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Introduction to the
Vulkan
Computer Graphics API

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Top Three Reasons that Prompted the Development of 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
Who is the Khronos Group?

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” with Khronos Membership

Over 140 members worldwide
Any company is welcome to join

Promoter Members

AMD | apple | ARM | Epic | Google | Imagination | Intel | NVIDIA | QUALCOMM | SAMSUNG | SONY | Valve | Vivaldi

Logos of various companies are shown, indicating their membership in the Khronos Group.
Who's Been Specifically Working on Vulkan?

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.
The Basic Computer Graphics Pipeline, Shader-style

Vertex Shader

- gl_Vertex, gl_Normal, gl_Color (Per-vertex in variables)
- gl_ModelViewMatrix, gl_ProjectionMatrix, gl_ModelViewProjectionMatrix (Uniform Variables)
- MC = Model Vertex Coordinates
- WC = World Vertex Coordinates
- EC = Eye Vertex Coordinates

Fragment Shader

- gl_FragColor (Per-fragment in variables)
- Uniform Variables

Framebuffer

The Basic Computer Graphics Pipeline, Vulkan-style

Vertex Shader

- Per-vertex in variables
- Uniform Variables
- gl_Position, Per-vertex out variables

Fragment Shader

- Output color(s)
- Per-fragment in variables
- Uniform Variables

Framebuffer
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 have adopted SPIR-V as well

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

Develop Time Run Time

Moving part of the driver into the application

Complex drivers lead to driver overhead and cross vendor unpredictability
Error management is always active
Driver processes full shading language source
Separate APIs for desktop and mobile markets

Application
Traditional graphics drivers include significant context, memory and error management

Application responsible for memory allocation and thread management to generate command buffers
Direct GPU Control

Simpler drivers for low-overhead efficiency and cross vendor portability
Layered architecture so validation and debug layers can be unloaded when not needed
Run-time only has to ingest SPIR-V intermediate language
Unified API for mobile, desktop, console and embedded platforms

Khronos Group
Vulkan Highlights: Command Buffers

- Graphics commands are sent to command buffers
- Think OpenCL…
- E.g., `vkCmdDoSomething(cmdBuffer, …);`
- You can have as many simultaneous Command Buffers as you want
- Buffers are flushed to Queues when the application wants them to be flushed
- Each command buffer can be filled from a different thread

Vulkan Highlights: Pipelines

- In OpenGL, your “pipeline state” is whatever your current graphics attributes are: color, transformations, textures, shaders, etc.
- Changing the state on-the-fly one item at-a-time is very expensive
- Vulkan forces you to set all your state variables at once into a “pipeline state object” (PSO) and then invoke the entire PSO whenever you want to use that state combination
- Think of the pipeline state as being immutable.
- Potentially, you could have thousands of these pre-prepared state objects
Vulkan Quick Reference Card – I Recommend you Get This!


Vulkan Highlights: Overall Block Diagram
Vulkan Highlights: a More Typical Block Diagram

Steps in Creating Graphics using Vulkan

1. Create the Vulkan Instance
2. Setup the Debug Callbacks
3. Create the Surface
4. List the Physical Devices
5. Pick the right Physical Device
6. Create the Logical Device
7. Create the Uniform Variable Buffers
8. Create the Vertex Data Buffers
9. Create the texture sampler
10. Create the texture images
11. Create the Swap Chain
12. Create the Depth and Stencil Images
13. Create the RenderPass
14. Create the Framebuffer(s)
15. Create the Descriptor Set Pool
16. Create the Command Buffer Pool
17. Create the Command Buffer(s)
18. Read the shaders
19. Create the Descriptor Set Layouts
20. Create and populate the Descriptor Sets
21. Create the Graphics Pipeline(s)
22. Update-Render-Update-Render-...
The Vulkan Sample Code Included with These Notes

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Sample Program Output
Sample Program Keyboard Inputs

- 'i', 'I': Toggle using a vertex buffer only vs. an index buffer
- 'l', 'L': Toggle lighting off and on
- 'm', 'M': Toggle display mode (textures vs. colors, for now)
- 'p', 'P': Pause the animation
- 'q', 'Q': quit the program
- Esc: quit the program
- 'r', 'R': Toggle rotation-animation and using the mouse

Caveats on the Sample Code, I

1. I've written everything out in appalling longhand.

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

3. 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 kept a secret from you.

4. 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.

5. At times, I’ve setup things that didn’t need to be setup just to show you what could go there.
Caveats on the Sample Code, II

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

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

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

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

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

Main Program

```c
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'
" );
        FpDebug = stderr;
    }
    fprintf(FpDebug, "FpDebug: Width = %d ; Height = %d
" );
    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
" );
    vkQueueWaitIdle( Queue );
    vkDeviceWaitIdle( LogicalDevice );
    DestroyAllVulkan();
    glfwDestroyWindow( MainWindow );
    glfwTerminate();
    return 0;
}
```
```c
void InitGraphics()
{
    HERE_I_AM( "InitGraphics" );
    VkResult result = VK_SUCCESS;
    Init01Instance();
    InitGLFW();
    Init02CreateDebugCallbacks();
    Init03PhysicalDeviceAndGetQueueFamilyProperties();
    Init04LogicalDeviceAndQueue();
    Init05UniformBuffer( sizeof(Matrices), &MyMatrixUniformBuffer );
    Fill05BufferData( MyMatrixUniformBuffer, (void *) &Matrices );
    Init05UniformBuffer( sizeof(Light), &MyLightUniformBuffer );
    Fill05BufferData( MyLightUniformBuffer, (void *) &Light );
    Init05MyVertexDataBuffer( sizeof(VertexData), &MyVertexDataBuffer );
    Fill05BufferData( 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 );
}
```
static GLuint CubeTriangleIndices[8] =
{
  {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 GLuint CubeColors[8] =
{
  {0.0, 0.0},
  {1.0, 0.0},
  {0.1, 0.0},
  {1.1, 0.0},
  {0.0, 1.0},
  {1.0, 1.0},
  {0.0, 1.1},
  {1.0, 1.1},
};

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 #1:
  { { 0.,  0., -1.},
     { 0., 0., 0. },
     { 1., 0. },
     { 0., 1. } },
  // vertex #5:
  { {-1., -1.,  1.},
     { 0., 0., -1.},
     { 0., 0., 1. },
     { 1., 0. } },
  // vertex #4:
  { { 1.,  1.,  1.},
     { 0., 0., -1.},
     { 1., 1.,  0.},
     { 0., 1. } },
  // vertex #7:
  { { 0.,  0.,  1.},
     { 0., 0., -1.},
     { 0., 1.,  1.},
     { 1., 1. } }
};
The Vertex Data is in a Separate File

#include “SampleVertexData.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. }    
},
...  

What if you don’t need all of this information?

For example, what if you are not doing texturing in this application? Should you re-do this struct and leave the texCoord element out?

As best as I can tell, the only penalties for leaving in vertex attributes that you aren’t going to use is memory space and possibly some inefficient uses of the cache, but not gross performance. So, I recommend keeping this struct intact, and, if you don’t need texturing, simply don’t use the texCoord values in your vertex shader.
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 Code has a Distinct “Style” of Setting Information in structs and then Passing that Information as a pointer-to-the-struct

```
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 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 `InitxYYY()` 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, IN and OUT have no significance. They are each actually #define’d to nothing.

```c
uint32_t count;
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT (VkPhysicalDevice *) nullptr );
VkPhysicalDevice * physicalDevices = new VkPhysicalDevice[count];
result = vkEnumeratePhysicalDevices( Instance, OUT &count, OUT &physicalDevices[0] );
```

**Querying the Number of Something and Allocating Enough Structures to Hold Them All**

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[0] );
```
Double-click here to launch Visual Studio 2019 with this solution

Linux shader compiler

Windows shader compiler

The "19" refers to the version of Visual Studio, not the year of development.

Extras in the Code

```c
#define REPORT(s)               { PrintVkError( result, s );  fflush(FpDebug); }

#define HERE_I_AM(s)          if( Verbose )  { fprintf( FpDebug, "***** %s *****
               
#define DEBUGFILE               "VulkanDebug.txt"

errno_t err = fopen_s( &FpDebug, DEBUGFILE, "w" );
```

```c
#define REPORT(s)               { PrintVkError( result, s );  fflush(FpDebug); }

#define HERE_I_AM(s)          if( Verbose )  { fprintf( FpDebug, "***** %s *****
               
#define DEBUGFILE               "VulkanDebug.txt"

errno_t err = fopen_s( &FpDebug, DEBUGFILE, "w" );
```
Geometry vs. Topology

Geometry:
Where things are (e.g., coordinates)

Topology:
How things are connected

Geometry = changed
Topology = same (1-2-3-4-1)

Geometry = same
Topology = changed (1-2-4-3-1)
typedef enum VkPrimitiveTopology
{
    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,
    VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY,
    VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY,
    VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY,
    VK_PRIMITIVE_TOPOLOGY_PATCH_LIST
} VkPrimitiveTopology;
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:

\[
\text{ProjectionMatrix}[1][1] = -1. ;
\]

This is like saying “Y’ = -Y”.

