Keeping your GPU fed without getting bitten

Tobias Hector
May 2016

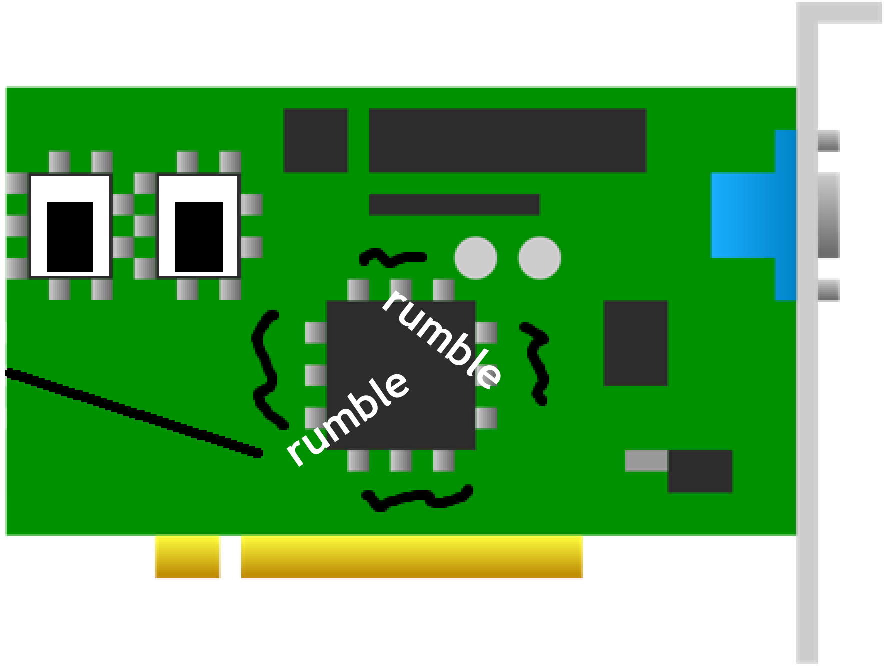
Introduction

- You have delicious draw calls
  - Yummy!

Introduction

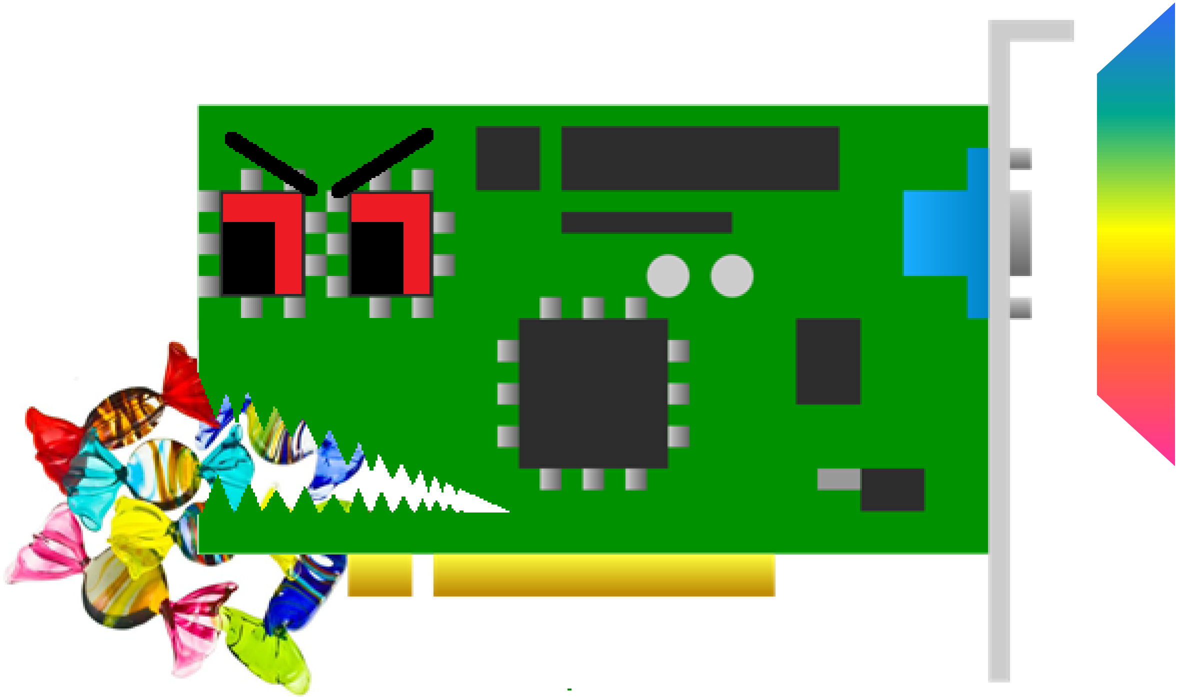
- You have delicious draw calls
  - Yummy!

