Introduction to the Vulkan Graphics API

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Ongoing Notes and Code

The notes and code presented here are constantly being updated.

Go to:

http://cs.oregonstate.edu/~mjb/vulkan

for all the latest versions.
Introduction to the Vulkan Graphics API

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Third, thanks to Kathleen Mattson and the Khronos Group for the great laminated Vulkan Quick Reference Cards!
What Prompted the Community’s Move to Vulkan?

1. Performance
2. Performance
3. Performance

Vulkan is better at keeping the GPU busy than OpenGL is. OpenGL drivers need to do a lot of CPU work before handing work off to the GPU. Vulkan lets you get more power from the GPU card you already have.

This is especially important if you can hide the complexity of Vulkan from your customer base and just let them see the improved performance. Thus, Vulkan has had a lot of support and interest from game engine developers, 3rd party software vendors, etc.

As an aside, the Vulkan development effort was originally called “glNext”, which created the false impression that this was a replacement for OpenGL. It’s not.
OpenGL 4.2 Pipeline Flowchart

OpenGL’s complexity has been hard on driver-writers.
Why is it so important to keep the GPU Busy?

Nvidia Titan V Specs vs. Titan Xp, 1080 Ti

<table>
<thead>
<tr>
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<th>Tesla P100</th>
<th>GTX 1080 Ti</th>
<th>GTX 1080</th>
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</table>

The Nvidia Titan V graphics card is not targeted at gamers, but rather at scientific and machine/deep learning applications. That does not, however, mean that the card is incapable of gaming, nor does it mean that we can't extrapolate future key performance metrics for Volta. The Titan V is a derivative of the earlier-released GV100 GPU, part of the Tesla accelerator card series. The key differentiator is that the Titan V ships at $3000, whereas the Tesla V100 was available as part of a $10,000 developer kit. The Tesla V100 still offers greater memory capacity by 4GB – 16GB HBM2 versus 12GB HBM2 – and has a wider memory interface, but other core features remain matched or nearly matched. Core count, for one, is 5120 CUDA cores on each GPU, with 840 Tensor cores (used for Tensorflow deep/machine learning workloads) on each GPU.
The Khronos Group, Inc. is a non-profit member-funded industry consortium, focused on the creation of open standard, royalty-free application programming interfaces (APIs) for authoring and accelerated playback of dynamic media on a wide variety of platforms and devices. Khronos members may contribute to the development of Khronos API specifications, vote at various stages before public deployment, and accelerate delivery of their platforms and applications through early access to specification drafts and conformance tests.
Playing “Where’s Waldo”
Who’s Been Specifically Working on Vulkan?
Vulkan

• Largely derived from AMD’s *Mantle* API

• Also heavily influenced by Apple’s *Metal* API and Microsoft’s *DirectX 12*

• Goal: much less driver complexity and overhead than OpenGL has

• Goal: much less user hand-holding

• Goal: higher single-threaded performance than OpenGL can deliver

• Goal: able to do multithreaded graphics

• Goal: able to handle tiled rendering
Vulkan Differences from OpenGL

• More low-level information must be provided (by you!) in the application, rather than the driver

• Screen coordinate system is Y-down

• No “current state”, at least not one maintained by the driver

• All of the things that we have talked about being *deprecated* in OpenGL are *really deprecated* in Vulkan: built-in pipeline transformations, begin-end, fixed-function, etc.

• You must manage your own transformations.

• All transformation, color, texture functionality must be done in shaders.

• Shaders are pre-”half-compiled” outside of your application. The compilation process is then finished during the pipeline-building process.
VkBufferCreateInfo vbci;
    vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
    vbci.pNext = nullptr;
    vbci.flags = 0;
    vbci.size = << buffer size in bytes >>
    vbci.usage = VK_USAGE_UNIFORM_BUFFER_BIT;
    vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vbci.queueFamilyIndexCount = 0;
    vbci.pQueueFamilyIndices = nullptr;

VK_RESULT result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR, OUT &Buffer );

VkMemoryRequirements vmr;

result = vkGetBufferMemoryRequirements( LogicalDevice, Buffer, OUT &vmr );  // fills vmr

VkMemoryAllocateInfo vmai;
    vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
    vmai.pNext = nullptr;
    vmai.flags = 0;
    vmai.allocationSize = vmr.size;
    vmai.memoryTypeIndex = 0;

result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, &MatrixBufferMemoryHandle );

result = vkBindBufferMemory( LogicalDevice, Buffer, MatrixBufferMemoryHandle, 0 );
Vulkan Quick Reference Card

Vulkan™ is an open-source, cross-platform, unified, and concurrent parallel API designed for modern graphics and general-purpose computing. The API is based on a pipeline model and uses a path-tracing technique. Vulkan provides a high-performance, low-overhead interface for access to modern hardware.

Vulkan 1.0 Quick Reference

Command Function Pointers

Return Codes

Success Codes

Error Codes

Physical Devices

Vulkan Graphics

Vulkan 1.0 Quick Reference

Continued on next page

Vulkan Quick Reference Card

Vulkan Pipeline Diagram [9]

FROM APPLICATION
- Draw
  - Input Assembler
    - Vertex Shader
      - Tessellation Assembler
        - Tessellation Control Shader
          - Tessellation Primitive Generator
            - Tessellation Evaluation Shader
              - Geometry Assembler
                - Geometry Shader
                  - Primitive Assembler
                    - Rasterization
                      - Per-Fragment Operations
                        - Fragment Assembler
                          - Fragment Shader
                            - Post-Fragment Operations
                              - Color/Blending Operations
                                - Framebuffer
                                  - Input Attachment
                                    - Depth/Stencil Attachment
                                      - Color Attachment
                                        - Framebuffer
                                          - Storage Buffer
                                            - Storage Tessel Buffer
                                              - Storage Image
                                                - Uniform Buffer
                                                  - Uniform Texel Buffer
                                                    - Sampled Image
                                                      - Descriptor Sets
                                                        - Push Constants
                                                          - Vertex Buffer Binding
                                                            - Index Buffer Binding
                                                              - Indirect Buffer Binding
                                                                - Draw
                                                                  - FROM APPLICATION
                                                                    - Dispatch
                                                                      - Compute Assembler
                                                                        - Compute Shader

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 heavy black arrows in this illustration show the Vulkan graphics and compute pipelines and indicate data flow:
- Fixed function stage
- Programmable stage
- Buffer
- Image
- Constants
Vulkan Highlights: a More Typical Block Diagram

- Application
- Instance
- Physical Device
- Logical Device
- Queue
  - Command Buffer
  - Command Buffer
  - Command Buffer
Vulkan Synchronization

- Synchronization is the responsibility of the application
- Events can be set, polled, and waited for (much like OpenCL)
- Vulkan does not ever lock – that’s the application’s job
- Threads can concurrently read from the same object
- Threads can concurrently write to different objects
Vulkan Shaders

• GLSL is the same as before … almost

• For places it’s not, an implied
  \#define VULKAN 100
  is automatically supplied by the compiler

• You pre-compile your shaders with an external compiler

• Your shaders get turned into an intermediate form known as SPIR-V (Standard Portable Intermediate Representation for Vulkan)

• SPIR-V gets turned into fully-compiled code at runtime

• The SPIR-V spec has been public for months – new shader languages are surely being developed

• OpenCL and OpenGL will be moving to SPIR-V as well

GLSL Source → External GLSL Compiler → SPIR-V → Compiler in driver → Vendor-specific code

Advantages:
1. Software vendors don’t need to ship their shader source
2. Software can launch faster because half of the compilation has already taken place
3. This guarantees a common front-end syntax
4. This allows for other language front-ends
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Data Buffers
A **Data Buffer** is just a group of contiguous bytes in GPU memory. They have no inherent meaning. The data that is stored there is whatever you want it to be. (This is sometimes called a “Binary Large Object”, or “BLOB”.)

It is up to you to be sure that the writer and the reader of the Data Buffer are interpreting the bytes in the same way!

Vulkan calls these things “Buffers”. But, Vulkan calls other things “Buffers”, too, such as Texture Buffers and Command Buffers. So, I have taken to calling these things “Data Buffers” and have even gone to far as to override some of Vulkan’s own terminology:

```c
typedef VkBuffer VkDataBuffer;
```
Vulkan: Buffers

**vkCreateBuffer()**
- LogicalDevice
- VkBufferCreateInfo
  - bufferUsage
  - queueFamilyIndices
  - size (bytes)

**Buffer**
- VkGetBufferMemoryRequirements()
  - memoryType
  - size

**VkMemoryAllocateInfo**
- VkAllocateMemory()
- LogicalDevice
  - bufferMemoryHandle

**vkBindBufferMemory()**
- VkMapMemory()
  - gpuAddress
Vulkan: Creating a Data Buffer

```
VkBufferCreateInfo vbci;
    vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
    vbci.pNext = nullptr;
    vbci.flags = 0;
    vbci.size = << buffer size in bytes >>
    vbci.usage = <<or'ed bits of: >>
        VK_USAGE_TRANSFER_SRC_BIT
        VK_USAGE_TRANSFER_DST_BIT
        VK_USAGE_UNIFORM_TEXEL_BUFFER_BIT
        VK_USAGE_STORAGE_TEXEL_BUFFER_BIT
        VK_USAGE_UNIFORM_BUFFER_BIT
        VK_USAGE_STORAGE_BUFFER_BIT
        VK_USAGE_INDEX_BUFFER_BIT
        VK_USAGE_VERTEX_BUFFER_BIT
        VK_USAGE_INDIRECT_BUFFER_BIT
    vbci.sharingMode = << one of: >>
        VK_SHARING_MODE_EXCLUSIVE
        VK_SHARING_MODE_CONCURRENT
    vbci.queueFamilyIndexCount = 0;
    vbci.pQueueFamilyIndices = (const iont32_t) nullptr;

VkBuffer Buffer;

result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR, OUT &Buffer );
```
Vulkan: Allocating Memory for a Buffer, Binding a Buffer to Memory, and Writing to the Buffer

```c
VkMemoryRequirements  vmr;
result = vkGetBufferMemoryRequirements( LogicalDevice, Buffer, OUT &vmr );

VkMemoryAllocateInfo  vmai;
  vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
  vmai.pNext = nullptr;
  vmai.flags = 0;
  vmai.allocationSize = vmr.size;
  vmai.memoryTypeIndex = FindMemoryThatIsHostVisible( );

... 

VkDeviceMemory  vdm;
result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm );

result = vkBindBufferMemory( LogicalDevice, Buffer, IN vdm, 0 ); // 0 is the offset

... 

result = vkMapMemory( LogicalDevice, IN vdm, 0, VK_WHOLE_SIZE, 0, &ptr );

  << do the memory copy >>

result = vkUnmapMemory( LogicalDevice, IN vdm );
```
Finding the Right Type of Memory

```c
int FindMemoryThatIsHostVisible( uint32_t memoryTypeBits )
{
    VkPhysicalDeviceMemoryProperties vpdmp;
    vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp );
    for( unsigned int i = 0; i < vpdmp.memoryTypeCount; i++ )
    {
        VkMemoryType vmt = vpdmp.memoryTypes[i];
        VkMemoryPropertyFlags vmpf = vmt.propertyFlags;
        if( ( memoryTypeBits & (1<<i) ) != 0 )
        {
            if( ( vmpf & VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT ) != 0 )
            {
                return i;
            }
        }
    }
}
```

Could also be `VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT`
### Finding the Right Type of Memory

```c
VkPhysicalDeviceMemoryProperties vpdmp;
vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp );
```

<table>
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<th>Memory Types</th>
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</tr>
<tr>
<td>Memory 1</td>
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<tr>
<td>Memory 2</td>
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<tr>
<td>Memory 3</td>
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<td>Memory 4</td>
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<td>Memory 5</td>
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<tr>
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</tr>
<tr>
<td>Memory 7 (DeviceLocal)</td>
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<tr>
<td>Memory 8 (DeviceLocal)</td>
</tr>
<tr>
<td>Memory 9 (HostVisible HostCoherent)</td>
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<tr>
<td>Memory 10 (HostVisible HostCoherent HostCached)</td>
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<table>
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<th>Memory Heaps</th>
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<td>Heap 0: size = 0xb7c00000 DeviceLocal</td>
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<tr>
<td>Heap 1: size = 0xfac00000</td>
</tr>
</tbody>
</table>
Something I’ve Found Useful

I find it handy to encapsulate buffer information in a struct:

```c
typedef struct MyBuffer
{
    VkDataBuffer buffer;
    VkDeviceMemory vdm;
    VkDeviceSize size;
} MyBuffer;

MyBuffer MyMatrixUniformBuffer;
```

It’s the usual object-oriented benefit – you can pass around just one data-item and everyone can access whatever information they need.
It's the usual object-oriented benefit – you can pass around just one data-item and everyone can access whatever information they need.

```c
VkResult
Init05DataBuffer( VkDeviceSize size, VkBufferUsageFlags usage, OUT MyBuffer * pMyBuffer )
{
    ...
    vbci.size = pMyBuffer->size = size;
    ...
    result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR, OUT &pMyBuffer->buffer );
    ...
    pMyBuffer->vdm = vdm;
    ...
}
```
Here’s the C struct to hold some uniform variables

```c
struct matBuf
{
    glm::mat4 uModelMatrix;
    glm::mat4 uViewMatrix;
    glm::mat4 uProjectionMatrix;
    glm::mat3 uNormalMatrix;
} Matrices;
```

Here’s the shader code to access those uniform variables

```c
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
    mat4 uModelMatrix;
    mat4 uViewMatrix;
    mat4 uProjectionMatrix;
    mat4 uNormalMatrix;
} Matrices;
```
Filling those Uniform Variables

glm::vec3 eye(0.,0.,EYEDIST);
glm::vec3 look(0.,0.,0.);
glm::vec3 up(0.,1.,0.);

Matrices.uModelMatrix = glm::mat4(); // identity
Matrices.uViewMatrix = glm::lookAt( eye, look, up );

Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Matrices.uProjectionMatrix[1][1] *= -1.;

Matrices.uNormalMatrix = glm::inverseTranspose( glm::mat3( Matrices.uModelMatrix ) );
This C struct is holding the actual data. It is writeable by the application.

MyBuffer MyMatrixUniformBuffer;

The MyBuffer does not hold any actual data itself. It just represents the collection of data buffer information that will be used by Vulkan.

The Data Buffer in GPU memory is holding the actual data. It is readable by the shaders.

uniform matBuf Matrices;

There is one more step in here—Descriptor Sets. Here’s a quick preview…

memory-mapped copy

The Parade of Data
Filling the Data Buffer

```c
typedef struct MyBuffer
{
    VkDataBuffer buffer;
    VkDeviceMemory vdm;
    VkDeviceSize size;
} MyBuffer;

Init05UniformBuffer( sizeof(Matrices), &MyMatrixUniformBuffer );

Fill05DataBuffer( MyMatrixUniformBuffer, (void *) &Matrices );

glm::vec3 eye(0.0f, 0.0f, EYEDIST);
glm::vec3 look(0.0f, 0.0f, 0.0f);
glm::vec3 up(0.0f, 1.0f, 0.0f);

Matrices.uModelMatrix = glm::mat4( ); // identity
Matrices.uViewMatrix = glm::lookAt( eye, look, up );
Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000.0f);
Matrices.uProjectionMatrix[1][1] *= -1.0f;

Matrices.uNormalMatrix = glm::inverseTranspose( glm::mat3( Matrices.uModelMatrix ) );
```
Creating and Filling the Data Buffer – the Details

```c
VkResult Init05DataBuffer( VkDeviceSize size, VkBufferUsageFlags usage, OUT MyBuffer * pMyBuffer )
{
    VkResult result = VK_SUCCESS;
    VkBufferCreateInfo vbci;
    vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
    vbci.pNext = nullptr;
    vbci.flags = 0;
    vbci.size = pMyBuffer->size = size;
    vbci.usage = usage;
    vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vbci.queueFamilyIndexCount = 0;
    vbci.pQueueFamilyIndices = (const uint32_t * )nullptr;
    result = vkCreateBuffer ( LogicalDevice, IN &vbci, PALLOCATOR, OUT &pMyBuffer->buffer );

    VkMemoryRequirements vmr;
    vkGetBufferMemoryRequirements( LogicalDevice, IN pMyBuffer->buffer, OUT &vmr );  // fills vmr

    VkMemoryAllocateInfo vmai;
    vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
    vmai.pNext = nullptr;
    vmai.allocationSize = vmr.size;
    vmai.memoryTypeIndex = FindMemoryThatIsHostVisible( );

    VkDeviceMemory vdm;
    result = vkAllocateMemory( LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm );
    pMyBuffer->vdm = vdm;

    result = vkBindBufferMemory( LogicalDevice, pMyBuffer->buffer, IN vdm, 0 );  // 0 is the offset
    return result;
}
```
Creating and Filling the Data Buffer – the Details

```c
VkResult Fill05DataBuffer( IN MyBuffer myBuffer, IN void * data )
{
    // the size of the data had better match the size that was used to Init the buffer!

    void * pGpuMemory;
    vkMapMemory( LogicalDevice, IN myBuffer.vdm, 0, VK_WHOLE_SIZE, 0, OUT &pGpuMemory );
    // 0 and 0 are offset and flags
    memcpy( pGpuMemory, data, (size_t)myBuffer.size );
    vkUnmapMemory( LogicalDevice, IN myBuffer.vdm );
    return VK_SUCCESS;
}
```

Remember – to Vulkan and GPU memory, these are just bits. It is up to you to handle their meaning correctly.
Vertex Buffers
Vertex Buffers are how you draw things in Vulkan. They are very much like Vertex Buffer Objects in OpenGL, but more detail is exposed to you (a lot more…).

But, the good news is that Vertex Buffers are really just ordinary Data Buffers, so some of the functions will look familiar to you.

First, a quick review of computer graphics geometry . . .
Vulkan Topologies

VK_PRIMITIVE_TOPOLOGY_POINT_LIST

VK_PRIMITIVE_TOPOLOGY_LINE_LIST

VK_PRIMITIVE_TOPOLOGY_LINE_STRIP

VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST

VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP

VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN
Vertex Orientation Issues

Thanks to OpenGL, we are all used to drawing in a right-handed coordinate system.

Internally, however, the Vulkan pipeline uses a left-handed system:

The best way to handle this is to continue to draw in a RH coordinate system and then fix it up in the projection matrix, like this:

```
ProjectionMatrix[1][1] *= -1.;
```

This is like saying “Y’ = -Y”.
A Colored Cube Example

```
staticGLuint CubeTriangleIndices [][3] = {
    {0, 2, 3},
    {0, 3, 1},
    {4, 5, 7},
    {4, 7, 6},
    {1, 3, 7},
    {1, 7, 5},
    {0, 4, 6},
    {0, 6, 2},
    {2, 6, 7},
    {2, 7, 3},
    {0, 1, 5},
    {0, 5, 4}
};
```

```
static GLfloat CubeVertices[][3] = {
    {-1, -1, -1},
    {1, -1, -1},
    {-1, 1, -1},
    {1, 1, -1},
    {-1, -1, 1},
    {1, -1, 1},
    {-1, 1, 1},
    {1, 1, 1}};
```

```
static GLfloat CubeColors[][3] = {
    {0, 0, 0},
    {1, 0, 0},
    {0, 1, 0},
    {1, 1, 0},
    {0, 0, 1},
    {1, 0, 1},
    {0, 1, 1},
    {1, 1, 1}};
```

Triangles in an Array of Structures

From the file `SampleVertexData.cpp`:

```cpp
struct vertex
{
    glm::vec3 position;
    glm::vec3 normal;
    glm::vec3 color;
    glm::vec2 texCoord;
};

struct vertex VertexData[ ] =
{
    // triangle 0-2-3:
    // vertex #0:
    { -1., -1., -1. },
    {  0.,  0., -1. },
    {  0.,  0.,  0. },
    {  1.,  0. }
},

    // vertex #2:
    { -1.,  1., -1. },
    {  0.,  0., -1. },
    {  0.,  1.,  0. },
    {  1.,  1. }
},

    // vertex #3:
    {  1.,  1., -1. },
    {  0.,  0., -1. },
    {  1.,  1.,  0. },
    {  0.,  1. }
};
```

Modeled in right-handed coordinates
Vertex Orientation Issues

This object was modeled such that triangles that face the viewer will look like their vertices are oriented CCW (this is detected by looking at vertex orientation at the start of the rasterization).

Because this 3D object is closed, Vulkan can save rendering time by not even bothering with triangles whose vertices look like they are oriented CW. This is called backface culling.

Vulkan’s change in coordinate systems can mess up the backface culling.

So I recommend, at least at first, that you do no culling.

```c
VkPipelineRasterizationStateCreateInfo vprsci;

...  

vprsci.cullMode = VK_CULL_MODE_NONE
vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;
```
MyBuffer MyVertexDataBuffer;

Init05MyVertexDataBuffer( sizeof(VertexData), &MyVertexDataBuffer );
Fill05DataBuffer( MyVertexDataBuffer, (void *) VertexData );

VkResult
Init05MyVertexDataBuffer( IN VkDeviceSize size, OUT MyBuffer * pMyBuffer )
{
    VkResult result = Init05DataBuffer( size, VK_BUFFER_USAGE_VERTEX_BUFFER_BIT, pMyBuffer );
    return result;
}
The Vulkan Pipeline

- Vertex Shader module
  - Specialization info
- Vertex Input Stage
  - Vertex Input binding
  - Vertex Input attributes

- Topology

- Tessellation Shaders, Geometry Shader

- Viewport
  - Scissoring

- Depth Clamping
  - DiscardEnable
  - PolygonMode
  - CullMode
  - FrontFace
  - LineWidth

- Which states are dynamic

- DepthTestEnable
  - DepthWriteEnable
  - DepthCompareOp
  - StencilTestEnable

- PipelineLayoutCreateInfo

- Pipeline Layout
- Which shaders are present

- Input Assembly
- Pipeline Layout

- Tessellation, Geometry

- Viewport

- Rasterization

- Dynamic State

- Depth/Stencil

- Fragment Shader Stage

- Color Blending Stage
Telling the Pipeline about its Input

We will come to the Pipeline later, but for now, know that a Vulkan pipeline is essentially a very large data structure that holds (what OpenGL would call) the **state**, including how to parse its input.

```cpp
struct vertex
{
    glm::vec3   position;
    glm::vec3   normal;
    glm::vec3   color;
    glm::vec2   texCoord;
};
```

```cpp
layout( location = 0 ) in vec3 aVertex;
layout( location = 1 ) in vec3 aNormal;
layout( location = 2 ) in vec3 aColor;
layout( location = 3 ) in vec2 aTexCoord;
```

```cpp
VkVertexInputBindingDescription vvibd[1]; // one of these per buffer data buffer
vvibd[0].binding = 0; // which binding # this is
vvibd[0].stride = sizeof( struct vertex ); // bytes between successive structs
vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
```
**Telling the Pipeline about its Input**

```
struct vertex
{
    glm::vec3       position;
    glm::vec3       normal;
    glm::vec3       color;
    glm::vec2       texCoord;
};
```

```
VkVertexInputAttributeDescription     vviad[4];       // array per vertex input attribute
    // 4 = vertex, normal, color, texture coord
    vviad[0].location = 0;                  // location in the layout decoration
    vviad[0].binding = 0;                   // which binding description this is part of
    vviad[0].format = VK_FORMAT_VEC3;       // x, y, z
    vviad[0].offset = offsetof( struct vertex, position );                  // 0

    vviad[1].location = 1;
    vviad[1].binding = 0;
    vviad[1].format = VK_FORMAT_VEC3;       // nx, ny, nz
    vviad[1].offset = offsetof( struct vertex, normal );                    // 12

    vviad[2].location = 2;
    vviad[2].binding = 0;
    vviad[2].format = VK_FORMAT_VEC3;       // r, g, b
    vviad[2].offset = offsetof( struct vertex, color );                    // 24

    vviad[3].location = 3;
    vviad[3].binding = 0;
    vviad[3].format = VK_FORMAT_VEC2;      // s, t
    vviad[3].offset = offsetof( struct vertex, texCoord );                // 36
```
We will come to the Pipeline later, but for now, know that a Vulkan Pipeline is essentially a very large data structure that holds (what OpenGL would call) the state, including how to parse its input.

```cpp
VkPipelineVertexInputStateCreateInfo vpvisci; // used to describe the input vertex attributes
    vpvisci.sType = VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO;
    vpvisci.pNext = nullptr;
    vpvisci.flags = 0;
    vpvisci.vertexBindingDescriptionCount = 1;
    vpvisci.pVertexBindingDescriptions = vvid;
    vpvisci.vertexAttributeDescriptionCount = 4;
    vpvisci.pVertexAttributeDescriptions = vviad;

VkPipelineInputAssemblyStateCreateInfo vpiasci;
    vpiasci.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
    vpiasci.pNext = nullptr;
    vpiasci.flags = 0;
    vpiasci.topology = VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST;
```
Telling the Pipeline about its Input

We will come to the Pipeline later, but for now, know that a Vulkan Pipeline is essentially a very large data structure that holds (what OpenGL would call) the state, including how to parse its input.

```c
VkGraphicsPipelineCreateInfo vgpci;
    vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
    vgpci.pNext = nullptr;
    vgpci.flags = 0;
    vgpci.stageCount = 2; // number of shader stages in this pipeline
    vgpci.pStages = vpssci;
    vgpci.pVertexInputState = &vpvisci;
    vgpci.pInputAssemblyState = &vpiasci;
    vgpci.pTessellationState = (VkPipelineTessellationStateCreateInfo *)nullptr; // &vptsci
    vgpci.pViewportState = &vpvsci;
    vgpci.pRasterizationState = &vprsci;
    vgpci.pMultisampleState = &vpmsci;
    vgpci.pDepthStencilState = &vpdssci;
    vgpci.pColorBlendState = &vpcbsci;
    vgpci.pDynamicState = &vpdsci;
    vgpci.layout = IN GraphicsPipelineLayout;
    vgpci.renderPass = IN RenderPass;
    vgpci.subpass = 0; // subpass number
    vgpci.basePipelineHandle = (VkPipeline) VK_NULL_HANDLE;
    vgpci.basePipelineIndex = 0;

result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN &vgpci,
                                   PALLOCATOR, OUT pGraphicsPipeline );
```
Telling the Command Buffer what Vertices to Draw

We will come to Command Buffers later, but for now, know that you will specify the vertex buffer that you want drawn.

```cpp
VkBuffer buffers[1] = MyVertexDataBuffer.buffer;

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, buffers, offsets);

const uint32_t vertexCount = sizeof(VertexData) / sizeof(VertexData[0]);
const uint32_t instanceCount = 1;
const uint32_t firstVertex = 0;
const uint32_t firstInstance = 0;

vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );
```
Drawing
Triangles Represented as an Array of Structures

From the file SampleVertexData.cpp:

```c++
struct vertex {
    glm::vec3    position;
    glm::vec3    normal;
    glm::vec3    color;
    glm::vec2    texCoord;
};

struct vertex VertexData[ ] = {
    // triangle 0-2-3:
    // vertex #0:
    {  -1.,  -1.,  -1. },
    {   0.,    0.,  -1. },
    {   0.,    0.,    0. },
    {   1.,    0. }     
},

    // vertex #2:
    {  -1.,   1.,  -1. },
    {   0.,   0.,  -1. },
    {   0.,    1.,    0. },
    {   1.,    1. }     
},

    // vertex #3:
    {   1.,   1.,  -1. },
    {   0.,   0.,  -1. },
    {   1.,    1.,    0. },
    {   0.,    1. }     
};
```

Modeled in right-handed coordinates
Non-indexed Buffer Drawing

From the file SampleVertexData.cpp:

```cpp
struct vertex
{
  glm::vec3       position;
  glm::vec3       normal;
  glm::vec3       color;
  glm::vec2       texCoord;
};

struct vertex VertexData[ ] =
{
  // triangle 0-2-3:
  // vertex #0:
  
    { -1., -1., -1. },
    { 0., 0., -1. },
    { 0., 0., 0. },
    { 1., 0. }
  },

  // vertex #2:
  
    { -1., 1., -1. },
    { 0., 0., -1. },
    { 0., 1., 0. },
    { 1., 1. }
  },

  // vertex #3:
  
    { 1., 1., -1. },
    { 0., 0., -1. },
    { 1., 1., 0. },
    { 0., 1. }
  },
};
```

Triangles

Draw
Filling the Vertex Buffer

```c
MyBuffer MyVertexDataBuffer;

Init05MyVertexDataBuffer( sizeof(VertexData), &MyVertexDataBuffer );
Fill05DataBuffer( MyVertexDataBuffer, (void *) VertexData );

VkResult
Init05MyVertexDataBuffer( IN VkDeviceSize size, OUT MyBuffer * pMyBuffer )
{
    VkResult result;
    result = Init05DataBuffer( size, VK_BUFFER_USAGE_VERTEX_BUFFER_BIT, pMyBuffer );
    return result;
}
```
We will come to the Pipeline later, but for now, know that a Vulkan pipeline is essentially a very large data structure that holds (what OpenGL would call) the state, including how to parse its input.

