, j)} \times (1 - i_{frac}) \times (1 - j_{frac}) + \\
\tau_{RB}^{(1 + i, j)} &= \tau_{RB}^{(i, j)} \times (i_{frac}) \times (1 - j_{frac}) + \\
\tau_{RB}^{(i, 1 + j)} &= \tau_{RB}^{(i, j)} \times (1 - i_{frac}) \times (j_{frac}) + \\
\tau_{RB}^{(1 + i, 1 + j)} &= \tau_{RB}^{(i, j)} \times (i_{frac}) \times (j_{frac})
\end{align*}
\]

**15.3.9. Sampler \(Y'C_bC_R\) Conversion**

Sampler \(Y'C_bC_R\) conversion performs the following operations, which an implementation \textbf{may} combine into a single mathematical operation:

- Sampler \(Y'C_bC_R\) Range Expansion
Sampler Y’CₐCᵦ Range Expansion

Sampler Y’CₐCᵦ range expansion is applied to color channel values after all texel input operations which are not specific to sampler Y’CₐCᵦ conversion. For example, the input values to this stage have been converted using the normal format conversion rules.

Sampler Y’CₐCᵦ range expansion is not applied if ycbcrModel is VK_SAMPLER_YCBCR_MODEL_CONVERSION_RGB_IDENTITY. That is, the shader receives the vector Cᵦrgba 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’CₐCᵦ 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’CₐCᵦ 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:

\[
Y' = C'_{rgb}[G] \\
C_B = C'_{rgb}[B] - \frac{2^{(n-1)}}{(2^n - 1)} \\
C_R = C'_{rgb}[R] - \frac{2^{(n-1)}}{(2^n - 1)}
\]

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:

\[
Y' = \frac{C'_{rgb}[G] \times (2^n - 1) - 16 \times 2^n - 8}{219 \times 2^n - 8} \\
C_B = \frac{C'_{rgb}[B] \times (2^n - 1) - 128 \times 2^n - 8}{224 \times 2^n - 8} \\
C_R = \frac{C'_{rgb}[R] \times (2^n - 1) - 128 \times 2^n - 8}{224 \times 2^n - 8}
\]

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 $C_b$ and $C_r$ fall in the range $[-0.5,0.5]$.

**Sampler $Y'C_bC_r$ 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; $Y'C_bC_r$ 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 $Y'C_bC_r$ form both in memory and in the shader; $Y'C_bC_r$ range expansion is applied to the channels as for other $Y'C_bC_r$ models, with the vector $(C_b,Y',C_b,A)$ provided to the shader.

- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_709**
  The color channels are transformed from a $Y'C_bC_r$ representation to an $R'G'B'$ representation as described in the “BT.709 $Y'C_bC_r$ conversion” section of the Khronos Data Format Specification.

- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_601**
  The color channels are transformed from a $Y'C_bC_r$ representation to an $R'G'B'$ representation as described in the “BT.601 $Y'C_bC_r$ conversion” section of the Khronos Data Format Specification.

- **VK_SAMPLER_YCBCR_MODEL_CONVERSION_YCBCR_2020**
  The color channels are transformed from a $Y'C_bC_r$ representation to an $R'G'B'$ representation as described in the “BT.2020 $Y'C_bC_r$ 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.
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 \(Y’C_bC_a\) 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 \(Y’C_bC_a\) conversion at each of these locations.
  4. Convert the non-linear \(A’R’G’B’\) outputs of the \(Y’C_bC_a\) 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 \(Y’C_bC_a\) 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 \(D_{\text{ref}}\) 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.

If the image or sampler object used by an implicit derivative image instruction is not uniform across the quad and quadDivergentImplicitLod is not supported, then the derivative and LOD values are undefined. Implicit derivatives are well-defined when the image and sampler and control flow are uniform across the quad, even if they diverge between different quads.

If quadDivergentImplicitLod is supported, then derivatives and implicit LOD values are well-defined even if the image or sampler object are not uniform within a quad. The derivatives are computed...
as specified above, and the implicit LOD calculation proceeds for each shader invocation using its respective image and sampler object.

### 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 \(r_z\). 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 18. 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 19. 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_x / \partial x)</td>
<td>(-\partial r_x / \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_x / \partial x)</td>
<td>(+\partial r_x / \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_x / \partial x)</td>
<td>(+\partial r_x / \partial y)</td>
<td>(+\partial r_z / \partial x)</td>
<td>(+\partial r_z / \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_x / \partial x)</td>
<td>(+\partial r_x / \partial y)</td>
<td>(-\partial r_z / \partial x)</td>
<td>(-\partial r_z / \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_x / \partial x)</td>
<td>(+\partial r_x / \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

\[ s_{\text{face}} = \frac{1}{2} \times \frac{s_c}{r_c} + \frac{1}{2} \]

\[ t_{\text{face}} = \frac{1}{2} \times \frac{t_c}{r_c} + \frac{1}{2} \]

15.5.6. Cube Map Derivative Transformation

\[ \frac{\partial s_{\text{face}}}{\partial x} = \frac{\partial}{\partial x} \left( \frac{1}{2} \times \frac{s_c}{r_c} + \frac{1}{2} \right) \]

\[ \frac{\partial s_{\text{face}}}{\partial x} = \frac{1}{2} \times \frac{\partial}{\partial x} \left( \frac{s_c}{r_c} \right) \]

\[ \frac{\partial s_{\text{face}}}{\partial x} = \frac{1}{2} \times \left( \frac{r_c \times \partial s_c / \partial x - s_c \times \partial r_c / \partial x}{(r_c)^2} \right) \]

\[ \frac{\partial s_{\text{face}}}{\partial y} = \frac{1}{2} \times \left( \frac{r_c \times \partial s_c / \partial y - s_c \times \partial r_c / \partial y}{(r_c)^2} \right) \]

\[ \frac{\partial t_{\text{face}}}{\partial x} = \frac{1}{2} \times \left( \frac{r_c \times \partial t_c / \partial x - t_c \times \partial r_c / \partial x}{(r_c)^2} \right) \]

\[ \frac{\partial t_{\text{face}}}{\partial y} = \frac{1}{2} \times \left( \frac{r_c \times \partial t_c / \partial y - t_c \times \partial r_c / \partial y}{(r_c)^2} \right) \]

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 \( d' \) 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:

\[ m_{ux} = |\partial s / \partial x| \times w_{\text{base}} \]

\[ m_{ux} = |\partial t / \partial x| \times h_{\text{base}} \]

\[ m_{wx} = |\partial r / \partial x| \times d_{\text{base}} \]

\[ m_{wy} = |\partial s / \partial y| \times w_{\text{base}} \]
\[ m_{vy} = |\partial t/\partial y| \times h_{base} \]

\[ m_{vy} = |\partial r/\partial y| \times d_{base} \]

where:

\[ \partial t/\partial x = \partial t/\partial y = 0 \text{ (for 1D images)} \]

\[ \partial r/\partial x = \partial r/\partial y = 0 \text{ (for 1D, 2D or Cube images)} \]

and:

\[ w_{base} = \text{image.w} \]

\[ h_{base} = \text{image.h} \]

\[ d_{base} = \text{image.d} \]

(for the \text{baseMipLevel}, from the image descriptor).

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:

\[ f_x \text{ is continuous and monotonically increasing in each of } m_{vx}, m_{vy}, \text{ and } m_{wx} \]
\[ f_y \text{ is continuous and monotonically increasing in each of } m_{vy}, m_{vy}, \text{ and } m_{wy} \]

\[ \max(|m_{ux}|, |m_{ux}|, |m_{wx}|) \leq f_x \leq \sqrt{2}(|m_{ux}| + |m_{vx}| + |m_{wx}|) \]
\[ \max(|m_{vy}|, |m_{vy}|, |m_{wy}|) \leq f_y \leq \sqrt{2}(|m_{vy}| + |m_{vy}| + |m_{wy}|) \]

The minimum and maximum scale factors (\( \rho_{\text{min}}, \rho_{\text{max}} \)) are determined by:

\[ \rho_{\text{max}} = \max(\rho_x, \rho_y) \]

\[ \rho_{\text{min}} = \min(\rho_x, \rho_y) \]

The ratio of anisotropy is determined by:

\[ \eta = \min(\rho_{\text{max}}/\rho_{\text{min}}, \max_{\text{Aniso}}) \]

where:

\[ \text{sampler.max}_{\text{Aniso}} = \max_{\text{Anisotropy}} \text{ (from sampler descriptor)} \]

\[ \text{limits.max}_{\text{Aniso}} = \max_{\text{SamplerAnisotropy}} \text{ (from physical device limits)} \]
\[
\maxAniso = \min(\text{sampler.}\maxAniso, \limits.\maxAniso)
\]

If \( \rho_{\max} = \rho_{\min} = 0 \), 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 \( \rho_{\max} \neq 0 \) and \( \rho_{\min} = 0 \) 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 \( \maxAniso \). However, anytime the footprint is small in texel space the implementation may use a smaller value of \( \eta \), even when \( \rho_{\min} \) is zero or close to zero. If either VkPhysicalDeviceFeatures::samplerAnisotropy or VkSamplerCreateInfo::anisotropyEnable are VK_FALSE, \( \maxAniso \) 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:

\[
\lambda_{\text{base}}(x, y) = \begin{cases} 
\text{shaderOp.Lod} & \text{from optional SPIR-V operand) } \\
\log_{\eta}(\frac{\rho_{\max}}{\eta}) & \text{otherwise}
\end{cases}
\]

\[
\lambda'(x, y) = \lambda_{\text{base}} + \text{clamp}(\text{sampler.bias} + \text{shaderOp.bias}, -\maxSamplerLodBias, \maxSamplerLodBias)
\]

\[
\lambda = \begin{cases} 
\lambda_{\text{max}}, & \lambda' > \lambda_{\text{max}} \\
\lambda', & \lambda_{\min} \leq \lambda' \leq \lambda_{\max} \\
\lambda_{\min}, & \lambda' < \lambda_{\min} \\
\text{undefined}, & \lambda_{\min} > \lambda_{\max}
\end{cases}
\]

where:

\[
\text{sampler.bias} = \text{mipLodBias}
\]

(from sampler descriptor)

\[
\text{shaderOp.bias} = \begin{cases} 
\text{Bias} & \text{from optional SPIR-V operand) } \\
0 & \text{otherwise}
\end{cases}
\]

(from sampler descriptor)

\[
\text{sampler.lod}_{\min} = \text{minLod}
\]

(from sampler descriptor)

\[
\text{shaderOp.lod}_{\min} = \begin{cases} 
\text{MinLod} & \text{from optional SPIR-V operand) } \\
0 & \text{otherwise}
\end{cases}
\]

\[
\lambda_{\min} = \max(\text{sampler.lod}_{\min}, \text{shaderOp.lod}_{\min})
\]

\[
\lambda_{\max} = \maxLod
\]

and maxSamplerLodBias is the value of the VkPhysicalDeviceLimits feature 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:

\[
d_l = \begin{cases} 
\text{nearest}(\lambda'), & \text{mipmapMode is VK_SAMPLER_MIPMAP_MODE_NEAREST} \\
\lambda', & \text{otherwise}
\end{cases}
\]

Chapter 15. Image Operations | 557
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 \( d = d_t \).

If the sampler’s \text{mipmapMode} is \text{VK_SAMPLER_MIPMAP_MODE_LINEAR}, two neighboring levels are selected:

\[
\begin{align*}
    d_{hi} &= \lfloor d_t \rfloor \\
    d_{lo} &= \min(d_{hi} + 1, q) \\
    \delta &= d_t - d_{hi}
\end{align*}
\]

\( \delta \) is the fractional value, quantized to the number of \text{mipmap precision bits}, used for \text{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 \text{filtering} (either \( d \), or \( d_{hi} \) and \( d_{lo} \)).

\[
\begin{align*}
    u(x, y) &= (x, y) \times \text{width}_{\text{scale}} + \Delta_i \\
    v(x, y) &= \begin{cases} 
0 & \text{for 1D images} \\
    t(x, y) \times \text{height}_{\text{scale}} + \Delta_j & \text{otherwise}
\end{cases} \\
    w(x, y) &= \begin{cases} 
0 & \text{for 2D or Cube images} \\
    r(x, y) \times \text{depth}_{\text{scale}} + \Delta_k & \text{otherwise}
\end{cases} \\
    a(x, y) &= \begin{cases} 
\bar{a}(x, y) & \text{for array images} \\
0 & \text{otherwise}
\end{cases}
\end{align*}
\]

where:

\[
\begin{align*}
    \text{width}_{\text{scale}} &= \text{width}_{\text{level}} \\
    \text{height}_{\text{scale}} &= \text{height}_{\text{level}} \\
    \text{depth}_{\text{scale}} &= \text{depth}_{\text{level}}
\end{align*}
\]

and where \((\Delta_i, \Delta_j, \Delta_k)\) are taken from the image instruction if it includes a \text{ConstOffset} or \text{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:

\[ l = \text{clamp}(RNE(a), 0, \text{layerCount} - 1) + \text{baseArrayLayer} \]

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:

\[ RNE(a) = \begin{cases} \text{roundTiesToEven}(a) & \text{preferred, from IEEE Std 754-2008 Floating-Point Arithmetic} \\ \lfloor a + 0.5 \rfloor & \text{alternative} \end{cases} \]

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:
\[
frac{x}{x} = x - \lfloor x \rfloor
\]

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:

\[
d = \text{level}_{\text{base}} + \begin{cases} 
\text{Lod} & \text{(from optional SPIR-V operand)} \\
0 & \text{otherwise}
\end{cases}
\]

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 `VK_FILTER_NEAREST` is used within a mip level then `VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE` is used, and if `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 `addressModeU` parameter of the sampler.

\[
i = \begin{cases} 
\text{\(i \mod size\)} & \text{for repeat} \\
(\text{\(size - 1\)} - \text{mirror (\((i \mod (2 \times size)) - size)\)}) \text{ clamp } (i, 0, size - 1) & \text{for mirrored repeat} \\
\text{clamp (\(i, -1, size\))} & \text{for clamp to edge} \\
\text{clamp (mirror (\(i, 0, size - 1\)))} & \text{for clamp to border} \\
\text{clamp (mirror (\(i\), 0, size - 1)))} & \text{for mirror clamp to edge}
\end{cases}
\]

where:

\[
\text{mirror (n)} = \begin{cases} 
n & \text{for } n \geq 0 \\
-(1 + n) & \text{otherwise}
\end{cases}
\]

\(j\) (for 2D and Cube image) and \(k\) (for 3D image) are similarly transformed based on the `addressModeV` and `addressModeW` parameters of the sampler, respectively.

#### 15.8.2. Texel Gathering

SPIR-V instructions with `Gather` in the name return a vector derived from 4 texels in the base level of the image view. The rules for the `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 Component value in the instruction from the swizzled color value of the four texels. If the operation does not use the ConstOffsets image operand then the four texels form the 2 × 2 rectangle used for texture filtering:

\[
\begin{align*}
\tau[R] &= \tau[i_0j_0\text{level}_\text{base}][\text{comp}] \\
\tau[G] &= \tau[i_1j_1\text{level}_\text{base}][\text{comp}] \\
\tau[B] &= \tau[i_2j_0\text{level}_\text{base}][\text{comp}] \\
\tau[A] &= \tau[i_2j_0\text{level}_\text{base}][\text{comp}]
\end{align*}
\]

If the operation does use the ConstOffsets image operand then the offsets allow a custom filter to be defined:

\[
\begin{align*}
\tau[R] &= \tau[i_0j_0 + \Delta_i\text{level}_\text{base}][\text{comp}] \\
\tau[G] &= \tau[i_0j_0 + \Delta_i\text{level}_\text{base}][\text{comp}] \\
\tau[B] &= \tau[i_0j_0 + \Delta_2\text{level}_\text{base}][\text{comp}] \\
\tau[A] &= \tau[i_0j_0 + \Delta_3\text{level}_\text{base}][\text{comp}]
\end{align*}
\]

where:

\[
\tau[\text{level}_\text{base}][\text{comp}] = \begin{cases} 
\tau[\text{level}_\text{base}][R], & \text{for comp} = 0 \\
\tau[\text{level}_\text{base}][G], & \text{for comp} = 1 \\
\tau[\text{level}_\text{base}][B], & \text{for comp} = 2 \\
\tau[\text{level}_\text{base}][A], & \text{for comp} = 3
\end{cases}
\]

\(\text{comp from SPIR-V operand Component}\)

\textbf{OpImage*Gather must not be used on a sampled image with sampler YC}_{\text{C}}\text{C}_{\text{Y}}\text{ conversion enabled.}

\section*{15.8.3. Texel Filtering}

Texel filtering is first performed for each level (either d or d_{hi} and d_{lo}).

If \(\lambda\) is less than or equal to zero, the texture is said to be \textit{magnified}, and the filter mode within a mip level is selected by the \texttt{magFilter} in the sampler. If \(\lambda\) is greater than zero, the texture is said to be \textit{minified}, and the filter mode within a mip level is selected by the \texttt{minFilter} in the sampler.

\textbf{Texel Nearest Filtering}

Within a mip level, \texttt{VK_FILTER_NEAREST} filtering selects a single value using the (i, j, k) texel coordinates, with all texels taken from layer \(l\).

\[
\tau[\text{level}] = \begin{cases} 
\tau[i,j,k][\text{level}], & \text{for 3D image} \\
\tau[i,j][\text{level}], & \text{for 2D or Cube image} \\
\tau[i][\text{level}], & \text{for 1D image}
\end{cases}
\]

\textbf{Texel Linear Filtering}

Within a mip level, \texttt{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:
The values of multiple texels, together with their weights, are combined to produce a filtered value.

The `VkSamplerReductionModeCreateInfo::reductionMode` can control the process by which multiple texels, together with their weights, are combined to produce a filtered texture value.

When the `reductionMode` is set (explicitly or implicitly) to `VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE`, a weighted average is computed:

\[
\tau_{3D} = \sum_{k = k_0}^{k_1} \sum_{j = j_0}^{j_1} \sum_{i = i_0}^{i_1} (w_j)(w_k)\tau_{ijk}
\]

\[
\tau_{2D} = \sum_{j = j_0}^{j_1} \sum_{i = i_0}^{i_1} (w_j)\tau_{ij}
\]

\[
\tau_{1D} = \sum_{i = i_0}^{i_1} (w_i)\tau_i
\]

However, if the reduction mode is `VK_SAMPLER_REDUCTION_MODE_MIN` or `VK_SAMPLER_REDUCTION_MODE_MAX`, the process operates on the above set of multiple texels, together with their weights, computing a component-wise minimum or maximum, respectively, of the components of the set of texels with non-zero weights.

**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 weights, are combined to produce a final filtered value.

The `VkSamplerReductionModeCreateInfo::reductionMode` can control the process by which multiple texels, together with their weights, are combined to produce a filtered texture value.

When the `reductionMode` is set (explicitly or implicitly) to `VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE`, a weighted average is computed:

\[
\tau = (w_{hi})\tau[hi] + (w_{lo})\tau[lo]
\]
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.

$$
\tau_{2Daniso} = \frac{1}{N} \sum_{i=1}^{N} \tau_{2D}\left(\left(x - \frac{1}{2} + \frac{i}{N+1}, \left(y - \frac{1}{2} + \frac{i}{N+1}\right)\right)\right),
$$

when $\rho_x > \rho_y$

$$
\tau_{2Daniso} = \frac{1}{N} \sum_{i=1}^{N} \tau_{2D}\left(\left(x, y - \frac{1}{2} + \frac{i}{N+1}\right)\right),
$$

when $\rho_y \geq \rho_x$

When `VkSamplerReductionModeCreateInfo::reductionMode` is set to `VK_SAMPLER_REDUCTION_MODE_WEIGHTED_AVERAGE`, the above summation is used. However, if the reduction mode is `VK_SAMPLER_REDUCTION_MODE_MIN` or `VK_SAMPLER_REDUCTION_MODE_MAX`, the process operates on the above values, together with their weights, computing a component-wise minimum or maximum, respectively, of the components of the values with non-zero weights.

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.

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,                // the logical device that creates the query pool.
    const VkQueryPoolCreateInfo* pCreateInfo,     // a pointer to a VkQueryPoolCreateInfo structure containing the number and type of queries to be managed by the pool.
    const VkAllocationCallbacks* pAllocator,      // controls host memory allocation as described in the Memory Allocation chapter.
    VkQueryPool* pQueryPool);                // a pointer to a VkQueryPool handle in which the resulting query pool object is returned.
```

- `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
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
- `queryCount` must be greater than 0
typedef VkFlags VkQueryPoolCreateFlags;

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

To destroy a query pool, call:

```c
void vkDestroyQueryPool(
    VkDevice device,                  // device is the logical device that destroys the query pool.
    VkQueryPool queryPool,           // queryPool is the query pool 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 `queryPool must` have completed execution
- If `VkAllocationCallbacks` were provided when `queryPool` was created, a compatible set of callbacks `must` be provided here
- If no `VkAllocationCallbacks` were provided when `queryPool` was created, `pAllocator must` be `NULL`

Valid Usage (Implicit)

- `device must` be a valid `VkDevice` handle
- If `queryPool` is not `VK_NULL_HANDLE`, `queryPool must` be a valid `VkQueryPool` handle
- If `pAllocator` is not `NULL`, `pAllocator must` be a valid pointer to a valid `VkAllocationCallbacks` structure
- If `queryPool` is a valid handle, it `must` have been created, allocated, or retrieved from `device`
Host Synchronization

- Host access to `queryPool` must be externally synchronized

Possible values of `VkQueryPoolCreateInfo::queryType`, specifying the type of queries managed by the pool, are:

```cpp
typedef enum VkQueryType {
    VK_QUERY_TYPE_OCCLUSION = 0,
    VK_QUERY_TYPE_PIPELINE_STATISTICS = 1,
    VK_QUERY_TYPE_TIMESTAMP = 2,
    VK_QUERY_TYPE_MAX_ENUM = 0x7FFFFFFF
} VkQueryType;
```

- `VK_QUERY_TYPE_OCCLUSION` specifies an occlusion query.
- `VK_QUERY_TYPE_PIPELINE_STATISTICS` specifies a pipeline statistics query.
- `VK_QUERY_TYPE_TIMESTAMP` specifies a timestamp 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` or `vkResetQueryPool` 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 `[firstQuery, firstQuery + queryCount - 1]` to unavailable.

