Keeping your GPU fed without getting bitten

Tobias Hector
May 2017

Introduction

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  - Yummy!

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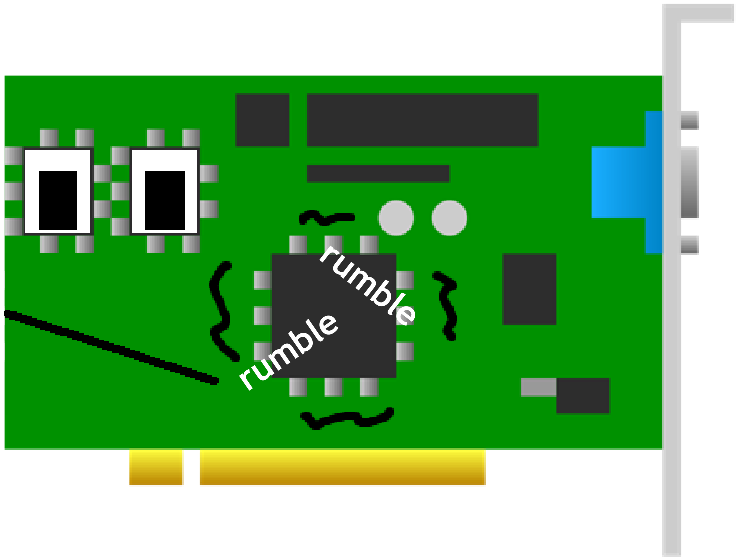
  - Yummy!

- Your GPU wants to eat them
  - It's **really** hungry



Introduction

- **You have delicious draw calls**
  - Yummy!
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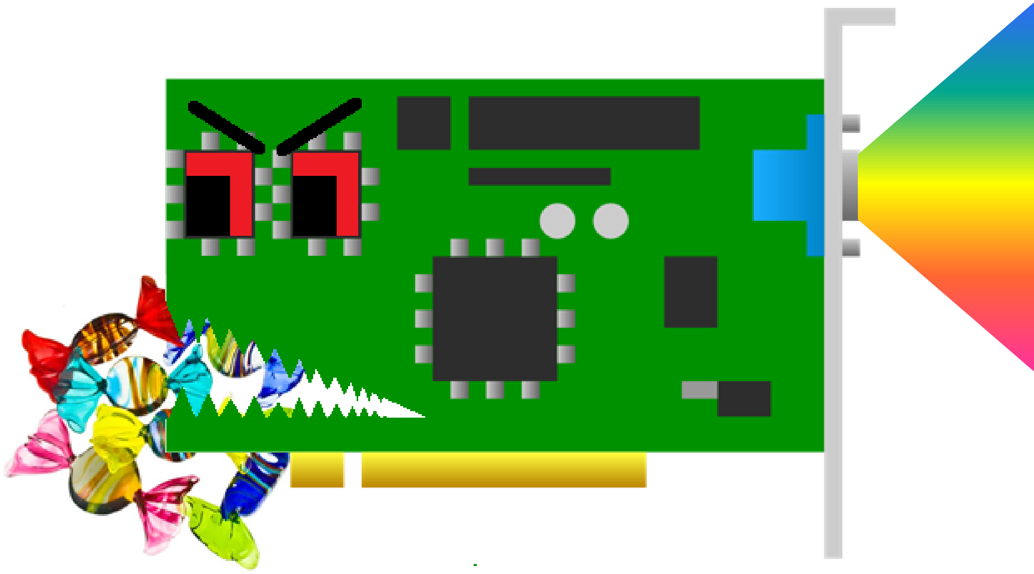
  - It’s **really** hungry
- **Keep it fed at all times**
  - So it keeps making pixels



Introduction

- **You have delicious draw calls**
  - Yummy!
- **Your GPU wants to eat them**
  - It's **really** hungry
- **Keep it fed at all times**
  - So it keeps making pixels
- **Don't want it biting your hand**
  - Look at those teeth!

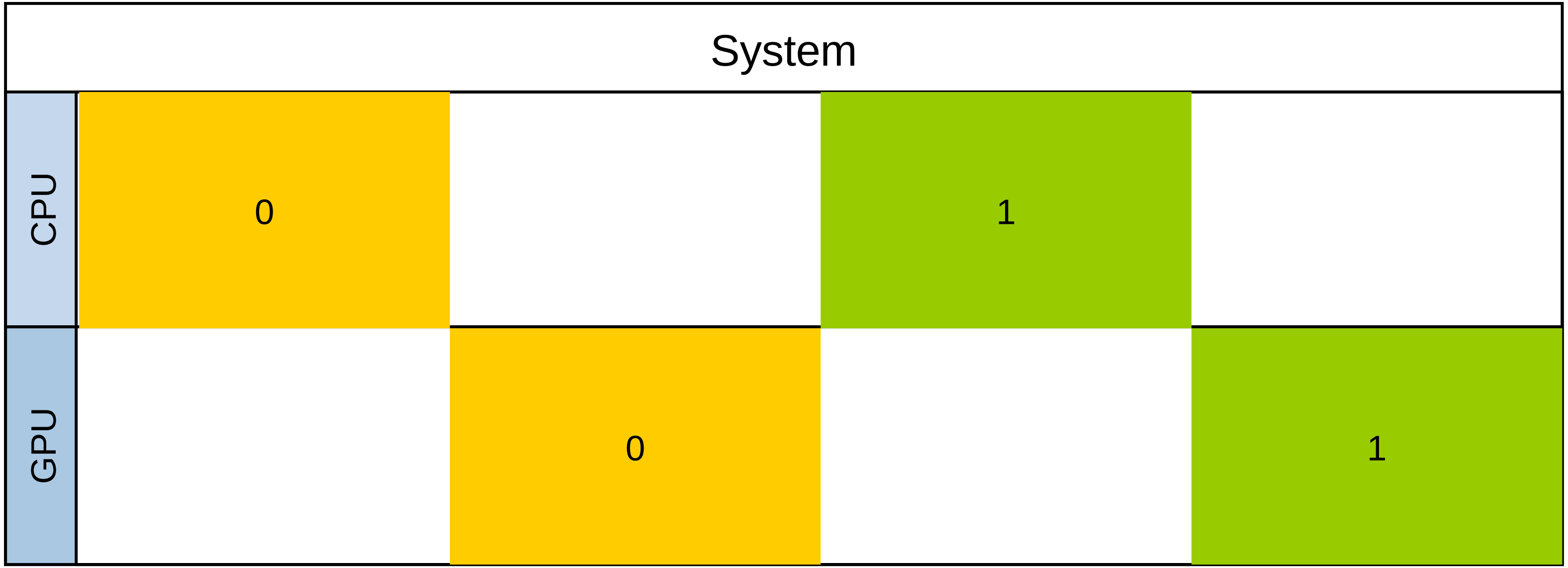
Keeping it fed

- **GPU needs a constant supply of food**
  - It doesn’t want to wait

- **Certain foods are tough to digest**
  - Provide multiple operations to hide stalls

- **Draw calls provide a variety of nutrition**
  - Vertex work, raster work, tessellation, vitamins A-K, etc.

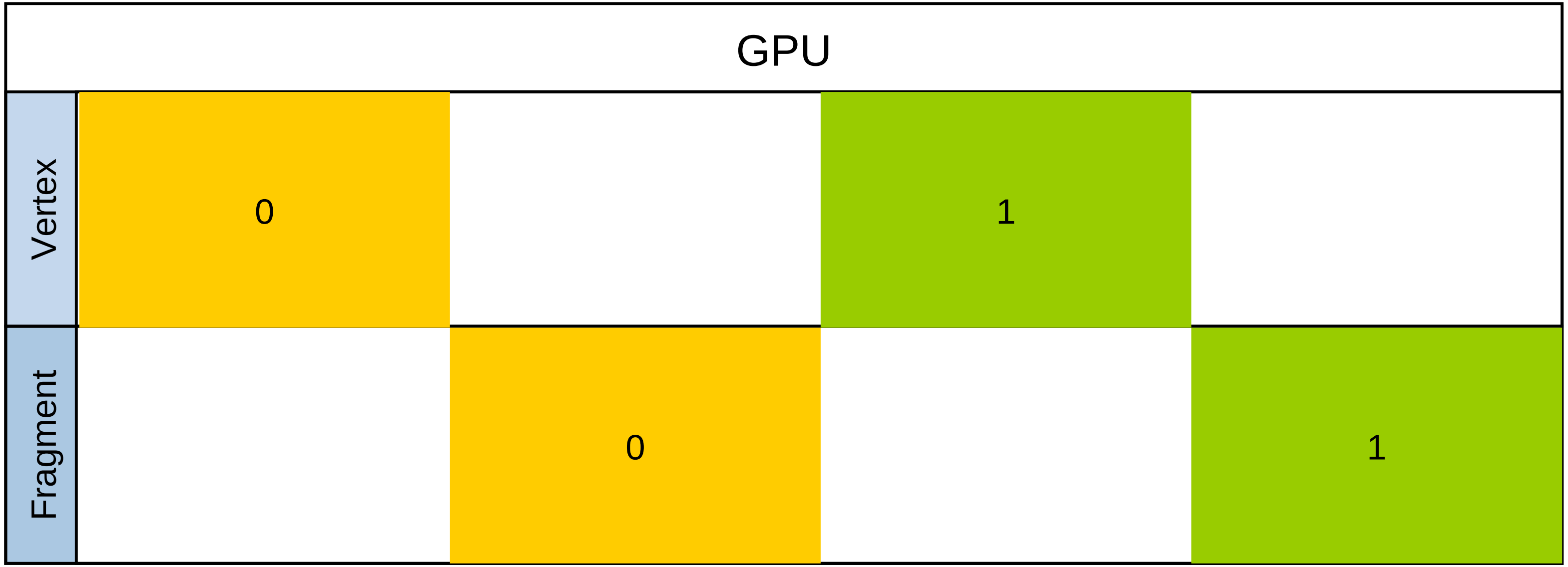
Keeping it fed



Keeping it fed

System				
CPU	0	1	2	
GPU		0	1	2

Keeping it fed



Keeping it fed

GPU				
Vertex	0	1	2	
Fragment		0	1	2

Not getting bitten

- **GPU eating from lots of different plates**
  - Don’t touch anything it’s using!