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



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



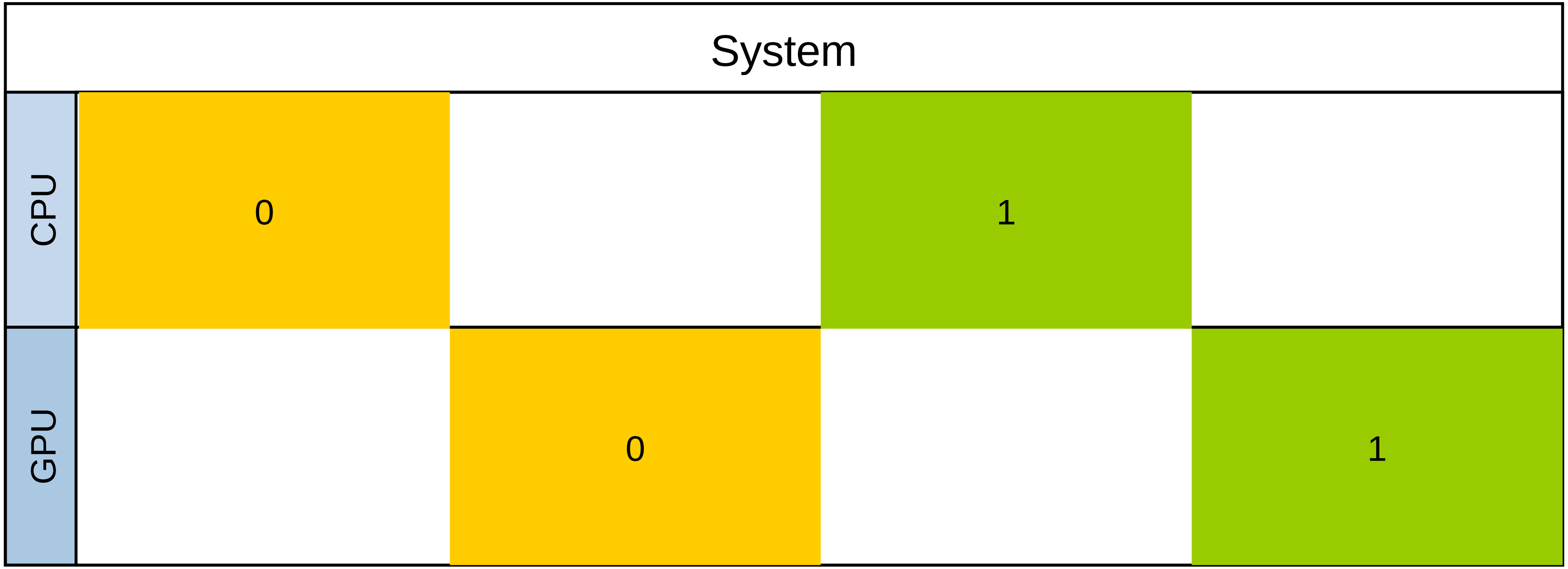
Introduction

- **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.