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.

```
VkPipelineRasterizationStateCreateInfo vprsci;
    ...
    vprsci.cullMode = VK_CULL_MODE_NONE;
    vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;
```
Triangles Represented as an Array of Structures

From the file SampleVertexData.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

Non-indexed Buffer Drawing

From the file SampleVertexData.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. }
  }
};
```
Filling the Vertex Buffer

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;
}

A Preview of What Init05DataBuffer Does

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

GLSL Shader:

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

```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;
```

```c
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
```
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, 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);
```

Drawing with an Indexed Buffer

```
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), IN &MyJustVertexDataBuffer );
Fill05DataBuffer( MyJustVertexDataBuffer, (void *) JustVertexData );

Init05MyIndexDataBuffer( sizeof(JustIndexData), IN &MyJustIndexDataBuffer );
Fill05DataBuffer( MyJustIndexDataBuffer, (void *) JustIndexData );

Drawing with an Indexed Buffer
Drawing with an Indexed Buffer

```cpp
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;  

evCmdDrawIndexed( CommandBuffers[nextImageIndex], indexCount, instanceCount, firstIndex,  
vertexOffset, firstInstance );
```

Sometimes the Same Point Needs Multiple Attributes

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

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http://cs.oregonstate.edu/~mjb/vulkan
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: GLSL Differences from OpenGL, I

Detecting that a GLSL Shader is being used with Vulkan/SPIR-V:

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

Vulkan Vertex and Instance indices: OpenGL uses:

- gl_VertexIndex
- gl_InstanceIndex
- gl_VertexID
- gl_InstanceID

- Both are 0-based

gl_FragColor:

- In OpenGL, gl_FragColor broadcasts to all color attachments
- In Vulkan, it just broadcasts to color attachment location #0
- Best idea: don’t use it at all – 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;

• Only for scalars, but a vector’s components can be constructed from specialization constants

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

• This sets gl_WorkGroupSize.x and gl_WorkGroupSize.y
• gl_WorkGroupSize.z is set as a constant

Vulkan: Shaders' use of Layouts for Uniform Variables

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

// non-sampler variables 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 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, which stands for **Standard Portable Intermediate Representation**.
- 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 have adopted 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
- .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/
Running glslangValidator.exe

```
MINGW64:/y/Vulkan/Sample2017
$ 185
glslangValidator.exe -V sample-vert.vert -o sample-vert.spv
sample-vert.vert
$ 186
glslangValidator.exe -V sample-frag.frag -o sample-frag.spv
sample-frag.frag
$ 186
ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$ !85
```

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 . . .
```cpp
#define SPIRV_MAGIC 0x07230203

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 );
    VkShaderModule ShaderModuleVertex;
    ...
    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, OUT & ShaderModuleVertex );
    fprintf( FpDebug, "Shader Module \"%s\" successfully loaded\n", filename.c_str() );
    delete [] code;
    return result;
}
```

---

**Reading a SPIR-V File into a Vulkan Shader Module**

```cpp
#define SPIRV_MAGIC 0x07230203

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 );
    VkShaderModule ShaderModuleVertex;
    ...
    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, OUT & ShaderModuleVertex );
    fprintf( FpDebug, "Shader Module \"%s\" successfully loaded\n", filename.c_str() );
    delete [] code;
    return result;
}
```
Vulkan: Creating a Graphics Pipeline

SPIR-V: More Information

SPIR-V Tools:
http://github.com/KhronosGroup/SPIRV-Tools
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 . . .
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;
}

---

Filling the Vertex Buffer

Data Buffers

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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'd 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 int32_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( )
{
  VkPhysicalDeviceMemoryProperties vpdp;
  vkGetPhysicalDeviceMemoryProperties( PhysicalDevice, OUT &vpdp );
  for( unsigned int i = 0; i < vpdp.memoryTypeCount; i++ )
  {
    VkMemoryType vmt = vpdp.memoryTypes[ i ];
    if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT ) != 0 )
    {
      return i;
    }
  }
  return -1;
}
```
FindMemoryThatIsDeviceLocal()
{
    VkPhysicalDeviceMemoryProperties vpdmp;
    vkGetPhysicalDeviceMemoryProperties(PhysicalDevice, OUT &vpdmp);
    for( unsigned int i = 0; i < vpdmp.memoryTypeCount; i++ )
    {
        VkMemoryType vmt = vpdmp.memoryTypes[i];
        if(( vmt.propertyFlags & VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT ) != 0 )
        {
            return i;
        }
    }
    return -1;
}

Finding the Right Type of Memory

11 Memory Types:
Memory 0:  DeviceLocal
Memory 1:  DeviceLocal
Memory 2:  DeviceLocal
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
I find it handy to encapsulate buffer information in a struct:

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.

---

**Initializing a Data Buffer**

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 a 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

```c
uint32_t                        Height, Width;
const double FOV =              glm::radians(60.);      // field-of-view angle
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.; // account for Vulkan’s LH screen coordinate system
Matrices.uNormalMatrix = glm::inverseTranspose( glm::mat3( Matrices.uModelMatrix ) );
```
The Parade of Data

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

MyBuffer MyMatrixUniformBuffer;

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...

The Descriptor Set for the Buffer

We will come to Descriptor Sets later, but for now think of them as the link between the BLOB of uniform variables in GPU memory and the block of variable names in your shader programs.
Filling the Data Buffer

```c
typedef struct MyBuffer {
    VkDeviceSize buffer;
    VkDeviceMemory vdm;
    VkDeviceSize size;
    MyBuffer;
    ...,
    MyBuffer MyMatrixUniformBuffer;
}...

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

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;
    vbci.usage = usage;
    vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vbci.queueFamilyIndexCount = 0;
    vbci.pQueueFamilyIndices = (const uint32_t *)nullptr;
    result = vkCreateBuffer( LogicalDevice, &vbci, PALLOCATOR, &pMyBuffer->buffer );

    VkMemoryRequirements vmr;
    vkGetBufferMemoryRequirements( LogicalDevice, pMyBuffer->buffer, &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, &vmai, PALLOCATOR, &vdm );
    pMyBuffer->vdm = vdm;

    result = vkBindBufferMemory( LogicalDevice, pMyBuffer->buffer, vdm, 0 );
    return result;
}
```
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.
### 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 );
}
```

### GLFW Keyboard Callback

```c
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, "Unknown key hit: 0x%04x = "%c\n", key, key );
                fflush(FpDebug);
                break;
        }
    }
}
```
GlFW Mouse Button Callback

```c
void
GLFWMouseButton( GLFWwindow *window, int button, int action, int mods )
{
    int b = 0;              // LEFT, MIDDLE, or RIGHT

    // get the proper button bit mask:
    switch( button )
    {
        case GLFW_MOUSE_BUTTON_LEFT:
            b = LEFT;               break;
        case GLFW_MOUSE_BUTTON_MIDDLE:
            b = MIDDLE;             break;
        case GLFW_MOUSE_BUTTON_RIGHT:
            b = RIGHT;              break;
        default:
            b = 0;
            fprintf( FpDebug, "Unknown mouse button: %d\n", button );
            break;
    }

    // button down sets the bit, up clears the bit:
    if( action == GLFW_PRESS )
    {
        double xpos, ypos;
        glfwGetCursorPos( window, &xpos, &ypos);
        Xmouse = (int)xpos;
        Ymouse = (int)ypos;
        ActiveButton |= b;              // set the proper bit
    }
    else
    {
        ActiveButton &= ~b;             // clear the proper bit
    }
}
```

GlFW Mouse Motion Callback

```c
void
GLFWMouseMotion( GLFWwindow *window, double xpos, double ypos )
{
    int dx = (int)xpos - Xmouse;            // change in mouse coords
    int dy = (int)ypos - Ymouse;

    if( (ActiveButton & LEFT ) != 0 )
    {
        Xrot += ( ANGFACT*dy );
        Yrot += ( ANGFACT*dx );
    }

    if( (ActiveButton & MIDDLE ) != 0 )
    {
        Scale += SCLFACT * (float) ( dx - dy );
        // keep object from turning inside-out or disappearing:
        if( Scale < MINScale )
            Scale = MINScale;
    }

    Xmouse = (int)xpos;                     // new current position
    Ymouse = (int)ypos;
}
```
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:

```
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:

```
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(); // identity matrix
glm::vec4();
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, 1. ) // promote a 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 );

// 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 );
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. 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;  // 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 );
        }
    }
} 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.uNormalMatrix = glm::inverseTranspose( glm::mat3(Matrices.uModelMatrix) );

Fill05DataBuffer( MyMatrixUniformBuffer, (void *)&Matrices );
Misc.uTime = (float)Time;
Misc.uMode = Mode;
Fill05DataBuffer( MyMiscUniformBuffer, (void *)&Misc );

Your Sample2019.zip File Contains GLM Already
Why Isn't The Normal Matrix just the Same as the Model Matrix?

It is, if the Model Matrix is all rotations and uniform scalings, but if it has non-uniform scalings, then it is not. These diagrams show you why.

Wrong!

Right!

glm::mat3 NormalMatrix = glm::mat3(Model);

glm::mat3 NormalMatrix = glm::inverseTranspose(glm::mat3(Model));

Instancing

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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

\[ \text{vkCmdDraw} \( \text{CommandBuffers[nextImageIndex]}, \text{vertexCount, instanceCount, firstVertex, firstInstance} \); \]

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?

Making each Instance look differently -- Approach #1

Use the built-in vertex shader variable \texttt{gl\_InstanceIndex} to define a unique display property, such as position or color.

\texttt{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;
```
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;

tvec3 vColor;
    ...

int index = gl_InstanceIndex % 1024; // 0 - 1023
vColor = Colors.uColors[ index ];
gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
```
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;

This definition says that we should advance through the input buffer by this much every time we hit a new vertex.

#version 400
#extension GL_ARB_separate_shader_objects : enable
#extension GL_ARB_shading_language_420pack : enable

layout( location = 0 ) in vec3 aVertex;
layout( location = 1 ) in vec3 aNormal;
layout( location = 2 ) in vec3 aColor;
layout( location = 3 ) in vec2 aTexCoord;
layout( location = 4 ) in vec3 aInstanceColor;
layout ( location = 0 ) out vec3 vNormal;
layout ( location = 1 ) out vec3 vColor;
layout ( location = 2 ) out vec2 vTexCoord;

void main()
{
    mat4 PVM = Matrices.uProjectionMatrix * Matrices.uViewMatrix * Matrices.uModelMatrix;
    vNormal = normalize( vec3( Matrices.uNormalMatrix * vec4(aNormal, 1.) ) );
    //vColor = aColor;
    vColor = aInstanceColor;
    vTexCoord = aTexCoord;
    gl_Position = PVM * vec4( aVertex, 1. );
}
Descriptor Sets

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In OpenGL

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 collection of related uniform variables all at once, without having to update the uniform variables that are not related to this collection?

```cpp
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;
```
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.