- **It doesn’t want a mouthful of beef choc chip ice cream**
  - Don’t change data whilst it’s accessing a resource

- **Hey I’m eating that!**
  - Don’t delete resources whilst the GPU is still using them


Tear Point #1 --->
Tear Point #2 --->

On to the serious bits…

Terminology

- **Operation**
  - An executable task

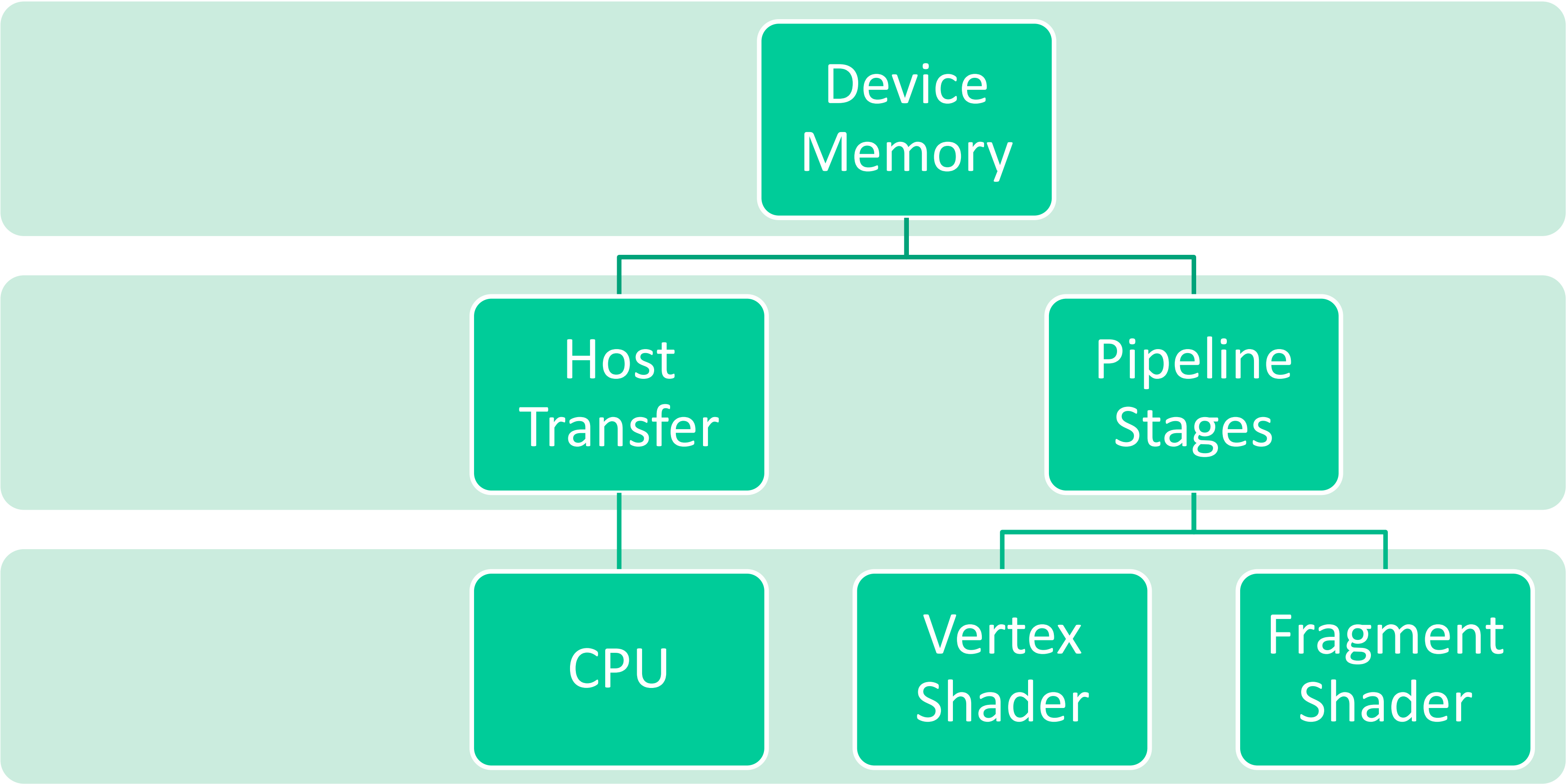
- **Execution Dependency**
  - Guarantee for one set of operations to wait on another set of operations

- **Memory Space**
  - RAM, caches or registers

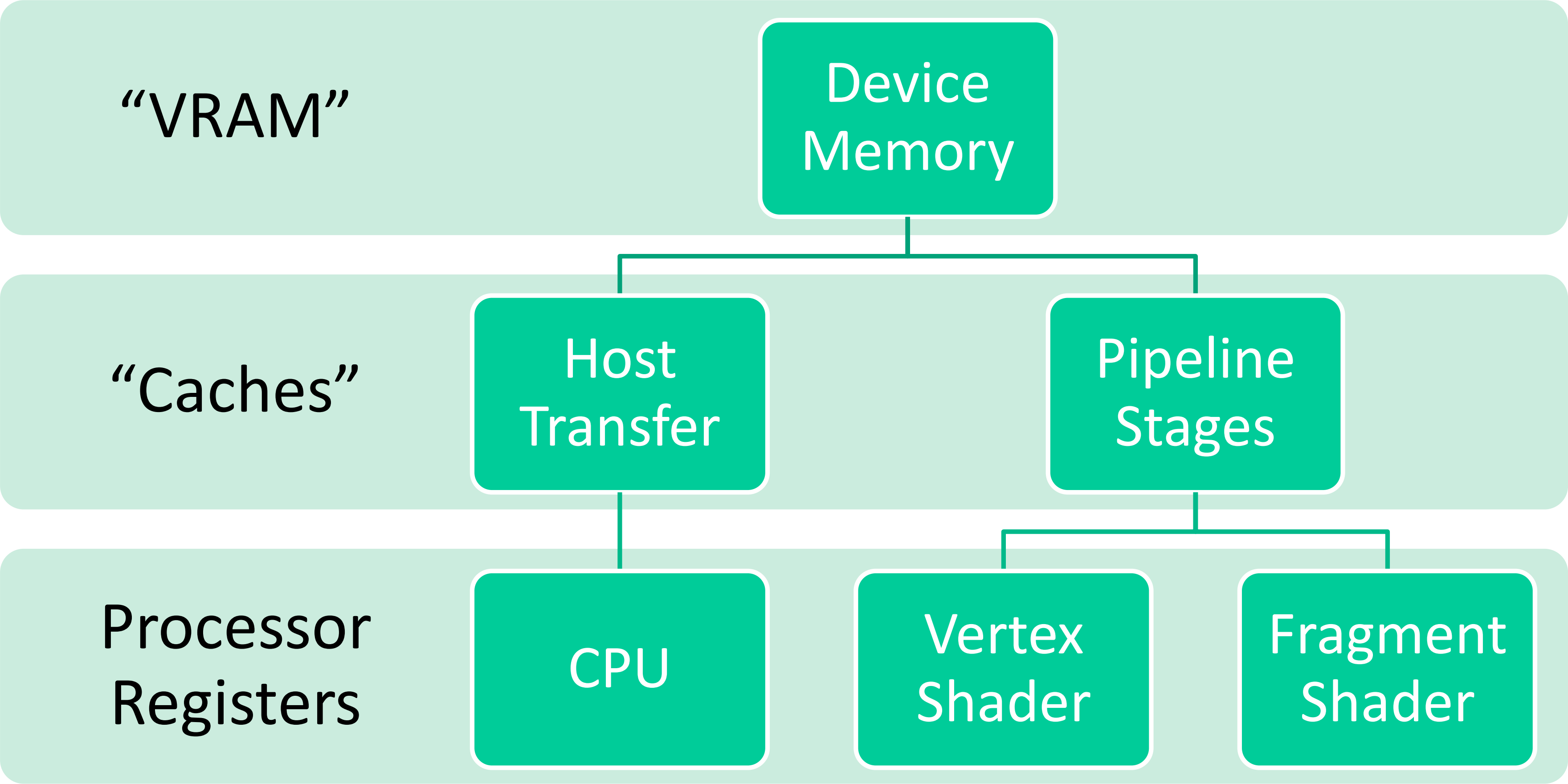
- **Write Propogation**
  - Operation that copies a written value between memory spaces