**Valid Usage**

- `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`
- All queries used by the command must not be active

**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
- This command must only be called outside of a render pass instance
- 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>
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<td>Primary</td>
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<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

To reset a range of queries in a query pool on the host, call:

```c
void vkResetQueryPool(
    VkDevice device,
    VkQueryPool queryPool,
    uint32_t firstQuery,
    uint32_t queryCount);
```

- `device` is the logical device that owns the query pool.
- `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.

This command sets the status of query indices \([firstQuery, firstQuery + queryCount - 1]\) to unavailable.

Valid Usage

- The `hostQueryReset` feature must be enabled
- `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`
- Submitted commands that refer to the range specified by `firstQuery` and `queryCount` in `queryPool` must have completed execution
- The range of queries specified by `firstQuery` and `queryCount` in `queryPool` must not be in use by calls to `vkGetQueryPoolResults` or `vkResetQueryPool` in other threads
Valid Usage (Implicit)

- `device` must be a valid `VkDevice` handle
- `queryPool` must be a valid `VkQueryPool` handle
- `queryPool` must have been created, allocated, or retrieved from `device`

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.

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 command 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
• If the queryType used to create queryPool was VK_QUERY_TYPE_PIPELINE_STATISTICS and any of the pipelineStatistics indicate compute operations, the VkCommandPool that commandBuffer was allocated from must support compute 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
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

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</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`

### 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

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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.

- 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.

- 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.
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 `vkResetQueryPool` is called or 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 `vkResetQueryPool` is called or the `vkCmdResetQueryPool` command has been executed since the last use of the query.

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.

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 set in **flags** then **pData** and **stride** must be multiples of 8
• 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**

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:
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.

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:

```c
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.

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**

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
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:

```c
typedef enum VkQueryPipelineStatisticFlagBits {
    VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_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`).

```c
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. Timesteps 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.

\texttt{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 \texttt{vkGetQueryPoolResults}. As with other queries, the query must be reset using \texttt{vkCmdResetQueryPool} or \texttt{vkResetQueryPool} before requesting the timestamp value be written to it.

While \texttt{vkCmdWriteTimestamp} can be called inside or outside of a render pass instance, \texttt{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 \texttt{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 \texttt{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 Secondary</td>
<td>Both</td>
<td>Transfer</td>
<td>Transfer</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>
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_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`. 

588 | Chapter 17. Clear Commands
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 YCbCr 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` or `VK_IMAGE_LAYOUT_GENERAL`.
- 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>
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<tr>
<td>Primary</td>
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</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`.
- If any element of `pRanges.aspect` includes `VK_IMAGE_ASPECT_STENCIL_BIT`, and image was created with separate stencil usage, `VK_IMAGE_USAGE_TRANSFER_DST_BIT` **must** have been included in the `VkImageStencilUsageCreateInfo::stencilUsage` used to create image.
- If any element of `pRanges.aspect` includes `VK_IMAGE_ASPECT_STENCIL_BIT`, and image was not created with separate stencil usage, `VK_IMAGE_USAGE_TRANSFER_DST_BIT` **must** have been included in the `VkImageCreateInfo::usage` used to create image.
- If any element of `pRanges.aspect` includes `VK_IMAGE_ASPECT_DEPTH_BIT`, `VK_IMAGE_USAGE_TRANSFER_DST_BIT` **must** have been included in the `VkImageCreateInfo::usage` used to create image.
- 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 `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** 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

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<td>Graphics</td>
<td>Transfer</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:
```c
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`
Values below.

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 host endianness.

`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 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>Graphics</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</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

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<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
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<tr>
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</tr>
<tr>
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<td></td>
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<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 `vkCmdCopyBuffer` and a portion of an image can be copied to another image with `vkCmdCopyImage`. Image data can also be copied to and from buffer memory using `vkCmdCopyImageToBuffer` and `vkCmdCopyBufferToImage`. Image data can be blitted (with or without scaling and filtering) with `vkCmdBlitImage`. Multisampled images can be resolved to a non-multisampled image with `vkCmdResolveImage`.

18.1. Common Operation

The following valid usage rules apply to all copy commands:

- Copy commands must be recorded outside of a render pass instance.
- The set of all bytes bound to all the source regions must not overlap the set of all bytes bound to the destination regions.
- The set of all bytes bound to each destination region must not overlap the set of all bytes bound to another destination region.
- Copy regions must be non-empty.
- Regions must not extend outside the bounds of the buffer or image level, except that regions of compressed images can extend as far as the dimension of the image level rounded up to a complete compressed texel block.
- Source image subresources must be in either the `VK_IMAGE_LAYOUT_GENERAL` or `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` layout. Destination image subresources must be in the `VK_IMAGE_LAYOUT_GENERAL` or `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 must be in the `VK_IMAGE_LAYOUT_GENERAL` layout.
- Source images must have `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT` in their format features.
- Destination images must have `VK_FORMAT_FEATURE_TRANSFER_DST_BIT` in their format features.
- Source buffers must have been created with the `VK_BUFFER_USAGE_TRANSFER_SRC_BIT` usage bit enabled and destination buffers must have been created with the `VK_BUFFER_USAGE_TRANSFER_DST_BIT` usage bit enabled.
- Source images must have been created with `VK_IMAGE_USAGE_TRANSFER_SRC_BIT` set in `VkImageCreateInfo::usage`
- Destination images must have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` set in `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,  // commandBuffer is the command buffer into which the command will be recorded.
    VkBuffer srcBuffer,             // srcBuffer is the source buffer.
    VkBuffer dstBuffer,             // dstBuffer is the destination buffer.
    uint32_t regionCount,           // regionCount is the number of regions to copy.
    const VkBufferCopy* pRegions);  // 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`.
**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, Graphics, Compute</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></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_B8G8R8_2PLANE_420_UNORM** image is compatible with an image of format **VK_FORMAT_B8G8_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 unformatted 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 `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 the image or *disjoint* plane to be copied **must** be bound completely and contiguously to a single `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 `VkDevice`.

- `srcImageLayout` **must** be `VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`.

- The **format features** of `dstImage` **must** contain `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`.

- `dstImage` **must** have been created with `VK_IMAGE_USAGE_TRANSFER_DST_BIT` usage flag.

- If `dstImage` is non-sparse then the image or *disjoint* plane that is the destination of the copy **must** be bound completely and contiguously to a single `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 `VkDevice`.

- `dstImageLayout` **must** be `VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`.

- If the `VkFormat` of each of `srcImage` and `dstImage` is not a *multi-planar format*, the `VkFormat` of each of `srcImage` and `dstImage` **must** be compatible, as defined above.

- In a copy to or from a plane of a *multi-planar image*, the `VkFormat` of the image and plane **must** be compatible according to the description of compatible planes for the plane being copied.

- The sample count of `srcImage` and `dstImage` **must** match.

- 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.
when \textit{dstImage} was created

- The \textit{srcOffset} and \textit{extent} members of each element of \textit{pRegions} must respect the image transfer granularity requirements of \textit{commandBuffer}’s command pool’s queue family, as described in \textit{VkQueueFamilyProperties}
- The \textit{dstOffset} and \textit{extent} members of each element of \textit{pRegions} must respect the image transfer granularity requirements of \textit{commandBuffer}’s command pool’s queue family, as described in \textit{VkQueueFamilyProperties}

### Valid Usage (Implicit)

- \textit{commandBuffer} must be a valid \texttt{VkCommandBuffer} handle
- \textit{srcImage} must be a valid \texttt{VkImage} handle
- \textit{srcImageLayout} must be a valid \texttt{VkImageLayout} value
- \textit{dstImage} must be a valid \texttt{VkImage} handle
- \textit{dstImageLayout} must be a valid \texttt{VkImageLayout} value
- \textit{pRegions} must be a valid pointer to an array of \textit{regionCount} valid \texttt{VkImageCopy} structures
- \textit{commandBuffer} must be in the recording state
- The \texttt{VkCommandPool} that \textit{commandBuffer} was allocated from must support transfer, graphics, or compute operations
- This command must only be called outside of a render pass instance
- \textit{regionCount} must be greater than 0
- Each of \textit{commandBuffer}, \textit{dstImage}, and \textit{srcImage} must have been created, allocated, or retrieved from the same \texttt{VkDevice}

### Host Synchronization

- Host access to \textit{commandBuffer} must be externally synchronized
- Host access to the \texttt{VkCommandPool} that \textit{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 Graphics</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td>Compute</td>
<td></td>
</tr>
</tbody>
</table>

The \texttt{VkImageCopy} structure is defined as:
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 \( \text{extent.depth} \) must be 1.

- If the calling command's dstImage is of type \( \text{VK_IMAGE_TYPE_1D} \), then \( \text{dstOffset.z} \) must be 0 and \( \text{extent.depth} \) must be 1.

- If the calling command's srcImage is of type \( \text{VK_IMAGE_TYPE_2D} \), then \( \text{srcOffset.z} \) must be 0.

- If the calling command's dstImage is of type \( \text{VK_IMAGE_TYPE_2D} \), then \( \text{dstOffset.z} \) must be 0.

- If both srcImage and dstImage are of type \( \text{VK_IMAGE_TYPE_2D} \) then \( \text{extent.depth} \) must be 1.

- If the calling command's srcImage is of type \( \text{VK_IMAGE_TYPE_2D} \), and the dstImage is of type \( \text{VK_IMAGE_TYPE_3D} \), then \( \text{extent.depth} \) must equal to the layerCount member of srcSubresource.

- If the calling command's dstImage is of type \( \text{VK_IMAGE_TYPE_2D} \), and the srcImage is of type \( \text{VK_IMAGE_TYPE_3D} \), then \( \text{extent.depth} \) must equal to the layerCount member of dstSubresource.

- \( \text{dstOffset.x} \) and \( (\text{extent.width} + \text{dstOffset.x}) \) must both be greater than or equal to 0 and less than or equal to the destination image subresource width

- \( \text{dstOffset.y} \) and \( (\text{extent.height} + \text{dstOffset.y}) \) 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 \( \text{VK_IMAGE_TYPE_1D} \), then \( \text{dstOffset.y} \) must be 0 and \( \text{extent.height} \) must be 1.

- \( \text{dstOffset.z} \) and \( (\text{extent.depth} + \text{dstOffset.z}) \) 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 srcImage is a compressed image, or a single-plane, “.422” image format, all members of srcOffset must be a multiple of the corresponding dimensions of the compressed texel block

- If the calling command's srcImage is a compressed image, or a single-plane, “.422” image format, \( \text{extent.width} \) must be a multiple of the compressed texel block width or \( (\text{extent.width} + \text{srcOffset.x}) \) must equal the source image subresource width

- If the calling command's srcImage is a compressed image, or a single-plane, “.422” image format, \( \text{extent.height} \) must be a multiple of the compressed texel block height or \( (\text{extent.height} + \text{srcOffset.y}) \) must equal the source image subresource height

- If the calling command's srcImage is a compressed image, or a single-plane, “.422” image format, \( \text{extent.depth} \) must be a multiple of the compressed texel block depth or \( (\text{extent.depth} + \text{srcOffset.z}) \) must equal the source image subresource depth

- If the calling command's dstImage is a compressed format image, or a single-plane, “.422” image format, all members of dstOffset must be a multiple of the corresponding dimensions of the compressed texel block

- If the calling command's dstImage is a compressed format image, or a single-plane, “.422” image format, \( \text{extent.width} \) must be a multiple of the compressed texel block width or \( (\text{extent.width} + \text{dstOffset.x}) \) must equal the destination image subresource width

- If the calling command's dstImage is a compressed format image, or a single-plane, “.422” image format, \( \text{extent.height} \) must be a multiple of the compressed texel block height or \( (\text{extent.height} + \text{dstOffset.y}) \) 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:

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* or *VK_IMAGE_LAYOUT_GENERAL*

- 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 *mipLevels* 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_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`.
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

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<tr>
<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
<th>Supported Queue Types</th>
<th>Pipeline Type</th>
</tr>
</thead>
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<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></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, bufferOffsetHeight 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,
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’sVkImage 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 blockcompressed 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:

```cpp
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:

  \[
  u_{\text{offset}} = u_{\text{base}} - x_{\text{dst0}} \\
  v_{\text{offset}} = v_{\text{base}} - y_{\text{dst0}} \\
  w_{\text{offset}} = w_{\text{base}} - z_{\text{dst0}} \\
  a_{\text{offset}} = a - \text{baseArrayCount}_{\text{dst}}
  \]
The scale is determined from the source and destination regions, and applied to the offset coordinates:

$$\text{scale}_u = \frac{x_{\text{src}1} - x_{\text{src}0}}{x_{\text{dst}1} - x_{\text{dst}0}}$$

$$\text{scale}_v = \frac{y_{\text{src}1} - y_{\text{src}0}}{y_{\text{dst}1} - y_{\text{dst}0}}$$

$$\text{scale}_w = \frac{z_{\text{src}1} - z_{\text{src}0}}{z_{\text{dst}1} - z_{\text{dst}0}}$$

$$u_{\text{scaled}} = u_{\text{offset}} \times \text{scale}_u$$

$$v_{\text{scaled}} = v_{\text{offset}} \times \text{scale}_v$$

$$w_{\text{scaled}} = w_{\text{offset}} \times \text{scale}_w$$

Finally the source offset is added to the scaled coordinates, to determine the final unnormalized coordinates used to sample from $\text{srcImage}$:

$$u = u_{\text{scaled}} + x_{\text{src}0}$$

$$v = v_{\text{scaled}} + y_{\text{src}0}$$

$$w = w_{\text{scaled}} + z_{\text{src}0}$$

$$q = \text{mipLevel}$$

$$a = a_{\text{offset}} + \text{baseArrayCount}_{\text{src}}$$

These coordinates are used to sample from the source image, as described in Image Operations chapter, with the filter mode equal to that of $\text{filter}$, a mipmap mode of $\text{VK_SAMPLER_MIPMAP_MODE_NEAREST}$ and an address mode of $\text{VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE}$. Implementations must clamp at the edge of the source image, and may additionally clamp to the edge of the source region.

**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 $\text{baseArrayLayer}$ member of $\text{srcSubresource}$ for the source and $\text{dstSubresource}$ for the destination. $\text{layerCount}$ layers are blitted to the destination image.

3D textures are blitted slice by slice. Slices in the source region bounded by $\text{srcOffsets}[0].z$ and $\text{srcOffsets}[1].z$ are copied to slices in the destination region bounded by $\text{dstOffsets}[0].z$ and $\text{dstOffsets}[1].z$. For each destination slice, a source $z$ coordinate is linearly interpolated between $\text{srcOffsets}[0].z$ and $\text{srcOffsets}[1].z$. If the $\text{filter}$ parameter is $\text{VK_FILTER_LINEAR}$ then the value
sampled from the source image is taken by doing linear filtering using the interpolated \( z \) coordinate. If \texttt{filter} parameter is \texttt{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 \texttt{can} only be converted to other integer formats with the same signedness.
- No format conversion is supported between depth/stencil images. The formats \texttt{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 `VK_FORMAT_FEATURE_BLIT_SRC_BIT`.
- `srcImage` must not use a format listed in Formats requiring sampler YCbCr conversion for `VK_IMAGE_ASPECT_COLOR_BIT` image views.
- `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.
- `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_TRANSFER_SRC_OPTIMAL` or `VK_IMAGE_LAYOUT_GENERAL`.
- The format features of `dstImage` must contain `VK_FORMAT_FEATURE_BLIT_DST_BIT`.
- `dstImage` must not use a format listed in Formats requiring sampler YCbCr conversion for `VK_IMAGE_ASPECT_COLOR_BIT` image views.
- `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.
- `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` or `VK_IMAGE_LAYOUT_GENERAL`.
- If either of `srcImage` or `dstImage` was created with a signed integer `VkFormat`, the other must also have been created with a signed integer `VkFormat`.
- If either of `srcImage` or `dstImage` was created with an unsigned integer `VkFormat`, the other must also have been created with an unsigned integer `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, `filter` must be `VK_FILTER_NEAREST`.
- `srcImage` must have been created with a `samples` value of `VK_SAMPLE_COUNT_1_BIT`.
- `dstImage` must have been created with a `samples` value of `VK_SAMPLE_COUNT_1_BIT`.
- If `filter` is `VK_FILTER_LINEAR`, then the format features of `srcImage` must contain `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
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.
```

- `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 resolve.
- `dstImage` is the destination image.
- `dstImageLayout` is the layout of the destination image subresources for the resolve.
- `regionCount` is the number of regions to resolve.
- `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_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_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>Outside</td>
<td>Graphics</td>
<td>Transfer</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The `VkImageResolve` structure is defined as:

```c
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**, 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`:

```cpp
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

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:
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:

<p>| ● | Vertex | A point in 3-dimensional space. Positions chosen within the diagrams are arbitrary and for illustration only. |
| 5 | Vertex Number | Sequence position of a vertex within the provided vertex data. |
| ● | Provoking Vertex | Provoking vertex within the main primitive. The arrow points along an edge of the relevant primitive, following winding order. Used in flat shading. |</p>
<table>
<thead>
<tr>
<th>Edge</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primitive</td>
<td>An edge connecting the points of a main primitive.</td>
</tr>
<tr>
<td>Adjacency</td>
<td>Points connected by these lines do not contribute to a main primitive, and</td>
</tr>
<tr>
<td>Edge</td>
<td>are only accessible in a geometry shader.</td>
</tr>
<tr>
<td>Winding</td>
<td>The relative order in which vertices are defined within a primitive, used</td>
</tr>
<tr>
<td>Order</td>
<td>in the facing determination. This ordering has no specific start or end</td>
</tr>
<tr>
<td></td>
<td>point.</td>
</tr>
</tbody>
</table>

The diagrams are supported with mathematical definitions where the vertices (v) and primitives (p) are numbered starting from 0; v₀ is the first vertex in the provided data and p₀ 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`.

```
0 4
2
1
3
```

### 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 \( \lfloor \text{vertexCount}/2 \rfloor \).

```
0 1
2 3
```

### 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:

```
0 1
2 3
```
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 \( \text{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST} \), 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 \( \left\lfloor \frac{\text{vertexCount}}{3} \right\rfloor \).

19.1.5. Triangle Strips

When the topology is \( \text{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP} \), 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 \( \text{VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN} \), 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 $\max(0, \text{vertexCount}-2)$.

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:

$$p_i = \{v_{4i}, v_{4i+1}, v_{4i+2}, v_{4i+3}\}$$

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 $\text{vertexCount}/4$.

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:

$$p_i = \{v_i, v_{i+1}, v_{i+2}, v_{i+3}\}$$

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 $\max(0, \text{vertexCount}-3)$.

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:

$$p_i = \{v_{6i}, v_{6i+1}, v_{6i+2}, v_{6i+3}, v_{6i+4}, v_{6i+5}\}$$
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 \( \lfloor \text{vertexCount}/6 \rfloor \).

![Diagram of triangle with vertices labeled 0 to 9]

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:

\[
p = \{v_0, v_1, v_2, v_3, v_4, v_5\}
\]

If \( n>1 \), the total primitive consists of different vertices according to where it is in the strip:

\[
p_i = \{v_{2i}, v_{2i+1}, v_{2i+2}, v_{2i+4}, v_{2i+3}\} \quad \text{when } i=0
\]

\[
p_i = \{v_{2i}, v_{2i+3}, v_{2i+4}, v_{2i+6}, v_{2i+2}, v_{2i+3}\} \quad \text{when } i>0, i<n-1, \text{ and } i\%2=1
\]

\[
p_i = \{v_{2i}, v_{2i+2}, v_{2i+3}, v_{2i+4}, v_{2i+6}, v_{2i+3}\} \quad \text{when } i>0, i<n-1, \text{ and } i\%2=0
\]

\[
p_i = \{v_{2i}, v_{2i+3}, v_{2i+4}, v_{2i+5}, v_{2i+2}, v_{2i+3}\} \quad \text{when } i=n-1 \text{ and } i\%2=1
\]

\[
p_i = \{v_{2i}, v_{2i+2}, v_{2i+3}, v_{2i+4}, v_{2i+5}, v_{2i+3}\} \quad \text{when } i=n-1 \text{ and } i\%2=0
\]

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 \( \lfloor \frac{\text{vertexCount}}{m} \rfloor \).

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 `vertexIndex` to a higher numbered `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 `tessellation`.

6. If geometry shading is active, by the order new primitives are generated by `geometry shading`.

7. If the `polygon mode` is not `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 `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 `vertexIndex` and the `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 `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 `vertexIndex`, as well as binding vertex buffers containing those attributes to a command buffer). These commands are:
  - `vkCmdDraw`
  - `vkCmdDrawIndirect`
  - `vkCmdDrawIndirectCount`

- Indexed drawing commands read index values from an `index buffer` and use this to compute the `vertexIndex` value for the vertex shader. These commands are:
  - `vkCmdDrawIndexed`
  - `vkCmdDrawIndexedIndirect`
To bind an index buffer to a command buffer, call:

```c
void vkCmdBindIndexBuffer(
    VkCommandBuffer                             commandBuffer,  // commandBuffer is the command buffer into which the command is recorded.
    VkBuffer                                    buffer,           // buffer is the buffer being bound.
    VkDeviceSize                                offset,          // offset is the starting offset in bytes within buffer used in index buffer address calculations.
    VkIndexType                                 indexType);      // 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

**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:

```plaintext
typedef enum VkIndexType {
    VK_INDEX_TYPE_UINT16 = 0,
    VK_INDEX_TYPE_UINT32 = 1,
    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.

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>
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<td></td>
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</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.