```cpp
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:

```cpp
// 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

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

Let's look at some code examples:

```c++
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.
Init13DescriptorSetPool()
{
VkResult result;
VkDescriptorPoolSize vdps[4];
vdps[0].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
vdps[0].descriptorCount = 1;
vdps[1].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
vdps[1].descriptorCount = 1;
vdps[2].type = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
vdps[2].descriptorCount = 1;
vdps[3].type = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
vdps[3].descriptorCount = 1;

#ifdef CHOICES
VK_DESCRIPTOR_TYPE_SAMPLER
VK_DESCRIPTOR_TYPE_SAMPLED_IMAGE
VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER
VK_DESCRIPTOR_TYPE_STORAGE_IMAGE
VK_DESCRIPTOR_TYPE_UNIFORM_TEXEL_BUFFER
VK_DESCRIPTOR_TYPE_STORAGE_TEXEL_BUFFER
VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER
VK_DESCRIPTOR_TYPE_STORAGE_BUFFER
VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER_DYNAMIC
VK_DESCRIPTOR_TYPE_STORAGE_BUFFER_DYNAMIC
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 = &vdps[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.
Step 2: Define the Descriptor Set Layouts

**MatrixSet DS Layout Binding:**
- binding: 0
- descriptorType: VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER
- descriptorCount: 1
- pipeline stage(s): VK_SHADER_STAGE_VERTEX_BIT
- set = 0

**LightSet DS Layout Binding:**
- binding: 0
- descriptorType: VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER
- descriptorCount: 1
- pipeline stage(s): VK_SHADER_STAGE_VERTEX_BIT
- set = 1

**MiscSet DS Layout Binding:**
- binding: 0
- descriptorType: VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER
- descriptorCount: 1
- pipeline stage(s): VK_SHADER_STAGE_VERTEX_BIT | VK_SHADER_STAGE_FRAGMENT_BIT
- set = 2

**TexSamplerSet DS Layout Binding:**
- binding: 0
- descriptorType: VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER
- descriptorCount: 1
- pipeline stage(s): VK_SHADER_STAGE_FRAGMENT_BIT
- set = 3

Uniform sampler2D uSampler;
vec4 rgba = texture(uSampler, vST);
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;
}
```
Init13DescriptorSets()
{
    VkResult result;
    VkDescriptorSetAllocateInfo vdsai = 
        {VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO, 
         nullptr,  
         DescriptorPool,  
         4,  
         DescriptorSetLayouts};

    result = vkAllocateDescriptorSets( LogicalDevice, 
                                       &vdsai, 
                                       &DescriptorSets[0]);
}

Step 4: Allocating the Memory for Descriptor Sets

Step 5: Tell the Descriptor Sets where their CPU Data is

This struct identifies what texture sampler and image view it owns

This struct identifies what buffer it owns and how big it is

This struct identifies what buffer it owns and how big it is

This struct identifies what buffer it owns and how big it is
Step 5: Tell the Descriptor Sets where their CPU Data is

```c
VkWriteDescriptorSet vwds0;
// ds 0:
vwds0.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
vwds0.pNext = nullptr;
vwds0.dstSet = DescriptorSets[0];
vwds0.dstBinding = 0;
vwds0.dstArrayElement = 0;
vwds0.descriptorCount = 1;
vwds0.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
vwds0.pBufferInfo = &vdbi0;
vwds0.pImageInfo = nullptr;
vwds0.pTexelBufferView = nullptr;

// ds 1:
VkWriteDescriptorSet vwds1;
vwds1.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
vwds1.pNext = nullptr;
vwds1.dstSet = DescriptorSets[1];
vwds1.dstBinding = 0;
vwds1.dstArrayElement = 0;
vwds1.descriptorCount = 1;
vwds1.descriptorType = VK_DESCRIPTOR_TYPE_UNIFORM_BUFFER;
vwds1.pBufferInfo = &vdbi1;
vwds1.pImageInfo = nullptr;
vwds1.pTexelBufferView = nullptr;
```

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

```c
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: Tell the Descriptor Sets where their data is

```c
VkWriteDescriptorSet vwds2;
// ds 2:
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 = &vdbi2;
vwds2.pImageInfo = nullptr;
vwds2.pTexelBufferView = 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 = nullptr;
vwds3.pImageInfo = &vdii0;
vwds3.pTexelBufferView = nullptr;
```

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

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

#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 = &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 );
```

So, the Pipeline Layout contains the **structure** of the Descriptor Sets. Any collection of Descriptor Sets that match that structure can be bound into that pipeline.
Textures

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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. }
    }
};
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

```c
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 );
```

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( IN 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.mipmapLodBias = 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 );
}

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_LINEAR
    VK_IMAGE_TILING_OPTIMAL
    #endif
vici.usage = 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;

    #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;

    // this second {...} is to create the texture image:
    // *******************************************************************************
    {
VkImageCreateInfo vici2;
vici2.sType = VK_STRUCTURE_TYPE_IMAGE_CREATE_INFO;
vici2.pNext = nullptr;
vici2.flags = 0;
vici2.imageType = VK_IMAGE_TYPE_2D;
vici2.format = VK_FORMAT_R8G8B8A8_UNORM;
vici2.extent.width = texWidth;
vici2.extent.height = texHeight;
vici2.extent.depth = 1;
vici2.mipLevels = 1;
vici2.arrayLayers = 1;
vici2.samples = VK_SAMPLE_COUNT_1_BIT;
vici2.tiling = VK_IMAGE_TILING_LINEAR;
    #ifdef CHOICES
    VK_IMAGE_TILING_LINEAR
    VK_IMAGE_TILING_OPTIMAL
    #endif
vici2.usage = 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;

    #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
vici2.sharingMode = VK_SHARING_MODE_EXCLUSIVE;

    if (texWidth != 0 || texHeight != 0)
        result = vkCreateImage( LogicalDevice, PALLOCATOR, OUT &textureImage );
    else
        result = VK_SUCCESS;
}

    // this third {...} is to fill the staging image:
    // *******************************************************************************
    {
VkCommandBuffer commandBuffer = vkBeginCommandBuffer( LogicalDevice, PALLOCATOR, IN &pMyTexture->commandBuffer );

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

VkBuffer buffer = textureBuffer;
VkDeviceSize offset = 0;
VkDeviceSize size = textureSize;

VkBufferImageCopy region;
region.bufferOffset = 0;
region.bufferRowLength = texHeight;
region.bufferImageHeight = 1;
region.imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
region.imageSubresource.mipLevel = 0;
region.imageSubresource.baseArrayLayer = 0;
region.imageSubresource.layerCount = 1;
region.imageOffset = 0;
region.imageExtent.width = texWidth;
region.imageExtent.height = texHeight;
region.imageExtent.depth = 1;

vkCmdCopyBufferToImage( commandBuffer, buffer, textureImage, region, 1, &subresource );

vkEndCommandBuffer( commandBuffer );
result = vkExecuteCommands( LogicalDevice, 1, &commandBuffer, PALLOCATOR );
}

    // this fourth {...} is to fill the texture image:
    // *******************************************************************************
    {
VkImageSubresourceRange subresource;
subresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
subresource.baseMipLevel = 0;
subresource.levelCount = 1;
subresource.baseArrayLayer = 0;
subresource.layerCount = 1;

VkBuffer buffer = textureBuffer;
VkDeviceSize offset = 0;
VkDeviceSize size = textureSize;

VkBufferImageCopy region;
region.bufferOffset = 0;
region.bufferRowLength = texHeight;
region.bufferImageHeight = 1;
region.imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
region.imageSubresource.mipLevel = 0;
region.imageSubresource.baseArrayLayer = 0;
region.imageSubresource.layerCount = 1;
region.imageOffset = 0;
region.imageExtent.width = texWidth;
region.imageExtent.height = texHeight;
region.imageExtent.depth = 1;

vkCmdCopyBufferToImage( commandBuffer, buffer, textureImage, region, 1, &subresource );

vkEndCommandBuffer( commandBuffer );
result = vkExecuteCommands( LogicalDevice, 1, &commandBuffer, PALLOCATOR );
}

    // this fifth {...} is to bind the texture buffer:
    // *******************************************************************************
    {
VkImageView stagingView = vkCreateImageView( LogicalDevice, PALLOCATOR, OUT &stagingView, textureImage, VK_IMAGE_VIEW_TYPE_2D, VK_FORMAT_R8G8B8A8_UNORM, &subresource );
VkImageView textureView = vkCreateImageView( LogicalDevice, PALLOCATOR, OUT &textureView, textureImage, VK_IMAGE_VIEW_TYPE_2D, VK_FORMAT_R8G8B8A8_UNORM, &subresource );

vkBindImageLayout( LogicalDevice, OUT &textureView, VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL, PALLOCATOR );

VkBufferImageCopy copyRegion;
    #ifdef CHOICES
    VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL
    VK_IMAGE_LAYOUT_GENERAL
    #endif

copyRegion.bufferOffset = 0;
copyRegion.bufferRowLength = texHeight;
copyRegion.bufferImageHeight = 1;
copyRegion.imageSubresource.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
copyRegion.imageSubresource.mipLevel = 0;
copyRegion.imageSubresource.baseArrayLayer = 0;
copyRegion.imageSubresource.layerCount = 1;
copyRegion.imageOffset = 0;
copyRegion.imageExtent.width = texWidth;
copyRegion.imageExtent.height = texHeight;
copyRegion.imageExtent.depth = 1;

result = vkCmdCopyImageToBuffer( commandBuffer, textureImage, stagingView, copyRegion, 1, &subresource );

vkEndCommandBuffer( commandBuffer );
result = vkExecuteCommands( LogicalDevice, 1, &commandBuffer, PALLOCATOR );
}

if (texture == NULL)
    result = VK_SUCCESS;
else
    result = texture->success;
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
", vmr.size);
    fprintf(FpDebug, "Image vmr.alignment = %lld
", vmr.alignment);
    fprintf(FpDebug, "Image vmr.memoryTypeBits = 0x%08x
", vmr.memoryTypeBits);
    fflush(FpDebug);
}

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

vma.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:
");
    fprintf(FpDebug, "	offset = %lld
", vsl.offset);
    fprintf(FpDebug, "	size = %lld
", vsl.size);
    fprintf(FpDebug, "	rowPitch = %lld
", vsl.rowPitch);
    fprintf(FpDebug, "	arrayPitch = %lld
", vsl.arrayPitch);
    fprintf(FpDebug, "	depthPitch = %lld
", vsl.depthPitch);
    fflush(FpDebug);
    |

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_OPTIMAL;
    vici.usage = VK_IMAGE_USAGE_TRANSFER_DST_BIT | VK_IMAGE_USAGE_SAMPLED_BIT;
    // because we are transferring into it and will eventual sample from it
    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.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
    vimb.image = stagingImage;
    vimb.srcAccessMask = VK_ACCESS_HOST_WRITE_BIT;
    vimb.dstAccessMask = 0;
    vimb.subresourceRange = visr;
    vkCmdPipelineBarrier(TextureCommandBuffer, VK_PIPELINE_STAGE_HOST_BIT, VK_PIPELINE_STAGE_HOST_BIT, 0,
        0, (VkMemoryBarrier *)nullptr,
        0, (VkBufferMemoryBarrier *)nullptr,
        1, IN &vimb );
}

// ******************************************************************************
//******************************************************************************

transition the texture buffer layout:

```c
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 = VK_ACCESS_TRANSFER_WRITE_BIT;
vimb.subresourceRange = visr;

vkCmdPipelineBarrier
(TextureCommandBuffer, VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT, VK_PIPELINE_STAGE_TRANSFER_BIT, 0, 0, (VkMemoryBarrier *)nullptr, 0, (VkBufferMemoryBarrier *)nullptr, 1, (VkImageMemoryBarrier *)vimb);
```

now do the final image transfer:

```c
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, &vic);
```
// transition the texture buffer layout a second time:

```cpp
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);
```

Note that, at this point, the Staging Buffer is no longer needed, and can be destroyed.

// create an image view for the texture image:

```cpp
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 = textureImage;
vivci.viewType = VK_IMAGE_VIEW_TYPE_2D;
vivci.format = VK_FORMAT_R8G8B8A8_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;
visr.subresourceRange = visr;

result = vkCreateImageView(LogicalDevice, IN &vivci, PALLOCATOR, OUT &pMyTexture->texImageView);
return result;
```
Reading in a Texture from a BMP File

typedef struct MyTexture
{
    uint32_t                        width;
    uint32_t                        height;
    VkImage                        texImage;
    VkimageView                    texImageView;
    VkSampler                      texSampler;
    VkDeviceMemory                 vdm;
} MyTexture;

MyTexture MyPuppyTexture;

result = Init06TextureBufferAndFillFromBmpFile ("puppy.bmp", &MyTexturePuppy);
Init06TextureSampler( &MyPuppyTexture.texSampler );

This function can be found in the sample.cpp file. The BMP file needs to be created by something that writes uncompressed 24-bit color BMP files, or was converted to the uncompressed BMP format by a tool such as ImageMagick's convert, Adobe Photoshop, or GNU's GIMP.

The Graphics Pipeline Data Structure

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What is the Vulkan Graphics Pipeline?

Here's what you need to know:

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

2. The Vulkan Graphics Pipeline is not the processes that OpenGL would call “the graphics pipeline”.

3. For the most part, the Vulkan 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.

The First Step: Create the Graphics Pipeline Layout

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;
}
```
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
Creating a Typical Graphics Pipeline

VkResult
int14GraphicsVertexFragmentPipeline( VkShaderModule vertexShader, VkShaderModule fragmentShader,
VkPrimitiveTopology topology, OUT VkPipeline *pGraphicsPipeline )
{
    #ifdef ASSUMPTIONS
    vvibd[0].inputRate = VK_VERTEX_INPUT_RATE_VERTEX;
    vprsci.depthClampEnable = VK_FALSE;
    vprsci.rasterizerDiscardEnable = VK_FALSE;
    vprsci.polygonMode = VK_POLYGON_MODE_FILL;
    vprsci.cullMode = VK_CULL_MODE_NONE;    // best to do this because of the projectionMatrix[1][1] *= -1.;
    vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;
    vprsci.rasterizationSamples = VK_SAMPLE_COUNT_ONE_BIT;
    vpcbas.blendEnable = VK_FALSE;
    vpcbsci.logicOpEnable = VK_FALSE;
    vpdssci.depthTestEnable = VK_TRUE;
    vpdssci.depthWriteEnable = VK_TRUE;
    vpdssci.depthCompareOp = VK_COMPARE_OP_LESS;
    #endif
    ...

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;
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];
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;

Use one vpssci array member per shader module you are using

Use one vvibd array member per vertex input array-of-structures you are using
Link in the Per-Vertex Attributes

VkVertexInputAttributeDescription vviad[4]; // an array containing one of these per vertex attribute in all bindings

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 = offsetof(struct vertex, position); // 0

#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_STP VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_XYZ VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_VEC2 VK_FORMAT_R32G32_SFLOAT
#define VK_FORMAT_ST VK_FORMAT_R32G32_SFLOAT
#define VK_FORMAT_XY 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

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

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; // describe the vertex topology
vpiasci.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
vpiasci.pNext = nullptr;
vpiasci.flags = 0;
vpiasci.topology = VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST;

#define CHOICES
VK_PRIMITIVE_TOPOLOGY_POINT_LIST
VK_PRIMITIVE_TOPOLOGY_LINE_LIST
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN
VK_PRIMITIVE_TOPOLOGY_LINE_LIST_WITH_ADJACENCY
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP_WITH_ADJACENCY
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST_WITH_ADJACENCY
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP_WITH_ADJACENCY

VkPipelineTessellationStateCreateInfo vptsci; // Tessellation Shader info
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; // Geometry Shader info
vpgsci.sType = VK_STRUCTURE_TYPE_PIPELINE_GEOMETRY_STATE_CREATE_INFO;
vpgsci.pNext = nullptr;
vpgsci.flags = 0;

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.
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:
...
What is the Difference Between Changing the Viewport and Changing the Scissoring?

**Viewport:**
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.

**Scissoring:**
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;
#endif 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.;
#endif CHOICES
  VK_CULL_MODE_NONE
  VK_CULL_MODE_FRONT_BIT
  VK_CULL_MODE_BACK_BIT
  VK_CULL_MODE_FRONT_AND_BACK_BIT
#endif 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;

Setting the Rasterizer State

What is “Depth Clamp Enable”?  

vprsci.depthClampEnable = VK_FALSE;

Depth Clamp Enable causes the fragments that would normally have been discarded because they are closer to the viewer than the near clipping plane to instead get projected to the near clipping plane and displayed.

A good use for this is Polygon Capping:

The front of the polygon is clipped, revealing to the viewer that this is really a shell, not a solid The gray area shows what would happen with depthClampEnable (except it would have been red).
What is “Depth Bias Enable”?  

```
vprsci.depthBiasEnable = VK_FALSE;
vprsci.depthBiasConstantFactor = 0.f;
vprsci.depthBiasClamp = 0.f;
vprsci.depthBiasSlopeFactor = 0.f;
```

Depth Bias Enable allows scaling and translation of the Z-depth values as they come through the rasterizer to avoid Z-fighting.

**Z-fighting**

Color Blending State for each Color Attachment  

Create an array with one of these for each color buffer attachment. Each color buffer attachment can use different blending operations.

```
VkPipelineColorBlendAttachmentState vpcbas;
vpcbas.blendEnable = VK_FALSE;
vpcbas.srcColorBlendFactor = VK_BLEND_FACTOR_SRC_COLOR;
vpcbas.dstColorBlendFactor = VK_BLEND_FACTOR_ONE_MINUS_SRC_COLOR;
vpcbas.colorBlendOp = VK_BLEND_OP_ADD;
vpcbas.srcAlphaBlendFactor = VK_BLEND_FACTOR_ONE;
vpcbas.dstAlphaBlendFactor = VK_BLEND_FACTOR_ZERO;
vpcbas.alphaBlendOp = VK_BLEND_OP_ADD;
vpcbas.colorWriteMask = VK_COLOR_COMPONENT_R_BIT | VK_COLOR_COMPONENT_G_BIT | VK_COLOR_COMPONENT_B_BIT | VK_COLOR_COMPONENT_A_BIT;
```

This controls blending between the output of each color attachment and its image memory.
Color Blending State for each Color Attachment

```cpp
VkPipelineColorBlendStateCreateInfo vpcbsci;

vpcbsci.sType = VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO;
// #ifdef CHOICES
vpcbsci.pNext = nullptr;
// #endif
vpcbsci.flags = 0;
vpcbsci.logicOpEnable = VK_FALSE;
// #ifdef CHOICES
vpcbsci.logicOp = VK_LOGIC_OP_COPY;
// #endif
vpcbsci.attachmentCount = 1;
vpcbsci.pAttachments = &vpcbas;

vpcbsci.blendConstants[0] = 0;
vpcbsci.blendConstants[1] = 0;
vpcbsci.blendConstants[2] = 0;
vpcbsci.blendConstants[3] = 0;
```

This controls blending between the output of the fragment shader and the input to the color attachments.

Which Pipeline Variables can be Set Dynamically

```cpp
VkDynamicState vds[] = { VK_DYNAMIC_STATE_VIEWPORT,
VK_DYNAMIC_STATE_SCISSOR,
// #ifdef CHOICES
VK_DYNAMIC_STATE_LINE_WIDTH,
VK_DYNAMIC_STATE_DEPTH_BIAS,
VK_DYNAMIC_STATE_BLEND_CONSTANTS,
VK_DYNAMIC_STATE_DEPTH_BOUNDS,
VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK,
VK_DYNAMIC_STATE_STENCIL_WRITE_MASK,
VK_DYNAMIC_STATE_STENCIL_REFERENCE,
// #endif

// #ifdef CHOICES
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;
```

```cpp
// #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        -- vkCmdSetBendConstants( )
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     -- vkCmdSetStencilReferences( )
// #endif
```
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

Polygon edges without Z-fighting

Magic Lenses
Operations for Depth Values

```cpp
VkPipelineDepthStencilStateCreateInfo vpdssi;
vpdssi.sType = VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO;
vpdssi.pNext = nullptr;
vpdssi.flags = 0;
vpdssi.depthTestEnable = VK_TRUE;
vpdssi.depthWriteEnable = VK_TRUE;
vpdssi.depthCompareOp = VK_COMPARE_OP_LESS;
#ifdef CHOICES
VK_COMPARE_OP_NEVER -- never succeeds
VK_COMPARE_OP_LESS -- succeeds if new depth value is < the existing value
VK_COMPARE_OP_EQUAL -- succeeds if new depth value is == the existing value
VK_COMPARE_OP_LESS_OR_EQUAL -- succeeds if new depth value is <= the existing value
VK_COMPARE_OP_GREATER -- succeeds if new depth value is > the existing value
VK_COMPARE_OP_NOT_EQUAL -- succeeds if new depth value is != the existing value
VK_COMPARE_OP_GREATER_OR_EQUAL -- succeeds if new depth value is >= the existing value
VK_COMPARE_OP_ALWAYS -- always succeeds
#endif
vpdssi.depthBoundsTestEnable = VK_FALSE;
vpdssi.front = vsosf;
vpdssi.back = vsosb;
vpdssi.minDepthBounds = 0.;
vpdssi.maxDepthBounds = 1.;
vpdssi.stencilTestEnable = VK_FALSE;
```

Putting it all Together! (finally…)

```cpp
 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 = &vpdssi;
vgpci.pColorBlendState = &vpcbsci;
vgpci.pDynamicState = &vpdsci;
vgpci.layout = IN GraphicsPipelineLayout;
vgpci.renderPass = IN RenderPass;              // subpass number
vgpci.subpass = 0;
vgpci.basePipelineHandle = (VkPipeline) VK_NULL_HANDLE;
vgpci.basePipelineIndex = 0;
result = vkCreateGraphicsPipelines( LogicalDevice, VK_NULL_HANDLE, 1, IN
&vgpci, PALLOCATOR, OUT pGraphicsPipeline );
return result;
```
Later on, we will Bind the Graphics Pipeline to the Command Buffer when Drawing

```c
vkCmdBindPipeline( CommandBuffers[nextImageIndex],
                  VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );
```
Vulkan Queues and Command Buffers