C/C++:

```cpp
struct vertex
{
    glm::vec3       position;
    glm::vec3       normal;
    glm::vec3       color;
    glm::vec2       texCoord;
};
```

GLSL Shader:

```glsl
layout( location = 0 ) in vec3 aVertex;
layout( location = 1 ) in vec3 aNormal;
layout( location = 2 ) in vec3 aColor;
layout( location = 3 ) in vec2 aTexCoord;
```

VectorVertexInputBindingDescription

```c
VkVertexInputBindingDescription vvibd[1]; // one of these per buffer data buffer
vvibd[0].binding = 0; // which binding # this is
vvibd[0].stride = sizeof( struct vertex ); // bytes between successive structs
vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
```
VkBuffer buffers[1] = MyVertexDataBuffer.buffer;

vkCmdBindVertexBuffers(CommandBuffers[nextImageIndex], 0, 1, vertexDataBuffers, offsets);

const uint32_t vertexCount = sizeof(VertexData) / sizeof(VertexData[0]);
const uint32_t instanceCount = 1;
const uint32_t firstVertex = 0;
const uint32_t firstInstance = 0;

vkCmdDraw(CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance);
struct vertex JustVertexData[] = {
    // vertex #0:
    { -1., -1., -1. },{ 0., 0., -1. },{ 0., 0., 0. },{ 1., 0. },
},

// vertex #1:
{ 1., -1., -1. },{ 0., 0., -1. },{ 1., 0., 0. },{ 0., 0. },
},
...

int JustIndexData[] = {
    0, 2, 3, 0, 3, 1, 4, 5, 7, 4, 7, 6, 1, 3, 7, 1, 7, 5, 0, 4, 6, 0, 6, 2, 2, 6, 7, 2, 7, 3, 0, 1, 5, 0, 5, 4,
};
vkCmdBindVertexBuffers( commandBuffer, firstBinding, bindingCount, vertexDataBuffers, vertexOffsets );

vkCmdBindIndexBuffer( commandBuffer, indexDataBuffer, indexOffset, indexType );

typedef enum VkIndexType
{
    VK_INDEX_TYPE_UINT16 = 0, // 0 – 65,535
    VK_INDEX_TYPE_UINT32 = 1, // 0 – 4,294,967,295
} VkIndexType;

vkCmdDrawIndexed( commandBuffer, indexCount, instanceCount, firstIndex, vertexOffset, firstInstance );
Drawing with an Indexed Buffer

VkResult
Init05MyIndexDataBuffer(IN VkDeviceSize size, OUT MyBuffer * pMyBuffer)
{
    VkResult result = Init05DataBuffer(size, VK_BUFFER_USAGE_INDEX_BUFFER_BIT, pMyBuffer);
    // fills pMyBuffer
    return result;
}

Init05MyVertexDataBuffer(  sizeof(JustVertexData), &MyJustVertexDataBuffer );
Fill05DataBuffer( MyJustVertexDataBuffer,               (void *) JustVertexData );

Init05MyIndexDataBuffer(  sizeof(JustIndexData), &MyJustIndexDataBuffer );
Fill05DataBuffer( MyJustIndexDataBuffer,                (void *) JustIndexData );
vkBuffer vBuffers[1] = { MyJustVertexDataBuffer.buffer };  
VkBuffer iBuffer = { MyJustIndexDataBuffer.buffer };  

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, vBuffers, offsets );  
    // 0, 1 = firstBinding, bindingCount  
vkCmdBindIndexBuffer( CommandBuffers[nextImageIndex], iBuffer, 0, VK_INDEX_TYPE_UINT32 );  

cnst uint32_t vertexCount = sizeof(JustVertexData) / sizeof(JustVertexData[0]);  
cnst uint32_t indexCount = sizeof(JustIndexData) / sizeof(JustIndexData[0]);  
cnst uint32_t instanceCount = 1;  
cnst uint32_t firstVertex = 0;  
cnst uint32_t firstIndex = 0;  
cnst uint32_t firstInstance = 0;  
cnst uint32_t vertexOffset = 0;  

#ifdef VERTEX_BUFFER  
    vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );  
#endif  

vkCmdDrawIndexed( CommandBuffers[nextImageIndex], indexCount, instanceCount, firstIndex, vertexOffset, firstInstance );
Sometimes a point that is common to multiple faces has the same attributes, no matter what face it is in. Sometimes it doesn’t.

A color-interpolated cube like this actually has both. Point #7 above has the same color, regardless of what face it is in. However, Point #7 has 3 different normal vectors, depending on which face you are defining. Same with its texture coordinates.

Thus, when using index-ed buffer drawing, you need to create a new vertex struct if any of {position, normal, color, texCoords} changes from what was previously-stored at those coordinates.
Sometimes the Same Point Needs Multiple Attributes

Where values match at the corners (color)

Where values do not match at the corners (texture coordinates)
Shaders and SPIR-V
The Shaders’ View of the Basic Computer Graphics Pipeline

• In general, you want to have a vertex and fragment shader as a minimum.

• A missing stage is OK. The output from one stage becomes the input of the next stage that is there.

• The last stage before the fragment shader feeds its output variables into the rasterizer. The interpolated values then go to the fragment shaders
Vulkan Shader Stages

Shader stages

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,
} VkPipelineStageFlagBits;
Detecting that a GLSL Shader is being used with Vulkan/SPIR-V:

- In the compiler, there is an automatic
  `#define VULKAN 100`

**Vertex and Instance indices:**

- `gl_VertexIndex`
- `gl_InstanceIndex`
- Both are 0-based

**gl_FragColor:**

- In OpenGL, it broadcasts to all color attachments
- In Vulkan, it just broadcasts to color attachment location #0
- Best idea: don’t use it – explicitly declare out variables to have specific location numbers
Shader combinations of separate texture data and samplers:
uniform sampler s;
uniform texture2D t;
vec4 rgba = texture(sampler2D(t, s), vST);

Descriptor Sets:
layout(set=0, binding=0) . . . ;

Push Constants:
layout(push_constant) . . . ;

Specialization Constants:
layout(constant_id = 3) const int N = 5;

• Can only use basic operators, declarations, and constructors
• Only for scalars, but a vector can be constructed from specialization constants

Specialization Constants for Compute Shaders:
layout(local_size_x_id = 8, local_size_y_id = 16);

• gl_WorkGroupSize.z is still as it was
Vulkan: Shaders’ use of Layouts for Uniform Variables

```c
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
    mat4 uModelMatrix;
    mat4 uViewMatrix;
    mat4 uProjectionMatrix;
    mat3 uNormalMatrix;
} Matrices;

// non-opaque must be in a uniform block:
layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
    vec4 uLightPos;
} Light;

layout( set = 2, binding = 0 ) uniform sampler2D uTexUnit;
```

All opaque (non-sampler) uniform variables must be in block buffers.
Vulkan Shader Compiling

- You pre-compile your shaders with an external compiler
- Your shaders get turned into an intermediate form known as SPIR-V
- SPIR-V gets turned into fully-compiled code at runtime
- SPIR-V spec has been public for a couple of years – new shader languages are surely being developed
- OpenGL and OpenCL will be moving to SPIR-V as well

**Advantages:**

1. Software vendors don’t need to ship their shader source
2. Syntax errors appear during the SPIR-V step, not during runtime
3. Software can launch faster because half of the compilation has already taken place
4. This guarantees a common front-end syntax
5. This allows for other language front-ends
SPIR-V:
Standard Portable Intermediate Representation for Vulkan


Shaderfile extensions:
.vert Vertex
.tesc Tessellation Control
.tese Tessellation Evaluation
.geom Geometry
.frag Fragment
.frag Fragment
.comp Compute
(Can be overridden by the –S option)

-V Compile for Vulkan
-G Compile for OpenGL
-I Directory(ies) to look in for #includes
-S Specify stage rather than get it from shaderfile extension
-c Print out the maximum sizes of various properties

Windows: glslangValidator.exe
Linux: setenv LD_LIBRARY_PATH /usr/local/common/gcc-6.3.0/lib64/
You Can Run the SPIR-V Compiler on Windows 10 from a Bash Shell

1. Click on the Microsoft Start icon
2. Type word *bash*
Running glslangValidator.exe

```bash
ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$ !85
  glslangValidator.exe -V sample-vert.vert -o sample-vert.spv
  sample-vert.vert

ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$ !86
  glslangValidator.exe -V sample-frag.frag -o sample-frag.spv
  sample-frag.frag

ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$ 
```
You can also run SPIR-V from a Linux Shell

$ glslangValidator.exe -V sample-vert.vert -o sample-vert.spv
$ glslangValidator.exe -V sample-frag.frag -o sample-frag.spv
How do you know if SPIR-V compiled successfully?

Same as C/C++ -- the compiler gives you no nasty messages.

Also, if you care, legal .spv files have a magic number of 0x07230203

So, if you do an `od -x` on the .spv file, the magic number looks like this: 0203 0723 . . .
Reading a SPIR-V File into a Vulkan Shader Module

VkResult
Init12SpirvShader( std::string filename, VkShaderModule * pShaderModule )
{
    FILE *fp;
    (void) fopen_s( &fp, filename.c_str(), "rb");
    if( fp == NULL )
    {
        fprintf( FpDebug, "Cannot open shader file '%s'\n", filename.c_str() );
        return VK_SHOULD_EXIT;
    }
    uint32_t magic;
    fread( &magic, 4, 1, fp );
    if( magic != SPIRV_MAGIC )
    {
        fprintf( FpDebug, "Magic number for spir-v file '%s' is 0x%08x -- should be 0x%08x\n",
                 filename.c_str(), magic, SPIRV_MAGIC );
        return VK_SHOULD_EXIT;
    }
    fseek( fp, 0L, SEEK_END );
    int size = ftell( fp );
    rewind( fp );
    unsigned char *code = new unsigned char [size];
    fread( code, size, 1, fp );
    fclose( fp );
Reading a SPIR-V File into a Shader Module

VkShaderModuleCreateInfo vsmci;
    vsmci.sType = VK_STRUCTURE_TYPE_SHADER_MODULE_CREATE_INFO;
    vsmci.pNext = nullptr;
    vsmci.flags = 0;
    vsmci.codeSize = size;
    vsmci.pCode = (uint32_t *)code;

VkResult result = vkCreateShaderModule( LogicalDevice, &vsmci, PALLOCATOR, pShaderModule );
fprintf( FpDebug, "Shader Module '%s' successfully loaded\n", filename.c_str() );
delete [] code;
return result;
}
Vulkan Sample Code
Sample Program Output
Caveats on the Sample Code

• I’ve written everything out in appalling longhand.

• Everything is in one .cpp file (except the geometry data). It really should be broken up, but this way you can find everything.

• At times, I could have hidden complexity, but I didn’t. At all stages, I have tried to err on the side of showing you everything, so that nothing happens in a way that’s a secret to you.

• I’ve setup Vulkan structs every time they are used, even though, in many cases, they could have been setup once and then re-used each time.

• At times, I’ve setup things that didn’t need to be setup just to show you what could go there.

• There are good uses for C++ classes and methods here to hide some complexity, but I’ve not done that.

• I’ve typedef’ed a couple things to make the Vulkan phraseology more consistent.

• Even though it is not good software style, I have put persistent information in global variables, rather than a separate data structure.

• At times, I have copied lines from vulkan.h into the code as comments to show you what certain options could be.

• I’ve divided functionality up into the pieces that make sense to me. Many other divisions are possible. Feel free to invent your own.
Sample Code Keyboard Commands

// Keyboard commands:
//      'i', 'I': Toggle using a vertex buffer only vs. a vertex/index buffer
//      'l', 'L': Toggle lighting off and on
//      'm', 'M': Toggle display mode (textures vs. colors)
//      'p', 'P': Pause the animation
//      'q', 'Q': Esc: exit the program
//      'r', 'R': Toggle rotation-animation and using the mouse
//      '1', '4', '9': Number of instances
int
main( int argc, char * argv[ ] )
{
    Width = 800;
    Height = 600;
    
    errno_t err = fopen_s( &FpDebug, DEBUGFILE, "w" );
    if( err != 0 )
    {
        fprintf( stderr, "Cannot open debug print file "%s"
", DEBUGFILE );
        FpDebug = stderr;
    }
    fprintf(FpDebug, "FpDebug: Width = %d ; Height = %d\n", Width, Height);
    
    Reset( );
    InitGraphics( );
    
    // loop until the user closes the window:
    
    while( glfwWindowShouldClose( MainWindow ) == 0 )
    {
        glfwPollEvents( );
        Time = glfwGetTime(); // elapsed time, in double-precision seconds
        UpdateScene( );
        RenderScene( );
    }
    
    fprintf(FpDebug, "Closing the GLFW window\n");
    
    vkQueueWaitIdle( Queue );
    vkDeviceWaitIdle( LogicalDevice );
    DestroyAllVulkan( );
    glfwDestroyWindow( MainWindow );
    glfwTerminate( );
    return 0;
}
void InitGraphics()
{
    HERE_I_AM( "InitGraphics" );

    VkResult result = VK_SUCCESS;
    Init01Instance();

    InitGLFW();

    Init02CreateDebugCallbacks();

    Init03PhysicalDeviceAndGetQueueFamilyProperties();

    Init04LogicalDeviceAndQueue();

    Init05UniformBuffer( sizeof(Matrices), &MyMatrixUniformBuffer );
    Fill05DataBuffer( MyMatrixUniformBuffer, (void *)&Matrices );

    Init05UniformBuffer( sizeof(Light), &MyLightUniformBuffer );
    Fill05DataBuffer( MyLightUniformBuffer, (void *)&Light );

    Init05MyVertexDataBuffer( sizeof(VertexData), &MyVertexDataBuffer );
    Fill05DataBuffer( MyVertexDataBuffer, (void *)&VertexData );

    Init06CommandPool();
    Init06CommandBuffers();
Init07TextureSampler( &MyPuppyTexture.texSampler );
Init07TextureBufferAndFillFromBmpFile("puppy.bmp", &MyPuppyTexture);

Init08Swapchain( );

Init09DepthStencilImage( );

Init10RenderPasses( );

Init11Framebuffers( );

Init12SpirvShader( "sample-vert.spv", &ShaderModuleVertex );
Init12SpirvShader( "sample-frag.spv", &ShaderModuleFragment );

Init13DescriptorSetPool( );
Init13DescriptorSetLayouts();
Init13DescriptorSets( );

Init14GraphicsVertexFragmentPipeline( ShaderModuleVertex, ShaderModuleFragment,
                                   VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST, &GraphicsPipeline );
}
#include “SampleVertexData.cpp”

```cpp
struct vertex
{
    glm::vec3       position;
    glm::vec3       normal;
    glm::vec3       color;
    glm::vec2       texCoord;
};

struct vertex VertexData[ ] =
{
    // triangle 0-2-3:
    // vertex #0:
    {
        { -1., -1., -1. },
        {  0.,  0., -1. },
        {  0.,  0.,  0. },
        {  1., 0. }
    },

    // vertex #2:
    {
        { -1.,  1., -1. },
        {  0.,  0., -1. },
        {  0.,  1.,  0. },
        {  1., 1. }
    },

    ...
Vulkan Software Philosophy

1. There are lots of typedefs that define C/C++ structs and enums

2. Vulkan takes a non-C++ object-oriented approach in that those typedef’ed structs pass all the necessary information into a function. For example, where we might normally say in C++:

   ```
   result = LogicalDevice->vkGetDeviceQueue (queueFamilyIndex, queueIndex, OUT &Queue);
   ```

   we would actually say in C:

   ```
   result = vkGetDeviceQueue (LogicalDevice, queueFamilyIndex, queueIndex, OUT &Queue);
   ```
Vulkan Conventions

**VkXxx** is a typedef, probably a struct

**vkXxx( )** is a function call

**VK_XXX** is a constant

My Conventions

“Init” in a function call name means that something is being setup that only needs to be setup once

The number after “Init” gives you the ordering

In the source code, after main( ) comes InitGraphics( ), then all of the InitxxYYY( ) functions in numerical order. After that comes the helper functions

“Find” in a function call name means that something is being looked for

“Fill” in a function call name means that some data is being supplied to Vulkan

“IN” and “OUT” ahead of function call arguments are just there to let you know how an argument is going to be used by the function. Otherwise, they have no significance.
Querying the Number of Something and Allocating Structures to Hold Them All

```c
uint32_t count;
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT (VkPhysicalDevice *)nullptr );

VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[count];
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT physicalDevices );
```

This way of querying information is a recurring OpenCL and Vulkan pattern (get used to it):

```c
result = vkEnumeratePhysicalDevices( Instance, &count, nullptr );
result = vkEnumeratePhysicalDevices( Instance, &count, physicalDevices );
```
Your Sample2017.zip File Contains This

Linux shader compiler

Windows shader compiler

Double-click here to launch Visual Studio 2017 with this solution
Setting Up GLFW

```c
void
InitGLFW( )
{
    glfwInit( );
    glfwWindowHint( GLFW_CLIENT_API, GLFW_NO_API );
    glfwWindowHint( GLFW_RESIZABLE, GLFW_FALSE );
    MainWindow = glfwCreateWindow( Width, Height, "Vulkan Sample", NULL, NULL );
    VkResult result = glfwCreateWindowSurface( Instance, MainWindow, NULL, &Surface );

    glfwSetErrorCallback( GLFWErrorCallback );
    glfwSetKeyCallback( MainWindow, GLFWKeyboard );
    glfwSetCursorPosCallback( MainWindow, GLFWMouseMotion );
    glfwSetMouseButtonCallback( MainWindow, GLFWMouseButton );
}
```
void GLFWKeyboard( GLFWwindow * window, int key, int scancode, int action, int mods )
{
    if( action == GLFW_PRESS )
    {
        switch( key )
        {
            //case GLFW_KEY_M:
            case 'm':
            case 'M':
                Mode++;
                if( Mode >= 2 )
                    Mode = 0;
                break;
            default:
                fprintf( FpDebug, "Unknow key hit: 0x%04x = '%c'n", key, key );
                fflush(FpDebug);
        }
    }
}
while( glfwWindowShouldClose( MainWindow ) == 0 )
{
    glfwPollEvents( );
    Time = glfwGetTime( );          // elapsed time, in double-precision seconds
    UpdateScene( );
    RenderScene( );
}

vkQueueWaitIdle( Queue );
vkDeviceWaitIdle( LogicalDevice );
DestroyAllVulkan( );
glfwDestroyWindow( MainWindow );
glfwTerminate( );
What is GLM?

GLM is a set of C++ classes and functions to fill in the programming gaps in writing the basic vector and matrix mathematics for OpenGL applications. However, even though it was written for OpenGL, it works fine with Vulkan (with one small exception which can be worked around).

Even though GLM looks like a library, it actually isn’t – it is all specified in \*.hpp header files so that it gets compiled in with your source code.

You can find it at:

http://glm.g-truc.net/0.9.8.5/

You invoke GLM like this:

#define    GLM_FORCE_RADIANS
#include <glm/glm.hpp>
#include <glm/gtc/matrix_transform.hpp>
#include <glm/gtc/matrix_inverse.hpp>

If GLM is not installed in a system place, put it somewhere you can get access to. Later on, these notes will show you how to use it from there.
Why are we even talking about this?

All of the things that we have talked about being deprecated in OpenGL are really deprecated in Vulkan -- built-in pipeline transformations, begin-end, fixed-function, etc. So, where you might have said in OpenGL:

```c
  gluLookAt( 0., 0., 3., 0., 0., 0., 0., 1., 0. );
  glRotatef( (GLfloat)Yrot, 0., 1., 0. );
  glRotatef( (GLfloat)Xrot, 1., 0., 0. );
  glScalef( (GLfloat)Scale, (GLfloat)Scale, (GLfloat)Scale );
```

you would now have to say:

```cpp
  glm::mat4 modelview;
  glm::vec3 eye(0.,0.,3.);
  glm::vec3 look(0.,0.,0.);
  glm::vec3 up(0.,1.,0.);
  modelview = glm::lookAt( eye, look, up );
  modelview = glm::rotate( modelview, D2R*Yrot, glm::vec3(0.,1.,0.) );
  modelview = glm::rotate( modelview, D2R*Xrot, glm::vec3(1.,0.,0.) );
  modelview = glm::scale( modelview, glm::vec3(Scale,Scale,Scale) );
```

Exactly the same concept, but a different expression of it. Read on for details …
The Most Useful GLM Variables, Operations, and Functions

// constructor:

glm::mat4( );
glm::vec4( ); // identity matrix
glm::vec3( );

GLM recommends that you use the “glm::” syntax and avoid “using namespace” syntax because they have not made any effort to create unique function names

// multiplications:

glm::mat4 * glm::mat4
glm::mat4 * glm::vec4
glm::mat4 * glm::vec4( glm::vec3 ) // promote vec3 to a vec4 via a constructor

// emulating OpenGL transformations with concatenation:

glm::mat4 glm::rotate( glm::mat4 const & m, float angle, glm::vec3 const & axis );
glm::mat4 glm::scale( glm::mat4 const & m, glm::vec3 const & factors );
glm::mat4 glm::translate( glm::mat4 const & m, glm::vec3 const & translation );
The Most Useful GLM Variables, Operations, and Functions

// viewing volume (assign, not concatenate):

glm::mat4 glm::ortho( float left, float right, float bottom, float top, float near, float far );
glm::mat4 glm::ortho( float left, float right, float bottom, float top );

glm::mat4 glm::frustum( float left, float right, float bottom, float top, float near, float far );
glm::mat4 glm::perspective( float fovy, float aspect, float near, float far );

// viewing (assign, not concatenate):

glm::mat4 glm::lookAt( glm::vec3 const & eye, glm::vec3 const & look, glm::vec3 const & up );
Installing GLM into your own space

I like to just put the whole thing under my Visual Studio project folder so I can zip up a complete project and give it to someone else.
Telling Visual Studio about where the GLM folder is

1. 
2. 

This is a sample OpenGL/GLUT program.

The objective is to draw a 3D object and change the color of the axes with a glut menu.

The left mouse button does rotation.

The middle mouse button does scaling.

The user interface allows:

1. The axes to be turned on and off.
2. The color of the axes to be changed.
3. Debugging to be turned on and off.
4. Depth culling to be turned on and off.
5. The projection to be changed.
6. The transformations to be reset.
Telling Visual Studio about where the GLM folder is

A *period*, indicating that the **project folder** should also be searched when a `#include <xxx>` is encountered. If you put it somewhere else, enter that full or relative path instead.
if( UseMouse )
{
    if( Scale < MINSCALE )
        Scale = MINSCALE;
    Matrices.uModelMatrix = glm::mat4( );       // identity
    Matrices.uModelMatrix = glm::scale( Matrices.uModelMatrix, glm::vec3(Scale,Scale,Scale) );
    Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Yrot, glm::vec3( 0.,1.,0.) );
    Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Xrot, glm::vec3( 1.,0.,0.) );
        // done this way, the Xrot is applied first, then the Yrot, then the Scale
}
else
{
    if( ! Paused )
    {
        const glm::vec3 axis = glm::vec3( 0., 1., 0. );
        Matrices.uModelMatrix = glm::rotate( glm::mat4( ), (float)glm::radians( 360.f*Time/SECONDS_PER_CYCLE ), axis );
    }
}
Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Matrices.uProjectionMatrix[1][1] *= -1.              // Vulkan’s projected Y is inverted from OpenGL
Matrices.uNormalMatrix = glm::inverseTranspose( glm::mat3( Matrices.uModelMatrix )
Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1, 1000. );
Matrices.uProjectionMatrix[1][1] *= -1.;
Matrices.uNormalMatrix = glm::inverseTranspose( glm::mat3( Matrices.uModelMatrix )
Fill05DataBuffer( MyMatrixUniformBuffer, (void *) &Matrices );

Misc.uTime = (float)Time;
Misc.uMode = Mode;
Fill05DataBuffer( MyMiscUniformBuffer, (void *) &Misc );
Your Sample2017.zip File Contains GLM Already
Instancing
Instancing – What and why?

• Instancing is the ability to draw the same object multiple times
• It uses all the same vertices and graphics pipeline each time
• It avoids the overhead of the program asking to have the object drawn again, letting the GPU/driver handle all of that

```c
vkCmdDraw(CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance);
```

But, this will only get us multiple instances of identical objects drawn on top of each other. How can we make each instance look differently?
Use the built-in vertex shader variable `gl_InstanceIndex` to define a unique display property, such as position or color.

`gl_InstanceIndex` starts at 0

In the vertex shader:

```cpp
int NUMINSTANCES = 16;
float DELTA = 3.0;

float xdelta = DELTA * float( gl_InstanceIndex % 4 );
float ydelta = DELTA * float( gl_InstanceIndex / 4 );
vColor = vec3( 1., float( (1.+gl_InstanceIndex) ) / float( NUMINSTANCES ), 0. );

xdelta -= DELTA * sqrt( float(NUMINSTANCES) ) / 2.;
ydelta -= DELTA * sqrt( float(NUMINSTANCES) ) / 2.;
vec4 vertex = vec4( aVertex.xyz + vec3( xdelta, ydelta, 0. ), 1. );

gl_Position = PVM * vertex;
```
Making each Instance look differently -- Approach #2

Put the unique characteristics in a uniform buffer and reference them

Still uses **gl_InstanceIndex**

In the vertex shader:

```glsl
layout( std140, set = 3, binding = 0 ) uniform colorBuf
{
    vec3 uColors[1024];
} Colors;

out vec3 vColor;

    

int index = gl_InstanceIndex % 1024;       // 0 - 1023
vColor = Colors.uColors[ index ];

gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
```
Descriptor Sets
OpenGL puts all uniform data in the same “set”, but with different binding numbers, so you can get at each one.

Each uniform variable gets updated one-at-a-time.

Wouldn’t it be nice if we could update a bunch of related uniform variables all at once?