(indexSize * (firstIndex + indexCount) + 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>
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<tr>
<td>Secondary</td>
<td></td>
<td></td>
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</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>
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</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:

```cpp
void vkCmdDrawIndirectCount(
    VkCommandBuffer commandBuffer,  // commandBuffer is the command buffer into which the command is recorded.
    VkBuffer buffer,                // buffer is the buffer containing draw parameters.
    VkDeviceSize offset,            // offset is the byte offset into buffer where parameters begin.
    VkBuffer countBuffer,           // countBuffer is the buffer containing the draw count.
    VkDeviceSize countBufferOffset, // countBufferOffset is the byte offset into countBuffer where the draw count begins.
    uint32_t maxDrawCount,          // 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.
    uint32_t stride)                // 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*))
must be less than or equal to the size of buffer

- If the count stored in countBuffer is greater than 1, \((\text{stride} \times (\text{drawCount} - 1) + \text{offset} + \text{sizeof(VkDrawIndirectCommand)))\) must be less than or equal to the size of buffer
- If drawIndirectCount is not enabled this function must not be used

### 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>
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</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.

• If drawIndirectCount is not enabled this function must not be used.
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 \text{indexType}, where the index buffer, \text{indexType}, and \text{offset} are specified via `vkCmdBindIndexBuffer`.
- If the drawIndirectFirst Instance feature is not enabled, \text{firstInstance} must be 0.

To record an indexed draw call with a draw call count sourced from a buffer, call:

```c
void vkCmdDrawIndexedIndirectCount(
    VkCommandBuffer commandBuffer,
    VkBuffer buffer,
    VkDeviceSize offset,
    VkBuffer countBuffer,
    VkDeviceSize countBufferOffset,
    uint32_t maxDrawCount,
    uint32_t stride);
```

- \text{commandBuffer} is the command buffer into which the command is recorded.
- \text{buffer} is the buffer containing draw parameters.
- \text{offset} is the byte offset into \text{buffer} where parameters begin.
- \text{countBuffer} is the buffer containing the draw count.
- \text{countBufferOffset} is the byte offset into \text{countBuffer} where the draw count begins.
- \text{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 \text{countBuffer} and \text{maxDrawCount}.
- \text{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 \text{countBuffer} located at \text{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, **(stride × (maxDrawCount - 1) + offset + sizeof(VkDrawIndexedIndirectCommand))** **must** be less than or equal to the size of **buffer**.

• If count stored in **countBuffer** is equal to 1, **(offset + sizeof(VkDrawIndexedIndirectCommand))**
**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>
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<td>Graphics</td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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`
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**

```
// 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 20. Input attribute components accessed by 32-bit input variables
<table>
<thead>
<tr>
<th>32-bit data type</th>
<th>Component decoration</th>
<th>Components consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>scalar</td>
<td>0 or unspecified</td>
<td>(x, o, o, o)</td>
</tr>
<tr>
<td>scalar</td>
<td>1</td>
<td>(o, y, o, o)</td>
</tr>
<tr>
<td>scalar</td>
<td>2</td>
<td>(o, o, z, o)</td>
</tr>
<tr>
<td>scalar</td>
<td>3</td>
<td>(o, o, o, w)</td>
</tr>
<tr>
<td>two-component vector</td>
<td>0 or unspecified</td>
<td>(x, y, o, o)</td>
</tr>
<tr>
<td>two-component vector</td>
<td>1</td>
<td>(o, y, z, o)</td>
</tr>
<tr>
<td>two-component vector</td>
<td>2</td>
<td>(o, o, z, w)</td>
</tr>
<tr>
<td>three-component vector</td>
<td>0 or unspecified</td>
<td>(x, y, z, o)</td>
</tr>
<tr>
<td>three-component vector</td>
<td>1</td>
<td>(o, y, z, w)</td>
</tr>
<tr>
<td>four-component vector</td>
<td>0 or unspecified</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, 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 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 21. 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>
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 \texttt{VkVertexInputAttributeDescription::location}. The locations and components used depend on the type of variable and the \texttt{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 22. 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 component 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>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, o, z, w)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w)</td>
<td></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),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(o, o, -, -)</td>
</tr>
<tr>
<td></td>
<td>scalar</td>
<td>i</td>
<td>2</td>
<td>(o, o, z, w),</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(o, o, -, -)</td>
</tr>
<tr>
<td></td>
<td>scalar</td>
<td>i+1</td>
<td>0 or unspecified</td>
<td>(o, o, o, o),</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(x, y, -, -)</td>
</tr>
<tr>
<td></td>
<td>two-component vector</td>
<td>i</td>
<td>0 or unspecified</td>
<td>(x, y, z, w),</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(o, o, -, -)</td>
</tr>
<tr>
<td></td>
<td>three-component vector</td>
<td>i</td>
<td>unspecified</td>
<td>(x, y, z, w),</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(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), (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, 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), (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), (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), (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), (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), (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), (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

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:

define 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 `firstBinding + i`, for `i` in `[0, 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)

- \texttt{commandBuffer} must be a valid \texttt{VkCommandBuffer} handle
- \texttt{pBuffers} must be a valid pointer to an array of \texttt{bindingCount} valid \texttt{VkBuffer} handles
- \texttt{pOffsets} must be a valid pointer to an array of \texttt{bindingCount} \texttt{VkDeviceSize} values
- \texttt{commandBuffer} must be in the \texttt{recording} state
- The \texttt{VkCommandPool} that \texttt{commandBuffer} was allocated from must support graphics operations
- \texttt{bindingCount} must be greater than 0
- Both of \texttt{commandBuffer}, and the elements of \texttt{pBuffers} 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

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 \texttt{vertexIndex} and \texttt{instanceIndex} is calculated as follows:

- Let \texttt{attribDesc} be the member of \texttt{VkPipelineVertexInputStateCreateInfo} ::\texttt{pVertexAttributeDescriptions} with \texttt{VkVertexInputAttributeDescription::location} equal to the vertex input attribute number.
- Let \texttt{bindingDesc} be the member of \texttt{VkPipelineVertexInputStateCreateInfo} ::\texttt{pVertexBindingDescriptions} with \texttt{VkVertexInputAttributeDescription::binding} equal to \texttt{attribDesc.binding}.
- Let \texttt{vertexIndex} be the index of the vertex within the draw (a value between \texttt{firstVertex} and \texttt{firstVertex+vertexCount} for \texttt{vkCmdDraw}, or a value taken from the index buffer for \texttt{vkCmdDrawIndexed}), and let \texttt{instanceIndex} be the instance number of the draw (a value between \texttt{firstInstance} and \texttt{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** `TessLevelOuter` and `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 **OpExecutionMode** instruction in the tessellation evaluation or tessellation control shader using one of execution modes **Triangles**, **Quads**, and **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:

- **Triangles**, **Quads**, and **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.
- **VertexOrderCw** and **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.
- **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.
- **SpacingEqual**, **SpacingFractionalEven**, and **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.
- **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 `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.

**Figure 11.** Domain parameterization for tessellation primitive modes (upper-left origin)

**Figure 12.** Domain parameterization for tessellation primitive modes (lower-left origin)
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 NaN (not a number) in implementations supporting NaN.

No new primitives are generated and the tessellation evaluation shader is not executed for patches that are discarded. For **Quads**, all four outer levels are relevant. For **Triangles** and **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 `OpExecutionMode` in the tessellation control or tessellation evaluation shader using one of the identifiers `SpacingEqual`, `SpacingFractionalEven`, or `SpacingFractionalOdd`.

If `SpacingEqual` is used, the floating-point tessellation level is first clamped to \([1, \text{maxLevel}]\), where `maxLevel` is the implementation-dependent maximum tessellation level (`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 `SpacingFractionalEven` is used, the tessellation level is first clamped to \([2, \text{maxLevel}]\) and then rounded up to the nearest even integer \(n\). If `SpacingFractionalOdd` is used, the tessellation level is clamped to \([1, \text{maxLevel} - 1]\) 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 **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 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 \( i \)th 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.

\[
\text{a} = u_0 v_1 - u_1 v_0 + u_1 v_2 - u_2 v_1 + u_2 v_0 - u_0 v_2
\]

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 \( i \)th 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-url)
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)

**Figure 14. Inner Quad Tessellation**

**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 \text{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;
```

- `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_MAX_ENUM = 0x7FFFFFFF
} VkTessellationDomainOrigin;
```

- `VK_TESSELLATION_DOMAIN_ORIGIN_UPPER_LEFT` specifies that the origin of the domain space is in the upper left corner, as shown in figure Domain parameterization for tessellation primitive modes (upper-left origin).
- `VK_TESSELLATION_DOMAIN_ORIGIN_LOWER_LEFT` specifies that the origin of the domain space is in the lower left corner, as shown in figure Domain parameterization for tessellation primitive modes (lower-left origin).

This enum affects how the `VertexOrderCw` and `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 `OpExecutionMode` instruction in the geometry shader, and **must** match the incoming primitive type specified by either the pipeline's **primitive topology** if tessellation is inactive, or the **tessellation mode** if tessellation is active, as follows:

- An input primitive type of **InputPoints** **must** only be used with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_POINT_LIST`, or with a tessellation shader that specifies `PointMode`. The input arrays always contain one element, as described by the **point list topology** or **tessellation in point mode**.

- An input primitive type of **InputLines** **must** only be used with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_LINE_LIST` or `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP`, or with a tessellation shader specifying **Isolines** that does not specify `PointMode`. The input arrays always contain two elements, as described by the **line list topology** or **line strip topology**, or by **isoline tessellation**.

- An input primitive type of **InputLinesAdjacency** **must** only be used when tessellation is inactive, with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY` or `VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY`. The input arrays always contain four elements, as described by the **line list with adjacency topology** or **line strip with adjacency topology**.

- An input primitive type of **Triangles** **must** only be used with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST`, `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP`, or `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN`; or with a tessellation shader specifying **Quads** or **Triangles** that does not specify `PointMode`. The input arrays always contain three elements, as described by the **triangle list topology**, **triangle strip topology**, or **triangle fan topology**, or by **triangle or quad tessellation**. Vertices **may** be in a different absolute order to that specified by the topology, but **must** adhere to the specified winding order.

- An input primitive type of **InputTrianglesAdjacency** **must** only be used when tessellation is inactive, with a pipeline topology of `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY` or `VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY`. The input arrays always contain six elements, as described by the **triangle list with adjacency topology** or **triangle strip with adjacency topology**. Vertices **may** be in a different absolute order to that specified by the topology, but **must** adhere to the specified winding order, and the vertices making up the main primitive **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 `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 `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 `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 `ClipDistance` and `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 `depthClampEnable` enable of the `VkPipelineRasterizationStateCreateInfo` structure. Depth clipping is disabled when `depthClampEnable` is `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 `VkPhysicalDevicePointClippingProperties::pointClippingBehavior`, specifying clipping behavior of a point primitive whose vertex lies outside the clip volume, are:

```c
typedef enum VkPointClippingBehavior {
    VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIP_PLANES = 0,
    VK_POINT_CLIPPING_BEHAVIOR_USER_CLIP_PLANES_ONLY = 1,
    VK_POINT_CLIPPING_BEHAVIOR_MAX_ENUM = 0x7FFFFFFF
} VkPointClippingBehavior;
```

- **VK_POINT_CLIPPING_BEHAVIOR_ALL_CLIP_PLANES** 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_CLIP_PLANES_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 \(w_0\), 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

\[
\begin{pmatrix}
x_d \\
y_d \\
z_d
\end{pmatrix} = \begin{pmatrix}
x_c \\
y_c \\
z_c
\end{pmatrix}
\]

### 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 min and 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

\[
\begin{align*}
x_f &= (p_x / 2) \times_d + o_x \\
y_f &= (p_y / 2) \times_d + o_y \\
z_f &= p_z \times_d + o_z
\end{align*}
\]

Multiple viewports are available, numbered zero up to `VkPhysicalDeviceLimits::maxViewports` minus one. The number of viewports used by a pipeline is controlled by the `viewportCount` member of the `VkPipelineViewportStateCreateInfo` structure used in pipeline creation.
The `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;
```

- `sType` is the type of this structure.
- `pNext` is `NULL` or a pointer to an extension-specific structure.
- `flags` is reserved for future use.
- `viewportCount` is the number of viewports used by the pipeline.
- `pViewports` is a pointer to an array of `VkViewport` structures, defining the viewport transforms. If the viewport state is dynamic, this member is ignored.
- `scissorCount` is the number of `scissors` and **must** match the number of viewports.
- `pScissors` is a pointer to an array of `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.

A *vertex processing stage* can direct each primitive to one of several viewports. The destination viewport for a primitive is selected by the last active vertex processing stage that has an output variable decorated with `ViewportIndex`. The viewport transform uses the viewport corresponding to the value assigned to `ViewportIndex`, and 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 last active vertex processing stage 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 the last vertex processing stage 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 `pViewports` member of `VkPipelineViewportStateCreateInfo` in the pipeline state object. If the pipeline state object was created with the `VK_DYNAMIC_STATE_VIEWPORT` dynamic state enabled, the viewport transformation parameters are dynamically set and changed with the command:

```c
void vkCmdSetViewport(
    VkCommandBuffer                             commandBuffer,
    uint32_t                                    firstViewport,
    uint32_t                                    viewportCount,
    const VkViewport*                           pViewports);
```

- **commandBuffer** is the command buffer into which the command will be recorded.
- **firstViewport** is the index of the first viewport whose parameters are updated by the command.
- **viewportCount** is the number of viewports whose parameters are updated by the command.
- **pViewports** is a pointer to an array of `VkViewport` structures specifying viewport parameters.
The viewport parameters taken from element \( i \) of \( p\text{Viewports} \) replace the current state for the viewport index \( \text{firstViewport} + i \), for \( i \) in \( [0, \text{viewportCount}) \).

### Valid Usage

- \( \text{firstViewport} \) must be less than \( \text{VkPhysicalDeviceLimits}::\text{maxViewports} \)
- The sum of \( \text{firstViewport} \) and \( \text{viewportCount} \) must be between \( 1 \) and \( \text{VkPhysicalDeviceLimits}::\text{maxViewports} \), inclusive
- If the multiple viewports feature is not enabled, \( \text{firstViewport} \) must be \( 0 \)
- If the multiple viewports feature is not enabled, \( \text{viewportCount} \) must be \( 1 \)

### Valid Usage (Implicit)

- \( \text{commandBuffer} \) must be a valid \( \text{VkCommandBuffer} \) handle
- \( \text{pViewports} \) must be a valid pointer to an array of \( \text{viewportCount} \) valid \( \text{VkViewport} \) structures
- \( \text{commandBuffer} \) must be in the recording state
- The \( \text{VkCommandPool} \) that \( \text{commandBuffer} \) was allocated from must support graphics operations
- \( \text{viewportCount} \) must be greater than \( 0 \)

### Host Synchronization

- Host access to \( \text{commandBuffer} \) must be externally synchronized
- Host access to the \( \text{VkCommandPool} \) that \( \text{commandBuffer} \) 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>Both</td>
<td>Graphics</td>
<td></td>
</tr>
</tbody>
</table>

Both \( \text{VkPipelineViewportStateCreateInfo} \) and \( \text{vkCmdSetViewport} \) use \( \text{VkViewport} \) to set the viewport transformation parameters.

The \( \text{VkViewport} \) structure is defined as:
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 \( z \), 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 \( k \in \{ 0, 1, \ldots, 2^m-1 \} \), 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

\[
\begin{align*}
o_x &= x + width / 2 \\
o_y &= y + height / 2 \\
o_z &= minDepth \\
p_x &= width \\
p_y &= height \\
p_z &= maxDepth - minDepth.
\end{align*}
\]

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:

```c
typedef struct VkPipelineRasterizationStateCreateInfo {
    VkStructureType sType;
    const void* pNext;
    VkPipelineRasterizationStateCreateFlags flags;
    VkBool32 depthClampEnable;
    VkBool32 rasterizerDiscardEnable;
    VkPolygonMode polygonMode;
    VkCullModeFlags cullMode;
    VkFrontFace frontFace;
    float depthBiasEnable;
    float depthBiasConstantFactor;
    float depthBiasClamp;
    float depthBiasSlopeFactor;
    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

```c
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:
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
2. Sample mask generation
3. Depth bounds test
4. Stencil test, stencil op and stencil write
5. Depth test and depth write
6. Sample counting for occlusion queries
7. Coverage reduction
8. Blending, logic operations, and color writes

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 ith 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 23. 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)</td>
<td>(0.375,0.125)</td>
<td>(0.5625, 0.3125)</td>
<td>(0.5625, 0.5625)</td>
</tr>
<tr>
<td>(0.25,0.25)</td>
<td>(0.875, 0.375)</td>
<td>(0.875, 0.6875)</td>
<td>(0.4375, 0.6875)</td>
<td>(0.4375, 0.3125)</td>
</tr>
<tr>
<td></td>
<td>(0.125, 0.625)</td>
<td>(0.8125, 0.5625)</td>
<td>(0.3125, 0.1875)</td>
<td>(0.3125, 0.625)</td>
</tr>
<tr>
<td></td>
<td>(0.625, 0.875)</td>
<td>(0.3125, 0.1875)</td>
<td>(0.1875, 0.3125)</td>
<td>(0.1875, 0.25)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.0625, 0.4375)</td>
<td>(0.0625, 0.4375)</td>
<td>(0.0625, 0.75)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.6875, 0.9375)</td>
<td>(0.6875, 0.9375)</td>
<td>(0.6875, 0.9375)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.9375, 0.0625)</td>
<td>(0.9375, 0.0625)</td>
<td>(0.9375, 0.0625)</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 × totalSamples, 1) unique associated data for each fragment, where minSampleShadingFactor is the minimum fraction of sample shading. totalSamples is the value of 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 SampleId or SamplePosition. In this case minSampleShadingFactor takes the value 1.0.
- Else if the sampleShadingEnable member of the VkPipelineMultisampleStateCreateInfo structure specified when creating the graphics pipeline is set to VK_TRUE. In this case minSampleShadingFactor takes the value of 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`:
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 Secondary</td>
<td>Both</td>
<td>Graphics</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 a fragment. When `rasterizationSamples` is `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:

\[
f = \frac{(1-t)f_a/w_a + tf_b/w_b}{(1-t)/w_a + t/w_b}
\]

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:

\[
z = (1 - t)z_a + tz_b
\]

where \( z_a \) and \( z_b \) are the depth values of the starting and ending endpoints of the segment, respectively.

The `NoPerspective` and `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 `NoPerspective` decoration is used, linear interpolation is performed in the same fashion as for depth values, as described above. When the `Flat` decoration is used, no interpolation is performed, and outputs are taken from the corresponding input value of the 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 `strictLines` limit in `VkPhysicalDeviceLimits` as `VK_TRUE`.

When `strictLines` is `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 Non strict lines, and each is `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.

![Diagram of a parallelogram with labeled vertices and line segments.](image)

*Figure 15. Non strict lines*

## 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:

\[
\alpha = -\frac{1}{2} \sum_{i=0}^{n-1} x_i y_{i+1} - y_i x_{i+1}
\]

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 \(i + 1\) is \((i + 1) \mod n\).

The interpretation of the sign of \(\alpha\) is determined by the `VkPipelineRasterizationStateCreateInfo ::frontFace` property of the currently active pipeline. Possible values are:

```cpp
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

\[
p = a p_a + b p_b + c p_c
\]
where $p_a$, $p_b$, and $p_c$ are the vertices of the triangle. $a$, $b$, and $c$ are determined by:

$$a = \frac{A(p_p p_b p_c)}{A(p_a p_b p_c)}, \quad b = \frac{A(p_p p_a p_c)}{A(p_a p_b p_c)}, \quad c = \frac{A(p_p p_a p_b)}{A(p_a p_b p_c)},$$

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, must be determined using perspective interpolation:

$$f = \frac{af_a/w_a + bf_b/w_b + cf_c/w_c}{a/w_a + b/w_b + c/w_c}$$

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 must be the location of the fragment center or the location of a sample. When $rasterizationSamples$ is $VK_SAMPLE_COUNT_1_BIT$, the fragment center must be used.

Depth values for triangles 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 NoPerspective and 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 NoPerspective decoration is used, linear interpolation is performed in the same fashion as for depth values, as described above. When the Flat decoration is used, no interpolation is performed, and outputs are taken from the corresponding input value of the 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 must be used to obtain the value assigned to each fragment produced by the rasterization algorithm. That is, it 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 $a_i$ may differ from fragment to fragment, but at vertex $i$, $a_i = 1$ and $a_j = 0$ for $j \neq i$. 
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 \[\text{triangle_perspective_interpolation}\] are iterated independently and a division performed for each fragment).

### 24.7.2. Polygon Mode

Possible values of the \texttt{VkPipelineRasterizationStateCreateInfo::polygonMode} property of the currently active pipeline, specifying the method of rasterization for polygons, are:

```c
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;
```

- \texttt{VK_POLYGON_MODE_POINT} specifies that polygon vertices are drawn as points.
- \texttt{VK_POLYGON_MODE_LINE} specifies that polygon edges are drawn as line segments.
- \texttt{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 \texttt{depthBiasEnable}, \texttt{depthBiasConstantFactor}, \texttt{depthBiasClamp}, and \texttt{depthBiasSlopeFactor} members of \texttt{VkPipelineRasterizationStateCreateInfo}, or by the corresponding parameters to the \texttt{vkCmdSetDepthBias} command if depth bias state is dynamic.

```c
void vkCmdSetDepthBias(
    VkCommandBuffer commandBuffer,
    float depthBiasConstantFactor,
    float depthBiasClamp,
    float depthBiasSlopeFactor);
```

- \texttt{commandBuffer} is the command buffer into which the command will be recorded.
- \texttt{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.

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

\[
r = 2^{e-n}
\]

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 \( \text{dbclamp}(x) = \begin{cases} x & \text{depthBiasClamp} = 0 \text{or } NaN \\ \min(x, \text{depthBiasClamp}) & \text{depthBiasClamp} > 0 \\ \max(x, \text{depthBiasClamp}) & \text{depthBiasClamp} < 0 \end{cases} \)

\( m \) 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 \texttt{VK_DYNAMIC_STATE_SCISSOR} enabled then the scissor rectangles are set by the \texttt{VkPipelineViewportStateCreateInfo} state of the pipeline state object. Otherwise, to dynamically set the scissor rectangles call:

```c
void vkCmdSetScissor(
    VkCommandBuffer commandBuffer,
    uint32_t firstScissor,
    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.
• **pScissors** is a pointer to an array of VkRect2D structures defining scissor rectangles.

The scissor rectangles taken from element i of **pScissors** replace the current state for the scissor index **firstScissor** + i, for i in [0, **scissorCount**).

Each scissor rectangle is described by a VkRect2D structure, with the **offset.x** and **offset.y** values determining the upper left corner of the scissor rectangle, and the **extent.width** and **extent.height** values determining the size in pixels.

---

**Valid Usage**

- **firstScissor** must be less than VkPhysicalDeviceLimits::maxViewports
- The sum of **firstScissor** and **scissorCount** must be between 1 and VkPhysicalDeviceLimits::maxViewports, inclusive
- If the multiple viewports feature is not enabled, **firstScissor** must be 0
- If the multiple viewports feature is not enabled, **scissorCount** must be 1
- 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)**

- **commandBuffer** must be a valid VkCommandBuffer handle
- **pScissors** must be a valid pointer to an array of **scissorCount** VkRect2D structures
- **commandBuffer** must be in the recording state
- The VkCommandPool that **commandBuffer** was allocated from must support graphics operations
- **scissorCount** 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
If \( \text{offset}.x \leq x < \text{offset}.x + \text{extent}.width \) and \( \text{offset}.y \leq y < \text{offset}.y + \text{extent}.height \) 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 \( \text{offset}.x + \text{extent}.width \) or \( \text{offset}.y + \text{extent}.height \) 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.

Note
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.