- **Memory Dependency**
  - Execution dependency including write propagations

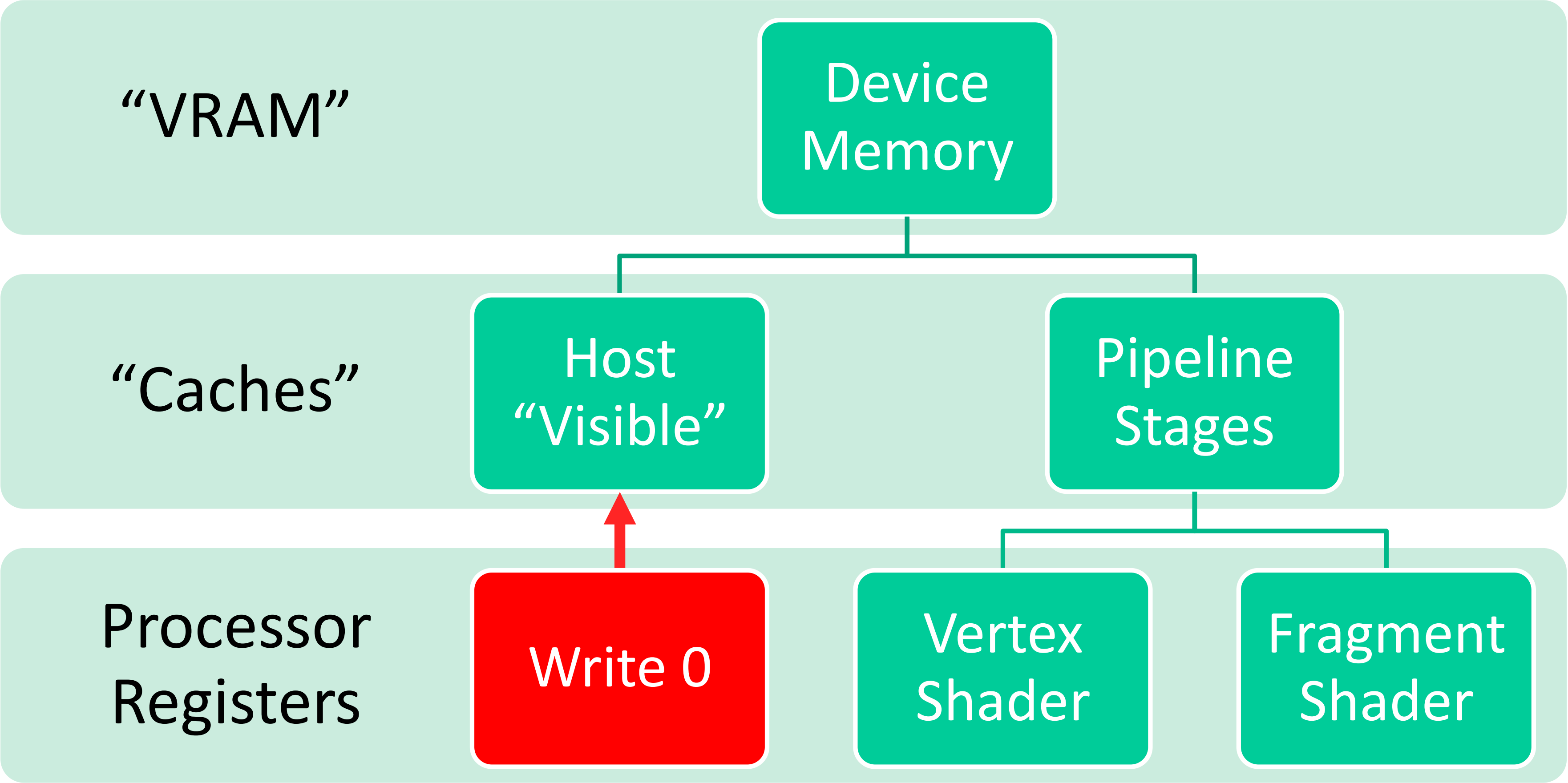
Vulkan Memory Spaces



Vulkan Memory Spaces



Vulkan Memory Spaces - Data Hazards



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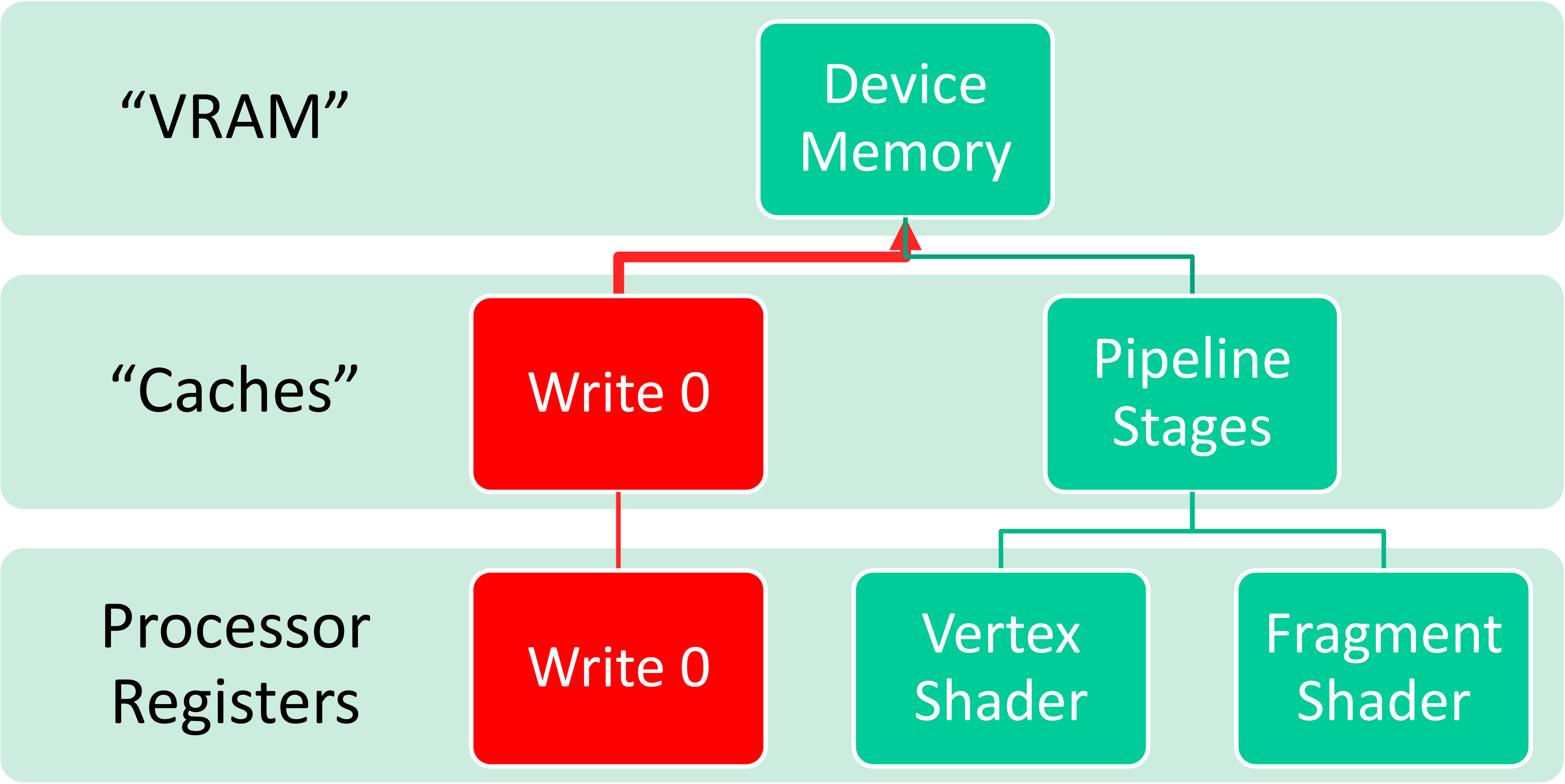
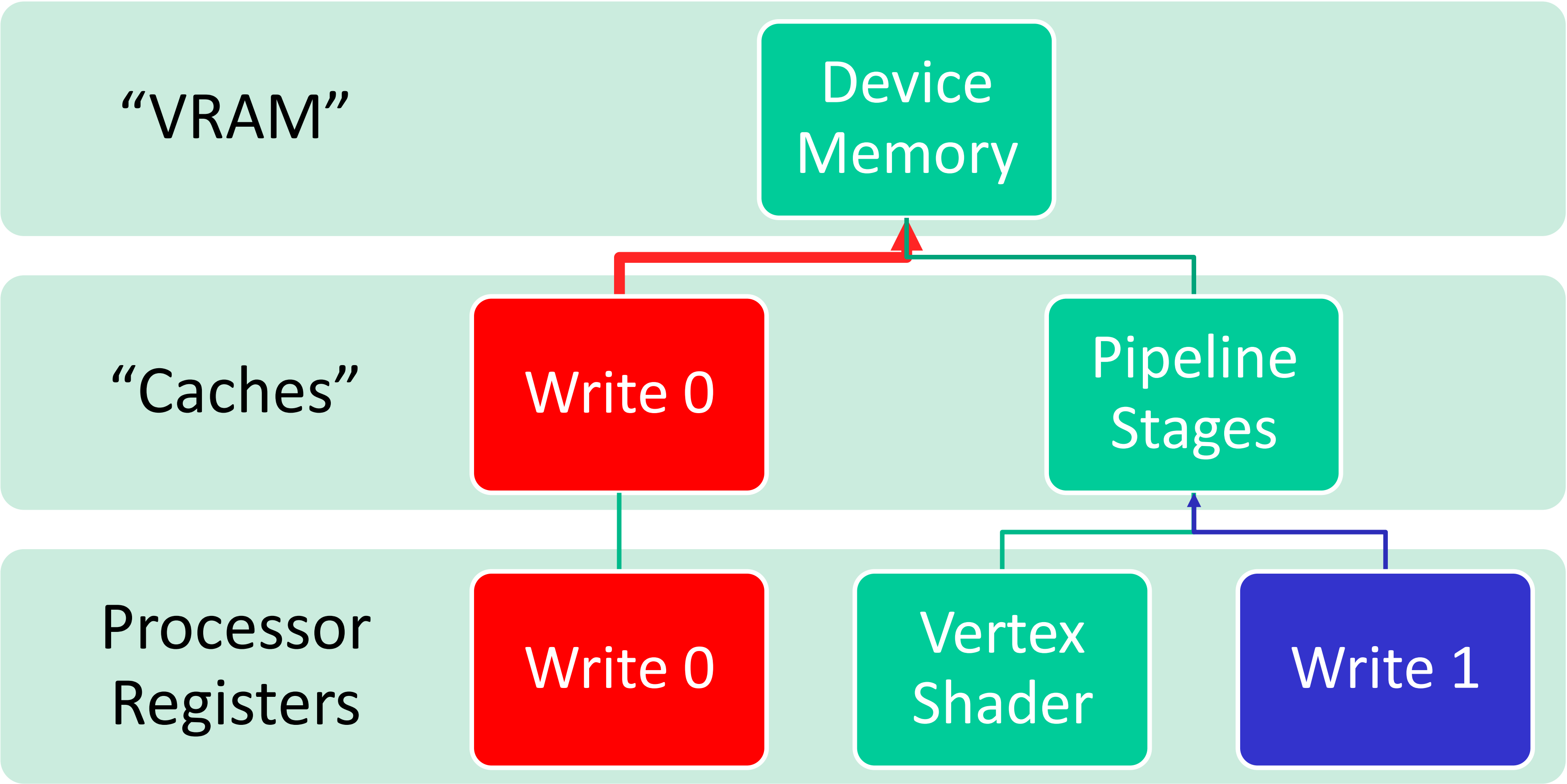