```
layout( std140, binding = 0 ) uniform mat4 uModelMatrix;
layout( std140, binding = 1 ) uniform mat4 uViewMatrix;
layout( std140, binding = 2 ) uniform mat4 uProjectionMatrix;
layout( std140, binding = 3 ) uniform mat3 uNormalMatrix;
layout( std140, binding = 4 ) uniform vec4 uLightPos;
layout( std140, binding = 5 ) uniform float uTime;
layout( std140, binding = 6 ) uniform int uMode;
layout( binding = 7 ) uniform sampler2D uSampler;
```
What are Descriptor Sets?

Descriptor Sets are an intermediate data structure that tells shaders how to connect information held in GPU memory to groups of related uniform variables and texture sampler declarations in shaders. There are three advantages in doing things this way:

• Related uniform variables can be updated as a group, gaining efficiency.

• Descriptor Sets are activated when the Command Buffer is filled. Different values for the uniform buffer variables can be toggled by just swapping out the Descriptor Set that points to GPU memory, rather than re-writing the GPU memory.

• Values for the shaders’ uniform buffer variables can be compartmentalized into what quantities change often and what change seldom (scene-level, model-level, draw-level), so that uniform variables need to be re-written no more often than is necessary.

```plaintext
for( each scene )
{
    Bind Descriptor Set #0
    for( each object )
    {
        Bind Descriptor Set #1
        for( each draw )
        {
            Bind Descriptor Set #2
            Do the drawing
        }
    }
}
```
Our example will assume the following shader uniform variables:

```glsl
// non-opaque must be in a uniform block:
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
    mat4 uModelMatrix;
    mat4 uViewMatrix;
    mat4 uProjectionMatrix;
    mat3 uNormalMatrix;
} Matrices;

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
    vec4 uLightPos;
} Light;

layout( std140, set = 2, binding = 0 ) uniform miscBuf
{
    float uTime;
    int uMode;
} Misc;

layout( set = 3, binding = 0 ) uniform sampler2D uSampler;
```
**Descriptor Sets**

**CPU:**
Uniform data created in a C++ data structure

- Knows the CPU data structure
- Knows where the data starts
- Knows the data’s size

**GPU:**
Uniform data in a “blob”*

- Knows where the data starts
- Knows the data’s size
- Doesn’t know the CPU or GPU data structure

**GPU:**
Uniform data used in the shader

- Knows the shader data structure
- Doesn’t know where each piece of data starts

```
struct matBuf
{
    glm::mat4 uModelMatrix;
    glm::mat4 uViewMatrix;
    glm::mat4 uProjectionMatrix;
    glm::mat3 uNormalMatrix;
};

struct lightBuf
{
    glm::vec4 uLightPos;
};

struct miscBuf
{
    float uTime;
    int uMode;
};

layout( std140, set = 0, binding = 0 ) uniform matBuf
{
    mat4 uModelMatrix;
    mat4 uViewMatrix;
    mat4 uProjectionMatrix;
    mat3 uNormalMatrix;
} Matrices;

layout( std140, set = 1, binding = 0 ) uniform lightBuf
{
    vec4 uLightPos;
} Light;

layout( std140, set = 2, binding = 0 ) uniform miscBuf
{
    float uTime;
    int uMode;
} Misc;

layout( set = 3, binding = 0 ) uniform sampler2D uSampler;
```

* "binary large object"
Step 1: Descriptor Set Pools

You don’t allocate Descriptor Sets on the fly – that is too slow. Instead, you allocate a “pool” of Descriptor Sets and then pull from that pool later.
VkResult
Init13DescriptorSetPool( )
{
    VkResult result;

    VkDescriptorPoolSize vdp[4];
    vdp[0].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
    vdp[0].descriptorCount = 1;
    vdp[1].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
    vdp[1].descriptorCount = 1;
    vdp[2].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
    vdp[2].descriptorCount = 1;
    vdp[3].type = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
    vdp[3].descriptorCount = 1;

    #ifdef CHOICES
    VK_DESCRIPTOR_TYPE_SAMPLER
    VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE
    VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER
    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
    VK_DESCRIPTOR_TYPE_INPUT_ATTACHMENT
    #endif

    VkDescriptorPoolCreateInfo vdpci;
    vdpci.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_POOL_CREATE_INFO;
    vdpci.pNext = nullptr;
    vdpci.flags = 0;
    vdpci.maxSets = 4;
    vdpci.poolSizeCount = 4;
    vdpci.pPoolSizes = &vdp[0];

    result = vkCreateDescriptorPool( LogicalDevice, IN &vdpci, PALLOCATOR, OUT &DescriptorPool);
    return result;
}
Step 2: Define the Descriptor Set Layouts

I think of Descriptor Set Layouts as a kind of “Rosetta Stone” that allows the Graphics Pipeline data structure to allocate room for the uniform variables and to access them.

https://discoveringegypt.com
VkResult
Init13DescriptorSetLayouts( )
{
    VkResult result;

    // DS #0:
    VkDescriptorSetLayoutBinding MatrixSet[1];
        MatrixSet[0].binding = 0;
        MatrixSet[0].descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
        MatrixSet[0].descriptorCount = 1;
        MatrixSet[0].stageFlags = VK_SHADER_STAGE_VERTEX_BIT;
        MatrixSet[0].pImmutableSamplers = (VkSampler *)nullptr;

    // DS #1:
    VkDescriptorSetLayoutBinding LightSet[1];
        LightSet[0].binding = 0;
        LightSet[0].descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
        LightSet[0].descriptorCount = 1;
        LightSet[0].stageFlags = VK_SHADER_STAGE_VERTEX_BIT | VK_SHADER_STAGE_FRAGMENT_BIT;
        LightSet[0].pImmutableSamplers = (VkSampler *)nullptr;

    // DS #2:
    VkDescriptorSetLayoutBinding MiscSet[1];
        MiscSet[0].binding = 0;
        MiscSet[0].descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
        MiscSet[0].descriptorCount = 1;
        MiscSet[0].stageFlags = VK_SHADER_STAGE_VERTEX_BIT | VK_SHADER_STAGE_FRAGMENT_BIT;
        MiscSet[0].pImmutableSamplers = (VkSampler *)nullptr;

    // DS #3:
    VkDescriptorSetLayoutBinding TexSamplerSet[1];
        TexSamplerSet[0].binding = 0;
        TexSamplerSet[0].descriptorType = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
        TexSamplerSet[0].descriptorCount = 1;
        TexSamplerSet[0].stageFlags = VK_SHADER_STAGE_FRAGMENT_BIT;
        TexSamplerSet[0].pImmutableSamplers = (VkSampler *)nullptr;

    uniform sampler2D uSampler;
    vec4 rgba = texture( uSampler, vST );
Step 2: Define the Descriptor Set Layouts

MatrixSet DS Layout Binding:
- binding
- descriptorType
- descriptorCount
- pipeline stage(s)

LightSet DS Layout Binding:
- binding
- descriptorType
- descriptorCount
- pipeline stage(s)

MiscSet DS Layout Binding:
- binding
- descriptorType
- descriptorCount
- pipeline stage(s)

TexSamplerSet DS Layout Binding:
- binding
- descriptorType
- descriptorCount
- pipeline stage(s)

vdslc0 DS Layout CI:
- bindingCount
- type
- number of that type
- pipeline stage(s)

vdslc1 DS Layout CI:
- bindingCount
- type
- number of that type
- pipeline stage(s)

vdslc2 DS Layout CI:
- bindingCount
- type
- number of that type
- pipeline stage(s)

vdslc3 DS Layout CI:
- bindingCount
- type
- number of that type
- pipeline stage(s)

Array of Descriptor Set Layouts

Pipeline Layout
VkDescriptorSetLayoutCreateInfo vdslc0;
    vdslc0.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc0.pNext = nullptr;
    vdslc0.flags = 0;
    vdslc0.bindingCount = 1;
    vdslc0.pBindings = &MatrixSet[0];

VkDescriptorSetLayoutCreateInfo vdslc1;
    vdslc1.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc1.pNext = nullptr;
    vdslc1.flags = 0;
    vdslc1.bindingCount = 1;
    vdslc1.pBindings = &LightSet[0];

VkDescriptorSetLayoutCreateInfo vdslc2;
    vdslc2.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc2.pNext = nullptr;
    vdslc2.flags = 0;
    vdslc2.bindingCount = 1;
    vdslc2.pBindings = &MiscSet[0];

VkDescriptorSetLayoutCreateInfo vdslc3;
    vdslc3.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
    vdslc3.pNext = nullptr;
    vdslc3.flags = 0;
    vdslc3.bindingCount = 1;
    vdslc3.pBindings = &TexSamplerSet[0];

result = vkCreateDescriptorSetLayout( LogicalDevice, &vdslc0, PALLOCATOR, OUT &DescriptorSetLayouts[0] );
result = vkCreateDescriptorSetLayout( LogicalDevice, &vdslc1, PALLOCATOR, OUT &DescriptorSetLayouts[1] );
result = vkCreateDescriptorSetLayout( LogicalDevice, &vdslc2, PALLOCATOR, OUT &DescriptorSetLayouts[2] );
result = vkCreateDescriptorSetLayout( LogicalDevice, &vdslc3, PALLOCATOR, OUT &DescriptorSetLayouts[3] );

return result;
Step 3: Include the Descriptor Set Layouts in a Graphics Pipeline Layout

```c
VkResult
Init14GraphicsPipelineLayout( )
{
    VkResult result;

    VkPipelineLayoutCreateInfo vplci;
    vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
    vplci.pNext = nullptr;
    vplci.flags = 0;
    vplci.setLayoutCount = 4;
    vplci.pSetLayouts = &DescriptorSetLayouts[0];
    vplci.pushConstantRangeCount = 0;
    vplci.pPushConstantRanges = (VkPushConstantRange *)nullptr;

    result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, PALLOCATOR, OUT &GraphicsPipelineLayout );

    return result;
}
```
Step 4: Allocating the Memory for Descriptor Sets

```
VkAllocateDescriptorSets( )
```

Diagram:
- DescriptorSetPool
- descriptorSetCount
- DescriptorSetLayouts
- VkDescriptorSetAllocateInfo
- vkAllocateDescriptorSets()
- Descriptor Set
VkResult
Init13DescriptorSets( )
{
    VkResult result;

    VkDescriptorSetAllocateInfo *vdsai;
    vdsai->sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO;
    vdsai->pNext = nullptr;
    vdsai->descriptorPool = DescriptorPool;
    vdsai->descriptorSetCount = 4;
    vdsai->pSetLayouts = DescriptorSetLayouts;

    result = vkAllocateDescriptorSets( LogicalDevice, IN &vdsai, OUT &DescriptorSets[0] );
}
Step 5: Tell the Descriptor Sets where their CPU Data is

<table>
<thead>
<tr>
<th>VkDescriptorBufferInfo vdbi0;</th>
</tr>
</thead>
<tbody>
<tr>
<td>vdbi0.buffer = MyMatrixUniformBuffer.buffer;</td>
</tr>
<tr>
<td>vdbi0.offset = 0;</td>
</tr>
<tr>
<td>vdbi0.range = sizeof(Matrices);</td>
</tr>
<tr>
<td>This struct identifies what buffer it owns and how big it is</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VkDescriptorBufferInfo vdbi1;</th>
</tr>
</thead>
<tbody>
<tr>
<td>vdbi1.buffer = MyLightUniformBuffer.buffer;</td>
</tr>
<tr>
<td>vdbi1.offset = 0;</td>
</tr>
<tr>
<td>vdbi1.range = sizeof(Light);</td>
</tr>
<tr>
<td>This struct identifies what buffer it owns and how big it is</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VkDescriptorBufferInfo vdbi2;</th>
</tr>
</thead>
<tbody>
<tr>
<td>vdbi2.buffer = MyMiscUniformBuffer.buffer;</td>
</tr>
<tr>
<td>vdbi2.offset = 0;</td>
</tr>
<tr>
<td>vdbi2.range = sizeof(Misc);</td>
</tr>
<tr>
<td>This struct identifies what buffer it owns and how big it is</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VkDescriptorImageInfo vdii0;</th>
</tr>
</thead>
<tbody>
<tr>
<td>vdii.sampler = MyPuppyTexture.texSampler;</td>
</tr>
<tr>
<td>vdii.imageView = MyPuppyTexture.texImageView;</td>
</tr>
<tr>
<td>vdii.imageLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;</td>
</tr>
<tr>
<td>This struct identifies what texture sampler and image view it owns</td>
</tr>
</tbody>
</table>
### Step 5: Tell the Descriptor Sets where their CPU Data is

This struct links a Descriptor Set to the buffer it is pointing to.

<table>
<thead>
<tr>
<th>VkWriteDescriptorSet</th>
<th>vwds0;</th>
</tr>
</thead>
<tbody>
<tr>
<td>// ds 0:</td>
<td></td>
</tr>
<tr>
<td>vwds0.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;</td>
<td></td>
</tr>
<tr>
<td>vwds0.pNext = nullptr;</td>
<td></td>
</tr>
<tr>
<td>vwds0.dstSet = DescriptorSets[0];</td>
<td></td>
</tr>
<tr>
<td>vwds0.dstBinding = 0;</td>
<td></td>
</tr>
<tr>
<td>vwds0.dstArrayElement = 0;</td>
<td></td>
</tr>
<tr>
<td>vwds0.descriptorCount = 1;</td>
<td></td>
</tr>
<tr>
<td>vwds0.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;</td>
<td></td>
</tr>
<tr>
<td>vwds0.pBufferInfo = IN &amp;vdbi0;</td>
<td></td>
</tr>
<tr>
<td>vwds0.pImageInfo = (VkDescriptorImageInfo *)nullptr;</td>
<td></td>
</tr>
<tr>
<td>vwds0.pTexelBufferView = (VkBufferView *)nullptr;</td>
<td></td>
</tr>
</tbody>
</table>

This struct links a Descriptor Set to the buffer it is pointing to.

<table>
<thead>
<tr>
<th>VkWriteDescriptorSet</th>
<th>vwds1;</th>
</tr>
</thead>
<tbody>
<tr>
<td>// ds 1:</td>
<td></td>
</tr>
<tr>
<td>vwds1.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;</td>
<td></td>
</tr>
<tr>
<td>vwds1.pNext = nullptr;</td>
<td></td>
</tr>
<tr>
<td>vwds1.dstSet = DescriptorSets[1];</td>
<td></td>
</tr>
<tr>
<td>vwds1.dstBinding = 0;</td>
<td></td>
</tr>
<tr>
<td>vwds1.dstArrayElement = 0;</td>
<td></td>
</tr>
<tr>
<td>vwds1.descriptorCount = 1;</td>
<td></td>
</tr>
<tr>
<td>vwds1.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;</td>
<td></td>
</tr>
<tr>
<td>vwds1.pBufferInfo = IN &amp;vdbi1;</td>
<td></td>
</tr>
<tr>
<td>vwds1.pImageInfo = (VkDescriptorImageInfo *)nullptr;</td>
<td></td>
</tr>
<tr>
<td>vwds1.pTexelBufferView = (VkBufferView *)nullptr;</td>
<td></td>
</tr>
</tbody>
</table>
Step 5: Tell the Descriptor Sets where their data is

```
// ds 2:
VkWriteDescriptorSet vwds2;
    vwds2.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
    vwds2.pNext = nullptr;
    vwds2.dstSet = DescriptorSets[2];
    vwds2.dstBinding = 0;
    vwds2.dstArrayElement = 0;
    vwds2.descriptorCount = 1;
    vwds2.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
    vwds2.pBufferInfo = IN &vdbi2;
    vwds2.pImageInfo = (VkDescriptorImageInfo *)nullptr;
    vwds2.pTexelBufferView = (VkBufferView *)nullptr;

// ds 3:
VkWriteDescriptorSet vwds3;
    vwds3.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
    vwds3.pNext = nullptr;
    vwds3.dstSet = DescriptorSets[3];
    vwds3.dstBinding = 0;
    vwds3.dstArrayElement = 0;
    vwds3.descriptorCount = 1;
    vwds3.descriptorType = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
    vwds3.pBufferInfo = (VkDescriptorBufferInfo *)nullptr;
    vwds3.pImageInfo = (VkDescriptorImageInfo *)nullptr;
    vwds3.pTexelBufferView = (VkBufferView *)nullptr;

uint32_t copyCount = 0;

// this could have been done with one call and an array of VkWriteDescriptorSets:

vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds0, IN copyCount, (VkCopyDescriptorSet *)nullptr );
vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds1, IN copyCount, (VkCopyDescriptorSet *)nullptr );
vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds2, IN copyCount, (VkCopyDescriptorSet *)nullptr );
vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds3, IN copyCount, (VkCopyDescriptorSet *)nullptr );
```
Step 6: Include the Descriptor Set Layout when Creating a Graphics Pipeline

```c
VkGraphicsPipelineCreateInfo vgpci;
    vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
    vgpci.pNext = nullptr;
    vgpci.flags = 0;
#endif
    vgpci.stageCount = 2;                           // number of stages in this pipeline
    vgpci.pStages = vpssci;
    vgpci.pVertexInputState = &vpvisci;
    vgpci.pInputAssemblyState = &vpiasci;
    vgpci.pTessellationState = (VkPipelineTessellationStateCreateInfo *)nullptr;
    vgpci.pViewportState = &vpvsci;
    vgpci.pRasterizationState = &vprsci;
    vgpci.pMultisampleState = &vpmsci;
    vgpci.pDepthStencilState = &vpdssci;
    vgpci.pColorBlendState = &vpcbsci;
    vgpci.pDynamicState = &vpdsci;
    vgpci.layout = IN GraphicsPipelineLayout;
    vgpci.renderPass = IN RenderPass;
    vgpci.subpass = 0;                              // subpass number
    vgpci.basePipelineHandle = (VkPipeline) VK_NULL_HANDLE;
    vgpci.basePipelineIndex = 0;

result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN &vgpci, 
                                      PALLOCATOR, OUT &GraphicsPipeline );
```
Step 7: Bind Descriptor Sets into the Command Buffer when Drawing

```c
vkCmdBindDescriptorSets(CommandBuffers[nextImageIndex],
    VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipelineLayout,
    0, 4, DescriptorSets, 0, (uint32_t *)nullptr);
```
The Graphics Pipeline
What is the Vulkan Graphics Pipeline?

1. The Vulkan Graphics Pipeline is like what OpenGL would call “The State”, or “The Context”.

2. There’s a lot that goes into it.

3. For the most part, the Graphics Pipeline is meant to be immutable – that is, once this combination of state variables is combined into a Pipeline, that Pipeline never gets changed. To make new combinations of state variables, create a new Graphics Pipelines.

4. The shaders get compiled the rest of the way when their Graphics Pipeline gets created.

Don’t worry if this is too small to read – a larger version is coming up.

There is also a Vulkan Compute Pipeline.
Graphics Pipeline Stages and what goes into Them

The GPU and Driver specify the Pipeline Stages – the Vulkan Graphics Pipeline declares what goes in them.

- **Vertex Shader module**
  - Specialization info
  - Vertex Input binding
  - Vertex Input attributes

- **Topology**

- **Tessellation Shaders, Geometry Shader**

- **Viewport**
  - Scissoring

- **Depth Clamping**
  - DiscardEnable
  - PolygonMode
  - CullMode
  - FrontFace
  - LineWidth

- **Which states are dynamic**

- **DepthTestEnable**
  - DepthWriteEnable
  - DepthCompareOp
  -StencilTestEnable

- **Fragment Shader module**
  - Specialization info

- **Color Blending parameters**

**Graphics Pipeline Stages**:
1. **Vertex Input Stage**
2. **Input Assembly**
3. **Tessellation, Geometry Shaders**
4. **Viewport**
5. **Rasterization**
6. **Dynamic State**
7. **Depth/Stencil**
8. **Fragment Shader Stage**
9. **Color Blending Stage**
The Graphics Pipeline Layout is fairly static. Only the layout of the Descriptor Sets and information on the Push Constants need to be supplied.