```c
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 $(x_i, y_i)$ (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,
    float minDepthBounds,
    float maxDepthBounds);

- `commandBuffer` is the command buffer into which the command will be recorded.
- `minDepthBounds` is the lower bound of the range of depth values used in the depth bounds test.
- `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 \( \text{minDepthBounds} \leq z \leq \text{maxDepthBounds} \), 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:

```
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.
Valid Usage (Implicit)

- `failOp` must be a valid `VkStencilOp` value
- `passOp` must be a valid `VkStencilOp` value
- `depthFailOp` must be a valid `VkStencilOp` value
- `compareOp` must be a valid `VkCompareOp` value

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,        commandBuffer,
    VkStencilFaceFlags faceMask,          faceMask,
    uint32_t compareMask);                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.

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.

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<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_FRONT_AND_BACK = VK_STENCIL_FACE_FRONT_AND_BACK,
    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,
    VkStencilFaceFlags faceMask,
    uint32_t writeMask);
```

- `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 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

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<th>Command Buffer Levels</th>
<th>Render Pass Scope</th>
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<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 ≤ 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 ≠ S.
• VK_COMPARE_OP_GREATER_OR_EQUAL specifies that the test passes when R ≥ 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.
• *VK_STENCIL_OP_INCREMENT_AND_WRAP* increments the current value and wraps to 0 when the maximum value would have been exceeded.

• *VK_STENCIL_OP_DECREMENT_AND_WRAP* decrements the current value and wraps to the maximum possible value when the value would go below 0.

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 `VkPipelineRasterizationStateCreateInfo::depthClampEnable` is enabled, before the incoming fragment’s \( z_f \) is compared to \( z_a \), \( z_f \) is clamped to \([\text{min}(n,f),\text{max}(n,f)]\), where \( n \) and \( f \) are the `minDepth` and `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 `depthWriteEnable` member of `VkPipelineDepthStencilStateCreateInfo`. The value is written if `depthWriteEnable` is `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 [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 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 `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.
Chapter 26. The Framebuffer

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.

```c
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:

```c
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 used 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_SRC1_ALPHA**, or **VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR**, **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_SRC1_ALPHA**, or **VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR**, **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_SRC1_ALPHA**, or **VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR**, **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_SRC1_ALPHA**, or **VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR**, **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:

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 ($S_a$ or $D_a$)</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>
<tr>
<td>VkBlendFactor</td>
<td>RGB Blend Factors ((S_r, S_g, S_b)) or ((D_r, D_g, D_b))</td>
<td>Alpha Blend Factor ((S_a\text{ or } D_a))</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_COLOR</td>
<td>((1-R_c, 1-G_c, 1-B_c))</td>
<td>(1-A_c)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_CONSTANT_ALPHA</td>
<td>((A_c, A_c, A_c))</td>
<td>(A_c)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_CONSTANT_ALPHA</td>
<td>((1-A_c, 1-A_c, 1-A_c))</td>
<td>(1-A_c)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC_ALPHA_SATURATE</td>
<td>((f, f, f); f = \min(A_s0, 1-A_d))</td>
<td>(1)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC1_COLOR</td>
<td>((R_s1, G_s1, B_s1))</td>
<td>(A_s1)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC1_COLOR</td>
<td>((1-R_s1, 1-G_s1, 1-B_s1))</td>
<td>(1-A_s1)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_SRC1_ALPHA</td>
<td>((A_s1, A_s1, A_s1))</td>
<td>(A_s1)</td>
</tr>
<tr>
<td>VK_BLEND_FACTOR_ONE_MINUS_SRC1_ALPHA</td>
<td>((1-A_s1, 1-A_s1, 1-A_s1))</td>
<td>(1-A_s1)</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,
    const float blendConstants[4]);
```

- `commandBuffer` is the command buffer into which the command will be recorded.
- `blendConstants` is a 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.
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

<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 \((R_{s1},G_{s1},B_{s1},A_{s1})\) \((\text{VK\_BLEND\_FACTOR\_SRC1\_COLOR, VK\_BLEND\_FACTOR\_ONE\_MINUS\_SRC1\_COLOR, VK\_BLEND\_FACTOR\_SRC1\_ALPHA, and VK\_BLEND\_FACTOR\_ONE\_MINUS\_SRC1\_ALPHA})\) **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_s \times S_r + R_d \times D_r ]</td>
<td>[ A = A_s \times S_a + A_d \times D_a ]</td>
</tr>
<tr>
<td></td>
<td>[ G = G_s \times S_g + G_d \times D_g ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ B = B_s \times S_b + B_d \times D_b ]</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_OP_SUBTRACT</td>
<td>[ R = R_s \times S_r - R_d \times D_r ]</td>
<td>[ A = A_s \times S_a - A_d \times D_a ]</td>
</tr>
<tr>
<td></td>
<td>[ G = G_s \times S_g - G_d \times D_g ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ B = B_s \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_s \times S_r ]</td>
<td>[ A = D_d \times D_d - A_s \times S_s ]</td>
</tr>
<tr>
<td></td>
<td>[ G = D_g \times D_g - G_s \times S_g ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ B = D_b \times D_b - B_s \times S_b ]</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_OP_MIN</td>
<td>[ R = \min(R_s, R_d) ]</td>
<td>[ A = \min(A_s, A_d) ]</td>
</tr>
<tr>
<td></td>
<td>[ G = \min(G_s, G_d) ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ B = \min(B_s, B_d) ]</td>
<td></td>
</tr>
<tr>
<td>VK_BLEND_OP_MAX</td>
<td>[ R = \max(R_s, R_d) ]</td>
<td>[ A = \max(A_s, A_d) ]</td>
</tr>
<tr>
<td></td>
<td>[ G = \max(G_s, G_d) ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ B = \max(B_s, 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/sample.
- \( S_r, S_g, S_b \) and \( S_s \) represent the source blend factor R, G, B, and A components, respectively.
- \( D_r, D_g, D_b \) and \( D_s \) 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\(^{-1}\)” section of the Khronos Data Format Specification.
If the framebuffer color attachment numeric format is not sRGB encoded then the resulting color 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

• ¬ is bitwise invert,
• ∧ is bitwise and,
• ∨ is bitwise or,
• ⊕ is bitwise exclusive or,
• s is the fragment’s R<sub>s0</sub>, G<sub>s0</sub>, B<sub>s0</sub> or A<sub>s0</sub> 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 ∧ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND_REVERSE</td>
<td>s ∧ ¬ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_COPY</td>
<td>s</td>
</tr>
<tr>
<td>VK_LOGIC_OP_AND_INVERTED</td>
<td>¬ s ∧ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NO_OP</td>
<td>d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_XOR</td>
<td>s ⊕ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR</td>
<td>s ∨ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NOR</td>
<td>¬ (s ∨ d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_EQUIVALENT</td>
<td>¬ (s ⊕ d)</td>
</tr>
<tr>
<td>VK_LOGIC_OP_INVERT</td>
<td>¬ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR_REVERSE</td>
<td>s ∨ ¬ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_COPY_INVERTED</td>
<td>¬ s</td>
</tr>
<tr>
<td>VK_LOGIC_OP_OR_INVERTED</td>
<td>¬ s ∨ d</td>
</tr>
<tr>
<td>VK_LOGIC_OP_NAND</td>
<td>¬ (s ∧ 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**.
Chapter 27. Dispatching Commands

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 \(\text{groupCountX} \times \text{groupCountY} \times \text{groupCountZ}\) local workgroups 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.

• 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 `vkCmd Dispatch` 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,  // The command buffer into which the command will be recorded.
    uint32_t            baseGroupX,    // The start value for the X component of `WorkgroupId`.
    uint32_t            baseGroupY,    // The start value for the Y component of `WorkgroupId`.
    uint32_t            baseGroupZ,    // The start value for the Z component of `WorkgroupId`.
    uint32_t            groupCountX,   // The number of local workgroups to dispatch in the X dimension.
    uint32_t            groupCountY,   // The number of local workgroups to dispatch in the Y dimension.
    uint32_t            groupCountZ);  // 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. \texttt{vkCmdDispatch} is equivalent to \texttt{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]*
  • *baseGroupX* **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>
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<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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` 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.
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.

![Figure 16. Sparse Image](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.

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)

**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.
**Note**

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 27. 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 28. 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 \( \rightarrow \) 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:

```c
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.

```c
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.
```c
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);
```

- **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;
```

- **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;
```

- `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.
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.

#### Buffers 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:

```c
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 logical device that owns the image.
    VkImage image,        // The VkImage object to get the memory requirements for.
    uint32_t* pSparseMemoryRequirementCount, // A pointer to an integer related to the number of sparse memory requirements available or queried, as described below.
    VkSparseImageMemoryRequirements* pSparseMemoryRequirements);      // 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 \texttt{pSparseMemoryRequirements} array, and on return the variable is overwritten with the number of structures actually written to \texttt{pSparseMemoryRequirements}. If \texttt{pSparseMemoryRequirementCount} is less than the number of sparse memory requirements available, at most \texttt{pSparseMemoryRequirementCount} structures will be written.

If the image was not created with \texttt{VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT} then \texttt{pSparseMemoryRequirementCount} will be set to zero and \texttt{pSparseMemoryRequirements} will not be written to.

\begin{quote}
\textbf{Note}

It is legal for an implementation to report a larger value in \texttt{VkMemoryRequirements::size} than would be obtained by adding together memory sizes for all \texttt{VkSparseImageMemoryRequirements} returned by \texttt{vkGetImageSparseMemoryRequirements}. This \textbf{may} occur when the implementation requires unused padding in the address range describing the resource.
\end{quote}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Valid Usage (Implicit)} & \\
\hline
\texttt{device} must be a valid \texttt{VkDevice} handle & \\
\texttt{image} must be a valid \texttt{VkImage} handle & \\
\texttt{pSparseMemoryRequirementCount} must be a valid pointer to a \texttt{uint32_t} value & \\
If the value referenced by \texttt{pSparseMemoryRequirementCount} is not 0, and \texttt{pSparseMemoryRequirements} is not \texttt{NULL}, \texttt{pSparseMemoryRequirements} must be a valid pointer to an array of \texttt{pSparseMemoryRequirementCount} \texttt{VkSparseImageMemoryRequirements} structures & \\
\texttt{image} must have been created, allocated, or retrieved from \texttt{device} & \\
\hline
\end{tabular}
\end{table}

To query sparse memory requirements for an image, call:

\begin{verbatim}
void vkGetImageSparseMemoryRequirements2(
    VkDevice device, 
    const VkImageSparseMemoryRequirementsInfo2* pInfo, 
    uint32_t* pSparseMemoryRequirementCount, 
    VkSparseImageMemoryRequirements2* pSparseMemoryRequirements);
\end{verbatim}

\begin{itemize}
\item \texttt{device} is the logical device that owns the image.
\item \texttt{pInfo} is a pointer to a \texttt{VkImageSparseMemoryRequirementsInfo2} structure containing parameters required for the memory requirements query.
\item \texttt{pSparseMemoryRequirementCount} is a pointer to an integer related to the number of sparse memory requirements available or queried, as described below.
\item \texttt{pSparseMemoryRequirements} is either \texttt{NULL} or a pointer to an array of \texttt{VkSparseImageMemoryRequirements2} structures.
\end{itemize}
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 `pSparseMemoryRequirementCount` `VkSparseImageMemoryRequirements2` structures

The `VkImageSparseMemoryRequirementsInfo2` structure is defined as:

```c
typedef struct VkImageSparseMemoryRequirementsInfo2 {
    VkStructureType    sType;
    const void*        pNext;
    VkImage            image;
} VkImageSparseMemoryRequirementsInfo2;
```

- `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;
```

- `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.
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:

\[
arrayMipTailOffset = imageMipTailOffset + arrayLayer \times imageMipTailStride;
\]

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:

```c
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** `[resourceOffset, resourceOffset + 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:

\[
\text{metadataRegion} = [base, base + imageMipTailSize)
\]

\[
base = imageMipTailOffset + imageMipTailStride \times n
\]

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`. 

Chapter 28. Sparse Resources | 781
If `flags` does not contain `VK_SPARSE_MEMORY_BIND_METADATA_BIT`, the binding range must be within the range `[0, 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 \([0, \text{VkMemoryRequirements::size})\). 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 \([\text{imageMipTailOffset}, \text{imageMipTailOffset} + \text{imageMipTailSize})\) 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>SPARSE_BINDING</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;
```

- `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 =
{
    VK_STRUCTURE_TYPE_BIND_SPARSE_INFO, // sType
    NULL, // pNext
    ...
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.

```cpp
const VkImageCreateInfo sparseImageInfo = {
    VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO,  // sType
    NULL,                                   // pNext
    VK_IMAGE_CREATE_SPARSE_RESIDENCY_BIT | ..., // flags
    ...,                                    // format
    ...,                                    // arrayLayers
    VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT | VK_IMAGE_USAGE_SAMPLED_BIT, // usage
...};

vkCreateImage(device, &sparseImageInfo, pAllocator, &sparseImage); // Allocate image object (both renderable and sampleable)
```

```cpp
// Get memory requirements
vkGetImageMemoryRequirements(device, sparseImage, &memoryRequirements);
```

```cpp
// vkQueueBindSparse is externally synchronized per queue object.
AcquireQueueOwnership(queue);

// Actually bind memory
vkQueueBindSparse(queue, 1, &bindSparseInfo, VK_NULL_HANDLE);

ReleaseQueueOwnership(queue);
```
// 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. 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.

29.1. Instance and Device Functionality

Commands that enumerate instance properties, or that accept a \texttt{VkInstance} object as a parameter, are considered instance-level functionality. Commands that enumerate physical device properties, or that accept a \texttt{VkDevice} object or any of a device's child objects as a parameter, are considered device-level functionality.

\textbf{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.

\textbf{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, \texttt{VK_KHR_get_physical_device_properties2} (and subsequently Vulkan 1.1) redefined device-level functionality to include physical device enumeration.

29.2. 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.

29.2.1. 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

VK_API_VERSION_1_2 returns the API version number for Vulkan 1.2.0.

// Vulkan 1.2 version number
#define VK_API_VERSION_1_2 VK_MAKE_VERSION(1, 2, 0)  // Patch version should always be set to 0

### 29.2.2. 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](#).

### 29.3. 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:

```c
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.

29.3.1. 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
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.

### 29.4. 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.

29.4.1. Instance Extensions

Instance extensions add new instance-level functionality to the API, outside of the core specification.

To query the available instance extensions, call:

```c
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`

### 29.4.2. 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:

```c
VkResult vkEnumerateDeviceExtensionProperties(
    VkPhysicalDevice physicalDevice,
    const char* pLayerName,        
    uint32_t* propertyCount,       
    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
29.5. 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 and Core Revisions 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.

29.6. 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.

29.6.1. 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 the patch and minor version will be reset to 0 for that major version.

### 29.6.2. 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 deprecating 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.
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.

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 30. 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 the *pNext* 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 29. 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);
```

- 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:
typedef struct VkPhysicalDeviceFeatures2 {
    VkStructureType     sType;
    void*               pNext;
    VkPhysicalDeviceFeatures    features;
} VkPhysicalDeviceFeatures2;

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:

typedef struct VkPhysicalDeviceFeatures {
    VkBool32    robustBufferAccess;
    VkBool32    fullDrawIndexUint32;
    VkBool32    imageCubeArray;
    VkBool32    independentBlend;
    VkBool32    geometryShader;
    VkBool32    tessellationShader;
    VkBool32    sampleRateShading;
    VkBool32    dualSrcBlend;
    VkBool32    logicOp;
    VkBool32    multiDrawIndirect;
    VkBool32    drawIndirectFirstInstance;
    VkBool32    depthClamp;
    VkBool32    depthBiasClamp;
    VkBool32    fillModeNonSolid;
    VkBool32    depthBounds;
    VkBool32    wideLines;
    VkBool32    largePoints;
    VkBool32    alphaToOne;
    VkBool32    multiViewport;
    VkBool32    samplerAnisotropy;
    VkBool32    textureCompressionETC2;
    VkBool32    textureCompressionASTC_LDR;
} VkPhysicalDeviceFeatures; 

Chapter 30. Features | 815
The members of the \texttt{VkPhysicalDeviceFeatures} structure describe the following features:

- \texttt{robustBufferAccess} specifies that accesses to buffers are bounds-checked against the range of the buffer descriptor (as determined by \texttt{VkDescriptorBufferInfo::range}, \texttt{VkBufferViewCreateInfo::range}, or the size of the buffer). Out of bounds accesses \textbf{must} not cause application termination, and the effects of shader loads, stores, and atomics \textbf{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 \texttt{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 \texttt{OpImageTexelPointer} and the object pointed to is not wholly contained within the bound range. This includes accesses performed via \textit{variable pointers} where the buffer descriptor being accessed cannot be statically determined. Uninitialized pointers and pointers equal to \texttt{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.

**Note**

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.

- If any buffer access is determined to be out of bounds, then any other access of the same type (load, store, or atomic) to the same buffer that accesses an address less than 16 bytes away from the out of bounds address may also be considered out of bounds.

  - **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
      - \((\text{vertexBufferRangeSize} - (\text{vertexBufferRangeSize} \% \text{bindingStride}))\)
      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**, and **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 **VkPhysicalDeviceLimits** 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:
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_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`
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_R16_SFLOAT
  - VK_FORMAT_R16G16B16A16_UNORM
  - VK_FORMAT_R16G16B16A16_SNORM
  - VK_FORMAT_R16G16UNORM
  - VK_FORMAT_R8G8_SINT
  - VK_FORMAT_R8_SINT
  - VK_FORMAT_R8G8B8A8_SINT
  - VK_FORMAT_R8G8B8A8_SNORM
  - VK_FORMAT_R8G8B8A8_UNORM
  - VK_FORMAT_R8G8B8A8_UINT
  - VK_FORMAT_R8G8B8A8_SINT
  - VK_FORMAT_R8G8B8A8_SNORM
  - VK_FORMAT_R8G8B8A8_UNORM
  - VK_FORMAT_R16G16_SINT
  - VK_FORMAT_R16G16_SNORM
  - VK_FORMAT_R16G16B16A16_SINT
  - VK_FORMAT_R16G16B16A16_SNORM
  - VK_FORMAT_R16G16B16A16_UNORM
  - VK_FORMAT_R16G16B16A16_SFLOAT
  - VK_FORMAT_R16G16B16A16_SINT
  - VK_FORMAT_R16G16B16A16_SNORM
  - VK_FORMAT_R16G16B16A16_UNORM
  - VK_FORMAT_R16G16B16A16_SFLOAT
  - VK_FORMAT_R16G16B16A16_SINT
  - VK_FORMAT_R16G16B16A16_SNORM
  - VK_FORMAT_R16G16B16A16_UNORM
  - VK_FORMAT_R16G16B16A16_SFLOAT
  - VK_FORMAT_R16G16B16A16_SINT
  - VK_FORMAT_R16G16B16A16_SNORM
  - VK_FORMAT_R16G16B16A16_UNORM
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.

• shaderStorageImageReadWriteWithoutFormat 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 StorageImageReadWriteWithoutFormat 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 dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER or 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.

• 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 VK_DESCRIPTOR_TYPE_SAMPLER, VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER, or 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.
• **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 `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `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.

• **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 `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.

• **shaderClipDistance** specifies whether clip distances are supported in shader code. If this feature is not enabled, any members decorated with the `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.

• **shaderCullDistance** specifies whether cull distances are supported in shader code. If this feature is not enabled, any members decorated with the `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.

• **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.

• **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.

• **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 `VkPhysicalDeviceVulkan11Features` structure is defined as:

```c
typedef struct VkPhysicalDeviceVulkan11Features {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           storageBuffer16BitAccess;
    VkBool32           uniformAndStorageBuffer16BitAccess;
    VkBool32           storagePushConstant16;
    VkBool32           storageInputOutput16;
    VkBool32           multiview;
    VkBool32           multiviewGeometryShader;
    VkBool32           multiviewTessellationShader;
    VkBool32           variablePointersStorageBuffer;
    VkBool32           variablePointers;
    VkBool32           protectedMemory;
    VkBool32           samplerYcbcrConversion;
    VkBool32           shaderDrawParameters;
} VkPhysicalDeviceVulkan11Features;
```

The members of the `VkPhysicalDeviceVulkan11Features` structure describe the following features:

- **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.
- **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.

- **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.

- **protectedMemory** specifies whether protected memory is supported.

- **samplerYcbcrConversion** specifies whether the implementation supports **sampler Y’C_bC_r conversion**. If **samplerYcbcrConversion** is **VK_FALSE**, sampler **Y’C_bC_r** conversion is not supported, and samplers using sampler **Y’C_bC_r** conversion **must** not be used.

- **shaderDrawParameters** specifies whether shader draw parameters are supported.

If the **VkPhysicalDeviceVulkan11Features** structure is included in the **pNext** chain of **VkPhysicalDeviceFeatures2**, it is filled with values indicating whether each feature is supported. **VkPhysicalDeviceVulkan11Features** can also be used in the **pNext** chain of **VkDeviceCreateInfo** to enable the features.

### Valid Usage (Implicit)

- **sType** **must** be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_1_FEATURES**

The **VkPhysicalDeviceVulkan12Features** structure is defined as:

```c
typedef struct VkPhysicalDeviceVulkan12Features {
    VkStructureType sType;
    void* pNext;
    VkBool32 samplerMirrorClampToEdge;
    VkBool32 drawIndirectCount;
    VkBool32 storageBuffer8BitAccess;
    VkBool32 uniformAndStorageBuffer8BitAccess;
    VkBool32 storagePushConstant8;
    VkBool32 shaderBufferInt64Atomics;
    VkBool32 shaderSharedInt64Atomics;
    VkBool32 shaderFloat16;
    VkBool32 shaderInt8;
} VkPhysicalDeviceVulkan12Features;
```
The members of the `VkPhysicalDeviceVulkan12Features` structure describe the following features:

- `samplerMirrorClampToEdge` indicates whether the implementation supports the `VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE` sampler address mode. If this feature is not enabled, the `VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE` sampler address mode must not be used.

- `drawIndirectCount` indicates whether the implementation supports the `vkCmdDrawIndirectCount` and `vkCmdDrawIndexedIndirectCount` functions. If this feature is not enabled, these functions must not be used.
• `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.

• `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.

• `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.

• `descriptorIndexing` indicates whether the implementation supports the minimum set of descriptor indexing features as described in the `Feature Requirements` section. Enabling the `descriptorIndexing` member when `vkCreateDevice` is called does not imply the other minimum descriptor indexing features are also enabled. Those other descriptor indexing features must be enabled individually as needed by the application.

• `shaderInputAttachmentArrayDynamicIndexing` indicates whether arrays of input attachments can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `InputAttachmentArrayDynamicIndexing` capability.

• `shaderUniformTexelBufferArrayDynamicIndexing` indicates whether arrays of uniform texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` must be indexed only by constant integral expressions...
when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformTexelBufferArrayDynamicIndexing` capability.

- `shaderStorageTexelBufferArrayDynamicIndexing` indicates whether arrays of storage texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageTexelBufferArrayDynamicIndexing` capability.

- `shaderUniformBufferArrayNonUniformIndexing` indicates whether arrays of uniform buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformBufferArrayNonUniformIndexing` capability.

- `shaderSampledImageArrayNonUniformIndexing` indicates whether arrays of samplers or sampled images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_SAMPLER`, `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, or `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `SampledImageArrayNonUniformIndexing` capability.

- `shaderStorageBufferArrayNonUniformIndexing` indicates whether arrays of storage buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageBufferArrayNonUniformIndexing` capability.

- `shaderStorageImageArrayNonUniformIndexing` indicates whether arrays of storage images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageImageArrayNonUniformIndexing` capability.

- `shaderInputAttachmentArrayNonUniformIndexing` indicates whether arrays of input attachments can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `InputAttachmentArrayNonUniformIndexing` capability.

- `shaderUniformTexelBufferArrayNonUniformIndexing` indicates whether arrays of uniform texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformTexelBufferArrayNonUniformIndexing` capability.
• **shaderStorageTexelBufferArrayNonUniformIndexing** indicates whether arrays of storage texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER** must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the **StorageTexelBufferArrayNonUniformIndexing** capability.

• **descriptorBindingUniformBufferUpdateAfterBind** indicates whether the implementation supports updating uniform buffer descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER**.

• **descriptorBindingSampledImageUpdateAfterBind** indicates whether the implementation supports updating sampled image descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_SAMPLER**, **VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER**, or **VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE**.

• **descriptorBindingStorageImageUpdateAfterBind** indicates whether the implementation supports updating storage image descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_STORAGE_IMAGE**.

• **descriptorBindingStorageBufferUpdateAfterBind** indicates whether the implementation supports updating storage buffer descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_STORAGE_BUFFER**.

• **descriptorBindingUniformTexelBufferUpdateAfterBind** indicates whether the implementation supports updating uniform texel buffer descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER**.

• **descriptorBindingStorageTexelBufferUpdateAfterBind** indicates whether the implementation supports updating storage texel buffer descriptors after a set is bound. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT** must not be used with **VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER**.

• **descriptorBindingUpdateUnusedWhilePending** indicates whether the implementation supports updating descriptors while the set is in use. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT** must not be used.

• **descriptorBindingPartiallyBound** indicates whether the implementation supports statically using a descriptor set binding in which some descriptors are not valid. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT** must not be used.

• **descriptorBindingVariableDescriptorCount** indicates whether the implementation supports descriptor sets with a variable-sized last binding. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT** must not be used.

• **runtimeDescriptorArray** indicates whether the implementation supports the SPIR-V RuntimeDescriptorArray capability. If this feature is not enabled, descriptors must not be declared in runtime arrays.
• **samplerFilterMinmax** indicates whether the implementation supports a minimum set of required formats supporting min/max filtering as defined by the `filterMinmaxSingleComponentFormats` property minimum requirements. If this feature is not enabled, then no `VkSamplerCreateInfo pNext` chain can include a `VkSamplerReductionModeCreateInfo` structure.

• **scalarBlockLayout** indicates that the implementation supports the layout of resource blocks in shaders using scalar alignment.

• **imagelessFramebuffer** indicates that the implementation supports specifying the image view for attachments at render pass begin time via `VkRenderPassAttachmentBeginInfo`.

• **uniformBufferStandardLayout** indicates that the implementation supports the same layouts for uniform buffers as for storage and other kinds of buffers. See Standard Buffer Layout.

• **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.

• **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.

• **hostQueryReset** indicates that the implementation supports resetting queries from the host with `vkResetQueryPool`.

• **timelineSemaphore** indicates whether semaphores created with a `VkSemaphoreType` of `VK_SEMAPHORE_TYPE_TIMELINE` are supported.

• **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` feature for logical devices created with multiple physical devices. If this feature is not supported, buffer addresses must not be queried on a logical device created with more than one physical device.

• **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.

• **shaderOutputViewportIndex** indicates whether the implementation supports the ShaderViewportIndex SPIR-V capability enabling variables decorated with the ViewportIndex built-in to be exported from vertex or tessellation evaluation shaders. If this feature is not enabled, the ViewportIndex built-in decoration must not be used on outputs in vertex or tessellation
evaluation shaders.

- `shaderOutputLayer` indicates whether the implementation supports the ShaderLayer SPIR-V capability enabling variables decorated with the Layer built-in to be exported from vertex or tessellation evaluation shaders. If this feature is not enabled, the Layer built-in decoration **must** not be used on outputs in vertex or tessellation evaluation shaders.

- If `subgroupBroadcastDynamicId` is `VK_TRUE`, the “Id” operand of `OpGroupNonUniformBroadcast` **can** be dynamically uniform within a subgroup, and the “Index” operand of `OpGroupNonUniformQuadBroadcast` **can** be dynamically uniform within the derivative group. If it is `VK_FALSE`, these operands **must** be constants.

If the `VkPhysicalDeviceVulkan12Features` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether each feature is supported. `VkPhysicalDeviceVulkan12Features` **can** also be used in the `pNext` chain of `VkDeviceCreateInfo` to enable the features.

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VULKAN_1_2_FEATURES`

The `VkPhysicalDeviceVariablePointersFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceVariablePointersFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           variablePointersStorageBuffer;
    VkBool32           variablePointers;
} VkPhysicalDeviceVariablePointersFeatures;
```

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;
```

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;
```

• **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;
```
• **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.

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### 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:

```c
typedef struct VkPhysicalDevice16BitStorageFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           storageBuffer16BitAccess;
    VkBool32           uniformAndStorageBuffer16BitAccess;
    VkBool32           storagePushConstant16;
    VkBool32           storageInputOutput16;
} VkPhysicalDevice16BitStorageFeatures;
```

• **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;
```

• `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`
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`

The `VkPhysicalDeviceDescriptorIndexingFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceDescriptorIndexingFeatures {
    VkStructureType  sType;
    void*             pNext;
    VkBool32          shaderInputAttachmentArrayDynamicIndexing;
    VkBool32          shaderUniformTexelBufferArrayDynamicIndexing;
    VkBool32          shaderStorageTexelBufferArrayDynamicIndexing;
    VkBool32          shaderUniformBufferArrayNonUniformIndexing;
    VkBool32          shaderStorageBufferArrayNonUniformIndexing;
    VkBool32          shaderStorageImageArrayNonUniformIndexing;
    VkBool32          shaderInputAttachmentArrayNonUniformIndexing;
    VkBool32          shaderUniformTexelBufferArrayNonUniformIndexing;
    VkBool32          shaderStorageTexelBufferArrayNonUniformIndexing;
    VkBool32          descriptorBindingUniformBufferUpdateAfterBind;
    VkBool32          descriptorBindingSampledImageUpdateAfterBind;
    VkBool32          descriptorBindingStorageImageUpdateAfterBind;
    VkBool32          descriptorBindingStorageBufferUpdateAfterBind;
    VkBool32          descriptorBindingUniformTexelBufferUpdateAfterBind;
    VkBool32          descriptorBindingStorageTexelBufferUpdateAfterBind;
    VkBool32          descriptorBindingUpdateUnusedWhilePending;
    VkBool32          descriptorBindingPartiallyBound;
    VkBool32          descriptorBindingVariableDescriptorCount;
    VkBool32          runtimeDescriptorArray;
} VkPhysicalDeviceDescriptorIndexingFeatures;
```

The members of the `VkPhysicalDeviceDescriptorIndexingFeatures` structure describe the following features:
• **shaderInputAttachmentArrayDynamicIndexing** indicates whether arrays of input attachments can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `InputAttachmentArrayDynamicIndexing` capability.

• **shaderUniformTexelBufferArrayDynamicIndexing** indicates whether arrays of uniform texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformTexelBufferArrayDynamicIndexing` capability.

• **shaderStorageTexelBufferArrayDynamicIndexing** indicates whether arrays of storage texel buffers can be indexed by dynamically uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` must be indexed only by constant integral expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageTexelBufferArrayDynamicIndexing` capability.

• **shaderUniformBufferArrayNonUniformIndexing** indicates whether arrays of uniform buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER` or `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformBufferArrayNonUniformIndexing` capability.

• **shaderSampledImageArrayNonUniformIndexing** indicates whether arrays of samplers or sampled images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_SAMPLER`, `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, or `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `SampledImageArrayNonUniformIndexing` capability.

• **shaderStorageBufferArrayNonUniformIndexing** indicates whether arrays of storage buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER` or `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageBufferArrayNonUniformIndexing` capability.

• **shaderStorageImageArrayNonUniformIndexing** indicates whether arrays of storage images can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageImageArrayNonUniformIndexing` capability.

• **shaderInputAttachmentArrayNonUniformIndexing** indicates whether arrays of input attachments can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `InputAttachmentArrayNonUniformIndexing` capability.
enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `InputAttachmentArrayNonUniformIndexing` capability.

- `shaderUniformTexelBufferArrayNonUniformIndexing` indicates whether arrays of uniform texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `UniformTexelBufferArrayNonUniformIndexing` capability.

- `shaderStorageTexelBufferArrayNonUniformIndexing` indicates whether arrays of storage texel buffers can be indexed by non-uniform integer expressions in shader code. If this feature is not enabled, resources with a descriptor type of `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER` must not be indexed by non-uniform integer expressions when aggregated into arrays in shader code. This also indicates whether shader modules can declare the `StorageTexelBufferArrayNonUniformIndexing` capability.

- `descriptorBindingUniformBufferUpdateAfterBind` indicates whether the implementation supports updating uniform buffer descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with `VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER`.

- `descriptorBindingSampledImageUpdateAfterBind` indicates whether the implementation supports updating sampled image descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with `VK_DESCRIPTOR_TYPE_SAMPLER`, `VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER`, or `VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE`.

- `descriptorBindingStorageImageUpdateAfterBind` indicates whether the implementation supports updating storage image descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with `VK_DESCRIPTOR_TYPE_STORAGE_IMAGE`.

- `descriptorBindingStorageBufferUpdateAfterBind` indicates whether the implementation supports updating storage buffer descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with `VK_DESCRIPTOR_TYPE_STORAGE_BUFFER`.

- `descriptorBindingUniformTexelBufferUpdateAfterBind` indicates whether the implementation supports updating uniform texel buffer descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with `VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER`.

- `descriptorBindingStorageTexelBufferUpdateAfterBind` indicates whether the implementation supports updating storage texel buffer descriptors after a set is bound. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_AFTER_BIND_BIT` must not be used with `VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER`.

- `descriptorBindingUpdateUnusedWhilePending` indicates whether the implementation supports updating descriptors while the set is in use. If this feature is not enabled, `VK_DESCRIPTOR_BINDING_UPDATE_UNUSED_WHILE_PENDING_BIT` must not be used.
• **descriptorBindingPartiallyBound** indicates whether the implementation supports statically using a descriptor set binding in which some descriptors are not valid. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_PARTIALLY_BOUND_BIT** must not be used.

• **descriptorBindingVariableDescriptorCount** indicates whether the implementation supports descriptor sets with a variable-sized last binding. If this feature is not enabled, **VK_DESCRIPTOR_BINDING_VARIABLE_DESCRIPTOR_COUNT_BIT** must not be used.

• **runtimeDescriptorArray** indicates whether the implementation supports the SPIR-V RuntimeDescriptorArray capability. If this feature is not enabled, descriptors must not be declared in runtime arrays.

If the **VkPhysicalDeviceDescriptorIndexingFeatures** structure is included in the **pNext** chain of **VkPhysicalDeviceFeatures2**, it is filled with values indicating whether each feature is supported. **VkPhysicalDeviceDescriptorIndexingFeatures** can also be included in the **pNext** chain of **VkDeviceCreateInfo** to enable features.

### Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_DESCRIPTOR_INDEXING_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;
```

- **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 VkPhysicalDeviceScalarBlockLayoutFeatures structure is defined as:

```c
typedef struct VkPhysicalDeviceScalarBlockLayoutFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 scalarBlockLayout;
} VkPhysicalDeviceScalarBlockLayoutFeatures;
```

The members of the VkPhysicalDeviceScalarBlockLayoutFeatures structure describe the following features:

- scalarBlockLayout indicates that the implementation supports the layout of resource blocks in shaders using scalar alignment.

If the VkPhysicalDeviceScalarBlockLayoutFeatures structure is included in the pNext chain of VkPhysicalDeviceFeatures2, it is filled with values indicating whether the feature is supported. VkPhysicalDeviceScalarBlockLayoutFeatures 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_SCALAR_BLOCK_LAYOUT_FEATURES

The VkPhysicalDeviceUniformBufferStandardLayoutFeatures structure is defined as:

```c
typedef struct VkPhysicalDeviceUniformBufferStandardLayoutFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 uniformBufferStandardLayout;
} VkPhysicalDeviceUniformBufferStandardLayoutFeatures;
```

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;
```

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** feature for logical devices created with multiple physical devices. If this feature is not supported, buffer addresses **must** not be queried on a logical device created with more than one physical device.

  **Note**

  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 *vkGetBufferDeviceAddress* for more information.

If the *VkPhysicalDeviceBufferDeviceAddressFeatures* structure is included in the *pNext* chain of *VkPhysicalDeviceFeatures2*, it is filled with values indicating whether the feature is supported. *VkPhysicalDeviceBufferDeviceAddressFeatures* can also be included in the *pNext* chain of *VkDeviceCreateInfo* to enable features.

Valid Usage (Implicit)

- **sType** must be **VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_BUFFER_DEVICE_ADDRESS_FEATURES**
The **VkPhysicalDeviceImagelessFramebufferFeatures** structure is defined as:

```c
typedef struct VkPhysicalDeviceImagelessFramebufferFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           imagelessFramebuffer;
} VkPhysicalDeviceImagelessFramebufferFeatures;
```

The members of the **VkPhysicalDeviceImagelessFramebufferFeatures** structure describe the following features:

- **imagelessFramebuffer** indicates that the implementation supports specifying the image view for attachments at render pass begin time via **VkRenderPassAttachmentBeginInfo**.

If the **VkPhysicalDeviceImagelessFramebufferFeatures** structure is included in the **pNext** chain of **VkPhysicalDeviceFeatures2**, it is filled with values indicating whether the feature is supported. **VkPhysicalDeviceImagelessFramebufferFeatures** 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_IMAGELESS_FRAMEBUFFER_FEATURES**

The **VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures** structure is defined as:

```c
typedef struct VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           shaderSubgroupExtendedTypes;
} VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures;
```

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.
The `VkPhysicalDeviceHostQueryResetFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceHostQueryResetFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           hostQueryReset;
} VkPhysicalDeviceHostQueryResetFeatures;
```

The members of the `VkPhysicalDeviceHostQueryResetFeatures` structure describe the following features:

- `hostQueryReset` indicates that the implementation supports resetting queries from the host with `vkResetQueryPool`.

If the `VkPhysicalDeviceHostQueryResetFeatures` structure is included in the `pNext` chain of `VkPhysicalDeviceFeatures2`, it is filled with values indicating whether the feature is supported. `VkPhysicalDeviceHostQueryResetFeatures` can also be included in the `pNext` chain of `VkDeviceCreateInfo` to enable features.

---

The `VkPhysicalDeviceTimelineSemaphoreFeatures` structure is defined as:

```c
typedef struct VkPhysicalDeviceTimelineSemaphoreFeatures {
    VkStructureType    sType;
    void*              pNext;
    VkBool32           timelineSemaphore;
} VkPhysicalDeviceTimelineSemaphoreFeatures;
```

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.
The `VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures` structure is defined as:

```plaintext
typedef struct VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures {
    VkStructureType sType;
    void* pNext;
    VkBool32 separateDepthStencilLayouts;
} VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures;
```

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.

---

### 30.1. 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.
- If the **descriptorIndexing** feature is supported, or if the `[VK_EXT_descriptor_indexing]` extension is supported:
  - **shaderSampledImageArrayDynamicIndexing**
  - **shaderStorageBufferArrayDynamicIndexing**
  - **shaderUniformTexelBufferArrayDynamicIndexing**

---

*Chapter 30. Features | 847*
• shaderStorageTexelBufferArrayDynamicIndexing
• shaderSampledImageArrayNonUniformIndexing
• shaderStorageBufferArrayNonUniformIndexing
• shaderUniformTexelBufferArrayNonUniformIndexing
• descriptorBindingSampledImageUpdateAfterBind
• descriptorBindingStorageImageUpdateAfterBind
• descriptorBindingStorageBufferUpdateAfterBind (see also robustBufferAccessUpdateAfterBind)
• descriptorBindingUniformTexelBufferUpdateAfterBind (see also robustBufferAccessUpdateAfterBind)
• descriptorBindingStorageTexelBufferUpdateAfterBind (see also robustBufferAccessUpdateAfterBind)
• descriptorBindingUpdateUnusedWhilePending
• descriptorBindingPartiallyBound
• runtimeDescriptorArray

• subgroupBroadcastDynamicId, if Vulkan 1.2 is supported.
• imagelessFramebuffer, if Vulkan 1.2 is supported.
• separateDepthStencilLayouts, if Vulkan 1.2 is supported.
• hostQueryReset, if Vulkan 1.2 is supported.
• timelineSemaphore, if Vulkan 1.2 or the [VK_KHR_timeline_semaphore] extension is supported.

All other features defined in the Specification are **optional**.
Chapter 31. 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              maxDescriptorSetSampledImages;
    uint32_t              maxDescriptorSetStorageImages;
    uint32_t              maxDescriptorSetInputAttachments;
    uint32_t              maxVertexInputAttributes;
    uint32_t              maxVertexInputBindings;
    uint32_t              maxVertexInputAttributeOffset;
    uint32_t              maxVertexInputBindingStride;
} VkPhysicalDeviceLimits;
```
uint32_t              maxVertexOutputComponents;
uint32_t              maxTessellationGenerationLevel;
uint32_t              maxTessellationPatchSize;
uint32_t              maxTessellationControlPerVertexInputComponents;
uint32_t              maxTessellationControlPerVertexOutputComponents;
uint32_t              maxTessellationControlPerPatchOutputComponents;
uint32_t              maxTessellationControlTotalOutputComponents;
uint32_t              maxTessellationEvaluationInputComponents;
uint32_t              maxTessellationEvaluationOutputComponents;
uint32_t              maxGeometryShaderInvocations;
uint32_t              maxGeometryInputComponents;
uint32_t              maxGeometryOutputComponents;
uint32_t              maxGeometryOutputVertices;
uint32_t              maxGeometryTotalOutputComponents;
uint32_t              maxFragmentInputComponents;
uint32_t              maxFragmentOutputAttachments;
uint32_t              maxFragmentDualSrcAttachments;
uint32_t              maxFragmentCombinedOutputResources;
uint32_t              maxComputeSharedMemorySize;
uint32_t              maxComputeWorkGroupCount[3];
uint32_t              maxComputeWorkGroupSize[3];
uint32_t              subPixelPrecisionBits;
uint32_t              subTexelPrecisionBits;
mipmapPrecisionBits;
uint32_t              maxDrawIndexedIndexValue;
uint32_t              maxDrawIndirectCount;
float                 maxSamplerLodBias;
float                 maxSamplerAnisotropy;
uint32_t              maxViewports;
uint32_t              maxViewportDimensions[2];
float                 viewportBoundsRange[2];
uint32_t              viewportSubPixelBits;
size_t                minMemoryMapAlignment;
VkDeviceSize          minTexelBufferOffsetAlignment;
VkDeviceSize          minUniformBufferOffsetAlignment;
VkDeviceSize          minStorageBufferOffsetAlignment;
int32_t               minTexelOffset;
int32_t               maxTexelOffset;
int32_t               minTexelGatherOffset;
int32_t               maxTexelGatherOffset;
float                 minInterpolationOffset;
float                 maxInterpolationOffset;
uint32_t              subPixelInterpolationOffsetBits;
uint32_t              maxFramebufferWidth;
uint32_t              maxFramebufferHeight;
uint32_t              maxFramebufferLayers;
VkSampleCountFlags    framebufferColorSampleCounts;
VkSampleCountFlags    framebufferDepthSampleCounts;
VkSampleCountFlags    framebufferStencilSampleCounts;
VkSampleCountFlags    framebufferNoAttachmentsSampleCounts;
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`. 

Chapter 31. Limits | 851
• **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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor
set layouts created without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit
set 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. Only descriptors in descriptor set layouts created without the
VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set 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. Only descriptors in descriptor set
layouts created without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set
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_UNIFORM_TEXEL_BUFFER,
VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER, VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER,
VK_DESCRIPTOR_TYPE_STORAGE_BUFFER, VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC,
VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC, or VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT count
against this limit. Only descriptors in descriptor set layouts created without the
VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set 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. Only descriptors in
descriptor set layouts created without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set 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. Only descriptors in
descriptor set layouts created without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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. Only descriptors in descriptor set layouts created without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set 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\_f and y\_f. 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. \(2^{\text{subTexelPrecisionBits}}\) 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. \(2^{\text{mipmapPrecisionBits}}\) 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 \text{size}, 2 \times \text{size} - 1]`, where \( \text{size} = \max(\text{maxViewportDimensions}[0], \text{maxViewportDimensions}[1]) \). See Controlling the Viewport.

  **Note**
  
  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.

1 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:

```c
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.

typedef VkFlags VkSampleCountFlags;

`VkSampleCountFlags` is a bitmask type for setting a mask of zero or more `VkSampleCountFlagBits`.

