Memory management in Vulkan

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Introduction
The challenge

• Previous generation APIs (OpenGL™, DirectX® 11) manage memory automatically.
  - You create a resource (e.g. texture, constant buffer), backing memory is allocated automatically.

```cpp
ID3D11Texture2D* pTexture;
pD3D11Device->CreateTexture2D(&desc, nullptr, &pTexture);
```

• Vulkan™ is lower level, requires explicit memory management.
The challenge

- It is now your responsibility to:

  - Create resource
  - Query it for:
    - supported memory types
    - required size & alignment
  - (Sub-)allocate block of memory
  - Bind them together
Advantages

Explicit memory management makes it possible to:

• Achieve a smaller memory footprint.
• Better optimize for specific platforms.
• Alias (overlap) transient resources.
Memory Types
Memory Heaps and types

- Heaps: Physical memory (e.g. VRAM, DRAM).
- Types: Describes the properties of the memory and which heap to use.
Memory types: Intel

• Example: Intel Iris Plus Graphics 640

Unified memory

Heap 0
Size = 3.57 GiB
Flags = DEVICE_LOCAL

Type 0
Flags = DEVICE_LOCAL |
HOST_VISIBLE |
HOST_COHERENT

Type 1
Flags = DEVICE_LOCAL |
HOST_VISIBLE |
HOST_COHERENT |
HOST_CACHED
Memory types: NVIDIA

- Example: NVIDIA GeForce GTX 1080 Ti

- Video memory
  - Heap 0
    - Size = 10.87 GiB
    - Flags = DEVICE_LOCAL

- System memory
  - Heap 1
    - Size = 16 GiB
    - Flags = 0

- Flags = HOST_VISIBLE | HOST_COHERENT | HOST_CACHED
Memory types: AMD

- Example: AMD Radeon RX Vega 64

Video memory

- Heap 0
  - Size = 7.75 GiB
  - Flags = DEVICE_LOCAL

- Type 0
  - Flags = DEVICE_LOCAL

System memory

- Heap 1
  - Size = 16 GiB
  - Flags = 0

- Type 1
  - Flags = HOST_VISIBLE
    | HOST_COHERENT

- Heap 2
  - Size = 256 MiB
  - Flags = DEVICE_LOCAL

- Type 2
  - Flags = DEVICE_LOCAL
    | HOST_VISIBLE
    | HOST_COHERENT

- Type 3
  - Flags = HOST_VISIBLE
    | HOST_COHERENT
    | HOST_CACHED
DEVICE_LOCAL

- Video memory. Fast access from GPU.
- No direct access from CPU - mapping not possible.
- Good for resources written and read frequently by GPU.
- Good for resources uploaded once (immutable) or infrequently by CPU, read frequently by GPU.
HOST_VISIBLE

- System memory. Accessible to CPU - mapping possible.
- Access from GPU possible but slow.
- Across PCIe® bus, reads cached on GPU.
- Good for CPU-side (staging) copy of your resources - used as source of transfer.
- Data written by CPU, read once by GPU (e.g. constant buffer) may work.
  - (always measure!)
- Large data read by GPU - place here as last resort.
- Large data written and read by GPU - shouldn’t ever be here.
- Hazard: Uncached. Writes may be write-combined.
DEVICE_LOCAL + HOST_VISIBLE

- Special pool of video memory.
- Exposed on AMD only. 256 MiB.
- Fast access from GPU.
- Direct access by both CPU and GPU.
  - You don’t need to do explicit transfer.
  - Mapping possible.
- Good for resources updated frequently by CPU (dynamic), read by GPU.
- Use as fallback if DEVICE_LOCAL is small and oversubscribed.
- Hazard: Driver will use this memory too.
- Hazard: Uncached. Writes may be write-combined.
HOST_VISIBLE + HOST_CACHED

- System memory
- CPU reads and writes cached (write-back).
- GPU access through PCIe.
- GPU reads snoop CPU cache.
- Good for resources written by GPU, read by CPU.
  - Results of computations.
- Direct access by both CPU and GPU.
  - No need to do explicit transfer.
- Use for any resources read or accessed randomly on CPU.
Memory types: AMD APU

- AMD integrated graphics reports various memory types, like discrete AMD GPUs.
- Reported DEVICE_LOCAL heap can be any size, 0 B ... few GiB.

