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2020 S2020.SIGGRAPH.ORG

Introduction to the Vulkan Computer Graphics API

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Introduction to the Vulkan Computer Graphics API

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SIGGRAPH 2020 Abridged Version

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

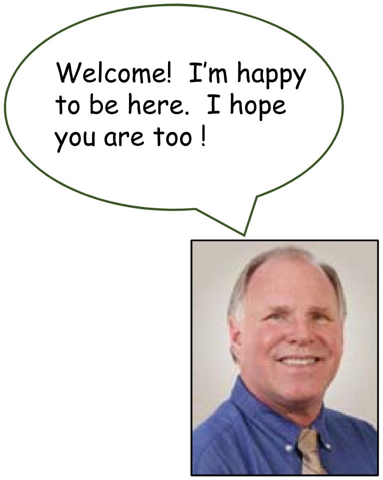
Course Goals

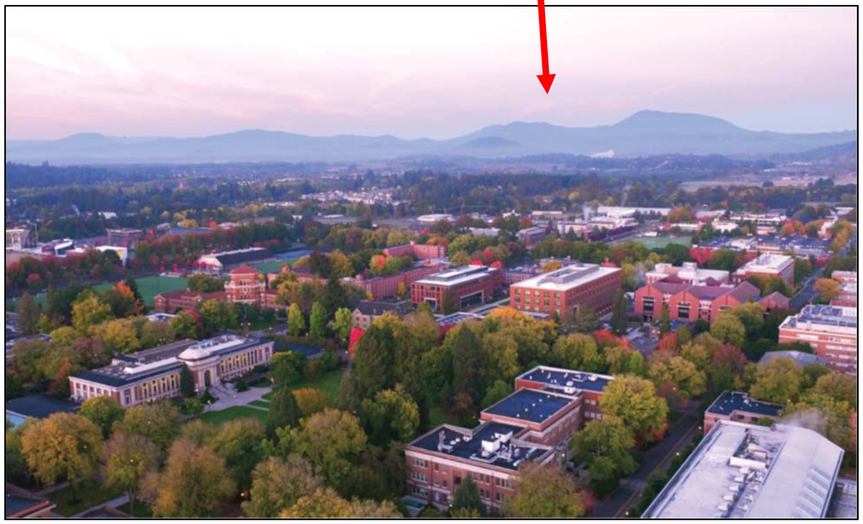
- **Give a sense of how Vulkan is different from OpenGL**
- **Show how to do basic drawing in Vulkan**
- **Leave you with working, documented, understandable sample code**

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

Mike Bailey

- **Professor of Computer Science, Oregon State University**
- **Has been in computer graphics for over 30 years**
- **Has had over 8,000 students in his university classes**
- **mjb@cs.oregonstate.edu**





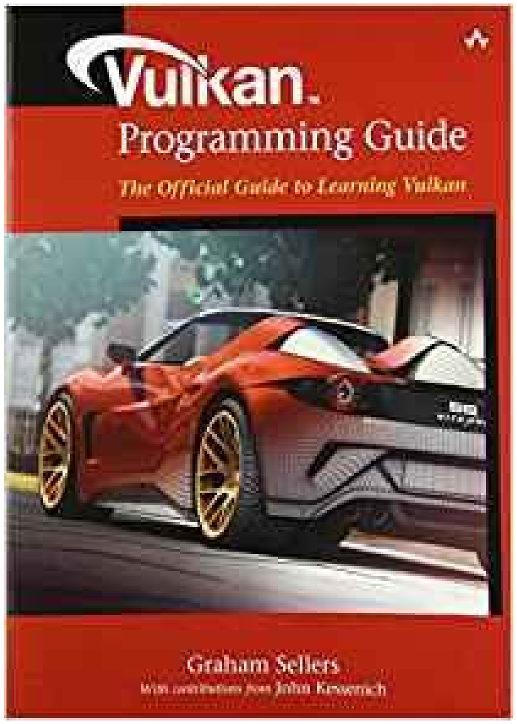
http://cs.oregonstate.edu/~mjb/vulkan

Sections

Section titles that have been greyed-out have not been included in the **ABRIDGED** noteset, i.e., the one that has been made to fit in SIGGRAPH's reduced time slot. These topics are in the **FULL** noteset, however, which can be found on the web page:

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

My Favorite Vulkan Reference



Graham Sellers, *Vulkan Programming Guide*, Addison-Wesley, 2017.

Vulkan.

Introduction

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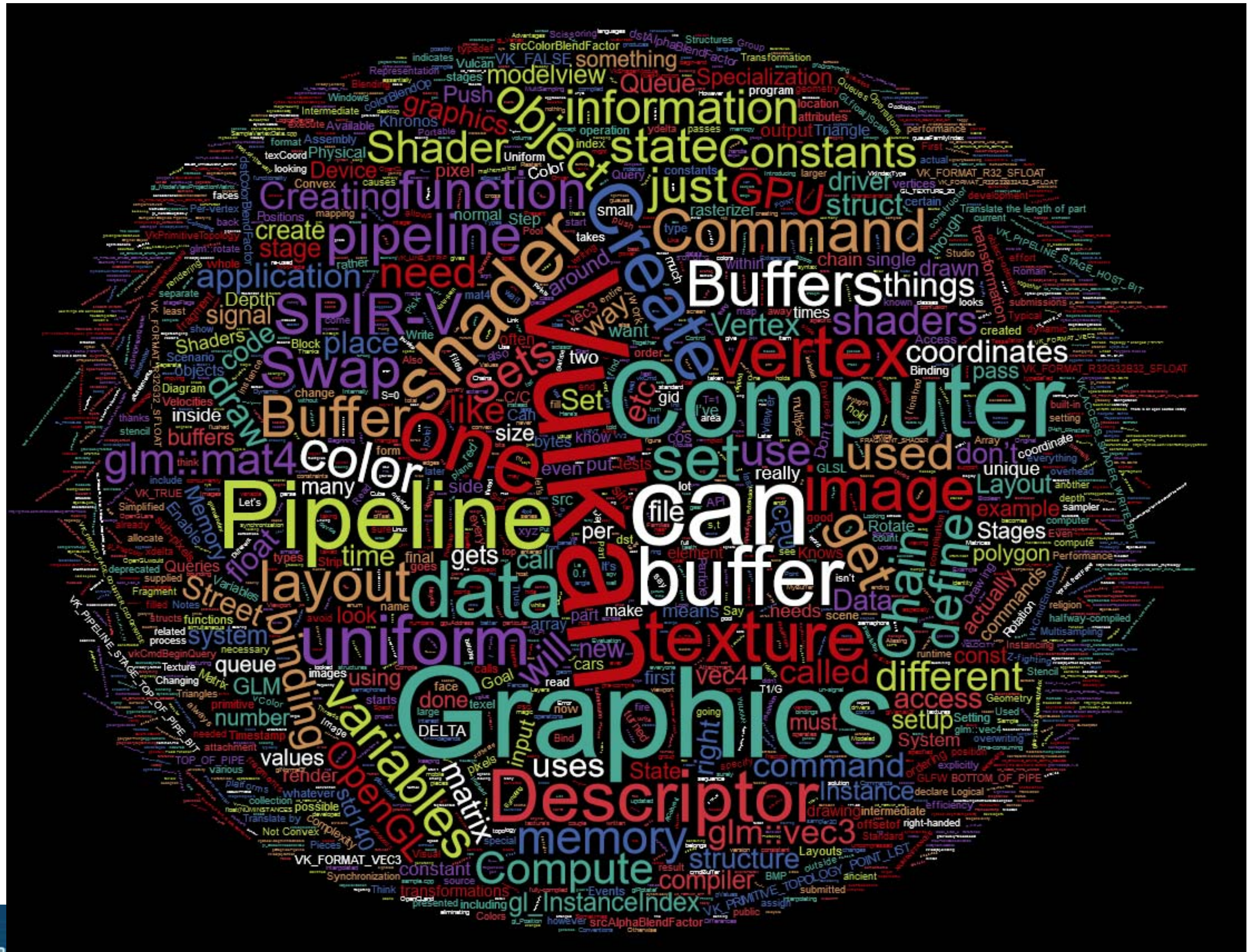
Everything You Need to Know is Right Here … Somewhere ☺



Top Three Reasons that Prompted the Development of Vulkan

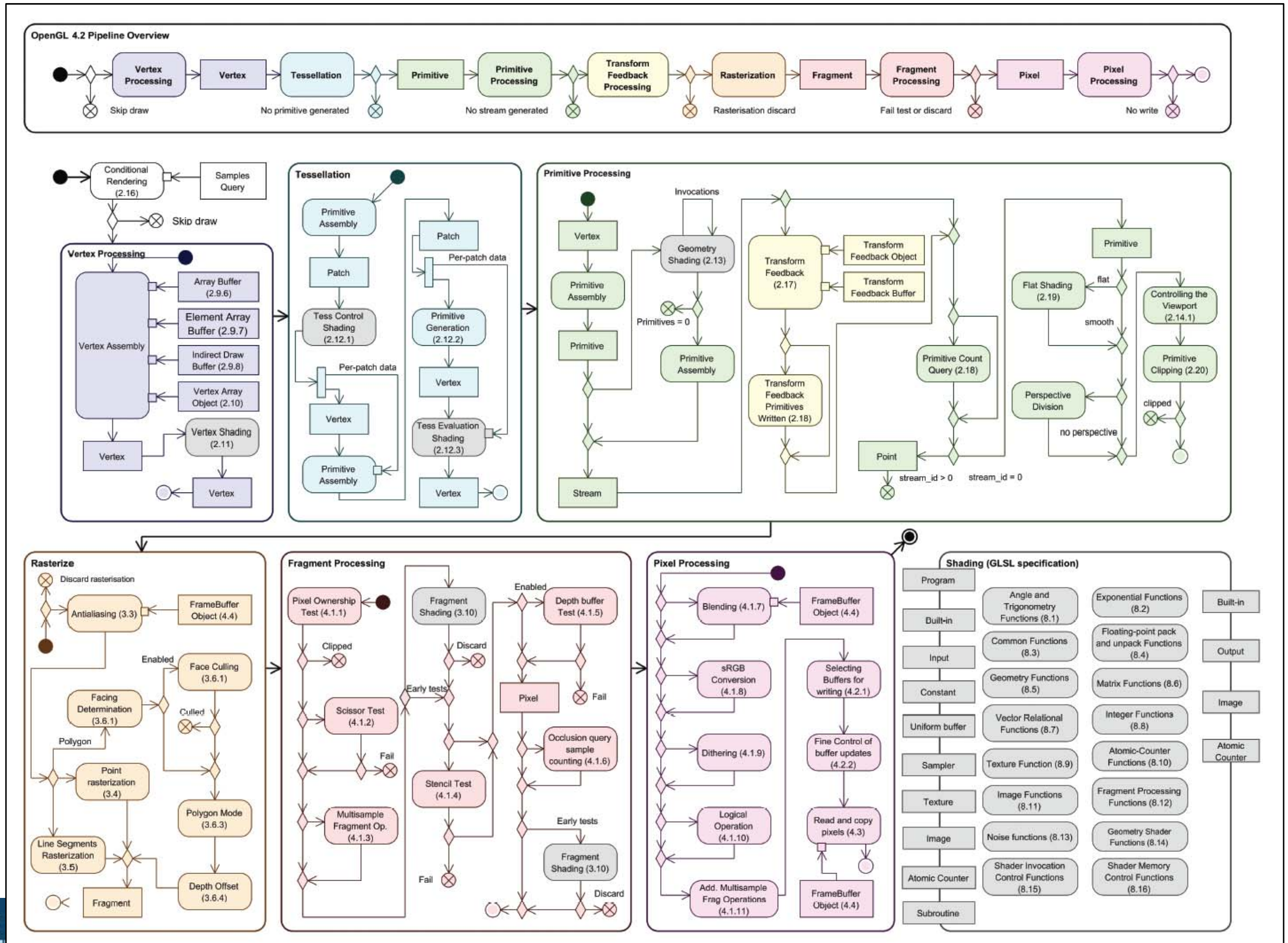
1. Performance
2. Performance
3. Performance

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

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-vertex*-end, fixed-function, etc.
- You must manage your own transformations.
- All transformation, color and texture functionality must be done in shaders.
- Shaders are pre-”half-compiled” outside of your application. The compilation process is then finished during the runtime pipeline-building process.

Vulkan Highlights: Pipeline State Data Structure

- In OpenGL, your “pipeline state” is the combination of whatever your current graphics attributes are: color, transformations, textures, shaders, etc.

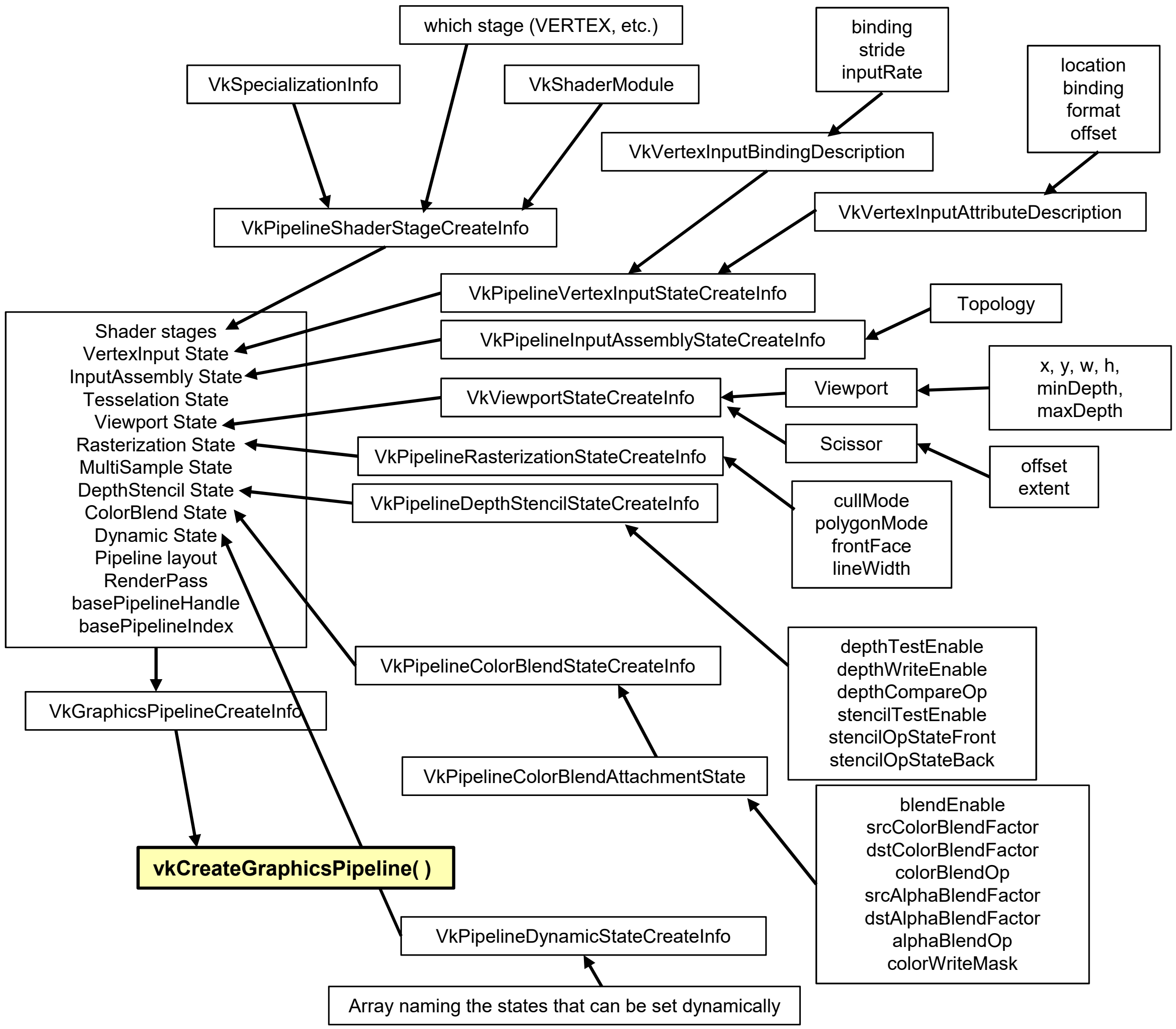
- Changing the state on-the-fly one item at-a-time is very expensive

- Vulkan forces you to set all your state variables at once into a “pipeline state object” (PSO) data structure and then invoke the entire PSO *at once* 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 pipeline state objects

Vulkan: Creating a Pipeline



Querying the Number of Something

```
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):

How many total there are — **Where to put them**

```
result = vkEnumeratePhysicalDevices( Instance,   &count,            nullptr   );

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

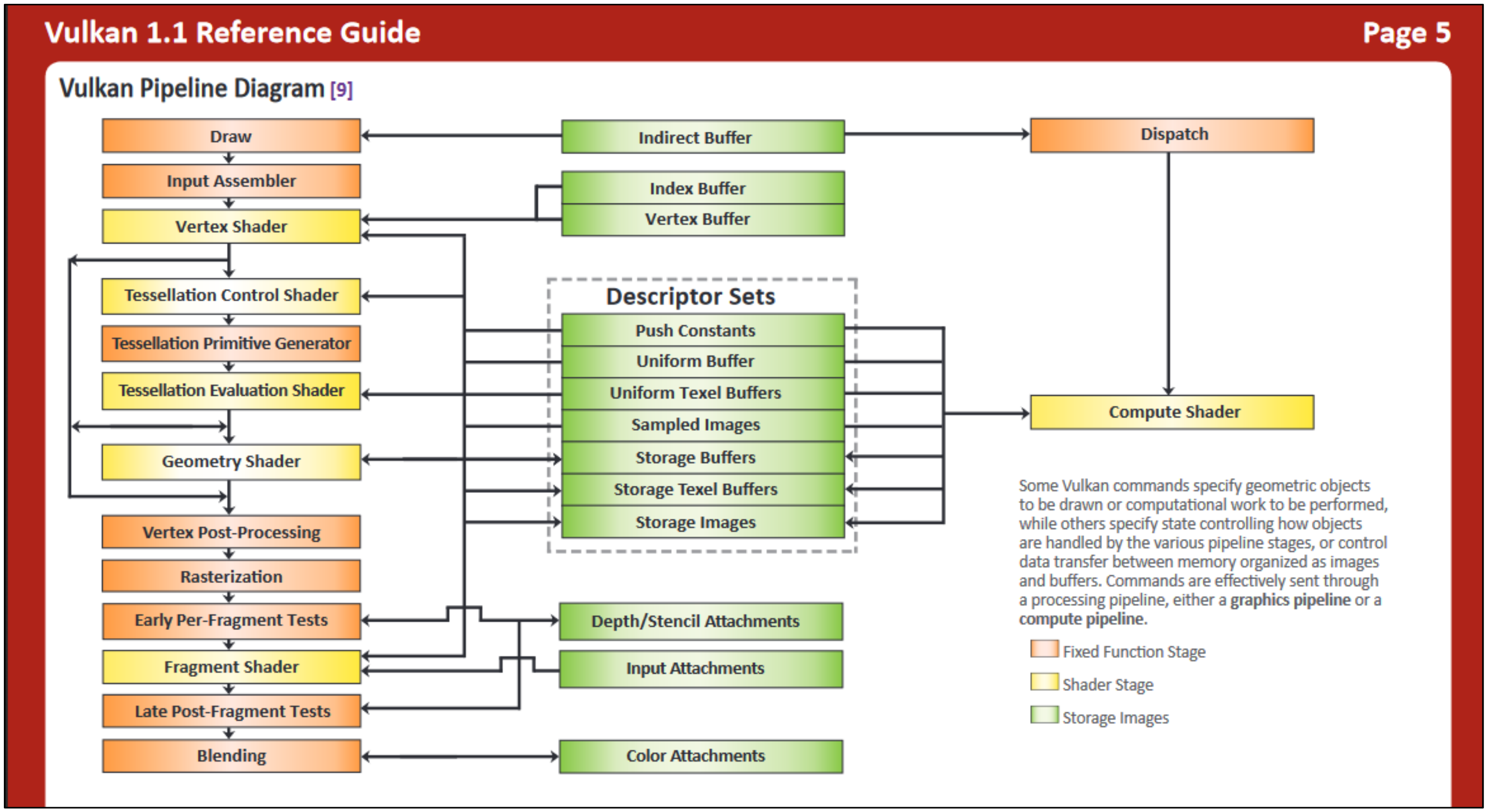
Vulkan Code has a Distinct "Style" of Setting Information in *structs* and then Passing that Information as a pointer-to-the-struct

```
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, OUT &MatrixBufferMemoryHandle );

result = vkBindBufferMemory( LogicalDevice, Buffer, MatrixBufferMemoryHandle, 0 );
```

Vulkan Quick Reference Card – I Recommend you Print This!

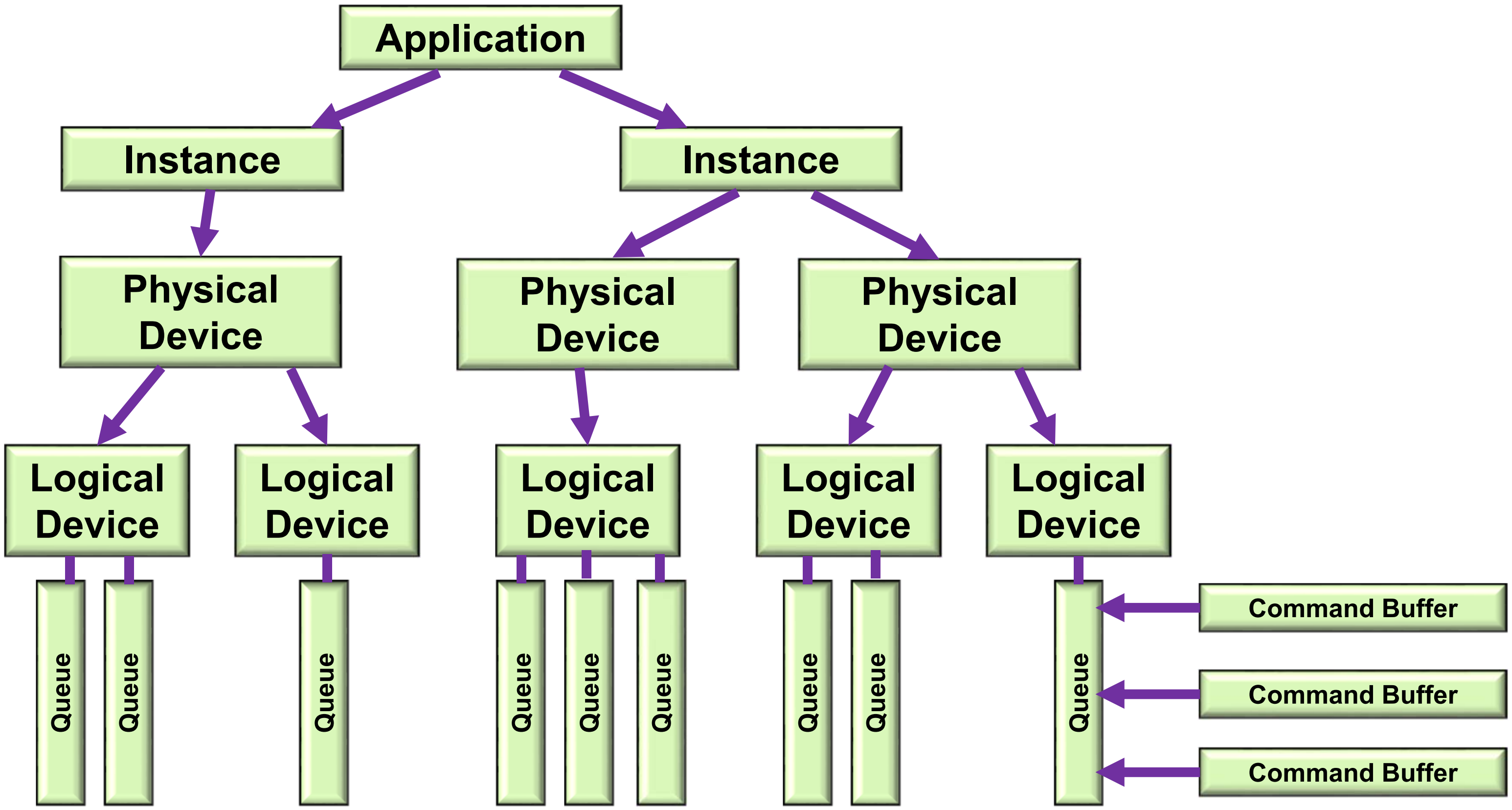
https://www.khronos.org/files/vulkan11-reference-guide.pdf

Vulkan Quick Reference Card

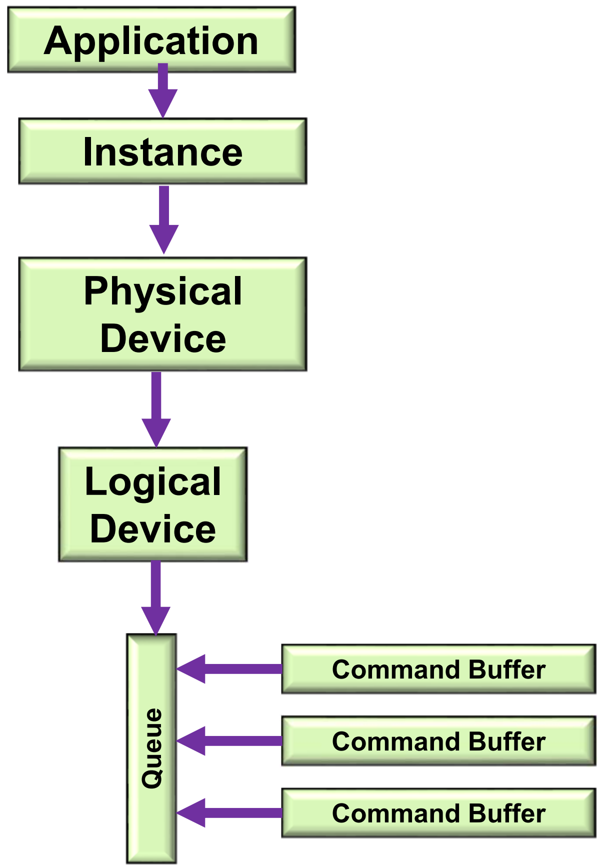


https://www.khronos.org/files/vulkan11-reference-guide.pdf

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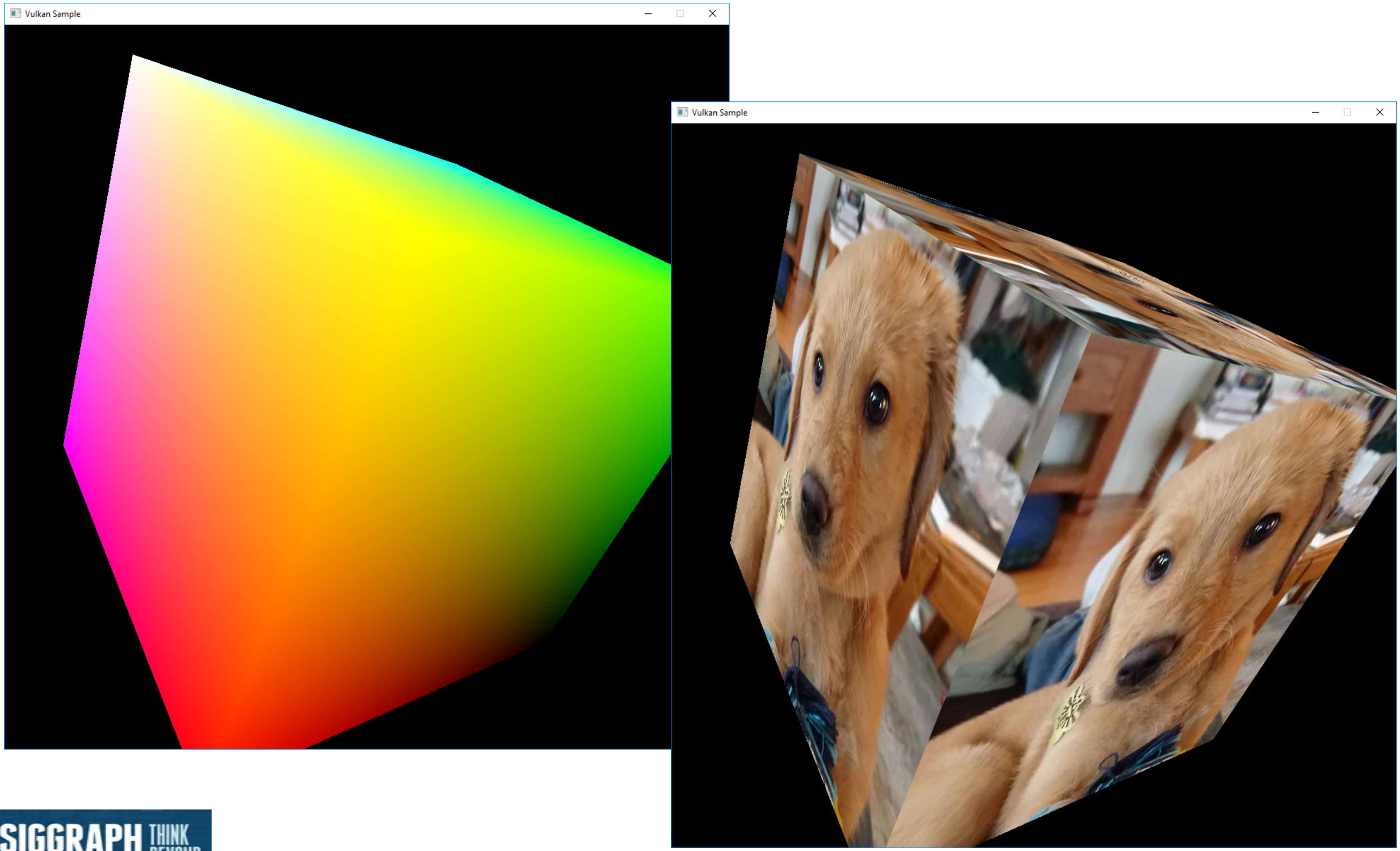
http://cs.oregonstate.edu/~mjb/vulkan

Sample Program Output



Sample Program Keyboard Inputs

'l', 'L':	Toggle **l**ighting off and on
'm', 'M':	Toggle display **m**ode (textures vs. colors, for now)
'p', 'P':	**P**ause the animation
'q', 'Q':	**q**uit the program
Esc:	quit the program
'r', 'R':	**T**oggle rotation-animation and using the mouse
'i', 'I':	Toggle using a vertex buffer only vs. an **i**ndex buffer (in the index buffer version)
'1', '4', '9'	Set the number of instances (in the instancing version)

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 (most?), 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 great 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. I hope it is clearer this way.