The `VkPhysicalDeviceMultiviewProperties` structure is defined as:

typedef struct VkPhysicalDeviceMultiviewProperties {
    VkStructureType    sType;
    void*              pNext;
    uint32_t           maxMultiviewViewCount;
    uint32_t           maxMultiviewInstanceIndex;
} VkPhysicalDeviceMultiviewProperties;

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:
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;

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_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;
```

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:
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 and VkPhysicalDeviceVulkan11Properties::subgroupSupportedOperations to specify supported group operations with subgroup scope are:
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.

typedef VkFlags VkSubgroupFeatureFlags;

**VkSubgroupFeatureFlags** is a bitmask type for setting a mask of zero or more `VkSubgroupFeatureFlagBits`.

The **VkPhysicalDeviceSamplerFilterMinmaxProperties** structure is defined as:

typedef struct VkPhysicalDeviceSamplerFilterMinmaxProperties {
    VkStructureType sType;
    void* pNext;
    VkBool32 filterMinmaxSingleComponentFormats;
    VkBool32 filterMinmaxImageComponentMapping;
} VkPhysicalDeviceSamplerFilterMinmaxProperties;
The members of the `VkPhysicalDeviceSamplerFilterMinmaxProperties` 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.
- **filterMinmaxSingleComponentFormats** is a boolean value indicating whether a minimum set of required formats support min/max filtering.
- **filterMinmaxImageComponentMapping** is a boolean value indicating whether the implementation supports non-identity component mapping of the image when doing min/max filtering.

If the `VkPhysicalDeviceSamplerFilterMinmaxProperties` structure is included in the `pNext` chain of `VkPhysicalDeviceProperties2`, it is filled with the implementation-dependent limits.

If `filterMinmaxSingleComponentFormats` is `VK_TRUE`, the following formats **must** support the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT` feature with `VK_IMAGE_TILING_OPTIMAL`, if they support `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`.

- `VK_FORMAT_R8_UNORM`
- `VK_FORMAT_R8_SNORM`
- `VK_FORMAT_R16_UNORM`
- `VK_FORMAT_R16_SNORM`
- `VK_FORMAT_R16_SFLOAT`
- `VK_FORMAT_R32_SFLOAT`
- `VK_FORMAT_D16_UNORM`
- `VK_FORMAT_X8_D24_UNORM_PACK32`
- `VK_FORMAT_D32_SFLOAT`
- `VK_FORMAT_D16_UNORM_S8_UINT`
- `VK_FORMAT_D24_UNORM_S8_UINT`
- `VK_FORMAT_D32_SFLOAT_S8_UINT`

If the format is a depth/stencil format, this bit only specifies that the depth aspect (not the stencil aspect) of an image of this format supports min/max filtering, and that min/max filtering of the depth aspect is supported when depth compare is disabled in the sampler.

If `filterMinmaxImageComponentMapping` is `VK_FALSE` the component mapping of the image view used with min/max filtering **must** have been created with the `r` component set to `VK_COMPONENT_SWIZZLE_IDENTITY`. Only the `r` component of the sampled image value is defined and the other component values are undefined. If `filterMinmaxImageComponentMapping` is `VK_TRUE` this restriction does not apply and image component mapping works as normal.

### Valid Usage (Implicit)

- **sType** **must** be `VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_SAMPLER_FILTER_MINMAX_PROPERTIES`

The `VkPhysicalDeviceProtectedMemoryProperties` structure is defined as:
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:

typedef struct VkPhysicalDeviceMaintenance3Properties {
    VkStructureType sType;
    void* pNext;
    uint32_t maxPerSetDescriptors;
    VkDeviceSize maxMemoryAllocationSize;
} VkPhysicalDeviceMaintenance3Properties;

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 `VkPhysicalDeviceDescriptorIndexingProperties` structure is defined as:

```c
typedef struct VkPhysicalDeviceDescriptorIndexingProperties {
    VkStructureType sType;
    void* pNext;
    uint32_t maxUpdateAfterBindDescriptorsInAllPools;
    VkBool32 shaderUniformBufferArrayNonUniformIndexingNative;
    VkBool32 shaderSampledImageArrayNonUniformIndexingNative;
    VkBool32 shaderStorageBufferArrayNonUniformIndexingNative;
    VkBool32 shaderStorageImageArrayNonUniformIndexingNative;
    VkBool32 shaderInputAttachmentArrayNonUniformIndexingNative;
    VkBool32 robustBufferAccessUpdateAfterBind;
    VkBool32 quadDivergentImplicitLod;
    uint32_t maxPerStageDescriptorUpdateAfterBindSamplers;
    uint32_t maxPerStageDescriptorUpdateAfterBindUniformBuffers;
    uint32_t maxPerStageDescriptorUpdateAfterBindStorageBuffers;
    uint32_t maxPerStageDescriptorUpdateAfterBindSampledImages;
    uint32_t maxPerStageDescriptorUpdateAfterBindStorageImages;
    uint32_t maxPerStageDescriptorUpdateAfterBindInputAttachments;
    uint32_t maxPerStageDescriptorUpdateAfterBindResources;
    uint32_t maxDescriptorSetUpdateAfterBindSamplers;
    uint32_t maxDescriptorSetUpdateAfterBindUniformBuffers;
    uint32_t maxDescriptorSetUpdateAfterBindUniformBuffersDynamic;
    uint32_t maxDescriptorSetUpdateAfterBindStorageBuffers;
    uint32_t maxDescriptorSetUpdateAfterBindStorageBuffersDynamic;
    uint32_t maxDescriptorSetUpdateAfterBindSampledImages;
    uint32_t maxDescriptorSetUpdateAfterBindStorageImages;
    uint32_t maxDescriptorSetUpdateAfterBindInputAttachments;
} VkPhysicalDeviceDescriptorIndexingProperties;
```

The members of the `VkPhysicalDeviceDescriptorIndexingProperties` 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.
- **maxUpdateAfterBindDescriptorsInAllPools** is the maximum number of descriptors (summed over all descriptor types) that can be created across all pools that are created with the `VK_DESCRIPTOR_POOL_CREATE_UPDATE_AFTER_BIND_BIT` bit set. Pool creation may fail when this limit is exceeded, or when the space this limit represents is unable to satisfy a pool creation due to fragmentation.
- **shaderUniformBufferArrayNonUniformIndexingNative** is a boolean value indicating whether uniform buffer descriptors natively support nonuniform indexing. If this is `VK_FALSE`, then a
single dynamic instance of an instruction that nonuniformly indexes an array of uniform buffers may execute multiple times in order to access all the descriptors.

- **shaderSampledImageArrayNonUniformIndexingNative** is a boolean value indicating whether sampler and image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of samplers or images may execute multiple times in order to access all the descriptors.

- **shaderStorageBufferArrayNonUniformIndexingNative** is a boolean value indicating whether storage buffer descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage buffers may execute multiple times in order to access all the descriptors.

- **shaderStorageImageArrayNonUniformIndexingNative** is a boolean value indicating whether storage image descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of storage images may execute multiple times in order to access all the descriptors.

- **shaderInputAttachmentArrayNonUniformIndexingNative** is a boolean value indicating whether input attachment descriptors natively support nonuniform indexing. If this is VK_FALSE, then a single dynamic instance of an instruction that nonuniformly indexes an array of input attachments may execute multiple times in order to access all the descriptors.

- **robustBufferAccessUpdateAfterBind** is a boolean value indicating whether robustBufferAccess can be enabled in a device simultaneously with descriptorBindingUniformBufferUpdateAfterBind, descriptorBindingStorageBufferUpdateAfterBind, descriptorBindingUniformTexelBufferUpdateAfterBind, and/or descriptorBindingStorageTexelBufferUpdateAfterBind. If this is VK_FALSE, then either robustBufferAccess must be disabled or all of these update-after-bind features must be disabled.

- **quadDivergentImplicitLod** is a boolean value indicating whether implicit level of detail calculations for image operations have well-defined results when the image and/or sampler objects used for the instruction are not uniform within a quad. See Derivative Image Operations.

- **maxPerStageDescriptorUpdateAfterBindSamplers** is similar to maxPerStageDescriptorSamplers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindUniformBuffers** is similar to maxPerStageDescriptorUniformBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindStorageBuffers** is similar to maxPerStageDescriptorStorageBuffers but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindSampledImages** is similar to maxPerStageDescriptorSampledImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.

- **maxPerStageDescriptorUpdateAfterBindStorageImages** is similar to maxPerStageDescriptorStorageImages but counts descriptors from descriptor sets created with or without the VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT bit set.
• `maxPerStageDescriptorUpdateAfterBindInputAttachments` is similar to `maxPerStageDescriptorInputAttachments` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxPerStageUpdateAfterBindResources` is similar to `maxPerStageResources` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindSamplers` is similar to `maxDescriptorSetSamplers` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindUniformBuffers` is similar to `maxDescriptorSetUniformBuffers` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindUniformBuffersDynamic` is similar to `maxDescriptorSetUniformBuffersDynamic` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindStorageBuffers` is similar to `maxDescriptorSetStorageBuffers` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindStorageBuffersDynamic` is similar to `maxDescriptorSetStorageBuffersDynamic` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindSampledImages` is similar to `maxDescriptorSetSampledImages` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindStorageImages` is similar to `maxDescriptorSetStorageImages` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

• `maxDescriptorSetUpdateAfterBindInputAttachments` is similar to `maxDescriptorSetInputAttachments` but counts descriptors from descriptor sets created with or without the `VK_DESCRIPTOR_SET_LAYOUT_CREATE_UPDATE_AFTER_BIND_POOL_BIT` bit set.

If the `VkPhysicalDeviceDescriptorIndexingProperties` 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_DESCRIPTOR_INDEXING_PROPERTIES`

The `VkPhysicalDeviceDepthStencilResolveProperties` structure is defined as:
typedef struct VkPhysicalDeviceDepthStencilResolveProperties {
    VkStructureType       sType;
    void*                 pNext;
    VkResolveModeFlags    supportedDepthResolveModes;
    VkResolveModeFlags    supportedStencilResolveModes;
    VkBool32              independentResolveNone;
    VkBool32              independentResolve;
} VkPhysicalDeviceDepthStencilResolveProperties;

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

To query the timeline semaphore properties of a physical device, add a VkPhysicalDeviceTimelineSemaphoreProperties structure to the pNext chain of the VkPhysicalDeviceProperties2 structure. The VkPhysicalDeviceTimelineSemaphoreProperties structure is defined as:

typedef struct VkPhysicalDeviceTimelineSemaphoreProperties {
    VkStructureType       sType;
    void*                 pNext;
    uint64_t              maxTimelineSemaphoreValueDifference;
} VkPhysicalDeviceTimelineSemaphoreProperties;

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

31.1. 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 30. Required Limit Types

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<th>Type</th>
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Table 31. Required Limits

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¹ Limit Type:
- min: Minimum value
- max: Maximum value

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</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.

4 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 $[1.0, 63.875]$. 
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].

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).

The `UpdateAfterBind` descriptor limits must each be greater than or equal to the corresponding non-`UpdateAfterBind` limit.
Chapter 32. 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.

32.1. 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.

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,
} VkFormat;
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VK_FORMAT_B8G8R8_UINT = 34,
VK_FORMAT_B8G8R8_SINT = 35,
VK_FORMAT_B8G8R8_SRGB = 36,
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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,
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VK_FORMAT_R16G16_SSCALED = 80,
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<tr>
<td>VK_FORMAT_R64G64_SFLOAT</td>
<td>115</td>
</tr>
<tr>
<td>VK_FORMAT_R64G64B64_UINT</td>
<td>116</td>
</tr>
<tr>
<td>VK_FORMAT_R64G64B64_SINT</td>
<td>117</td>
</tr>
<tr>
<td>VK_FORMAT_R64G64B64_SFLOAT</td>
<td>118</td>
</tr>
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<td>VK_FORMAT_R64G64B64A64_UINT</td>
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</tr>
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</tr>
<tr>
<td>VK_FORMAT_E5B9G9R9_UFLOAT_PACK32</td>
<td>123</td>
</tr>
<tr>
<td>VK_FORMAT_D16_UNORM</td>
<td>124</td>
</tr>
<tr>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
<td>125</td>
</tr>
<tr>
<td>VK_FORMAT_D32_SFLOAT</td>
<td>126</td>
</tr>
<tr>
<td>VK_FORMAT_S8_UINT</td>
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</tr>
<tr>
<td>VK_FORMAT_D16_UNORM_S8_UINT</td>
<td>128</td>
</tr>
<tr>
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</tr>
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</tr>
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<td>VK_FORMAT_BC1_RGB_UNORM_BLOCK</td>
<td>131</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGB_SRGB_BLOCK</td>
<td>132</td>
</tr>
<tr>
<td>VK_FORMAT_BC1_RGBA_UNORM_BLOCK</td>
<td>133</td>
</tr>
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<td>VK_FORMAT_BC1_RGBA_SRGB_BLOCK</td>
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<tr>
<td>VK_FORMAT_BC2_SRGB_BLOCK</td>
<td>136</td>
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<tr>
<td>VK_FORMAT_BC3_UNORM_BLOCK</td>
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</tr>
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</tr>
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<td>VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
<td>144</td>
</tr>
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<td>145</td>
</tr>
<tr>
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<td>146</td>
</tr>
<tr>
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<td>147</td>
</tr>
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<td>148</td>
</tr>
<tr>
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<td>149</td>
</tr>
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<td>151</td>
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<td>152</td>
</tr>
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<td>153</td>
</tr>
<tr>
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<td>154</td>
</tr>
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<td>156</td>
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<td>157</td>
</tr>
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<td>158</td>
</tr>
<tr>
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<td>159</td>
</tr>
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<td>160</td>
</tr>
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<td>161</td>
</tr>
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<td>162</td>
</tr>
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<td>163</td>
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</tr>
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<td>165</td>
</tr>
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<td>171</td>
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</tr>
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<td>174</td>
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<td>177</td>
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</tr>
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</tr>
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VK_FORMAT_R10X6G10X6_UNORM_2PACK16 = 1000156007,
VK_FORMAT_R10X6B10X6A10X6_UNORM_4PACK16 = 1000156008,
VK_FORMAT_R10X6B10X6R10X6_2PLANE_420_UNORM_3PACK16 = 1000156009,
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VK_FORMAT_B10X6G10X6R10X6G10X6_422_UNORM_4PACK16 = 1000156011,
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VK_FORMAT_B16G16R16G16_422_UNORM = 1000156028

- **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.

• **VK_FORMAT_R8G8_SRGB** specifies a two-component, 16-bit unsigned normalized format that has an 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 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 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 B 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 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_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_USCALED** specifies a four-component, 32-bit unsigned scaled 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_SSCALED** specifies a four-component, 32-bit signed scaled 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_UNORM_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 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_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.
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
• **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 4×4 rectangle of unsigned normalized RGB texel
**VK_FORMAT_BC1_RGB_SRGB_BLOCK** specifies a three-component, block-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_BC1_RGBA_UNORM_BLOCK** specifies a four-component, block-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_BC1_RGBA_SRGB_BLOCK** specifies a four-component, block-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_BC2_UNORM_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 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 4×4 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 $4 \times 4$ 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 $4 \times 4$ 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 $4 \times 4$ 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 $4 \times 4$ 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 $4 \times 4$ rectangle of unsigned normalized RGB texel data with sRGB nonlinear encoding. This format has no alpha and is considered opaque.

• **VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK** specifies a four-component, ETC2 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_ETC2_R8G8B8A8_SRGB_BLOCK** specifies a four-component, ETC2 compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ 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 $4 \times 4$ 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 $4 \times 4$ 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 $4 \times 4$ rectangle of unsigned normalized RG texel data with the first 64 bits encoding red values followed by 64 bits encoding green values.

• **VK_FORMAT_EAC_R11G11_SNORM_BLOCK** specifies a two-component, ETC2 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_ASTC_4x4_UNORM_BLOCK** specifies a four-component, ASTC compressed format where each 128-bit compressed texel block encodes a $4 \times 4$ 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 $4 \times 4$ 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 $5 \times 4$ 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 texel data.
• **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_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 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.

900 | Chapter 32. Formats
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_B8_R8_3PLANE_420_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 \(\lfloor i_G \times 0.5\rfloor = i_B = i_R\) and \(\lfloor j_G \times 0.5\rfloor = j_B = j_R\). 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 and height that is a multiple of two.

- **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 \(\lfloor i_G \times 0.5\rfloor = i_B = i_R\). 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_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 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 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_G8_BBR8_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 \(\lfloor i_G \times 0.5\rfloor = i_B = i_R\). 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_G8_B8R8_3PLANE_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 $2 \times 1$ 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 $2 \times 1$ 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 $2 \times 1$ 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 $2 \times 1$ 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 $|L_G \times 0.5| = I_B = I_R$ and $|L_G \times 0.5| = I_B = J_R$. 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
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 multi-planar 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 \( i_x \times 0.5 \leq i_x = i_R \) and \( j_x \times 0.5 \leq j_x = j_R \). 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 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 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 \( i_x \times 0.5 \leq i_x = i_R \). 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 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 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 \( i_x \times 0.5 = i_x = i_R \). 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 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. 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_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_R12X4G12X4B12X4A12X4_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 $2 \times 1$ 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 $2 \times 1$ 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 $2 \times 1$ 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 $2 \times 1$ compressed texel block.

- **VK_FORMAT_G12X4_B12X4R12X4_3PLANE_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 $l_G \times 0.5 = l_B = l_R$ and $u_G \times 0.5 = u_B = u_R$. 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_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 \( |l_G \times 0.5| = i_B = i_R \) 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, and \( \text{VK\_IMAGE\_ASPECT\_PLANE\_1\_BIT} \) for the BR plane. Images in this format must be defined with a width and height that is a multiple of two.

- **\( \text{VK\_FORMAT\_G12X4\_B12X4\_R12X4\_3PLANE\_422\_UNORM\_3PACK16} \)** 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 \( |l_G \times 0.5| = i_B = i_R \). 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 that is a multiple of two.

- **\( \text{VK\_FORMAT\_G12X4\_B12X4R12X4\_2PLANE\_422\_UNORM\_3PACK16} \)** 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 \( |l_G \times 0.5| = i_B = i_R \). 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, and \( \text{VK\_IMAGE\_ASPECT\_PLANE\_1\_BIT} \) for the BR plane. Images in this format must be defined with a width that is a multiple of two.

- **\( \text{VK\_FORMAT\_G12X4\_B12X4R12X4\_3PLANE\_444\_UNORM\_3PACK16} \)** 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 \( \text{vkGetImageSubresourceLayout} \), 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.

- **\( \text{VK\_FORMAT\_G16B16G16R16\_422\_UNORM} \)** 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.

- **\( \text{VK\_FORMAT\_B16G16R16G16\_422\_UNORM} \)** 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. 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 \( |i_G \times 0.5| = i_B = i_R \) 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, `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 \( |i_G \times 0.5| = i_B = i_R \) 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_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. 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_G16_B16R16_2PLANE_444_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 \( |i_G \times 0.5| = i_B = i_R \). 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, 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.
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.

### 32.1.1. 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 32. 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>VK_FORMAT_G8_B8_R8_3PLANE_420_UNORM</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>( w )</td>
<td>( h )</td>
</tr>
<tr>
<td>0</td>
<td>VK_FORMAT_R8_UNORM</td>
<td>( w )</td>
<td>( h )</td>
</tr>
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<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>VK_FORMAT_R8_UNORM</td>
<td>( w )</td>
<td>( h )</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>VK_FORMAT_R8_UNORM</td>
<td>( w )</td>
<td>( h )</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>
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<td>Height relative to the height $h$ of the plane with the largest dimensions</td>
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<tr>
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<td>Compatible format for plane</td>
<td>Width relative to the width $w$ of the plane with the largest dimensions</td>
<td>Height relative to the height $h$ of the plane with the largest dimensions</td>
</tr>
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<tr>
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<td>VK_FORMAT_R16_UNORM</td>
<td>$w$</td>
<td>$h$</td>
</tr>
</tbody>
</table>

### 32.1.2. 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
32.1.3. 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:

```
VK_FORMAT_{component-format|compression-scheme}_{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 33. 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 34. 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 both horizontally and vertically, and _444 for consistency to indicate that all three planes of a three-planar image are the same size.

No common format has a single plane containing both R and B channels but does not store these channels at reduced horizontal resolution.