Unified memory

- Type 0
  - Flags = DEVICE_LOCAL
  - Heap 0
    - Size = 8 GiB
    - Flags = DEVICE_LOCAL

- Type 1
  - Flags = HOST_VISIBLE | HOST_COHERENT
  - Heap 1
    - Size = 16 GiB
    - Flags = 0

- Type 2
  - Flags = DEVICE_LOCAL | HOST_VISIBLE | HOST_COHERENT
  - Heap 2
    - Size = 256 MiB
    - Flags = DEVICE_LOCAL

- Type 3
  - Flags = HOST_VISIBLE | HOST_COHERENT | HOST_CACHED
Memory types: AMD APU

- Memory is really unified.
  - DEVICE_LOCAL is still faster.
  - Render and Depth Targets will see the most benefit.

- If you detect integrated graphics:
  VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU:
  - Count size of all memory heaps together.
  - Put your resources in DEVICE_LOCAL first. If that heap is full then try other heaps.
Tips & Tricks
Memory blocks

- In Old API’s the resource owns the memory.
  - Memory is allocated when creating the resource.
  - No control of where that memory is placed.

- In Vulkan the memory is allocated by itself.
  - Memory is allocated in blocks.
  - A single block can have many resources.

- Allows many new optimization techniques
  - Pool similar resources for tighter packing.
  - Keep object resources together to simplify streaming of that objects required resources.
Suballocation

• Don’t allocate a separate memory block for each resource.
  - Small limit on maximum number of allocations (e.g. 4096).

• Allocate bigger blocks and sub-allocate ranges for your resources.
  - 256 MiB is good default block size.
  - For heaps <= 1 GiB use smaller blocks.
    (e.g. heap size / 8).

• Allocations are slow.
  - Prefer not to allocate or free memory blocks during gameplay to avoid hitching.
  - If you need to, you can do it on background thread.
Over-commitment

What happens when you exceed the maximum amount of physical video memory?

- It depends on the driver.
  - Allocation may fail (VK_ERROR_OUT_OF_DEVICE_MEMORY).
  - Allocation may succeed (VK_SUCCESS).
    - Some blocks are silently migrated to system memory.

- Blocks may be migrated to system memory anyway.
  - You are not alone – other applications can use video memory.
  - Using blocks migrated to system memory on GPU degrades performance.

- Don’t use 100% of the heap
  - Leave room for implicit resources
  - (e.g. 20% of DEVICE_LOCAL,
    33% of DEVICE_LOCAL + HOST_VISIBLE).
Mapping

• No more versioning of resources by the API.
• Having entire memory block persistently mapped is generally OK.
  - You don’t need to unmap before using on GPU.
• Exceptions:
  - AMD, Windows® version < 10: Blocks of DEVICE_LOCAL + HOST_VISIBLE memory that stay mapped for the time of any call to Submit or Present are migrated to system memory.
  - Keeping many large memory blocks mapped may impact stability or performance of debugging tools.
Transfer

• Transfer queue is designed for efficient transfer via PCIe.
  - Heavily underutilized queue.
  - Use it in parallel with 3D rendering, even asynchronously to rendering frames.
    - Good for texture streaming.
  - Fastest way to copy across the PCIe bus.
  - Does not use any compute or graphics hardware.
  - Do your transfers long before the data is needed on graphics queue.

• Transfer queue can be used for defragmenting.
  - Copy a resource to a new address asynchronously to rendering.
  - When done update next frames descriptor.
Transfer

- Some hardware supports more than one queue.
  - e.g. AMD RX 580 has 2 transfer queues.
  - Can use one queue to defrag while the other one updates frame resources.
    (constant buffers, etc.)

- GPU to (the same) GPU copies are much faster on graphics queue.
  - Use it if graphics queue needs to wait for transfer result anyway.

- Be careful with granularity.
  - Always respect queue granularly for copies otherwise you may have corruption, crash, or even deadlock.
  - Don’t need to worry when doing full sub resource copies.
Aliasing

- You can alias different resources - bind them to the same or overlapping range of memory.
- It saves memory.
- Good for transient resources (e.g. render targets) used only during part of the frame.
- After the memory was used by different resource, treat your resource as uninitialized.
  - ...unless you really know what you’re doing.
Resource Creation

• Don’t use images with TILING_LINEAR unless you have to.
  - Use TILING_OPTIMAL.
  - Copy images from/to buffers.