- Graphics commands are recorded in command buffers, e.g., `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 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

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

```
int FindQueueFamilyThatDoesGraphics( )
{
    uint32_t count = -1;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, OUT &count, OUT (VkQueueFamilyProperties *)nullptr );
VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
vkGetPhysicalDeviceQueueFamilyProperties( PhysicalDevice, IN &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 Needs to Know Queue Family Information

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

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

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

```c
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;
    // other flags
    vcpci.queueFamilyIndex = FindQueueFamilyThatDoesGraphics();
    result = vkCreateCommandPool(LogicalDevice, IN &vcpci, PALLOCATOR, OUT &CommandPool);
    return result;
}
```
Creating the Command Buffers

```cpp
class VkResult
Init06CommandBuffers()
{
  VkResult result;
  // allocate 2 command buffers for the double-buffered rendering:
  
  VkCommandBufferAllocateInfo
  xcbai;
  xcbai.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO;
  xcbai.pNext = nullptr;
  xcbai.commandPool = CommandPool;
  xcbai.level = VK_COMMAND_BUFFER_LEVEL_PRIMARY;
  xcbai.commandBufferCount = 2;           // 2, because of double-buffering
  result = vkAllocateCommandBuffers( LogicalDevice, IN &xcbai, OUT &CommandBuffers[0] );

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

  return result;
}
```

Beginning a Command Buffer

```cpp
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] );
```
These are the Commands that could be entered into the Command Buffer, I

- vkCmdBeginQuery
- vkCmdBeginRenderPass
- vkCmdBindDescriptorSets
- vkCmdBindPipeline
- vkCmdBindVertexBuffer
- vkCmdBindIndexBuffer
- vkCmdBindPipeline
- vkCmdBindVertexBuffers
- vkCmdBlitImage
- vkCmdClearAttachments
- vkCmdClearColorImage
- vkCmdClearDepthStencilImage
- vkCmdCopyBuffer
- vkCmdCopyBufferToImage
- vkCmdCopyImage
- vkCmdCopyImageToBuffer
- vkCmdCopyQueryPoolResults
- vkCmdDebugMarkerBeginEXT
- vkCmdDebugMarkerEndEXT
- vkCmdDebugMarkerInsertEXT
- vkCmdDispatch
- vkCmdDispatchIndirect
- vkCmdDraw
- vkCmdDrawIndexed
- vkCmdDrawIndexedIndirect
- vkCmdDrawIndirect
- vkCmdEndQuery
- vkCmdEndRenderPass
- vkCmdExecuteCommands
- vkCmdFillBuffer
- vkCmdNextSubpass
- vkCmdPipelineBarrier
- vkCmdProcessCommandsNVX
- vkCmdPushConstants
- vkCmdPushDescriptorSetKHR
- vkCmdPushDescriptorSetWithTemplateKHR
- vkCmdReserveSpaceForCommandsNVX
- vkCmdResetEvent
- vkCmdResetQueryPool
- vkCmdResolveImage
- vkCmdSetBlendConstants
- vkCmdSetDepthBias
- vkCmdSetDepthBounds
- vkCmdSetDeviceMaskKHX
- vkCmdSetDiscardRectangleEXT
- vkCmdSetViewport
- vkCmdSetViewportWScalingNV
- vkCmdUpdateBuffer
- vkCmdWaitEvents
- vkCmdWriteTimestamp
- vkCmdWriteTimestamp

These are the Commands that could be entered into the Command Buffer, II

- vkCmdFillBuffer
- vkCmdNextSubpass
- vkCmdPipelineBarrier
- vkCmdProcessCommandsNVX
- vkCmdPushConstants
- vkCmdPushDescriptorSetKHR
- vkCmdPushDescriptorSetWithTemplateKHR
- vkCmdReserveSpaceForCommandsNVX
- vkCmdResetEvent
- vkCmdResetQueryPool
- vkCmdResolveImage
- vkCmdSetBlendConstants
- vkCmdSetDepthBias
- vkCmdSetDepthBounds
- vkCmdSetDeviceMaskKHX
- vkCmdSetDiscardRectangleEXT
- vkCmdSetViewport
- vkCmdSetViewportWScalingNV
- vkCmdUpdateBuffer
- vkCmdWaitEvents
- vkCmdWriteTimestamp
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 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);

    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,           // width
(float)Height,          // height
0.,                     // minDepth
1.                      // maxDepth
};

vkCmdSetViewport(CommandBuffers[nextImageIndex], 0, 1, IN &viewport);

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);

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

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);

vkCmdEndRenderPass(CommandBuffers[nextImageIndex]);

vkEndCommandBuffer(CommandBuffers[nextImageIndex]);

VkFenceCreateInfo vfci;

vfci.sType = VK_STRUCTURE_TYPE_FENCE_CREATE_INFO;

VkFence renderFence;

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

result = VK_SUCCESS;

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;

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

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

result = vkQueuePresentKHR(presentQueue, IN &p);
What Happens After a Queue has Been Submitted?

As the Vulkan 1.1 Specification says:

“Command buffer submissions to a single queue respect submission order and other implicit ordering guarantees, but otherwise may overlap or execute out of order. Other types of batches and queue submissions against a single queue (e.g. sparse memory binding) have no implicit ordering constraints with any other queue submission or batch. Additional explicit ordering constraints between queue submissions and individual batches can be expressed with semaphores and fences.”

In other words, the Vulkan driver on your system will execute the commands in a single buffer in the order in which they were put there.

But, between different command buffers submitted to different queues, the driver is allowed to execute commands between buffers in-order or out-of-order or overlapped-order, depending on what it thinks it can get away with.

The message here is, I think, always consider using some sort of Vulkan synchronization when one command depends on a previous command reaching a certain state first.
The Swap Chain

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How We Think of OpenGL Framebuffers

Video Driver

Update

Refresh

Depth-Buffer

Front

Back

Double-buffered Color Framebuffers
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. This 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 really 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”)

---

Diagram:

- **Swap Chain**
  - **Update**
  - **Present**
  - **Depth-Buffer**
  - **Front**
  - **Back**
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.
We Need to Find Out What our Display Capabilities Are

```c
VkSurfaceCapabilitiesKHR vsc;
vkGetPhysicalDeviceSurfaceCapabilitiesKHR( PhysicalDevice, Surface, OUT &vsc );
VkExtent2D surfaceRes = vsc.currentExtent;
fprintf( FpDebug, "vkGetPhysicalDeviceSurfaceCapabilitiesKHR:\n" );
  ...
VkBool32 supported;
result = vkGetPhysicalDeviceSurfaceSupportKHR( PhysicalDevice, FindQueueFamilyThatDoesGraphics( ), Surface, &supported );
if( supported == VK_TRUE )
  fprintf( FpDebug, "** This Surface is supported by the Graphics Queue **\n" );
uint32_t formatCount;
vkGetPhysicalDeviceSurfaceFormatsKHR( PhysicalDevice, Surface, &formatCount, (VkSurfaceFormatKHR *) nullptr );
VkSurfaceFormatKHR * surfaceFormats = new VkSurfaceFormatKHR[ formatCount ];
vkGetPhysicalDeviceSurfaceFormatsKHR( PhysicalDevice, Surface, &formatCount, surfaceFormats );
fprintf( FpDebug, "Found %d Surface Formats:\n", formatCount );
  ...
uint32_t presentModeCount;
vkGetPhysicalDeviceSurfacePresentModesKHR( PhysicalDevice, Surface, &presentModeCount, (VkPresentModeKHR *) nullptr );
VkPresentModeKHR * presentModes = new VkPresentModeKHR[ presentModeCount ];
vkGetPhysicalDeviceSurfacePresentModesKHR( PhysicalDevice, Surface, &presentModeCount, presentModes );
fprintf( FpDebug, "Found %d Present Modes:\n", presentModeCount );
```

VulkanDebug.txt output:

We Need to Find Out What our Display Capabilities Are

```
VkSurfaceCapabilitiesKHR:
  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 )
```
Creating a Swap Chain

```cpp
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 ] );
}

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

```c
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
```

Rendering into the Swap Chain, III

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

VkPresentFileInfoKHR 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);
```
Vulkan: a More Typical (and Simplified) Block Diagram

Application

Instance

Physical Device

Logical Device

Queue

Command Buffer

Command Buffer

Command Buffer
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):

result = vkEnumeratePhysicalDevices( Instance, &count, NULLptr );
result = vkEnumeratePhysicalDevices( Instance, &count, physicalDevices );

Vulkan: Identifying the Physical Devices

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
" );
    return VK_SHOULD_EXIT;
}

fprintf( FpDebug, "Could not enumerate the %d physical devices
", 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;
}
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, "API version: %d\n", vpdp.apiVersion );
  fprintf( FpDebug, "Driver version: %d\n", vpdp.apiVersion );
  fprintf( FpDebug, "Vendor ID: 0x%04x\n", vpdp.vendorID );
  fprintf( FpDebug, "Device ID: 0x%04x\n", vpdp.deviceID );
  fprintf( FpDebug, "Device Name: %s\n", vpdp.deviceName );
  fprintf( FpDebug, "Pipeline Cache Size: %d\n", vpdp.pipelineCacheUUID[0] );
  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" );
}

// need some logical here to decide which physical device to select:
if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU )
  discreteSelect = i;
else 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, "Physical 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 RTX 2080 Ti Produced

```
vkEnumeratePhysicalDevices:

Device 0:
    API version: 4198499
    Driver version: 4198499
    Vendor ID: 0x10de
    Device ID: 0x1e04
    Physical Device Type: 2 = (Discrete GPU)
    Device Name: RTX 2080 Ti
    Pipeline Cache Size: 206

Device #0 selected ('RTX 2080 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 = 1
```
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
  MultiDrawIndirect = 1

Asking About the Physical Device's Different Memories

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, "nMemory %2d: n", 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_MEMORYPROPERTY_LAZILY_ALLOCATED_BIT   ) != 0 )    fprintf( FpDebug, " LazilyAllocated" );
}

fprintf( FpDebug, "n%d Memory Heaps: n", vpdmp.memoryHeapCount );
for( unsigned int i = 0; i < vpdmp.memoryHeapCount; i++ )
{
  VkMemoryHeap vmh = vpdmp.memoryHeaps[i];
  fprintf( FpDebug, "nHeap %d: n", i );
  fprintf( FpDebug, "n 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

Asking About the Physical Device’s Queue Families

```c
uint32_t count = -1;
vkGetPhysicalDeviceQueueFamilyProperties(IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *)nullptr);
fprintf( FpDebug, "Found %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, ": 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

Found 3 Queue Families:
0: queueCount = 16 ; Graphics Compute Transfer
1: queueCount =  2 ; Transfer
2: queueCount =  8 ; Compute