32.1.4. 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 35. Byte mappings for non-packed/compressed color formats**

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<td>VK_FORMAT_G10X6B10X6G10X6R10X6_4PACK16_422_UNORM</td>
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<td>VK_FORMAT_G12X4B12X4G12X4R12X4_4PACK16_422_UNORM</td>
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<td>VK_FORMAT_G16B16G16R16_422_UNORM</td>
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<tr>
<td>B G0 R G1</td>
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<td>VK_FORMAT_B10X6G10X6R10X6G10X6_4PACK16_422_UNORM</td>
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<td>VK_FORMAT_B12X4G12X4R12X4G12X4_4PACK16_422_UNORM</td>
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<td></td>
<td>VK_FORMAT_B16G16R16G16_422_UNORM</td>
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<tr>
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<td></td>
<td></td>
<td>VK_FORMAT_R32_*</td>
</tr>
</tbody>
</table>
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 36. Bit mappings for packed 8-bit formats

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>6</td>
<td>5</td>
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</tbody>
</table>

\[
\text{VK_FORMAT_R8G8_UNORM_PACK8}
\]

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

\[
\text{VK_FORMAT_R4G4_UNORM_PACK8}
\]

Table 37. Bit mappings for packed 16-bit formats

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>11</td>
</tr>
</tbody>
</table>

\[
\text{VK_FORMAT_R16G16B16A16_UNORM_PACK16}
\]

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
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</table>

\[
\text{VK_FORMAT_R4G4B4A4_UNORM_PACK16}
\]

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>G</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
</tr>
</tbody>
</table>

\[
\text{VK_FORMAT_R5G5B5A1_UNORM_PACK16}
\]

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
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</table>

\[
\text{VK_FORMAT_A1R5G5B5_UNORM_PACK16}
\]

Chapter 32. Formats | 913
### Table 38. Bit mappings for packed 32-bit formats

<table>
<thead>
<tr>
<th>Bit</th>
<th>A</th>
<th>R</th>
<th>G</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
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<td>1</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**VK_FORMAT_R10X6_UNORM_PACK16**

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>8</td>
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<td>9</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

**VK_FORMAT_R12X4_UNORM_PACK16**

<table>
<thead>
<tr>
<th>Bit</th>
<th>R</th>
<th>X</th>
</tr>
</thead>
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<tr>
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<td>10</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>

#### 32.1.5. 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).

#### 32.1.6. 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 39. 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>
<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------</td>
</tr>
<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_A2R10G10B10_SRGB_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>
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</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>
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<tr>
<td>64-bit B10G10R10A10 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>
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<tr>
<td>64-bit B12G12R12G12 Block size 8 bytes 1 texel/block</td>
<td>VK_FORMAT_B12X4G12X4R12X4G12X4_422_UNORM_4PACK16</td>
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<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
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<tr>
<td>----------------------------------------</td>
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</tr>
<tr>
<td>64-bit G16B16G16R16 8 bytes 1 texel/block</td>
<td>VK_FORMAT_G16B16G16R16_422_UNORM</td>
</tr>
<tr>
<td>64-bit B16G16R16G16 8 bytes 1 texel/block</td>
<td>VK_FORMAT_B16G16R16G16_422_UNORM</td>
</tr>
<tr>
<td>96-bit 12 bytes 1 texel/block</td>
<td>VK_FORMAT_R32G32B32_UINT, VK_FORMAT_R32G32B32_SINT, VK_FORMAT_R32G32B32_SFLOAT</td>
</tr>
<tr>
<td>128-bit 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 24 bytes 1 texel/block</td>
<td>VK_FORMAT_R64G64B64_UINT, VK_FORMAT_R64G64B64_SINT, VK_FORMAT_R64G64B64_SFLOAT</td>
</tr>
<tr>
<td>256-bit 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) 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) 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) 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC2_UNORM_BLOCK, VK_FORMAT_BC2_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC3 (128 bit) 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC3_UNORM_BLOCK, VK_FORMAT_BC3_SRGB_BLOCK</td>
</tr>
<tr>
<td>BC4 (64 bit) 8 bytes 16 texels/block</td>
<td>VK_FORMAT_BC4_UNORM_BLOCK, VK_FORMAT_BC4_SNORM_BLOCK</td>
</tr>
<tr>
<td>BC5 (128 bit) 16 bytes 16 texels/block</td>
<td>VK_FORMAT_BC5_UNORM_BLOCK, VK_FORMAT_BC5_SNORM_BLOCK</td>
</tr>
<tr>
<td>BC6H (128 bit) 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_G8_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_G8_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_G8_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_G8_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>
<tr>
<td>Class, Texel Block Size, # Texels/Block</td>
<td>Formats</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>16-bit 3-plane 420 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM</td>
</tr>
<tr>
<td>16-bit 2-plane 420 Block size (2,4) bytes 1 texel/block</td>
<td>VK_FORMAT_G16_B16R16_2PLANE_420_UNORM</td>
</tr>
<tr>
<td>16-bit 3-plane 422 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G16_B16_R16_3PLANE_422_UNORM</td>
</tr>
<tr>
<td>16-bit 2-plane 422 Block size (2,4) bytes 1 texel/block</td>
<td>VK_FORMAT_G16_B16R16_2PLANE_422_UNORM</td>
</tr>
<tr>
<td>16-bit 3-plane 444 Block size (2,2,2) bytes 1 texel/block</td>
<td>VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM</td>
</tr>
</tbody>
</table>

### 32.2. Format Properties

To query supported format features which are properties of the physical device, call:

```c
void vkGetPhysicalDeviceFormatProperties(
    VkPhysicalDevice physicalDevice,  physicalDevice,
    VkFormat format,                     format,
    VkFormatProperties* pFormatProperties);                     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:
```c
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_CHROMA_RECONSTRUCTION_EXPLICIT_BIT = 0x00100000,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT = 0x00200000,
    VK_FORMAT_FEATURE_DISJOINT_BIT = 0x00400000,
    VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_BIT = 0x00800000,
    VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT = 0x00010000,
    VK_FORMAT_FEATURE_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} 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 images.
- **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_SAMPLED_IMAGE_FILTER_MINMAX_BIT** specifies that `VkImage` can be used as a sampled image with a min or max `VkSamplerReductionMode`. This bit must only be exposed for formats that also support the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT`.

- **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. 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);
```

• **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;
```

- **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

### 32.3. 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_SAMPLED_IMAGE_BIT must also support VK_FORMAT_FEATURE_TRANSFER_SRC_BIT and VK_FORMAT_FEATURE_TRANSFER_DST_BIT.
Table 40. Key for format feature tables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>This feature <strong>must</strong> be supported on the named format</td>
</tr>
<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 41. Feature bits in `optimalTilingFeatures`

<table>
<thead>
<tr>
<th>Feature Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_FEATURE_TRANSFER_SRC_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_TRANSFER_DST_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_BLIT_SRC_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_BLIT_DST_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT</td>
</tr>
</tbody>
</table>

Table 42. Feature bits in `bufferFeatures`

<table>
<thead>
<tr>
<th>Feature Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT</td>
</tr>
</tbody>
</table>

928 | Chapter 32. Formats
<table>
<thead>
<tr>
<th>Format</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_UNDEFINED</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_R4G4_UNORM_PACK8</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_R4G4B4A4_UNORM_PACK16</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_B4G4R4A4_UNORM_PACK16</td>
<td>✓ ✓ ✓</td>
</tr>
<tr>
<td>VK_FORMAT_R5G6B5_UNORM_PACK16</td>
<td>✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>VK_FORMAT_B5G6R5A1_UNORM_PACK16</td>
<td></td>
</tr>
<tr>
<td>VK_FORMAT_A1R5G5B5_UNORM_PACK16</td>
<td>✓ ✓ ✓ ✓</td>
</tr>
</tbody>
</table>

**Table 43. Mandatory format support: sub-byte channels**

- **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT**
- **VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT**
- **VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT**
- **VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT**
- **VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT**
- **VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT**
- **VK_FORMAT_FEATURE_BLIT_DST_BIT**
- **VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT**
- **VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT**
- **VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT**
- **VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT**
- **VK_FORMAT_FEATURE_BLIT_SRC_BIT**
- **VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT**
Table 44. Mandatory format support: 1-3 byte-sized channels

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_R8_UNORM</th>
<th>VK_FORMAT_R8_SNORM</th>
<th>VK_FORMAT_R8_USCALED</th>
<th>VK_FORMAT_R8_SSCALED</th>
<th>VK_FORMAT_R8_UINT</th>
<th>VK_FORMAT_R8_SINT</th>
<th>VK_FORMAT_R8_SRGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_R8G8_B8G8_UNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_B8G8_SNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_B8G8_USCALED</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_B8G8_SSCALED</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_B8G8_UINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_B8G8_SINT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_R8G8_B8G8_SRGB</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>VK_FORMAT_B8G8R8_B8G8_UNORM</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>VK_FORMAT_B8G8R8_B8G8_SNORM</td>
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<td>VK_FORMAT_B8G8R8_B8G8_USCALED</td>
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<tr>
<td>VK_FORMAT_B8G8R8_B8G8_SSCALED</td>
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<tr>
<td>VK_FORMAT_B8G8R8_B8G8_SINT</td>
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<tr>
<td>VK_FORMAT_B8G8R8_B8G8_SRGB</td>
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</tbody>
</table>
Format features marked with ‡ must be supported for optimalTilingFeatures if the 
VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
Table 45. Mandatory format support: 4 byte-sized channels

| Format | 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 |
|--------|--------------------------|---------------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Format | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
### Table 46. 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>
</tr>
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<tr>
<td>VK_FORMAT_R10X6_UNORM_PACK16</td>
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<td>VK_FORMAT_R10X6G10X6_UNORM_2PACK16</td>
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<tr>
<td>VK_FORMAT_R12X4_UNORM_PACK16</td>
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</table>

Format features marked with ‡ **must** be supported for **optimalTilingFeatures** if the VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
### Table 47. Mandatory format support: 16-bit channels

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<tbody>
<tr>
<td>VK_FORMAT_R16G16B16A16_UINT</td>
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</tr>
<tr>
<td>Format features marked with ‡</td>
<td>must</td>
<td>be supported for optimalTilingFeatures if the</td>
<td>VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.</td>
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</table>
Table 48. Mandatory format support: 32-bit channels

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<tr>
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### Table 49. Mandatory format support: 64-bit/uneven channels

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_R64_UINT</th>
<th>VK_FORMAT_R64_SINT</th>
<th>VK_FORMAT_R64_SFLOAT</th>
<th>VK_FORMAT_R64G64_UINT</th>
<th>VK_FORMAT_R64G64_SINT</th>
<th>VK_FORMAT_R64G64_SFLOAT</th>
<th>VK_FORMAT_R64G64B64_UINT</th>
<th>VK_FORMAT_R64G64B64_SINT</th>
<th>VK_FORMAT_R64G64B64_SFLOAT</th>
<th>VK_FORMAT_B10G11R11_UFLOAT_PACK32</th>
<th>VK_FORMAT_E5B9G9R9_UFLOAT_PACK32</th>
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Format features marked with ‡ must be supported for optimalTilingFeatures if the VkPhysicalDevice supports the shaderStorageImageExtendedFormats feature.
Table 50. Mandatory format support: depth/stencil with VkImageType VK_IMAGE_TYPE_2D

<table>
<thead>
<tr>
<th>Format</th>
<th>VK_FORMAT_D16_UNORM</th>
<th>VK_FORMAT_X8_D24_UNORM_PACK32</th>
<th>VK_FORMAT_D32_SFLOAT</th>
<th>VK_FORMAT_S8_UINT</th>
<th>VK_FORMAT_D16_UNORM_S8_UINT</th>
<th>VK_FORMAT_D24_UNORM_S8_UINT</th>
<th>VK_FORMAT_D32_SFLOAT_S8_UINT</th>
<th>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</th>
<th>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.</th>
</tr>
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<td>Format</td>
<td>VK_FORMAT_D16_UNORM</td>
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<tr>
<td>Format</td>
<td>VK_FORMAT_X8_D24_UNORM_PACK32</td>
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<tr>
<td>Format</td>
<td>VK_FORMAT_D32_SFLOAT</td>
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<tr>
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</table>
### Table 51. Mandatory format support: BC compressed formats with VkImageType VK_IMAGE_TYPE_2D and VK_IMAGE_TYPE_3D

<table>
<thead>
<tr>
<th>Feature</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT</td>
<td>VK_FORMAT_BC1_RGB_UNORM_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT</td>
<td>VK_FORMAT_BC1_RGB_SRGB_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT</td>
<td>VK_FORMAT_BC1_RGBA_UNORM_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT</td>
<td>VK_FORMAT_BC1_RGBA_SRGB_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT</td>
<td>VK_FORMAT_BC2_UNORM_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT</td>
<td>VK_FORMAT_BC2_SRGB_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_BLIT_DST_BIT</td>
<td>VK_FORMAT_BC3_UNORM_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT</td>
<td>VK_FORMAT_BC3_SRGB_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT</td>
<td>VK_FORMAT_BC4_UNORM_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_BLIT_SRC_BIT</td>
<td>VK_FORMAT_BC4_SNORM_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT</td>
<td>VK_FORMAT_BC5_UNORM_BLOCK</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
<td>VK_FORMAT_BC5_SNORM_BLOCK</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
<td>VK_FORMAT_BC6H_UFLOAT_BLOCK</td>
</tr>
<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
<td>VK_FORMAT_BC6H_SFLOAT_BLOCK</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
<td>VK_FORMAT_BC7_UNORM_BLOCK</td>
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<tr>
<td>VK_FORMAT_FEATURE_SAMPLED_IMAGE_ATOMIC_BIT</td>
<td>VK_FORMAT_BC7_SRGB_BLOCK</td>
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</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 52. Mandatory format support: ETC2 and EAC compressed formats with `VkImageType
VK_IMAGE_TYPE_2D`

<table>
<thead>
<tr>
<th>Format</th>
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<tbody>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8_UNORM_BLOCK</td>
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<tr>
<td>VK_FORMAT_ETC2_R8G8B8_SRGB_BLOCK</td>
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<td>†</td>
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<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_UNORM_BLOCK</td>
<td>†</td>
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<tr>
<td>VK_FORMAT_ETC2_R8G8B8A1_SRGB_BLOCK</td>
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<td>†</td>
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<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_UNORM_BLOCK</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>VK_FORMAT_ETC2_R8G8B8A8_SRGB_BLOCK</td>
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<td>VK_FORMAT_EAC_R11G11_UNORM_BLOCK</td>
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<tr>
<td>VK_FORMAT_EAC_R11G11_SNORM_BLOCK</td>
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</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`. 
Table 53. Mandatory format support: ASTC LDR compressed formats with `VkImageType VK_IMAGE_TYPE_2D`

| VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_ATOMIC_BIT | VK_FORMAT_FEATURE_STORAGE_TEXEL_BUFFER_BIT |
| VK_FORMAT_FEATURE_UNIFORM_TEXEL_BUFFER_BIT | VK_FORMAT_FEATURE_VERTEX_BUFFER_BIT |
| VK_FORMAT_FEATURE_DEPTH_STENCIL_ATTACHMENT_BIT | VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BLEND_BIT |
| VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT | VK_FORMAT_FEATURE_STORAGE_IMAGE_ATOMIC_BIT |
| VK_FORMAT_FEATURE_STORAGE_IMAGE_BIT | VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_LINEAR_BIT |
| VK_FORMAT_FEATURE_BLIT_SRC_BIT | VK_FORMAT_FEATURE_SAMPLED_IMAGE_BIT |

Format

- `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_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`
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 54. 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_B8G8R8B8_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_B8B8_2PLANE_420_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_422_UNORM</td>
<td>3</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8B8_2PLANE_422_UNORM</td>
<td>2</td>
</tr>
<tr>
<td>VK_FORMAT_G8_B8_R8_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_B10X6_R10X6_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>Count</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’C_bC_r conversion. To determine whether the implementation supports sparse image creation flags with these formats use `vkGetPhysicalDeviceImageFormatProperties` or `vkGetPhysicalDeviceImageFormatProperties2`. 
Chapter 33. 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

33.1. 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’CbCr 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’CbCr 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);

- **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:

```c
typedef struct VkPhysicalDeviceImageFormatInfo2 {
    VkStructureType       sType;
    const void*           pNext;
    VkFormat              format;
    VkImageType           type;
    VkImageTiling         tiling;
    VkImageUsageFlags     usage;
    VkImageCreateFlags    flags;
} VkPhysicalDeviceImageFormatInfo2;
```
- `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 `vkGetPhysicalDeviceImageFormatProperties2`.
- `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`, `VkImageStencilUsageCreateInfo`, 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;
```

- `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;
```

• **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
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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalMemoryHandleTypeFlagBits;
```

- `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 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 `IDXGIFactory1::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 55. 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_D3D12RESOURCE_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
</tbody>
</table>

typedef VkFlags VkExternalMemoryHandleTypeFlags;

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;
```

- **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:
typedef struct VkExternalMemoryProperties {
    VkExternalMemoryFeatureFlags externalMemoryFeatures;
    VkExternalMemoryHandleTypeFlags exportFromImportedHandleTypes;
    VkExternalMemoryHandleTypeFlags compatibleHandleTypes;
} VkExternalMemoryProperties;

- **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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalMemoryFeatureFlagBits;

- **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_KMT_BIT**
VK_EXTERNAL_MEMORY_HANDLE_TYPE_D3D12_RESOURCE_BIT

typedef VkFlags VkExternalMemoryFeatureFlags;

`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 the `pNext` chain of the `VkImageFormatProperties2` structure in a call to `vkGetPhysicalDeviceImageFormatProperties2`.

The `VkSamplerYcbcrConversionImageFormatProperties` structure is defined as:

```c
typedef struct VkSamplerYcbcrConversionImageFormatProperties {
    VkStructureType sType;
    void* pNext;
    uint32_t combinedImageSamplerDescriptorCount;
} VkSamplerYcbcrConversionImageFormatProperties;
```

- `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.
Note

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.

33.1.1. 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’C_bC_r 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_COLOR_ATTACHMENT_BIT and format is an integer format, a superset of VkPhysicalDeviceVulkan12Properties::framebufferIntegerColorSampleCounts
- 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 VkPhysicalDeviceLimits::sampledImageDepthSampleCounts

- If `usage` includes `VK_IMAGE_USAGE_SAMPLED_BIT`, and `format` is an integer format, a superset of VkPhysicalDeviceLimits::sampledImageIntegerSampleCounts

- If `usage` includes `VK_IMAGE_USAGE_STORAGE_BIT`, a superset of VkPhysicalDeviceLimits::storageImageSampleCounts

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`.

### 33.1.2. 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

33.2. Additional Buffer Capabilities

To query the external handle types supported by buffers, call:

```c
void vkGetPhysicalDeviceExternalBufferProperties(
  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;
```

- `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`.

Chapter 33. Additional Capabilities | 957
• `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;
```

- **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.

### Valid Usage (Implicit)

- **sType** must be `VK_STRUCTURE_TYPE_EXTERNAL_BUFFER_PROPERTIES`
- **pNext** must be `NULL`

### 33.3. 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);
```
• `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:

```c
typedef struct VkPhysicalDeviceExternalSemaphoreInfo {
    VkStructureType sType;
    const void* pNext;
    VkExternalSemaphoreHandleTypeFlagBits handleType;
} VkPhysicalDeviceExternalSemaphoreInfo;
```

- `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:
```c
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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalSemaphoreHandleTypeFlagBits;
```

- **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 56. External semaphore 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_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>

**typedef** VkFlags VkExternalSemaphoreHandleTypeFlags;

**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;
    VkExternalSemaphoreHandleTypeFlags compatibleHandleTypes;
    VkExternalSemaphoreFeatureFlags externalSemaphoreFeatures;
} VkExternalSemaphoreProperties;
```

- **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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalSemaphoreFeatureFlagBits;
```

- `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;
```

`VkExternalSemaphoreFeatureFlags` is a bitmask type for setting a mask of zero or more `VkExternalSemaphoreFeatureFlagBits`.

### 33.4. 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);
```

- `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;
```

- `sType` is the type of this structure
- `pNext` is NULL or a pointer to an extension-specific structure.
- `handleType` is a `VkExternalFenceHandleTypeFlagBits` 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` 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:
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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalFenceHandleTypeFlagBits;

- **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 57. 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_FENCEHANDLE_TYPE_OPAQUE_FD_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCEHANDLE_TYPE_OPAQUE_WIN32_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCEHANDLE_TYPE_OPAQUE_WIN32_KMT_BIT</td>
<td>Must match</td>
<td>Must match</td>
</tr>
<tr>
<td>VK_EXTERNAL_FENCEHANDLE_TYPE_SYNC_FD_BIT</td>
<td>No restriction</td>
<td>No restriction</td>
</tr>
</tbody>
</table>

```c
typedef VkFlags VkExternalFenceHandleTypeFlags;
```

**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;
```

- **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_FLAG_BITS_MAX_ENUM = 0x7FFFFFFF
} VkExternalFenceFeatureFlagBits;
```

- **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;
```