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

```
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'\n", DEBUGFILE );
		FpDebug = stderr;
	}
	fprintf(FpDebug, "FpDebug: Width = %d ; Height = %d\n", Width, Height);

	Reset( );
	InitGraphics( );

	// loop until the user closes the window:

	while( glfwWindowShouldClose( MainWindow ) == 0 )
	{
		glfwPollEvents( );
		Time = glfwGetTime( );		// elapsed time, in double-precision seconds
		UpdateScene( );
		RenderScene( );
	}

	fprintf(FpDebug, "Closing the GLFW window\n");

	vkQueueWaitIdle( Queue );
	vkDeviceWaitIdle( LogicalDevice );
	DestroyAllVulkan( );
	glfwDestroyWindow( MainWindow );
	glfwTerminate( );
	return 0;
}
```

Vulkan Conventions

VkXxx is a typedef, probably a struct

vkYyy( ) is a function call

VK_ZZZ is a constant

My Conventions

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

The number after “Init” gives you the ordering

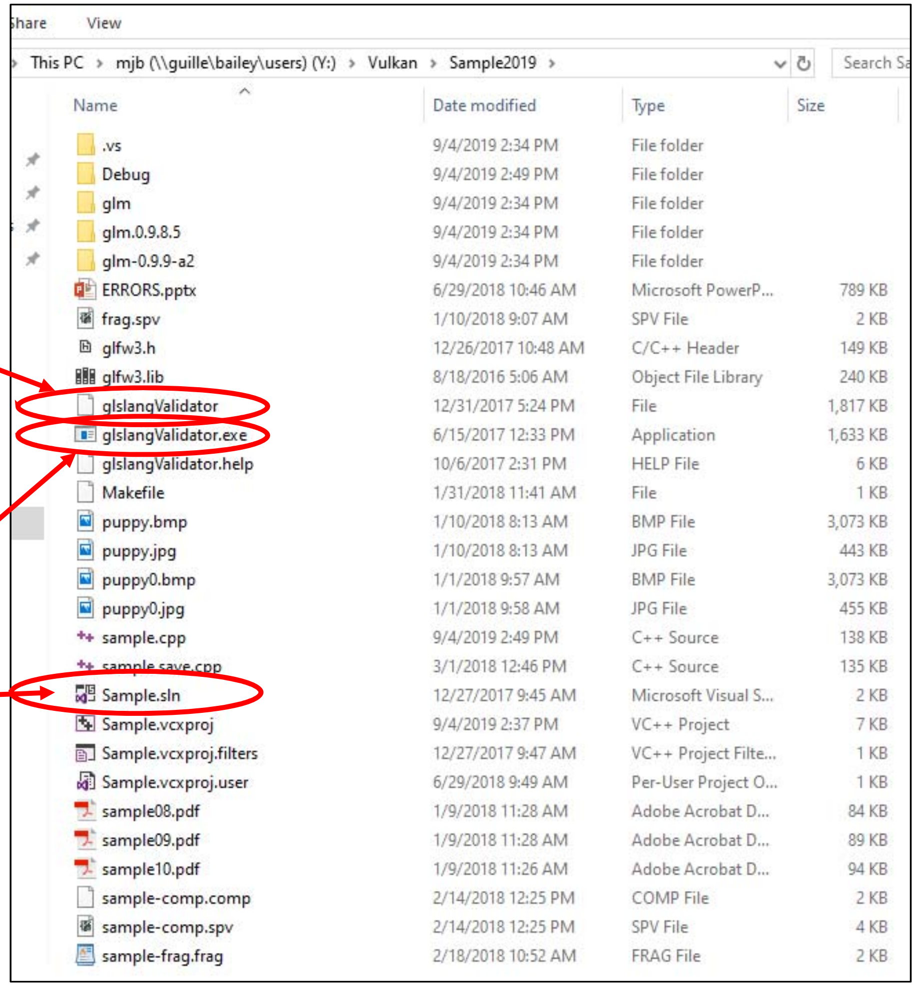
In the source code, after main( ) comes InitGraphics( ), then all of the InitxxYYY( ) functions in numerical order. After that comes the helper functions

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

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

“IN” and “OUT” ahead of function call arguments are just there to let you know how an argument is going to be used by the function. Otherwise, IN and OUT have no significance. They are actually #define’d to nothing.

Your Sample2019.zip File Contains This



Linux shader compiler

Windows shader compiler

Double-click here to launch Visual Studio 2019 with this solution

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

Reporting Error Results, I


```
struct errorcode
{
	VkResult	resultCode;
	std::stringmeaning;
}
ErrorCodes[ ] =
{
	{ VK_NOT_READY,				"Not Ready“		},
	{ VK_TIMEOUT,				"Timeout“		},
	{ VK_EVENT_SET,				"Event Set“		},
	{ VK_EVENT_RESET,			"Event Reset“		},
	{ VK_INCOMPLETE,			"Incomplete“		},
	{ VK_ERROR_OUT_OF_HOST_MEMORY,		"Out of Host Memory“	},
	{ VK_ERROR_OUT_OF_DEVICE_MEMORY,	"Out of Device Memory“	},
	{ VK_ERROR_INITIALIZATION_FAILED,	"Initialization Failed“	},
	{ VK_ERROR_DEVICE_LOST,			"Device Lost“		},
	{ VK_ERROR_MEMORY_MAP_FAILED,		"Memory Map Failed“	},
	{ VK_ERROR_LAYER_NOT_PRESENT,		"Layer Not Present“	},
	{ VK_ERROR_EXTENSION_NOT_PRESENT,	"Extension Not Present“	},
	{ VK_ERROR_FEATURE_NOT_PRESENT,		"Feature Not Present“	},
	{ VK_ERROR_INCOMPATIBLE_DRIVER,		"Incompatible Driver“	},
	{ VK_ERROR_TOO_MANY_OBJECTS,		"Too Many Objects“	},
	{ VK_ERROR_FORMAT_NOT_SUPPORTED,	"Format Not Supported“	},
	{ VK_ERROR_FRAGMENTED_POOL,		"Fragmented Pool“	},
	{ VK_ERROR_SURFACE_LOST_KHR,		"Surface Lost“		},
	{ VK_ERROR_NATIVE_WINDOW_IN_USE_KHR,	"Native Window in Use“	},
	{ VK_SUBOPTIMAL_KHR,			"Suboptimal“		},
	{ VK_ERROR_OUT_OF_DATE_KHR,		"Error Out of Date“	},
	{ VK_ERROR_INCOMPATIBLE_DISPLAY_KHR,	"Incompatible Display“	},
	{ VK_ERROR_VALIDATION_FAILED_EXT,	"Valuidation Failed“	},
	{ VK_ERROR_INVALID_SHADER_NV,		"Invalid Shader“	},
	{ VK_ERROR_OUT_OF_POOL_MEMORY_KHR,	"Out of Pool Memory“	},
	{ VK_ERROR_INVALID_EXTERNAL_HANDLE,	"Invalid External Handle“	},
};
```

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Reporting Error Results, II


```
void
PrintVkError( VkResult result, std::string prefix )
{
	if (Verbose  &&  result == VK_SUCCESS)
	{
		fprintf(FpDebug, "%s: %s\n", prefix.c_str(), "Successful");
		fflush(FpDebug);
		return;
	}

	const int numErrorCodes = sizeof( ErrorCodes ) / sizeof( struct errorcode );
	std::string meaning = "";
	for( int i = 0; i < numErrorCodes; i++ )
	{
		if( result == ErrorCodes[i].resultCode )
		{
			meaning = ErrorCodes[i].meaning;
			break;
		}
	}

	fprintf( FpDebug, "\n%s: %s\n", prefix.c_str(), meaning.c_str() );
	fflush(FpDebug);
}
```

Extras in the Code


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

#define HERE_I_AM(s)           if( Verbose )  { fprintf( FpDebug, "***** %s *****\n", s );  fflush(FpDebug); }

bool                Paused;

bool                Verbose;

#define DEBUGFILE              "VulkanDebug.txt"

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

const int32_t   OFFSET_ZERO =   0;
```

Drawing

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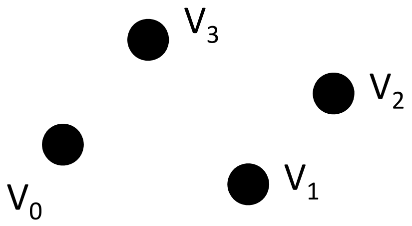
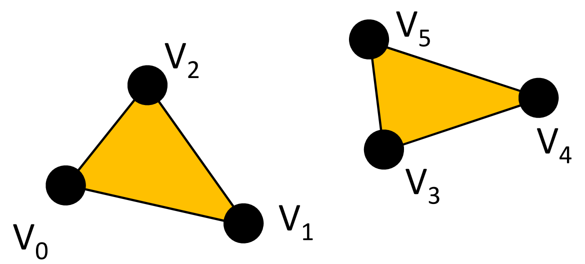
Vulkan Topologies

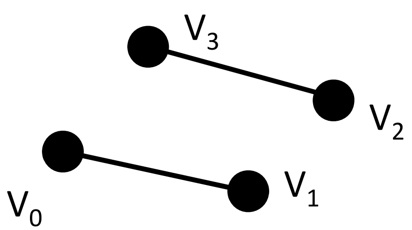
VK_PRIMITIVE_TOPOLOGY_POINT_LIST



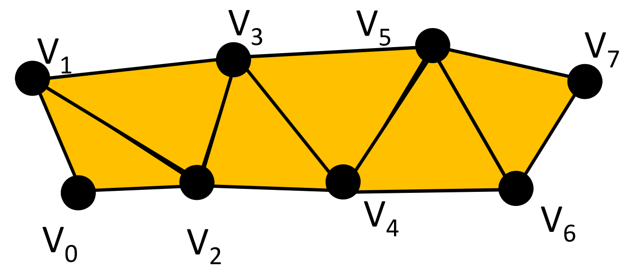
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



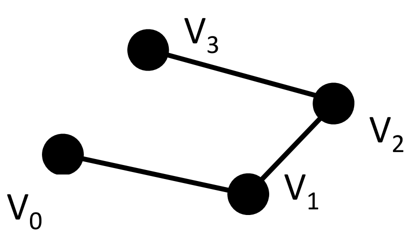
VK_PRIMITIVE_TOPOLOGY_LINE_LIST



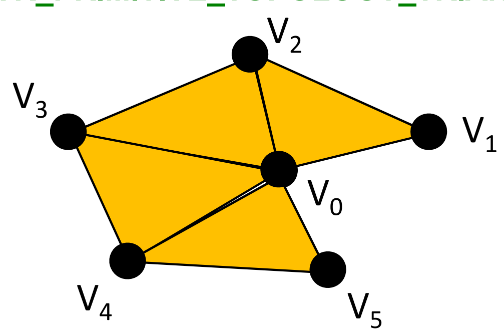
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP



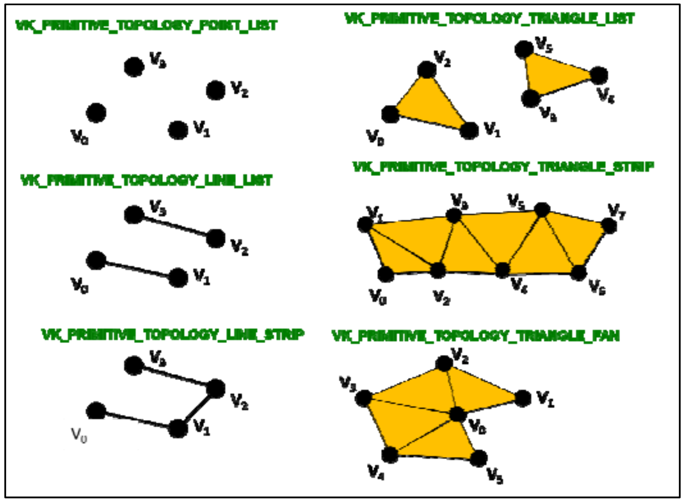
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP



VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN

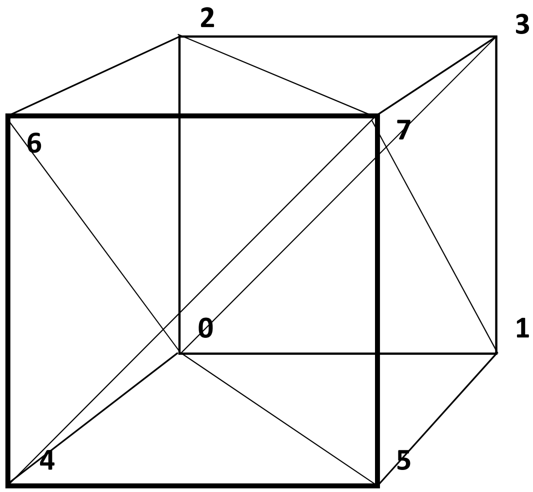


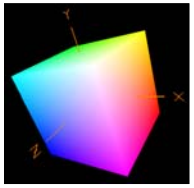
Vulkan Topologies




```
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;
```

A Colored Cube Example





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

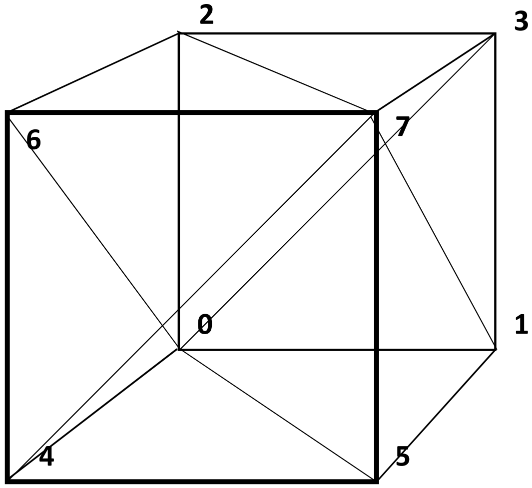
```
static GLfloat CubeVertices[ ][3] =
{
        { -1., -1., -1. },
        {  1., -1., -1. },
        { -1.,  1., -1. },
        {  1.,  1., -1. },
        { -1., -1.,  1. },
        {  1., -1.,  1. },
        { -1.,  1.,  1. },
        {  1.,  1.,  1. }
};
```

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

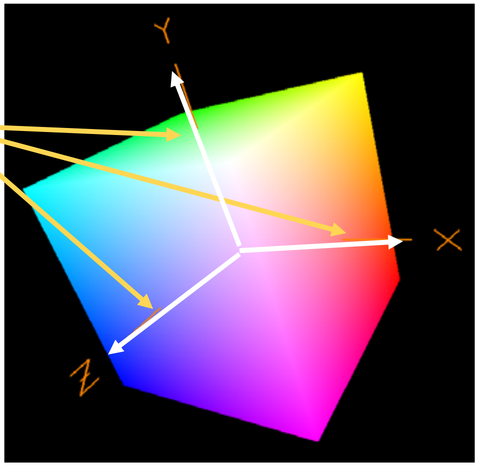
Triangles Represented as an Array of Structures

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

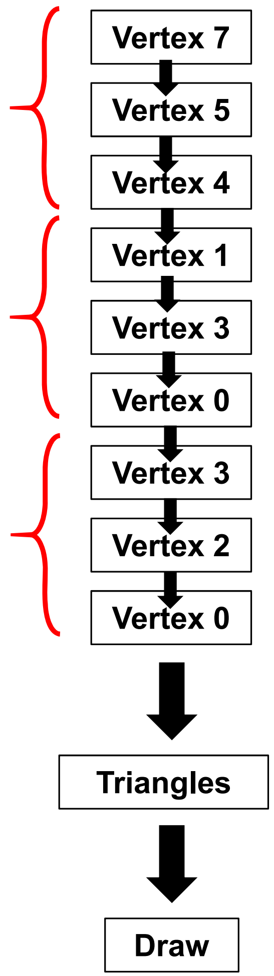


Non-indexed Buffer Drawing

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. }
        },
```

Stream of Vertices



Filling the Vertex Buffer

```
struct vertex  VertexData[ ] =
{
        . . .
};

MyBuffer          MyVertexDataBuffer;


Init05MyVertexDataBuffer(  sizeof(VertexData), OUT &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;
}
```

Telling the Pipeline about its Input

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

C/C++:

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

GLSL Shader:

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

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

Telling the Pipeline about its Input

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

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

```
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
```

Always use the C/C++ construct ***offsetof***, rather than hardcoding the value!

Telling the Pipeline about its Input

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

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

VkPipelineInputAssemblyStateCreateInfo        vpiasci;
        vpiasci.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
        vpiasci.pNext = nullptr;
        vpiasci.flags = 0;
        vpiasci.topology = VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST;;
```

Telling the Pipeline about its Input

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

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

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

Telling the Command Buffer what Vertices to Draw

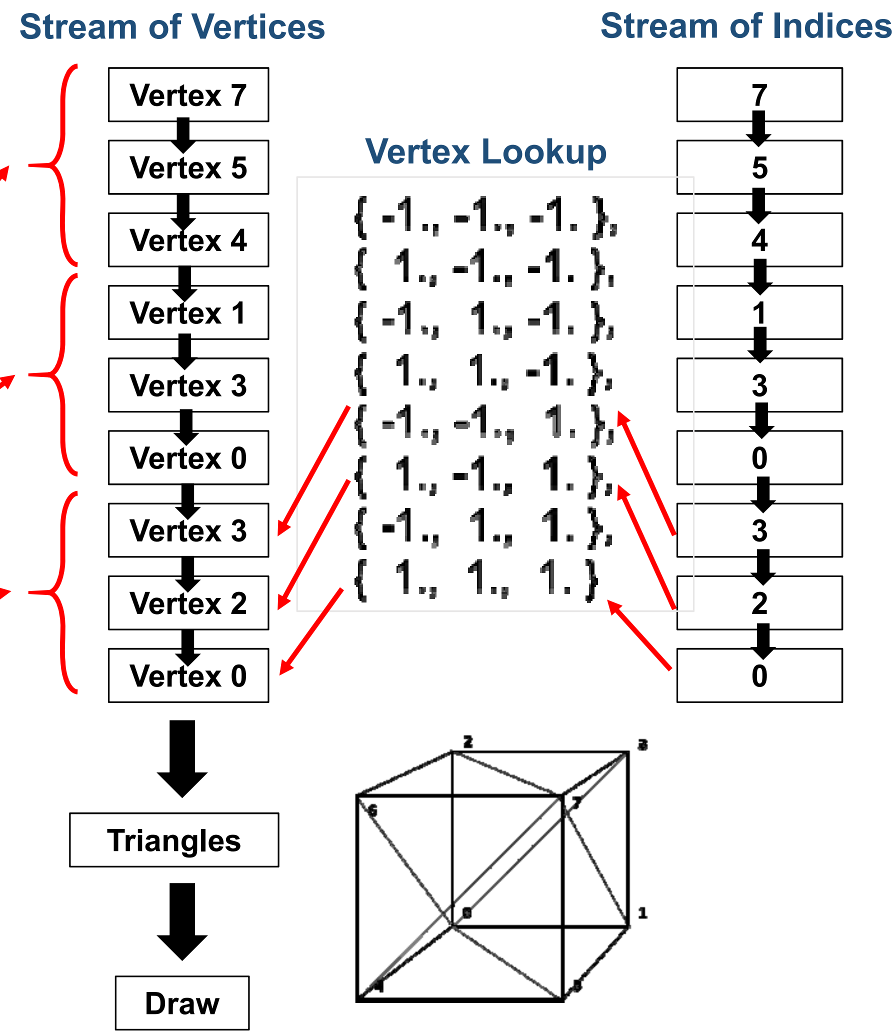
We will come to Command Buffers later, but for now, know that you will specify the vertex buffer that you want drawn.

```
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 );
```

Always use the C/C++ construct ***sizeof***, rather than hardcoding a count!

Drawing with an Index 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,
};
```



Drawing with an Index Buffer


```
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 Index Buffer

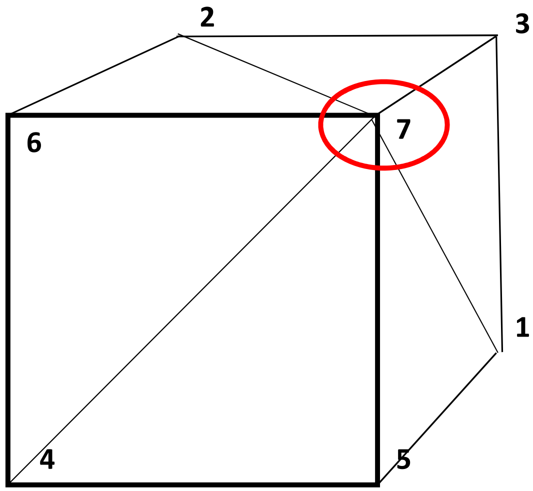
```
VkResult
Init05MyIndexDataBuffer(IN VkDeviceSize size, OUT MyBuffer * pMyBuffer)
{
	VkResult result = Init05DataBuffer(size, VK_BUFFER_USAGE_INDEX_BUFFER_BIT, pMyBuffer);
							// fills pMyBuffer
	return result;
}
```

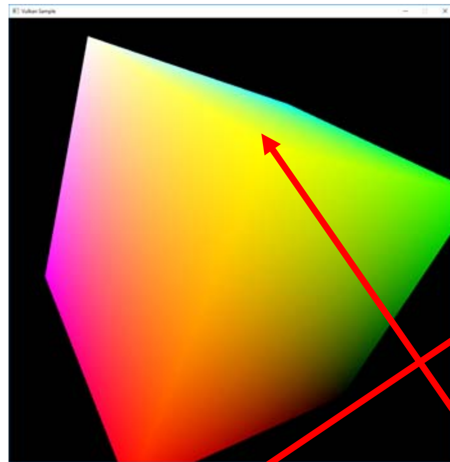
```
Init05MyVertexDataBuffer(  sizeof(JustVertexData), IN &MyJustVertexDataBuffer );
Fill05DataBuffer( MyJustVertexDataBuffer,           (void *) JustVertexData );

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

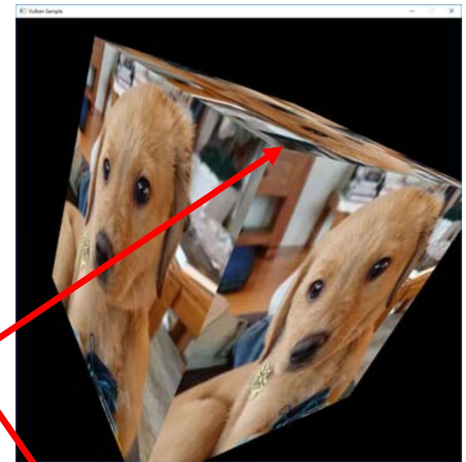
Drawing with an Index Buffer


```
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 );

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

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

Sometimes the Same Point Needs Multiple Attributes





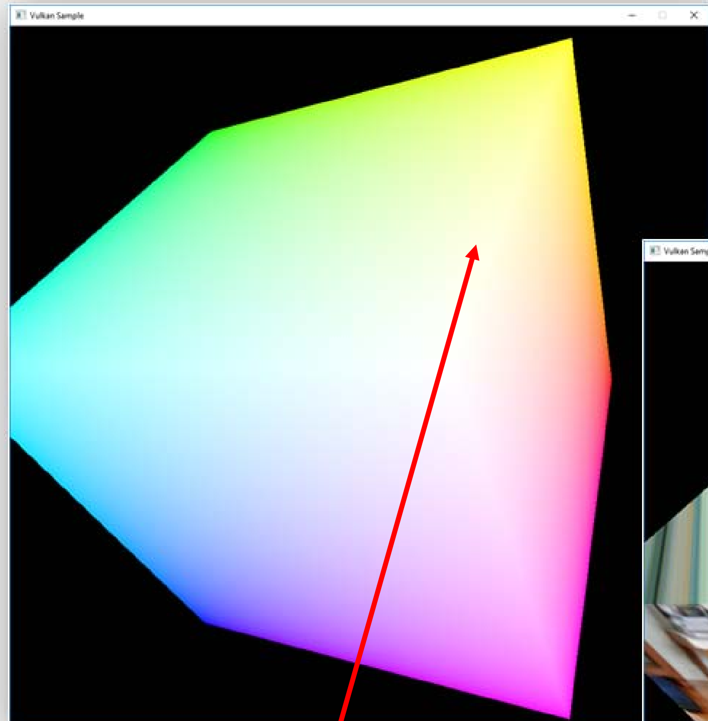


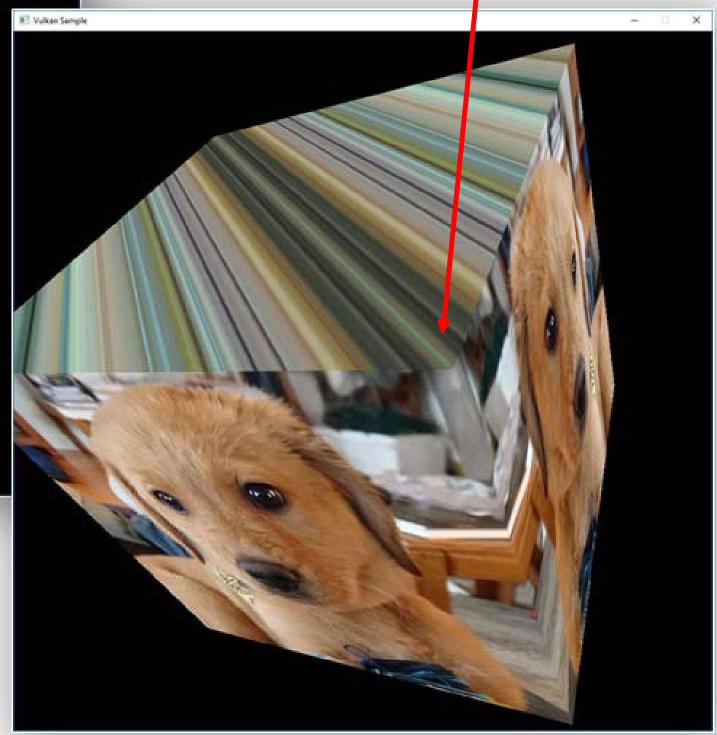
Sometimes a point that is common to multiple faces has the same attributes, no matter what face it is in. Sometimes it doesn't.

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 indexed 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 do not match at the corners (texture coordinates)

Where values match at the corners (color)

Shaders and SPIR-V

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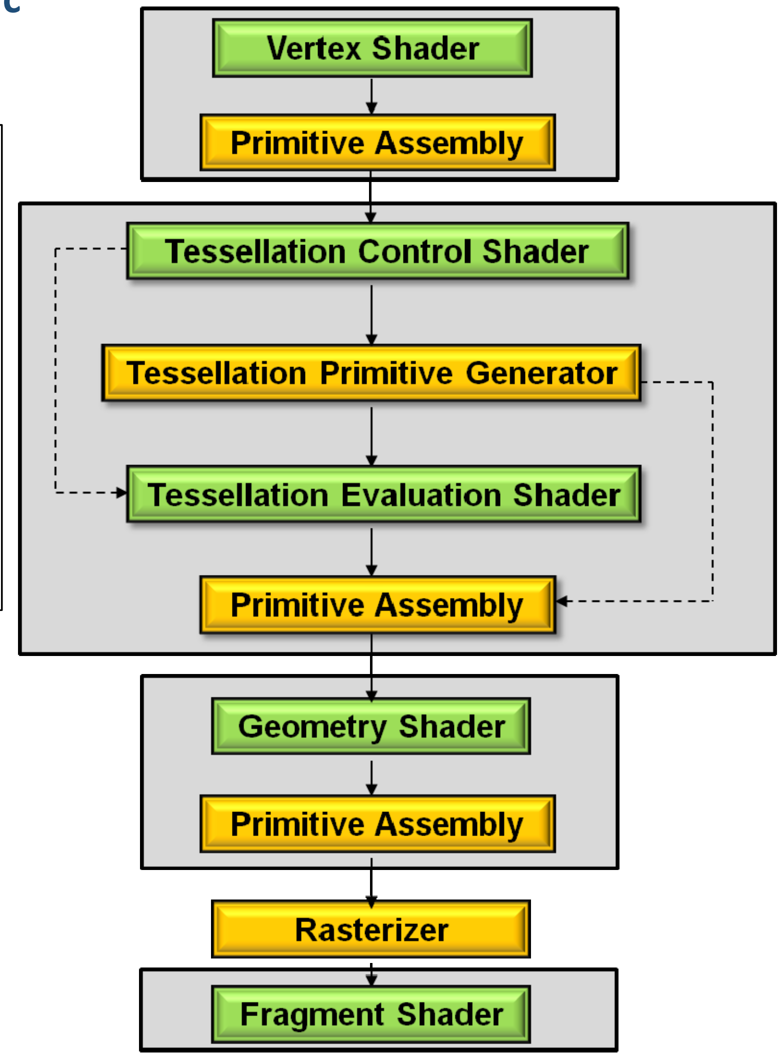
The Shaders' View of the Basic Computer Graphics Pipeline

• 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



= Fixed Function

= Programmable

Vulkan Shader Stages

Shader stages

```
typedef enum VkPipelineStageFlagBits {
    VK_PIPELINE_STAGE_TOP_OF_PIPE_BIT = 0x00000001,
    VK_PIPELINE_STAGE_DRAW_INDIRECT_BIT = 0x00000002,
    VK_PIPELINE_STAGE_VERTEX_INPUT_BIT = 0x00000004,
    VK_PIPELINE_STAGE_VERTEX_SHADER_BIT = 0x00000008,
    VK_PIPELINE_STAGE_TESSELLATION_CONTROL_SHADER_BIT = 0x00000010,
    VK_PIPELINE_STAGE_TESSELLATION_EVALUATION_SHADER_BIT = 0x00000020,
    VK_PIPELINE_STAGE_GEOMETRY_SHADER_BIT = 0x00000040,
    VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT = 0x00000080,
    VK_PIPELINE_STAGE_EARLY_FRAGMENT_TESTS_BIT = 0x00000100,
    VK_PIPELINE_STAGE_LATE_FRAGMENT_TESTS_BIT = 0x00000200,
    VK_PIPELINE_STAGE_COLOR_ATTACHMENT_OUTPUT_BIT = 0x00000400,
    VK_PIPELINE_STAGE_COMPUTE_SHADER_BIT = 0x00000800,
    VK_PIPELINE_STAGE_TRANSFER_BIT = 0x00001000,
    VK_PIPELINE_STAGE_BOTTOM_OF_PIPE_BIT = 0x00002000,
    VK_PIPELINE_STAGE_HOST_BIT = 0x00004000,
    VK_PIPELINE_STAGE_ALL_GRAPHICS_BIT = 0x00008000,
    VK_PIPELINE_STAGE_ALL_COMMANDS_BIT = 0x00010000,
} VkPipelineStageFlagBits;
```

How Vulkan GLSL Differs from OpenGL GLSL

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_VertexID
gl_InstanceIndex	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

How Vulkan GLSL Differs from OpenGL GLSL

Shader combinations of separate texture data and samplers:

```
uniform sampler s;
uniform texture2D t;
vec4 rgba = texture(  sampler2D( t, s ),  vST  );
```

Note: our sample code doesn't use this.

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

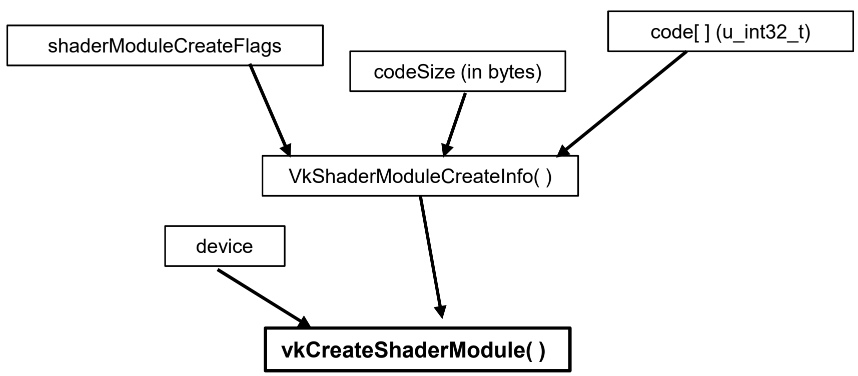
Vulkan: Shaders' use of Layouts for Uniform Variables

```
// 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 half-precompile 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, when the pipeline structure is finally created
- The SPIR-V spec has been public for a few years –new shader languages are surely being developed
- OpenGL and OpenCL have now 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

glslangValidator shaderFile -V [-H] [-I<dir>] [-S <stage>] -o shaderBinaryFile.spv

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: glslangValidator

Running glslangValidator.exe

glslangValidator.exe -V sample-vert.vert -o sample-vert.spv

Compile for Vulkan ("-G" is compile for OpenGL)

Specify the output file

The input file. The compiler determines the shader type by the file extension:

.vert	Vertex shader
.tccs	Tessellation Control Shader
.tecs	Tessellation Evaluation Shader
.geom	Geometry shader
.frag	Fragment shader
.comp	Compute shader

Running glslangValidator.exe

```
MINGW64:/y/Vulkan/Sample2017

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

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

ONID+mjb@pooh MINGW64 /y/Vulkan/Sample2017
$
```

How do you know if SPIR-V compiled successfully?