```c
VkResult Init14GraphicsPipelineLayout( )
{
    VkResult result;

    VkPipelineLayoutCreateInfo vplci;
    vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
    vplci.pNext = nullptr;
    vplci.flags = 0;
    vplci.setLayoutCount = 4;
    vplci.pSetLayouts = &DescriptorSetLayouts[0];
    vplci.pushConstantRangeCount = 0;
    vplci.pPushConstantRanges = (VkPushConstantRange *)nullptr;

    result = vkCreatePipelineLayout( LogicalDevice, IN &vplci, PALLOCATOR, OUT &GraphicsPipelineLayout );

    return result;
}
```

Let the Pipeline Layout know about the Descriptor Set and Push Constant layouts.
Vulkan: A Pipeline Records the Following Items:

- Pipeline Layout: DescriptorSets, PushConstants
- Which Shaders are going to be used
- Per-vertex input attributes: location, binding, format, offset
- Per-vertex input bindings: binding, stride, inputRate
- Assembly: topology
- **Viewport**: x, y, w, h, minDepth, maxDepth
- **Scissoring**: x, y, w, h
- Rasterization: cullMode, polygonMode, frontFace, **lineWidth**
- Depth: depthTestEnable, depthWriteEnable, depthCompareOp
- Stencil: stencilTestEnable, stencilOpStateFront, stencilOpStateBack
- Blending: blendEnable, **srcColorBlendFactor**, **dstColorBlendFactor**, colorBlendOp, **srcAlphaBlendFactor**, **dstAlphaBlendFactor**, alphaBlendOp, colorWriteMask
- DynamicState: which states can be set dynamically (bound to the command buffer, outside the Pipeline)

*Bold/Italics* indicates that this state item can also be set with Dynamic Variables
Creating a Graphics Pipeline from a lot of Pieces

vkCreateGraphicsPipelineCreateInfo

VkSpecializationInfo

VkShaderModule

VkPipelineShaderStageCreateInfo

VkPipelineVertexInputStateCreateInfo

VkVertexInputBindingDescription

VkViewportStateCreateInfo

Viewport

x, y, w, h, minDepth, maxDepth

VkPipelineInputAssemblyStateCreateInfo

Topology

cullMode
polygonMode
frontFace
lineWidth

VkPipelineRasterizationStateCreateInfo

VkPipelineDepthStencilStateCreateInfo

dePTHTestEnable
depthWriteEnable
depthCompareOp
stencilTestEnable
stencilOpStateFront
stencilOpStateBack

VkPipelineColorBlendStateCreateInfo

blendEnable
srcColorBlendFactor
dstColorBlendFactor
colorBlendOp
srcAlphaBlendFactor
dstAlphaBlendFactor
alphaBlendOp
colorWriteMask

VkPipelineDynamicStateCreateInfo

Array naming the states that can be set dynamically
These settings seem pretty typical to me. Let’s write a simplified Pipeline-creator that accepts Vertex and Fragment shader modules and the topology, and always uses the settings in red above.
Link in the Shaders

VkPipelineShaderStageCreateInfo vpssci[2];
    vpssci[0].sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
    vpssci[0].pNext = nullptr;
    vpssci[0].flags = 0;
    vpssci[0].stage = VK_SHADER_STAGE_VERTEX_BIT;
#ifdef BITS
    VK_SHADER_STAGE_VERTEX_BIT
    VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT
    VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT
    VK_SHADER_STAGE_GEOMETRY_BIT
    VK_SHADER_STAGE_FRAGMENT_BIT
    VK_SHADER_STAGE_COMPUTE_BIT
    VK_SHADER_STAGE_ALL_GRAPHICS
    VK_SHADER_STAGE_ALL
#endif
    vpssci[0].module = vertexShader;
    vpssci[0].pName = "main";
    vpssci[0].pSpecializationInfo = (VkSpecializationInfo *)nullptr;

    vpssci[1].sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
    vpssci[1].pNext = nullptr;
    vpssci[1].flags = 0;
    vpssci[1].stage = VK_SHADER_STAGE_FRAGMENT_BIT;
    vpssci[1].module = fragmentShader;
    vpssci[1].pName = "main";
    vpssci[1].pSpecializationInfo = (VkSpecializationInfo *)nullptr;

VkVertexInputBindingDescription vvibd[1];       // an array containing one of these per buffer being used
    vvibd[0].binding = 0;           // which binding # this is
    vvibd[0].stride = sizeof( struct vertex );              // bytes between successive
    vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;

#ifdef CHOICES
    VK_VERTEX_INPUT_RATE_VERTEX
    VK_VERTEX_INPUT_RATE_INSTANCE
#endif

Use one \texttt{vpssci} array member per shader module you are using

Use one \texttt{vvibd} array member per vertex input array-of-structures you are using
Use one **vviad** array member per element in the struct for the array-of-structures element you are using as vertex input.

These are defined at the top of the sample code so that you don’t need to use confusing image-looking formats for positions, normals, and tex coords.

```c
#include <vkglm.h>

// A simple structure to store vertex data
struct vertex {   
    float position[3];   
    float normal[3];   
    float color[3];   
    float texCoord[2];   
};

// A constant to hold the offset of the position field
#define POSITION_OFFSET offsetof( struct vertex, position )

// A constant to hold the offset of the normal field
#define NORMAL_OFFSET offsetof( struct vertex, normal )

// A constant to hold the offset of the color field
#define COLOR_OFFSET offsetof( struct vertex, color )

// A constant to hold the offset of the texCoord field
#define TEXCOORD_OFFSET offsetof( struct vertex, texCoord )

// VkVertexInputAttributeDescription array
VkVertexInputAttributeDescription vviad[4];  

// An array containing one of these per vertex attribute in all bindings
// 4 = vertex, normal, color, texture coord

// Declaration 1
vviad[0].location = 0;  
// location in the layout
vviad[0].binding = 0;  
// which binding description this is part of
vviad[0].format = VK_FORMAT_VEC3;  
// x, y, z
vviad[0].offset = POSITION_OFFSET;  
// 0

// Declaration 2
vviad[1].location = 1;  
vviad[1].binding = 0;  
vviad[1].format = VK_FORMAT_VEC3;  
// nx, ny, nz
vviad[1].offset = NORMAL_OFFSET;  
// 12

// Declaration 3
vviad[2].location = 2;  
vviad[2].binding = 0;  
vviad[2].format = VK_FORMAT_VEC3;  
// r, g, b
vviad[2].offset = COLOR_OFFSET;  
// 24

// Declaration 4
vviad[3].location = 3;  
vviad[3].binding = 0;  
vviad[3].format = VK_FORMAT_VEC2;  
// s, t
vviad[3].offset = TEXCOORD_OFFSET;  
// 36

#if defined(EXTRAS_DEFINED_AT_THE_TOP)
// these are here for convenience and readability:
#define VK_FORMAT_VEC4 VK_FORMAT_R32G32B32A32_SFLOAT
#define VK_FORMAT_XYZW VK_FORMAT_R32G32B32A32_SFLOAT
#define VK_FORMAT_VEC3 VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_XYZ VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_VEC2 VK_FORMAT_R32G32_SFLOAT
#define VK_FORMAT_FLOAT VK_FORMAT_R32_SFLOAT
#define VK_FORMAT_S VK_FORMAT_R32_SFLOAT
#define VK_FORMAT_X VK_FORMAT_R32_SFLOAT
#endif
```
VkPipelineVertexInputStateCreateInfo *vpvisci;  // used to describe the input vertex attributes
vpvisci.sType = VK_STRUCTURE_TYPE_PIPELINE_VERTEX_INPUT_STATE_CREATE_INFO;
vpvisci.pNext = nullptr;
vpvisci.flags = 0;
vpvisci.vertexBindingDescriptionCount = 1;
vpvisci.pVertexBindingDescriptions = vvibd;
vpvisci.vertexAttributeDescriptionCount = 4;
vpvisci.pVertexAttributeDescriptions = vviad;

VkPipelineInputAssemblyStateCreateInfo *vpiasci;
 vpiasci.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
 vpiasci.pNext = nullptr;vpiasci.flags = 0;
vpiasci.topology = VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST;
#ifndef CHOICES
Vk_PIPELINE_TOPOLOGY_POINT_LIST
Vk_PIPELINE_TOPOLOGY_LINE_LIST
Vk_PIPELINE_TOPOLOGY_TRIANGLE_LIST
Vk_PIPELINE_TOPOLOGY_LINE_STRIP
Vk_PIPELINE_TOPOLOGY_TRIANGLE_STRIP
Vk_PIPELINE_TOPOLOGY_TRIANGLE_FAN
Vk_PIPELINE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY
Vk_PIPELINE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY
Vk_PIPELINE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY
Vk_PIPELINE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY
#endif
vpiasci.primitiveRestartEnable = VK_FALSE;

VkPipelineTessellationStateCreateInfo *vptsci;
 vptsci.sType = VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO;
 vptsci.pNext = nullptr;vptsci.flags = 0;
vptsci.patchControlPoints = 0;  // number of patch control points

// VkPipelineGeometryStateCreateInfo *vpgsci;
// vpgsci.sType = VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO;
// vpgsci.pNext = nullptr;
// vpgsci.flags = 0;

Declare the binding descriptions and attribute descriptions

Declare the vertex topology

Tessellation Shader info

Geometry Shader info
What is “Primitive Restart Enable”?  

```c
vpiasci.primitiveRestartEnable = VK_FALSE;
```

“Restart Enable” is used with:
- Indexed drawing.
- Triangle Fan and *Strip topologies

If `vpiasci.primitiveRestartEnable` is VK_TRUE, then a special “index” indicates that the primitive should start over. This is more efficient than explicitly ending the current primitive and explicitly starting a new primitive of the same type.

```c
typedef enum VkIndexType
{
    VK_INDEX_TYPE_UINT16 = 0, // 0 – 65,535
    VK_INDEX_TYPE_UINT32 = 1,  // 0 – 4,294,967,295
} VkIndexType;
```

If your `VkIndexType` is VK_INDEX_TYPE_UINT16, then the special index is 0xffff. If your `VkIndexType` is VK_INDEX_TYPE_UINT32, it is 0xffffffff.
One Really Good use of Restart Enable is in Drawing Terrain Surfaces with Triangle Strips

Triangle Strip #0:
Triangle Strip #1:
Triangle Strip #2:
...
VkViewport
    vv;
    vv.x = 0;
    vv.y = 0;
    vv.width = (float)Width;
    vv.height = (float)Height;
    vv.minDepth = 0.0f;
    vv.maxDepth = 1.0f;

VkRect2D
    vr;
    vr.offset.x = 0;
    vr.offset.y = 0;
    vr.extent.width = Width;
    vr.extent.height = Height;

VkPipelineViewportStateCreateInfo
    vpvsci;
    vpvsci.sType = VK_STRUCTURE_TYPE_PIPELINE_VIEWPORT_STATE_CREATE_INFO;
    vpvsci.pNext = nullptr;
    vpvsci.flags = 0;
    vpvsci.viewportCount = 1;
    vpvsci.pViewports = &vv;
    vpvsci.scissorCount = 1;
    vpvsci.pScissors = &vr;

Declare the viewport information

Declare the scissoring information

Group the viewport and scissor information together
What is the Difference Between Changing the Viewport and Changing the Scissoring?

Viewporting operates on *vertices* and takes place right before the rasterizer. Changing the vertical part of the *viewport* causes the entire scene to get scaled (scrunched) into the viewport area.

Original Image

Scissoring operates on *fragments* and takes place right after the rasterizer. Changing the vertical part of the *scissor* causes the entire scene to get clipped where it falls outside the scissor area.
VkPipelineRasterizationStateCreateInfo vprsci;
vprsci.sType = VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO;
vprsci.pNext = nullptr;
vprsci.flags = 0;
vprsci.depthClampEnable = VK_FALSE;
vprsci.rasterizerDiscardEnable = VK_FALSE;
vprsci.polygonMode = VK_POLYGON_MODE_FILL;

#ifdef CHOICES
VK_POLYGON_MODE_FILL
VK_POLYGON_MODE_LINE
VK_POLYGON_MODE_POINT
#endif

vprsci.cullMode = VK_CULL_MODE_NONE;  // recommend this because of the projMatrix[1][1] *= -1.;

#ifdef CHOICES
VK_CULL_MODE_NONE
VK_CULL_MODE_FRONT_BIT
VK_CULL_MODE_BACK_BIT
VK_CULL_MODE_FRONT_AND_BACK_BIT
#endif

vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;

#ifdef CHOICES
VK_FRONT_FACE_COUNTER_CLOCKWISE
VK_FRONT_FACE_CLOCKWISE
#endif

vprsci.depthBiasEnable = VK_FALSE;
vprsci.depthBiasConstantFactor = 0.f;
vprsci.depthBiasClamp = 0.f;
vprsci.depthBiasSlopeFactor = 0.f;
vprsci.lineWidth = 1.f;

Declare information about how the rasterization will take place
Which Pipeline Variables can be Set Dynamically

```c
VkDynamicState vds[ ] = { VK_DYNAMIC_STATE_VIEWPORT, VK_DYNAMIC_STATE_SCISSOR }; #ifdef CHOICES
VK_DYNAMIC_STATE_VIEWPORT -- vkCmdSetViewport( )
VK_DYNAMIC_STATE_SCISSOR -- vkCmdSetScissor( )
VK_DYNAMIC_STATE_LINE_WIDTH -- vkCmdSetLineWidth( )
VK_DYNAMIC_STATE_DEPTH_BIAS -- vkCmdSetDepthBias( )
VK_DYNAMIC_STATE_BLEND_CONSTANTS -- vkCmdSetBlendConstants( )
VK_DYNAMIC_STATE_DEPTH_BOUNDS -- vkCmdSetDepthZBounds( )
VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK -- vkCmdSetStencilCompareMask( )
VK_DYNAMIC_STATE_STENCIL_WRITE_MASK -- vkCmdSetStencilWriteMask( )
VK_DYNAMIC_STATE_STENCIL_REFERENCE -- vkCmdSetStencilReference( )
#endif

VkPipelineDynamicStateCreateInfo vpdsci;
vpdsci.sType = VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO;
vpdsci.pNext = nullptr;
vpdsci.flags = 0;
vpdsci.dynamicStateCount = 0; // leave turned off for now
vpdsci.pDynamicStates = vds;
```

Stencil Operations for Front and Back Faces

```c
VkStencilOpState vsosf; // front
vsosf.depthFailOp = VK_STENCIL_OP_KEEP; // what to do if depth operation fails
vsosf.failOp = VK_STENCIL_OP_KEEP; // what to do if stencil operation fails
vsosf.passOp = VK_STENCIL_OP_KEEP; // what to do if stencil operation succeeds
#ifdef CHOICES
VK_STENCIL_OP_KEEP -- keep the stencil value as it is
VK_STENCIL_OP_ZERO -- set stencil value to 0
VK_STENCIL_OP_REPLACE -- replace stencil value with the reference value
VK_STENCIL_OP_INCREMENT_AND_CLAMP -- increment stencil value
VK_STENCIL_OP_DECREMENT_AND_CLAMP -- decrement stencil value
VK_STENCIL_OP_INVERT -- bit-invert stencil value
VK_STENCIL_OP_INCREMENT_AND_WRAP -- increment stencil value
VK_STENCIL_OP_DECREMENT_AND_WRAP -- decrement stencil value
#endif
vsosf.compareOp = VK_COMPARE_OP_NEVER;
#ifdef CHOICES
VK_COMPARE_OP_NEVER -- never succeeds
VK_COMPARE_OP_LESS -- succeeds if stencil value is < the reference value
VK_COMPARE_OP_EQUAL -- succeeds if stencil value is == the reference value
VK_COMPARE_OP_LESS_OR_EQUAL -- succeeds if stencil value is <= the reference value
VK_COMPARE_OP_GREATER -- succeeds if stencil value is > the reference value
VK_COMPARE_OP_NOT_EQUAL -- succeeds if stencil value is != the reference value
VK_COMPARE_OP_GREATER_OR_EQUAL -- succeeds if stencil value is >= the reference value
VK_COMPARE_OP_ALWAYS -- always succeeds
#endif
vsosf.compareMask = ~0;
vsosf.writeMask = ~0;
vsosf.reference = 0;

VkStencilOpState vsosb; // back
vsosb.depthFailOp = VK_STENCIL_OP_KEEP;
vsosb.failOp = VK_STENCIL_OP_KEEP;
vsosb.passOp = VK_STENCIL_OP_KEEP;
vsosb.compareOp = VK_COMPARE_OP_NEVER;
vsosb.compareMask = ~0;
vsosb.writeMask = ~0;
vsosb.reference = 0;
```
Uses for Stencil Operations

Magic Lenses

Polygon edges without Z-fighting
Group all of the individual state information and create the pipeline

```c
VkGraphicsPipelineCreateInfo vgpci;
vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
vgpci.pNext = nullptr;
vgpci.flags = 0;

#ifdef CHOICES
VK_PIPELINE_CREATE_DISABLE_OPTIMIZATION_BIT
VK_PIPELINE_CREATE_ALLOW_DERIVATIVES_BIT
VK_PIPELINE_CREATE_DERIVATIVE_BIT
#endif

vgpci.stageCount = 2;                           // number of stages in this pipeline
vgpci.pStages = vpssci;
vgpci.pVertexInputState = &vpvisci;
vgpci.pInputAssemblyState = &vpiasci;
vgpci.pTessellationState = (VkPipelineTessellationStateCreateInfo *)nullptr;
vgpci.pViewportState = &vpvsci;
vgpci.pRasterizationState = &vprsci;
vgpci.pMultisampleState = &vpmsci;
vgpci.pDepthStencilState = &vpdsscii;
vgpci.pColorBlendState = &vpcbsci;
vgpci.pDynamicState = &vpdscci;
vgpci.layout = IN GraphicsPipelineLayout;
vgpci.renderPass = IN RenderPass;
vgpci.subpass = 0;                               // subpass number
vgpci.basePipelineHandle = (VkPipeline) VK_NULL_HANDLE;
vgpci.basePipelineIndex = 0;

result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN &vgpci,
                                     PALLOCATOR, OUT pGraphicsPipeline );

return result;
```

Putting it all Together! (finally…)
Later on, we will Bind the Graphics Pipeline to the Command Buffer when Drawing

```c
vkCmdBindPipeline( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );
```
Queues and Command Buffers
Vulkan: a More Typical (and Simplified) Block Diagram

Application

Instance

Physical Device

Logical Device

Queue

Command Buffer

Command Buffer

Command Buffer
Vulkan Queues and Command Buffers

- Graphics commands are recorded in command buffers, e.g., \texttt{vkCmdDoSomething( cmdBuffer, … );}
- You can have as many simultaneous Command Buffers as you want
- Each command buffer can be filled from a different thread
- Command Buffers record our commands, but no work takes place until a Command Buffer is submitted to a Queue
- We don’t create Queues – the Logical Device has them already
- Each Queue belongs to a Queue Family
- We don’t create Queue Families – the Physical Device already has them
Querying what Queue Families are Available

```c
uint32_t count;

vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *) nullptr);

VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
vkGetPhysicalDeviceFamilyProperties( PhysicalDevice, &count, OUT &vqfp, );

for( unsigned int i = 0; i < count; i++ )
{
    fprintf( FpDebug, "\t%d: Queue Family Count = %2d ;   ", i, vqfp[i].queueCount );
    if( ( vqfp[i].queueFlags & VK_QUEUE_GRAPHICS_BIT ) != 0 )       fprintf( FpDebug, " Graphics" );
    if( ( vqfp[i].queueFlags & VK_QUEUE_COMPUTE_BIT  ) != 0 )       fprintf( FpDebug, " Compute ");
    if( ( vqfp[i].queueFlags & VK_QUEUE_TRANSFER_BIT ) != 0 )       fprintf( FpDebug, " Transfer" );
    fprintf(FpDebug, "\n");
}
```

Found 3 Queue Families:
- 0: Queue Family Count = 16 ; Graphics Compute Transfer
- 1: Queue Family Count =  1 ; Transfer
- 2: Queue Family Count =  8 ; Compute
Similarly, we Can Write a Function that Finds the Proper Queue Family

```c
int FindQueueFamilyThatDoesGraphics() {
    uint32_t count = -1;
    vkGetPhysicalDeviceQueueFamilyProperties(IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *)nullptr);
    VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[count];
    vkGetPhysicalDeviceQueueFamilyProperties(IN PhysicalDevice, &count, OUT vqfp);
    for(unsigned int i = 0; i < count; i++) {
        if((vqfp[i].queueFlags & VK_QUEUE_GRAPHICS_BIT) != 0)
            return i;
    }
    return -1;
}
```
Creating a Logical Device Queue Needs to Know Queue Family Information

```c
float queuePriorities[] =
{
    1.0f,  // one entry per queueCount
};

VkDeviceQueueCreateInfo vdqci[1];
vdqci.sType = VK_STRUCTURE_TYPE_QUEUE_CREATE_INFO;
vdqci.pNext = nullptr;
vdqci.flags = 0;
vdqci.queueFamilyIndex = FindQueueFamilyThatDoesGraphics();
vdqci.queueCount = 1;
vdqci.queuePriorities = (float *) queuePriorities;

VkDeviceCreateInfo vdci;
vdci.sType = VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO;
vdci.pNext = nullptr;
vdci.flags = 0;
vdci.queueCreateInfoCount = 1; // # of device queues wanted
vdci.pQueueCreateInfos = &vdqci[0]; // array of VkDeviceQueueCreateInfo's
vdci.enabledLayerCount = sizeof(myDeviceLayers) / sizeof(char *);
vdci.ppEnabledLayerNames = myDeviceLayers;
vdci.enabledExtensionCount = sizeof(myDeviceExtensions) / sizeof(char *);
vdci.ppEnabledExtensionNames = myDeviceExtensions;
vdci.pEnabledFeatures = IN &PhysicalDeviceFeatures; // already created

result = vkCreateLogicalDevice( PhysicalDevice, IN &vdci, PALLOCATOR, OUT &LogicalDevice );

VkQueue Queue;
uint32_t queueFamilyIndex = FindQueueFamilyThatDoesGraphics();
uint32_t queueIndex = 0;

result = vkGetDeviceQueue ( LogicalDevice, queueFamilyIndex, queueIndex, OUT &Queue );
```
Creating the Command Pool as part of the Logical Device

```cpp
VkResult Init06CommandPool( )
{
    VkResult result;

    VkCommandPoolCreateInfo vcpci;
    vcpci.sType = VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO;
    vcpci.pNext = nullptr;
    vcpci.flags = VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT |
                 VK_COMMAND_POOL_CREATE_TRANSIENT_BIT;

    #ifdef CHOICES
    VK_COMMAND_POOL_CREATE_TRANSIENT_BIT
    VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT
    #endif
    vcpci.queueFamilyIndex = FindQueueFamilyThatDoesGraphics( );

    result = vkCreateCommandPool( LogicalDevice, IN &vcpci, PALLOCATOR, OUT &CommandPool );

    return result;
}
```
Creating the Command Buffers

```c
VkResult
Init06CommandBuffers( )
{
    VkResult result;

    // allocate 2 command buffers for the double-buffered rendering:
    {
        VkCommandBufferAllocateInfo vcbai;
        vcbai.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO;
        vcbai.pNext = nullptr;
        vcbai.commandPool = CommandPool;
        vcbai.level = VK_COMMAND_BUFFER_LEVEL_PRIMARY;
        vcbai.commandBufferCount = 2;  // 2, because of double-buffering
        result = vkAllocateCommandBuffers( LogicalDevice, IN &vcbai, OUT &CommandBuffers[0] );
    }

    // allocate 1 command buffer for the transferring pixels from a staging buffer to a texture buffer:
    {
        VkCommandBufferAllocateInfo vcbai;
        vcbai.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO;
        vcbai.pNext = nullptr;
        vcbai.commandPool = CommandPool;
        vcbai.level = VK_COMMAND_BUFFER_LEVEL_PRIMARY;
        vcbai.commandBufferCount = 1;
        result = vkAllocateCommandBuffers( LogicalDevice, IN &vcbai, OUT &TextureCommandBuffer );
    }

    return result;
}
```
Beginning a Command Buffer

```c
VkSemaphoreCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;

VkSemaphore imageReadySemaphore;
result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore );

uint32_t nextImageIndex;
vkAcquireNextImageKHR( LogicalDevice, IN SwapChain, IN UINT64_MAX,
                        IN imageReadySemaphore, IN VK_NULL_HANDLE, OUT &nextImageIndex );

VkCommandBufferBeginInfo vcbbi;
    vcbbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
    vcbbi.pNext = nullptr;
    vcbbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
    vcbbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;

result = vkBeginCommandBuffer( CommandBuffers[nextImageIndex], IN &vcbbi );

    ...

vkEndCommandBuffer( CommandBuffers[nextImageIndex] );
```
Beginning a Command Buffer

1. `vkBeginCommandBuffer()`
2. `VkCommandBufferBeginInfo`
3. `vkCreateCommandBufferPool()`
4. `VkCommandBufferPoolCreateInfo`
5. `vkAllocateCommandBuffer()`
6. `VkCommandBufferAllocateInfo`
These are the Commands that could be entered into the Command Buffer, I

```c
vkCmdBeginQuery( commandBuffer, flags );
vkCmdBeginRenderPass( commandBuffer, const contents );
vkCmdBindDescriptorSets( commandBuffer, pDynamicOffsets );
vkCmdBindIndexBuffer( commandBuffer, indexType );
vkCmdBindPipeline( commandBuffer, pipeline );
vkCmdBindVertexBuffers( commandBuffer, firstBinding, bindingCount, const pOffsets );
vkCmdBlitImage( commandBuffer, filter );
vkCmdClearColorImage( commandBuffer, pRanges );
vkCmdClearColorImage( commandBuffer, pRanges );
vkCmdClearDepthStencilImage( commandBuffer, pRanges );
vkCmdCopyBuffer( commandBuffer, pRegions );
vkCmdCopyBufferToImage( commandBuffer, pRegions );
vkCmdCopyImage( commandBuffer, pRegions );
vkCmdDebugMarkerBeginEXT( commandBuffer, pMarkerInfo );
vkCmdDebugMarkerEndEXT( commandBuffer );
vkCmdDispatch( commandBuffer, groupCountX, groupCountY, groupCountZ );
vkCmdDispatchIndirect( commandBuffer, offset );
vkCmdDraw( commandBuffer, vertexCount, instanceCount, firstVertex, firstInstance );
vkCmdDrawIndexed( commandBuffer, indexCount, instanceCount, firstIndex, int32_t vertexOffset, firstInstance );
vkCmdDrawIndexedIndirect( commandBuffer, stride );
vkCmdDrawIndexedIndirectCountAMD( commandBuffer, stride );
vkCmdEndQuery( commandBuffer, query );
vkCmdEndRenderPass( commandBuffer );
vkCmdExecuteCommands( commandBuffer, commandBufferCount, const pCommandBuffers );
```
These are the Commands that could be entered into the Command Buffer, II

vkCmdFillBuffer( commandBuffer, dstBuffer, dstOffset, size, data );
vkCmdNextSubpass( commandBuffer, contents );
vkCmdPipelineBarrier( commandBuffer, srcStageMask, dstStageMask, dependencyFlags, memoryBarrierCount, pMemoryBarriers, bufferMemoryBarrierCount, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdProcessCommandsNVX( commandBuffer, processCommandsInfo );
vkCmdPushConstants( commandBuffer, layout, stageFlags, offset, size, pValues );
vkCmdPushDescriptorSetKHR( commandBuffer, pipelineBindPoint, layout, set, descriptorWriteCount, pDescriptorWrites );
vkCmdPushDescriptorSetWithTemplateKHR( commandBuffer, descriptorUpdateTemplate, layout, set, pData );
vkCmdResetSpaceForCommandsNVX( commandBuffer, pReserveSpaceInfo );
vkCmdResetEvent( commandBuffer, event, stageMask );
vkCmdResetQueryPool( commandBuffer, queryPool, firstQuery, queryCount );
vkCmdResolveImage( commandBuffer, srcImage, srcImageLayout, dstImage, dstImageLayout, regionCount, pRegions );
vkCmdSetBlendConstants( commandBuffer, blendConstants[4] );
vkCmdSetDepthBias( commandBuffer, depthBiasConstantFactor, depthBiasClamp, depthBiasSlopeFactor );
vkCmdSetDepthBounds( commandBuffer, minDepthBounds, maxDepthBounds );
vkCmdSetDeviceMaskKHX( commandBuffer, deviceMask );
vkCmdSetDiscardRectangleEXT( commandBuffer, firstDiscardRectangle, discardRectangleCount, pDiscardRectangles );
vkCmdSetEvent( commandBuffer, event, stageMask );
vkCmdSetLineWidth( commandBuffer, lineWidth );
vkCmdSetScissor( commandBuffer, firstScissor, scissorCount, pScissors );
vkCmdSetStencilCompareMask( commandBuffer, faceMask, compareMask );
vkCmdSetStencilReference( commandBuffer, faceMask, reference );
vkCmdSetStencilWriteMask( commandBuffer, faceMask, writeMask );
vkCmdSetViewport( commandBuffer, firstViewport, viewportCount, pViewports );
vkCmdSetViewportWScalingNV( commandBuffer, firstViewport, viewportCount, pViewportWScalings );
vkCmdUpdateBuffer( commandBuffer, dstBuffer, dstOffset, dataSize, pData );
vkCmdWaitEvents( commandBuffer, eventCount, pEvents, srcStageMask, dstStageMask, memoryBarrierCount, pMemoryBarriers, bufferMemoryBarrierCount, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdWriteTimestamp( commandBuffer, pipelineStage, queryPool, query );
VkResult
RenderScene()
{
    VkResult result;
    VkSemaphoreCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;

    VkSemaphore imageReadySemaphore;
    result = vkCreateSemaphore(LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore);

    uint32_t _nextImageIndex;
    vkAcquireNextImageKHR(LogicalDevice, IN SwapChain, IN UINT64_MAX, IN VK_NULL_HANDLE,
                          IN VK_NULL_HANDLE, OUT &_nextImageIndex);

    VkCommandBufferBeginInfo vcbbi;
    vcbbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
    vcbbi.pNext = nullptr;
    vcbbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
    vcbbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;

    result = vkBeginCommandBuffer(CommandBuffers[_nextImageIndex], IN &vcbbi);
```cpp
VkClearColorValue vccv;
    vccv.float32[0] = 0.0;
    vccv.float32[1] = 0.0;
    vccv.float32[2] = 0.0;
    vccv.float32[3] = 1.0;