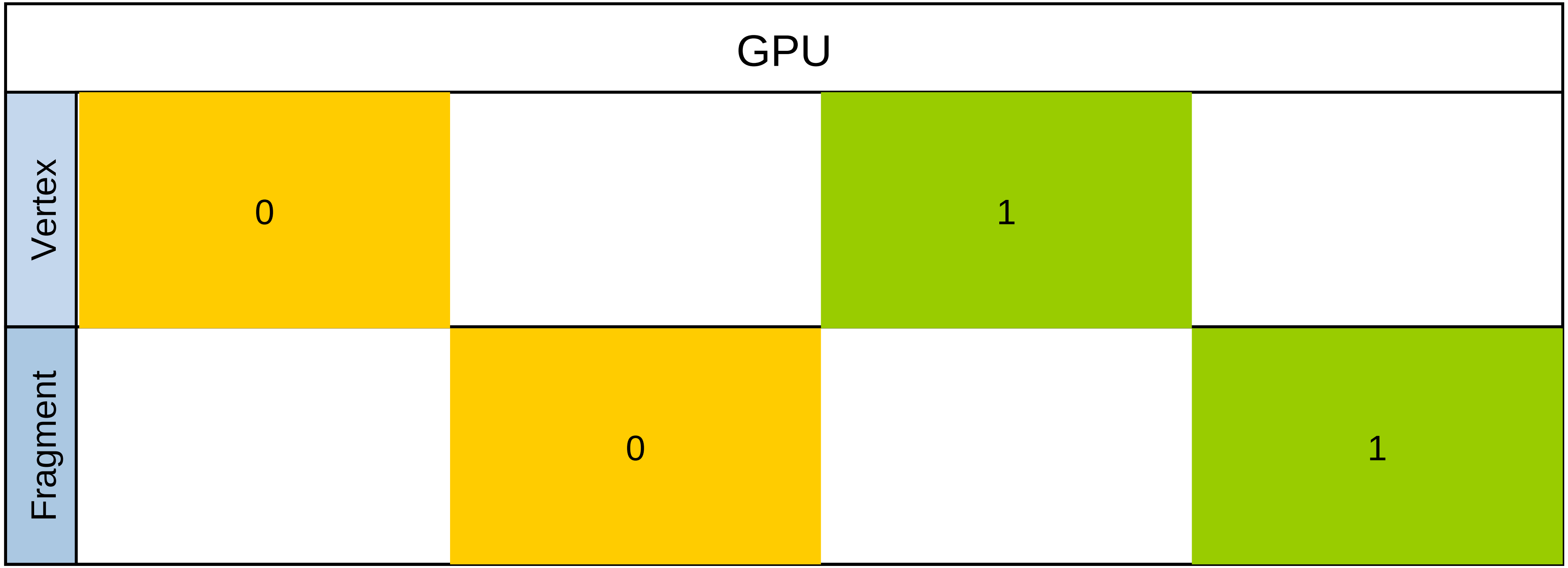
Keeping it fed



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**
  - Anything that can be executed
    - Includes synchronization and memory barriers
- **Execution Dependency**
  - Operations waiting on other operations
  - All synchronization expresses these
- **Memory Barrier**
  - Flush/invalidate caches
  - Determination of access and visibility
- **Memory Dependency**
  - Execution dependency involving a Memory Barrier

Note: Memory barrier does not mean quite the same thing as GL's memory barrier, though there is some relation.