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

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

So, if you do an **od –x** on the .spv file, the magic number looks like this:

0203 0723 . . .

Reading a SPIR-V File into a Vulkan Shader Module

```
#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 );
```

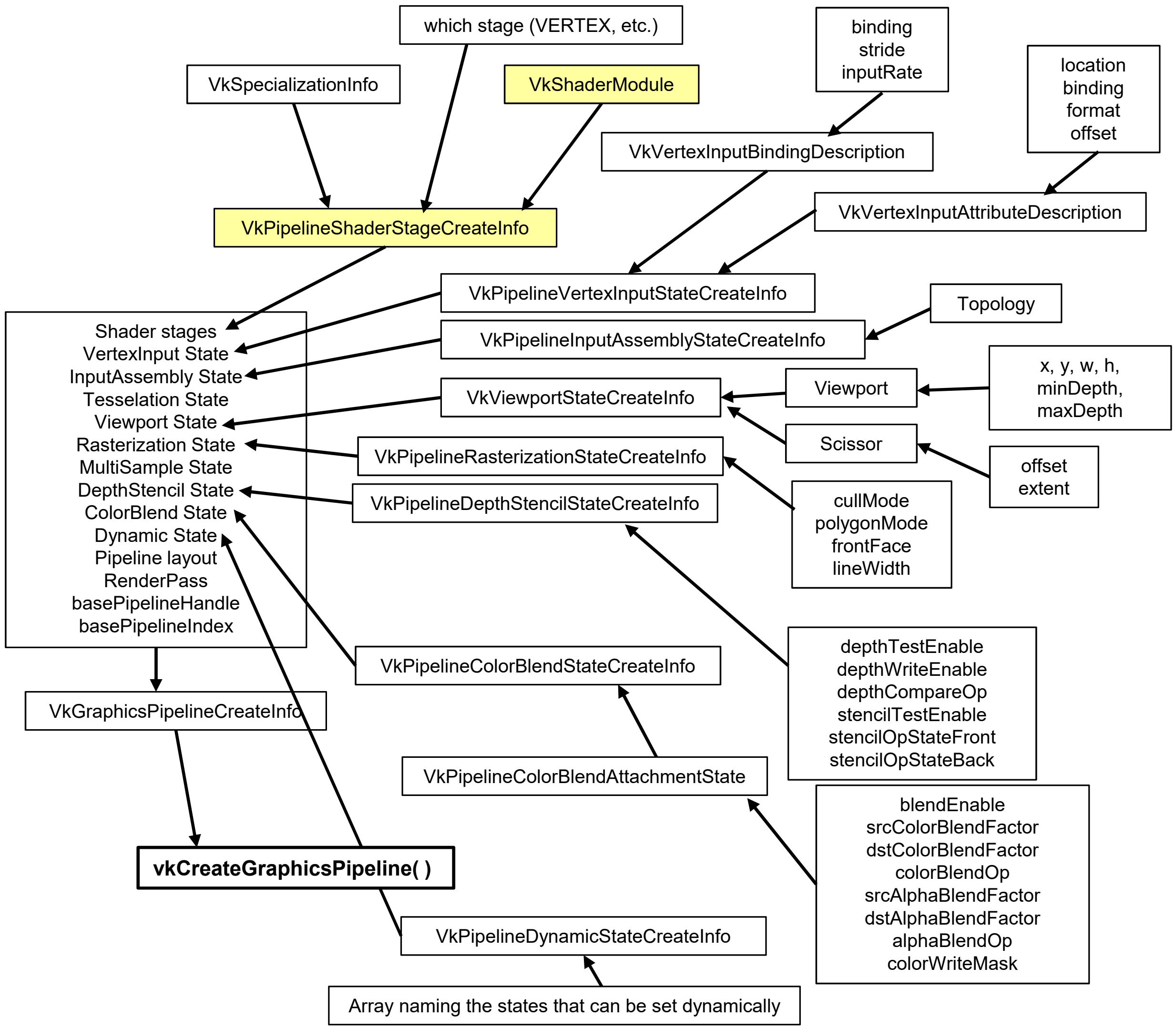
Reading a SPIR-V File into a Shader Module

```
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 Pipeline



You can also take a look at SPIR-V Assembly

```
glslangValidator.exe   -V   -H   sample-vert.vert   -o   sample-vert.spv
```

This prints out the SPIR-V "assembly" to standard output.
Other than nerd interest, there is no graphics-programming reason to look at this. ☺

For example, if this is your Shader Source

```
#version 400
#extension GL_ARB_separate_shader_objects  : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
        mat4 uModelMatrix;
        mat4 uViewMatrix;
        mat4 uProjectionMatrix;
        mat3 uNormalMatrix;
} Matrices;

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

layout( 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 = 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;
        gl_Position = PVM * vec4( aVertex, 1. );

        vNormal   = Matrices.uNormalMatrix * aNormal;
        vColor    = aColor;
        vTexCoord = aTexCoord;
}
```

This is the SPIR-V Assembly, Part I

```
#version 400
#extension GL_ARB_separate_shader_objects : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat3 uNormalMatrix;
} Matrices;

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

layout( 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 = 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;
	gl_Position = PVM * vec4( aVertex, 1. );

	vNormal   = Matrices.uNormalMatrix * aNormal;
	vColor    = aColor;
	vTexCoord = aTexCoord;
}
```

```
                  Capability Shader
   1:             ExtInstImport  "GLSL.std.450"
                  MemoryModel Logical GLSL450
                  EntryPoint Vertex 4  "main" 34 37 48 53 56 57 61 63
                  Source GLSL 400
                  SourceExtension  "GL_ARB_separate_shader_objects"
                  SourceExtension  "GL_ARB_shading_language_420pack"
                  Name 4  "main"
                  Name 10  "PVM"
                  Name 13  "matBuf"
                  MemberName 13(matBuf) 0  "uModelMatrix"
                  MemberName 13(matBuf) 1  "uViewMatrix"
                  MemberName 13(matBuf) 2  "uProjectionMatrix"
                  MemberName 13(matBuf) 3  "uNormalMatrix"
                  Name 15  "Matrices"
                  Name 32  "gl_PerVertex"
                  MemberName 32(gl_PerVertex) 0  "gl_Position"
                  MemberName 32(gl_PerVertex) 1  "gl_PointSize"
                  MemberName 32(gl_PerVertex) 2  "gl_ClipDistance"
                  Name 34  ""
                  Name 37  "aVertex"
                  Name 48  "vNormal"
                  Name 53  "aNormal"
                  Name 56  "vColor"
                  Name 57  "aColor"
                  Name 61  "vTexCoord"
                  Name 63  "aTexCoord"
                  Name 65  "lightBuf"
                  MemberName 65(lightBuf) 0  "uLightPos"
                  Name 67  "Light"
                  MemberDecorate 13(matBuf) 0 ColMajor
                  MemberDecorate 13(matBuf) 0 Offset 0
                  MemberDecorate 13(matBuf) 0 MatrixStride 16
                  MemberDecorate 13(matBuf) 1 ColMajor
                  MemberDecorate 13(matBuf) 1 Offset 64
                  MemberDecorate 13(matBuf) 1 MatrixStride 16
                  MemberDecorate 13(matBuf) 2 ColMajor
                  MemberDecorate 13(matBuf) 2 Offset 128
                  MemberDecorate 13(matBuf) 2 MatrixStride 16
                  MemberDecorate 13(matBuf) 3 ColMajor
                  MemberDecorate 13(matBuf) 3 Offset 192
                  MemberDecorate 13(matBuf) 3 MatrixStride 16
                  Decorate 13(matBuf) Block
                  Decorate 15(Matrices) DescriptorSet 0
```

This is the SPIR-V Assembly, Part II

```
#version 400
#extension GL_ARB_separate_shader_objects : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat3 uNormalMatrix;
} Matrices;

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

layout( 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 = 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;
	gl_Position = PVM * vec4( aVertex, 1. );

	vNormal   = Matrices.uNormalMatrix * aNormal;
	vColor    = aColor;
	vTexCoord = aTexCoord;
}
```

```
                              Decorate 15(Matrices) Binding 0
                              MemberDecorate 32(gl_PerVertex) 0 BuiltIn Position
                              MemberDecorate 32(gl_PerVertex) 1 BuiltIn PointSize
                              MemberDecorate 32(gl_PerVertex) 2 BuiltIn ClipDistance
                              Decorate 32(gl_PerVertex) Block
                              Decorate 37(aVertex) Location 0
                              Decorate 48(vNormal) Location 0
                              Decorate 53(aNormal) Location 1
                              Decorate 56(vColor) Location 1
                              Decorate 57(aColor) Location 2
                              Decorate 61(vTexCoord) Location 2
                              Decorate 63(aTexCoord) Location 3
                              MemberDecorate 65(lightBuf) 0 Offset 0
                              Decorate 65(lightBuf) Block
                              Decorate 67(Light) DescriptorSet 1
                              Decorate 67(Light) Binding 0
               2:             TypeVoid
               3:             TypeFunction 2
               6:             TypeFloat 32
               7:             TypeVector 6(float) 4
               8:             TypeMatrix 7(fvec4) 4
               9:             TypePointer Function 8
              11:             TypeVector 6(float) 3
              12:             TypeMatrix 11(fvec3) 3
     13(matBuf):              TypeStruct 8 8 8 12
              14:             TypePointer Uniform 13(matBuf)
   15(Matrices):      14(ptr) Variable Uniform
              16:             TypeInt 32 1
              17:     16(int) Constant 2
              18:             TypePointer Uniform 8
              21:     16(int) Constant 1
              25:     16(int) Constant 0
              29:             TypeInt 32 0
              30:     29(int) Constant 1
              31:             TypeArray 6(float) 30
32(gl_PerVertex):             TypeStruct 7(fvec4) 6(float) 31
              33:             TypePointer Output 32(gl_PerVertex)
              34:     33(ptr) Variable Output
              36:             TypePointer Input 11(fvec3)
    37(aVertex):      36(ptr) Variable Input
              39:    6(float) Constant 1065353216
              45:             TypePointer Output 7(fvec4)
              47:             TypePointer Output 11(fvec3)
    48(vNormal):      47(ptr) Variable Output
              49:     16(int) Constant 3
```

This is the SPIR-V Assembly, Part III

```
#version 400
#extension GL_ARB_separate_shader_objects : enable
#extension GL_ARB_shading_language_420pack : enable
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
	mat4 uModelMatrix;
	mat4 uViewMatrix;
	mat4 uProjectionMatrix;
	mat3 uNormalMatrix;
} Matrices;

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

layout( 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 = 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;
	gl_Position = PVM * vec4( aVertex, 1. );

	vNormal   = Matrices.uNormalMatrix * aNormal;
	vColor    = aColor;
	vTexCoord = aTexCoord;
}
```

```
         50:          TypePointer Uniform 12
 53(aNormal):      36(ptr) Variable Input
  56(vColor):      47(ptr) Variable Output
  57(aColor):      36(ptr) Variable Input
         59:          TypeVector 6(float) 2
         60:          TypePointer Output 59(fvec2)
61(vTexCoord):      60(ptr) Variable Output
         62:          TypePointer Input 59(fvec2)
63(aTexCoord):      62(ptr) Variable Input
65(lightBuf):          TypeStruct 7(fvec4)
         66:          TypePointer Uniform 65(lightBuf)
   67(Light):      66(ptr) Variable Uniform
    4(main):           2 Function None 3
          5:          Label
    10(PVM):        9(ptr) Variable Function
         19:    18(ptr) AccessChain 15(Matrices) 17
         20:          8 Load 19
         22:    18(ptr) AccessChain 15(Matrices) 21
         23:          8 Load 22
         24:          8 MatrixTimesMatrix 20 23
         26:    18(ptr) AccessChain 15(Matrices) 25
         27:          8 Load 26
         28:          8 MatrixTimesMatrix 24 27
                        Store 10(PVM) 28
         35:          8 Load 10(PVM)
         38:  11(fvec3) Load 37(aVertex)
         40:   6(float) CompositeExtract 38 0
         41:   6(float) CompositeExtract 38 1
         42:   6(float) CompositeExtract 38 2
         43:   7(fvec4) CompositeConstruct 40 41 42 39
         44:   7(fvec4) MatrixTimesVector 35 43
         46:    45(ptr) AccessChain 34 25
                        Store 46 44
         51:    50(ptr) AccessChain 15(Matrices) 49
         52:         12 Load 51
         54:  11(fvec3) Load 53(aNormal)
         55:  11(fvec3) MatrixTimesVector 52 54
                        Store 48(vNormal) 55
         58:  11(fvec3) Load 57(aColor)
                        Store 56(vColor) 58
         64:  59(fvec2) Load 63(aTexCoord)
                        Store 61(vTexCoord) 64
                        Return
                        FunctionEnd
```

A Google-Wrapped Version of glslangValidator

The shaderc project from Google (https://github.com/google/shaderc) provides a glslangValidator wrapper program called ***glslc*** that has a much improved command-line interface. You use, basically, the same way:

glslc.exe –target-env=vulkan sample-vert.vert -o sample-vert.spv

There are several really nice features. The two I really like are:

1. You can #include files into your shader source

2. You can "#define" definitions on the command line like this:
   glslc.exe --target-env=vulkan -DNUMPONTS=4 sample-vert.vert -o sample-vert.spv

glslc is included in your Sample .zip file

Vulkan.

Data Buffers

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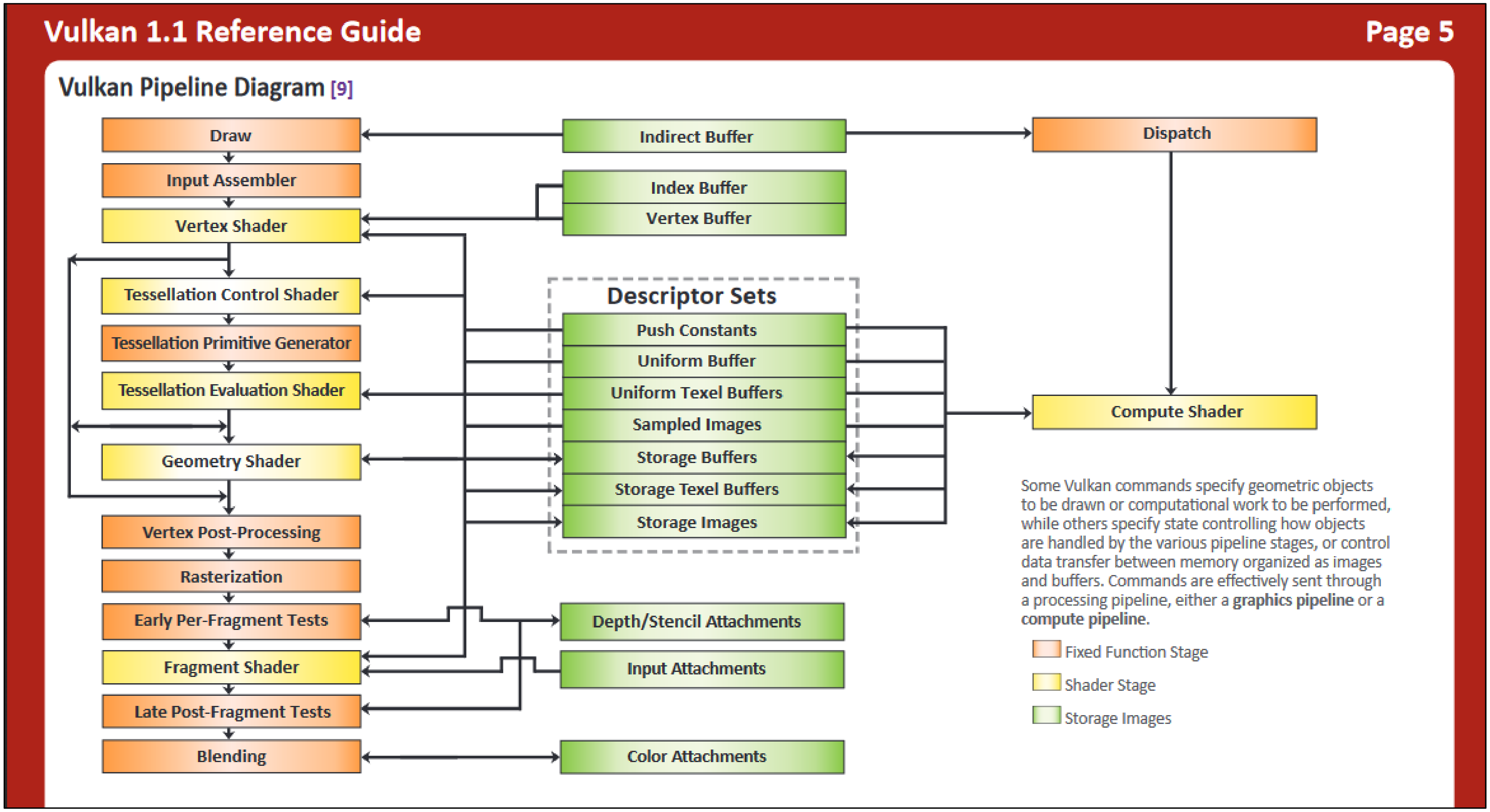
From the Quick Reference Card



Terminology Issues

A Vulkan **Data Buffer** is just a group of contiguous bytes in GPU memory. They have no inherent meaning. The data that is stored there is whatever you want it to be. (This is sometimes called a “Binary Large Object”, or “BLOB”.)

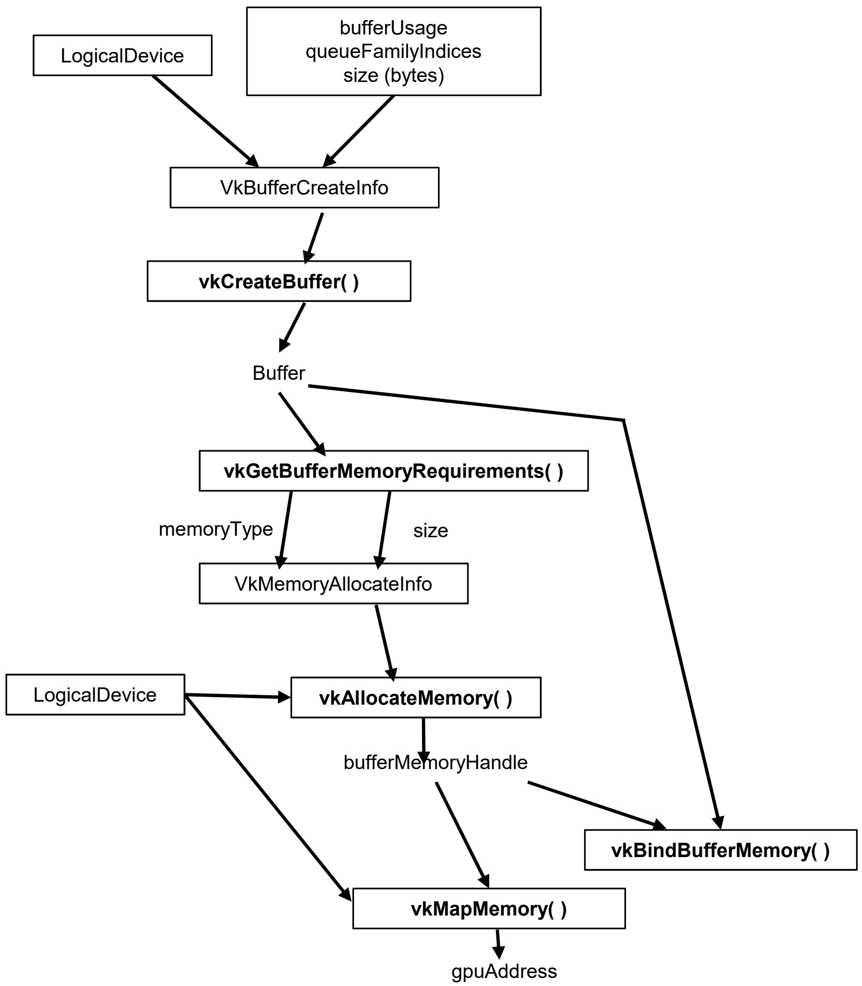
It is up to you to be sure that the writer and the reader of the Data Buffer are interpreting the bytes in the same way!

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

```
typedef VkBuffer          VkDataBuffer;
```

This is probably a bad idea in the long run.

Creating and Filling Vulkan Data Buffers



Creating a Vulkan Data Buffer

```
VkBuffer  Buffer;

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

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

Allocating Memory for a Vulkan Data Buffer, Binding a Buffer to Memory, and Writing to the 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 );
```

Finding the Right Type of Memory


```
int
FindMemoryThatIsHostVisible( )
{
	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_HOST_VISIBLE_BIT ) != 0 )
		{
			return i;
		}
	}
	return  -1;
}
```

Finding the Right Type of Memory

```
int
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

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

```
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
```

Sidebar: The Vulkan Memory Allocator (VMA)

The **Vulkan Memory Allocator** is a set of functions to simplify your view of allocating buffer memory. I don't have experience using it (yet), so I'm not in a position to confidently comment on it. But, I am including its github link here and a little sample code in case you want to take a peek.

https://github.com/GPUOpen-LibrariesAndSDKs/VulkanMemoryAllocator

This repository includes a smattering of documentation.

Sidebar: The Vulkan Memory Allocator (VMA)

```
#define VMA_IMPLEMENTATION
#include "vk_mem_alloc.h"
. . .
VkBufferCreateInfo              vbci;
. . .
VmaAllocationCreateInfo         vaci;
        vaci.physicalDevice = PhysicalDevice;
        vaci.device = LogicalDevice;
        vaci.usage = VMA_MEMORY_USAGE_GPU_ONLY;

VmaAllocator                    var;
vmaCreateAllocator( IN &vaci, OUT &var );
. . .
. .
VkBuffer                        Buffer;
VmaAllocation                   van;
vmaCreateBuffer( IN var, IN &vbci, IN &vaci, OUT &Buffer. OUT &van, nullptr );
```

```
void *mappedDataAddr;
vmaMapMemory( IN var, IN van, OUT &mappedDataAddr );
        memcpy( mappedDataAddr, &MyData, sizeof(MyData) );
vmaUnmapMemory( IN var, IN van );
```

Something I've Found Useful

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.

It also makes it impossible to accidentally associate the wrong VkDeviceMemory and/or VkDeviceSize with the wrong data buffer.

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.

```
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 used by the Sample Code to hold some uniform variables

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

Here's the associated GLSL shader code to access those uniform variables

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

Filling those Uniform Variables


```
uint32_t                    Height, Width;
const double FOV =          glm::radians(60.);    // field-of-view angle in radians

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

Matrices.uModelMatrix      = glm::mat4( 1. );          // 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 )  );
```

This code assumes that this line:

#define   GLM_FORCE_RADIANS

is listed before GLM is included!

The Parade of Buffer Data

MyBuffer MyMatrixUniformBuffer;

The MyBuffer does not hold any actual data itself. It just information about what is in the data buffer

```
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;
. . .
}
```

This C struct is holding the original data, written by the application.

Memory-mapped copy operation

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

struct matBuf Matrices;

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

Matrices.uModelMatrix      = glm::mat4( );          // identity

Matrices.uViewMatrix       = glm::lookAt( eye, look, up );

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

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

uniform matBuf Matrices;

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

Filling the Data Buffer

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

. . .

MyBuffer                      MyMatrixUniformBuffer;
```

```
Init05UniformBuffer( sizeof(Matrices),      OUT &MyMatrixUniformBuffer );

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

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

Matrices.uModelMatrix      = glm::mat4( );          // identity

Matrices.uViewMatrix       = glm::lookAt( eye, look, up );

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

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

Creating and Filling the Data Buffer – the Details


```
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, OFFSET_ZERO );
	return result;
}
```

Creating and Filling the Data Buffer – the Details

```
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.

GLFW

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Setting Up GLFW

```
#define GLFW_INCLUDE_VULKAN
#include "glfw3.h"
        . . .

uint32_t                Width, Height;
VkSurfaceKHR            Surface;
        . . .

void
InitGLFW( )
{
        glfwInit( );
        if( ! glfwVulkanSupported( )  )
        {
                fprintf( stderr, "Vulkan is not supported on this system!\n" );
                exit( 1 );
        }
        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, OUT &Surface );

        glfwSetErrorCallback( GLFWErrorCallback );
        glfwSetKeyCallback( MainWindow,             GLFWKeyboard );
        glfwSetCursorPosCallback( MainWindow,       GLFWMouseMotion );
        glfwSetMouseButtonCallback( MainWindow,     GLFWMouseButton );
}
```

You Can Also Query What Vulkan Extensions GLFW Requires

```
uint32_t count;
const char ** extensions = glfwGetRequiredInstanceExtensions (&count);

fprintf( FpDebug, "\nFound %d GLFW Required Instance Extensions:\n", count );

for( uint32_t  i = 0; i < count; i++ )
{
	fprintf( FpDebug, "\t%s\n", extensions[ i ] );
}
```

```
Found 2 GLFW Required Instance
Extensions:
	VK_KHR_surface
	VK_KHR_win32_surface
```

GLFW Keyboard Callback


```
void
GLFWKeyboard( GLFWwindow * window, int key, int scancode, int action, int mods )
{
	if( action == GLFW_PRESS )
	{
		switch( key )
		{
			//case GLFW_KEY_M:
			case 'm':
			case 'M':
				Mode++;
				if( Mode >= 2 )
					Mode = 0;
				break;

			default:
				fprintf( FpDebug, "Unknow key hit: 0x%04x = '%c'\n", key, key );
				fflush(FpDebug);
		}
	}
}
```

GLFW Mouse Button Callback

```
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 );
	}

	// 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


```
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;
}
```

Looping and Closing GLFW


```
while( glfwWindowShouldClose( MainWindow ) == 0 )
{
        glfwPollEvents( );
        Time = glfwGetTime( );          // elapsed time, in double-precision seconds
        UpdateScene( );
        RenderScene( );
}

vkQueueWaitIdle( Queue );
vkDeviceWaitIdle( LogicalDevice );
DestroyAllVulkan( );
glfwDestroyWindow( MainWindow );
glfwTerminate( );
```

Does not block –
processes any waiting events, then returns

Looping and Closing GLFW

If you would like to *block* waiting for events, use:

glfwWaitEvents( );

You can have the blocking wake up after a timeout period with:

glfwWaitEventsTimeout(double secs);

You can wake up one of these blocks from another thread with:

glfwPostEmptyEvent( );

GLM

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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.

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>
```

OpenGL treats all angles as given in *degrees*. This line forces GLM to treat all angles as given in *radians*. I recommend this so that *all* angles you create in *all* programming will be in radians.

If GLM is not installed in a system place, put it somewhere you can get access to.

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:

```
glMatrixMode( GL_MODELVIEW );
glLoadIdentity( );
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 say:

```
glm::mat4 modelview = glm::mat4( 1. );      // identity
glm::vec3 eye(0.,0.,3.);
glm::vec3 look(0.,0.,0.);
glm::vec3   up(0.,1.,0.);
modelview = glm::lookAt( eye, look, up );                                  // {x',y',z'} = [v]*{x,y,z}
modelview = glm::rotate( modelview, D2R*Yrot, glm::vec3(0.,1.,0.) );   // {x',y',z'} = [v]*[yr]*{x,y,z}
modelview = glm::rotate( modelview, D2R*Xrot, glm::vec3(1.,0.,0.) );   // {x',y',z'} = [v]*[yr]*[xr]*{x,y,z}
modelview = glm::scale( modelview, glm::vec3(Scale,Scale,Scale) );    // {x',y',z'} = [v]*[yr]*[xr]*[s]*{x,y,z}
```

This is exactly the same concept as OpenGL, but a different expression of it. Read on for details …

The Most Useful GLM Variables, Operations, and Functions

```
// constructor:

glm::mat4( 1. );               // 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);

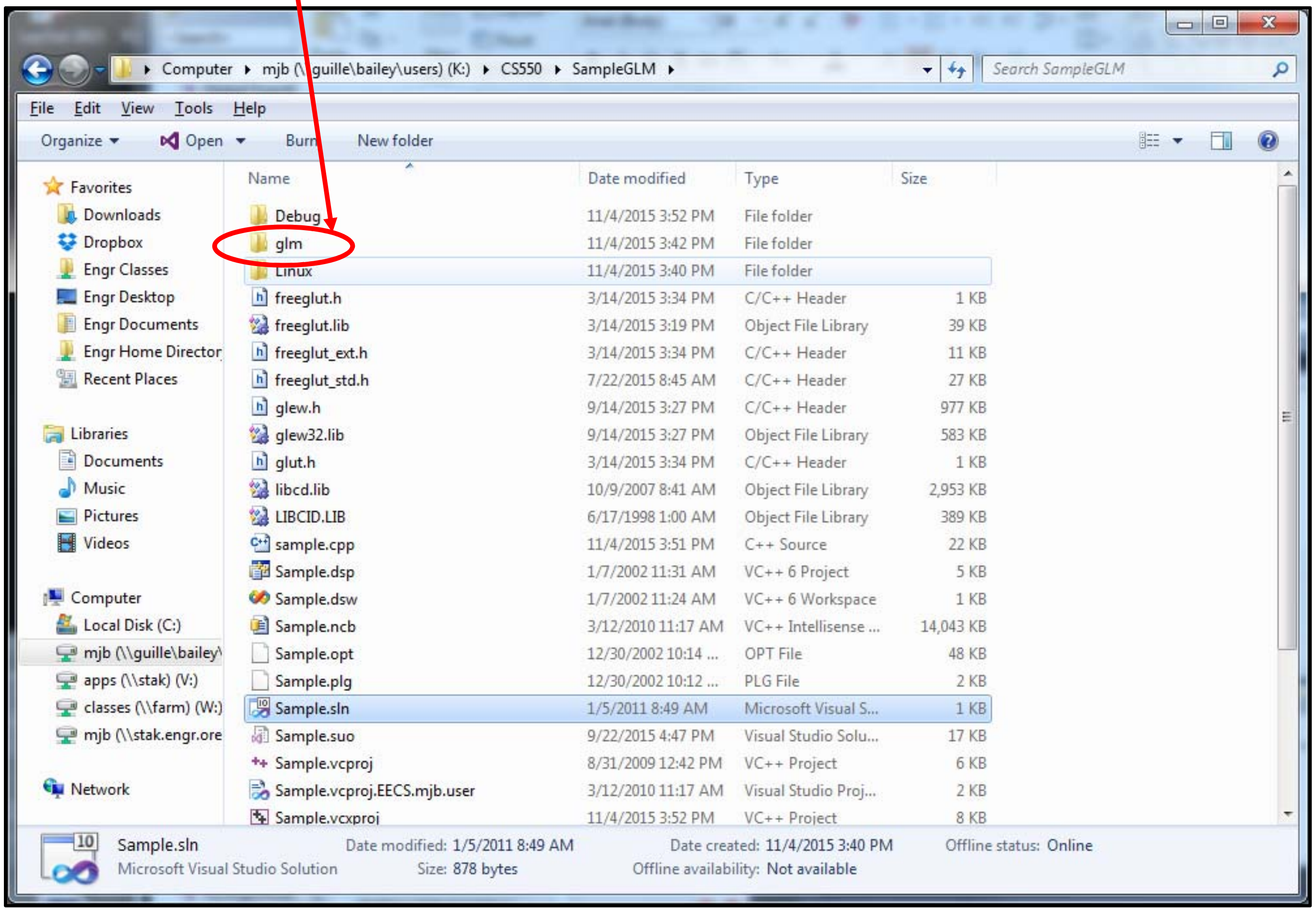
glm::mat4 **glm::translate**(glm::mat4 const & m, glm::vec3 const & translation);