Vulkan Memory Spaces - Data Hazards



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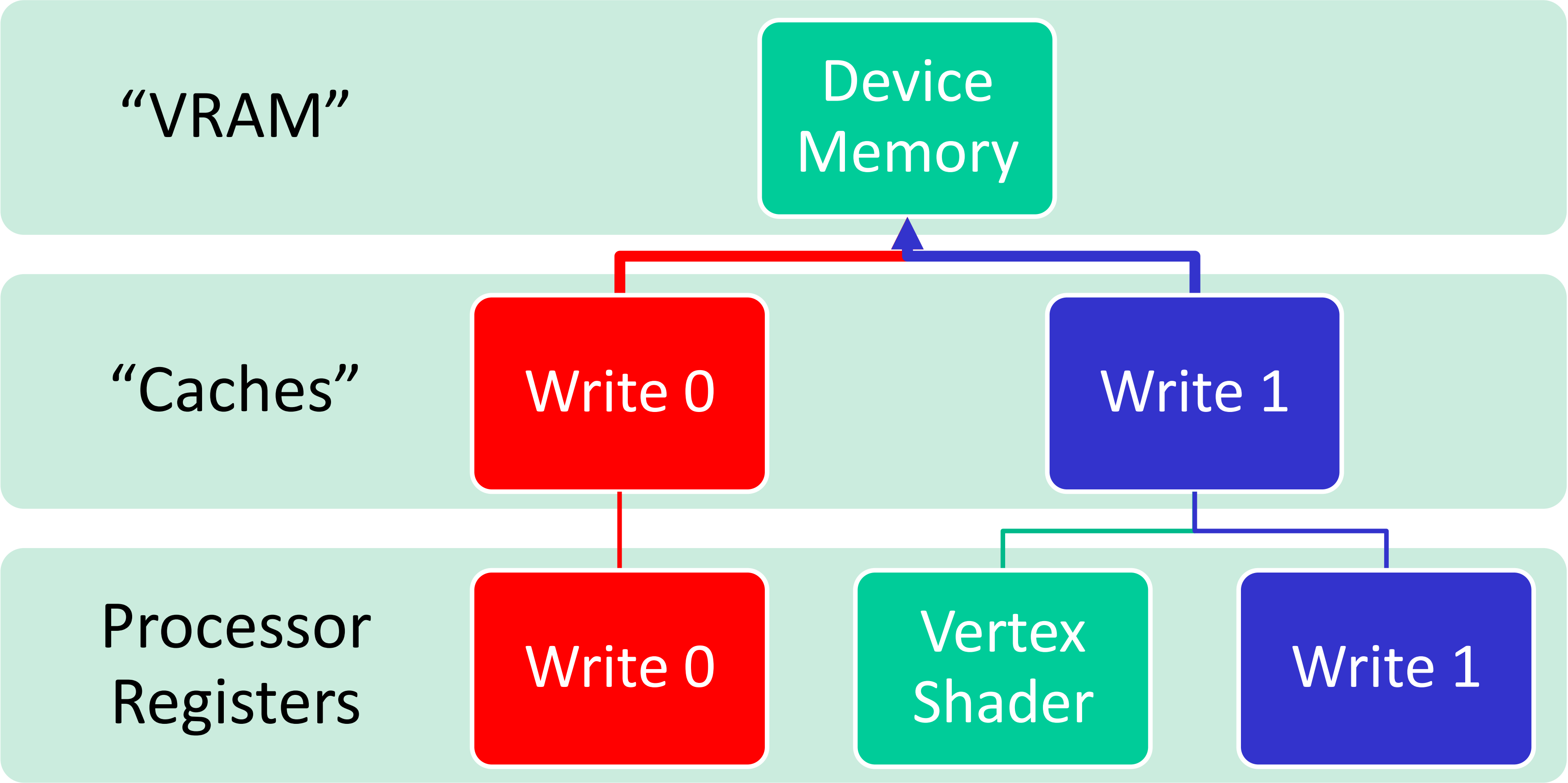

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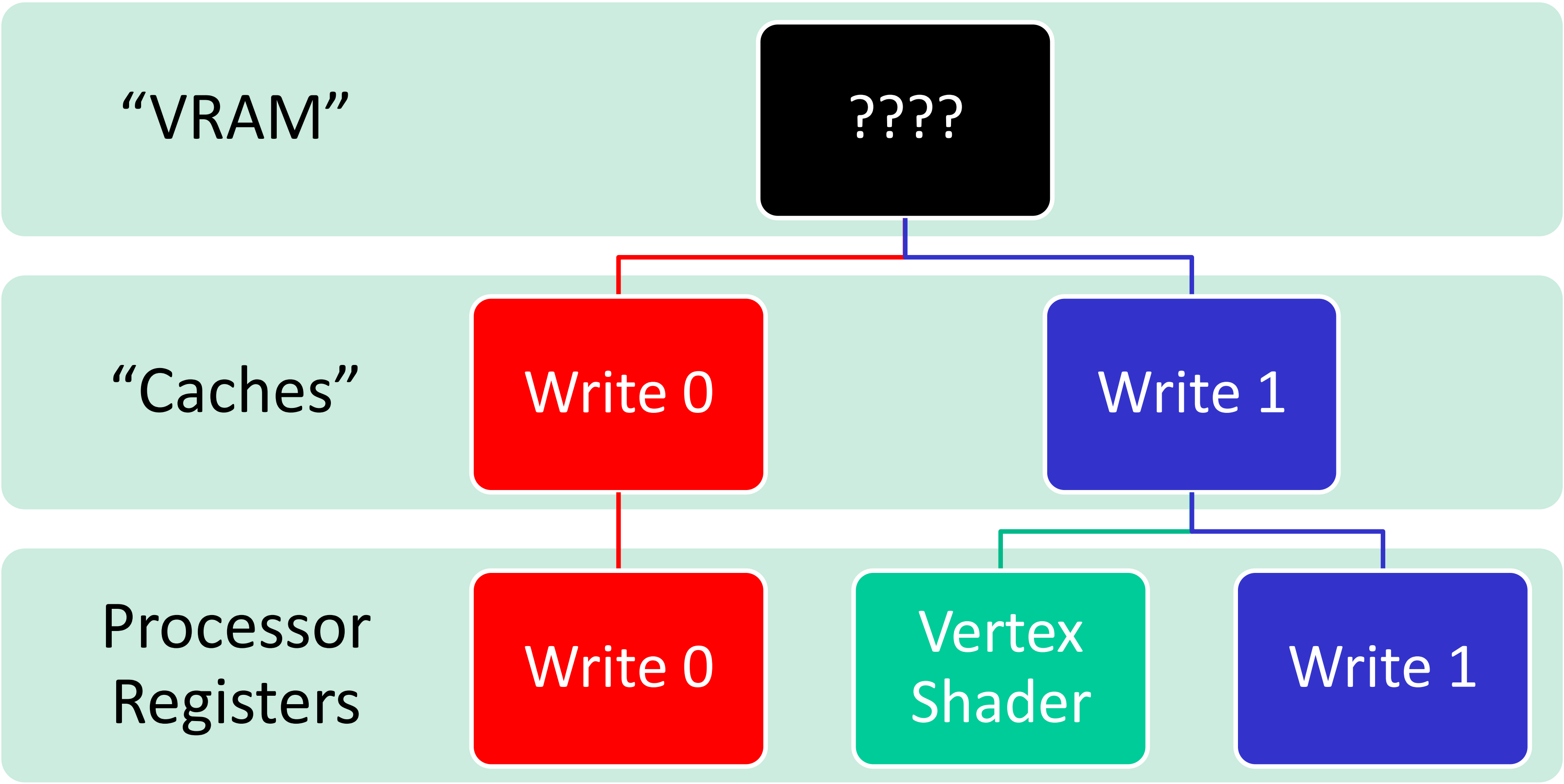