Logical Devices

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```c
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_surface",
    "VK_KHR_win32_surface",
    "VK_EXT_debug_report"
};

// see what device layers are available:
uint32_t  layerCount;
vkEnumerateDeviceLayerProperties(PhysicalDevice, &layerCount, (VkLayerProperties *)nullptr);
VkLayerProperties * deviceLayers = new VkLayerProperties[layerCount];
result = vkEnumerateDeviceLayerProperties(PhysicalDevice, &layerCount, deviceLayers);
```
Looking to See What Device Extensions are Available

// 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);

What Device Layers and Extensions are Available

4 physical device layers enumerated:

0x00401063  1 'VK_LAYER_NV_optimus' 'NVIDIA Optimus layer'
  0 device extensions enumerated for 'VK_LAYER_NV_optimus':

0x00401072  1 'VK_LAYER_LUNARG_core_validation' 'LunarG Validation Layer'
  2 device extensions enumerated for 'VK_LAYER_LUNARG_core_validation':
    0x00000001 'VK_EXT_validation_cache'
    0x00000004 'VK_EXT_debug_marker'

0x00401072  1 'VK_LAYER_LUNARG_object_tracker' 'LunarG Validation Layer'
  2 device extensions enumerated for 'VK_LAYER_LUNARG_object_tracker':
    0x00000001 'VK_EXT_validation_cache'
    0x00000004 'VK_EXT_debug_marker'

0x00401072  1 'VK_LAYER_LUNARG_parameter_validation' 'LunarG Validation Layer'
  2 device extensions enumerated for 'VK_LAYER_LUNARG_parameter_validation':
    0x00000001 'VK_EXT_validation_cache'
    0x00000004 'VK_EXT_debug_marker'
float queuePriorities[1] = 
{ 
    1. 
};
VkDeviceQueueCreateInfo vdqci;
vqci.sType = VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO;
vqci.pNext = nullptr;
vqci.flags = 0;
vqci.queueFamilyIndex = 0;
vqci.queueCount = 1;
vqci.pQueueProperties = queuePriorities;

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

// get the queue for this logical device:
vkGetDeviceQueue( LogicalDevice, 0, 0, &Queue ); // 0, 0 = queueFamilyIndex, queueIndex
Creating a Pipeline with Dynamically Changeable State Variables

The graphics pipeline is full of state information, and, as previously-discussed, is immutable, that is, the information contained inside it is fixed, and can only be changed by creating a new graphics pipeline with new information.

That isn't quite true. To a certain extent, you can declare parts of the pipeline state changeable. This allows you to change pipeline information on the fly.

This is useful for managing state information that needs to change frequently. This also creates possible optimization opportunities for the Vulkan driver.
Which Pipeline State Variables can be Changed Dynamically

The possible uses for dynamic variables are shown in the `VkDynamicState` enum:

- `VK_DYNAMIC_STATE_VIEWPORT`
- `VK_DYNAMIC_STATE_SCISSOR`
- `VK_DYNAMIC_STATE_LINE_WIDTH`
- `VK_DYNAMIC_STATE_DEPTH_BIAS`
- `VK_DYNAMIC_STATE_BLEND_CONSTANTS`
- `VK_DYNAMIC_STATEDEPTH_BOUNDS`
- `VK_DYNAMIC_STATE_STENCIL_COMPARE_MASK`
- `VK_DYNAMIC_STATE_STENCIL_WRITE_MASK`
- `VK_DYNAMIC_STATE_STENCIL_REFERENCE`

Creating a Pipeline

```cpp
VkDynamicState
{
    VK_DYNAMIC_STATE_VIEWPORT,
    VK_DYNAMIC_STATE_LINE_WIDTH
};

VkPipelineDynamicStateCreateInfo
    vpdsci;
    vpdsci.sType = VK_STRUCTURE_TYPE_PIPELINE_DYNAMIC_STATE_CREATE_INFO;
    vpdsci.pNext = nullptr;
    vpdsci.flags = 0;
    vpdsci.dynamicStateCount = sizeof(vds) / sizeof(VkDynamicState);
    vpdsci.pDynamicStates = &vds;

VkGraphicsPipelineCreateInfo
    vgpci;
    . . .
    vgpci.pDynamicState = &vpdsci;
    . . .

vkCreateGraphicsPipelines( LogicalDevice, pipelineCache, 1, &vgpci, PALLOCATOR, &GraphicsPipeline );
```

If you declare certain state variables to be dynamic like this, then you must fill them in the command buffer! Otherwise, they are undefined.
Filling the Dynamic State Variables in the Command Buffer

The command buffer-bound function calls to set these dynamic states are:

- `vkCmdSetViewport( commandBuffer, firstViewport, viewportCount, pViewports );`
- `vkCmdSetScissor( commandBuffer, firstScissor, scissorCount, pScissors );`
- `vkCmdSetLineWidth( commandBuffer, linewidth );`
- `vkCmdSetDepthBias( commandBuffer, depthBiasConstantFactor, depthBiasClamp, depthBiasSlopeFactor );`
- `vkCmdSetBlendConstants( commandBuffer, blendConstants[4] );`
- `vkCmdSetDepthBounds( commandBuffer, minDepthBounds, maxDepthBounds );`
- `vkCmdSetStencilCompareMask( commandBuffer, faceMask, compareMask );`
- `vkCmdSetStencilWriteMask( commandBuffer, faceMask, writeMask );`
- `vkCmdSetStencilReference( commandBuffer, faceMask, reference );`

Push Constants

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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.

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[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[0];

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

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

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

```
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[0];

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

In the UpdateScene Function

```
float rot1 = (float)Time;
float rot2 = 2.f * rot1;
float rot3 = 2.f * rot2;

glm::vec3 zaxis = glm::vec3(0., 0., 1.);

glm::mat4 m1g = glm::mat4();

m1g = glm::translate(m1g, glm::vec3(0., 0., 0.));

m1g = glm::rotate(m1g, rot1, zaxis);

glm::mat4 m21 = glm::mat4();

m21 = glm::translate(m21, glm::vec3(2.*Arm1.armScale, 0., 0.));

m21 = glm::rotate(m21, rot2, zaxis);

m21 = glm::translate(m21, glm::vec3(0., 0., 2.));

glm::mat4 m32 = glm::mat4();

m32 = glm::translate(m32, glm::vec3(2.*Arm2.armScale, 0., 0.));

m32 = glm::rotate(m32, rot3, zaxis);

m32 = glm::translate(m32, glm::vec3(0., 0., 2.));

Arm1.armMatrix = m1g;              // m1g
Arm2.armMatrix = m1g * m21;        // m2g
Arm3.armMatrix = m1g * m21 * m32;  // m3g
```
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

```c
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  
```
• There are 3 types of Queries: Occlusion, Pipeline Statistics, and Timestamp

• Vulkan requires you to first setup “Query Pools”, one for each specific type

• This indicates that Vulkan thinks that Queries are time-consuming (relatively) to setup, and thus better to set them up in program-setup than in program-runtime
Setting up Query Pools

```c
VkQueryPoolCreateInfo vqpci;

vqpci.sType = VK_STRUCTURE_TYPE_QUERY_POOL_CREATE_INFO;

vqpci.pNext = nullptr;

vqpci.flags = 0;

vqpci.queryType = << one of >>
VK_QUERY_TYPE_OCCLUSION
VK_QUERY_TYPE_PIPELINE_STATISTICS
VK_QUERY_TYPE_TIMESTAMP

vqpci.queryCount = 1;

vqpci.pipelineStatistics = 0; // bitmask of what stats you are querying for if you are doing a pipeline statistics query

VkQueryPool occlusionQueryPool;

result = vkCreateQueryPool( LogicalDevice, IN &vqpci, PALLOCATOR, OUT &occlusionQueryPool );

VkQueryPool statisticsQueryPool;

result = vkCreateQueryPool( LogicalDevice, IN &vqpci, PALLOCATOR, OUT &statisticsQueryPool );

VkQueryPool timestampQueryPool;

result = vkCreateQueryPool( LogicalDevice, IN &vqpci, PALLOCATOR, OUT &timestampQueryPool );
```

Resetting, Filling, and Examining a Query Pool

```c
vkCmdResetQueryPool( CommandBuffer, occlusionQueryPool, 0, 1 );

vkCmdBeginQuery( CommandBuffer, occlusionQueryPool, 0, VK_QUERY_CONTROL_PRECISE_BIT );

. . .

vkCmdEndQuery( CommandBuffer, occlusionQueryPool, 0 );

#define DATASIZE 128

uint32_t data[DATASIZE];

result = vkGetQueryPoolResults( LogicalDevice, occlusionQueryPool, 0, 1, DATASIZE*sizeof(uint32_t), data, stride, flags );
```

// or'ed combinations of:
// VK_QUERY_RESULT_64_BIT
// VK_QUERY_RESULT_WAIT_BIT
// VK_QUERY_RESULT_WITH_AVAILABILITY_BIT
// VK_QUERY_RESULT_PARTIAL_BIT
// stride is # of bytes in between each result
Occlusion Queries count the number of fragments drawn between the `vkCmdBeginQuery` and the `vkCmdEndQuery` that pass both the Depth and Stencil tests. This is commonly used to see what level-of-detail should be used when drawing a complicated object.

Some hints:

- Don’t draw the whole scene – just draw the object you are interested in
- Don’t draw the whole object – just draw a simple bounding volume at least as big as the object
- Don’t draw the whole bounding volume – cull away the back faces (two reasons: time and correctness)
- Don’t draw the colors – just draw the depths (especially if the fragment shader is time-consuming)

```
uint32_t fragmentCount;
result = vkGetQueryPoolResults( LogicalDevice, occlusionQueryPool, 0, 1,
                               sizeof(uint32_t), &fragmentCount, 0, VK_QUERY_RESULT_WAIT_BIT );
```

Pipeline Statistics Queries count how many of various things get done between the `vkCmdBeginQuery` and the `vkCmdEndQuery`.

```
uint32_t counts[NUM_STATS];
result = vkGetQueryPoolResults( LogicalDevice, statisticsQueryPool, 0, 1,
                                NUM_STATS*sizeof(uint32_t), counts, 0, VK_QUERY_RESULT_WAIT_BIT );
```

// vqpci.pipelineStatistics = or’ed bits of:
// VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_VERTICES_BIT
// VK_QUERY_PIPELINE_STATISTIC_INPUT_ASSEMBLY_PRIMITIVES_BIT
// VK_QUERY_PIPELINE_STATISTIC_VERTEX_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_GEOMETRY_SHADER_PRIMITIVES_BIT
// VK_QUERY_PIPELINE_STATISTIC_CLIPPING_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_CLIPPING_PRIMITIVES_BIT
// VK_QUERY_PIPELINE_STATISTIC_FRAGMENT_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_CONTROL_SHADER_PATCHES_BIT
// VK_QUERY_PIPELINE_STATISTIC_TESSELLATION_EVALUATION_SHADER_INVOCATIONS_BIT
// VK_QUERY_PIPELINE_STATISTIC_COMPUTE_SHADER_INVOCATIONS_BIT
```
Timestamp Query

Timestamp Queries count how many nanoseconds of time elapsed between the `vkCmdBeginQuery` and the `vkCmdEndQuery`.