• Minimize number of USAGE_BITS used during resource creation.
  - Only fill out what you need.

• Avoid VK_SHARING_MODE_CONCURRENT on render and depth target textures.
  - It disables optimizations.
  - Prefer VK_SHARING_MODE_EXCLUSIVE and do explicit queue family ownership transfer barriers.

• Use VK_KHR_image_format_list for mutable formats.
  - If you need different formats e.g. to interpret as linear/sRGB, use the VK_KHR_image_format_list extension with the VK_IMAGE_CREATE_MUTABLE_FORMAT_BIT.
Libraries
Vulkan Memory Allocator

- [https://github.com/GPUOpen-LibrariesAndSDKs/VulkanMemoryAllocator](https://github.com/GPUOpen-LibrariesAndSDKs/VulkanMemoryAllocator)

- Library from AMD.
  - MIT license
  - easy to integrate - single header
  - interface in C (same style as Vulkan™), implementation in C++
  - well documented

- Already used in some AAA titles.
- Great starting point even if you write your own.
Vulkan Memory Allocator

- Functions that help to choose the correct and optimal memory type based on intended usage.
- Functions that allocate memory blocks, reserve and return parts of them to the user.
  - Library keeps track of allocated memory blocks, used and unused ranges inside them,
  - respects alignment and buffer/image granularity.
Vulkan Memory Allocator

- Functions that create image/buffer, (sub-)allocate memory for it and bind them together - all in one call.

```cpp
VkBufferCreateInfo bufferInfo = { VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO };  
bufferInfo.size = 65536;  
bufferInfo.usage = VK_BUFFER_USAGE_VERTEX_BUFFER_BIT | VK_BUFFER_USAGE_TRANSFER_DST_BIT;  

VmaAllocationCreateInfo allocInfo = {};  
allocInfo.usage = VMA_MEMORY_USAGE_GPU_ONLY;  

VkBuffer buffer;  
VmaAllocation allocation;  
vmaCreateBuffer(allocator, &bufferInfo, &allocInfo, &buffer, &allocation, nullptr);  
```
VmaDumpVis.py

- Auxiliary tool that visualizes JSON dump from Vulkan Memory Allocator.
- Light gray - unused by any allocation.
- Yellow - buffer.
- Aqua - image with TILING_OPTIMAL.
- Green - image with TILING_LINEAR.
- Black - one or more allocations that are too small to visualize.
Conclusions

- Vulkan® is lower level, requires explicit memory management.
  - Creating resources is a multi-stage process.
  - Former driver magic is now under your control.
- You need to deal with differences between GPUs.
- By following good practices you can achieve optimal performance on any GPU.
- There are open-source libraries that can help you with this task.
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Backup
Cache control

• Any memory type that doesn’t have HOST_COHERENT flag needs manual cache control:
  - vkInvalidateMappedMemoryRanges before read on CPU
  - vkFlushMappedMemoryRanges after write on CPU

• In practice, all PC GPU vendors (AMD, Intel, NVIDIA) support HOST_COHERENT on every memory type that is HOST_VISIBLE.
  - No need to worry about it on current Windows PCs.
Dedicated allocation

- Some resources may benefit from having their own, dedicated memory block instead of region suballocated from a bigger block.
  - Driver may use additional optimizations.
  - VK_KHR_dedicated_allocation

- Use the get_memory_requirements2 extension to query the driver if it recommends or requires using a dedicated allocation.

- Use for:
  - Render targets, depth-stencil, UAV.
  - Shared resources. (required)
  - Very large buffers and images. (dozens of MiB)
  - Large allocations that may need to be resized (freed and reallocated) at runtime.
MISC

• Avoid VK_IMAGE_LAYOUT_GENERAL. Always transition image to appropriate VK_IMAGE_LAYOUT_*_OPTIMAL.
  - Exception: storage image requires VK_IMAGE_LAYOUT_GENERAL.

• Memory requirements (e.g. size) can vary for different resources (e.g. images) even when created with same parameters (format, width, height, mip levels etc.)
  - It really happens in the wild. Be prepared for that. Don’t cache result. Query each resource for requirements.