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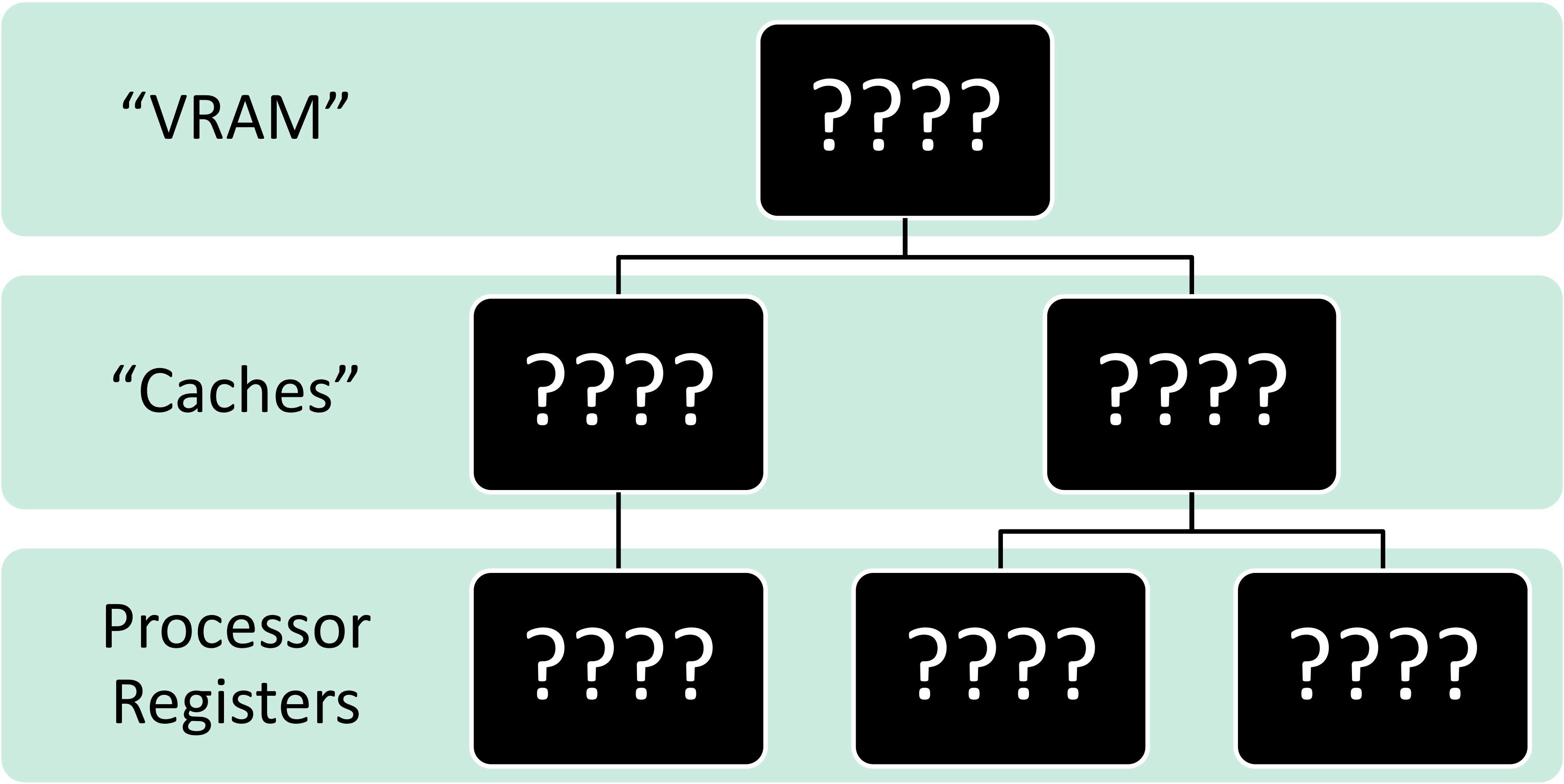
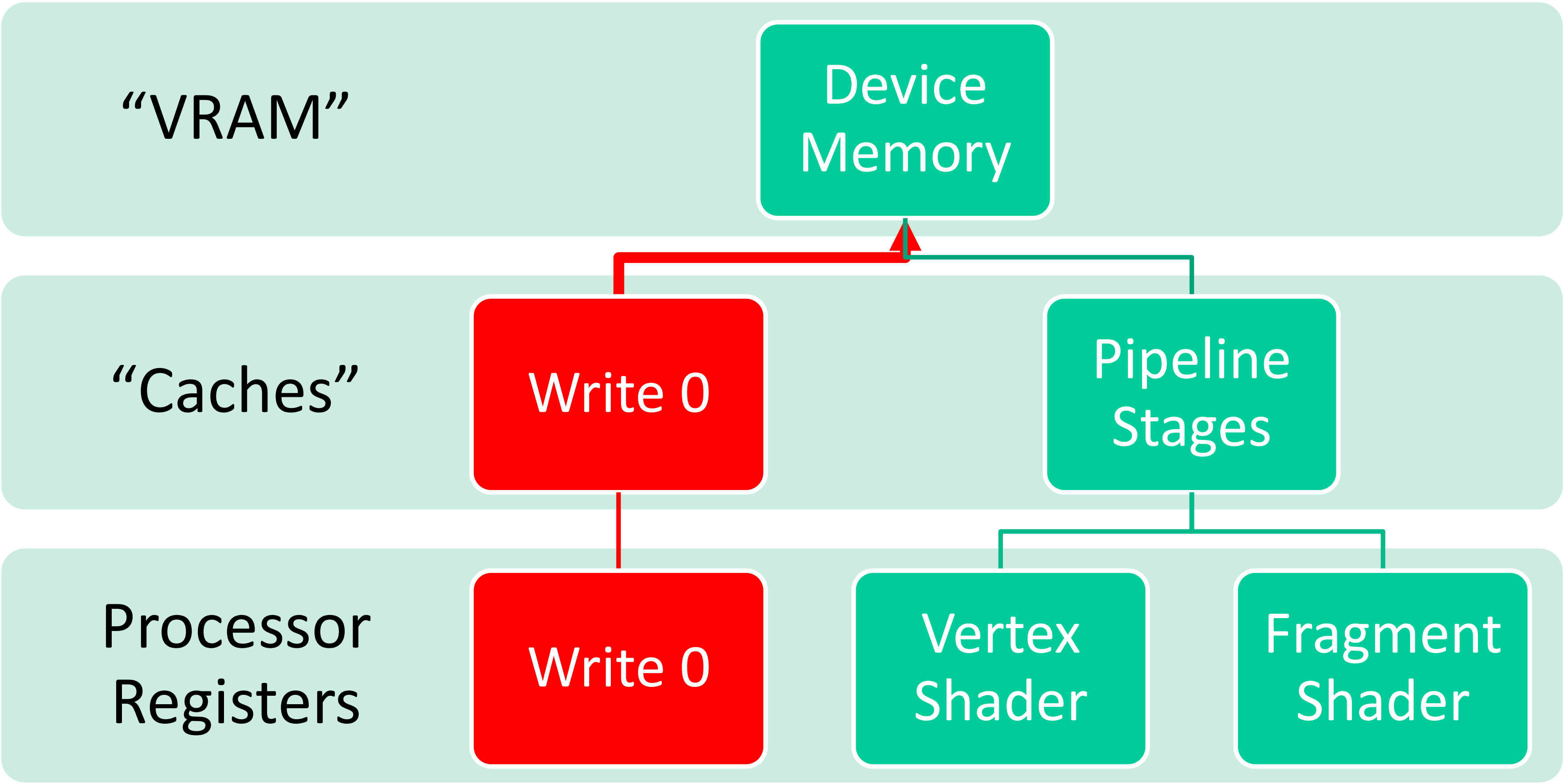


Oops

- Let’s try that again…
- This time, with a memory dependency!

Vulkan Memory Spaces - Data Hazards



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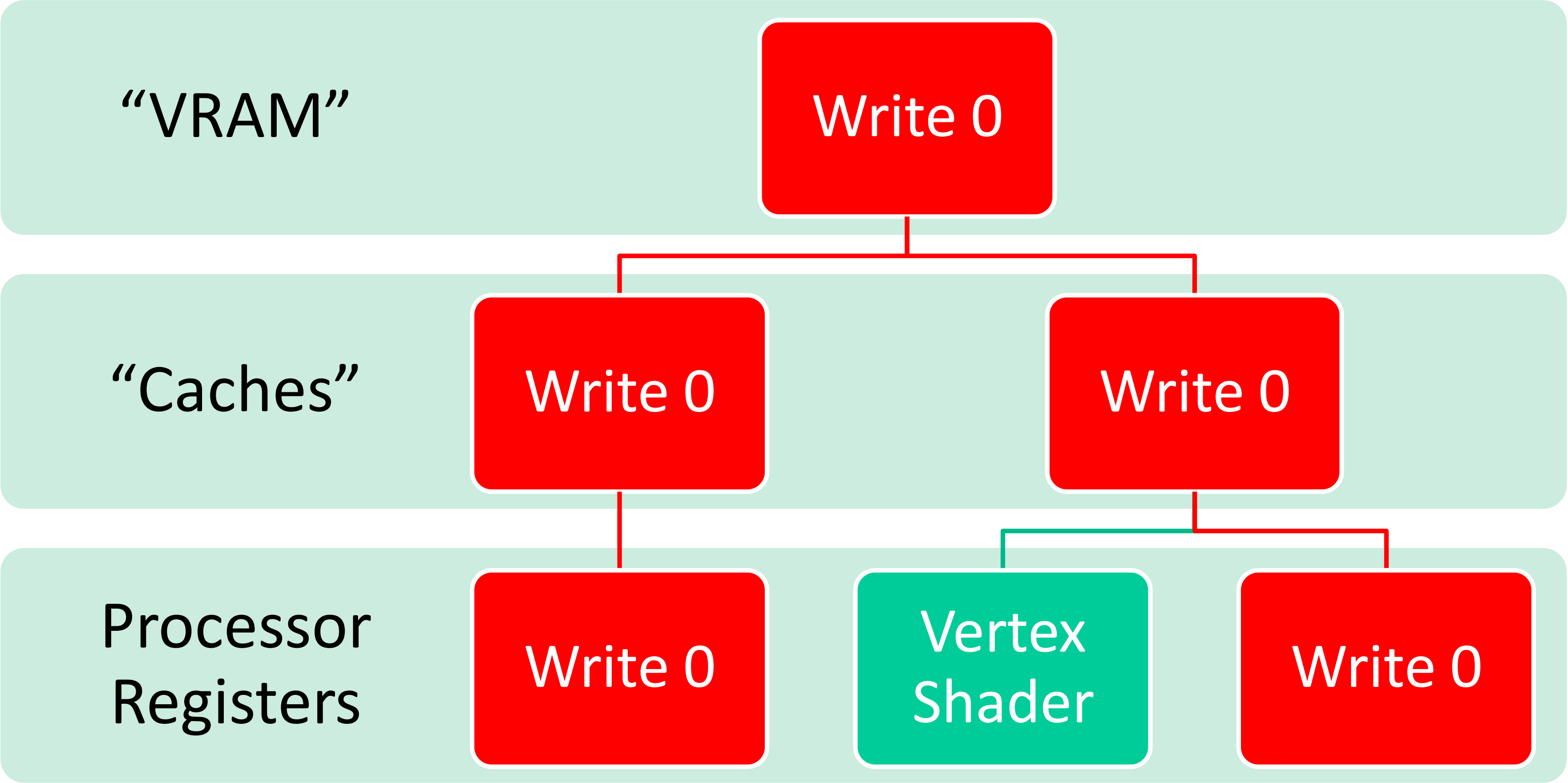