```c
uint64_t nanosecondsCount;
result = vkGetQueryPoolResults( LogicalDevice, timestampQueryPool, 0, 1,
    sizeof(uint64_t), &nanosecondsCount, 0,
    VK_QUERY_RESULT_64_BIT | VK_QUERY_RESULT_WAIT_BIT);
```

Timestamp Query

The `vkCmdWriteTimeStamp( )` function produces the time between when this function is called and when the first thing reaches the specified pipeline stage.

Even though the stages are “bits”, you are supposed to only specify one of them, not “or” multiple ones together

```c
vkCmdWriteTimeStamp( CommandBuffer, pipelineStages, timestampQueryPool, 0 );
```
Compute Shaders

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Here is how you create a Compute Pipeline

VkPipelineLayoutCreateInfo

 VkPipelineLayout

 VkPipelineShaderStageCreateInfo

 Shader

 VkSpecializationInfo

 VkShaderModule

 which stage (COMPUTE)

 VkCreatePipelineLayout()
Start by Creating the Data Buffers

This is a Particle System application, so we need Positions, Velocities, and (possibly) Colours.

```
lAYOUT( std140, set = 0, binding = 0 ) BUFFER Pos
{
    vec4 Positions[ ]; // array of structures
};

LAYOUT( std140, set = 0, binding = 1 ) BUFFER Vel
{
    vec4 Velocities[ ]; // array of structures
};

LAYOUT( std140, set = 0, binding = 2 ) BUFFER Col
{
    vec4 Colours[ ]; // array of structures
};
```

You can use the empty brackets, but only on the last element of the buffer. The actual dimension will be determined for you when Vulkan examines the size of this buffer's data store.

Creating a Shader Storage Buffer

```
VkBuffer Buffer;
...

VkBufferCreateInfo vhci;
    vhci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
    vhci.pNext = nullptr;
    vhci.flags = 0;
    vhci.size = << buffer size in bytes >>
    vhci.usage = VK_USAGE_STORAGE_BUFFER_BIT;
    vhci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vhci.queueFamilyIndexCount = 0;
    vhci.pQueueFamilyIndices = (const iont32_t) nullptr;

result = vkCreateBuffer ( LogicalDevice, IN &vhci, PALLOCATOR, OUT &Buffer );
```
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 );

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, &pGpuMemory );
  // 0 and 0 are offset and flags
  memcpy( pGpuMemory, data, (size_t)myBuffer.size );
  vkUnmapMemory( LogicalDevice, IN myBuffer.vdm );
  return VK_SUCCESS;
}
Create the Compute Pipeline Layout

```cpp
// VkPipelineLayout
// VkDescriptorSetLayout
// ... 

// VkDescriptorSetLayoutBinding
// ComputeSet[0]:
// ComputeSet[0].binding = 0;
// ComputeSet[0].descriptorType = VK_DESCRIPTOR_TYPE_STORAGE_BUFFER;
// ComputeSet[0].descriptorCount = 3;
// ComputeSet[0].stageFlags = VK_SHADER_STAGE_COMPUTE_BIT;
// ComputeSet[0].pImmutableSamplers = (VkSampler *)nullptr;

// VkDescriptorSetLayoutCreateInfo vdslc;
// vdslc.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
// vdslc.pNext = nullptr;
// vdslc.flags = 0;
// vdslc.bindingCount = 1;
// vdslc.pBindings = &ComputeSet[0];

result = vkCreateDescriptorSetLayout( LogicalDevice, &vdslc, PALLOCATOR, OUT &ComputeSetLayout );

// VkPipelineLayoutCreateInfo vplci;
// vplci.sType = VK_STRUCTURE_TYPE_PIPELINE_LAYOUT_CREATE_INFO;
// vplci.pNext = nullptr;
// vplci.flags = 0;
// vplci.setLayoutCount = 1;
// vplci.pSetLayouts = ComputeSetLayout;
// vplci.pushConstantRangeCount = 0;
// vplci.pPushConstantRanges = (VkPushConstantRange *)nullptr;

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

Create the Compute Pipeline

```cpp
// VkPipeline
// ... 

// VkPipelineShaderStageCreateInfo vpssci;
// vpssci.sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
// vpssci.pNext = nullptr;
// vpssci.flags = 0;
// vpssci.stage = VK_SHADER_STAGE_COMPUTE_BIT;
// vpssci.module = computeShader;
// vpssci.pName = "main";
// vpssci.pSpecializationInfo = (VkSpecializationInfo *)nullptr;

// VkComputePipelineCreateInfo vcpci[1];
// vcpci[0].sType = VK_STRUCTURE_TYPE_COMPUTE_PIPELINE_CREATE_INFO;
// vcpci[0].pNext = nullptr;
// vcpci[0].flags = 0;
// vcpci[0].stage = vpssci;
// vcpci[0].layout = ComputePipelineLayout;
// vcpci[0].basePipelineHandle = VK_NULL_HANDLE;
// vcpci[0].basePipelineIndex = 0;

result = vkCreateComputePipelines( LogicalDevice, VK_NULL_HANDLE, 1, &vcpci[0], PALLOCATOR, &ComputePipeline );
```
The Particle System Compute Shader -- Setup

```
#version 430
#extension GL_ARB_compute_shader : enable
layout( std140, set = 0, binding = 0 )  buffer  Pos
{
   vec4  Positions[   ]; // array of structures
};
layout( std140, set = 0, binding = 1 )  buffer  Vel
{
   vec4  Velocities[   ]; // array of structures
};
layout( std140, set = 0, binding = 2 )  buffer  Col
{
   vec4  Colours[   ]; // array of structures
};
layout( local_size_x = 64, local_size_y = 1, local_size_z = 1 )   in;
```

This is the number of work-items per work-group, set in the compute shader.
The number of work-groups is set in the vkCmdDispatch() function call in the C/C++ program.

The Particle System Compute Shader -- The Physics

```
#define POINT vec3
#define VELOCITY vec3
#define VECTOR vec3
#define SPHERE vec4

const VECTOR  G        =  VECTOR( 0., -9.8, 0. );
const float        DT        =  0.1;
const SPHERE Sphere = vec4( -100., -800., 0., 600. ); // x, y, z, r
...

uint  gid = gl_GlobalInvocationID.x; // the .y and .z are both 1 in this case

POIINT        p  = Positions[ gid ].xyz;
VELOCITY  v  = Velocities[ gid ].xyz;
POIINT        pp = p + v*DT + .5*DT*DT*G;
VELOCITY  vp = v + G*DT;

Positions[ gid ].xyz = pp;
Velocities[ gid ].xyz = vp;
```
The Particle System Compute Shader –
How About Introducing a Bounce?

VELOCITY
Bounce( VELOCITY vin, VECTOR n )
{
    VELOCITY vout = reflect( vin, n );
    return vout;
}

VELOCITY
BounceSphere( POINT p, VELOCITY v, SPHERE s )
{
    VECTOR n = normalize( p - s.xyz );
    return Bounce( v, n );
}

bool
IsInsideSphere( POINT p, SPHERE s )
{
    float r = length( p - s.xyz );
    return ( r < s.w );
}

The Particle System Compute Shader –
How About Introducing a Bounce?

uint gid = gl_GlobalInvoca\_tionID.x; // the .y and .z are both 1 in this case
POINT p = Positions[ gid ].xyz;
VELOCITY v = Velocities[ gid ].xyz;

POINT pp = p + v\*DT + .5\*DT\*DT\*G;
VELOCITY vp = v + G\*DT;

if( IsInsideSphere( pp, Sphere ) )
{
    vp = BounceSphere( p, v, S );
    pp = p + vp\*DT + .5\*DT\*DT\*G;
}

Positions[ gid ].xyz = pp;
Velocities[ gid ].xyz = vp;

Graphics Trick Alert: Making the bounce happen from the surface of the sphere is time-consuming. Instead, bounce from the previous position in space. If DT is small enough (and it is), nobody will ever know...
Dispatching the Compute Shader from the Command Buffer

```
const int NUM_PARTICLES = 1024*1024;
const int NUM_WORK_ITEMS = 64;
const int NUM_X_WORK_GROUPS = NUM_PARTICLES / NUM_WORK_ITEMS;
.
.
vkCmdBindPipeline( CommandBuffer, VK_PIPELINE_BIND_POINT_COMPUTE, ComputePipeline );
vkCmdDispatch( CommandBuffer, NUM_X_WORK_GROUPS, 1, 1 );
```

This is the number of work-groups, set in the C/C++ program. The number of work-items per work-group is set in a layout in the compute shader.

Or,

```
vkCmdBindPipeline( CommandBuffer, VK_PIPELINE_BIND_POINT_COMPUTE, ComputePipeline );
vkCmdDispatchIndirect( CommandBuffer, Buffer, 0 ); // Buffer holds the 3 sizes, offset=0
```

The Bouncing Particle System Compute Shader – What Does It Look Like?
What Are Specialization Constants?

In Vulkan, all shaders get halfway-compiled by SPIR-V and then the rest-of-the-way compiled by the Vulkan driver.

Normally, the half-way compile fixes all constant values and compiles the code that uses them.

But, it would be nice every so often to have your Vulkan program sneak into the halfway-compiled binary and manipulate some constants at runtime. This is what Specialization Constants are for. A Specialization Constant is a way of injecting an integer, Boolean, uint, float, or double constant into an halfway-compiled version of a shader right before the rest-of-the-way compilation.

That final compilation happens when you call \texttt{vkCreateComputePipelines( )}

Without Specialization Constants, you would have to commit to a final value before the SPIR-V compile was done, which could have been a long time ago.
Why Do We Need Specialization Constants?