`VkExternalFenceFeatureFlags` is a bitmask type for setting a mask of zero or more `VkExternalFenceFeatureFlagBits`. 
Chapter 34. 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.

```c
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_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>
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Table 58. VkObjectType and Vulkan Handle Relationship
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<tr>
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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 1.2 implementation must support the 1.0, 1.1, 1.2, 1.3, 1.4, and 1.5 versions of SPIR-V and the 1.0 version of the SPIR-V Extended Instructions for GLSL.

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>
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### SPIR-V OpCapability

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<tr>
<td>PhysicalStorageBufferAddresses</td>
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</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
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_EXT_shader_viewport_index_layer SPIR-V extension.

The application can pass a SPIR-V module to `vkCreateShaderModule` that uses the SPV_EXT_descriptor_indexing 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_physical_storage_buffer 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
  - Workgroup
    - The Workgroup storage class must only be used in the compute execution model(s).
  - Private
  - Function
  - PushConstant
  - Image
  - StorageBuffer
  - 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 the result type pointing to an 8-bit integer object or an object containing an 8-bit integer element must not have one of the following as its Storage Class operand:
  - Uniform
  - PushConstant
  - StorageBuffer

- Any OpVariable with the result type pointing to a 16-bit floating-point object or an object
containing a 16-bit floating-point element must not have one of the following as its Storage Class operand:

- **Uniform**
- **PushConstant**
- **StorageBuffer**

- Any *OpVariable* with an *Initializer* operand must have one of the following as its Storage Class operand:
  - **Output**
  - **Private**
  - **Function**

- 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*
  - 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.
- 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.
  - If the RuntimeDescriptorArray capability is supported, an array of variables with storage class Uniform, StorageBuffer, or UniformConstant, or for the outermost dimension of an array of arrays of such variables.

- 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 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**

• If **subgroupBroadcastDynamicId** is **VK_TRUE**, and the shader module version is 1.5 or higher, the “**Index**” for **OpGroupNonUniformQuadBroadcast** must be dynamically uniform within the derivative group. Otherwise, “**Index**” must be a constant.

• If **subgroupBroadcastDynamicId** is **VK_TRUE**, and the shader module version is 1.5 or higher, the “**Id**” for **OpGroupNonUniformBroadcast** must be dynamically uniform within the subgroup. Otherwise, “**Id**” must be a constant.

• Atomic instructions must declare a scalar 32-bit integer type, for the value pointed to by **Pointer**.

• The **Pointer** operand of all atomic instructions must have a **Storage Class** limited to:
  - **Uniform**
  - **Workgroup**
  - **Image**
- **StorageBuffer**
- If an instruction loads from or stores to a resource (including atomics and image instructions) and the resource descriptor being accessed is not dynamically uniform, then the operand corresponding to that resource (e.g. the pointer or sampled image operand) **must** be decorated with `NonUniform`.
- 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 `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.

• 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.


- 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.

*Correctly Rounded*

Operations described as “correctly rounded” will return the infinitely precise result, $x$, rounded so 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 \( \text{ulp}(x) \) is the minimum possible distance between such numbers, \( \text{ulp}(x) = \min_{a, b} |b - a| \). 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>
<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>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>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>OpFOrdLessThan, OpFUnordLessThan</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdGreaterThan, OpFUnordGreaterThan</td>
<td>Correct result.</td>
<td></td>
</tr>
<tr>
<td>OpFOrdGreaterThanEqual, OpFUnordGreaterThanEqual</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 61. 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 \times</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 \times log2(x)).</td>
<td></td>
</tr>
<tr>
<td>sqrt()</td>
<td>Inherited from 1.0 / <strong>inversesqrt</strong>().</td>
<td></td>
</tr>
<tr>
<td>inversesqrt()</td>
<td>2 ULP.</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>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>sin()</td>
<td>Absolute error $\leq 2^{-11}$ inside the range $[-\pi, \pi]$</td>
<td>Absolute error $\leq 2^{-7}$ inside the range $[-\pi, \pi]$</td>
</tr>
<tr>
<td>cos()</td>
<td>Absolute error $\leq 2^{-11}$ inside the range $[-\pi, \pi]$</td>
<td>Absolute error $\leq 2^{-7}$ inside the range $[-\pi, \pi]$</td>
</tr>
<tr>
<td>tan()</td>
<td>Inherited from $\frac{\sin()}{\cos()}$</td>
<td></td>
</tr>
<tr>
<td>asin(x)</td>
<td>Inherited from $\arctan2(x, \sqrt{1 - x \times x})$</td>
<td></td>
</tr>
<tr>
<td>acos(x)</td>
<td>Inherited from $\arctan2(\sqrt{1 - x \times x}, x)$</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 $\frac{\sinh()}{\cosh()}$</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 $\log\left(\frac{1 + x}{1 - x}\right) \times 0.5.$</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 $\text{dot}(\text{NRef}, I) &lt; 0.0 ? N : -N.$</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>refract(I, N, eta)</td>
<td>Inherited from $k &lt; 0.0 ? 0.0 : \text{eta} \times I - (\text{eta} \times \text{dot}(N, I) + \sqrt{k}) \times N$, where $k = 1 - \text{eta} \times \text{eta} \times (1.0 - \text{dot}(N, I) \times \text{dot}(N, I))$.</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>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>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 $x \times (1.0 - a) + y \times a.$</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 $t = \text{clamp}(\frac{x - edge0}{edge1 - edge0}, 0.0, 1.0)$.</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.

### Compatibility Between SPIR-V Image Formats And Vulkan Formats

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 62. 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_SFLOAT</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>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_UINT_PACK32</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”).
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 memory fences.

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, 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.

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 `inter-thread-happens-before<SC>` 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 `happens-before` 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

**Happens-after** is defined similarly.

Unlike C++, happens-before is not always sufficient for a write to be visible to a read. Additional *availability and visibility* operations *may* be required for writes to be *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

*Availability* and *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. Availability state is per *memory domain*. Visibility state is per (agent,reference) pair. Availability and 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 *scopes*. Each memory domain is considered the *dual* of a scope, and vice versa. 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.
• *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, with memory domains later in the list nested in the domains earlier in the list.
Memory domains do not correspond to storage classes or device-local and host-local \texttt{VkDeviceMemory} allocations, rather they indicate whether a write can be made visible only to agents in the same subgroup, same workgroup, in any shader invocation, or anywhere on the device, or host. The shader, queue family 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.

\textit{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
- **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 for visibility operations.

**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 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 D₁ and D₂ are different memory domains, then let DOM(D₁,D₂) be a memory domain operation from D₁ to D₂. 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:

- Aₙ = Aₚ and Rₙ = Rₚ 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 Rₙ = Rₚ and Aₙ and Aₚ 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(Aₙ, Rₙ, D, L) is an availability chain making (X,L) available to domain D, and X →_{rcpo} AVC(Aₙ, Rₙ, D, L) → Y
  - X is a write, Y is a read, AVC(Aₙ, Rₙ, D, L) is an availability chain making (X,L) available to domain D, VISC(Aₚ, Rₚ, D, L) is a visibility chain making writes to L available in domain D visible to Y, and X →_{rcpo} AVC(Aₙ, Rₙ, D, L) → VISC(Aₚ, Rₚ, D, L) →_{rcpo} 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 Dₙ and Dₚ each be either the device domain or the host domain, depending on whether Aₙ and Aₚ execute on the device or host:
  - X is a write and Y is a write, and X → AV(Aₙ, Rₙ, Dₙ, L) → DOM(Dₙ,Dₚ) → Y
  - X is a write and Y is a read, and X → AV(Aₙ, Rₙ, Dₙ, L) → DOM(Dₙ,Dₚ) → VIS(Aₚ, Rₚ, Dₚ, L) → 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”.

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Appendix B: Memory Model | 997
**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 ($M_2$) 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 Input, then X is system-synchronized-after all writes to the corresponding 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.
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 63. 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>Formats described in the “S3TC Compressed Texture Image Formats” chapter</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>Formats described in the “RGTC Compressed Texture Image Formats” chapter</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>Formats described in the “BPTC Compressed Texture Image Formats” chapter</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 64. Mapping of Vulkan ETC formats to descriptions

<table>
<thead>
<tr>
<th>VkFormat</th>
<th>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 65. 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_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 1.2

Vulkan Version 1.2 promoted a number of key extensions into the core API:

- VK_KHR_8bit_storage
- VK_KHR_buffer_device_address
- VK_KHR_create_renderpass2
- VK_KHR_depth_stencil_resolve
- VK_KHR_draw_indirect_count
- VK_KHR_driver_properties
- VK_KHR_image_format_list
- VK_KHR_imageless_framebuffer
- VK_KHR_sampler_mirror_clamp_to_edge
- VK_KHR_separate_depthStencil_layouts
- VK_KHR_shader_atomic_int64
- VK_KHR_shader_float16_int8
- VK_KHR_shader_float_controls
- VK_KHR_shader_subgroup_extended_types
VK_KHR_spirv_1_4

• VK_KHR_timeline_semaphore
• VK_KHR_uniform_buffer_standard_layout
• VK_KHR_vulkan_memory_model
• VK_EXT_descriptor_indexing
• VK_EXT_host_query_reset
• VK_EXT_sampler_filter_minmax
• VK_EXT_scalar_block_layout
• VK_EXT_separate_stencil_usage
• VK_EXT_shader_viewport_index_layer

All differences in behavior between these extensions and the corresponding Vulkan 1.2 functionality are summarized below.

**Differences relative to VK_KHR_8bit_storage**

If the [VK_KHR_8bit_storage] extension is not supported, support for the SPIR-V StorageBuffer8BitAccess capability in shader modules is optional. Support for this feature is defined by 

```
VkPhysicalDeviceVulkan12Features::storageBuffer8BitAccess
```

when queried via 

```
vkGetPhysicalDeviceFeatures2
```

**Differences relative to VK_KHR_draw_indirect_count**

If the [VK_KHR_draw_indirect_count] extension is not supported, support for the entry points 

```
vkCmdDrawIndirectCount
```

and 

```
vkCmdDrawIndexedIndirectCount
```

is optional. Support for this feature is defined by 

```
VkPhysicalDeviceVulkan12Features::drawIndirectCount
```

when queried via 

```
vkGetPhysicalDeviceFeatures2
```

**Differences relative to VK_KHR_sampler_mirror_clamp_to_edge**

If the [VK_KHR_sampler_mirror_clamp_to_edge] extension is not supported, support for the 

```
VkSamplerAddressMode VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE
```

is optional. Support for this feature is defined by 

```
VkPhysicalDeviceVulkan12Features::samplerMirrorClampToEdge
```

when queried via 

```
vkGetPhysicalDeviceFeatures2
```
Differences relative to **VK_EXT_descriptor_indexing**

If the [VK_EXT_descriptor_indexing] extension is not supported, support for the descriptorIndexing feature is optional. Support for this feature is defined by `VkPhysicalDeviceVulkan12Features::descriptorIndexing` when queried via `vkGetPhysicalDeviceFeatures2`.

Differences relative to **VK_EXT_scalar_block_layout**

If the [VK_EXT_scalar_block_layout] extension is not supported, support for the scalarBlockLayout feature is optional. Support for this feature is defined by `VkPhysicalDeviceVulkan12Features::scalarBlockLayout` when queried via `vkGetPhysicalDeviceFeatures2`.

Differences relative to **VK_EXT_shader_viewport_index_layer**

If the [VK_EXT_shader_viewport_index_layer] extension is not supported, support for the ShaderViewportIndexLayerEXT SPIR-V capability is optional. Support for this feature is defined by `VkPhysicalDeviceVulkan12Features::shaderOutputViewportIndex` and `VkPhysicalDeviceVulkan12Features::shaderOutputLayer` when queried via `vkGetPhysicalDeviceFeatures2`.

**Additional Vulkan 1.2 Feature Support**

In addition to the promoted extensions described above, Vulkan 1.2 added support for:

- SPIR-V version 1.4.
- SPIR-V version 1.5.
- The `samplerMirrorClampToEdge` feature which indicates whether the implementation supports the `VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE` sampler address mode.
- The `ShaderNonUniform` capability in SPIR-V version 1.5.
- The `shaderOutputViewportIndex` feature which indicates that the `ShaderViewportIndex` capability can be used.
- The `shaderOutputLayer` feature which indicates that the `ShaderLayer` capability can be used.
- The `subgroupBroadcastDynamicId` feature which allows the “Id” operand of `OpGroupNonUniformBroadcast` to be dynamically uniform within a subgroup, and the “Index” operand of `OpGroupNonUniformQuadBroadcast` to be dynamically uniform within a derivative group, in shader modules of version 1.5 or higher.
- The `drawIndirectCount` feature which indicates whether the `vkCmdDrawIndirectCount` and `vkCmdDrawIndexedIndirectCount` functions can be used.
- The `descriptorIndexing` feature which indicates the implementation supports the minimum number of descriptor indexing features as defined in the Feature Requirements section.
- The `samplerFilterMinmax` feature which indicates whether the implementation supports the minimum number of image formats that support the `VK_FORMAT_FEATURE_SAMPLED_IMAGE_FILTER_MINMAX_BIT` feature bit as defined by the `filterMinmaxSingleComponentFormats` property minimum requirements.
- The `framebufferIntegerColorSampleCounts` limit which indicates the color sample counts that
are supported for all framebuffer color attachments with integer formats.

**New Object Types**

**New Defines**

- **VK_API_VERSION_1_2**

**New Enum Constants**

**New Enums**

**New Structures**

- VkPhysicalDeviceVulkan11Features
- VkPhysicalDeviceVulkan11Properties
- VkPhysicalDeviceVulkan12Features
- VkPhysicalDeviceVulkan12Properties
- VkPhysicalDevice8BitStorageFeatures
- VkPhysicalDeviceBufferDeviceAddressFeatures
- VkBufferDeviceAddressInfo
- VkBufferOpaqueCaptureAddressCreateInfo
- VkMemoryOpaqueCaptureAddressAllocateInfo
- VkDeviceMemoryOpaqueCaptureAddressInfo
- VkAttachmentDescription2
- VkAttachmentReference2
- VkSubpassDescription2
- VkSubpassDependency2
- VkRenderPassCreateInfo2
- VkSubpassBeginInfo
- VkSubpassEndInfo
- VkPhysicalDeviceDepthStencilResolveProperties
- VkSubpassDescriptionDepthStencilResolve
- VkConformanceVersion
- VkPhysicalDeviceDriverProperties
- VkImageFormatListCreateInfo
- VkPhysicalDeviceImagelessFramebufferFeatures
- VkFramebufferAttachmentsCreateInfo
New Functions

- VkFramebufferAttachmentImageInfo
- VkRenderPassAttachmentBeginInfo
- VkPhysicalDeviceSeparateDepthStencilLayoutsFeatures
- VkAttachmentReferenceStencilLayout
- VkAttachmentDescriptionStencilLayout
- VkPhysicalDeviceShaderAtomicInt64Features
- VkPhysicalDeviceShaderFloat16Int8Features
- VkPhysicalDeviceFloatControlsProperties
- VkPhysicalDeviceShaderSubgroupExtendedTypesFeatures
- VkPhysicalDeviceTimelineSemaphoreFeatures
- VkPhysicalDeviceTimelineSemaphoreProperties
- VkSemaphoreTypeCreateInfo
- VkTimelineSemaphoreSubmitInfo
- VkSemaphoreWaitInfo
- VkSemaphoreSignalInfo
- VkPhysicalDeviceUniformBufferStandardLayoutFeatures
- VkPhysicalDeviceVulkanMemoryModelFeatures
- VkDescriptorSetLayoutBindingFlagsCreateInfo
- VkPhysicalDeviceDescriptorIndexingFeatures
- VkPhysicalDeviceDescriptorIndexingProperties
- VkDescriptorSetVariableDescriptorCountAllocateInfo
- VkDescriptorSetVariableDescriptorCountLayoutSupport
- VkPhysicalDeviceHostQueryResetFeatures
- VkSamplerReductionModeCreateInfo
- VkPhysicalDeviceSamplerFilterMinmaxProperties
- VkPhysicalDeviceScalarBlockLayoutFeatures
- VkImageStencilUsageCreateInfo
- VkImageStencilUsageCreateInfo

- vkGetBufferDeviceAddress
- vkGetBufferOpaqueCaptureAddress
- vkGetDeviceMemoryOpaqueCaptureAddress
- vkCreateRenderPass2
- vkCmdBeginRenderPass2
- vkCmdNextSubpass2
• vkCmdEndRenderPass2
• vkCmdDrawIndirectCount
• vkCmdDrawIndexedIndirectCount
• vkGetSemaphoreCounterValue
• vkWaitSemaphores
• vkSignalSemaphore
• vkResetQueryPool

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
The only changes to the functionality added by these extensions were to \texttt{VK_KHR\_shader\_draw\_parameters}, which had the \texttt{shaderDrawParameters} feature bit added to determine support in the core API, and \texttt{variablePointersStorageBuffer} from \texttt{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**

- \texttt{VkDescriptorUpdateTemplate}
- \texttt{VkSamplerYcbcrConversion}

**New Defines**

- \texttt{VK\_API\_VERSION\_1\_1}

**New Enum Constants**

- Extending \texttt{VkBufferCreateFlagBits}:
  - \texttt{VK\_BUFFER\_CREATE\_PROTECTED\_BIT}
- Extending \texttt{VkCommandPoolCreateFlagBits}:
  - \texttt{VK\_COMMAND\_POOL\_CREATE\_PROTECTED\_BIT}
- Extending \texttt{VkDependencyFlagBits}:
  - \texttt{VK\_DEPENDENCY\_DEVICE\_GROUP\_BIT}
• Extending `VkDeviceQueueCreateInfo`:
  • `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_R10X6_2PACK16`
  • `VK_FORMAT_R10X6G10X6_A10X6_A4_4PACK16`
  • `VK_FORMAT_B10X6G10X6R10X6_422_UNORM_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_R12X4_UNORM_PACK16`
  • `VK_FORMAT_R12X4G12X4_R12X4_2PACK16`
  • `VK_FORMAT_R12X4G12X4_B12X4_4PACK16`
  • `VK_FORMAT_B12X4G12X4R12X4_422_UNORM_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_G16B16G16R16_422_UNORM`
  • `VK_FORMAT_B16G16R16G16_422_UNORM`
  • `VK_FORMAT_G16_B16_R16_3PLANE_420_UNORM`
  • `VK_FORMAT_G16_B16R16_2PLANE_420_UNORM`
  • `VK_FORMAT_G16_B16R16_3PLANE_422_UNORM`
  • `VK_FORMAT_G16_B16R16_2PLANE_422_UNORM`
  • `VK_FORMAT_G16_B16_R16_3PLANE_444_UNORM`

• Extending `VkFormatFeatureFlagBits`:
  • `VK_FORMAT_FEATURE_TRANSFER_SRC_BIT`
  • `VK_FORMAT_FEATURE_TRANSFER_DST_BIT`
- VK_FORMAT_FEATURE_MIDPOINT_CHROMA_SAMPLES_BIT
- VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_LINEAR_FILTER_BIT
- VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_SEPARATE_RECONSTRUCTION_FILTER_BIT
- VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_BIT
- VK_FORMAT_FEATURE_SAMPLED_IMAGE_YCBCR_CONVERSION_CHROMA_RECONSTRUCTION_EXPLICIT_FORCEABLE_BIT
- VK_FORMAT_FEATURE_DISJOINT_BIT
- VK_FORMAT_FEATURE_COSITED_CHROMA_SAMPLES_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
- VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_INFO
- VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_INFO
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_16BIT_STORAGE_FEATURES
- VK_STRUCTURE_TYPE_MEMORY_DEDICATED_REQUIREMENTS
- VK_STRUCTURE_TYPE_MEMORY_DEDICATED_ALLOCATE_INFO
- VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_FLAGS_INFO
- VK_STRUCTURE_TYPE_DEVICE_GROUP_RENDER_PASS_BEGIN_INFO
- VK_STRUCTURE_TYPE_DEVICE_GROUP_COMMAND_BUFFER_BEGIN_INFO
- VK_STRUCTURE_TYPE_DEVICE_GROUP_SUBMIT_INFO
- VK_STRUCTURE_TYPE_DEVICE_GROUP_BIND_SPARSE_INFO
- VK_STRUCTURE_TYPE_BIND_BUFFER_MEMORY_DEVICE_GROUP_INFO
- VK_STRUCTURE_TYPE_BIND_IMAGE_MEMORY_DEVICE_GROUP_INFO
- VK_STRUCTURE_TYPE_PHYSICAL DEVICE_GROUP_PROPERTIES
- VK_STRUCTURE_TYPE_DEVICE_GROUP_DEVICE_CREATE_INFO
- VK_STRUCTURE_TYPE_BUFFER_MEMORY_REQUIREMENTS_INFO_2
- VK_STRUCTURE_TYPE_IMAGE_MEMORY_REQUIREMENTS_INFO_2
- VK_STRUCTURE_TYPE_IMAGE_SPARSE_MEMORY_REQUIREMENTS_INFO_2
- VK_STRUCTURE_TYPE_MEMORY_REQUIREMENTS_2
- VK_STRUCTURE_TYPE_SPARSE_IMAGE_MEMORY_REQUIREMENTS_2
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_FEATURES_2
- VK_STRUCTURE_TYPE_PHYSICAL DEVICE_PROPERTIES_2
- VK_STRUCTURE_TYPE_FORMAT_PROPERTIES_2
- VK_STRUCTURE_TYPE_IMAGE_FORMAT_PROPERTIES_2
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_IMAGE_FORMAT_INFO_2
- VK_STRUCTURE_TYPE_QUEUE_FAMILY_PROPERTIES_2
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MEMORY_PROPERTIES_2
- VK_STRUCTURE_TYPE_SPARSE_IMAGE_FORMAT_PROPERTIES_2
- VK_STRUCTURE_TYPE_PHYSICAL DEVICE_SPARSE_IMAGE_FORMAT_INFO_2
- VK_STRUCTURE_TYPE_PHYSICAL DEVICE_POINT_CLIPPING_PROPERTIES
- VK_STRUCTURE_TYPE_RENDER_PASS_INPUT_ATTACHMENT ASPECT_CREATE_INFO
- VK_STRUCTURE_TYPE_IMAGE VIEW USAGE_CREATE_INFO
- VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_DOMAIN_ORIGIN_STATE_CREATE_INFO
- VK_STRUCTURE_TYPE_RENDER_PASS_MULTIVIEW_CREATE_INFO
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_MULTIVIEW_PROPERTIES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_VARIABLE_POINTERS_FEATURES
- VK_STRUCTURE_TYPE_PROTECTED_SUBMIT_INFO
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_FEATURES
- VK_STRUCTURE_TYPE_PHYSICAL_DEVICE_PROTECTED_MEMORY_PROPERTIES
- VK_STRUCTURE_TYPE_DEVICE_QUEUE_INFO_2
- VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_CREATE_INFO
- VK_STRUCTURE_TYPE_SAMPLER_YCBCR_CONVERSION_INFO
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
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 Extensions**
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.
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.
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 66. 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 Vulcan.h Macro</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>[VK_KHR_win32_surface], [VK_KHR_external_memory_win32], [VK_KHR_win32_keyed_mutex], [VK_KHR_external_semaphore_win32], [VK_KHR_external_fence_win32],</td>
<td>Microsoft Windows</td>
<td>vulkan32.h</td>
<td>&lt;windows.h&gt;</td>
<td>VK_USE_PLATFORM_WIN32_KHR</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.

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.

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 \texttt{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 (\texttt{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 \texttt{VkFormat} where \texttt{VK_FORMAT_FEATURE_COLOR_ATTACHMENT_BIT} is set in one of the following, depending on the image's tiling:

- \texttt{VkImageFormatProperties::linearTilingFeatures}
- \texttt{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 \texttt{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 size*. See *Image Mipmap Sizing*.

**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.

**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`, `vkCmdDrawIndirectCount`, `vkCmdDrawIndexedIndirectCount`, `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_bC_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 \( \text{vkMapMemory} \).

**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 \( \text{VK_IMAGE_LAYOUT_PREINITIALIZED} \) or \( \text{VK_IMAGE_LAYOUT_GENERAL} \) 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 \text{can be mapped on the host} and \text{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 \text{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 \text{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′C_bC_r 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.

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, vkCmdDrawIndexedIndirectCount, and vkCmdDrawIndexedIndirect.

Indirect Commands
Drawing or dispatching commands that source some of their parameters from structures in buffer memory. Includes vkCmdDrawIndirect, vkCmdDrawIndexedIndirect, vkCmdDrawIndirectCount, vkCmdDrawIndexedIndirectCount, and vkCmdDispatchIndirect.

Indirect Drawing Commands
Drawing commands that source some of their parameters from structures in buffer memory. Includes vkCmdDrawIndirect, vkCmdDrawIndirectCount, vkCmdDrawIndexedIndirectCount, 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.

**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
Minimum Miplevel Size
The smallest size that is permitted for a mipmap level. For conventional images this is 1x1x1. See Image Miplevel 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 and opaquely.

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, vkCmdDrawIndirectCount, 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 aVkPhysicalDeviceobject.

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 aVkPipelineobject.

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 aVkPipelineCacheobject.

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 aVkPipelineLayoutobject.

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.

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.

**Provoking 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.

**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.

**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 Code**
A stream of instructions used to describe the operation of a shader.

**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.

**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)
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• 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)
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• Jean-François Roy, Google (versions 1.1, 1.2)
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• Jeff Juliano, NVIDIA (versions 1.0, 1.1, 1.2)
• Jeff Leger, Qualcomm Technologies, Inc. (version 1.1)
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• 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)
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• 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)
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• 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)
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• Mark Young, LunarG (version 1.1)
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• Michael Wong, Codeplay Software Ltd. (version 1.1)
• Michael Worcester, Imagination Technologies (versions 1.0, 1.1)
• Michal Pietrasik, Intel (version 1.0)
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• Pierre-Loup Griffais, Valve Software (versions 1.0, 1.1, 1.2)
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• 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)
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• Rob Stepinski, Transgaming (version 1.0)
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• 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)

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