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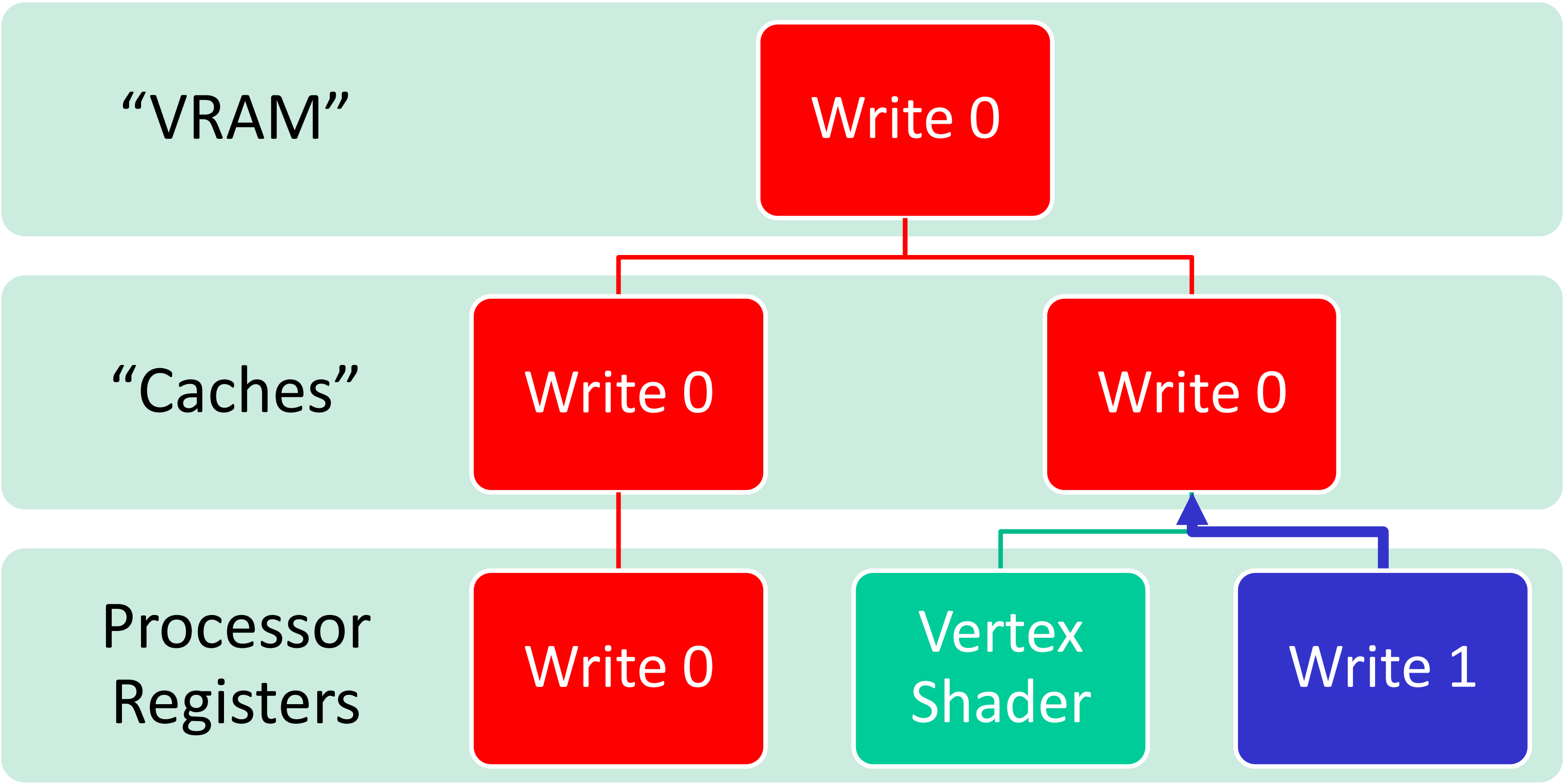

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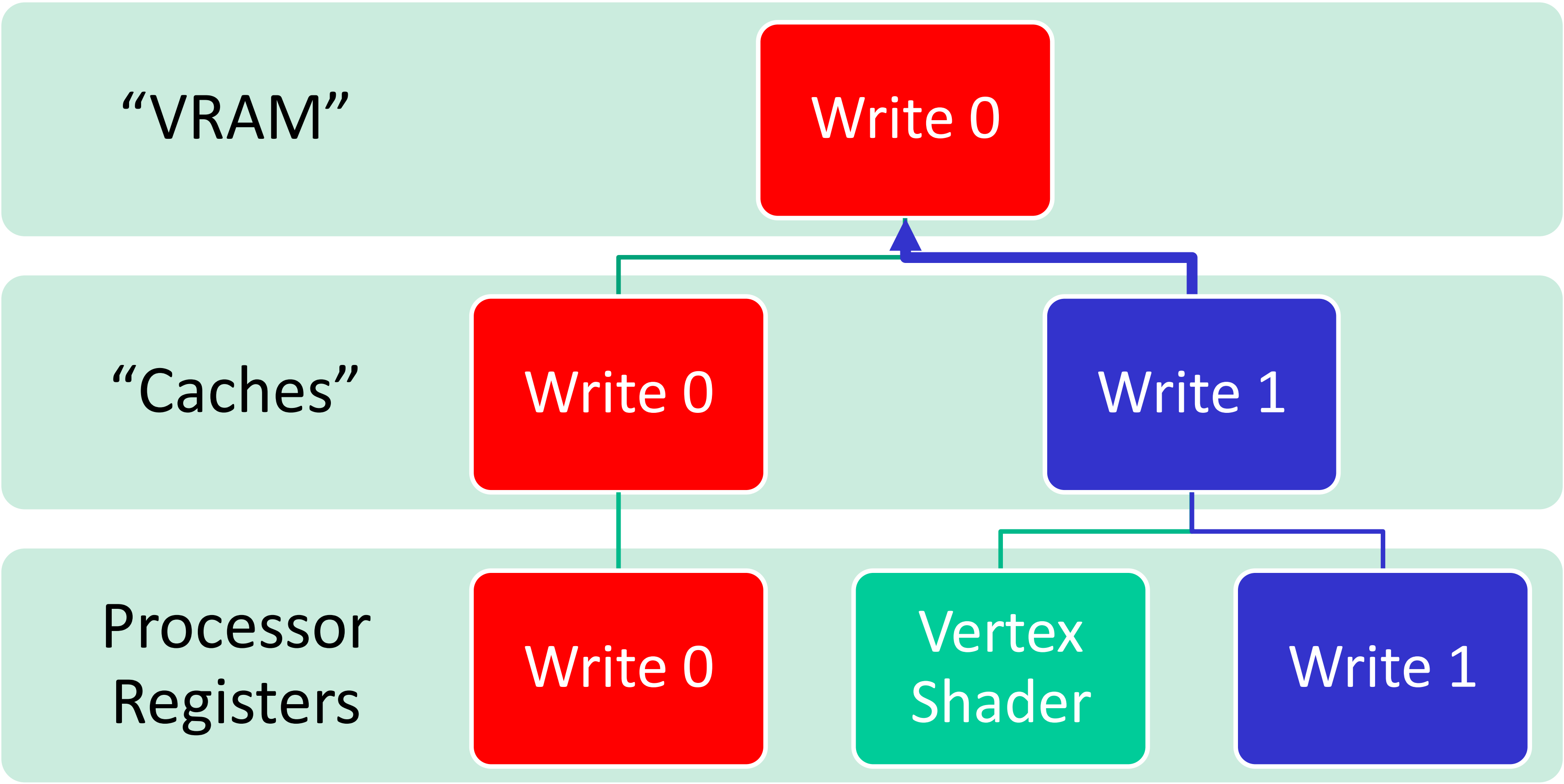