The Most Useful GLM Variables, Operations, and Functions

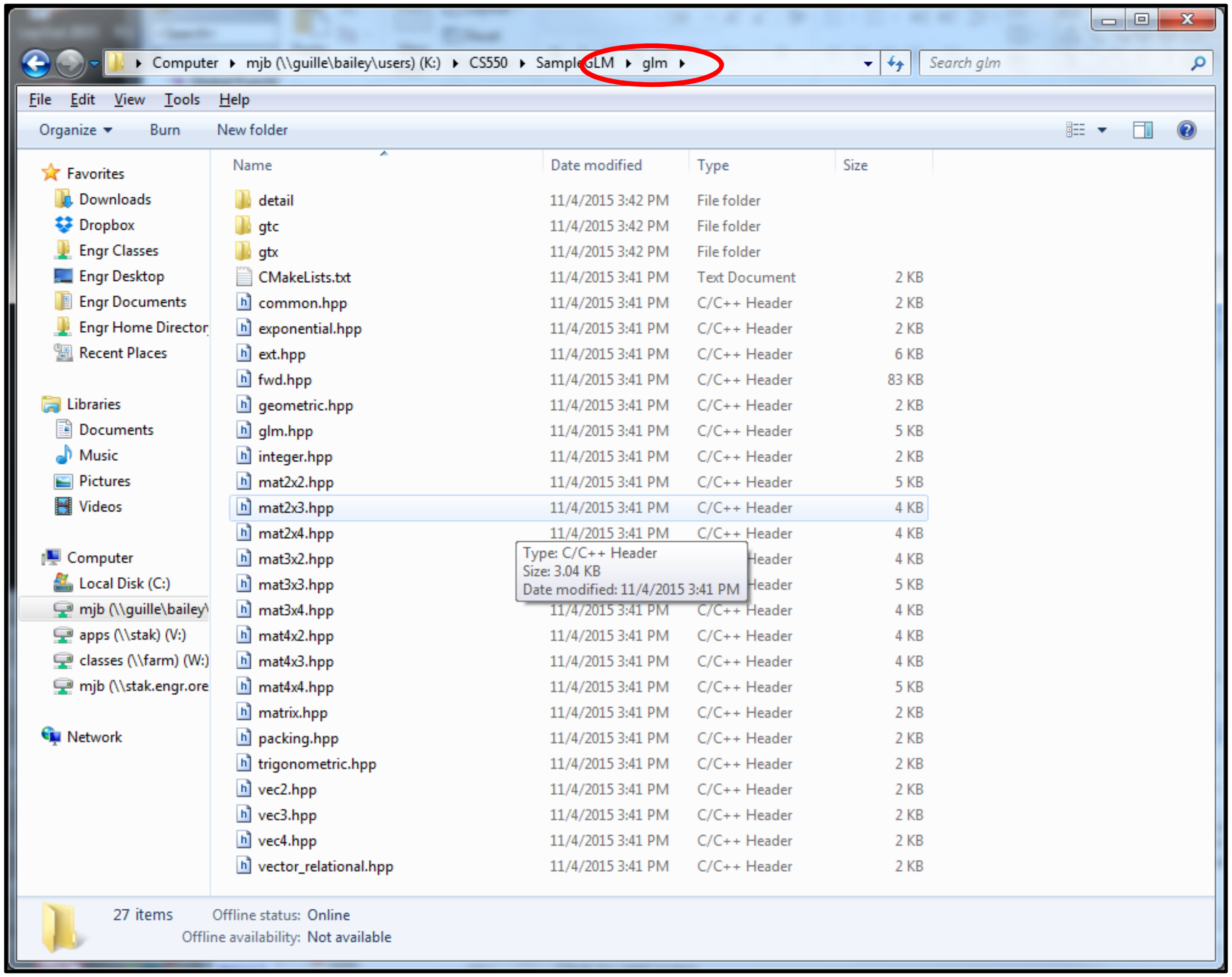

```
// viewing volume  (assign, not concatenate):

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

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


// viewing  (assign, not concatenate):

glm::mat4  glm::lookAt(  glm::vec3 const & eye,  glm::vec3 const & look,  glm::vec3 const & up );
```

Installing GLM into your own space

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



Here's what that GLM folder looks like

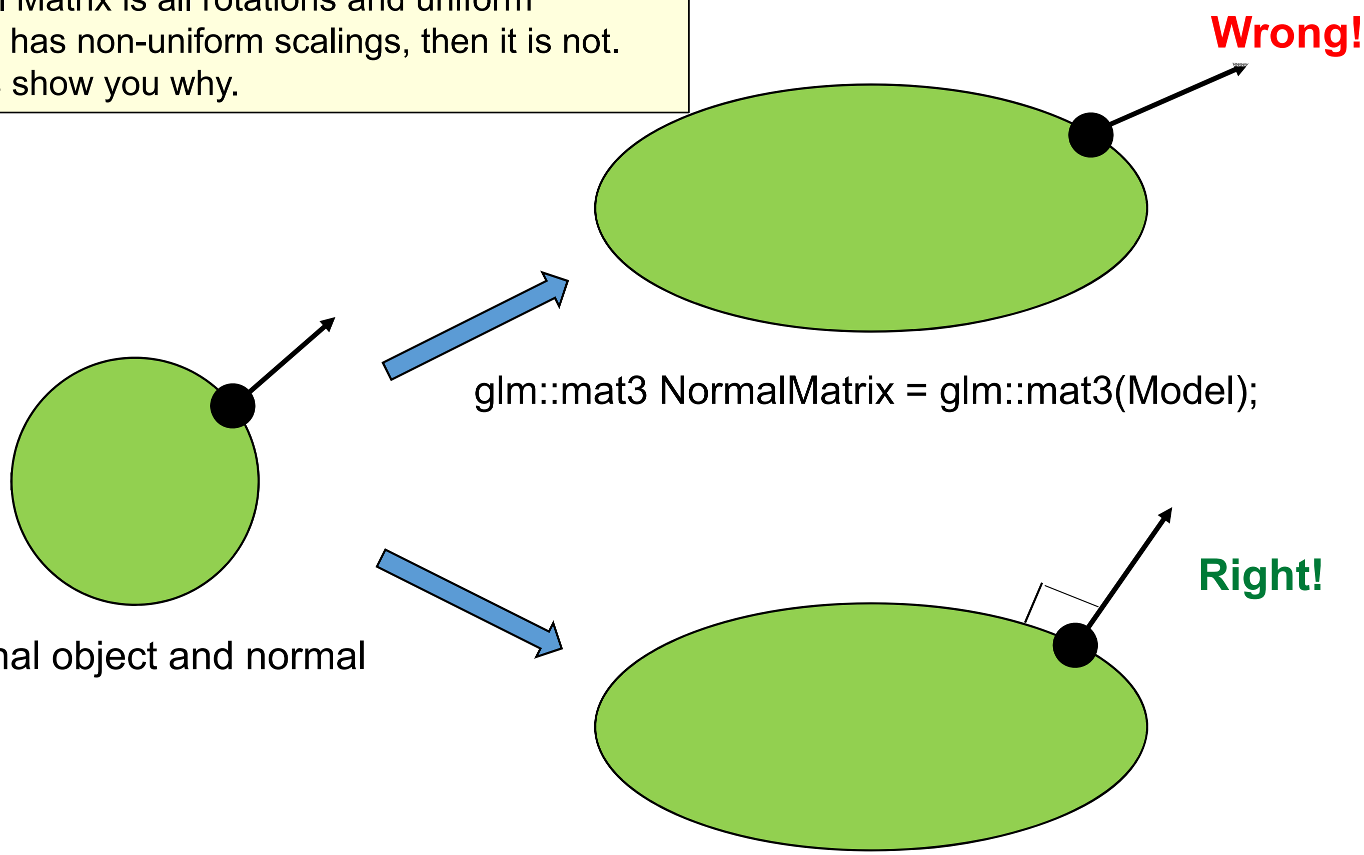


GLM in the Vulkan sample.cpp Program

```
if( UseMouse )
{
        if( Scale < MINSCALE )
            Scale = MINSCALE;
        Matrices.uModelMatrix = glm::mat4( 1. );        // identity
        Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Yrot, glm::vec3( 0.,1.,0.) );
        Matrices.uModelMatrix = glm::rotate( Matrices.uModelMatrix, Xrot, glm::vec3( 1.,0.,0.) );
        Matrices.uModelMatrix = glm::scale(  Matrices.uModelMatrix, glm::vec3(Scale,Scale,Scale) );
                                // done this way, the Scale is applied first, then the Xrot, then the Yrot
}
else
{
    if( ! Paused )
    {
        const glm::vec3 axis = glm::vec3( 0., 1., 0. );
        Matrices.uModelMatrix    = glm::rotate( glm::mat4( 1. ),  (float)glm::radians( 360.f*Time/SECONDS_PER_CYCLE ),   axis );
    }
}

glm::vec3 eye(0.,0.,EYEDIST );
glm::vec3 look(0.,0.,0.);
glm::vec3   up(0.,1.,0.);
Matrices.uVewMatrix = glm::lookAt( eye, look, up );

Matrices.uProjectionMatrix = glm::perspective( FOV, (double)Width/(double)Height, 0.1f, 1000.f );
Matrices.uProjectionMatrix[1][1] *= -1.;            // Vulkan's projected Y is inverted from OpenGL

Matrices.uNormalMatrix = glm::inverseTranspose(  glm::mat3( Matrices.uModelMatrix );   // note: inverseTransform !

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

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

Sidebar: Why Isn’t The Normal Matrix exactly 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.



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

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

But, this will only get us multiple instances of identical objects drawn on top of each other. How can we make each instance look differently?

BTW, when not using instancing, be sure the **instanceCount** is **1**, not **0** !

Making each Instance look differently -- Approach #1

Use the built-in vertex shader variable **gl_InstanceIndex** to define a unique display property, such as position or color.

gl_InstanceIndex starts at 0

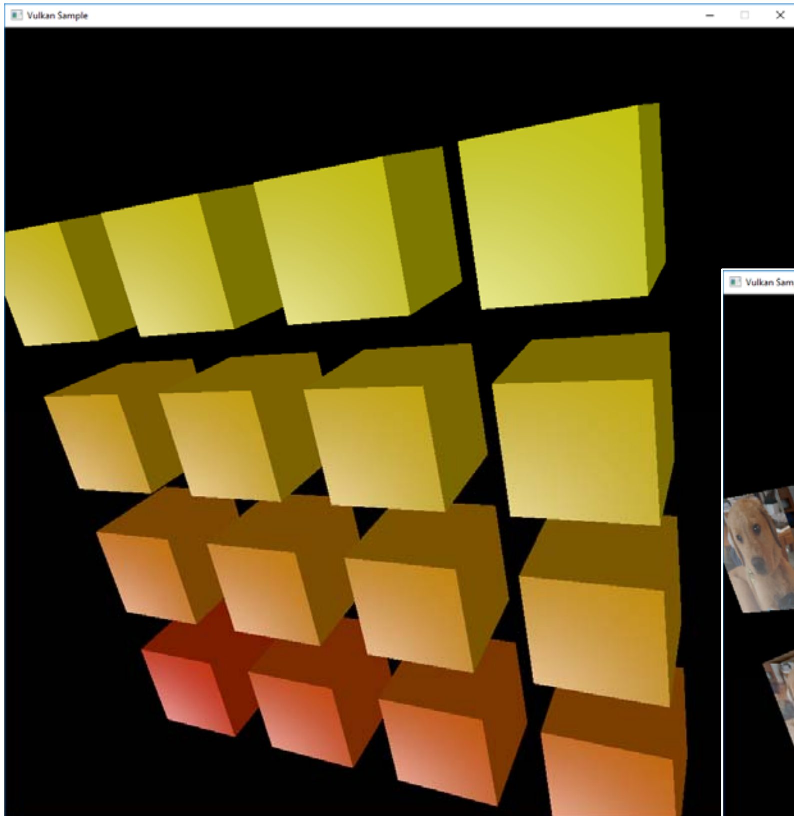
In the vertex shader:

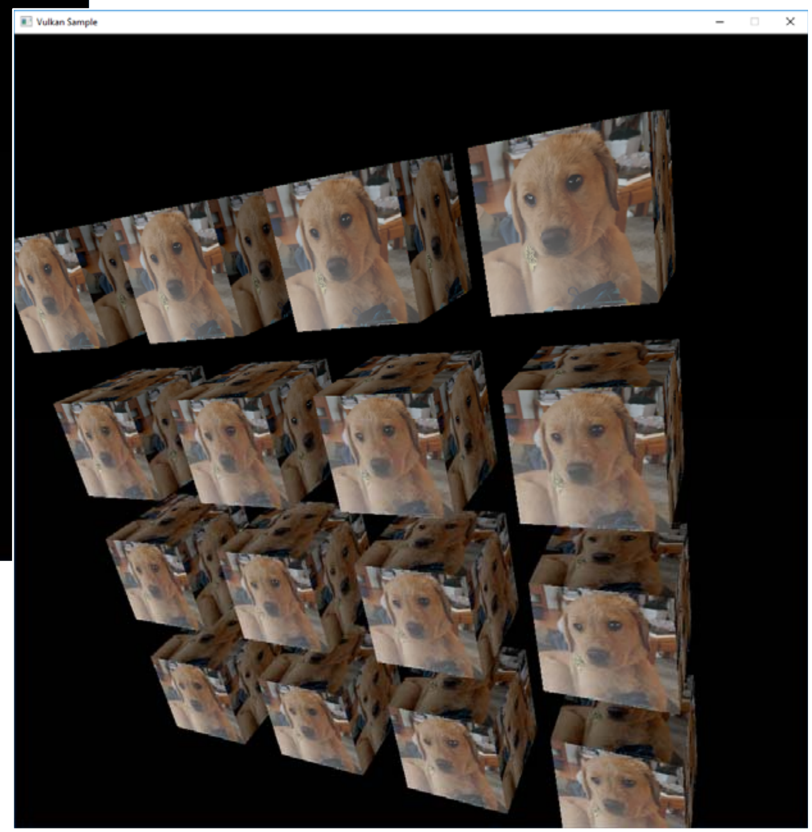
```
out vec3 vColor;
const int    NUMINSTANCES = 16;
const float DELTA                  =   3.0;

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;              // [p]*[v]*[m]
```


Vulkan Sample


Vulkan Sample

Making each Instance look differently -- Approach #2

Put the unique characteristics in a uniform buffer array and reference them

Still uses **gl_InstanceIndex**

In the vertex shader:

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

out vec3 vColor;

      . . .

int index = gl_InstanceIndex % 1024;      // or “& 1023” – gives 0 - 1023
vColor = Colors.uColors[ index ];

vec4 vertex = . . .

gl_Position = PVM * vertex;              // [p]*[v]*[m]
```

The Graphics Pipeline Data Structure

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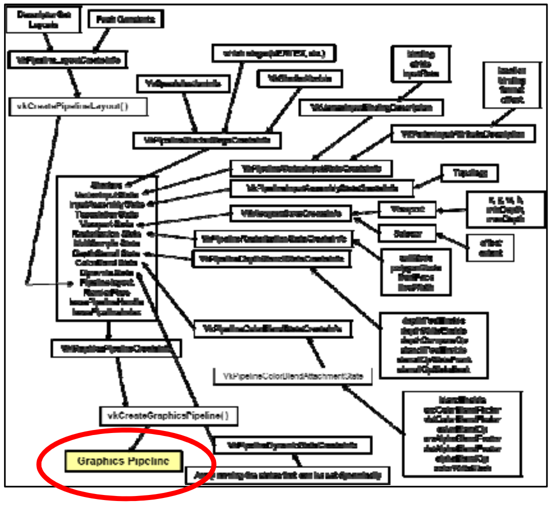
What is the Vulkan Graphics Pipeline?



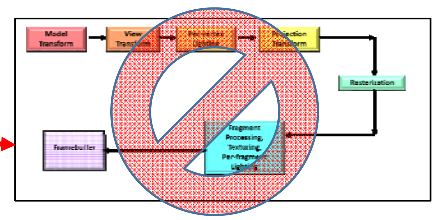
Don’t worry if this is too small to read – a larger version is coming up.

There is also a Vulkan **Compute Pipeline Data Structure**.

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”.

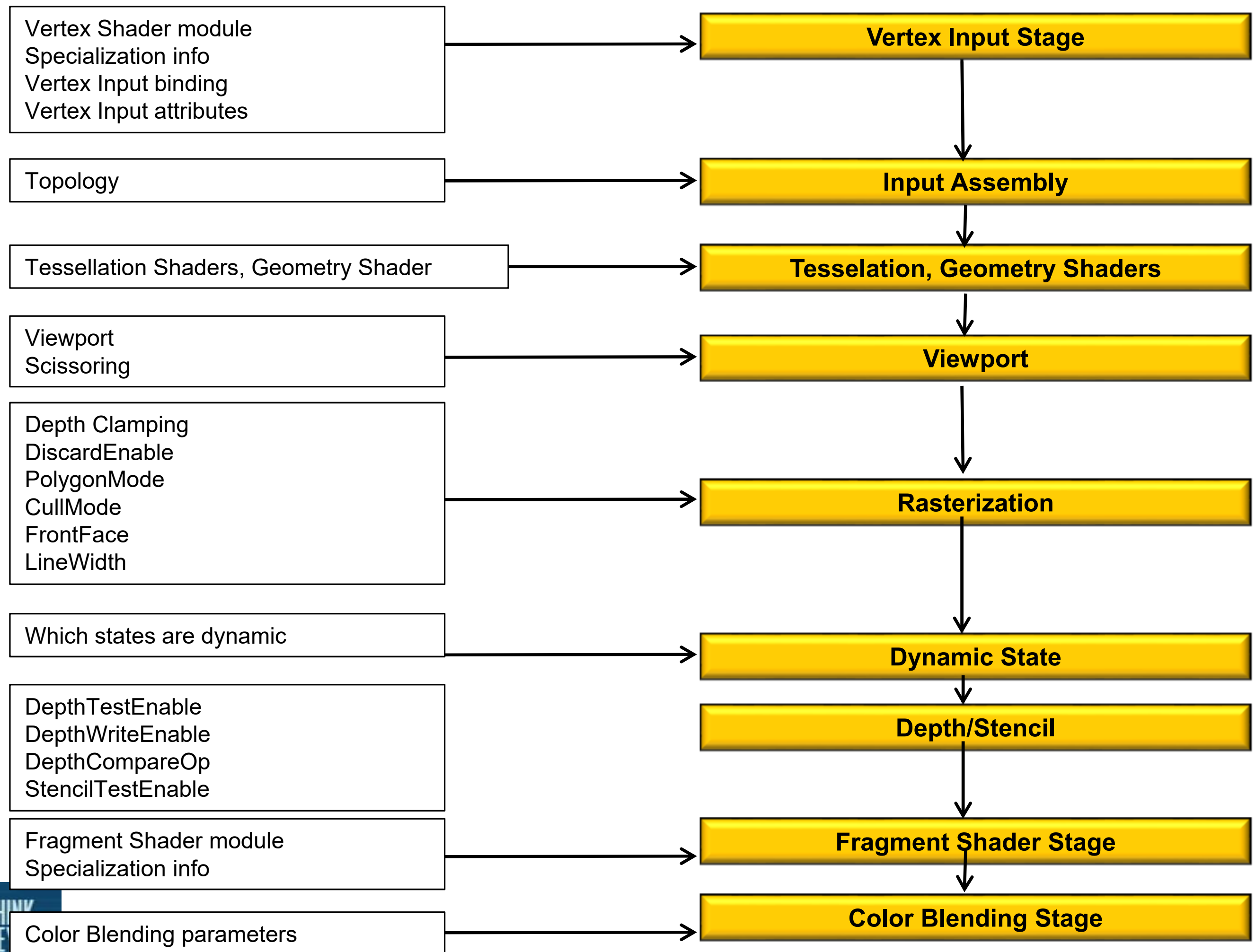


3. For the most part, the Vulkan Graphics Pipeline Data Structure is immutable – that is, once this combination of state variables is combined into a Pipeline, that Pipeline never gets changed. To make new combinations of state variables, create a new Graphics Pipeline.

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

Graphics Pipeline Stages and what goes into Them

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



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.

```
VkResult
Init14GraphicsPipelineLayout( )
{
	VkResult result;

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

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

	return result;
}
```

Let the Pipeline Layout know about the Descriptor Set and Push Constant layouts.

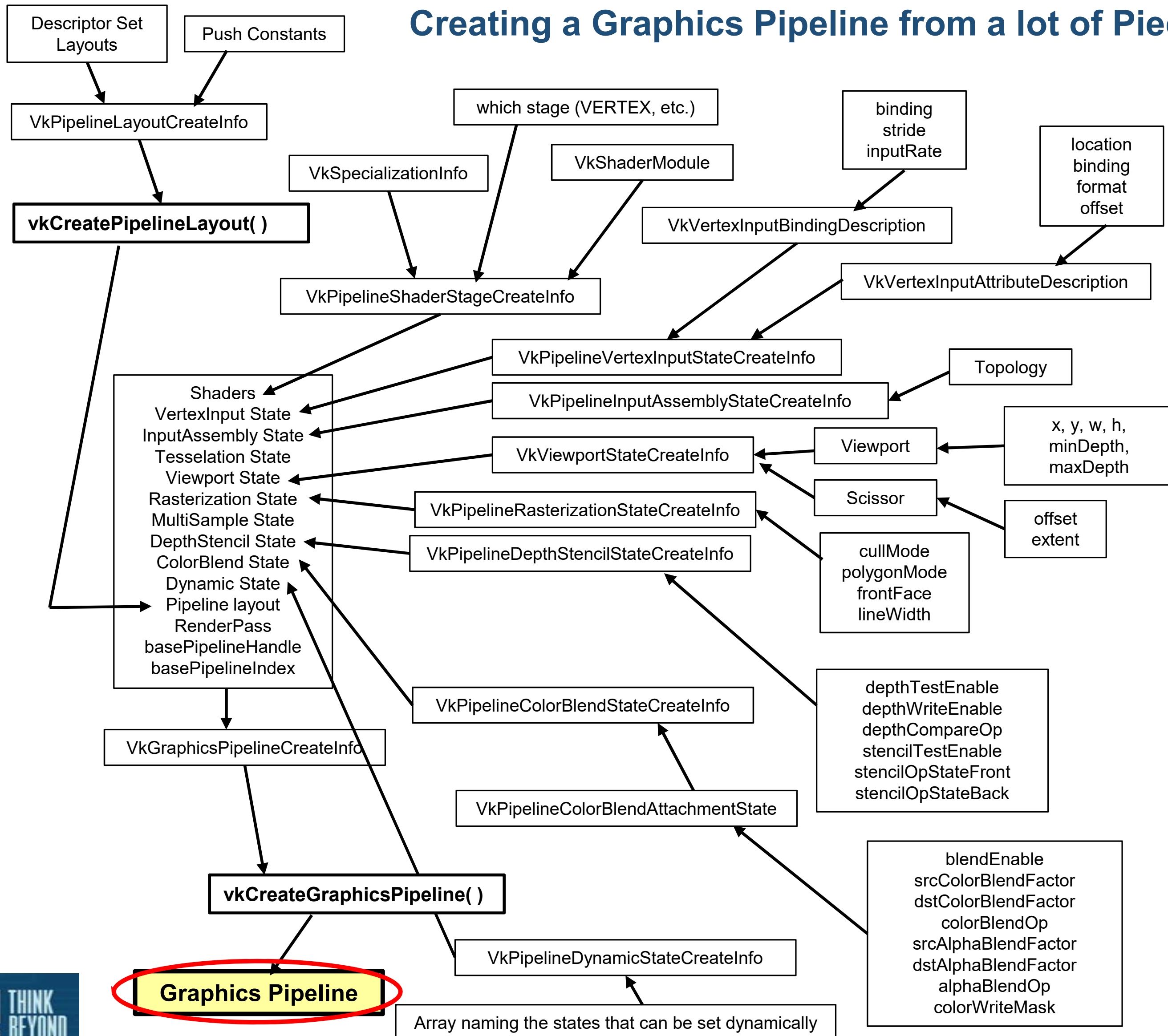
Why is this necessary? It is because the Descriptor Sets and Push Constants data structures have different sizes depending on how many of each you have. So, the exact structure of the Pipeline Layout depends on you telling Vulkan about the Descriptor Sets and Push Constants that you will be using.

A Pipeline Data Structure Contains the Following State Items:

- Pipeline Layout: Descriptor Sets, Push Constants
- Which Shaders to use
- 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 State Variables

Creating a Graphics Pipeline from a lot of Pieces



Creating a Typical Graphics Pipeline

```
VkResult
Init14GraphicsVertexFragmentPipeline( 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;
        vpmsci.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.

The Shaders to Use


```
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;
#ifdef BITS
VK_SHADER_STAGE_VERTEX_BIT
VK_SHADER_STAGE_TESSELLATION_CONTROL_BIT
VK_SHADER_STAGE_TESSELLATION_EVALUATION_BIT
VK_SHADER_STAGE_GEOMETRY_BIT
VK_SHADER_STAGE_FRAGMENT_BIT
VK_SHADER_STAGE_COMPUTE_BIT
VK_SHADER_STAGE_ALL_GRAPHICS
VK_SHADER_STAGE_ALL
#endif
        vpssci[1].sType = VK_STRUCTURE_TYPE_PIPELINE_SHADER_STAGE_CREATE_INFO;
        vpssci[1].pNext = nullptr;
        vpssci[1].flags = 0;
        vpssci[1].stage = VK_SHADER_STAGE_FRAGMENT_BIT;
        vpssci[1].module = fragmentShader;
        vpssci[1].pName = "main";
        vpssci[1].pSpecializationInfo = (VkSpecializationInfo *)nullptr;

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

Use one **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
        // 4 = vertex, normal, color, texture coord
        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
#ifdef EXTRAS_DEFINED_AT_THE_TOP
// these are here for convenience and readability:
#define VK_FORMAT_VEC4        VK_FORMAT_R32G32B32A32_SFLOAT
#define VK_FORMAT_XYZW        VK_FORMAT_R32G32B32A32_SFLOAT
#define VK_FORMAT_VEC3        VK_FORMAT_R32G32B32_SFLOAT
#define VK_FORMAT_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
#endif
        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
```

Use one **vviad** array member per element in the struct for the array-of-structures element you are using as vertex input

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

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

    VkPipelineInputAssemblyStateCreateInfo        vpiasci;
        vpiasci.sType = VK_STRUCTURE_TYPE_PIPELINE_INPUT_ASSEMBLY_STATE_CREATE_INFO;
        vpiasci.pNext = nullptr;
        vpiasci.flags = 0;
        vpiasci.topology = VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST;;
#ifdef 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
#endif
        vpiasci.primitiveRestartEnable = VK_FALSE;

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

    VkPipelineGeometryStateCreateInfo        vpgsci;
        vptsci.sType = VK_STRUCTURE_TYPE_PIPELINE_TESSELLATION_STATE_CREATE_INFO;
        vptsci.pNext = nullptr;
        vptsci.flags = 0;
```

Declare the binding descriptions and attribute descriptions

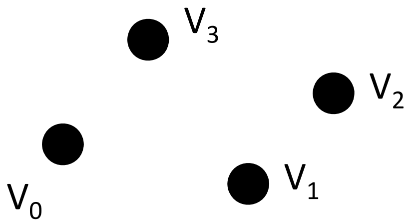
Declare the vertex topology

Tessellation Shader info

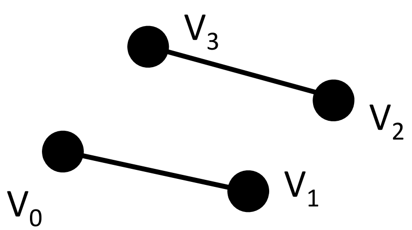
Geometry Shader info

Options for vpiasci.topology

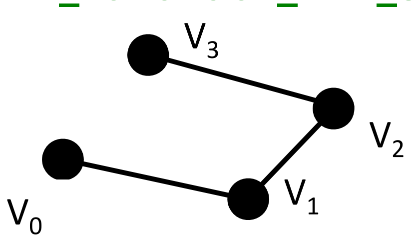
VK_PRIMITIVE_TOPOLOGY_POINT_LIST



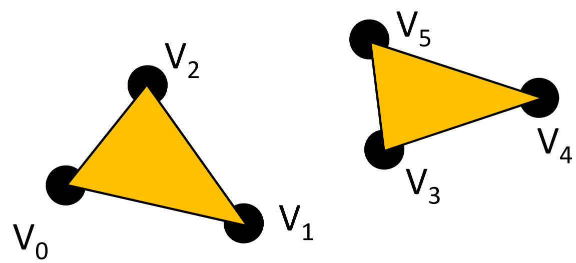
VK_PRIMITIVE_TOPOLOGY_LINE_LIST



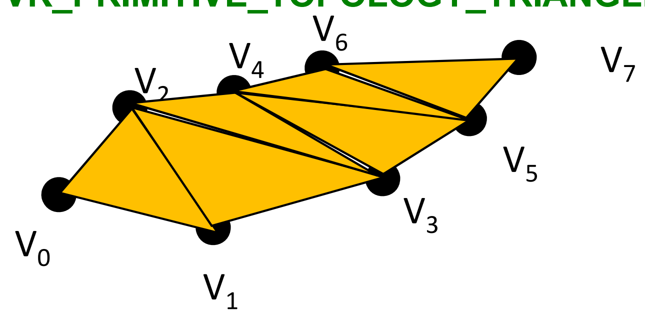
VK_PRIMITIVE_TOPOLOGY_LINE_STRIP



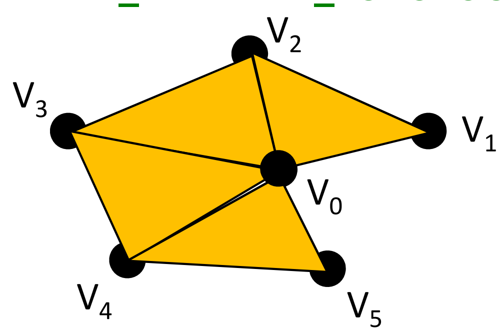
VK_PRIMITIVE_TOPOLOGY_TRIANGLE_LIST



VK_PRIMITIVE_TOPOLOGY_TRIANGLE_STRIP



VK_PRIMITIVE_TOPOLOGY_TRIANGLE_FAN



What is “Primitive Restart Enable”?

```
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.

```
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**.