Specialization Constants could be used for:

- Setting the work-items per work-group in a compute shader
- Setting a Boolean flag and then eliminating the if-test that used it
- Setting an integer constant and then eliminating the switch-statement that looked for it
- Making a decision to unroll a for-loop because the number of passes through it are small enough
- Collapsing arithmetic expressions into a single value
- Collapsing trivial simplifications, such as adding by zero or multiplying by 1

```cpp
layout( constant_id = 7 ) const int ASIZE = 32;
int array[ASIZE];

int asize = 64;
VkSpecializationMapEntry vsme[1]; // one array element for each
    // Specialization Constant
vsme[0].constantID = 7; // # bytes into the Specialization Constant
vsme[0].offset = 0; // array this one item is
vsme[0].size = sizeof(asize); // size of just this Specialization Constant

VkSpecializationInfo vsi;
    vsi.mapEntryCount = 1;
    vsi.pMapEntries = &vsme[0];
    vsi dataSize = sizeof(asize); // size of all the Specialization Constants together
    vsi pData = &asize; // array of all the Specialization Constants
```

In the compute shader

```
layout( constant_id = 7 ) const int ASIZE = 32;
int array[ASIZE];
```

In the Vulkan C/C++ program:

```cpp
int asize = 64;
VkSpecializationMapEntry vsme[1]; // one array element for each
    // Specialization Constant
vsme[0].constantID = 7; // # bytes into the Specialization Constant
vsme[0].offset = 0; // array this one item is
vsme[0].size = sizeof(asize); // size of just this Specialization Constant

VkSpecializationInfo vsi;
    vsi.mapEntryCount = 1;
    vsi.pMapEntries = &vsme[0];
    vsi dataSize = sizeof(asize); // size of all the Specialization Constants together
    vsi pData = &asize; // array of all the Specialization Constants
```
Linking the Specialization Constants into the Compute Pipeline

---

Specialization Constant Example – Setting Multiple Constants

---
Specialization Constants – Setting the Number of Work-items
Per Work-Group in the Compute Shader

In the compute shader

```cpp
layout( local_size_x_id=12 ) in;
layout( local_size_x = 32, local_size_y = 1, local_size_z = 1 ) in;
```

In the C/C++ program:

```cpp
int numXworkItems = 64;
VkSpecializationMapEntry vsme[1];
vsme[0].constantID = 12;
vsme[0].offset = 0;
vsme.size = sizeof(int);
VkSpecializationInfo vsi;
vsi.mapEntryCount = 1;
vsi.pMapEntries = &vsme[0];
vsi.dataSize = sizeof(int);
vsi.pData = &numXworkItems;
```
Where Synchronization Fits in the Overall Block Diagram

Application

Instance

Physical Device

Logical Device

Queue

Queue

Logical Device

Queue

Queue

Logical Device

Queue

Queue

Queue

Command Buffer

Event

Command Buffer

Command Buffer

Fence

Host

Semaphores

- 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

```
#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, 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

- 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 me 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

```c
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 for it

Controlling Events from the Device

```c
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 );

Could be an array of events
Where signaled, where wait for the signal
Memory barriers get executed after events have been signaled
```

Note: the device cannot test for an event, but it can block
From the Command Buffer Notes:
These are the Commands that can be entered into the Command Buffer, I
From the Command Buffer Notes:
These are the Commands that can 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, pBufferMemoryBarriers, imageMemoryBarrierCount, pImageMemoryBarriers );
vkCmdProcessCommandsNVX( commandBuffer, pProcessCommandsInfo );
vkCmdPushConstants( commandBuffer, layout, stageFlags, offset, size, pValues );
vkCmdPushDescriptorSetWithTemplateKHR( commandBuffer, descriptorUpdateTemplate, layout, set, pData );
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 );
vkCmdSetStencilCompareMask( commandBuffer, faceMask, compareMask );
vkCmdSetStencilReference( commandBuffer, faceMask, reference );
vkCmdSetStencilWriteMask( commandBuffer, writeMask );
vkCmdSetViewport( commandBuffer, firstViewport, viewportCount, pViewports );
vkCmdSetViewportWScalingNV( commandBuffer, firstViewport, viewportCount, pViewportsWScalings );
vkCmdWriteTimestamp( commandBuffer, pipelineStage, queryPool, query );

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
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
);
```

The Scenario

The diagram shows the scenario with various stages in the pipeline process, including:
- `TOP_OF_PIPE` Street
- `VERTEX_INPUT` Street
- `COLOR_ATTACHMENT_OUTPUT` Street
- `BOTTOM_OF_PIPE` Street
- `VERTTEX_SHADER` Street
- `FRAGMENT_SHADER` Street
- `TRANSFER_BIT` Street
- `COLOR_ATTACHMENT_OUTPUT` Street

The process involves blocking/un-blocking on different stages as indicated by the arrows and labels. The scenario illustrates how commands are sequenced and dependencies are established across different pipeline stages.
The Scenario

1. The cross-streets are named after pipeline stages
2. All traffic lights start out green
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 proper dst traffic light will be turned red
5. When the last car in the src group completely makes it through its intersection, the proper 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 Masks – Where in the Pipeline is this Memory Data being Generated or Consumed?

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
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
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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

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>
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<td>VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT</td>
<td>VK_ACCESS_INDIRECT_COMMAND_READ_BIT</td>
</tr>
<tr>
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<td>VK_ACCESS_DEPTH_STENCIL_ATTACHMENT_WRITE_BIT</td>
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<tr>
<td>VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT</td>
<td>VK_ACCESS_TRANSFER_READ_BIT</td>
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<td>VK_ACCESS_MEMORY_READ_BIT</td>
</tr>
<tr>
<td>VK_PIPELINE_STAGE_HOST_BIT</td>
<td>VK_ACCESS_MEMORY_WRITE_BIT</td>
</tr>
</tbody>
</table>

### Access Operations and what Pipeline Stages they can be used In

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<th>Pipeline Stages</th>
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<tr>
<td>VK_ACCESS_VERTEX_ATTRIBUTE_READ_BIT</td>
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<tr>
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<tr>
<td>VK_ACCESS_INPUT_ATTACHMENT_READ_BIT</td>
<td>VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT</td>
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</tbody>
</table>
Example: Be sure we are done writing an output image before using it for something else

<table>
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<th>Stages</th>
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</tr>
</tbody>
</table>

The Scenario

src cars are generating the image

dst cars are doing something with that image
### Example: Don’t read a buffer back to the host until a shader is done writing it

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<td>VK_ACCESS_MEMORY_WRITE_BIT</td>
</tr>
</tbody>
</table>

### The Scenario

#### src cars
- TOP_OF_PIPE Street
- VERTEX_INPUT Street
- VERTEX_SHADER Street
- COLOR_ATTACHMENT_OUTPUT Street
- TRANSFER_BIT Street
- BOTTOM_OF_PIPE Street

#### dst cars
- TOP_OF_PIPE Street
- VERTEX_INPUT Street
- VERTEX_SHADER Street
- COLOR_ATTACHMENT_OUTPUT Street
- TRANSFER_BIT Street
- BOTTOM_OF_PIPE Street

**dst (no access setting needed)**
VkImageLayout – How an Image gets Laid Out in Memory
depends on how it will be Used

VkImageMemoryBarrier
  vimb
  vimb.sType = VK_STRUCTURE_TYPE_IMAGE_MEMORY_BARRIER;
  vimb.pNext = nullptr;
  vimb.srcAccessMask = ??;
  vimb.dstAccessMask = ??;
  vimb.oldLayout = ??;
  vimb.newLayout = ??;
  vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
  vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
  vimb.image = ??;
  vimb.subresourceRange = visr;

VK_IMAGE_LAYOUT_UNDEFINED
VK_IMAGE_LAYOUT_GENERAL
VK_IMAGE_LAYOUT_COLOR_ATTACHMENT_OPTIMAL
VK_IMAGE_LAYOUT_DEPTH_STENCIL_ATTACHMENT_OPTIMAL
VK_IMAGE_LAYOUT_DEPTH_STENCIL_READ_ONLY_OPTIMAL
VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL
VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL
VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL
VK_IMAGE_LAYOUT_PREINITIALIZED
VK_IMAGE_LAYOUT_PRESENT_SRC_KHR
VK_IMAGE_LAYOUT_SHARED_PRESENT_KHR

Here, the use of vkCmdPipelineBarrier( ) is to simply change the layout of an image

Antialiasing and Multisampling

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http://cs.oregonstate.edu/~mjb/vulkan
"Aliasing" is a signal-processing term for "under-sampled compared with the frequencies in the signal".

What the signal really is: what we want

What we think the signal is: too often, what we get
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 sub-pixels within a pixel, render the image at each of these sub-pixels (including depth and stencil tests), then average them together.

2. **Multisampling**: Perform a single color render for the one pixel. Then, pick some number of unique sub-pixels within that pixel and perform depth and stencil tests there. Assign the single color to all the sub-pixels that made it through the depth and stencil tests.
### Vulkan Distribution of Sampling Points within a Pixel

#### VK_SAMPLE_COUNT_1_BIT

<table>
<thead>
<tr>
<th>Value</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.25, 0.25)</td>
<td>(0.5625, 0.375)</td>
</tr>
<tr>
<td>(0.75, 0.75)</td>
<td>(0.5625, 0.375)</td>
</tr>
</tbody>
</table>

#### VK_SAMPLE_COUNT_2_BIT

<table>
<thead>
<tr>
<th>Value</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.25, 0.25)</td>
<td>(0.3125, 0.125)</td>
</tr>
<tr>
<td>(0.75, 0.75)</td>
<td>(0.3125, 0.125)</td>
</tr>
</tbody>
</table>

#### VK_SAMPLE_COUNT_4_BIT

<table>
<thead>
<tr>
<th>Value</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.25, 0.25)</td>
<td>(0.3125, 0.125)</td>
</tr>
<tr>
<td>(0.75, 0.75)</td>
<td>(0.3125, 0.125)</td>
</tr>
</tbody>
</table>

#### VK_SAMPLE_COUNT_8_BIT

<table>
<thead>
<tr>
<th>Value</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.25, 0.25)</td>
<td>(0.3125, 0.125)</td>
</tr>
<tr>
<td>(0.75, 0.75)</td>
<td>(0.3125, 0.125)</td>
</tr>
</tbody>
</table>

#### VK_SAMPLE_COUNT_16_BIT

<table>
<thead>
<tr>
<th>Value</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.25, 0.25)</td>
<td>(0.3125, 0.125)</td>
</tr>
<tr>
<td>(0.75, 0.75)</td>
<td>(0.3125, 0.125)</td>
</tr>
</tbody>
</table>

---

**mjb – September 12, 2019**
Consider two triangles whose edges pass through the same pixel.

**Supersampling**

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

# 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

Setting up the Image

```c
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 );
```
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

```cpp
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

```cpp
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

```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
VkOffset3D 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 );
```
Introduction to the

Computer Graphics API

Thanks for coming today!

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