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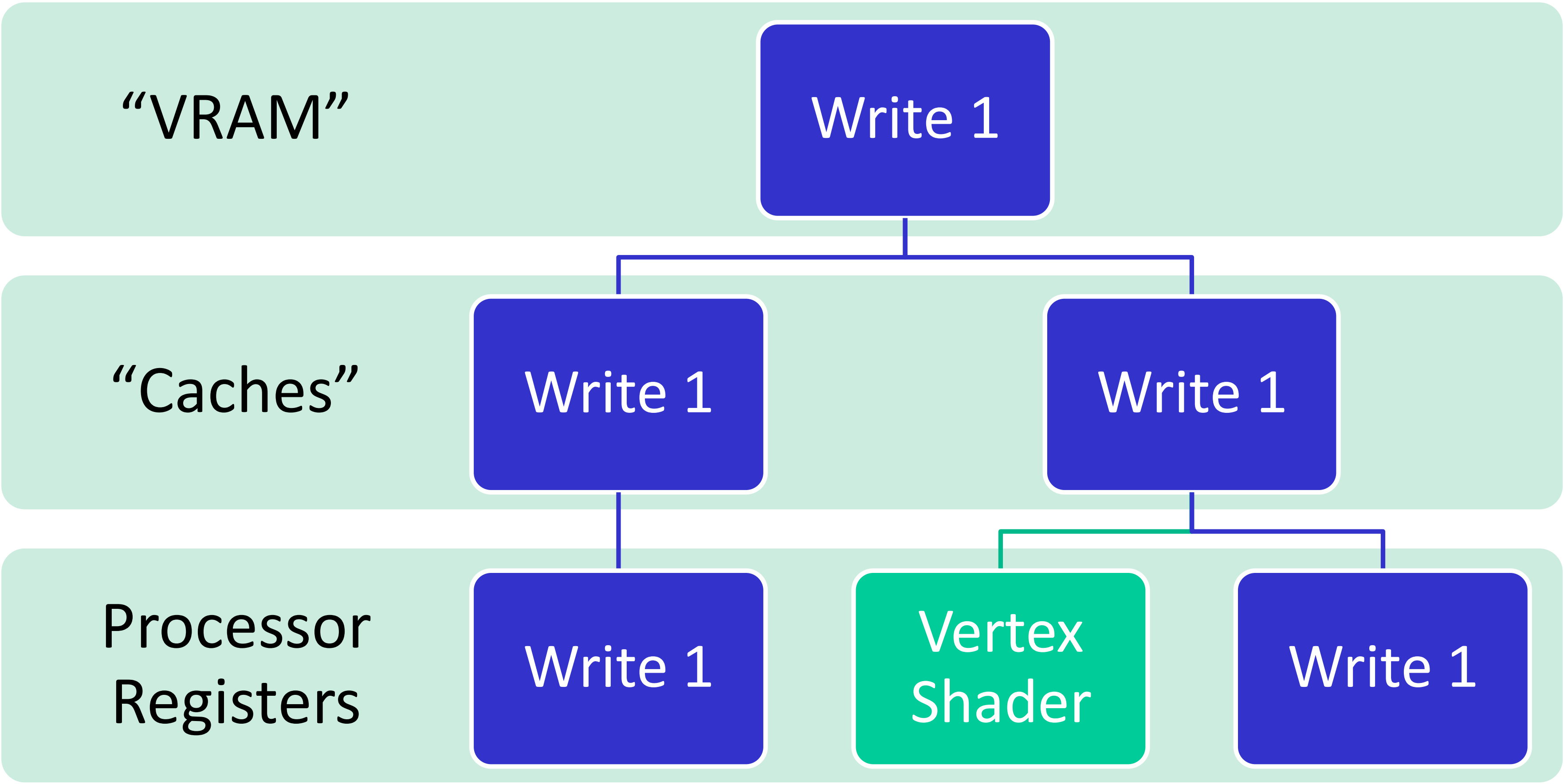

How do I do that?

- Synchronization primitives!

Synchronization Types

- 3 types of explicit synchronization in Vulkan

- Pipeline Barriers, Events and Subpass Dependencies
  - Within a queue
  - Explicit memory dependencies

- Semaphores
  - Between Queues

- Fences
  - Whole queue operations to CPU

OpenGL has just two, very coarse synchronization primitives: memory barriers and fences. They are loosely similar to the equivalently named concepts in Vulkan

Pipeline Barriers

- Pipeline Barriers
  - Precise set of pipeline stages
  - Memory Barriers to execute
  - Single point in time

```
void vkCmdPipelineBarrier(
  VkCommandBuffer              commandBuffer,
  VkPipelineStageFlags         srcStageMask,
  VkPipelineStageFlags         dstStageMask,
  VkDependencyFlags            dependencyFlags,
  uint32_t                     memoryBarrierCount,
  const VkMemoryBarrier*       pMemoryBarriers,
  uint32_t                     bufferMemoryBarrierCount,
  const VkBufferMemoryBarrier* pBufferMemoryBarriers,
  uint32_t                     imageMemoryBarrierCount,
  const VkImageMemoryBarrier*  pImageMemoryBarriers);
```

Executing a pipeline barrier is similar to a glMemoryBarrier call, though with much more control.

Events

- Events
  - Same info as Pipeline Barriers
  - ...but operate over a range

```
void vkCmdSetEvent(
  VkCommandBuffer              commandBuffer,
  VkEvent                      event,
  VkPipelineStageFlags         stageMask);
void vkCmdResetEvent(
  VkCommandBuffer              commandBuffer,
  VkEvent                      event,
  VkPipelineStageFlags         stageMask);

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);
```

Events

- **Events**
  - Same info as Pipeline Barriers
  - …but operate over a range

- **CPU interaction**
  - No explicit CPU wait

```
VkResult vkSetEvent(
  VkDevice                    device,
  VkEvent                     event);

VkResult vkResetEvent(
  VkDevice                    device,
  VkEvent                     event);


VkResult vkGetEventStatus(
  VkDevice                    device,
  VkEvent                     event);
```

Events

- **Events**
  - Same info as Pipeline Barriers
  - …but operate over a range

- **CPU interaction**
  - No explicit CPU wait

- **Warning!**
  - May timeout
  - Set events soon after submission
  - Could you just defer submission?

```
VkResult vkSetEvent(
  VkDevice                    device,
  VkEvent                     event);

VkResult vkResetEvent(
  VkDevice                    vice,
  VkEvent                     t);


VkResult vkGetEve
  VkDevice
  VkEvent
```

Pipeline Barriers vs Events

- **Use pipeline barriers for point synchronization**
  - Dependant operation immediately precedes operation that depends on it
  - May be more optimal than set/wait event pair

- **Use events if other work possible between two operations**
  - Set immediately after the dependant operation
  - Wait immediately before the operation that depends on it
  - Allows more overlap of work

- **Use events for CPU/GPU synchronization**
  - Memory accesses between processors
  - Late latching of data to reduce latency

Memory Barriers

- **Defines write propagations**
  - Between “visible” and device memory
- **Three types…**

OpenGL’s memory barriers imply execution dependencies, which Vulkan memory barriers do not - execution dependencies are provided by a pipeline barrier, event or subpass dependency.

Global Memory Barriers

- **Global Memory Barriers**
  - All memory used by access types
  - Flushes/invalidates whole caches

- **Use when many resources transition**
  - Cheaper than one-by-one
  - Don’t transition unnecessarily!

- **User defines prior access**
  - Driver not tracking for you

```
typedef struct VkMemoryBarrier {
  VkStructureType              sType;
  const void*                  pNext;
  VkAccessFlags                srcAccessMask;
  VkAccessFlags                dstAccessMask;
} VkMemoryBarrier;
```

Buffer Barriers

- **Buffer Barriers**
  - A single buffer range
  - Defines access types
  - Defines queue ownership

- **Buffer Range**
  - Offset and size within a buffer

- **Queue Ownership**
  - Defines which queue families are *allowed* to access a write

```
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;
```

Image Barriers

- **Image Barriers**
  - A single image subresource range
  - Defines access types
  - Defines queue ownership
  - Defines image layout

- **Image subresource range**
  - Specific levels/layers of an image

- **Image layouts**
  - Additional access information for images
  - Enables GPU image compression
  - Use GENERAL rather than frequent switching

```
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;
```

Example - Texture Upload

```
// Read image from file, flush to 'host visible' memory space
fread(mappedBufferMemory, 1, imageDataSize, imageFile);
vkFlushMappedMemoryRanges(..., {mappedBufferMemory, ...});
// Transition the buffer from host write to transfer read
bBarrier.srcAccessMask = VK_ACCESS_HOST_WRITE_BIT; // Buffer being written to
bBarrier.dstAccessMask = VK_ACCESS_TRANSFER_READ_BIT; // Buffer will be read
// Transition the image to transfer destination
iBarrier.srcAccessMask = 0; // No prior access
iBarrier.dstAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT; // Get image prepared to be transferred to
iBarrier.oldLayout = VK_IMAGE_LAYOUT_UNDEFINED; // No prior access
iBarrier.newLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL; // Get image prepared to be transferred to
// Pipeline barrier for pre-transfer memory dependency – buffer write was on the host
vkCmdPipelineBarrier(commandBuffer, VK_PIPELINE_STAGE_HOST_BIT, VK_PIPELINE_STAGE_TRANSFER_BIT, &bBarrier, &iBarrier);
// Copy from buffer to image
vkCmdCopyBufferToImage(commandBuffer, srcBuffer, image, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, &copy);
// Transition the image from transfer destination to shader read
iBarrier.srcAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT; // Image was just written to
iBarrier.dstAccessMask = VK_ACCESS_SHADER_READ_BIT; // Get image prepared to be read by a shader
iBarrier.oldLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL; // Image was just written to
iBarrier.newLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL; // Get image prepared to be read by a shader
// Pipeline barrier for post-transfer memory dependency – fragment shader will read
vkCmdPipelineBarrier(commandBuffer, VK_PIPELINE_STAGE_TRANSFER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, &iBarrier);
```

Usually though…

- **Many pipeline barrier operations doable via a render pass**
  - At least for drawing operations

- **Render passes are a dependency graph**
  - Allows driver to plan ahead of time how to execute
  - Typically much more efficient than manual barriers

Subpass Dependencies

- **Subpass dependencies**
  - Similar info to Pipeline Barriers
  - Explicitly between two subpasses
- **Memory barriers**
  - Implicit for attachments
  - Explicit for other resources
- **Framebuffer-local dependencies**
  - Same fragment/sample location
  - Cheap for most implementations
  - Use region dependency flag:
    - VK_DEPENDENCY_BY_REGION_BIT

```
typedef struct VkSubpassDependency {
  uint32_t                  srcSubpass;
  uint32_t                  dstSubpass;
  VkPipelineStageFlags      srcStageMask;
  VkPipelineStageFlags      dstStageMask;
  VkAccessFlags             srcAccessMask;
  VkAccessFlags             dstAccessMask;
  VkDependencyFlags         dependencyFlags;
} VkSubpassDependency;
```