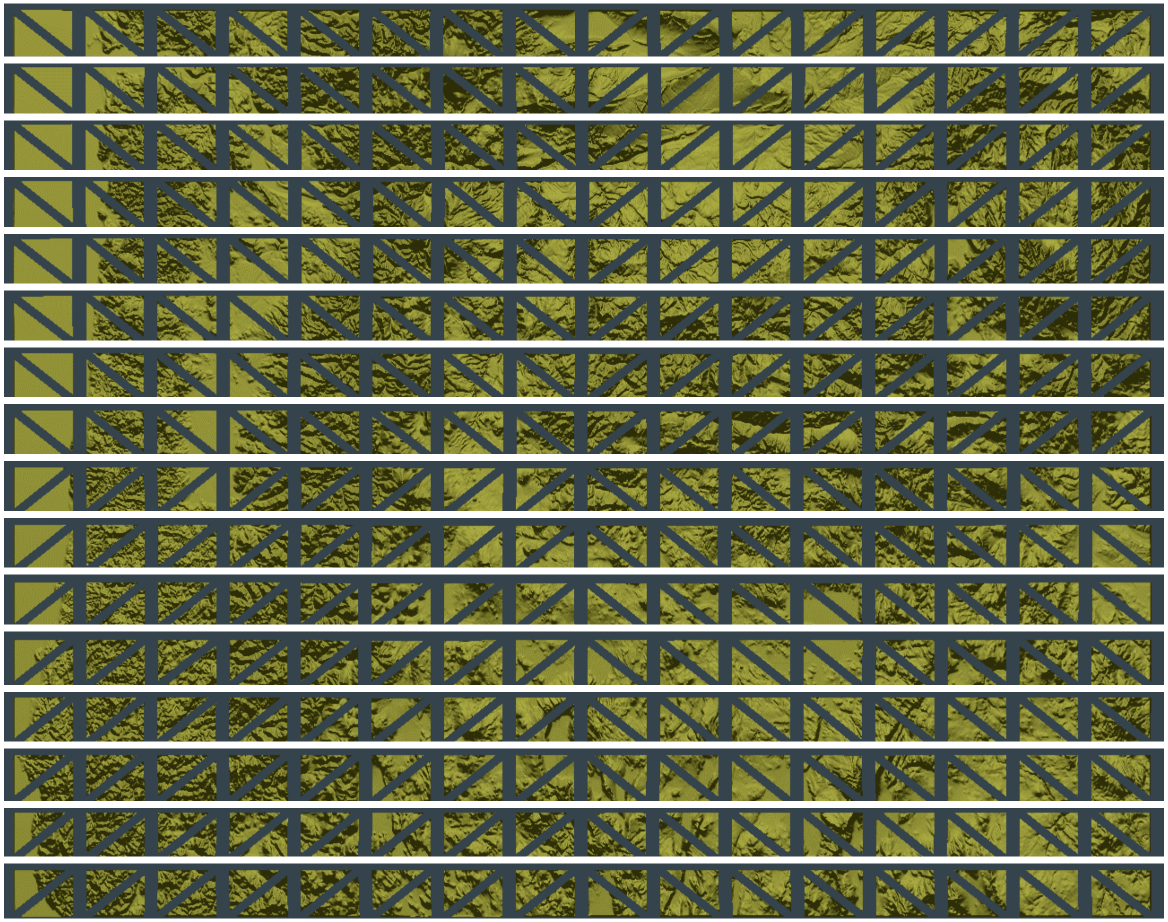
One Really Good use of Restart Enable is in Drawing Terrain Surfaces with Triangle Strips

Triangle Strip #0:

Triangle Strip #1:

Triangle Strip #2:

. . .



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```
VkViewport                                       vv;
        vv.x = 0;
        vv.y = 0;
        vv.width = (float)Width;
        vv.height = (float)Height;
        vv.minDepth = 0.0f;
        vv.maxDepth = 1.0f;

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

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

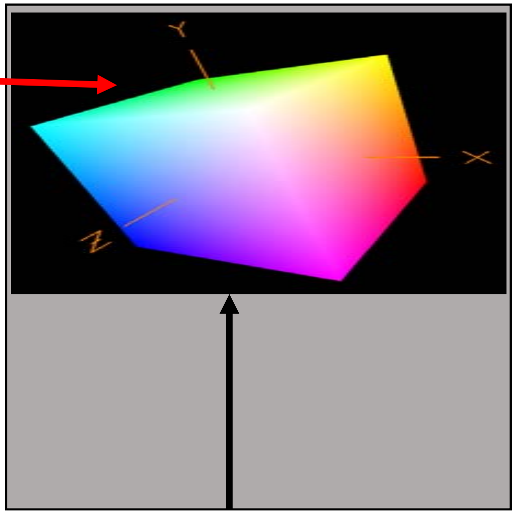
Declare the viewport information

Declare the scissoring information

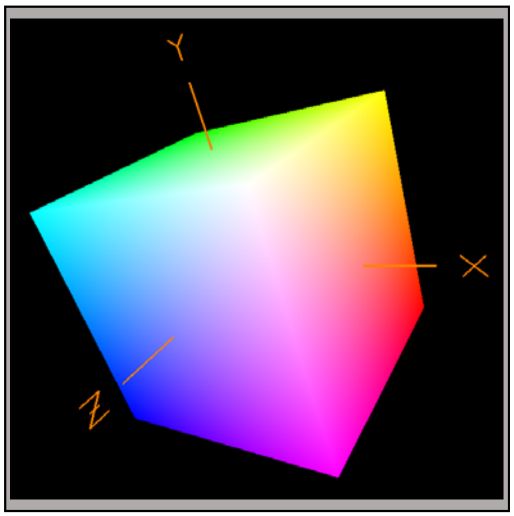
Group the viewport and scissor information together

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

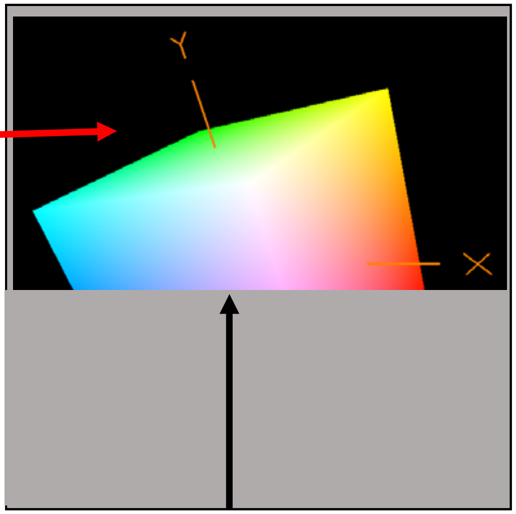
Viewport
:Viewporting operates on ***vertices*** and takes place right before the rasterizer. Changing the vertical part of the **viewport** causes the entire scene to get scaled (scrunched) into the viewport area.



Original Image



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.



Setting the Rasterizer State

```
 VkPipelineRasterizationStateCreateInfo            vprsci;
          vprsci.sType = VK_STRUCTURE_TYPE_PIPELINE_RASTERIZATION_STATE_CREATE_INFO;
          vprsci.pNext = nullptr;
          vprsci.flags = 0;
          vprsci.depthClampEnable = VK_FALSE;
          vprsci.rasterizerDiscardEnable = VK_FALSE;
          vprsci.polygonMode = VK_POLYGON_MODE_FILL;
#ifdef CHOICES
VK_POLYGON_MODE_FILL
VK_POLYGON_MODE_LINE
VK_POLYGON_MODE_POINT
#endif
          vprsci.cullMode = VK_CULL_MODE_NONE;       // recommend this because of the projMatrix[1][1] *= -
1.;
#ifdef CHOICES
VK_CULL_MODE_NONE
VK_CULL_MODE_FRONT_BIT
VK_CULL_MODE_BACK_BIT
VK_CULL_MODE_FRONT_AND_BACK_BIT
#endif
          vprsci.frontFace = VK_FRONT_FACE_COUNTER_CLOCKWISE;
#ifdef CHOICES
VK_FRONT_FACE_COUNTER_CLOCKWISE
VK_FRONT_FACE_CLOCKWISE
#endif
          vprsci.depthBiasEnable = VK_FALSE;
          vprsci.depthBiasConstantFactor = 0.f;
          vprsci.depthBiasClamp = 0.f;
          vprsci.depthBiasSlopeFactor = 0.f;
          vprsci.lineWidth = 1.f;
```

Declare information about how the rasterization will take place

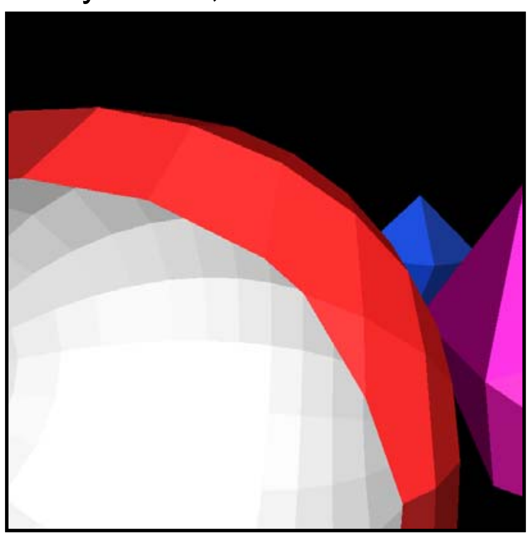
What is "Depth Clamp Enable"?

```
vprsci.depthClampEnable = VK_FALSE;
```

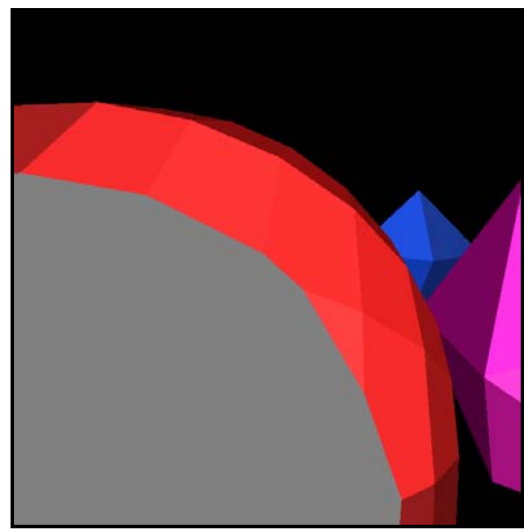
Depth Clamp Enable causes the fragments that would normally have been discarded because they are closer to the viewer than the near clipping plane to instead get projected to the near clipping plane and displayed.

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).

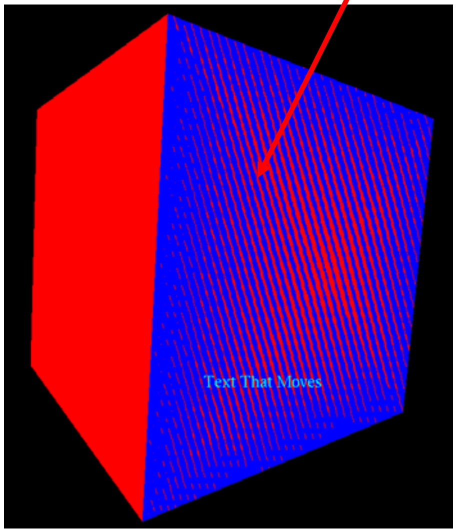


What is “Depth Bias Enable”?

```
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



MultiSampling State

```
VkPipelineMultisampleStateCreateInfo            vpmsci;
        vpmsci.sType = VK_STRUCTURE_TYPE_PIPELINE_MULTISAMPLE_STATE_CREATE_INFO;
        vpmsci.pNext = nullptr;
        vpmsci.flags = 0;
        vpmsci.rasterizationSamples = VK_SAMPLE_COUNT_1_BIT;
        vpmsci.sampleShadingEnable = VK_FALSE;
        vpmsci.minSampleShading = 0;
        vpmsci.pSampleMask = (VkSampleMask *)nullptr;
        vpmsci.alphaToCoverageEnable = VK_FALSE;
        vpmsci.alphaToOneEnable = VK_FALSE;
```

Declare information about how the multisampling will take place

We will discuss MultiSampling in a separate noteset.

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.

$$Color_{new} = (1.-\alpha) * Color_{existing} + \alpha * Color_{incoming}$$

$$0. \leq \alpha \leq 1.$$

*A “Color Attachment” is a framebuffer to be rendered into.
You can have as many of these as you want.

Raster Operations for each Color Attachment

```
VkPipelineColorBlendStateCreateInfo            vpcbsci;
        vpcbsci.sType = VK_STRUCTURE_TYPE_PIPELINE_COLOR_BLEND_STATE_CREATE_INFO;
        vpcbsci.pNext = nullptr;
        vpcbsci.flags = 0;
        vpcbsci.logicOpEnable = VK_FALSE;
        vpcbsci.logicOp = VK_LOGIC_OP_COPY;
#ifdef CHOICES
VK_LOGIC_OP_CLEAR
VK_LOGIC_OP_AND
VK_LOGIC_OP_AND_REVERSE
VK_LOGIC_OP_COPY
VK_LOGIC_OP_AND_INVERTED
VK_LOGIC_OP_NO_OP
VK_LOGIC_OP_XOR
VK_LOGIC_OP_OR
VK_LOGIC_OP_NOR
VK_LOGIC_OP_EQUIVALENT
VK_LOGIC_OP_INVERT
VK_LOGIC_OP_OR_REVERSE
VK_LOGIC_OP_COPY_INVERTED
VK_LOGIC_OP_OR_INVERTED
VK_LOGIC_OP_NAND
VK_LOGIC_OP_SET
#endif
        vpcbsci.attachmentCount = 1;
        vpcbsci.pAttachments = &vpcbas;
        vpcbsci.blendConstants[0] = 0;
        vpcbsci.blendConstants[1] = 0;
        vpcbsci.blendConstants[2] = 0;
        vpcbsci.blendConstants[3] = 0;
```

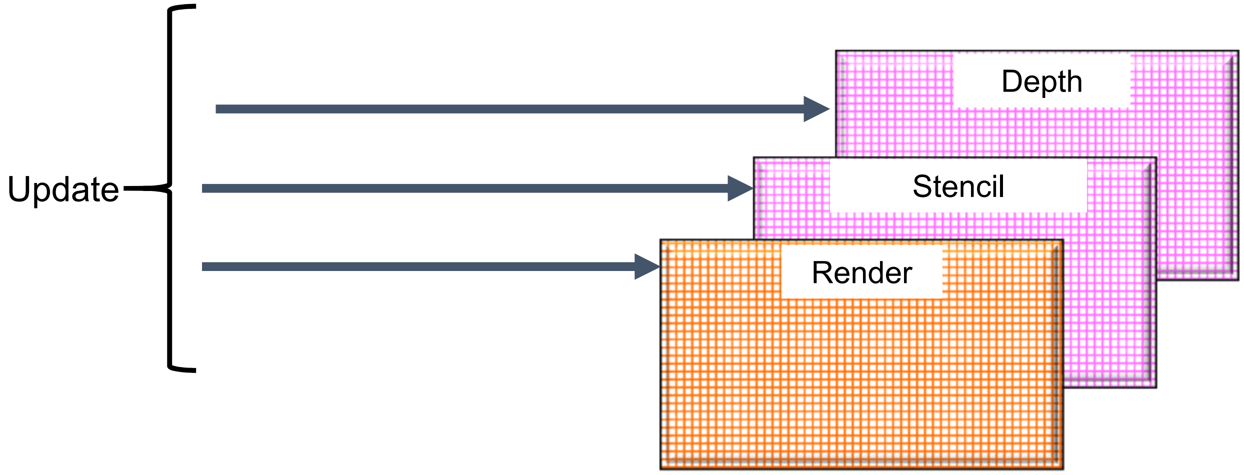
This controls blending between the output of the fragment shader and the input to the color attachments.

Which Pipeline Variables can be Set Dynamically

Just used as an example in the Sample Code

```
VkDynamicState                vds[ ] = { VK_DYNAMIC_STATE_VIEWPORT, VK_DYNAMIC_STATE_SCISSOR };
#ifdef CHOICES
VK_DYNAMIC_STATE_VIEWPORT                        --  vkCmdSetViewport( )
VK_DYNAMIC_STATE_SCISSOR                         --  vkCmdSetScissor( )
VK_DYNAMIC_STATE_LINE_WIDTH                      --  vkCmdSetLineWidth( )
VK_DYNAMIC_STATE_DEPTH_BIAS                      -- vkCmdSetDepthBias( )
VK_DYNAMIC_STATE_BLEND_CONSTANTS                 -- 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
    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;
```

The Stencil Buffer



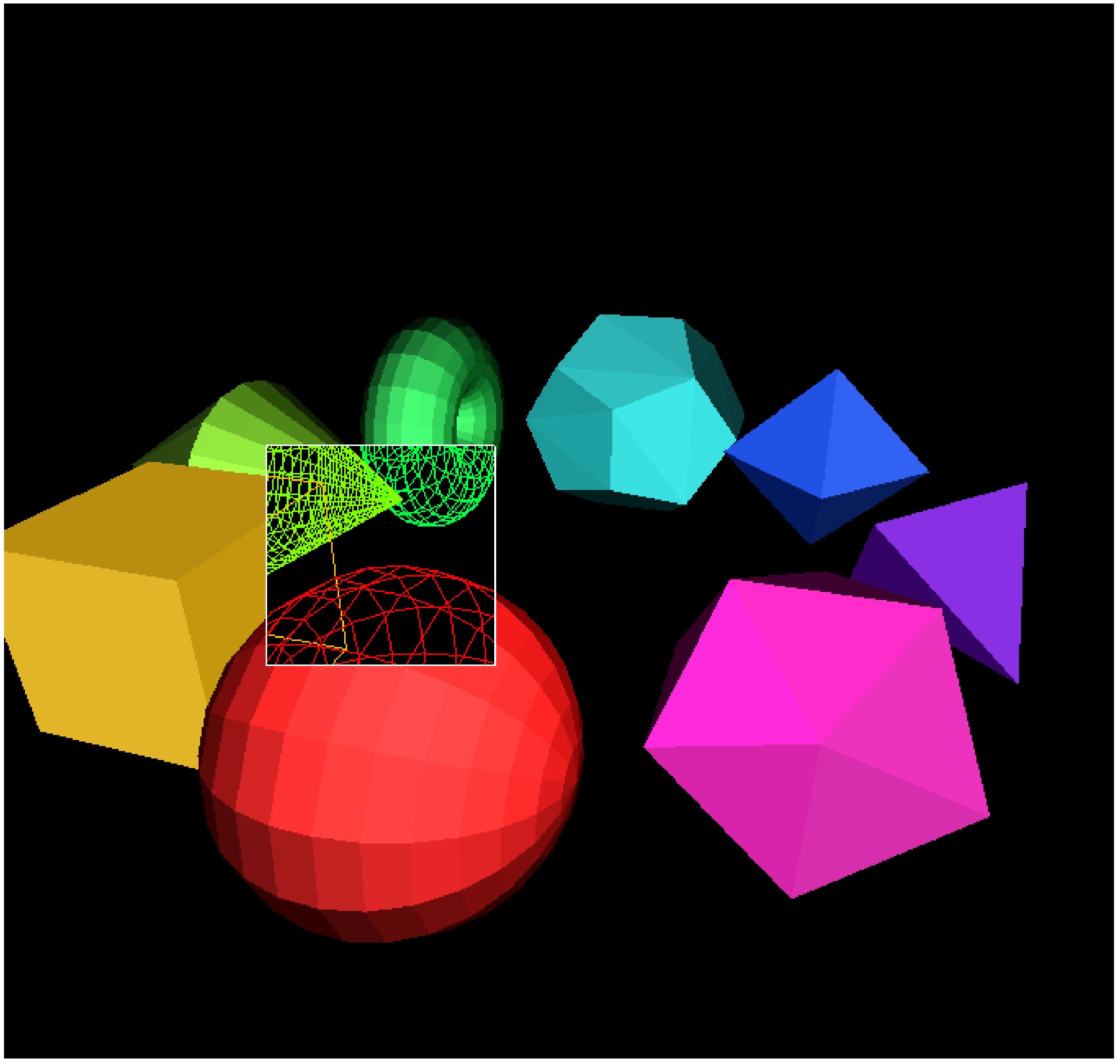
Here's how the Stencil Buffer works:

1. While drawing into the Render Buffer, you can write values into the Stencil Buffer at the same time.

2. While drawing into the Render Buffer, you can do arithmetic on values in the Stencil Buffer at the same time.

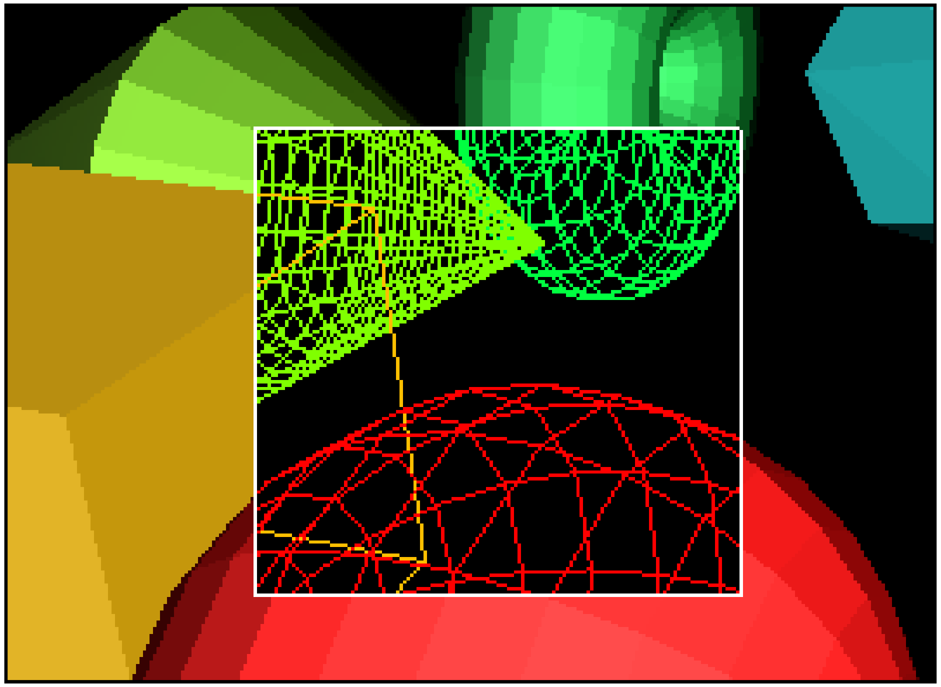
3. When drawing into the Render Buffer, you can write-protect certain parts of the Render Buffer based on values that are in the Stencil Buffer

Using the Stencil Buffer to Create a *Magic Lens*

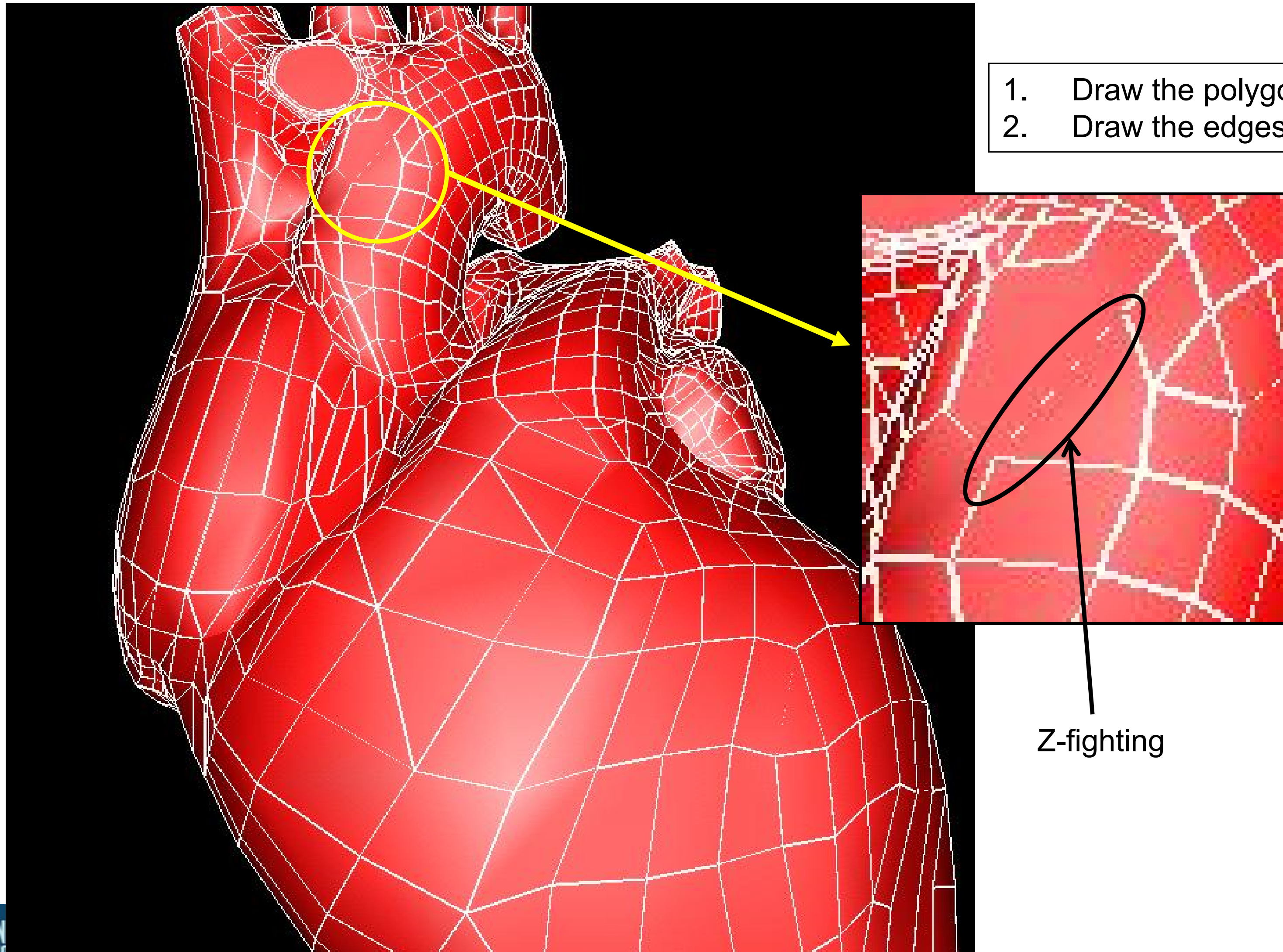


Using the Stencil Buffer to Create a *Magic Lens*

1. Clear the SB = 0
2. Write protect the color buffer
3. Fill a square, setting SB = 1
4. Write-enable the color buffer
5. Draw the solids wherever SB == 0
6. Draw the wireframes wherever SB == 1

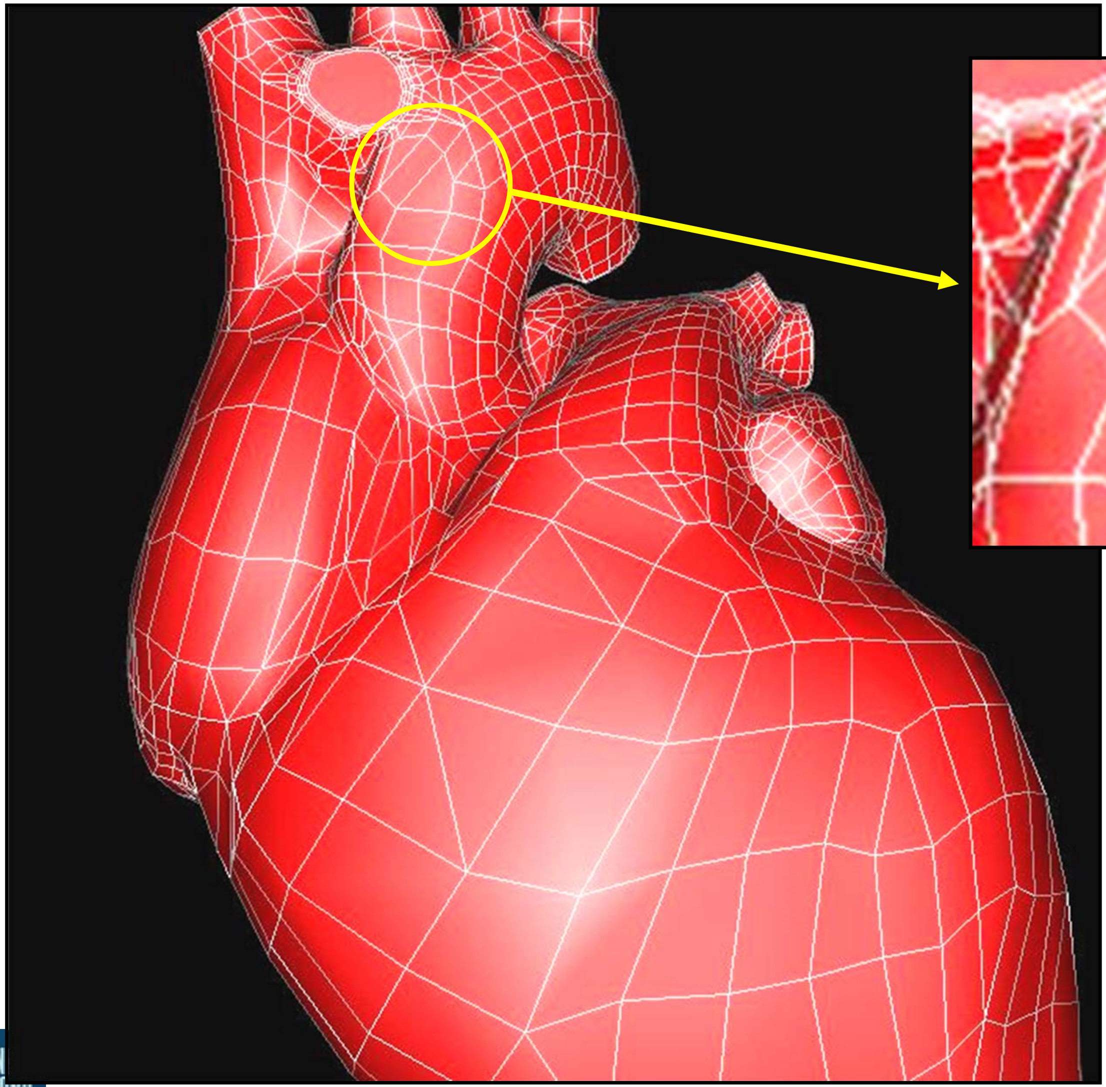


Outlining Polygons the Naīve Way



1. Draw the polygons
2. Draw the edges

Using the Stencil Buffer to Better Outline Polygons



Using the Stencil Buffer to Better Outline Polygons

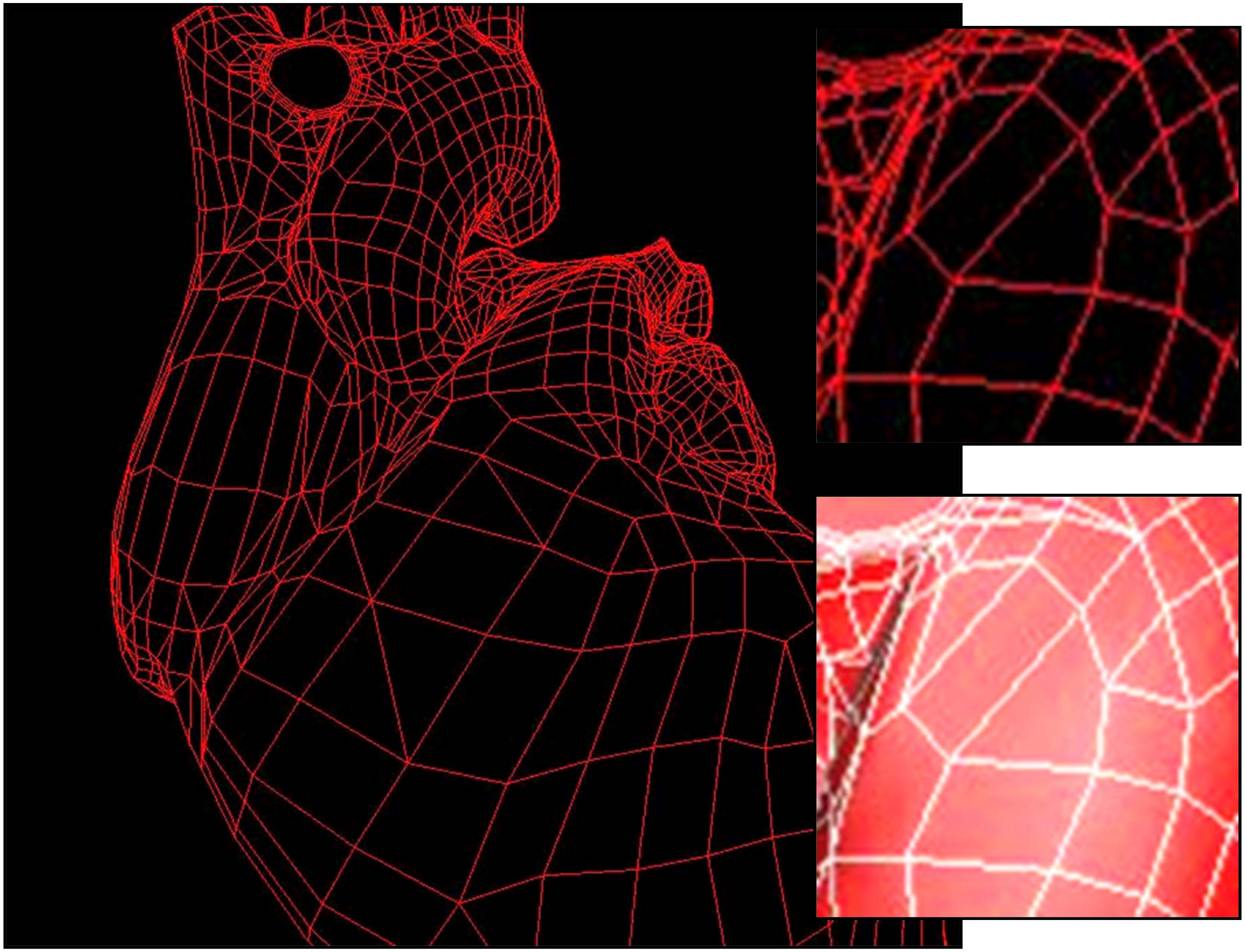
```
Clear the SB = 0

for( each polygon )
{
        Draw the edges, setting SB = 1
        Draw the polygon wherever SB  !=  1
        Draw the edges, setting SB = 0
}
```

Before

After

Using the Stencil Buffer to Perform *Hidden Line Removal*



Stencil Operations for Front and Back Faces