VkClearDepthStencilValue vcdsv;
    vcdsv.depth = 1.f;
    vcdsv.stencil = 0;

VkClearValue vcv[2];
    vcv[0].color = vccv;
    vcv[1].depthStencil = vcdsv;

VkOffset2D o2d = { 0, 0 };
VkExtent2D e2d = { Width, Height };
VkRect2D r2d = { o2d, e2d };

VkRenderPassBeginInfo vrpbi;
    vrpbi.sType = VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO;
    vrpbi.pNext = nullptr;
    vrpbi.renderPass = RenderPass;
    vrpbi.framebuffer = Framebuffers[ nextImageIndex ];
    vrpbi.renderArea = r2d;
    vrpbi.clearValueCount = 2;
    vrpbi.pClearValues = vcv;   // used for VK_ATTACHMENT_LOAD_OP_CLEAR

vkCmdBeginRenderPass( CommandBuffers[nextImageIndex], IN &vrpbi, IN VK_SUBPASS_CONTENTS_INLINE );
```
VkViewport viewport =
{
    0., // x
    0., // y
    (float)Width,
    (float)Height,
    0., // minDepth
    1.   // maxDepth
};

vkCmdSetViewport( CommandBuffers[nextImageIndex], 0, 1, IN &viewport ); // 0=firstViewport, 1=viewportCount

VkRect2D scissor =
{
    0,
    0,
    Width,
    Height
};

vkCmdSetScissor( CommandBuffers[nextImageIndex], 0, 1, IN &scissor );

vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS,
    GraphicsPipelineLayout, 0, 4, DescriptorSets, 0, (uint32_t *)nullptr );
    // dynamic offset count, dynamic offsets

vkCmdBindPushConstants( CommandBuffers[nextImageIndex], PipelineLayout, VK_SHADER_STAGE_ALL, offset, size, void *values );

VkBuffer buffers[1] = { MyVertexDataBuffer.buffer };

VkDeviceSize offsets[1] = { 0 };

vkCmdBindVertexBuffer( CommandBuffers[nextImageIndex], 0, 1, buffers, offsets ); // 0, 1 = firstBinding, bindingCount

const uint32_t vertexCount = sizeof(VertexData) / sizeof(VertexData[0]);
const uint32_t instanceCount = 1;
const uint32_t firstVertex = 0;
const uint32_t firstInstance = 0;

vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );

vkCmdEndRenderPass( CommandBuffers[nextImageIndex] );

vkEndCommandBuffer( CommandBuffers[nextImageIndex] );
Submitting a Command Buffer to a Queue for Execution

```c
VkSubmitInfo vsi;
  vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
  vsi.pNext = nullptr;
  vsi.commandBufferCount = 1;
  vsi.pCommandBuffers = &CommandBuffer;
  vsi.waitSemaphoreCount = 1;
  vsi.pWaitSemaphores = imageReadySemaphore;
  vsi.signalSemaphoreCount = 0;
  vsi.pSignalSemaphores = (VkSemaphore *)nullptr;
  vsi.pWaitDstStageMask = (VkPipelineStageFlags *)nullptr;
```

The Entire Submission / Wait / Display Process

```cpp
VkFenceCreateInfo  veci;
    veci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;
    veci.pNext = nullptr;
    veci.flags = 0;

VkFence  renderFence;
vkCreateFence( LogicalDevice, &veci, PALLOCATOR, OUT &renderFence );
result = VK_SUCCESS;

VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;
VkQueue  presentQueue;
vkGetDeviceQueue( LogicalDevice, FindQueueFamilyThatDoesGraphics( ), 0, OUT &presentQueue );
    // 0 = queueIndex

VkSubmitInfo  vsi;
    vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
    vsi.pNext = nullptr;
    vsi.waitSemaphoreCount = 1;
    vsi.pWaitSemaphores = &imageReadySemaphore;
    vsi.pWaitDstStageMask = &waitAtBottom;
    vsi.commandBufferCount = 1;
    vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
    vsi.signalSemaphoreCount = 0;
    vsi.pSignalSemaphores = &SemaphoreRenderFinished;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence );    // 1 = submitCount
result = vkWaitForFences( LogicalDevice, 1, IN &renderFence, VK_TRUE, UINT64_MAX );    // waitAll, timeout

vkDestroyFence( LogicalDevice, renderFence, PALLOCATOR );

VkPresentInfoKHR  vpi;
    vpi.sType = VK_STRUCTURE_TYPE_PRESENT_INFO_KHR;
    vpi.pNext = nullptr;
    vpi.waitSemaphoreCount = 0;
    vpi.pWaitSemaphores = (VkSemaphore *)nullptr;
    vpi.swapchainCount = 1;
    vpi.pSwapchains = &SwapChain;
    vpi.pImageIndices = &nextImageIndex;
    vpi.pResults = (VkResult *)nullptr;

result = vkQueuePresentKHR( presentQueue, IN &vpi );
```
The Swap Chain
How We Think of OpenGL Framebuffers

Video Driver

Double-buffered Color Framebuffers

Depth-Buffer

Update

Refresh
Vulkan Thinks of it This Way

Update

Depth-Buffer

Swap Chain

Front

Back

Back
What is a Swap Chain?

Vulkan does not use the idea of a “back buffer”. So, we need a place to render into before moving an image into place for viewing. The is called the **Swap Chain**.

In essence, the Swap Chain manages one or more image objects that form a sequence of images that can be drawn into and then given to the Surface to be presented to the user for viewing.

Swap Chains are arranged as a ring buffer

Swap Chains are tightly coupled to the window system.

After creating the Swap Chain in the first place, the process for using the Swap Chain is:

1. Ask the Swap Chain for an image
2. Render into it via the Command Buffer and a Queue
3. Return the image to the Swap Chain for presentation
4. Present the image to the viewer (copy to “front buffer”)
What is a Swap Chain?

Because it has the word “chain” in it, let’s try to visualize the Swap Chain as a physical chain.

A bicycle chain isn’t far off. A bicycle chain goes around and around, each section of the chain taking its turn on the gear teeth, off the gear teeth, on, off, on, off, etc.

Because the Swap Chain is actually a ring buffer, the images in a Swap Chain go around and around too, each image taking its turn being drawn into, being presented, drawn into, being presented etc.

In the same way that bicycle chain links are “re-used”, Swap Chain images get re-used too.
What is a Swap Chain?
VulkanDebug.txt output:

vkGetPhysicalDeviceSurfaceCapabilitiesKHR:
minImageCount = 2 ; maxImageCount = 8
currentExtent = 1024 x 1024
minImageExtent = 1024 x 1024
maxImageExtent = 1024 x 1024
maxImageArrayLayers = 1
supportedTransforms = 0x0001
currentTransform = 0x0001
supportedCompositeAlpha = 0x0001
supportedUsageFlags = 0x009f

** This Surface is supported by the Graphics Queue **

Found 2 Surface Formats:
0: 44 0 ( VK_FORMAT_B8G8R8A8_UNORM, VK_COLOR_SPACE_SRGB_NONLINEAR_KHR )
1: 50 0 ( VK_FORMAT_B8G8R8A8_SRGB, VK_COLOR_SPACE_SRGB_NONLINEAR_KHR )

Found 3 Present Modes:
0: 2 ( VK_PRESENT_MODE_FIFO_KHR )
1: 3 ( VK_PRESENT_MODE_FIFO_RELAXED_KHR )
2: 1 ( VK_PRESENT_MODE_MAILBOX_KHR )

SRGB gives more accurate perceived colors
MAILBOX more likely to avoid image tearing
Creating a Swap Chain

vkCreateSwapchain()

VkSwapchainCreateInfo

surface
imageFormat
imageColorSpace
imageExtent
imageArrayLayers
imageUsage
imageSharingMode
preTransform
compositeAlpha
presentMode
clipped

vkGetDevicePhysicalSurfaceCapabilities()

VkSurfaceCapabilities

minImageCount
maxImageCount
currentExtent
minImageExtent
maxImageExtent
maxImageArrayLayers
supportedTransforms
currentTransform
supportedCompositeAlpha

vkGetSwapChainImages()

vkCreateImageView()

vkCreateSwapchain()
Creating a Swap Chain

```c
VkSurfaceCapabilitiesKHR vsc;
vkGetPhysicalDeviceSurfaceCapabilitiesKHR( PhysicalDevice, Surface, OUT &vsc );
VkExtent2D surfaceRes = vsc.currentExtent;

VkSwapchainCreateInfoKHR vscci;
    vscci.sType = VK_STRUCTURE_TYPE_SWAPCHAIN_CREATE_INFO_KHR;
    vscci.pNext = nullptr;
    vscci.flags = 0;
    vscci.surface = Surface;
    vscci.minImageCount = 2; // double buffering
    vscci.imageFormat = VK_FORMAT_B8G8R8A8_UNORM;
    vscci.imageColorSpace = VK_COLORSPACE_SRGB_NONLINEAR_KHR;
    vscci.imageExtent.width = surfaceRes.width;
    vscci.imageExtent.height = surfaceRes.height;
    vscci.imageUsage = VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT;
    vscci.preTransform = VK_SURFACE_TRANSFORM_IDENTITY_BIT_KHR;
    vscci.compositeAlpha = VK_COMPOSITE_ALPHA_OPAQUE_BIT_KHR;
    vscci.imageArrayLayers = 1;
    vscci.imageSharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vscci.queueFamilyIndexCount = 0;
    vscci.pQueueFamilyIndices = (const uint32_t *)nullptr;
    vscci.presentMode = VK_PRESENT_MODE_MAILBOX_KHR;
    vscci.oldSwapchain = VK_NULL_HANDLE;
    vscci.clipped = VK_TRUE;

result = vkCreateSwapchainKHR( LogicalDevice, IN &vscci, PALLOCATOR, OUT &SwapChain );
```
uint32_t imageCount;       // # of display buffers – 2? 3?
result = vkGetSwapchainImagesKHR( LogicalDevice, IN SwapChain, OUT &imageCount, (VkImage *)nullptr );

PresentImages = new VkImage[ imageCount ];
result = vkGetSwapchainImagesKHR( LogicalDevice, SwapChain, OUT &imageCount, PresentImages );

// present views for the double-buffering:
PresentImageViews = new VkImageView[ imageCount ];

for( unsigned int i = 0; i < imageCount; i++ )
{
    VkImageViewCreateInfo vivci;
    vivci.sType = VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO;
    vivci.pNext = nullptr;
    vivci.flags = 0;
    vivci.viewType = VK_IMAGE_VIEW_TYPE_2D;
    vivci.format = VK_FORMAT_B8G8R8A8_UNORM;
    vivci.components.r = VK_COMPONENT_SWIZZLE_R;
    vivci.components.g = VK_COMPONENT_SWIZZLE_G;
    vivci.components.b = VK_COMPONENT_SWIZZLE_B;
    vivci.components.a = VK_COMPONENT_SWIZZLE_A;
    vivci.subresourceRange.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    vivci.subresourceRange.baseMipLevel = 0;
    vivci.subresourceRange.levelCount = 1;
    vivci.subresourceRange.baseArrayLayer = 0;
    vivci.subresourceRange.layerCount = 1;
    vivci.image = PresentImages[ i ];

    result = vkCreateImageView( LogicalDevice, IN &vivci, PALLOCATOR, OUT &PresentImageViews[ i ] );
}

Creating the Swap Chain Images and Image Views
Rendering into the Swap Chain, I

```c
VkSemaphoreCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;

VkSemaphore imageReadySemaphore;
result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore );

uint32_t nextImageIndex;
uint64_t timeout = UINT64_MAX;
vkAcquireNextImageKHR( LogicalDevice, IN SwapChain, IN timeout, IN imageReadySemaphore,
    IN VK_NULL_HANDLE, OUT &nextImageIndex );
...

result = vkBeginCommandBuffer( CommandBuffers[ nextImageIndex ], IN &vcbbi );
...

vkCmdBeginRenderPass( CommandBuffers[ nextImageIndex ], IN &vrpbi,
    IN VK_SUBPASS_CONTENTS_INLINE );

vkCmdBindPipeline( CommandBuffers[ nextImageIndex ], VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );
...

vkCmdEndRenderPass( CommandBuffers[ nextImageIndex ] );
vkEndCommandBuffer( CommandBuffers[ nextImageIndex ] );
```
Rendering into the Swap Chain, II

```cpp
VkFenceCreateInfo vfci;
vfci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;
vfci.pNext = nullptr;
vfci.flags = 0;

VkFence renderFence;
vkCreateFence( LogicalDevice, &vfci, PALLOCATOR, OUT &renderFence );

VkQueue presentQueue;
vkGetDeviceQueue( LogicalDevice, FindQueueFamilyThatDoesGraphics( ), 0, OUT &presentQueue );

...  

VkSubmitInfo vsi;
vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
vsi.pNext = nullptr;
vsi.waitSemaphoreCount = 1;
vsi.pWaitSemaphores = &imageReadySemaphore;
vsi.pWaitDstStageMask = &waitAtBottom;
vsi.commandBufferCount = 1;
vsi.pCommandBuffers = &CommandBuffers[ nextImageIndex ];
vsi.signalSemaphoreCount = 0;
vsi.pSignalSemaphores = &SemaphoreRenderFinished;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence );  // 1 = submitCount
```
result = vkWaitForFences( LogicalDevice, 1, IN &renderFence, VK_TRUE, UINT64_MAX );

VkPresentInfoKHR vpi;
    vpi.sType = VK_STRUCTURE_TYPE_PRESENT_INFO_KHR;
    vpi.pNext = nullptr;
    vpi.waitSemaphoreCount = 0;
    vpi.pWaitSemaphores = (VkSemaphore *)nullptr;
    vpi.swapchainCount = 1;
    vpi.pSwapchains = &SwapChain;
    vpi.pImageIndices = &nextImageIndex;
    vpi.pResults = (VkResult *) nullptr;

result = vkQueuePresentKHR( presentQueue, IN &vpi );
Rendering
1. `vkBeginRenderPass()`
2. `vkCmdBindPipeline(CommandBuffer, ...)`
3. `vkCmdSetxxx(CommandBuffer, yyy)` — dynamic states
4. `vkCmdBindDescriptorSets(CommandBuffer, ...)`
5. `vkCmdBindVertexBuffers(CommandBuffer, ...)`
6. `vkCmdDraw(CommandBuffer, vertexCount, instanceCount, firstVertex, firstInstance)`
7. `vkEndRenderPass()`
Vulkan: Beginning a Command Buffer

- VkCommandBufferPoolCreateInfo
  - vkCreateCommandBufferPool()
    - VkCommandBufferAllocateInfo
      - VkCommandBufferBeginInfo
        - vkAllocateCommandBuffer()
  - vkBeginCommandBuffer()
Vulkan: Submitting to a Queue

- VkSubmitInfo
  - waitSemaphores
  - pipelineStageFlags
  - cmdBufferCount
  - cmdBuffers
  - vkQueueSubmit()
VkResult
RenderScene( )
{
    VkResult result ;

    VkSemaphoreCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;

    VkSemaphore imageReadySemaphore;
    result = vkCreateSemaphore( LogicalDevice, &vsci, PALLOCATOR, OUT &imageReadySemaphore );
    uint32_t nextImageIndex;
    vkAcquireNextImageKHR( LogicalDevice, IN SwapChain, IN UINT64_MAX,
                           IN imageReadySemaphore, IN VK_NULL_HANDLE, OUT &nextImageIndex );

    VkCommandBufferBeginInfo vcbbi;
    vcbbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
    vcbbi.pNext = nullptr;
    vcbbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
    vcbbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;

    result = vkBeginCommandBuffer( CommandBuffers[nextImageIndex], &vcbbi );
VkClearColorValue vccv;
  vccv.float32[0] = 0.0;
  vccv.float32[1] = 0.0;
  vccv.float32[2] = 0.0;
  vccv.float32[3] = 1.0;

VkClearDepthStencilValue vcdsv;
  vcdsv.depth = 1.f;
  vcdsv.stencil = 0;

VkClearValue vcv[2];
  vcv[0].color = vccv;
  vcv[1].depthStencil = vcdsv;

VkOffset2D o2d = { 0, 0 };
VkExtent2D e2d = { Width, Height };
VkRect2D r2d = { o2d, e2d };

VkRenderPassBeginInfo vrpbi;
  vrpbi.sType = VK_STRUCTURE_TYPE_RENDER_PASS_BEGIN_INFO;
  vrpbi.pNext = nullptr;
  vrpbi.renderPass = ... = r2d;
  vrpbi.clearValueCount = 2;
  vrpbi.pClearValues = vcv; // used for VK_ATTACHMENT_LOAD_OP_CLEAR
vkCmdBeginRenderPass( CommandBuffers[nextImageIndex], IN &vrpbi, IN VK_SUBPASS_CONTENTS_INLINE );

vkCmdBindPipeline( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );
VkViewport viewport =
{
    0., // x
    0., // y
    (float)Width,
    (float)Height,
    0., // minDepth
    1. // maxDepth
};

vkCmdSetViewport( CommandBuffers[nextImageIndex], 0, 1, IN &viewport ); // 0=firstViewport, 1=viewportCount

VkRect2D scissor =
{
    0,
    0,
    Width,
    Height
};

vkCmdSetScissor( CommandBuffers[nextImageIndex], 0, 1, &scissor );

vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS,
    GraphicsPipelineLayout, 0, 4, DescriptorSets, 0, (uint32_t *)nullptr );

//vkCmdBindPushConstants( CommandBuffers[nextImageIndex], PipelineLayout, VK_SHADER_STAGE_ALL,
//    offset, size, void *values );
VkBuffer buffers[1] = { MyVertexDataBuffer.buffer};
VkDeviceSize offsets[1] = { 0 };  
vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, buffers, offsets ); // 0, 1 = firstBinding, bindingCount

const uint32_t vertexCount = sizeof(VertexData) / sizeof(VertexData[0]);
const uint32_t instanceCount = 1;
const uint32_t firstVertex = 0;
const uint32_t firstInstance = 0;
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );

vkCmdEndRenderPass( CommandBuffers[nextImageIndex] );

vkEndCommandBuffer( CommandBuffers[nextImageIndex] );

VkFenceCreateInfo vfci;
vfci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;
vfci.pNext = nullptr;
vfci.flags = 0;

VkFence renderFence;
vkCreateFence( LogicalDevice, &vfci, PALLOCATOR, OUT &renderFence );
VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;

VkQueue presentQueue;
vkGetDeviceQueue( LogicalDevice, FindQueueFamilyThatDoesGraphics( ), 0, OUT &presentQueue ); // 0 = queueIndex

VkSubmitInfo vsi;
    vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
    vsi.pNext = nullptr;
    vsi.waitSemaphoreCount = 1;
    vsi.pWaitSemaphores = &imageReadySemaphore;
    vsi.pWaitDstStageMask = &waitAtBottom;
    vsi.commandBufferCount = 1;
    vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
    vsi.signalSemaphoreCount = 0;
    vsi.pSignalSemaphores = &SemaphoreRenderFinished;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence ); // 1 = submitCount

result = vkWaitForFences( LogicalDevice, 1, IN &renderFence, VK_TRUE, UINT64_MAX ); // waitAll, timeout

vkDestroyFence( LogicalDevice, renderFence, PALLOCATOR );

VkPresentInfoKHR vpi;
    vpi.sType = VK_STRUCTURE_TYPE_PRESENT_INFO_KHR;
    vpi.pNext = nullptr;
    vpi.waitSemaphoreCount = 0;
    vpi.pWaitSemaphores = (VkSemaphore *)nullptr;
    vpi.swapchainCount = 1;
    vpi.pSwapchains = &SwapChain;
    vpi.pImageIndices = &nextImageIndex;
    vpi.pResults = (VkResult *)nullptr;

result = vkQueuePresentKHR( presentQueue, IN &vpi );

vkDestroySemaphore( LogicalDevice, imageReadySemaphore, PALLOCATOR );
struct vertex
{
    glm::vec3 position;
    glm::vec3 normal;
    glm::vec3 color;
    glm::vec2 texCoord;
};

struct vertex VertexData[ ] =
{
    // triangle 0-2-3:
    // vertex #0:
    {
        { -1., -1., -1. },
        {  0.,  0., -1. },
        {  0.,  0.,  0. },
        {  1., 0. },
    },

    // vertex #2:
    {
        { -1.,  1., -1. },
        {  0.,  0., -1. },
        {  0.,  1.,  0. },
        {  1., 1. },
    },

    // vertex #3:
    {
        {  1.,  1., -1. },
        {  0.,  0., -1. },
        {  1.,  1.,  0. },
        {  0., 1. },
    },

    // vertex #4:
    {
        {  1.,  1., -1. },
        {  0.,  0., -1. },
        {  1.,  1.,  0. },
        {  0., 1. },
    },

    // vertex #5:
    {
        {  1.,  1., -1. },
        {  0.,  0., -1. },
        {  1.,  1.,  0. },
        {  0., 1. },
    },

    // vertex #6:
    {
        {  1.,  1., -1. },
        {  0.,  0., -1. },
        {  1.,  1.,  0. },
        {  0., 1. },
    },

    // vertex #7:
    {
        {  1.,  1., -1. },
        {  0.,  0., -1. },
        {  1.,  1.,  0. },
        {  0., 1. },
    }
};
VkDescriptorSetLayoutBinding TexSamplerSet[1];
    TexSamplerSet[0].binding = 0;
    TexSamplerSet[0].descriptorType = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
    // uniform sampler2D uSampler
    // vec4 rgba = texture(uSampler, vST);
    TexSamplerSet[0].descriptorCount = 1;
    TexSamplerSet[0].stageFlags = VK_SHADER_STAGE_FRAGMENT_BIT;
    TexSamplerSet[0].pImmutableSamplers = (VkSampler *)nullptr;

    ... VkDescriptorImageInfo vdii0;
    vdii0.sampler = MyPuppyTexture.texSampler;
    vdii0.imageView = MyPuppyTexture.texImageView;
    vdii0.imageLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
    ... VkWriteDescriptorSet vwds3;
    vwds3.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
    vwds3.pNext = nullptr;
    vwds3.dstSet = DescriptorSets[3];
    vwds3.dstBinding = 0;
    vwds3.dstArrayElement = 0;
    vwds3.descriptorCount = 1;
    vwds3.descriptorType = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
    vwds3.pBufferInfo = (VkDescriptorBufferInfo *)nullptr;
    vwds3.pImageInfo = &vdii0;
    vwds3.pTexelBufferView = (VkBufferView *)nullptr;
Memory Types

**NVIDIA Discrete Graphics:**

11 Memory Types:
- Memory 0:  
- Memory 1:  
- Memory 2:  
- Memory 3:  
- Memory 4:  
- Memory 5:  
- Memory 6:  
- Memory 7: DeviceLocal  
- Memory 8: DeviceLocal  
- Memory 9: HostVisible HostCoherent  
- Memory 10: HostVisible HostCoherent HostCached

**Intel Integrated Graphics:**

3 Memory Types:
- Memory 0: DeviceLocal  
- Memory 1: DeviceLocal HostVisible HostCoherent  
- Memory 2: DeviceLocal HostVisible HostCoherent HostCached
Texture Sampling Parameters

glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );

XmlSamplerCreateInfo vsci;
    vsci.magFilter = VK_FILTER_LINEAR;
    vsci.minFilter = VK_FILTER_LINEAR;
    vsci.mipmapMode = VK_SAMPLER_MIPMAP_MODE_LINEAR;
    vsci.addressModeU = VK_SAMPLER_ADDRESS_MODE_REPEAT;
    vsci.addressModeV = VK_SAMPLER_ADDRESS_MODE_REPEAT;
    vsci.addressModeW = VK_SAMPLER_ADDRESS_MODE_REPEAT;

    ...

result = vkCreateSampler( LogicalDevice, IN &vsci, PALLOCATOR, pTextureSampler );
Textures’ Undersampling Artifacts

As an object gets farther away and covers a smaller and smaller part of the screen, the texels : pixels ratio used in the coverage becomes larger and larger. This means that there are pieces of the texture leftover in between the pixels that are being drawn into, so that some of the texture image is not being taken into account in the final image. This means that the texture is being undersampled and could end up producing artifacts in the rendered image.

Consider a texture that consists of one red texel and all the rest white. It is easy to imagine an object rendered with that texture as ending up all white, with the red texel having never been included in the final image. The solution is to create lower-resolutions of the same texture so that the red texel gets included somehow in all resolution-level textures.
Texture Mip*-mapping

- Total texture storage is ~ 2x what it was without mip-mapping
- Graphics hardware determines which level to use based on the texels : pixels ratio.
- In addition to just picking one mip-map level, the rendering system can sample from two of them, one less that the T:P ratio and one more, and then blend the two RGBAs returned. This is known as **VK_SAMPLER_MIPMAP_MODE_LINEAR**.

* Latin: *multim in parvo*, “many things in a small place”
VkResult Init07TextureSampler( MyTexture * pMyTexture )
{
    VkResult result;

    VkSamplerCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;
    vsci.magFilter = VK_FILTER_LINEAR;
    vsci.minFilter = VK_FILTER_LINEAR;
    vsci.mipmapMode = VK_SAMPLER_MIPMAP_MODE_LINEAR;
    vsci.addressModeU = VK_SAMPLER_ADDRESS_MODE_REPEAT;
    vsci.addressModeV = VK_SAMPLER_ADDRESS_MODE_REPEAT;
    vsci.addressModeW = VK_SAMPLER_ADDRESS_MODE_REPEAT;

    #ifdef CHOICES
    VK_SAMPLER_ADDRESS_MODE_REPEAT
    VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE
    VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER
    VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE
    #endif

    vsci.mipLodBias = 0.;
    vsci.anisotropyEnable = VK_FALSE;
    vsci.maxAnisotropy = 1.;
    vsci.compareEnable = VK_FALSE;
    vsci.compareOp = VK_COMPARE_OP_NEVER;

    #ifdef CHOICES
    VK_COMPARE_OP_NEVER
    VK_COMPARE_OP_LESS
    VK_COMPARE_OP_EQUAL
    VK_COMPARE_OP_LESS_OR_EQUAL
    VK_COMPARE_OP_GREATER
    VK_COMPARE_OP_NOT_EQUAL
    VK_COMPARE_OP_GREATER_OR_EQUAL
    VK_COMPARE_OP_ALWAYS
    #endif

    vsci.minLod = 0.;
    vsci.maxLod = 0.;
    vsci.borderColor = VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK;

    #ifdef CHOICES
    VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK
    VK_BORDER_COLOR_INT_TRANSPARENT_BLACK
    VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK
    VK_BORDER_COLOR_INT_OPAQUE_BLACK
    VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE
    VK_BORDER_COLOR_INT_OPAQUE_WHITE
    #endif

    vsci.unnormalizedCoordinates = VK_FALSE;    // VK_TRUE means we are using raw texels as the index
    // VK_FALSE means we are using the usual 0. - 1.

    result = vkCreateSampler( LogicalDevice, IN &vsci, PALLOCATOR, OUT &pMyTexture->texSampler );
    return result;
}

enable comparison against a reference value during lookups
VkResult
Init07TextureBuffer( INOUT MyTexture * pMyTexture)
{
    VkResult result;
    
    uint32_t texWidth = pMyTexture->width;
    uint32_t texHeight = pMyTexture->height;
    unsigned char *texture = pMyTexture->pixels;
    VkDeviceSize textureSize = texWidth * texHeight * 4;  // rgba, 1 byte each

    VkImage stagingImage;
    VkImage textureImage;

    // ******************************************************
    // this first {...} is to create the staging image:
    // ******************************************************
    
    VkImageCreateInfo vici;
    vici.sType = VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO;
    vici.pNext = nullptr;
    vici.flags = 0;
    vici.imageType = VK_IMAGE_TYPE_2D;
    vici.format = VK_FORMAT_R8G8B8A8_UNORM;
    vici.extent.width = texWidth;
    vici.extent.height = texHeight;
    vici.extent.depth = 1;
    vici.mipLevels = 1;
    vici.arrayLayers = 1;
    vici.samples = VK_SAMPLE_COUNT_1_BIT;
    vici.tiling = VK_IMAGE_TILING_LINEAR;

    #ifdef CHOICES
    VK_IMAGE_TILING_OPTIMAL
    VK_IMAGE_TILING_LINEAR
    #endif
    vici.usage = VK_IMAGE_USAGE_TRANSFER_SRC_BIT;

    #ifdef CHOICES
    VK_IMAGE_USAGE_TRANSFER_SRC_BIT
    VK_IMAGE_USAGE_TRANSFER_DST_BIT
    VK_IMAGE_USAGE_SAMPLED_BIT
    VK_IMAGE_USAGE_STORAGE_BIT
    VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT
    VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
    VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT
    VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT
    #endif
    vici.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
```c
#ifdef CHOICES
VK_IMAGE_LAYOUT_UNDEFINED
VK_IMAGE_LAYOUT_PREINITIALIZED
#endif