Subpass Self-Dependencies

- **Subpass self-dependencies**
  - Subpasses can wait on themselves
  - A pipeline barrier in the subpass

- **Forward progress only**
  - Can't wait on later stages
  - Must wait on earlier or same stage

- **Only framebuffer-local for fragments**
  - Must use flag:
    - VK_DEPENDENCY_BY_REGION_BIT

```
typedef struct VkSubpassDependency {
  uint32_t                      srcSubpass;
  uint32_t                      dstSubpass;
  VkPipelineStageFlags          srcStageMask;
  VkPipelineStageFlags          dstStageMask;
  VkAccessFlags                 srcAccessMask;
  VkAccessFlags                 dstAccessMask;
  VkDependencyFlags             dependencyFlags;
} VkSubpassDependency;

void vkCmdPipelineBarrier(
  VkCommandBuffer               commandBuffer,
  VkPipelineStageFlags          srcStageMask,
  VkPipelineStageFlags          dstStageMask,
  VkDependencyFlags             dependencyFlags,
  uint32_t                      memoryBarrierCount,
  const VkMemoryBarrier*        pMemoryBarriers,
  uint32_t                      bufferMemoryBarrierCount,
  const VkBufferMemoryBarrier*  pBufferMemoryBarriers,
  uint32_t                      imageMemoryBarrierCount,
  const VkImageMemoryBarrier*   pImageMemoryBarriers);
```

Subpass External Dependencies

- **Subpass external dependencies**
  - Wait on ‘external’ operations
  - vkCmdWaitEvent in the subpass
  - Events set outside the render pass

- **Very useful for common dependencies**
  - Use to move between PRESENT_SRC and COLOR_ATTACHMENT_OUTPUT
  - Avoids need for pipeline barriers

```
typedef struct VkSubpassDependency {
  uint32_t                      srcSubpass;
  uint32_t                      dstSubpass;
  VkPipelineStageFlags          srcStageMask;
  VkPipelineStageFlags          dstStageMask;
  VkAccessFlags                 srcAccessMask;
  VkAccessFlags                 dstAccessMask;
  VkDependencyFlags             dependencyFlags;
} VkSubpassDependency;
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);
```

Example - Acquire, Render, Present

```
// Subpass dependency to express that an attachment has just been acquired
acquiredDependency.srcSubpass = VK_SUBPASS_EXTERNAL;
acquiredDependency.dstSubpass = 0; // First subpass it's used in
acquiredDependency.srcStageMask = VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT; // Semaphore/Submit guarantees this is sufficient
acquiredDependency.dstStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT; // Latest possible stage
acquiredDependency.srcAccessMask = 0; // Previous semaphore will guarantee it is in device memory
acquiredDependency.dstAccessMask = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT; // Access type
```

```
// Subpass dependency to express that an attachment will be presented
presentDependency.srcSubpass = 4; // Last subpass it's used in
presentDependency.dstSubpass = VK_SUBPASS_EXTERNAL;
presentDependency.srcStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT; // Earliest possible stage
presentDependency.dstStageMask = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT; // Semaphore/Submit guarantees this is sufficient
presentDependency.srcAccessMask = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT; // Access type
presentDependency.dstAccessMask = 0; // Previous semaphore will guarantee it is in device memory
```

```
// Acquire image, render to it, then present it (render loop!)
vkAcquireImageKHR(...);
vkQueueSubmit(...); // Includes execution of render pass
vkQueuePresentKHR(...);
```

KHRONOS GROUP

Semaphores

- **Semaphores**
  - Used to synchronize queues
  - Not necessary for single-queue
- **Fairly coarse**
  - Per submission batch
    - E.g. a set of command buffers
  - Multiple per submit command
- **Some implicit memory dependencies**
  - Writes propagated between all device "visible" memory spaces
    - Not guaranteed visible to host

```
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;
```

Example - Acquire, Render, Present 2

```
// Acquire an image. Pass in a semaphore to be signalled
vkAcquireNextImageKHR(device, swapchain, UINT64_MAX, acquireSemaphore, VK_NULL_HANDLE, &imageIndex);
```

```
// Submit command buffers
submitInfo.waitSemaphoreCount = 1;
submitInfo.pWaitSemaphores = &acquireSemaphore;
submitInfo.commandBufferCount = 1;
submitInfo.pCommandBuffers = &commandBuffer;
submitInfo.signalSemaphoreCount = 1;
submitInfo.pSignalSemaphores = &graphicsSemaphore;

vkQueueSubmit(graphicsQueue, 1, &submitInfo, fence);
```

```
// Present images to the display
presentInfo.waitSemaphoreCount = 1;
presentInfo.pWaitSemaphores = &graphicsSemaphore;
presentInfo.swapchainCount = 1;
presentInfo.pSwapchains = &swapchain;
presentInfo.pImageIndices = &imageIndex;

vkQueuePresentKHR(presentQueue, &presentInfo);
```

Fences

- **Fences**
  - Used to synchronize queue to CPU
- **Very coarse grain**
  - Per queue submit command
- **Implicit memory dependency**
  - Writes propagated between all device “visible” memory spaces
    - Not guaranteed visible to host

GL’s fences are like a combination of a semaphore and a fence in Vulkan - they can synchronize GPU and CPU in multiple ways at a coarse granularity.

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

VkResult vkResetFences(
  VkDevice                   device,
  uint32_t                   fenceCount,
  const VkFence*             pFences);

VkResult vkGetFenceStatus(
  VkDevice                   device,
  VkFence                    fence);

VkResult vkWaitForFences(
  VkDevice                   device,
  uint32_t                   fenceCount,
  const VkFence*             pFences,
  VkBool32                   waitAll,
  uint64_t                   timeout);
```

Other important synchronization…

- Implicit… ish?

Queue Submit

- **Queue Submission**
  - Used to push operations to a device
- **Guaranteed forward progress**
  - Operations will execute once pushed
- **Implicit memory dependency**
  - Writes propagated from ‘host visible’ to all ‘device visible’ memory spaces

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

Wait Idle

- **Ensures execution completes**
  - VERY heavy-weight

- **vkQueueWaitIdle**
  - Wait for queue operations to finish
  - Equivalent to waiting on a fence

- **vkDeviceWaitIdle**
  - Waits for device operations to finish
  - Includes vkQueueWaitIdle for queues

```
VkResult vkQueueWaitIdle(
  VkQueue                            queue);

VkResult vkDeviceWaitIdle(
  VkDevice                           device);
```

Wait Idle

- **Ensures execution completes**
  - VERY heavy-weight

- **vkQueueWaitIdle**
  - Wait for queue operations to finish
  - Equivalent to waiting on a fence

- **vkDeviceWaitIdle**
  - Waits for device operations to finish
  - Includes vkQueueWaitIdle for queues

- **Warning!**
  - Only use for tear-down
  - Will guarantee no overlap

```
VkResult vkQueueWaitIdle(
  VkQueue                      queue);

VkResult vkDeviceWaitIdle(
  VkDevice                     device);
```

Programmer Guidelines

- **Specify EXACTLY the right amount of synchronization**
  - Too much and you risk starving your GPU
  - Miss any and your GPU will bite you
- **Use the validation layers to help!**
  - Won’t catch everything, improving over time
- **Pay particular attention to the pipeline stages**
  - Fiddly but become intuitive as you use them
- **Consider Image Layouts**
  - If your GPU can save bandwidth it will
- **Prefer render passes**
  - Driver able to plan workloads efficiently
- **Pay attention to implicit dependencies**
  - Submit and Semaphores guarantee a lot – don’t add more!
- **Different behaviour depending on implementation**
  - Test/Tune on every platform you can find!

Keep your GPU fed without getting bitten!

Questions?

BACKUP SLIDES

Example - Compute to Draw Indirect

```
// Add a subpass dependency to express the wait on an external event
externalDependency.srcSubpass = VK_SUBPASS_EXTERNAL;
externalDependency.srcStageMask = VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT;
externalDependency.dstStageMask = VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT;
externalDependency.srcAccessMask = VK_ACCESS_SHADER_WRITE_BIT;
externalDependency.dstAccessMask = VK_ACCESS_INDIRECT_COMMAND_READ_BIT;
```

```
// Dispatch a compute shader that generates indirect command structures
vkCmdDispatch(...);
// Set an event that can be later waited on (same source stage).
vkCmdSetEvent(commandBuffer, event, VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT);
```

```
vkCmdBeginRenderPass(...);

// Transition the buffer from shader write to indirect command – details match external dependency!
bufferBarrier.srcAccessMask = VK_ACCESS_SHADER_WRITE_BIT;
bufferBarrier.dstAccessMask = VK_ACCESS_INDIRECT_COMMAND_READ_BIT;
bufferBarrier.buffer = indirectBuffer;
vkCmdWaitEvent(commandBuffer, event, VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT, VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT,
&bufferBarrier);

vkCmdDrawIndirect(commandBuffer, indirectBuffer, ...);
```

Example - Multi-buffering

```
// Have enough resources and fences to have one per in-flight-frame, usually the swapchain image count
VkBuffer buffers[swapchainImageCount];
VkFence fence[swapchainImageCount];

// Can use the index from the presentation engine - 1:1 mapping between swapchain images and resources
vkAcquireNextImageKHR(device, swapchain, UINT64_MAX, semaphore, VK_NULL_HANDLE, &nextIndex);

// Make absolutely sure that the work has completed
vkWaitForFences(device, 1, &fence[nextIndex], true, UINT64_MAX);

// Reset the fences we waited on, so they can be re-used
vkResetFences(device, 1, &fence[nextIndex]);

// Change the data in your per-frame resources (with appropriate events/barriers!)
...

// Submit any work to the queue, with those fences being re-used for the next time around
vkQueueSubmit(graphicsQueue, 1, &sSubmitInfo, fence[nextIndex]);
```