```
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;
```

Operations for Depth Values

```
        VkPipelineDepthStencilStateCreateInfo           vpdssci;
                vpdssci.sType = VK_STRUCTURE_TYPE_PIPELINE_DEPTH_STENCIL_STATE_CREATE_INFO;
                vpdssci.pNext = nullptr;
                vpdssci.flags = 0;
                vpdssci.depthTestEnable  = VK_TRUE;
                vpdssci.depthWriteEnable = VK_TRUE;
                vpdssci.depthCompareOp = VK_COMPARE_OP_LESS;
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
                vpdssci.depthBoundsTestEnable = VK_FALSE;
                vpdssci.front  = vsosf;
                vpdssci.back  = vsosb;
                vpdssci.minDepthBounds  = 0.;
                vpdssci.maxDepthBounds = 1.;
                vpdssci.stencilTestEnable = VK_FALSE;
```

Putting it all Together! (finally…)

```
VkPipeline   GraphicsPipeline;

      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 );

      return result;
```

Group all of the individual state information and create the pipeline

Later on, we will Bind a Specific Graphics Pipeline Data Structure to the Command Buffer when Drawing

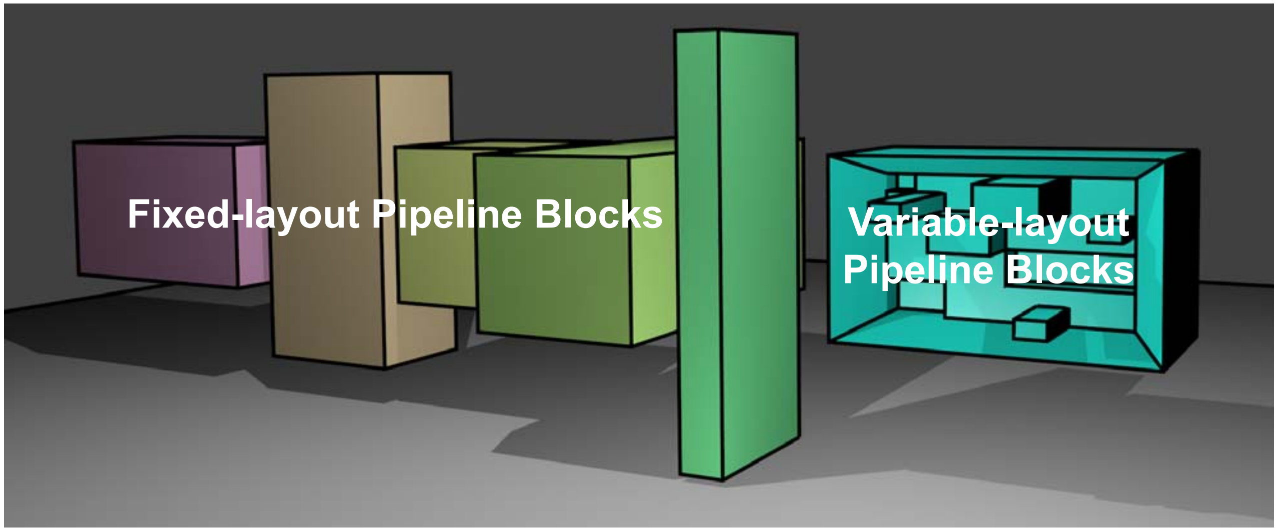
```
vkCmdBindPipeline( CommandBuffers[nextImageIndex],
                   VK_PIPELINE_BIND_POINT_GRAPHICS, GraphicsPipeline );
```

Sidebar: What is the Organization of the Pipeline Data Structure?

If you take a close look at the pipeline data structure creation information, you will see that almost all the pieces have a *fixed size*. For example, the viewport only needs 6 pieces of information – ever:

```
VkViewport          vv;
    vv.x = 0;
    vv.y = 0;
    vv.width   = (float)Width;
    vv.height = (float)Height;
    vv.minDepth  = 0.0f;
    vv.maxDepth = 1.0f;
```

There are two exceptions to this -- the Descriptor Sets and the Push Constants. Each of these two can be almost any size, depending on what you allocate for them. So, I think of the Pipeline Data Structure as consisting of some fixed-layout blocks and 2 variable-layout blocks, like this:



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?

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

What are Descriptor Sets?

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

- Related uniform variables can be updated as a group, gaining efficiency.
- Descriptor Sets are activated when the Command Buffer is filled. Different values for the uniform buffer variables can be toggled by just swapping out the Descriptor Set that points to GPU memory, rather than re-writing the GPU memory.
- Values for the shaders' uniform buffer variables can be compartmentalized into what quantities change often and what change seldom (scene-level, model-level, draw-level), so that uniform variables need to be re-written no more often than is necessary.

```
for( each scene )
{
        Bind Descriptor Set #0
        for( each object )
        {
                Bind Descriptor Set #1
                for( each draw )
                {
                        Bind Descriptor Set #2
                        Do the drawing
                }
        }
}
```

Descriptor Sets

Our example will assume the following shader uniform variables:

```
// 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:	GPU:	GPU:
Uniform data created in a C++ data structure	Uniform data in a “blob”*	Uniform data used in the shader

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

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

GPU: Uniform data in a “blob”*

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

GPU: Uniform data used in the shader

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

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

struct lightBuf
{
        glm::vec4 uLightPos;
};

struct miscBuf
{
        float uTime;
        int   uMode;
};
```

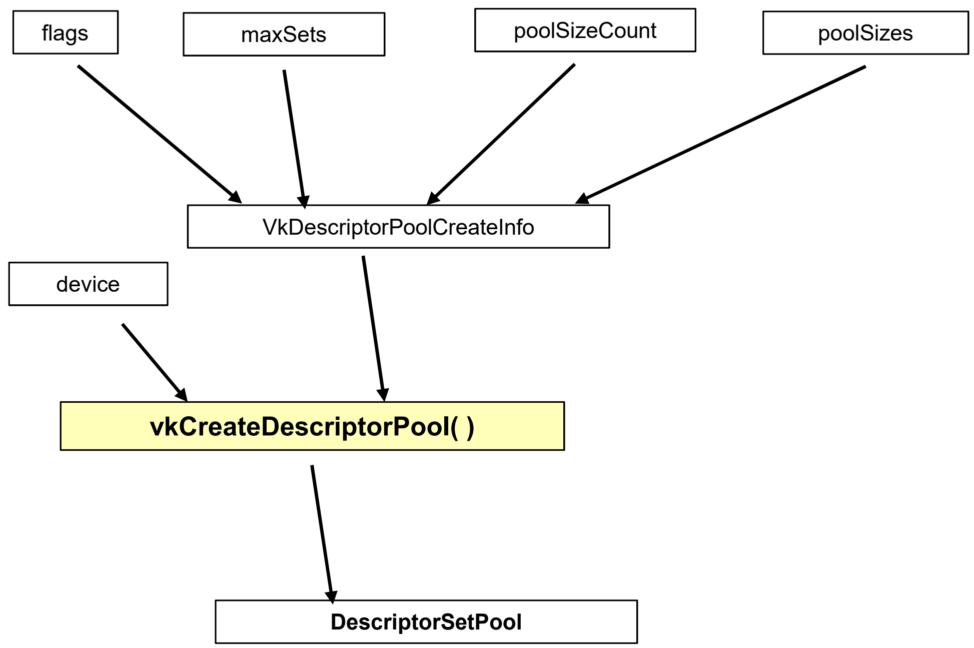

10111001010101111101000
10000101110110101110100
11011001100000011101011
11001110110100110010111
11010111001101101010000
01001000111101000100101
01010100111111001000011
10010101010011000110110
10110111110111111111100
1010100001011101100
0001101000101001111
01110101110100110001110
10001010001111010111101
10111010010010001101011
00000001111100011000010
00001101100111010100011
10100011001100110010000
11000011001111001001111
01001000100101100111000
10111000000101000010111
11101011111001110001011
10000110011101001111001
11110111011111111011111
10100111101111010111100
10101000000111100100110
01110011111010010110011
10110011100011011000111
10110000111110001110010
11001001110011010111011
10010100


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

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

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

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

* “binary large object”

Step 1: Descriptor Set Pools

You don't allocate Descriptor Sets on the fly – that is too slow.
Instead, you allocate a "pool" of Descriptor Sets and then pull from that pool later.



```
VkResult
Init13DescriptorSetPool( )
{
	VkResult result;

	VkDescriptorPoolSize			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.

https://www.britishmuseum.org

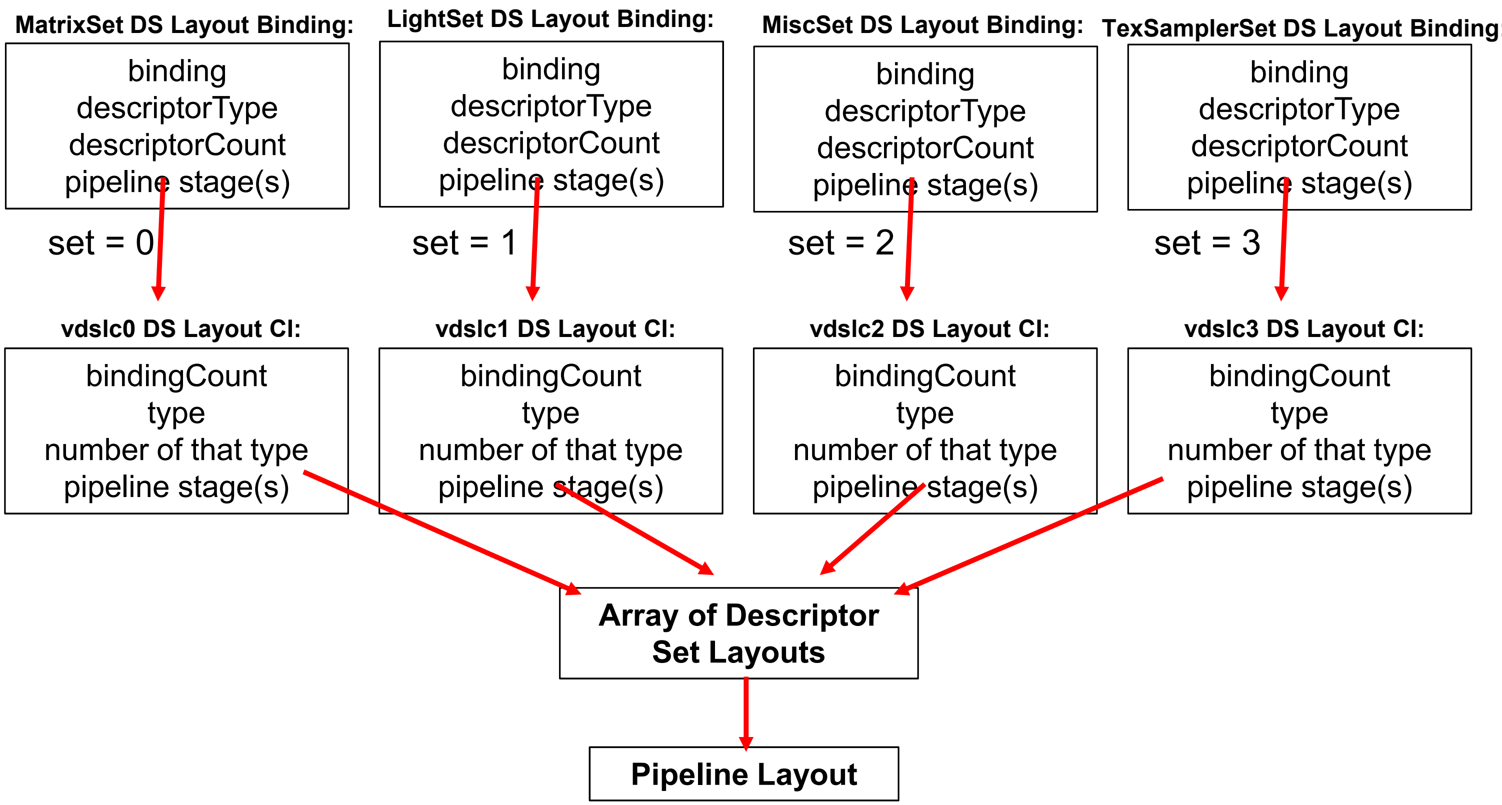
```
layout( std140, set = 0, binding = 0 ) uniform matBuf
{
        mat4 uModelMatrix;
        mat4 uViewMatrix;
        mat4 uProjectionMatrix;
        mat3 uNormalMatrix;
} Matrices;

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;
```

MatrixSet DS Layout Binding:	LightSet DS Layout Binding:	MiscSet DS Layout Binding:	TexSamplerSet DS Layout Binding:
binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)	binding descriptorType descriptorCount pipeline stage(s)
set = 0	set = 1	set = 2	set = 3

```
VkResult
Init13DescriptorSetLayouts( )
{
	VkResult result;

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

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

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

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

```
uniform sampler2D   uSampler;
vec4 rgba = texture( uSampler, vST );
```

Step 2: Define the Descriptor Set Layouts

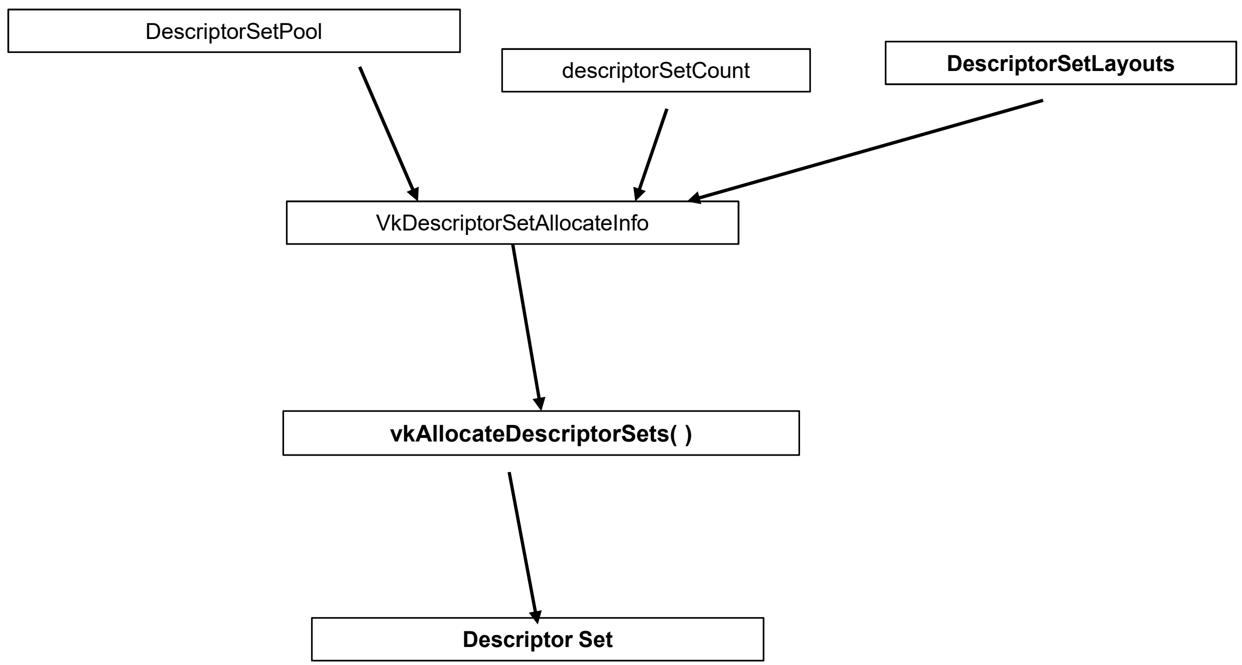


```
    VkDescriptorSetLayoutCreateInfo          vdslc0;
        vdslc0.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_LAYOUT_CREATE_INFO;
        vdslc0.pNext = nullptr;
        vdslc0.flags = 0;
        vdslc0.bindingCount = 1;
        vdslc0.pBindings = &MatrixSet[0];

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

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

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

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

    return result;
}
```

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

```
VkResult
Init14GraphicsPipelineLayout( )
{
	VkResult result;

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

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

	return result;
}
```

Step 4: Allocating the Memory for Descriptor Sets



Step 4: Allocating the Memory for Descriptor Sets


```
VkResult
Init13DescriptorSets( )
{
	VkResult result;

	VkDescriptorSetAllocateInfo		vdsai;
		vdsai.sType = VK_STRUCTURE_TYPE_DESCRIPTOR_SET_ALLOCATE_INFO;
		vdsai.pNext = nullptr;
		vdsai.descriptorPool = DescriptorPool;
		vdsai.descriptorSetCount = 4;
		vdsai.pSetLayouts = DescriptorSetLayouts;

	result = vkAllocateDescriptorSets( LogicalDevice, IN &vdsai, OUT &DescriptorSets[0] );
```

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


```
VkDescriptorBufferInfo                  vdbi0;
    vdbi0.buffer = MyMatrixUniformBuffer.buffer;
    vdbi0.offset = 0;
    vdbi0.range = sizeof(Matrices);

VkDescriptorBufferInfo                  vdbi1;
    vdbi1.buffer = MyLightUniformBuffer.buffer;
    vdbi1.offset = 0;
    vdbi1.range = sizeof(Light);

VkDescriptorBufferInfo                  vdbi2;
    vdbi2.buffer = MyMiscUniformBuffer.buffer;
    vdbi2.offset = 0;
    vdbi2.range = sizeof(Misc);

VkDescriptorImageInfo                   vdii0;
    vdii.sampler     = MyPuppyTexture.texSampler;
    vdii.imageView = MyPuppyTexture.texImageView;
    vdii.imageLayout = VK_IMAGE_LAYOUT_SHADER_READ_ONLY_OPTIMAL;
```

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

This struct identifies what texture sampler and image view it owns

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

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

```
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 = IN &vdbi0;
        vwds0.pImageInfo = (VkDescriptorImageInfo *)nullptr;
        vwds0.pTexelBufferView = (VkBufferView *)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 = IN &vdbi1;
        vwds1.pImageInfo = (VkDescriptorImageInfo *)nullptr;
        vwds1.pTexelBufferView = (VkBufferView *)nullptr;
```

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

Step 5: Tell the Descriptor Sets where their data is

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

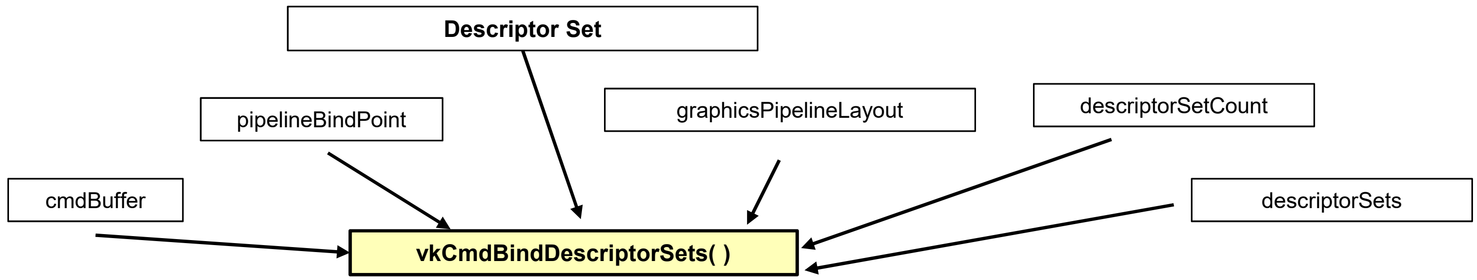
```
VkWriteDescriptorSet                    vwds2;
        // ds 2:
        vwds2.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
        vwds2.pNext = nullptr;
        vwds2.dstSet = DescriptorSets[2];
        vwds2.dstBinding = 0;
        vwds2.dstArrayElement = 0;
        vwds2.descriptorCount = 1;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

        // ds 3:
VkWriteDescriptorSet                    vwds3;
        vwds3.sType = VK_STRUCTURE_TYPE_WRITE_DESCRIPTOR_SET;
        vwds3.pNext = nullptr;
        vwds3.dstSet = DescriptorSets[3];
        vwds3.dstBinding = 0;
        vwds3.dstArrayElement = 0;
        vwds3.descriptorCount = 1;
        vwds3.descriptorType = VK_DESCRIPTOR_TYPE_COMBINED_IMAGE_SAMPLER;
        vwds3.pBufferInfo = (VkDescriptorBufferInfo *)nullptr;
        vwds3.pImageInfo = IN &vdii0;
        vwds3.pTexelBufferView = (VkBufferView *)nullptr;

uint32_t copyCount = 0;

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

vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds0, IN copyCount, (VkCopyDescriptorSet *)nullptr );
vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds1, IN copyCount, (VkCopyDescriptorSet *)nullptr );
vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds2, IN copyCount, (VkCopyDescriptorSet *)nullptr );
vkUpdateDescriptorSets( LogicalDevice, 1, IN &vwds3, IN copyCount, (VkCopyDescriptorSet *)nullptr );
```

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

```
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




```
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.

Sidebar: The Entire Collection of Descriptor Set Paths

VkDescriptorPoolCreateInfo

vkCreateDescriptorPool( )

Create the pool of Descriptor Sets for future use

VkDescriptorSetLayoutBinding

VkDescriptorSetLayoutCreateInfo

vkCreateDescriptorSetLayout( )

vkCreatePipelineLayout( )

Describe a particular Descriptor Set layout and use it in a specific Pipeline layout

VkDescriptorSetAllocateInfo

vkAllocateDescriptorSets( )

Allocate memory for particular Descriptor Sets

VkDescriptorBufferInfo

VkDescriptorImageInfo

VkWriteDescriptorSet

Tell a particular Descriptor Set where its CPU data is

vkUpdateDescriptorSets( )

Re-write CPU data into a particular Descriptor Set

vkCmdBindDescriptorSets( )

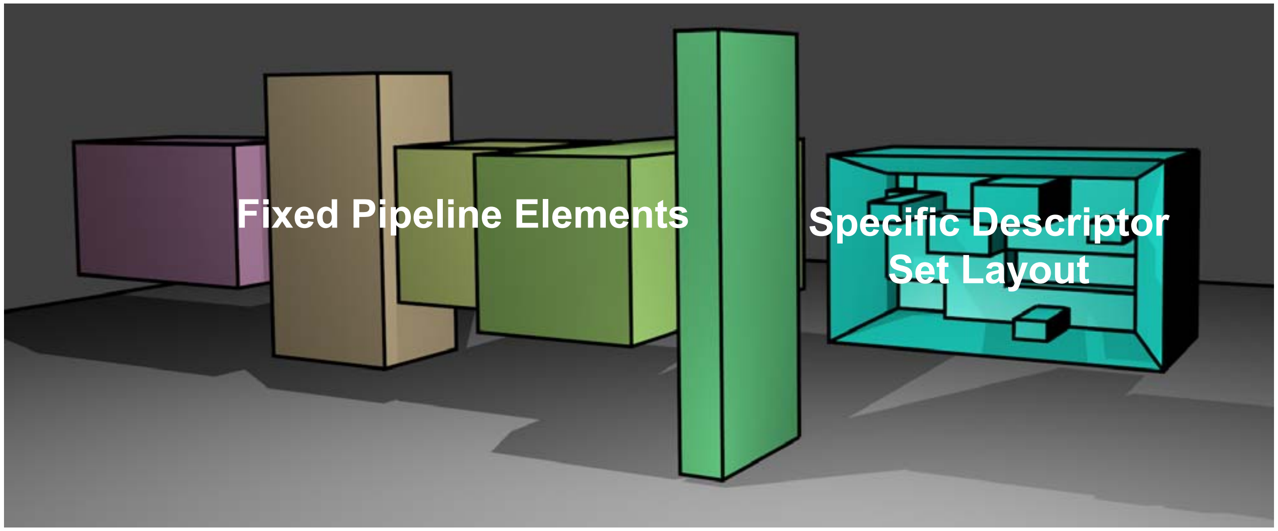
Make a particular Descriptor Set "current" for rendering

Sidebar: Why Do Descriptor Sets Need to Provide Layout Information to the Pipeline Data Structure?

The pieces of the Pipeline Data Structure are fixed in size – with the exception of the Descriptor Sets and the Push Constants. Each of these two can be any size, depending on what you allocate for them. So, the Pipeline Data Structure needs to know how these two are configured before it can set its own total layout.

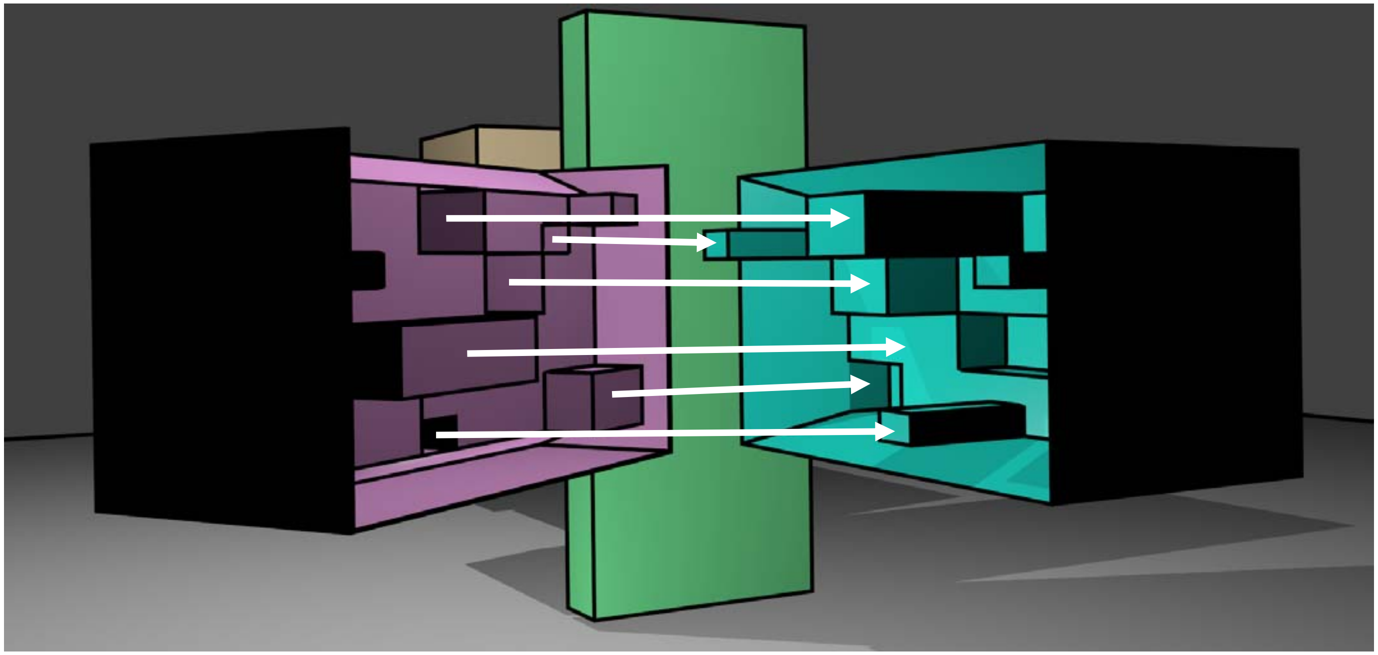
Think of the DS layout as being a particular-sized hole in the Pipeline Data Structure. Any data you have that matches this hole's shape and size can be plugged in there.

The Pipeline Data Structure



Sidebar: Why Do Descriptor Sets Need to Provide Layout Information to the Pipeline Data Structure?

Any set of data that matches the Descriptor Set Layout can be plugged in there.



Textures

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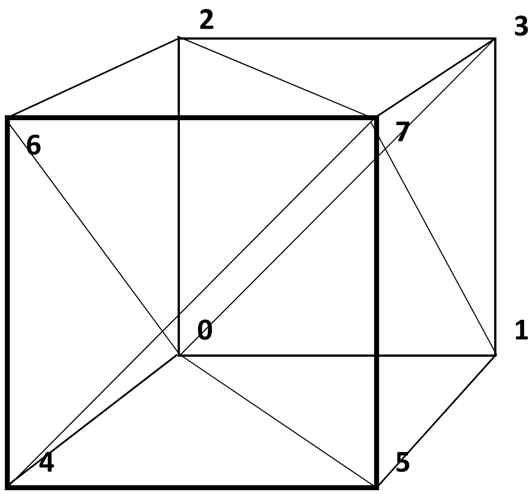
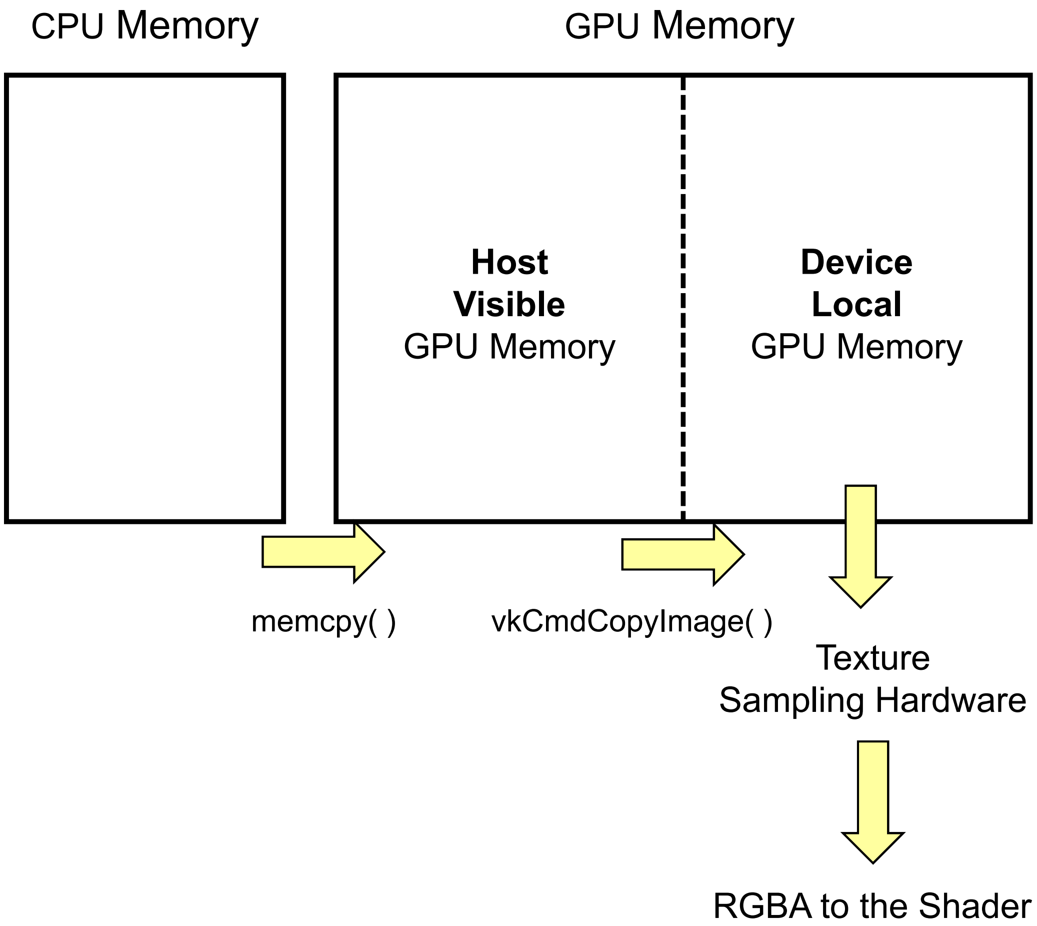
Triangles in an Array of Structures