vici.queueFamilyIndexCount = 0;
vici.pQueueFamilyIndices = (const uint32_t *)nullptr;

result = vkCreateImage(LogicalDevice, IN &vici, PALLOCATOR, OUT &stagingImage); // allocated, but not filled

VkMemoryRequirements vmr;
vkGetImageMemoryRequirements(LogicalDevice, IN stagingImage, OUT &vmr);

if (Verbose)
{
    fprintf(FpDebug, "Image vmr.size = %lld\n", vmr.size);
    fprintf(FpDebug, "Image vmr.alignment = %lld\n", vmr.alignment);
    fprintf(FpDebug, "Image vmr.memoryTypeBits = 0x%08lx\n", vmr.memoryTypeBits);
    fflush(FpDebug);
}

VkMemoryAllocateInfo vmai;
    vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
    vmai.pNext = nullptr;
    vmai.allocationSize = vmr.size;
    vmai.memoryTypeIndex = FindMemoryThatIsHostVisible(); // because we want to mmap it

VkDeviceMemory vdm;
result = vkAllocateMemory(LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm);
pMyTexture->vdm = vdm;

result = vkBindImageMemory(LogicalDevice, IN stagingImage, IN vdm, 0); // 0 = offset

// we have now created the staging image -- fill it with the pixel data:

VkImageSubresource vis;
    vis.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    vis.mipLevel = 0;
    vis.arrayLayer = 0;

VkSubresourceLayout vsl;
vkGetImageSubresourceLayout(LogicalDevice, stagingImage, IN &vis, OUT &vsl);

if (Verbose)
{
    fprintf(FpDebug, "Subresource Layout:\n");
    fprintf(FpDebug, "tOffset = %lld\n", vsl.offset);
    fprintf(FpDebug, "tSize = %lld\n", vsl.size);
    fprintf(FpDebug, "rowPitch = %lld\n", vsl.rowPitch);
    fprintf(FpDebug, "arrayPitch = %lld\n", vsl.arrayPitch);
    fprintf(FpDebug, "depthPitch = %lld\n", vsl.depthPitch);
    fflush(FpDebug);
}
```
```c
void * gpuMemory;
vkMapMemory( LogicalDevice, vdm, 0, VK_WHOLE_SIZE, 0, OUT &gpuMemory);
// 0 and 0 = offset and memory map flags

if (vsl.rowPitch == 4 * texWidth)
{
    memcpy(gpuMemory, (void *)texture, (size_t)textureSize);
}
else
{
    unsigned char *gpuBytes = (unsigned char *)gpuMemory;
    for (unsigned int y = 0; y < texHeight; y++)
    {
        memcpy(&gpuBytes[y * vsl.rowPitch], &texture[4 * y * texWidth], (size_t)(4*texWidth) );
    }
}

vkUnmapMemory( LogicalDevice, vdm);

// ******************************************************************************
```
// this second {...} is to create the actual texture image:

VkImageCreateInfo vici;
    vici.sType = VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO;
    vici.pNext = nullptr;
    vici.flags = 0;
    vici.imageType = VK_IMAGE_TYPE_2D;
    vici.format = VK_FORMAT_R8G8B8A8_UNORM;
    vici.extent.width = texWidth;
    vici.extent.height = texHeight;
    vici.extent.depth = 1;
    vici.mipLevels = 1;
    vici.arrayLayers = 1;
    vici.samples = VK_SAMPLE_COUNT_1_BIT;
    vici.tiling = VK_IMAGE_TILING_OPAQUE.hashCode();
    vici.usage = VK_IMAGE_USAGE_TRANSFER_DST_BIT | VK_IMAGE_USAGE_SAMPLED_BIT;
    vici.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vici.initialLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
    vici.queueFamilyIndexCount = 0;
    vici.pQueueFamilyIndices = (const uint32_t *)nullptr;

result = vkCreateImage(LogicalDevice, IN &vici, PALLOCATOR, OUT &textureImage); // allocated, but not filled

VkMemoryRequirements vmr;
vkGetImageMemoryRequirements(LogicalDevice, IN textureImage, OUT &vmr);

if(Verbose)
{
    fprintf(FpDebug, "Texture vmr.size = %lld\n", vmr.size);
    fprintf(FpDebug, "Texture vmr.alignment = %lld\n", vmr.alignment);
    fprintf(FpDebug, "Texture vmr.memoryTypeBits = 0x%08x\n", vmr.memoryTypeBits);
    fflush(FpDebug);
}

VkMemoryAllocateInfo vmai;
    vmai.sType = VK_STRUCTURE_TYPE_MEMORY_ALLOCATE_INFO;
    vmai.pNext = nullptr;
    vmai.allocationSize = vmr.size;
    vmai.memoryTypeIndex = FindMemoryThatIsDeviceLocal(); // because we want to sample from it

VkDeviceMemory vdm;
result = vkAllocateMemory(LogicalDevice, IN &vmai, PALLOCATOR, OUT &vdm);

result = vkBindImageMemory(LogicalDevice, IN textureImage, IN vdm, 0); // 0 = offset

// ******************************************************************************
// copy pixels from the staging image to the texture:

VkCommandBufferBeginInfo vcbbi;
vcbbi.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_BEGIN_INFO;
vcbbi.pNext = nullptr;
vcbbi.flags = VK_COMMAND_BUFFER_USAGE_ONE_TIME_SUBMIT_BIT;
vcbbi.pInheritanceInfo = (VkCommandBufferInheritanceInfo *)nullptr;

result = vkBeginCommandBuffer(TextureCommandBuffer, IN &vcbbi);

// *******************************************************************************
// transition the staging buffer layout:
// *******************************************************************************
{
    VkImageSubresourceRange visr;
    visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    visr.baseMipLevel = 0;
    visr.levelCount = 1;
    visr.baseArrayLayer = 0;
    visr.layerCount = 1;

    VkImageMemoryBarrier vimb;
    vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
    vimb.pNext = nullptr;
    vimb.oldLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
    vimb.newLayout = VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL;
    vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.image = stagingImage;
    vimb.srcAccessMask = 0;
    vimb.dstAccessMask = 0;
    vimb.subresourceRange = visr;

    vkCmdPipelineBarrier(TextureCommandBuffer,
                         VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, 0, 0, (VkMemoryBarrier *)nullptr, 0, (VkBufferMemoryBarrier *)nullptr, 1, IN &vimb);
}

// *******************************************************************************
// transition the texture buffer layout:

VkImageSubresourceRange visr;
    visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    visr.baseMipLevel = 0;
    visr.levelCount = 1;
    visr.baseArrayLayer = 0;
    visr.layerCount = 1;

VkImageMemoryBarrier vimb;
    vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
    vimb.pNext = nullptr;
    vimb.oldLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
    vimb.newLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
    vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.image = textureImage;
    vimb.srcAccessMask = 0;
    vimb.dstAccessMask = 0;
    vimb.subresourceRange = visr;

vkCmdPipelineBarrier( TextureCommandBuffer,
    VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, 0,
    0, (VkMemoryBarrier *)nullptr,
    0, (VkBufferMemoryBarrier *)nullptr,
    1, IN &vimb);

// now do the final image transfer:

VkImageSubresourceLayers visl;
    visl.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    visl.baseArrayLayer = 0;
    visl.mipLevel = 0;
    visl.layerCount = 1;

VkOffset3D vo3;
    vo3.x = 0;
    vo3.y = 0;
    vo3.z = 0;

VkExtent3D ve3;
    ve3.width = texWidth;
    ve3.height = texHeight;
    ve3.depth = 1;
VkImageCopy vic;
    vic.srcSubresource = visl;
    vic.srcOffset = vo3;
    vic.dstSubresource = visl;
    vic.dstOffset = vo3;
    vic.extent = ve3;

    vkCmdCopyImage(TextureCommandBuffer,
                   stagingImage, VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL,
                   textureImage, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, IN &vic);
}
// ***************************************************************
// *******************************************************************************
// transition the texture buffer layout a second time:
// *******************************************************************************
{
    VkImageSubresourceRange visr;
    visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    visr.baseMipLevel = 0;
    visr.levelCount = 1;
    visr.baseArrayLayer = 0;
    visr.layerCount = 1;

    VkImageMemoryBarrier vimb;
    vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
    vimb.pNext = nullptr;
    vimb.oldLayout = VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL;
    vimb.newLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
    vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.image = textureImage;
    vimb.srcAccessMask = 0;
    vimb.dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
    vimb.subresourceRange = visr;

    vkCmdPipelineBarrier(TextureCommandBuffer,
        VK_PIPELINE_STAGE_TRANSFER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, 0,
        0, (VkMemoryBarrier *)nullptr,0, (VkBufferMemoryBarrier *)nullptr,1, IN &vimb);
}

result = vkEndCommandBuffer( TextureCommandBuffer );

VkSubmitInfo vsi;
    vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
    vsi.pNext = nullptr;
    vsi.commandBufferCount = 1;
    vsi.pCommandBuffers = &TextureCommandBuffer;
    vsi.waitSemaphoreCount = 0;
    vsi.pWaitSemaphores = (VkSemaphore *)nullptr;
    vsi.signalSemaphoreCount = 0;
    vsi.pSignalSemaphores = (VkSemaphore *)nullptr;
    vsi.pWaitDstStageMask = (VkPipelineStageFlags *)nullptr;

result = vkQueueSubmit( Queue, 1, IN &vsi, VK_NULL_HANDLE );
result = vkQueueWaitIdle( Queue );
// create an image view for the texture image:

```
VkImageSubresourceRange visr;
    visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    visr.baseMipLevel = 0;
    visr.levelCount = 1;
    visr.baseArrayLayer = 0;
    visr.layerCount = 1;

VkImageViewCreateInfo vivci;
    vivci.sType = VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO;
    vivci.pNext = nullptr;
    vivci.flags = 0;
    vivci.image = ...
    vivci.components.a = VK_COMPONENT_SWIZZLE_B;
    vivci.components.a = VK_COMPONENT_SWIZZLE_A;
    vivci.subresourceRange = visr;

result = vkCreateImageView( LogicalDevice, IN &vivci, PALLOCATOR, OUT &pMyTexture->texImageView);
```

return result;
```

Note that, at this point, the Staging Buffer is no longer needed, and can be destroyed.
Physical Devices
uint32_t count;
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT (VkPhysicalDevice *)nullptr );

VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[ count ];
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT physicalDevices );

This way of querying information is a recurring OpenCL and Vulkan pattern (get used to it):

```c
result = vkEnumeratePhysicalDevices( Instance, &count, nullptr );
result = vkEnumeratePhysicalDevices( Instance, &count, physicalDevices );
```
VkResult result = VK_SUCCESS;

result = vkEnumeratePhysicalDevices( Instance, OUT &PhysicalDeviceCount, (VkPhysicalDevice *)nullptr );
if( result != VK_SUCCESS || PhysicalDeviceCount <= 0 )
{
    fprintf( FpDebug, "Could not count the physical devices\n" );
    return VK_SHOULD_EXIT;
}

fprintf(FpDebug, "\n%d physical devices found.\n", PhysicalDeviceCount);

VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[ PhysicalDeviceCount ];
result = vkEnumeratePhysicalDevices( Instance, OUT &PhysicalDeviceCount, OUT physicalDevices );
if( result != VK_SUCCESS )
{
    fprintf( FpDebug, "Could not enumerate the %d physical devices\n", PhysicalDeviceCount );
    return VK_SHOULD_EXIT;
}
Which Physical Device to Use, I

```c
int discreteSelect = -1;
int integratedSelect = -1;
for( unsigned int i = 0; i < PhysicalDeviceCount; i++ )
{
    VkPhysicalDeviceProperties vpdp;
    vkGetPhysicalDeviceProperties( IN physicalDevices[i], OUT &vpdp );
    if( result != VK_SUCCESS )
    {
        fprintf( FpDebug, "Could not get the physical device properties of device %d\n", i );
        return VK_SHOULD_EXIT;
    }
    fprintf( FpDebug, "Device %2d:
", i );
    fprintf( FpDebug, "\n\tAPI version: %d\n", vpdp.apiVersion );
    fprintf( FpDebug, "\tDriver version: %d\n", vpdp.apiVersion );
    fprintf( FpDebug, "\tVendor ID: 0x%04x\n", vpdp.vendorID );
    fprintf( FpDebug, "\tDevice ID: 0x%04x\n", vpdp.deviceID );
    fprintf( FpDebug, "\tPhysical Device Type: %d =", vpdp.deviceType );
    if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU )
        fprintf( FpDebug, " (Discrete GPU)\n" );
    if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU )
        fprintf( FpDebug, " (Integrated GPU)\n" );
    if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_VIRTUAL_GPU )
        fprintf( FpDebug, " (Virtual GPU)\n" );
    if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_CPU )
        fprintf( FpDebug, " (CPU)\n" );
    fprintf( FpDebug, "\tDevice Name: %s\n", vpdp.deviceName );
    fprintf( FpDebug, "\tPipeline Cache Size: %d\n", vpdp.pipelineCacheUUID[0] );
}
```
// need some logical here to decide which physical device to select:

if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU )
    discreteSelect = i;

if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU )
    integratedSelect = i;
}

int which = -1;
if( discreteSelect >= 0 )
{
    which = discreteSelect;
    PhysicalDevice = physicalDevices[which];
}
else if( integratedSelect >= 0 )
{
    which = integratedSelect;
    PhysicalDevice = physicalDevices[which];
}
else
{
    fprintf( FpDebug, "Could not select a Physical Device\n" );
    return VK_SHOULD_EXIT;
}
Asking About the Physical Device’s Features

VkPhysicalDeviceProperties PhysicalDeviceFeatures;
vkGetPhysicalDeviceFeatures( IN PhysicalDevice, OUT &PhysicalDeviceFeatures );

fprintf( FpDebug, "\nPhysical Device Features:\n" );
fprintf( FpDebug, "geometryShader = %2d\n", PhysicalDeviceFeatures.geometryShader );
fprintf( FpDebug, "tessellationShader = %2d\n", PhysicalDeviceFeatures.tessellationShader );
fprintf( FpDebug, "multiDrawIndirect = %2d\n", PhysicalDeviceFeatures.multiDrawIndirect );
fprintf( FpDebug, "wideLines = %2d\n", PhysicalDeviceFeatures.wideLines );
fprintf( FpDebug, "largePoints = %2d\n", PhysicalDeviceFeatures.largePoints );
fprintf( FpDebug, "multiViewport = %2d\n", PhysicalDeviceFeatures.multiViewport );
fprintf( FpDebug, "occlusionQueryPrecise = %2d\n", PhysicalDeviceFeatures.occlusionQueryPrecise );
fprintf( FpDebug, "pipelineStatisticsQuery = %2d\n", PhysicalDeviceFeatures.pipelineStatisticsQuery );
fprintf( FpDebug, "shaderFloat64 = %2d\n", PhysicalDeviceFeatures.shaderFloat64 );
fprintf( FpDebug, "shaderInt64 = %2d\n", PhysicalDeviceFeatures.shaderInt64 );
fprintf( FpDebug, "shaderInt16 = %2d\n", PhysicalDeviceFeatures.shaderInt16 );
Here’s What the NVIDIA 1080ti Produced

vkEnumeratePhysicalDevices:

Device 0:
  API version: 4194360
  Driver version: 4194360
  Vendor ID: 0x10de
  Device ID: 0x1b06
  Physical Device Type: 2 = (Discrete GPU)
  Device Name: GeForce GTX 1080 Ti
  Pipeline Cache Size: 13

Device #0 selected ('GeForce GTX 1080 Ti')

Physical Device Features:
  geometryShader = 1
  tessellationShader = 1
  multiDrawIndirect = 1
  wideLines = 1
  largePoints = 1
  multiViewport = 1
  occlusionQueryPrecise = 1
  pipelineStatisticsQuery = 1
  shaderFloat64 = 1
  shaderInt64 = 1
  shaderInt16 = 0
Here's What the Intel HD Graphics 520 Produced

vkEnumeratePhysicalDevices:

Device 0:
  API version: 4194360  
  Driver version: 4194360  
  Vendor ID: 0x8086  
  Device ID: 0x1916  
  Physical Device Type: 1 = (Integrated GPU)  
  Device Name: Intel(R) HD Graphics 520  
  Pipeline Cache Size: 213

Device #0 selected ('Intel(R) HD Graphics 520')

Physical Device Features:
  geometryShader = 1
  tessellationShader = 1
  multiDrawIndirect = 1
  wideLines = 1
  largePoints = 1
  multiViewport = 1
  occlusionQueryPrecise = 1
  pipelineStatisticsQuery = 1
  shaderFloat64 = 1
  shaderInt64 = 1
  shaderInt16 = 1
Asking About the Physical Device’s Different Memories

```c
VkPhysicalDeviceMemoryProperties vpdmp;
vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp);

fprintf( FpDebug, "\n%d Memory Types:\n", vpdmp.memoryTypeCount );
for( unsigned int i = 0; i < vpdmp.memoryTypeCount; i++ )
{
    VkMemoryType vmt = vpdmp.memoryTypes[i];
    fprintf( FpDebug, "Memory %2d: ", i );
    if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT ) != 0 )    fprintf( FpDebug, " DeviceLocal" );
    if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT ) != 0 )    fprintf( FpDebug, " HostVisible" );
    if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_COHERENT_BIT ) != 0 )    fprintf( FpDebug, " HostCoherent" );
    if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_CACHED_BIT  ) != 0 )    fprintf( FpDebug, " HostCached" );
    if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT ) != 0 )    fprintf( FpDebug, " LazilyAllocated" );
    fprintf(FpDebug, "\n");
}

fprintf( FpDebug, "\n%d Memory Heaps:\n", vpdmp.memoryHeapCount );
for( unsigned int i = 0; i < vpdmp.memoryHeapCount; i++ )
{
    fprintf(FpDebug, "Heap %d: ", i);
    VkMemoryHeap vmh = vpdmp.memoryHeaps[i];
    fprintf( FpDebug, " size = 0x%08lx", (unsigned long int)vmh.size );
    if( ( vmh.flags & VK_MEMORY_HEAP_DEVICE_LOCAL_BIT ) != 0 )    fprintf( FpDebug, " DeviceLocal" );    // only one in use
    fprintf(FpDebug, "\n");
}
```
Here’s What I Got

11 Memory Types:
Memory 0:
Memory 1:
Memory 2:
Memory 3:
Memory 4:
Memory 5:
Memory 6:
Memory 7: DeviceLocal
Memory 8: DeviceLocal
Memory 9: HostVisible HostCoherent
Memory 10: HostVisible HostCoherent HostCached

2 Memory Heaps:
Heap 0: size = 0xb7c00000 DeviceLocal
Heap 1: size = 0xfac00000
uint32_t count = -1;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *)nullptr );
fprintf( FpDebug, "\nFound %d Queue Families:\n", count );

VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT vqfp );
for( unsigned int i = 0; i < count; i++ )
{
    fprintf( FpDebug, "\t%d: queueCount = %2d ;   ", i, vqfp[i].queueCount );
    if( ( vqfp[i].queueFlags & VK_QUEUE_GRAPHICS_BIT ) != 0 ) fprintf( FpDebug, " Graphics" );
    if( ( vqfp[i].queueFlags & VK_QUEUE_COMPUTE_BIT  ) != 0 ) fprintf( FpDebug, " Compute ");
    if( ( vqfp[i].queueFlags & VK_QUEUE_TRANSFER_BIT ) != 0 ) fprintf( FpDebug, " Transfer" );
    fprintf(FpDebug, "\n");
}
Here’s What I Got