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

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

```
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);
```

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
  - No Memory Barriers

```
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
  - No Memory Barriers

- **Warning!**
  - OS may apply a timeout
  - Set events soon after submission
  - Could you just defer submission?

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

VkResult vkResetEvent(
  VkDevice                        evice,
  VkEvent                         nt);


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

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

Memory Barrier Types

- **Global Memory Barrier**
  - All memory-backed resources
- **Buffer Barrier**
  - For a single buffer range
- **Image Barrier**
  - For a single image subresource range

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

Global Memory Barriers

- **Global Memory Barriers**
  - All memory used by accessed stages
  - Effectively flushes entire caches
- **Use when many resources transition**
  - Cheaper than one-by-one
  - Don't transition unnecessarily!
- **User must define 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 stages
  - Defines queue ownership

- **User must define prior access**
  - Driver not tracking for you

```
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 stages
  - Defines queue ownership
  - Defines image layout

- **User must define prior access**
  - Driver not tracking for you
  - For images, this includes prior layout

- **Appropriate layouts allow compression**
  - GPU may use image compression
  - Saves bandwidth
  - Use GENERAL instead of switching frequently

```
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;
```

Subpass Dependencies

- **Subpass dependencies**
  - Similar info to Pipeline Barriers
  - Explicitly between two subpasses
- **Memory barriers**
  - Implicit for attachments
  - Explicit for other resources
- **Pixel 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 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
- **Pixel local only between 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 Dependencies

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

```
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 - Texture Upload

```
// Transition the buffer from host write to transfer read
bufferBarrier.srcAccessMask = VK_ACCESS_HOST_WRITE_BIT;
bufferBarrier.dstAccessMask = VK_ACCESS_TRANSFER_READ_BIT;
// Transition the image to transfer destination
imageBarrier.srcAccessMask = 0;
imageBarrier.dstAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT;
imageBarrier.oldLayout = VK_IMAGE_LAYOUT_UNDEFINED;
imageBarrier.newLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;

vkCmdPipelineBarrier(commandBuffer, VK_PIPELINE_STAGE_HOST_BIT, VK_PIPELINE_STAGE_TRANSFER_BIT, &bufferBarrier,
&imageBarrier);

vkCmdCopyBufferToImage(commandBuffer, srcBuffer, image, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, &copy);

// Transition the image from transfer destination to shader read
imageBarrier.srcAccessMask = VK_ACCESS_TRANSFER_WRITE_BIT;
imageBarrier.dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
imageBarrier.oldLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
imageBarrier.newLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;

vkCmdPipelineBarrier(commandBuffer, VK_PIPELINE_STAGE_TRANSFER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT,
&imageBarrier);
```

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
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, ...);
```

Semaphores

- **Semaphores**
  - Used to synchronize queues
  - Not necessary for single-queue
- **Fairly coarse grain**
  - Per submission batch
    - E.g. a set of command buffers
  - Multiple per submit command
- **Implicit memory guarantees**
  - Effects visible to future operations on the same device
    - 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 and Present

```
// 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.pWaitSemaphores = &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;

vkQueuePresent(presentQueue, &presentInfo);
```

KHRONOS GROUP

Example - Acquire and Present (same queue)

```
// 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 = 0;


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

```
// Present images to the display
presentInfo.waitSemaphoreCount = 0;

presentInfo.swapchainCount = 1;
presentInfo.pSwapchains = &swapchain;
presentInfo.pImageIndices = &imageIndex;

vkQueuePresent(universalQueue, &presentInfo);
```

KHRONOS GROUP

Fences

- **Fences**
  - Used to synchronize queue to CPU
- **Very coarse grain**
  - Per queue submit command
- **Implicit memory guarantees**
  - Effects visible to future operations on the same device
    - 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);
```

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]);
```

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

These are a lot like glFinish, and should be treated similarly - use them VERY SPARINGLY.

```
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);
```

Wait Idle

- **Useful primarily at teardown**
  - Use it to quickly ensure all work is done

- **Favour other synchronization at all other times**
  - Extremely heavyweight, will cause serialization!

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 yet, but 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
- **Different behaviour depending on implementation**
  - Test/Tune on every platform you can find!

Keep your GPU fed without getting bitten!

Questions?