```
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. }
	},
```



Memory Types



Memory Types

NVIDIA Discrete Graphics:

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

Intel Integrated Graphics:

3 Memory Types:
Memory 0: DeviceLocal
Memory 1: DeviceLocal HostVisible HostCoherent
Memory 2: DeviceLocal HostVisible HostCoherent HostCached

Texture Sampling Parameters

OpenGL

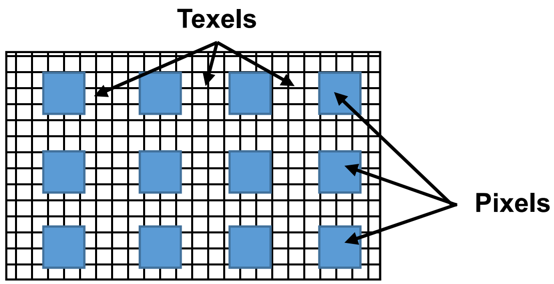
```
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
glTexParameteri( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
```

Vulkan

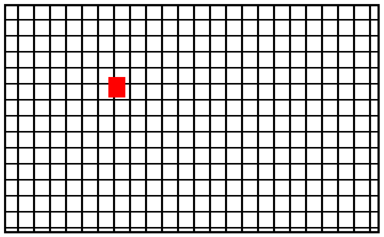
```
VkSamplerCreateInfo                      vsci;
        vsci.magFilter = VK_FILTER_LINEAR;
        vsci.minFilter  = VK_FILTER_LINEAR;
        vsci.mipmapMode    = VK_SAMPLER_MIPMAP_MODE_LINEAR;
        vsci.addressModeU  = VK_SAMPLER_ADDRESS_MODE_REPEAT;
        vsci.addressModeV  = VK_SAMPLER_ADDRESS_MODE_REPEAT;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

        . . .

result = vkCreateSampler( LogicalDevice, IN &vsci, PALLOCATOR, pTextureSampler );
```

Textures' Undersampling Artifacts

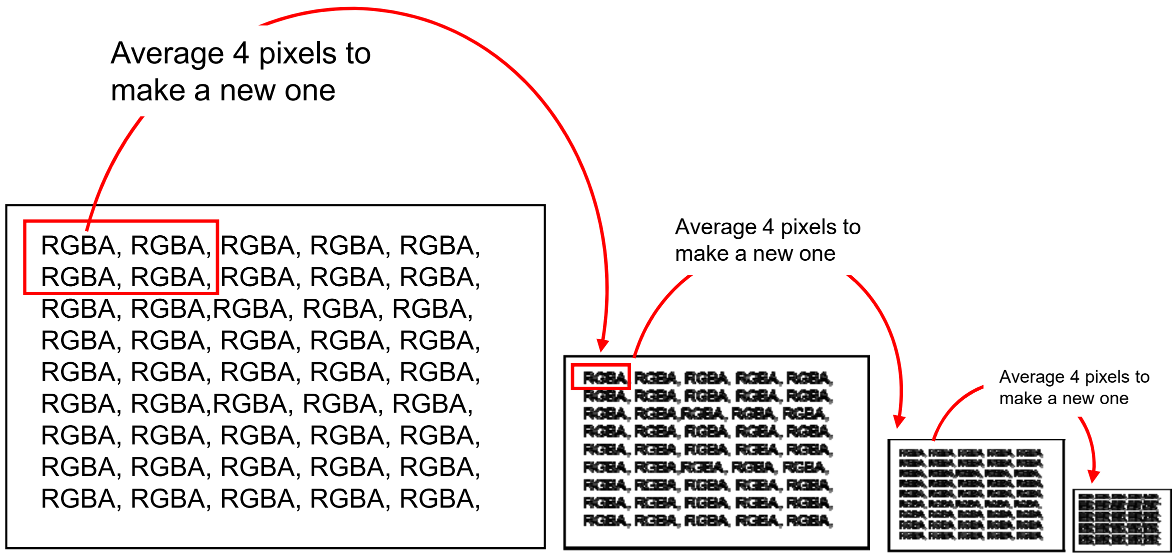
As an object gets farther away and covers a smaller and smaller part of the screen, the **texels : pixels ratio** used in the coverage becomes larger and larger. This means that there are pieces of the texture leftover in between the pixels that are being drawn into, so that some of the texture image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



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



Texture Mip*-mapping



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

* Latin: *multim in parvo*, “many things in a small place”

```
VkResult
Init07TextureSampler( MyTexture * pMyTexture )
{
	VkResult result;

	VkSamplerCreateInfo			vsci;
		vsci.sType = VK_STRUCTURE_TYPE_SAMPLER_CREATE_INFO;
		vsci.pNext = nullptr;
		vsci.flags = 0;
		vsci.magFilter = VK_FILTER_LINEAR;
		vsci.minFilter = VK_FILTER_LINEAR;
		vsci.mipmapMode = VK_SAMPLER_MIPMAP_MODE_LINEAR;
		vsci.addressModeU = VK_SAMPLER_ADDRESS_MODE_REPEAT;
		vsci.addressModeV = VK_SAMPLER_ADDRESS_MODE_REPEAT;
		vsci.addressModeW = VK_SAMPLER_ADDRESS_MODE_REPEAT;
#ifdef CHOICES
VK_SAMPLER_ADDRESS_MODE_REPEAT
VK_SAMPLER_ADDRESS_MODE_MIRRORED_REPEAT
VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_EDGE
VK_SAMPLER_ADDRESS_MODE_CLAMP_TO_BORDER
VK_SAMPLER_ADDRESS_MODE_MIRROR_CLAMP_TO_EDGE
#endif
		vsci.mipLodBias = 0.;
		vsci.anisotropyEnable = VK_FALSE;
		vsci.maxAnisotropy = 1.;
		vsci.compareEnable = VK_FALSE;
		vsci.compareOp = VK_COMPARE_OP_NEVER;
#ifdef CHOICES
VK_COMPARE_OP_NEVER
VK_COMPARE_OP_LESS
VK_COMPARE_OP_EQUAL
VK_COMPARE_OP_LESS_OR_EQUAL
VK_COMPARE_OP_GREATER
VK_COMPARE_OP_NOT_EQUAL
VK_COMPARE_OP_GREATER_OR_EQUAL
VK_COMPARE_OP_ALWAYS
#endif
		vsci.minLod = 0.;
		vsci.maxLod = 0.;
		vsci.borderColor = VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK;
#ifdef CHOICES
VK_BORDER_COLOR_FLOAT_TRANSPARENT_BLACK
VK_BORDER_COLOR_INT_TRANSPARENT_BLACK
VK_BORDER_COLOR_FLOAT_OPAQUE_BLACK
VK_BORDER_COLOR_INT_OPAQUE_BLACK
VK_BORDER_COLOR_FLOAT_OPAQUE_WHITE
VK_BORDER_COLOR_INT_OPAQUE_WHITE
#endif
		vsci.unnormalizedCoordinates = VK_FALSE;	// VK_TRUE means we are use 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_OPTIMAL
VK_IMAGE_TILING_LINEAR
#endif
			vici.usage = VK_IMAGE_USAGE_TRANSFER_SRC_BIT;
#ifdef CHOICES
VK_IMAGE_USAGE_TRANSFER_SRC_BIT
VK_IMAGE_USAGE_TRANSFER_DST_BIT
VK_IMAGE_USAGE_SAMPLED_BIT
VK_IMAGE_USAGE_STORAGE_BIT
VK_IMAGE_USAGE_COLOR_ATTACHMENT_BIT
VK_IMAGE_USAGE_DEPTH_STENCIL_ATTACHMENT_BIT
VK_IMAGE_USAGE_TRANSIENT_ATTACHMENT_BIT
VK_IMAGE_USAGE_INPUT_ATTACHMENT_BIT
#endif
			vici.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
```

```
#ifdef CHOICES
VK_IMAGE_LAYOUT_UNDEFINED
VK_IMAGE_LAYOUT_PREINITIALIZED
#endif
        vici.queueFamilyIndexCount = 0;
        vici.pQueueFamilyIndices = (const uint32_t *)nullptr;

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

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

    if (Verbose)
    {
        fprintf(FpDebug, "Image vmr.size = %lld\n", vmr.size);
        fprintf(FpDebug, "Image vmr.alignment = %lld\n", vmr.alignment);
        fprintf(FpDebug, "Image vmr.memoryTypeBits = 0x%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 = FindMemoryThatIsHostVisible();   // because we want to mmap it

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

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

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

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

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

    if (Verbose)
    {
        fprintf(FpDebug, "Subresource Layout:\n");
        fprintf(FpDebug, "\toffset = %lld\n", vsl.offset);
        fprintf(FpDebug, "\tsize = %lld\n", vsl.size);
        fprintf(FpDebug, "\trowPitch = %lld\n", vsl.rowPitch);
        fprintf(FpDebug, "\tarrayPitch = %lld\n", vsl.arrayPitch);
        fprintf(FpDebug, "\tdepthPitch = %lld\n", 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
}
// ******************************************************************************
```

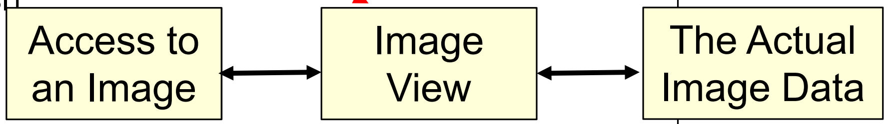
```
// copy pixels from the staging image to the texture:

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.oldLayout = VK_IMAGE_LAYOUT_PREINITIALIZED;
            vimb.newLayout = VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL;
            vimb.srcQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
            vimb.dstQueueFamilyIndex = VK_QUEUE_FAMILY_IGNORED;
            vimb.image = stagingImage;
            vimb.srcAccessMask = 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:
// ******************************************************************************
{
	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, IN &vimb);

	// now do the final image transfer:

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

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

	VkExtent3D			ve3;
		ve3.width = texWidth;
		ve3.height = texHeight;
		ve3.depth = 1;
```

```
	VkImageCopy			vic;
		vic.srcSubresource = visl;
		vic.srcOffset = vo3;
		vic.dstSubresource = visl;
		vic.dstOffset = vo3;
		vic.extent = ve3;

	vkCmdCopyImage(TextureCommandBuffer,
		stagingImage, VK_IMAGE_LAYOUT_TRANSFER_SRC_OPTIMAL,
		textureImage, VK_IMAGE_LAYOUT_TRANSFER_DST_OPTIMAL, 1, IN &vic);
}
// ******************************************************************************
```

```
// *******************************************************************************
// transition the texture buffer layout a second time:
// *******************************************************************************
	{
		VkImageSubresourceRange		visr;
			visr.aspectMask = VK_IMAGE_ASPECT_COLOR_BIT;
			visr.baseMipLevel = 0;
			visr.levelCount = 1;
			visr.baseArrayLayer = 0;
			visr.layerCount = 1;

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

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

	result = vkEndCommandBuffer( TextureCommandBuffer );

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

	result = vkQueueSubmit( Queue, 1, IN &vsi, VK_NULL_HANDLE );
	result = vkQueueWaitIdle( Queue );
```

```
    // create an image view for the texture image:
    // (an "image view" is used to indirectly access an image)

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

    VkImageViewCreateInfo            vivci;
        vivci.sType = VK_STRUCTURE_TYPE_IMAGE_VIEW_CREATE_INFO;
        vivci.pNext = nullptr;
        vivci.flags = 0;
        vivci.image = 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;
        vivci.subresourceRange = visr;

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

    return result;
}
```



8 bits Red	8 bits Green	8 bits Blue	8 bits Alpha

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

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*.

Queues and Command Buffers

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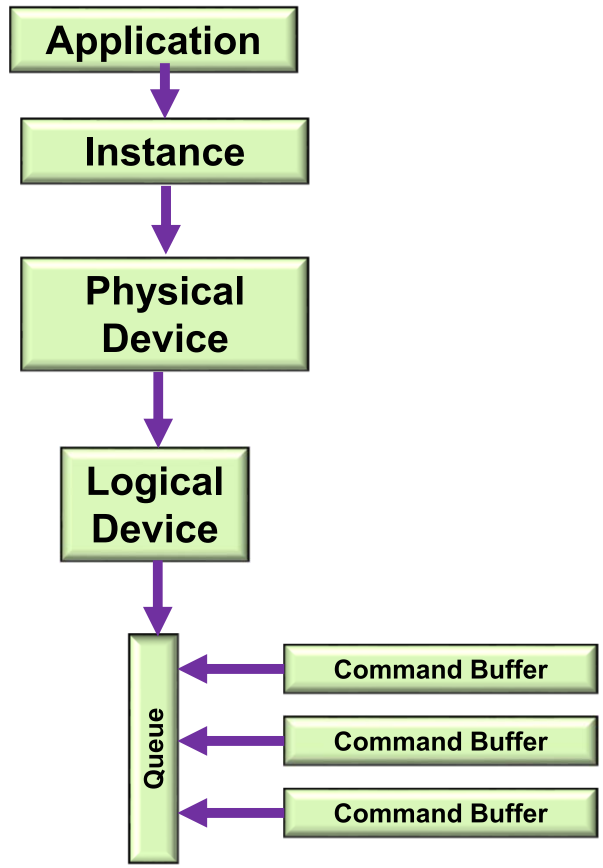
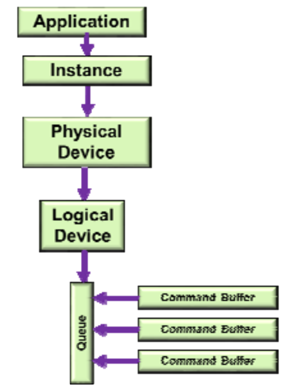
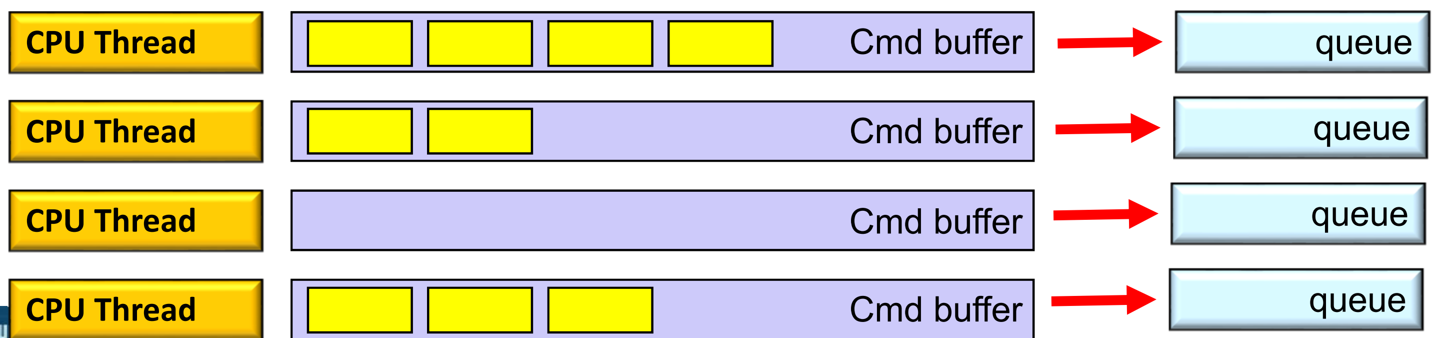
Simplified Block Diagram



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

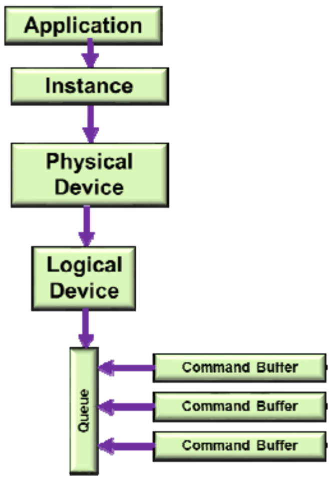
```
uint32_t  count;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *) nullptr );

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

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

```
Found 3 Queue Families:
        0: Queue Family Count = 16  ;    Graphics Compute Transfer
        1: Queue Family Count =   1  ;    Transfer
        2: Queue Family Count =   8  ;    Compute
```

Similarly, we Can Write a Function that Finds the Proper Queue Family

```
int
FindQueueFamilyThatDoesGraphics( )
{
	uint32_t count = -1;
	vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, OUT &count, OUT (VkQueueFamilyProperties *)nullptr );

	VkQueueFamilyProperties *vqfp = new VkQueueFamilyProperties[ count ];
	vkGetPhysicalDeviceQueueFamilyProperties( IN 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

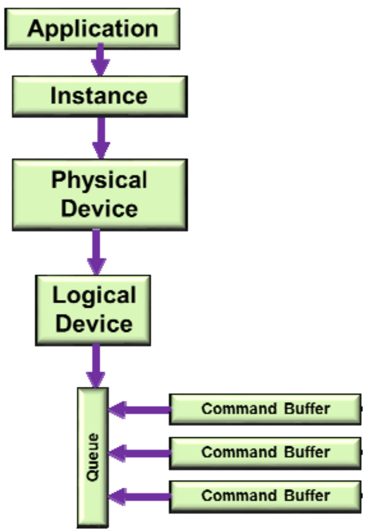



```
float   queuePriorities[ ] =
{
            1.                  // one entry per queueCount
};

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

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

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

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

Creating the Command Pool as part of the Logical Device

```
VkResult
Init06CommandPool( )
{
	VkResult result;

	VkCommandPoolCreateInfo			vcpci;
		vcpci.sType = VK_STRUCTURE_TYPE_COMMAND_POOL_CREATE_INFO;
		vcpci.pNext = nullptr;
		vcpci.flags =	VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT
				| VK_COMMAND_POOL_CREATE_TRANSIENT_BIT;
#ifdef CHOICES
VK_COMMAND_POOL_CREATE_TRANSIENT_BIT
VK_COMMAND_POOL_CREATE_RESET_COMMAND_BUFFER_BIT
#endif
		vcpci.queueFamilyIndex = FindQueueFamilyThatDoesGraphics( );

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

	return result;
}
```

Creating the Command Buffers

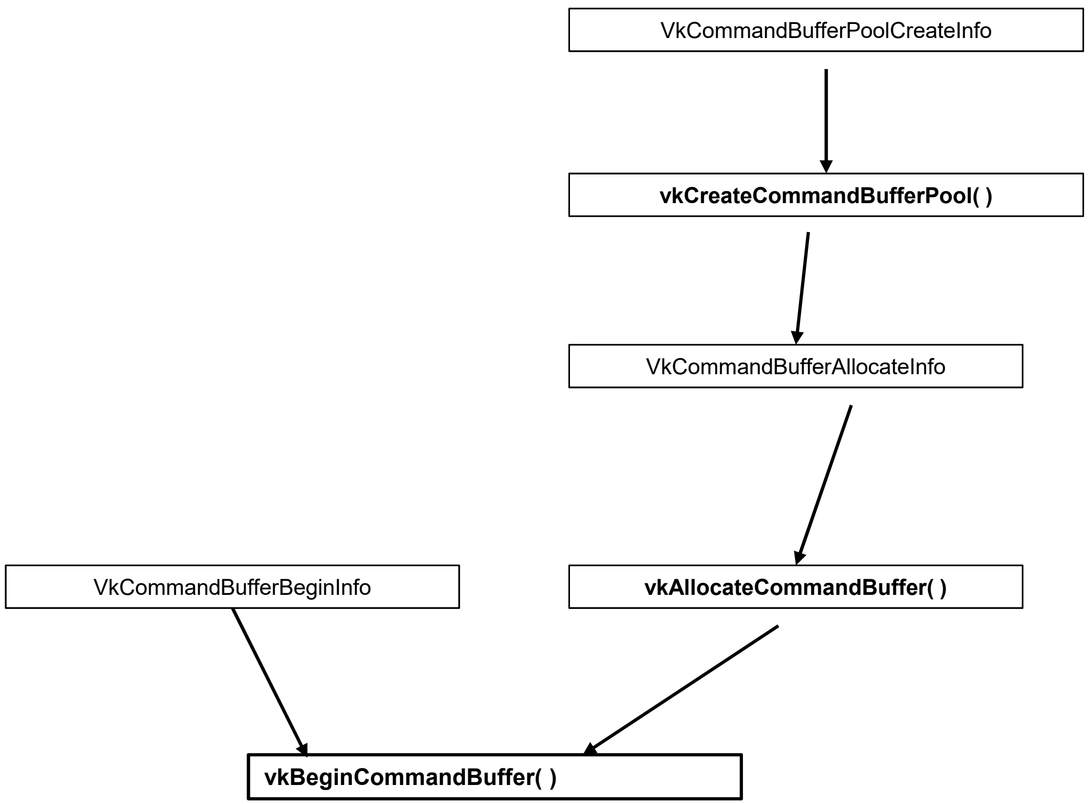



```
VkResult
Init06CommandBuffers( )
{
	VkResult result;

	// allocate 2 command buffers for the double-buffered rendering:

	{
		VkCommandBufferAllocateInfo		vcbai;
			vcbai.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO;
			vcbai.pNext = nullptr;
			vcbai.commandPool = CommandPool;
			vcbai.level = VK_COMMAND_BUFFER_LEVEL_PRIMARY;
			vcbai.commandBufferCount = 2;		// 2, because of double-buffering

		result = vkAllocateCommandBuffers( LogicalDevice, IN &vcbai, OUT &CommandBuffers[0] );
	}


	// allocate 1 command buffer for the transferring pixels from a staging buffer to a texture buffer:

	{
		VkCommandBufferAllocateInfo		vcbai;
			vcbai.sType = VK_STRUCTURE_TYPE_COMMAND_BUFFER_ALLOCATE_INFO;
			vcbai.pNext = nullptr;
			vcbai.commandPool = CommandPool;
			vcbai.level = VK_COMMAND_BUFFER_LEVEL_PRIMARY;
			vcbai.commandBufferCount = 1;

		result = vkAllocateCommandBuffers( LogicalDevice, IN &vcbai, OUT &TextureCommandBuffer );
	}

	return result;
}
```

Beginning a Command Buffer – One per Image

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

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

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


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

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

        . . .

vkEndCommandBuffer( CommandBuffers[nextImageIndex] );
```

Beginning a Command Buffer



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


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

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

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

```
VkResult
RenderScene( )
{
        VkResult result;
        VkSemaphoreCreateInfo             vsci;
         vsci.sType = VK_STRUCTURE_TYPE_SEMAPHORE_CREATE_INFO;
         vsci.pNext = nullptr;
         vsci.flags = 0;

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

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

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

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

```
VkClearColorValue              vccv;
        vccv.float32[0] = 0.0;
        vccv.float32[1] = 0.0;
        vccv.float32[2] = 0.0;
        vccv.float32[3] = 1.0;

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

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

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

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

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

```
VkViewport viewport =
{
        0.,                 // x
        0.,                 // y
        (float)Width,
        (float)Height,
        0.,                 // minDepth
        1.                  // maxDepth
};

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

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

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

vkCmdBindDescriptorSets( CommandBuffers[nextImageIndex], VK_PIPELINE_BIND_POINT_GRAPHICS,
                        GraphicsPipelineLayout, 0, 4, DescriptorSets, 0, (uint32_t *)nullptr );
                                                // dynamic offset count, dynamic offsets
vkCmdBindPushConstants( CommandBuffers[nextImageIndex], PipelineLayout, VK_SHADER_STAGE_ALL, offset, size, void *values );

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

VkDeviceSize offsets[1] = { 0 };

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

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

vkCmdEndRenderPass( CommandBuffers[nextImageIndex] );

vkEndCommandBuffer( CommandBuffers[nextImageIndex] );
```

Submitting a Command Buffer to a Queue for Execution


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

The Entire Submission / Wait / Display Process


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

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 );\
                                    // 0 =, queueIndex

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

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

vkDestroyFence( LogicalDevice, renderFence, PALLOCATOR );

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

result = vkQueuePresentKHR( presentQueue, IN &vpi );
```

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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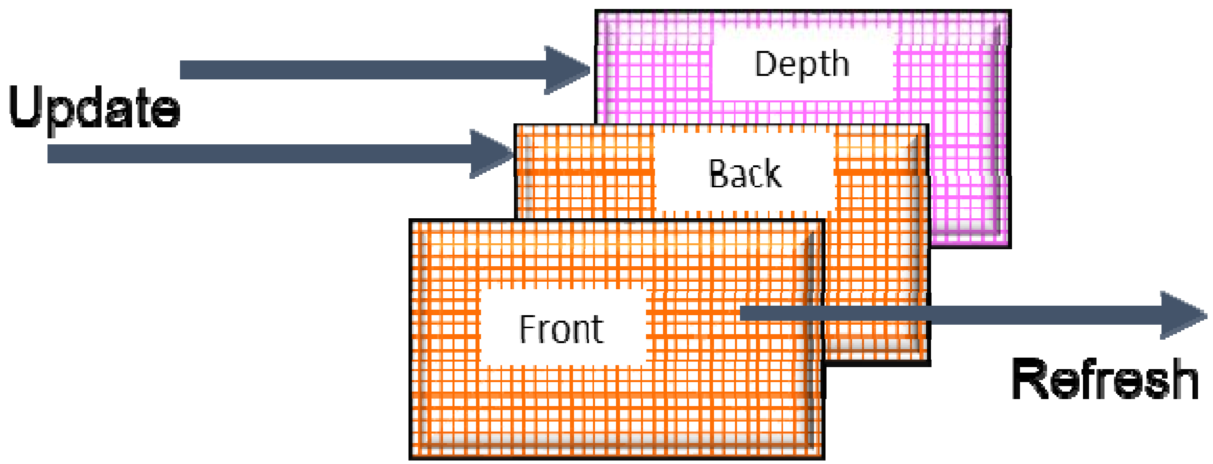
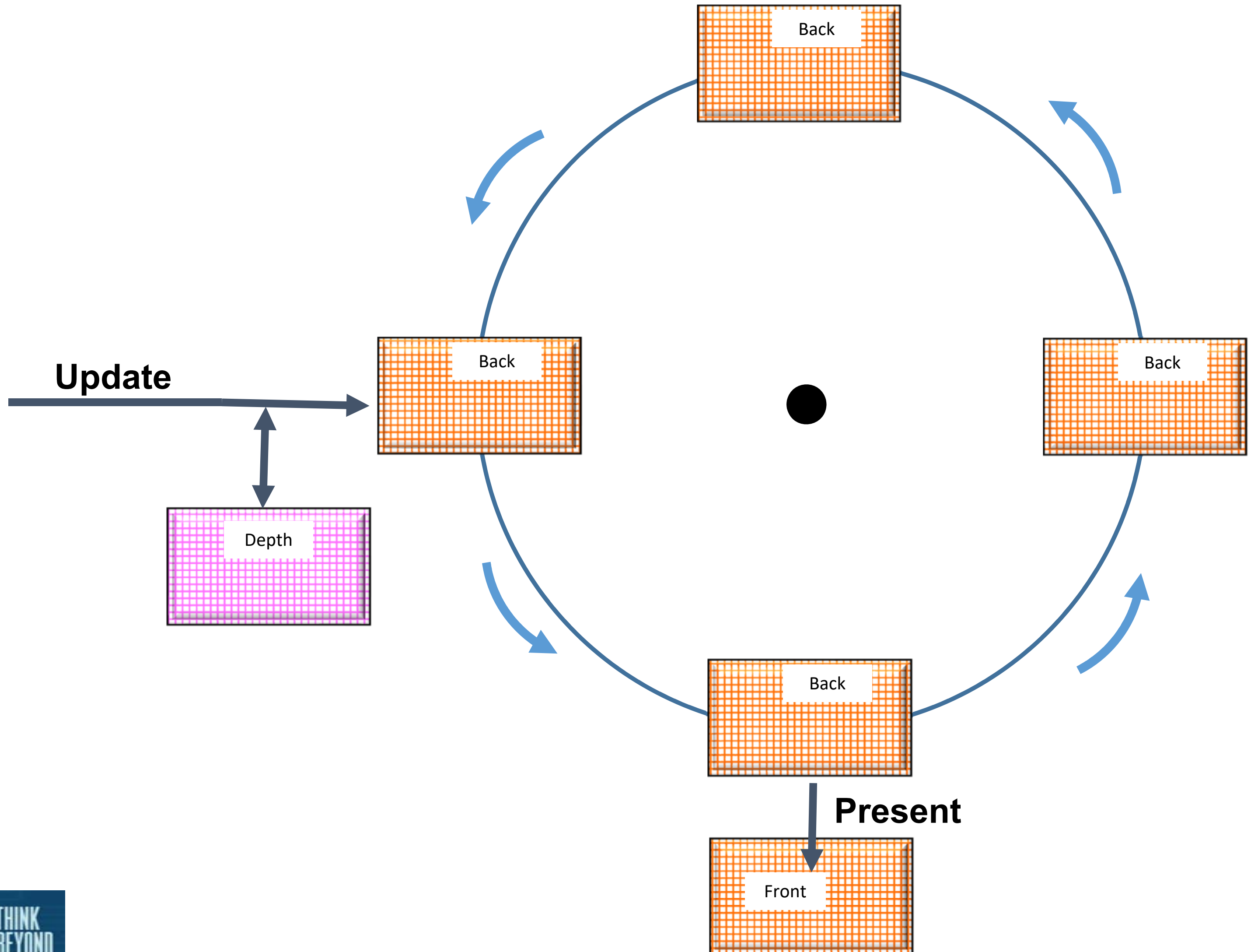
How OpenGL Thinks of Framebuffers



How Vulkan Thinks of Framebuffers – the Swap Chain

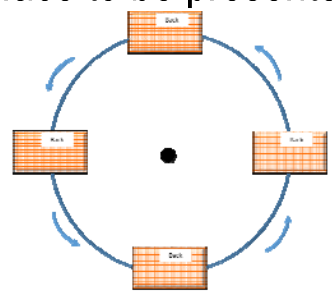


What is a Swap Chain?

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

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

Swap Chains are arranged as a ring buffer



Swap Chains are tightly coupled to the window system.