<table>
<thead>
<tr>
<th>Queue Family</th>
<th>Queue Count</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16</td>
<td>Graphics, Compute, Transfer</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Transfer</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>Compute</td>
</tr>
</tbody>
</table>
Logical Devices
Vulkan: Specifying a Logical Device Queue

```c
float queuePriorities[1] =
{
    1.
};

VkDeviceQueueCreateInfo vdqci;
    vdqci.sType = VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO;
    vdqci.pNext = nullptr;
    vdqci.flags = 0;
    vdqci.queueFamilyIndex = 0;
    vdqci.queueCount = 1;
    vdqci.pQueueProperties = queuePriorities;
```
VkDeviceCreateInfo vdci;
    vdci.sType = VK_STRUCTURE_TYPE_DEVICE_CREATE_INFO;
    vdci.pNext = nullptr;
    vdci.flags = 0;
    vdci.queueCreateInfoCount = 1; // # of device queues
    vdci.pQueueCreateInfos = IN vdqci; // array of VkDeviceQueueCreateInfo's
    vdci.enabledLayerCount = sizeof(myDeviceLayers) / sizeof(char *);
    vdci.enabledLayerCount = 0;
    vdci.ppEnabledLayerNames = myDeviceLayers;
    vdci.enabledExtensionCount = 0;
    vdci.ppEnabledExtensionNames = (const char **)nullptr; // no extensions
    vdci.enabledExtensionCount = sizeof(myDeviceExtensions) / sizeof(char *);
    vdci.ppEnabledExtensionNames = myDeviceExtensions;
    vdci.pEnabledFeatures = IN &PhysicalDeviceFeatures;

    result = vkCreateLogicalDevice( PhysicalDevice, IN &vdci, PALLOCATOR, OUT &LogicalDevice );
// get the queue for this logical device:

vkGetDeviceQueue( LogicalDevice, 0, 0, OUT &Queue );  // 0, 0 = queueFamilyIndex, queueIndex
Layers and Extensions
const char * instanceLayers[ ] =
{
    //"VK_LAYER_LUNARG_api_dump",  // turn this on if want to see each function call and its arguments (very slow!)
    "VK_LAYER_LUNARG_core_validation",
    "VK_LAYER_LUNARG_object_tracker",
    "VK_LAYER_LUNARG_parameter_validation",
    "VK_LAYER_NV_optimus"
};

const char * instanceExtensions[ ] =
{
    "VK_KHR_surface",
    #ifdef _WIN32
        "VK_KHR_win32_surface",
    #endif
    "VK_EXT_debug_report",
};

uint32_t numExtensionsWanted = sizeof(instanceExtensions) / sizeof(char *);

// see what layers are available:

vkEnumerateInstanceLayerProperties( &numLayersAvailable, (VkLayerProperties *)nullptr );
InstanceLayers = new VkLayerProperties[ numLayersAvailable ];
result = vkEnumerateInstanceLayerProperties( &numLayersAvailable, InstanceLayers );

// see what extensions are available:

uint32_t numExtensionsAvailable;
vkEnumerateInstanceExtensionProperties( (char *)nullptr, &numExtensionsAvailable, (VkExtensionProperties *)nullptr );
InstanceExtensions = new VkExtensionProperties[ numExtensionsAvailable ];
result = vkEnumerateInstanceExtensionProperties( (char *)nullptr, &numExtensionsAvailable, InstanceExtensions );
vkEnumerateInstanceLayerProperties:

13 instance layers enumerated:

0x00400033  2 'VK_LAYER_LUNARG_api_dump' 'LunarG debug layer'
0x00400033  1 'VK_LAYER_LUNARG_core_validation' 'LunarG Validation Layer'
0x00400033  1 'VK_LAYER_LUNARG_monitor' 'Execution Monitoring Layer'
0x00400033  1 'VK_LAYER_LUNARG_object_tracker' 'LunarG Validation Layer'
0x00400033  1 'VK_LAYER_LUNARG_parameter_validation' 'LunarG Validation Layer'
0x00400033  1 'VK_LAYER_LUNARG_screenshot' 'LunarG image capture layer'
0x00400033  1 'VK_LAYER_LUNARG_standard_validation' 'LunarG Standard Validation'
0x00400033  1 'VK_LAYER_GOOGLE_threading' 'Google Validation Layer'
0x00400033  1 'VK_LAYER_GOOGLE_unique_objects' 'Google Validation Layer'
0x00400033  1 'VK_LAYER_LUNARG_vktrace' 'Vktrace tracing library'
0x00400038  1 'VK_LAYER_NV_optimus' 'NVIDIA Optimus layer'
0x0040000d  1 'VK_LAYER_NV_nsitg' 'NVIDIA Nsight interception layer'
0x00400000  34 'VK_LAYER_RENDERDOC_Capture' 'Debugging capture layer for RenderDoc'
vkEnumerateInstanceExtensionProperties:

11 extensions enumerated:
0x00000008 'VK_EXT_debug_report'
0x00000001 'VK_EXT_display_surface_counter'
0x00000001 'VK_KHR_get_physical_device_properties2'
0x00000001 'VK_KHR_get_surface_capabilities2'
0x00000019 'VK_KHR_surface'
0x00000006 'VK_KHR_win32_surface'
0x00000001 'VK_KHX_device_group_creation'
0x00000001 'VK_KHR_external_fence_capabilities'
0x00000001 'VK_KHR_external_memory_capabilities'
0x00000001 'VK_KHR_external_semaphore_capabilities'
0x00000001 'VK_NV_external_memory_capabilities'
vkEnumerateDeviceLayerProperties:

3 physical device layers enumerated:
0x00400038 1 'VK_LAYER_NV_optimus' 'NVIDIA Optimus layer'
   0 device extensions enumerated for 'VK_LAYER_NV_optimus':

0x00400033 1 'VK_LAYER_LUNARG_object_tracker' 'LunarG Validation Layer'
   0 device extensions enumerated for 'VK_LAYER_LUNARG_object_tracker':

0x00400033 1 'VK_LAYER_LUNARG_parameter_validation' 'LunarG Validation Layer'
   0 device extensions enumerated for 'VK_LAYER_LUNARG_parameter_validation':
// look for extensions both on the wanted list and the available list:

std::vector<char *> extensionsWantedAndAvailable;
extensionsWantedAndAvailable.clear();
for( uint32_t wanted = 0; wanted < numExtensionsWanted; wanted++ )
{
    for( uint32_t available = 0; available < numExtensionsAvailable; available++ )
    {
        if( strcmp( instanceExtensions[wanted], InstanceExtensions[available].extensionName ) == 0 )
        {
            extensionsWantedAndAvailable.push_back( InstanceExtensions[available].extensionName );
            break;
        }
    }
}

// create the instance, asking for the layers and extensions:

VkInstanceCreateInfo vici;
vici.sType = VK_STRUCTURE_TYPE_INSTANCE_CREATE_INFO;
vici.pNext = nullptr;
vici.flags = 0;
vici.pApplicationInfo = &vai;
vici.enabledLayerCount = sizeof(instanceLayers) / sizeof(char *);
vici.ppEnabledLayerNames = instanceLayers;
vici.enabledExtensionCount = extensionsWantedAndAvailable.size();
vici.ppEnabledExtensionNames = extensionsWantedAndAvailable.data();

result = vkCreateInstance( IN &vici, PALLOCATOR, OUT &Instance );
Will now ask for only 3 instance extensions
  VK_KHR_surface
  VK_KHR_win32_surface
  VK_EXT_debug_report
result = vkEnumeratePhysicalDevices( Instance, OUT &PhysicalDeviceCount, (VkPhysicalDevice *)nullptr);
VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[ PhysicalDeviceCount ];
result = vkEnumeratePhysicalDevices( Instance, OUT &PhysicalDeviceCount, OUT physicalDevices );

int discreteSelect = -1;
int integratedSelect = -1;
for( unsigned int i = 0; i < PhysicalDeviceCount; i++ )
{
    VkPhysicalDeviceProperties vpdp;
vkGetPhysicalDeviceProperties( IN physicalDevices[i], OUT &vpdp );

    // need some logical here to decide which physical device to select:
    if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU )
        discreteSelect = i;
    if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU )
        integratedSelect = i;
}

int which = -1;
if( discreteSelect >= 0 )
{
    which = discreteSelect;
    PhysicalDevice = physicalDevices[which];
}
else if( integratedSelect >= 0 )
{
    which = integratedSelect;
    PhysicalDevice = physicalDevices[which];
}
else
{
    fprintf( FpDebug, "Could not select a Physical Device\n" );
    return VK_SHOULD_EXIT;
}
delete[ ] physicalDevices;
vkGetPhysicalDeviceProperties( PhysicalDevice, OUT &PhysicalDeviceProperties );

vkGetPhysicalDeviceFeatures( IN PhysicalDevice, OUT &PhysicalDeviceFeatures );

vkGetPhysicalDeviceFormatProperties( PhysicalDevice, IN VK_FORMAT_R32G32B32A32_SFLOAT, &vfp );
vkGetPhysicalDeviceFormatProperties( PhysicalDevice, IN VK_FORMAT_R8G8B8A8_UNORM, &vfp );
vkGetPhysicalDeviceFormatProperties( PhysicalDevice, IN VK_FORMAT_B8G8R8A8_UNORM, &vfp );

VkPhysicalDeviceMemoryProperties vpdmp;
vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdmp );

uint32_t count = -1;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *)nullptr );
VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT vqfp );

delete[] vqfp;
VkResult result;
float queuePriorities[NUM_QUEUES_WANTED] =
{
    1.
};

VkDeviceQueueCreateInfo vdqci[NUM_QUEUES_WANTED];
    vdqci[0].sType = VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO;
    vdqci[0].pNext = nullptr;
    vdqci[0].flags = 0;
    vdqci[0].queueFamilyIndex = FindQueueFamilyThatDoesGraphics();
    vdqci[0].queueCount = 1; // how many queues to create
    vdqci[0].pQueuePriorities = queuePriorities; // array of queue priorities [0.,1.]

const char * myDeviceLayers[] =
{
    "VK_LAYER_LUNARG_api_dump",
    "VK_LAYER_LUNARG_core_validation",
    "VK_LAYER_LUNARG_image",
    "VK_LAYER_LUNARG_object_tracker",
    "VK_LAYER_LUNARG_parameter_validation",
    "VK_LAYER_NV_optimus"
};

const char * myDeviceExtensions[] =
{
    "VK_KHR_swapchain",
};
```c
uint32_t layerCount;
vkEnumerateDeviceLayerProperties(PhysicalDevice, &layerCount, (VkLayerProperties *)nullptr);
VkLayerProperties * deviceLayers = new VkLayerProperties[layerCount];
result = vkEnumerateDeviceLayerProperties(PhysicalDevice, &layerCount, deviceLayers);
for (unsigned int i = 0; i < layerCount; i++)
{
    // see what device extensions are available:

    uint32_t extensionCount;
vkEnumerateDeviceExtensionProperties(PhysicalDevice, deviceLayers[i].layerName, &extensionCount,
(VkExtensionProperties *)nullptr);
    VkExtensionProperties * deviceExtensions = new VkExtensionProperties[extensionCount];
    result = vkEnumerateDeviceExtensionProperties(PhysicalDevice, deviceLayers[i].layerName, &extensionCount,
    deviceExtensions);
}

delete[] deviceLayers;
```
4 physical device layers enumerated:
0x00400038 1 'VK_LAYER_NV_optimus' 'NVIDIA Optimus layer'
vkEnumerateDeviceExtensionProperties: Successful
   0 device extensions enumerated for 'VK_LAYER_NV_optimus':

0x00400033 1 'VK_LAYER_LUNARG_core_validation' 'LunarG Validation Layer'
vkEnumerateDeviceExtensionProperties: Successful
   0 device extensions enumerated for 'VK_LAYER_LUNARG_core_validation':

0x00400033 1 'VK_LAYER_LUNARG_object_tracker' 'LunarG Validation Layer'
vkEnumerateDeviceExtensionProperties: Successful
   0 device extensions enumerated for 'VK_LAYER_LUNARG_object_tracker':

0x00400033 1 'VK_LAYER_LUNARG_parameter_validation' 'LunarG Validation Layer'
vkEnumerateDeviceExtensionProperties: Successful
   0 device extensions enumerated for 'VK_LAYER_LUNARG_parameter_validation':
Synchronization
Vulkan Highlights: Overall Block Diagram
• Used to control readiness of resources within one queue or across different queues belonging to the same logical device

• You create them, and give them to a Vulkan function which sets them. Later on, you tell a Vulkan function to wait on this particular semaphore

• You don’t end up setting, resetting, or checking the semaphore yourself

• Semaphores must be initialized ("created") before they can be used
Creating a Semaphore

```
VkSemaphoreCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;

VkSemaphore semaphore;
result = vkCreateSemaphore(LogicalDevice, IN &vsci, PALLOCATOR, OUT &semaphore);
```
Semaphores Example during the Render Loop

```
VkSemaphore imageReadySemaphore;

VkSemaphoreCreateInfo vsci;
    vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
    vsci.pNext = nullptr;
    vsci.flags = 0;

result = vkCreateSemaphore( LogicalDevice, IN &vsci, PALLOCATOR, OUT &imageReadySemaphore );

uint32_t nextImageIndex;
vkAcquireNextImageKHR( LogicalDevice, IN SwapChain, IN UINT64_MAX,
                        IN imageReadySemaphore, IN VK_NULL_HANDLE, OUT &nextImageIndex );

    VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;
    VkSubmitInfo vsi;
        vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
        vsi.pNext = nullptr;
        vsi.waitSemaphoreCount = 1;
        vsi.pWaitSemaphores = &imageReadySemaphore;
        vsi.pWaitDstStageMask = &waitAtBottom;
        vsi.commandBufferCount = 1;
        vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
        vsi.signalSemaphoreCount = 0;
        vsi.pSignalSemaphores = (VkSemaphore) nullptr;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence );
```
Fences

- Used to synchronize the application with commands submitted to a queue
- Announces that queue-submitted work is finished
- Much finer control than semaphores
- You can un-signal, signal, test or block-while-waiting
Fences

```c
#define VK_FENCE_CREATE_UNSIGNALED_BIT 0

VkFenceCreateInfo vfci;
    vfci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;
    vfci.pNext = nullptr;
    vfci.flags = VK_FENCE_CREATE_UNSIGNALED_BIT; // = 0
        // VK_FENCE_CREATE_SIGNALED_BIT is only other option

VkFence fence;
result = vkCreateFence( LogicalDevice, IN &vfci, PALLOCATOR, OUT &fence );

// returns right away:
result = vkGetFenceStatus( LogicalDevice, IN fence );
    // result = VK_SUCCESS means it has signaled
    // result = VK_NOT_READY means it has not signaled

// blocks:
result = vkWaitForFences( LogicalDevice, 1, IN &fence, waitForAll, timeout );
    // waitForAll = VK_TRUE: wait for all fences in the list
    // waitForAll = VK_FALSE: wait for any one fence in the list
    // timeout is a uint64_t timeout in nanoseconds (could be 0, which means to return immediately)
    // timeout can be up to UINT64_MAX = 0xffffffffffffffff (= 580+ years)
    // result = VK_SUCCESS means it returned because a fence (or all fences) signaled
    // result = VK_TIMEOUT means it returned because the timeout was exceeded

Could be an array of fences
```
Fence Example

```
VkFence renderFence;
vkCreateFence( LogicalDevice, &vfci, PALLOCATOR, OUT &renderFence);

VkPipelineStageFlags waitAtBottom = VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT;

VkQueue presentQueue;
vkGetDeviceQueue( LogicalDevice, FindQueueFamilyThatDoesGraphics( ), 0, OUT &presentQueue);

VkSubmitInfo vsi;
    vsi.sType = VK_STRUCTURE_TYPE_SUBMIT_INFO;
    vsi.pNext = nullptr;
    vsi.waitSemaphoreCount = 1;
    vsi.pWaitSemaphores = &imageReadySemaphore;
    vsi.pWaitDstStageMask = &waitAtBottom;
    vsi.commandBufferCount = 1;
    vsi.pCommandBuffers = &CommandBuffers[nextImageIndex];
    vsi.signalSemaphoreCount = 0;
    vsi.pSignalSemaphores = (VkSemaphore) nullptr;

result = vkQueueSubmit( presentQueue, 1, IN &vsi, IN renderFence );
    ...

result = vkWaitForFences( LogicalDevice, 1, IN &renderFence, VK_TRUE, UINT64_MAX );
    ...

result = vkQueuePresentKHR( presentQueue, IN &vpi );
```
• Events provide even finer-grained synchronization

• Events are a primitive that can be signaled by the host or the device

• Can even signal at one place in the pipeline and wait for it at another place in the pipeline

• Signaling in the pipeline means “signal as the last piece of this draw command passes that point in the pipeline”.

• You can signal, un-signal, or test from a vk function or from a vkCmd function

• Can wait from a vkCmd function
Controlling Events from the Host

VkEventCreateInfo veci;
veci.sType = VK_STRUCTURE_TYPE_EVENT_CREATE_INFO;
veci.pNext = nullptr;
veci.flags = 0;

VkEvent event;
result = vkCreateEvent( LogicalDevice, IN &veci, PALLOCATOR, OUT &event);
result = vkSetEvent( LogicalDevice, IN event);
result = vkResetEvent( LogicalDevice, IN event);
result = vkGetEventStatus( LogicalDevice, IN event);
// result = VK_EVENT_SET: signaled
// result = VK_EVENT_RESET: not signaled

Note: the host cannot block waiting for an event, but it can test
Controlling Events from the Device

result = vkCmdSetEvent( CommandBuffer, IN event, pipelineStageBits );
result = vkCmdResetEvent( CommandBuffer, IN event, pipelineStageBits );
result = vkCmdWaitEvents( CommandBuffer, 1, &event,
srcPipelineStageBits, dstPipelineStageBits,
memoryBarrierCount, pMemoryBarriers,
bufferMemoryBarrierCount, pBufferMemoryBarriers,
imageMemoryBarrierCount, pImageMemoryBarriers );

Note: the device cannot test for an event, but it can block
Pipeline Barriers
From the Command Buffer Notes:
These are the Commands that could be entered into the Command Buffer, I

vkCmdBeginQuery( commandBuffer, flags );
vkCmdBeginRenderPass( commandBuffer, const contents );
vkCmdBindDescriptorSets( commandBuffer, pDynamicOffsets );
vkCmdBindIndexBuffer( commandBuffer, indexType );
vkCmdBindPipeline( commandBuffer, pipeline );
vkCmdBindVertexBuffers( commandBuffer, firstBinding, bindingCount, const pOffsets );
vkCmdBlitImage( commandBuffer, filter );
vkCmdClearAttachments( commandBuffer, attachmentCount, const pRects );
vkCmdClearColorImage( commandBuffer, pRanges );
vkCmdClearDepthStencilImage( commandBuffer, pRanges );
vkCmdCopyBuffer( commandBuffer, pRegions );
vkCmdCopyBufferToImage( commandBuffer, pRanges );
vkCmdCopyImage( commandBuffer, pRegions );
vkCmdCopyImageToBuffer( commandBuffer, pRegions );
vkCmdCopyQueryPoolResults( commandBuffer, flags );
vkCmdDebugMarkerBeginEXT( commandBuffer, pMarkerInfo );
vkCmdDebugMarkerEndEXT( commandBuffer );
vkCmdDebugMarkerInsertEXT( commandBuffer, pMarkerInfo );
vvkCmdDispatch( commandBuffer, groupCountX, groupCountY, groupCountZ );
vkCmdDispatchIndirect( commandBuffer, offset );
vkCmdDraw( commandBuffer, vertexCount, instanceCount, firstVertex, firstInstance );
vkCmdDrawIndexed( commandBuffer, indexCount, instanceCount, firstIndex, int32_t vertexOffset, firstInstance );
vkCmdDrawIndexedIndirect( commandBuffer, stride );
vkCmdDrawIndexedIndirectCountAMD( commandBuffer, stride );
vkCmdDrawIndirect( commandBuffer, stride );
vkCmdDrawIndirectCountAMD( commandBuffer, stride );
vkCmdEndQuery( commandBuffer, query );
vkCmdEndRenderPass( commandBuffer );
vkCmdExecuteCommands( commandBuffer, commandBufferCount, const pCommandBuffers );
From the Command Buffer Notes:
These are the Commands that could be entered into the Command Buffer, II

vkCmdFillBuffer( commandBuffer, dstBuffer, dstOffset, size, data );
vkCmdNextSubpass( commandBuffer, contents );
vkCmdPipelineBarrier( commandBuffer, srcStageMask, dstStageMask, dependencyFlags, memoryBarrierCount, VkMemoryBarrier* pMemoryBarriers, bufferMemoryBarrierCount, pBufferSizeMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdProcessCommandsNVX( commandBuffer, pProcessCommandsInfo );
vkCmdPushConstants( commandBuffer, layout, stageFlags, offset, size, pValues );
vkCmdPushDescriptorSetKHR( commandBuffer, pipelineBindPoint, layout, set, descriptorWriteCount, pDescriptorWrites );
vkCmdPushDescriptorSetWithTemplateKHR( commandBuffer, descriptorUpdateTemplate, layout, set, pData );
vkCmdReserveSpaceForCommandsNVX( commandBuffer, pReserveSpaceInfo );
vkCmdResetEvent( commandBuffer, event, stageMask );
vkCmdResetQueryPool( commandBuffer, queryPool, firstQuery, queryCount );
vkCmdResolveImage( commandBuffer, srcImage, srcImageLayout, dstImage, dstImageLayout, regionCount, pRegions );
vkCmdSetBlendConstants( commandBuffer, blendConstants[4] );
vkCmdSetDepthBias( commandBuffer, depthBiasConstantFactor, depthBiasClamp, depthBiasSlopeFactor );
vkCmdSetDepthBounds( commandBuffer, minDepthBounds, maxDepthBounds );
vkCmdSetDeviceMaskKHX( commandBuffer, deviceMask );
vkCmdSetDiscardRectangleEXT( commandBuffer, firstDiscardRectangle, discardRectangleCount, pDiscardRectangles );
vkCmdSetEvent( commandBuffer, event, stageMask );
vkCmdSetLineWidth( commandBuffer, lineWidth );
vkCmdSetScissor( commandBuffer, firstScissor, scissorCount, pScissors );
vkCmdSetStencilCompareMask( commandBuffer, faceMask, compareMask );
vkCmdSetStencilReference( commandBuffer, faceMask, reference );
vkCmdSetStencilWriteMask( commandBuffer, faceMask, writeMask );
vkCmdSetViewport( commandBuffer, firstViewport, viewportCount, pViewports );
vkCmdSetViewportWScalingNV( commandBuffer, firstViewport, viewportCount, pViewportWScaleings );
vkCmdUpdateBuffer( commandBuffer, dstBuffer, dstOffset, dataSize, pData );
vkCmdWaitEvents( commandBuffer, eventCount, pEvents, srcStageMask, dstStageMask, memoryBarrierCount, pMemoryBarriers, bufferMemoryBarrierCount, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdWriteTimestamp( commandBuffer, pipelineStage, queryPool, query );

We want all of these commands to be able to run “flat-out”, but, if we do that, surely there will be race conditions!
Potential Memory Race Conditions that Pipeline Barriers can Prevent

1. Write-then-Read (WtR) – the memory write in one operation starts overwriting the memory that another operation’s read needs to use

2. Read-then-Write (RtW) – the memory read in one operation hasn’t yet finished before another operation starts overwriting that memory

3. Write-then-Write (WtW) – two operations start overwriting the same memory and the end result is non-deterministic

Note: there is no problem with Read-then-Read (RtR) as no data has been changed
vkCmdPipelineBarrier( ) Function Call

A Pipeline Barrier is a way to establish a memory dependency between commands that were submitted before the barrier and commands that are submitted after the barrier.

```c
vkCmdPipelineBarrier( commandBuffer,
    srcStageMask, dstStageMask,
    VK_DEPENDENCY_BY_REGION_BIT,
    memoryBarrierCount, pMemoryBarriers,
    bufferMemoryBarrierCount, pBufferMemoryBarriers,
    imageMemoryBarrierCount, pImageMemoryBarriers
);
```

- `srcStageMask`: Guarantee that this pipeline stage has completely finished with one set of data before ...
- `dstStageMask`: … allowing this pipeline stage to proceed with the next set of data
- `VK_DEPENDENCY_BY_REGION_BIT`: Defines what data we will be blocking/un-blocking on
1. The cross-streets are named after pipeline stages
2. All traffic lights start out green ("we want all of these commands to be able to run flat-out")
3. There are special sensors at all intersections that will know when the first car in the src group enters that intersection
4. There are connections from those sensors to the traffic lights so that when the first car in the src group enters its intersection, the dst traffic light will be turned red
5. When the last car in the src group completely makes it through its intersection, the dst traffic light can be turned back to green
6. The Vulkan command pipeline ordering is this: (1) the src cars get released, (2) the pipeline barrier is invoked (which turns some lights red), (3) the dst cars get released (which end up being stopped by a red light somewhere)
Pipeline Stage Flags –
Where in the Pipeline is this Memory being Accessed?

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_COMPUTE_SHADER_BIT
VK_PIPELINE_STAGE_TRANSFER_BIT
VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT
VK_PIPELINE_STAGE_HOST_BIT
VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

Note: the concept of an in-order pipeline is accurate, but really the src and dst triggering action only depends on the name of the street where you are right now.
Pipeline Stages

- 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_COMPUTE_SHADER_BIT
- VK_PIPELINE_STAGE_TRANSFER_BIT
- VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT
- VK_PIPELINE_STAGE_HOST_BIT
- VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT
- VK_PIPELINE_STAGE_ALL_COMMANDS_BIT

Diagram:
- Vertex Shader
  - Primitive Assembly
  - Tessellation Control Shader
    - Tessellation Primitive Generator
    - Tessellation Evaluation Shader
    - Primitive Assembly
  - Geometry Shader
    - Primitive Assembly
    - Rasterizer
    - Fragment Shader
Access Masks –
What are you Interested in Generating or Consuming this Memory for?

| VK_ACCESS_INDIRECT_COMMAND_READ_BIT |
| VK_ACCESS_INDEX_READ_BIT |
| VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT |
| VK_ACCESS_UNIFORM_READ_BIT |
| VK_ACCESS_INPUT_ATTACHMENT_READ_BIT |
| VK_ACCESS_SHADER_READ_BIT |
| VK_ACCESS_SHADER_WRITE_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 |
| VK_ACCESS_TRANSFER_READ_BIT |
| VK_ACCESS_TRANSFER_WRITE_BIT |
| VK_ACCESS_HOST_READ_BIT |
| VK_ACCESS_HOST_WRITE_BIT |
| VK_ACCESS_MEMORY_READ_BIT |
| VK_ACCESS_MEMORY_WRITE_BIT |
### Pipeline Stages and what Access Operations can Happen There

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<thead>
<tr>
<th>Pipeline Stage</th>
<th>Access Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT</td>
<td>VK_ACCESS_COMMAND_READ_BIT</td>
</tr>
<tr>
<td>2. VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT</td>
<td>VK_ACCESS_INDEX_READ_BIT, VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT</td>
</tr>
<tr>
<td>3. VK_PIPELINE_STAGE_VERTEX_INPUT_BIT</td>
<td>VK_ACCESS_UNIFORM_READ_BIT, VK_ACCESS_INDEX_READ_BIT</td>
</tr>
<tr>
<td>4. VK_PIPELINE_STAGE_VERTEX_SHADER_BIT</td>
<td>VK_ACCESS_INPUT_ATTACHMENT_READ_BIT, VK_ACCESS_SHADER_READ_BIT</td>
</tr>
<tr>
<td>5. VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT</td>
<td>VK_ACCESS_SHADER_WRITE_BIT</td>
</tr>
<tr>
<td>6. VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</td>
<td>VK_ACCESS_COLOR_ATTACHMENT_READ_BIT, VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT</td>
</tr>
<tr>
<td>7. VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</td>
<td>VK_ACCESSTRANSFER_READ_BIT, VK_ACCESS_HOST_READ_BIT, VK_ACCESS_MEMORY_READ_BIT</td>
</tr>
<tr>
<td>8. VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT</td>
<td>VK_ACCESSTRANSFER_WRITE_BIT, VK_ACCESS_HOST_WRITE_BIT, VK_ACCESS_MEMORY_WRITE_BIT</td>
</tr>
<tr>
<td>9. VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT</td>
<td>VK_ACCESSTRANSFER_READ_BIT, VK_ACCESS_HOST_READ_BIT, VK_ACCESS_MEMORY_READ_BIT</td>
</tr>
<tr>
<td>10. VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT</td>
<td>VK_ACCESSTRANSFER_WRITE_BIT, VK_ACCESS_HOST_WRITE_BIT, VK_ACCESS_MEMORY_WRITE_BIT</td>
</tr>
<tr>
<td>11. VK_PIPELINE_STAGE_COMPUTE_SHADER</td>
<td>VK_ACCESS_HOST_READ_BIT</td>
</tr>
<tr>
<td>12. VK_PIPELINE_STAGE_TRANSFER_BIT</td>
<td>VK_ACCESS_HOST_WRITE_BIT</td>
</tr>
</tbody>
</table>

*Note: The table above illustrates the access operations that can occur during each pipeline stage.*
### Access Operations and what Pipeline Stages they can be used In

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<tr>
<th>Access Operation</th>
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<th>11</th>
<th>12</th>
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<tbody>
<tr>
<td>VK_ACCESS_INDIRECT_COMMAND_READ_BIT</td>
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<tr>
<td>VK_ACCESS_INDEX_READ_BIT</td>
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<td>VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT</td>
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<td>VK_ACCESS_UNIFORM_READ_BIT</td>
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<td>VK_ACCESS_INPUT_ATTACHMENT_READ_BIT</td>
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<td>VK_ACCESS_SHADER_READ_BIT</td>
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<td>VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_READ_BIT</td>
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</table>

- ● Indicates the access operation can be used in that pipeline stage.
Example: Be sure we are done writing an output image before using it for something else

<table>
<thead>
<tr>
<th>Stages</th>
</tr>
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<tbody>
<tr>
<td>VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_VERTEX_INPUT_BIT</td>
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<td>VK_PIPELINE_STAGE_VERTEX_SHADER_BIT</td>
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<td>VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT</td>
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<td>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT</td>
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<tr>
<td><strong>VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT</strong></td>
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<tr>
<td>VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_HOST_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_ALL_COMMANDS_BIT</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Access types</th>
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<tr>
<td>VK_ACCESS_INDIRECT_COMMAND_READ_BIT</td>
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<tr>
<td>VK_ACCESS_INDEX_READ_BIT</td>
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<td>VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT</td>
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<td>VK_ACCESS_UNIFORM_READ_BIT</td>
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<td>VK_ACCESS_INPUT_ATTACHMENT_READ_BIT</td>
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<td><strong>VK_ACCESS_SHADER_READ_BIT</strong></td>
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<td>VK_ACCESS_MEMORY_READ_BIT</td>
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<td>VK_ACCESS_MEMORY_WRITE_BIT</td>
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</tbody>
</table>

**src**

**dst** (no access setting needed)
src cars are generating the image

dst cars are doing something with that image
Push Constants
In an effort to expand flexibility and retain efficiency, Vulkan provides something called **Push Constants**. Like the name implies, these let you “push” constant values out to the shaders. These are typically used for small, frequently-updated data values. This is good, since Vulkan, at times, makes it cumbersome to send changes to the graphics.

By “small”, Vulkan specifies that these must be at least 128 bytes in size, although they can be larger. For example, the maximum size is 256 bytes on the NVIDIA 1080ti. (You can query this limit by looking at the `maxPushConstantSize` parameter in the `VkPhysicalDeviceLimits` structure.) Unlike uniform buffers and vertex buffers, these are not backed by memory. They are actually part of the Vulkan pipeline.
Push Constants

On the shader side, if, for example, you are sending a 4x4 matrix, the use of push constants in the shader looks like this:

```cpp
layout( push_constant ) uniform matrix
{
    mat4 modelMatrix;
} Matrix;
```

On the application side, push constants are pushed at the shaders by binding them to the Vulkan Command Buffer:

```cpp
vkCmdPushConstants( CommandBuffer, PipelineLayout, stageFlags,
offset, size, pValues );
```

where:

- `stageFlags` are or’ed bits of `VK_PIPELINE_STAGE_VERTEX_SHADER_BIT`, `VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT`, etc.
- `size` is in bytes
- `pValues` is a void * pointer to the data, which in this 4x4 matrix example, would be of type `glm::mat4`.
Prior to that, however, the pipeline layout needs to be told about the Push Constants:

```
VkPushConstantRange vpcr[1];

vpcr[0].stageFlags =
    VK_PIPELINE_STAGE_VERTEX_SHADER_BIT |
    VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
vpcr[0].offset = 0;
vpcr[0].size = sizeof(glm::mat4);

VkPipelineLayoutCreateInfo vplci;

vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;

vplci.pNext = nullptr;
vplci.flags = 0;
vplci.setLayoutCount = 4;

vplci.pSetLayouts = DescriptorSetLayouts;

vplci.pushConstantRangeCount = 1;

vplci.pPushConstantRanges = vpcr;

result = vkCreatePipelineLayout(LogicalDevice, IN &vplci, PALLOCATOR,
    OUT &GraphicsPipelineLayout);
```
Creating a Pipeline

vkCreatePipelineLayout( )

Descriptors
- VkPipelineShaderStageCreateInfo
  - VkSpecializationInfo
    - which stage (VERTEX, etc.)
  - VkShaderModule
  - VkPipelineShaderStageCreateInfo

State Configurations
- VkPipelineVertexInputStateCreateInfo
  - VkVertexInputBindingDescription
    - binding
    - stride
    - inputRate
    - location
    - format
    - offset
  - VkVertexInputAttributeDescription
    - binding
    - stride
    - inputRate
    - location

- VkViewportStateCreateInfo
  - Viewport
    - x, y, w, h
    - minDepth
    - maxDepth
  - Scissor
    - offset
    - extent
  - Topology

- VkPipelineRasterizationStateCreateInfo
  - Cull Mode
  - Polygon Mode
  - Front Face
  - Line Width

- VkPipelineDepthStencilStateCreateInfo
  - Depth Test Enable
  - Depth Write Enable
  - Depth Compare Op
  - Stencil Test Enable
  - Stencil Op State Front
  - Stencil Op State Back

- VkPipelineColorBlendStateCreateInfo
  - Blend Enable
  - Source Color Blend Factor
  - Destination Color Blend Factor
  - Color Blend Op
  - Source Alpha Blend Factor
  - Destination Alpha Blend Factor
  - Alpha Blend Op
  - Color Write Mask

- VkPipelineDynamicStateCreateInfo
  - Array naming the states that can be set dynamically

Graphical Pipeline

vkCreateGraphicsPipeline( )

VkGraphicsPipelineCreateInfo

VkPipelineLayoutCreateInfo

Push Constants

Descriptor Set Layouts

Debugging and Profiling

VkPipelineColorBlendAttachmentState

Pipeline Creation

Graphics Pipeline
An Robotic Example using Push Constants

A robotic animation (i.e., a hierarchical transformation system)

Where each arm is represented by:

```cpp
struct arm
{
    glm::mat4 armMatrix;
    glm::vec3 armColor;
    float armScale; // scale factor in x
};

struct armArm1;
struct armArm2;
struct armArm3;
```
In the Reset Function

```cpp
struct arm          Arm1;
struct arm          Arm2;
struct arm          Arm3;

Arm1.armMatrix = glm::mat4();
Arm1.armColor  = glm::vec3( 0.f, 1.f, 0.f );
Arm1.armScale  = 6.f;

Arm2.armMatrix = glm::mat4();
Arm2.armColor  = glm::vec3( 1.f, 0.f, 0.f );
Arm2.armScale  = 4.f;

Arm3.armMatrix = glm::mat4();
Arm3.armColor  = glm::vec3( 0.f, 0.f, 1.f );
Arm3.armScale  = 2.f;
```

The constructor `glm::mat4()` produces an identity matrix. The actual transformation matrices will be set in `UpdateScene()`.
Setup the Push Constant for the Pipeline Structure

```c
VkPushConstantRange vpcr[1];

vpcr[0].stageFlags =
    VK_PIPELINE_STAGE_VERTEX_SHADER_BIT |
    VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;

vpcr[0].offset = 0;
vpcr[0].size = sizeof( struct arm );

VkPipelineLayoutCreateInfo vplci;

vplci.sType =
    VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;

vplci.pNext = nullptr;
vplci.flags = 0;
vplci.setLayoutCount = 4;
vplci.pSetLayouts = DescriptorSetLayouts;
vplci.pushConstantRangeCount = 1;
vplci.pPushConstantRanges = vpcr;

result = vkCreatePipelineLayout( LogicalDevice, IN &vplci,
                                 PALLOCATOR,
                                 OUT &GraphicsPipelineLayout );
```
In the UpdateScene Function

\[
\begin{align*}
\text{float rot1} &= (\text{float})\text{Time}; \\
\text{float rot2} &= 2.f \times \text{rot1}; \\
\text{float rot3} &= 2.f \times \text{rot2}; \\
\text{glm::vec3 zaxis} &= \text{glm::vec3}(0., 0., 1.); \\
\text{glm::mat4 m1g} &= \text{glm::mat4}(); \\
\text{m1g} &= \text{glm::translate(m1g, glm::vec3(0., 0., 0.))}; \\
\text{m1g} &= \text{glm::rotate(m1g, rot1, zaxis)}; \\
\text{glm::mat4 m21} &= \text{glm::mat4}(); \\
\text{m21} &= \text{glm::translate(m21, glm::vec3(2.*Arm1.armScale, 0., 0.))}; \\
\text{m21} &= \text{glm::rotate(m21, rot2, zaxis)}; \\
\text{m21} &= \text{glm::translate(m21, glm::vec3(0., 0., 2.))}; \\
\text{glm::mat4 m32} &= \text{glm::mat4}(); \\
\text{m32} &= \text{glm::translate(m32, glm::vec3(2.*Arm2.armScale, 0., 0.))}; \\
\text{m32} &= \text{glm::rotate(m32, rot3, zaxis)}; \\
\text{m32} &= \text{glm::translate(m32, glm::vec3(0., 0., 2.))}; \\
\text{Arm1.armMatrix} &= \text{m1g} \quad // \text{m1g} \\
\text{Arm2.armMatrix} &= \text{m1g} \times \text{m21}; \quad // \text{m2g} \\
\text{Arm3.armMatrix} &= \text{m1g} \times \text{m21} \times \text{m32}; \quad // \text{m3g}
\end{align*}
\]
In the `RenderScene` Function

```c
VkBuffer buffers[1] = { MyVertexDataBuffer.buffer };

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, buffers, offsets );

vkCmdPushConstants( CommandBuffers[nextImageIndex], GraphicsPipelineLayout,
    VK_SHADER_STAGE_ALL, 0, sizeof(struct arm), (void *)&Arm1 );
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );

vkCmdPushConstants( CommandBuffers[nextImageIndex], GraphicsPipelineLayout,
    VK_SHADER_STAGE_ALL, 0, sizeof(struct arm), (void *)&Arm2 );
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );

vkCmdPushConstants( CommandBuffers[nextImageIndex], GraphicsPipelineLayout,
    VK_SHADER_STAGE_ALL, 0, sizeof(struct arm), (void *)&Arm3 );
vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );
```
In the Vertex Shader

```glsl
layout( push_constant ) uniform arm
{
  mat4  armMatrix;
  vec3  armColor;
  float armScale;  // scale factor in x
}
RobotArm;

layout( location = 0 ) in vec3 aVertex;

  ...  

vec3 bVertex = aVertex;  // arm coordinate system is [-1., 1.] in X
bVertex.x += 1.;  // now is [0., 2.]
bVertex.x /= 2.;  // now is [0., 1.]
bVertex.x *= (RobotArm.armScale );  // now is [0., RobotArm.armScale]
bVertex = vec3( RobotArm.armMatrix * vec4( bVertex, 1. ) );
  ...

gl_Position = PVM * vec4( bVertex, 1. );  // Projection * Viewing * Modeling matrices
```
Antialiasing and Multisampling
Multisampling is a computer graphics technique to improve the quality of your output image by looking inside every pixel to see what the rendering is doing there.

There are two approaches to this:

1. **Supersampling**: Pick some number of unique points within a pixel, render the image into each of these sub-pixels (including depth and stencil tests), then average them together.

2. **Multisampling**: Pick some number of unique points within each pixel and perform a depth and stencil render there. Then, perform a single color render for that pixel. Assign that RGBA to all the sub-pixels that made it through the depth and stencil tests.
Vulkan Distribution of Sampling Points within a Pixel
Consider Two Triangles Whose Edges Pass Through the Same Pixel
Supersampling

Final Pixel Color = \frac{\sum_{i=1}^{8} \text{Color sample from subpixel}_i}{8}

# Fragment Shader calls = 8
Multisampling

\[
\text{Final Pixel Color} = \frac{3 \times \text{One color sample from A} + 5 \times \text{One color sample from B}}{8}
\]

# Fragment Shader calls = 2
VkPipelineMultisampleStateCreateInfo  vpmsci;
    vpmsci.sType = VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO;
    vpmsci.pNext = nullptr;
    vpmsci.flags = 0;
    vpmsci.rasterizationSamples = VK_SAMPLE_COUNT_8_BIT;
    vpmsci.sampleShadingEnable = VK_TRUE;
    vpmsci.minSampleShading = 0.5f;
    vpmsci.pSampleMask = (VkSampleMask *)nullptr;
    vpmsci.alphaToCoverageEnable = VK_FALSE;
    vpmsci.alphaToOneEnable = VK_FALSE;

VkGraphicsPipelineCreateInfo  vgpci;
    vgpci.sType = VK_STRUCTURE_TYPE_GRAPHICS_PIPELINE_CREATE_INFO;
    vgpci.pNext = nullptr;
    . . .
    vgpci.pMultisampleState = &vpmsci;

result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN &vgpci,
PALLOCATOR, OUT pGraphicsPipeline );
Setting up the Image

VkPipelineMultisampleStateCreateInfo vpmsci;

...  

vpmsci.minSampleShading = 0.5;

...

**At least** this fraction of samples will get their own fragment shader calls (as long as they pass the depth and stencil tests).

- 0. produces simple multisampling
- (0.,1.) produces partial supersampling
- 1. Produces complete supersampling
Setting up the Image

```c
VkAttachmentDescription vad[2];
    vad[0].format = VK_FORMAT_B8G8R8A8_SRGB;
    vad[0].samples = VK_SAMPLE_COUNT_8_BIT;
    vad[0].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
    vad[0].storeOp = VK_ATTACHMENT_STORE_OP_STORE;
    vad[0].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
    vad[0].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
    vad[0].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
    vad[0].finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR;
    vad[0].flags = 0;

    vad[1].format = VK_FORMAT_D32_SFLOAT_S8_UINT;
    vad[1].samples = VK_SAMPLE_COUNT_8_BIT;
    vad[1].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
    vad[1].storeOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
    vad[1].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
    vad[1].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
    vad[1].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
    vad[1].finalLayout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;
    vad[1].flags = 0;

VkAttachmentReference colorReference;
    colorReference.attachment = 0;
    colorReference.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

VkAttachmentReference depthReference;
    depthReference.attachment = 1;
    depthReference.layout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;
```

`Setting up the Image`
Setting up the Image

```c
VkSubpassDescription vsd;
    vsd.flags = 0;
    vsd.pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
    vsd.inputAttachmentCount = 0;
    vsd.pInputAttachments = (VkAttachmentReference *)nullptr;
    vsd.colorAttachmentCount = 1;
    vsd.pColorAttachments = &colorReference;
    vsd.pResolveAttachments = (VkAttachmentReference *)nullptr;
    vsd.pDepthStencilAttachment = &depthReference;
    vsd.preserveAttachmentCount = 0;
    vsd.pPreserveAttachments = (uint32_t *)nullptr;

VkRenderPassCreateInfo vrpci;
    vrpci.sType = VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO;
    vrpci.pNext = nullptr;
    vrpci.flags = 0;
    vrpci.attachmentCount = 2; // color and depth/stencil
    vrpci.pAttachments = vad;
    vrpci.subpassCount = 1;
    vrpci.pSubpasses = &vsd;
    vrpci.dependencyCount = 0;
    vrpci.pDependencies = (VkSubpassDependency *)nullptr;

result = vkCreateRenderPass( LogicalDevice, IN &vrpci, PALLOCATOR, OUT &RenderPass );
```
Resolving the Image:
Converting the multisampled image to a VK_SAMPLE_COUNT_1_BIT image

```c
VLOffset3D vo3;
    vo3.x = 0;
    vo3.y = 0;
    vo3.z = 0;

VkExtent3D ve3;
    ve3.width = Width;
    ve3.height = Height;
    ve3.depth = 1;

VkImageSubresourceLayers visl;
    visl.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
    visl.mipLevel = 0;
    visl.baseArrayLayer = 0;
    visl.layerCount = 1;

VkImageResolve vir;
    vir.srcSubresource = visl;
    vir.srcOffset = vo3;
    vir.dstSubresource = visl;
    vir.dstOffset = vo3;
    vir.extent = ve3;

vkCmdResolveImage( cmdBuffer, srcImage, srcImageLayout, dstImage, dstImageLayout, 1, &vir );
```
Multipass Rendering
Multipass Rendering uses Attachments -- What is a Vulkan Attachment Anyway?

“[An attachment is] an image associated with a renderpass that can be used as the input or output of one or more of its subpasses.”

-- Vulkan Programming Guide

An attachment can be written to, read from, or both.

For example:
So far, we've only performed single-pass rendering, within a single Vulkan RenderPass.
So far, we’ve only performed single-pass rendering, but within a single Vulkan RenderPass, we can also have several subpasses, each of which is feeding information to the next subpass or subpasses.

In this case, we will look at following up a 3D rendering with some image processing on the outcome.
Multipass Algorithm to Render and then Image Process

Original

Sharpened

Edge Detected

No Noise

Noise
VkAttachmentDescription
    vad[3];
    vad[0].flags = 0;
vad[0].format = VK_FORMAT_B8G8R8A8_SRGB;
vad[0].samples = VK_SAMPLE_COUNT_1_BIT;
vad[0].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
vad[0].storeOp = VK_ATTACHMENT_STORE_OP_STORE;
vad[0].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
vad[0].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
vad[0].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
vad[0].finalLayout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

    vad[1].flags = 0;
vad[1].format = VK_FORMAT_D32_SFLOAT_S8_UINT;
vad[1].samples = VK_SAMPLE_COUNT_1_BIT;
vad[1].loadOp = VK_ATTACHMENT_LOAD_OP_CLEAR;
vad[1].storeOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
vad[1].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
vad[1].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
vad[1].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
vad[1].finalLayout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;

    vad[2].flags = 0;
vad[2].format = VK_FORMAT_B8G8R8A8_SRGB;
vad[2].samples = VK_SAMPLE_COUNT_1_BIT;
vad[2].loadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
vad[2].storeOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
vad[2].stencilLoadOp = VK_ATTACHMENT_LOAD_OP_DONT_CARE;
vad[2].stencilStoreOp = VK_ATTACHMENT_STORE_OP_DONT_CARE;
vad[2].initialLayout = VK_IMAGE_LAYOUT_UNDEFINED;
vad[2].finalLayout = VK_IMAGE_LAYOUT_PRESENT_SRC_KHR;
Multipass, II

VkAttachmentReference colorReference;
colorReference.attachment = 0;
colorReference.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;

VkAttachmentReference depthReference;
depthReference.attachment = 1;
depthReference.layout = VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL;

VkAttachmentReference outputReference;
outputReference.attachment = 2;
outputReference.layout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;
VkSubpassDescription vsd[2];
    vsd[0].flags = 0;
    vsd[0].pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
    vsd[0].inputAttachmentCount = 0;
    vsd[0].pInputAttachments = (VkAttachmentReference *)nullptr;
    vsd[0].colorAttachmentCount = 1;
    vsd[0].pColorAttachments = colorReference;
    vsd[0].pResolveAttachments = (VkAttachmentReference *)nullptr;
    vsd[0].pDepthStencilAttachment = &depthReference;
    vsd[0].preserveAttachmentCount = 0;
    vsd[0].pPreserveAttachments = (uint32_t *) nullptr;
    vsd[1].flags = 0;
    vsd[1].pipelineBindPoint = VK_PIPELINE_BIND_POINT_GRAPHICS;
    vsd[1].inputAttachmentCount = 1;
    vsd[1].pInputAttachments = colorReference;
    vsd[1].colorAttachmentCount = 1;
    vsd[1].pColorAttachments = &outputReference;
    vsd[1].pResolveAttachments = (VkAttachmentReference *)nullptr;
    vsd[1].pDepthStencilAttachment = (VkAttachmentReference *) nullptr;
    vsd[1].preserveAttachmentCount = 0;
    vsd[1].pPreserveAttachments = (uint32_t *) nullptr;
VkSubpassDependency vsdp[1];
vsdp[0].srcSubpass = 0; // 3D rendering
vsdp[0].dstSubpass = 1; // image processing
vsdp[0].srcStageMask = VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT;
vsdp[0].dstStageMask = VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
vsdp[0].srcAccessMask = VK_ACCESS_COLOR_ATTACHMENT_WRITE_BIT;
vsdp[0].dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
vsdp[0].dependencyFlags = VK_DEPENDENCY_BY_REGION_BIT;

VkRenderPassCreateInfo vrpci;
vrpci.sType = VK_STRUCTURE_TYPE_RENDER_PASS_CREATE_INFO;
vrpci.pNext = nullptr;
vrpci.flags = 0;
vrpci.attachmentCount = 3; // color, depth/stencil, output
vrpci.pAttachments = vad;
vrpci.subpassCount = 2;
vrpci.pSubpasses = vsd;
vrpci.dependencyCount = 1;
vrpci.pDependencies = vsdp;

result = vkCreateRenderPass(LogicalDevice, IN &vrpci, PALLOCATOR, OUT &RenderPass );
Placing a Pipeline Barrier so an Image is not used before it is Ready

```c
VkImageMemoryBarrier vimb;
    vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
    vimb.pNext = nullptr;
    vimb.oldLayout = VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL;
    vimb.newLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
    vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.image = textureImage;
    vimb.srcAccessMask = VK_ACCESS_COLOR_ATTACHMENT_OUTPUT_BIT;
    vimb.dstAccessMask = VK_ACCESS_SHADER_READ_BIT;
    vimb.subresourceRange = visr;

vkCmdPipelineBarrier(TextureCommandBuffer,
    VK_PIPELINE_STAGE_TRANSFER_BIT, VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT, 0,
    0, (VkMemoryBarrier *)nullptr,
    0, (VkBufferMemoryBarrier *)nullptr,
    1, IN &vimb);
```
vkCmdBeginRenderPass( CommandBuffers[nextImageIndex], IN &vrpbi, IN VK_SUBPASS_MODE_INLINE );

// first subpass is automatically started here

vkCmdBindPipeline( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );

vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipelineLayout, 0, 4, DescriptorSets, 0, (uint32_t *) nullptr );

vkCmdBindVertexBuffers( CommandBuffers[nextImageIndex], 0, 1, vBuffers, offsets );

vkCmdDraw( CommandBuffers[nextImageIndex], vertexCount, instanceCount, firstVertex, firstInstance );

. . .

vkCmdNextSubpass( CommandBuffers[nextImageIndex], VK_SUBPASS_MODE_INLINE );

// second subpass is started here – doesn’t need any new drawing vkCmd’s

. . .

vkCmdEndRenderPass( CommandBuffers[nextImageIndex] );
A Wrap-up: Here are some good Vulkan References (there are probably more by now – check the SIGGRAPH Bookstore)


The notes and code presented here are constantly being updated. Go to:

http://cs.oregonstate.edu/~mjb/vulkan

for all the latest versions.

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