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

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

We Need to Find Out What our Display Capabilities Are

```
VkSurfaceCapabilitiesKHR            vsc;
vkGetPhysicalDeviceSurfaceCapabilitiesKHR( PhysicalDevice, Surface, OUT &vsc );
VkExtent2D surfaceRes = vsc.currentExtent;
fprintf( FpDebug, "\nvkGetPhysicalDeviceSurfaceCapabilitiesKHR:\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, "\nFound %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, "\nFound %d Present Modes:\n", presentModeCount );

        . . .
```

We Need to Find Out What our Display Capabilities Are

VulkanDebug.txt output:

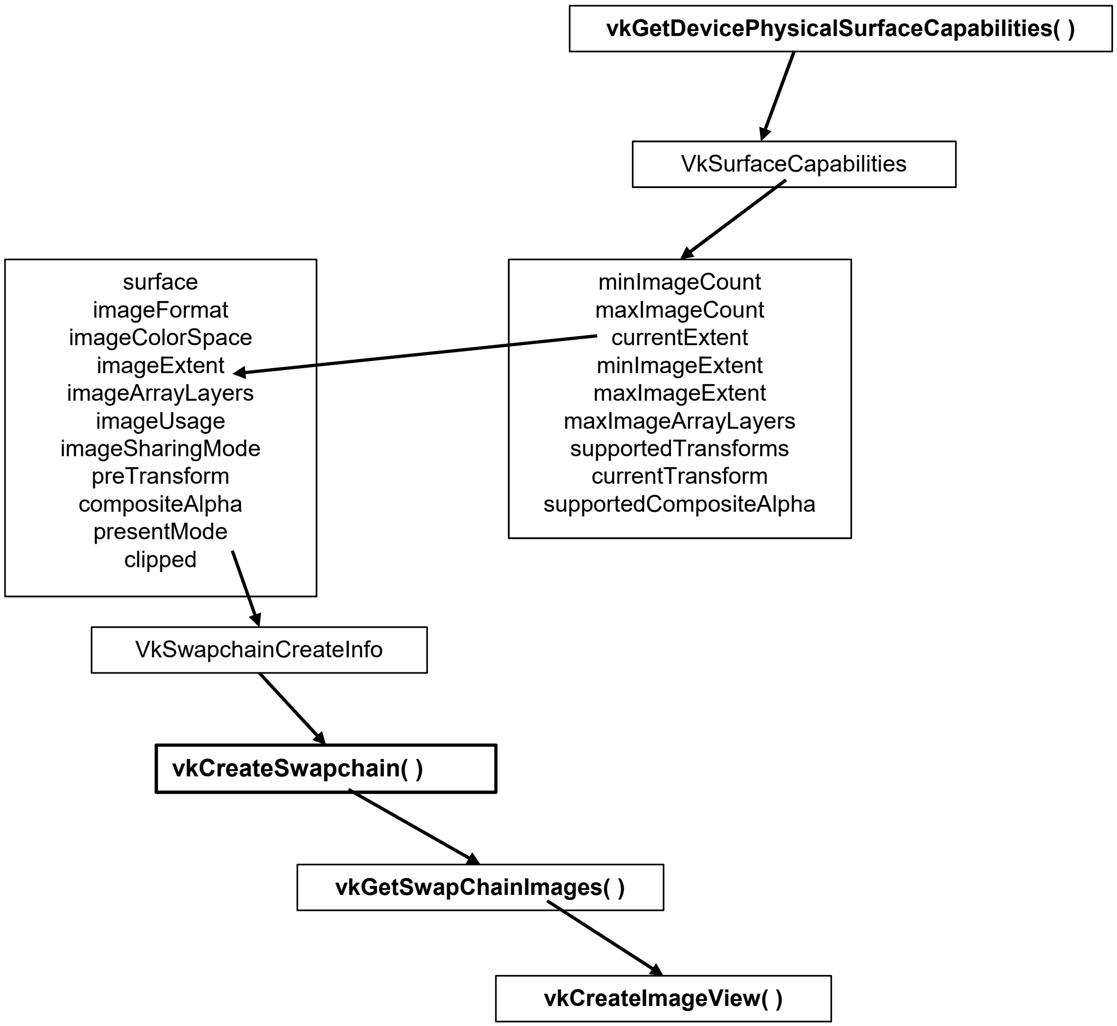
```
vkGetPhysicalDeviceSurfaceCapabilitiesKHR:
        minImageCount = 2 ; maxImageCount = 8
        currentExtent = 1024 x 1024
        minImageExtent = 1024 x 1024
        maxImageExtent = 1024 x 1024
        maxImageArrayLayers = 1
        supportedTransforms = 0x0001
        currentTransform = 0x0001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

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


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


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

Creating a Swap Chain



Creating a Swap Chain

```
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 );
```

Creating the Swap Chain Images and Image Views

```
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 ] );
}
```

Rendering into the Swap Chain, 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  tmeout = 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


```
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

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

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

result = vkQueuePresentKHR( presentQueue, IN &vpi );
```

Push Constants

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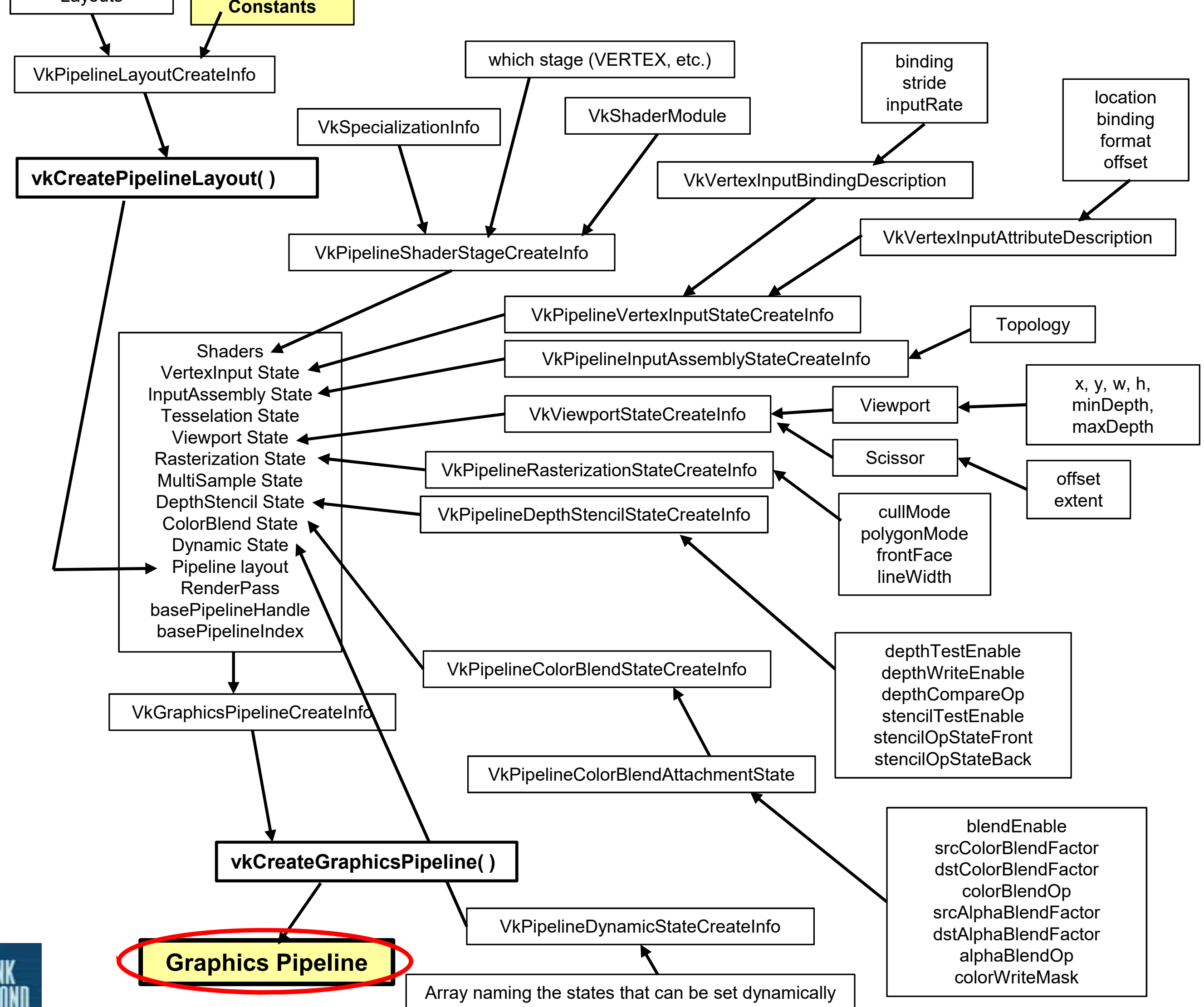
Push Constants

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.

Creating a Pipeline



Push Constants

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

```
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:

```
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**.

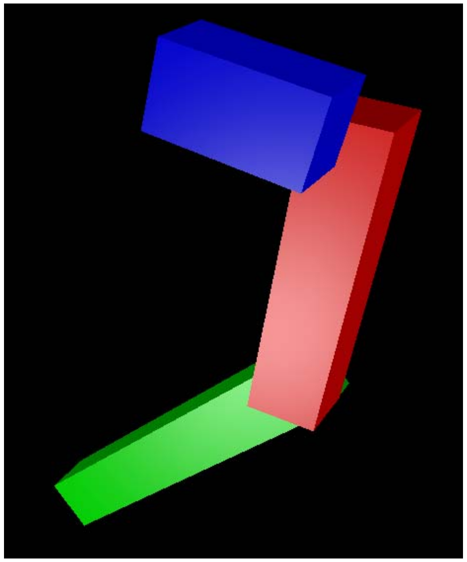
Setting up the Push Constants for the Pipeline Structure

Prior to that, however, the pipeline layout needs to be told about the Push Constants:

```
VkPushConstantRange                    vpcr[1];
    vpcr[0].stageFlags =
                VK_PIPELINE_STAGE_VERTEX_SHADER_BIT
               |VK_PIPELINE_STAGE_FRAGMENT_SHADER_BIT;
    vpcr[0].offset = 0;
    vpcr[0].size = sizeof( glm::mat4 );

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

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

An Robotic Example using Push Constants

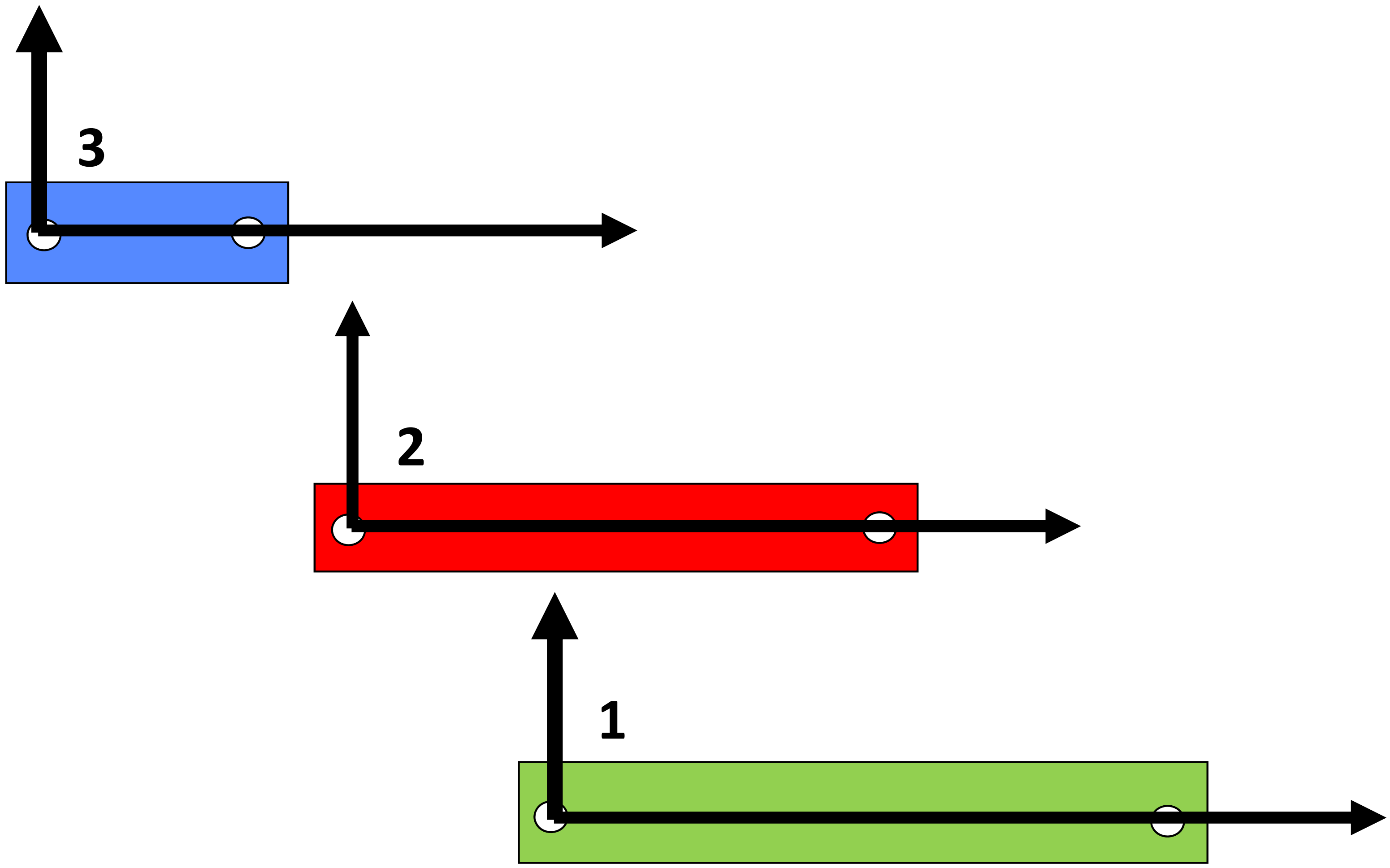
A robotic animation (i.e., a hierarchical transformation system)



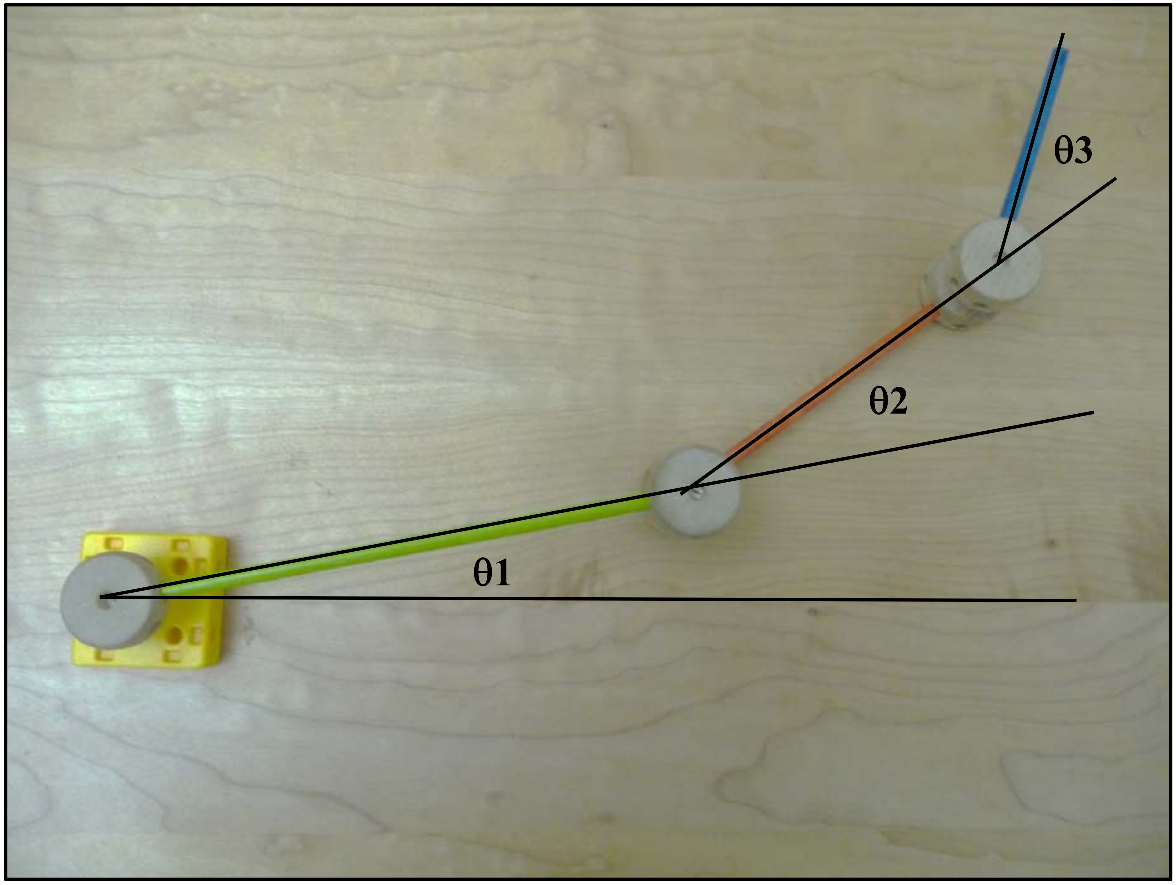
Where each arm is represented by:

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

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

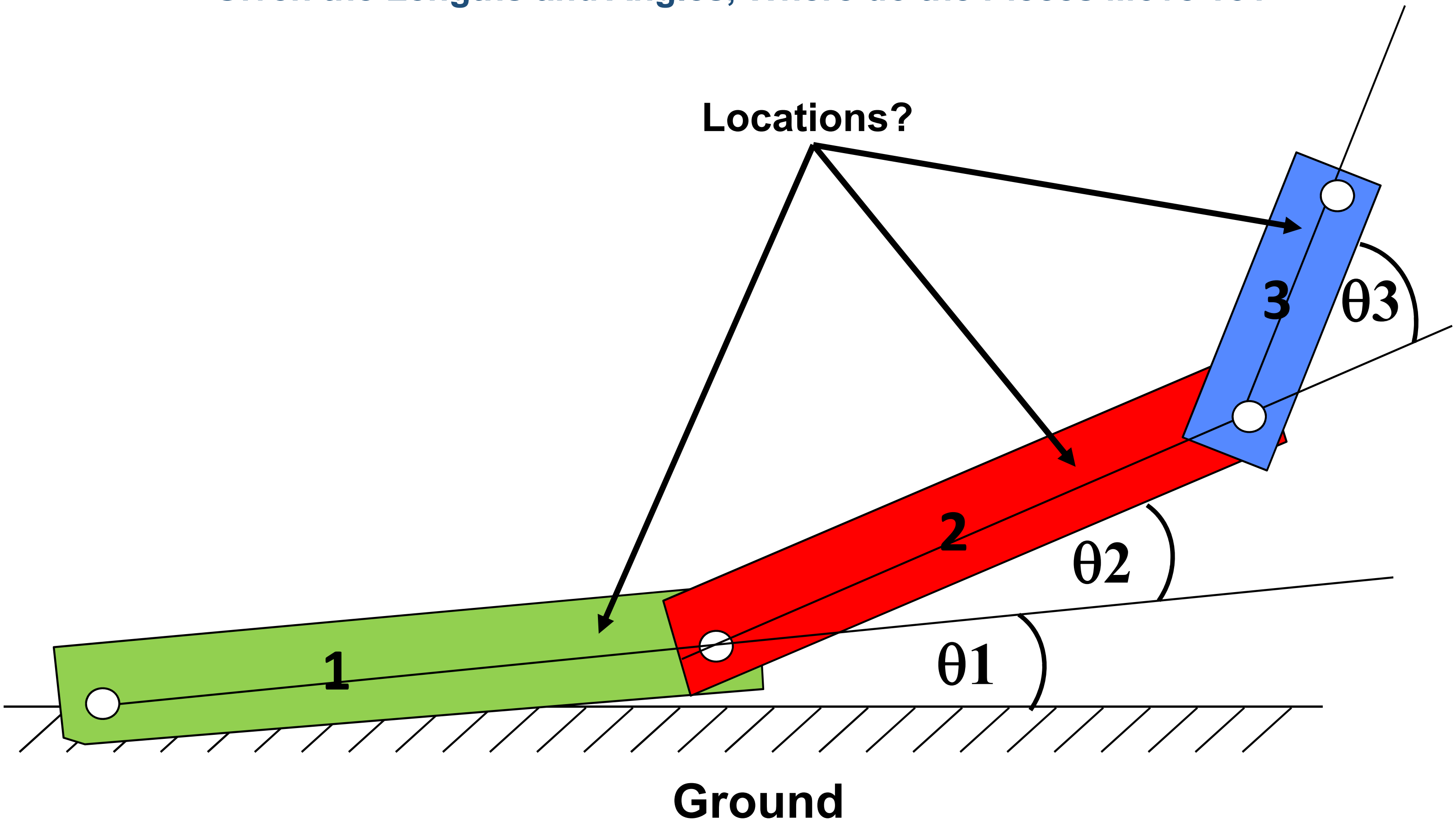
Forward Kinematics:
You Start with Separate Pieces, all Defined in their Own Local Coordinate System



Forward Kinematics:
Hook the Pieces Together, Change Parameters, and Things Move
(All Young Children Understand This)



Forward Kinematics:
Given the Lengths and Angles, Where do the Pieces Move To?



Positioning Part #1 With Respect to Ground

1. Rotate by Θ1
2. Translate by $T_{1/G}$

Write it

$$\left[M_{1/G} \right] = \left[T_{1/G} \right] * \left[R_{\theta 1} \right]$$

Say it

Positioning Part #2 With Respect to Ground

1. Rotate by Θ2
2. Translate the length of part 1
3. Rotate by Θ 1
4. Translate by $T_{1/G}$

Write it

$$[M_{2/G}] = [T_{1/G}]*[R_{\theta 1}]*[T_{2/1}]*[R_{\theta 2}]$$

$$[M_{2/G}] = [M_{1/G}]*[M_{2/1}]$$

Say it

Positioning Part #3 With Respect to Ground

1. Rotate by Θ3
2. Translate the length of part 2
3. Rotate by Θ2
4. Translate the length of part 1
5. Rotate by Θ1
6. Translate by $T_{1/G}$

Write it

$$[M_{3/G}] = [T_{1/G}]*[R_{\theta 1}]*[T_{2/1}]*[R_{\theta 2}]*[T_{3/2}]*[R_{\theta 3}]$$

$$[M_{3/G}] = [M_{1/G}]*[M_{2/1}]*[M_{3/2}]$$

Say it

In the *Reset* Function


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

. . .

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

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

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

The constructor **glm::mat4(1.)** 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;

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

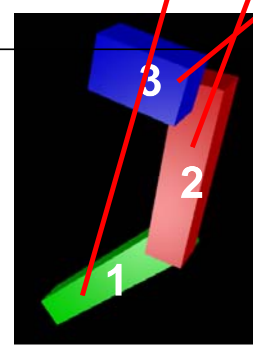
In the *UpdateScene* Functiom

```
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( 1. );    // identity
m1g = glm::translate(m1g, glm::vec3(0., 0., 0.));
m1g = glm::rotate(m1g, rot1, zaxis);                    // [T]*[R]

glm::mat4 m21 = glm::mat4( 1. );    // identity
m21 = glm::translate(m21, glm::vec3(2.*Arm1.armScale, 0., 0.));
m21 = glm::rotate(m21, rot2, zaxis);                    // [T]*[R]
m21 = glm::translate(m21, glm::vec3(0., 0., 2.));    // z-offset from previous arm

glm::mat4 m32 = glm::mat4( 1. );    // identity
m32 = glm::translate(m32, glm::vec3(2.*Arm2.armScale, 0., 0.));
m32 = glm::rotate(m32, rot3, zaxis);                    // [T]*[R]
m32 = glm::translate(m32, glm::vec3(0., 0., 2.));    // z-offset from previous arm

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

In the *RenderScene* Function

```
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 );
```

The strategy is to draw each link using the same vertex buffer, but modified with a unique color, length, and matrix transformation



In the Vertex Shader

```
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
```

Physical Devices

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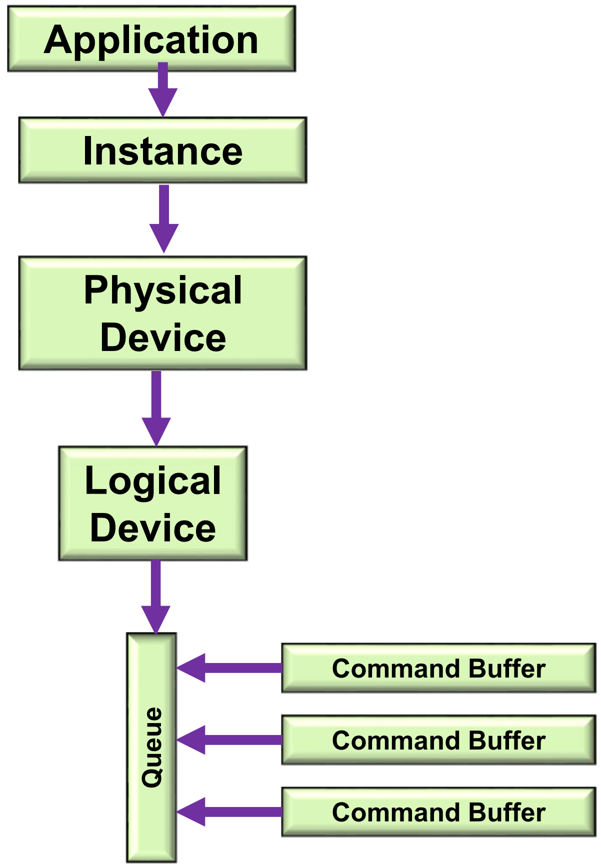
Vulkan: a More Typical (and Simplified) Block Diagram



Querying the Number of Physical Devices

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

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

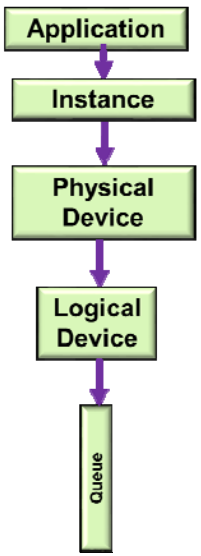
This way of querying information is a recurring OpenCL and Vulkan pattern (get used to it):

How many total there are — **Where to put them**

```
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\n" );
        return VK_SHOULD_EXIT;
}

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

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

Which Physical Device to Use, I

```
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, " \n\nDevice %2d:\n", i );
	fprintf( FpDebug, "\tAPI version: %d\n", vpdp.apiVersion );
	fprintf( FpDebug, "\tDriver version: %d\n", vpdp.apiVersion );
	fprintf( FpDebug, "\tVendor ID: 0x%04x\n", vpdp.vendorID );
	fprintf( FpDebug, "\tDevice ID: 0x%04x\n", vpdp.deviceID );
	fprintf( FpDebug, "\tPhysical Device Type: %d =", vpdp.deviceType );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_DISCRETE_GPU )	fprintf( FpDebug, " (Discrete GPU)\n" );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_INTEGRATED_GPU )	fprintf( FpDebug, " (Integrated GPU)\n" );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_VIRTUAL_GPU )	fprintf( FpDebug, " (Virtual GPU)\n" );
	if( vpdp.deviceType == VK_PHYSICAL_DEVICE_TYPE_CPU )		fprintf( FpDebug, " (CPU)\n" );
	fprintf( FpDebug, "\tDevice Name: %s\n", vpdp.deviceName );
	fprintf( FpDebug, "\tPipeline Cache Size: %d\n", vpdp.pipelineCacheUUID[0] );
```

Which Physical Device to Use, II

```
		// need some logical here to decide which physical device to select:

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

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

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

Asking About the Physical Device's Features

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

fprintf( FpDebug, "\nPhysical Device Features:\n");
fprintf( FpDebug, "geometryShader = %2d\n", PhysicalDeviceFeatures.geometryShader);
fprintf( FpDebug, "tessellationShader = %2d\n", PhysicalDeviceFeatures.tessellationShader );
fprintf( FpDebug, "multiDrawIndirect = %2d\n", PhysicalDeviceFeatures.multiDrawIndirect );
fprintf( FpDebug, "wideLines = %2d\n", PhysicalDeviceFeatures.wideLines );
fprintf( FpDebug, "largePoints = %2d\n", PhysicalDeviceFeatures.largePoints );
fprintf( FpDebug, "multiViewport = %2d\n", PhysicalDeviceFeatures.multiViewport );
fprintf( FpDebug, "occlusionQueryPrecise = %2d\n", PhysicalDeviceFeatures.occlusionQueryPrecise );
fprintf( FpDebug, "pipelineStatisticsQuery = %2d\n", PhysicalDeviceFeatures.pipelineStatisticsQuery );
fprintf( FpDebug, "shaderFloat64 = %2d\n", PhysicalDeviceFeatures.shaderFloat64 );
fprintf( FpDebug, "shaderInt64 = %2d\n", PhysicalDeviceFeatures.shaderInt64 );
fprintf( FpDebug, "shaderInt16 = %2d\n", PhysicalDeviceFeatures.shaderInt16 );
```

Here's What the NVIDIA 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
```

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, "Memory %2d: ", i );
        if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_DEVICE_LOCAL_BIT      ) != 0 )      fprintf( FpDebug, " DeviceLocal" );
        if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_VISIBLE_BIT      ) != 0 )      fprintf( FpDebug, " HostVisible" );
        if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_COHERENT_BIT     ) != 0 )      fprintf( FpDebug, " HostCoherent" );
        if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_HOST_CACHED_BIT       ) != 0 )      fprintf( FpDebug, " HostCached" );
        if( ( vmt.propertyFlags & VK_MEMORY_PROPERTY_LAZILY_ALLOCATED_BIT  ) != 0 )      fprintf( FpDebug, " LazilyAllocated" );
        fprintf(FpDebug, "\n");
}

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

Here's What I Got

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

2 Memory Heaps:
Heap 0:  size = 0xb7c00000 DeviceLocal
Heap 1:  size = 0xfac00000
```

Asking About the Physical Device's Queue Families

```
uint32_t count = -1;
vkGetPhysicalDeviceQueueFamilyProperties( IN PhysicalDevice, &count, OUT (VkQueueFamilyProperties *)nullptr );
fprintf( FpDebug, "\nFound %d Queue Families:\n", count );

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

Here's What I Got

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

Vulkan.

Logical Devices

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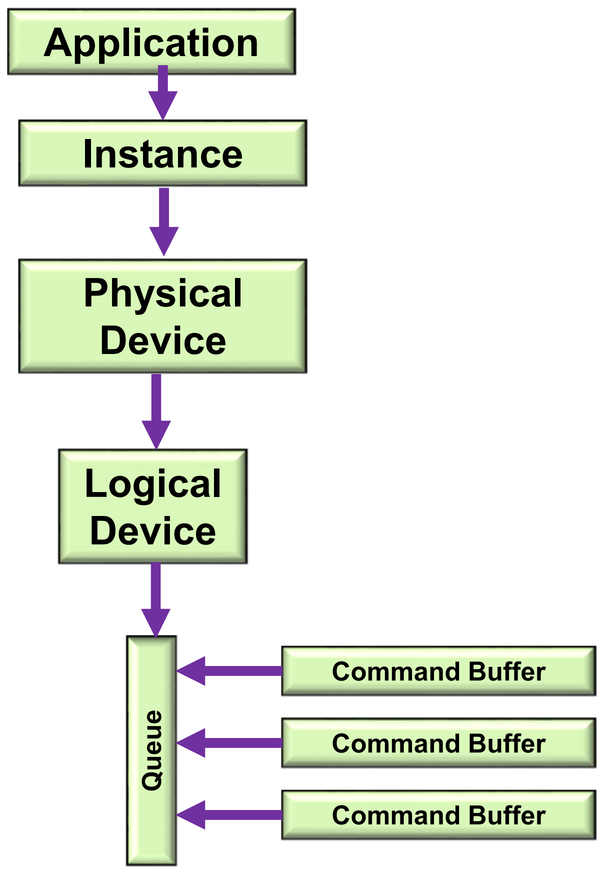
Vulkan: a More Typical (and Simplified) Block Diagram



Looking to See What Device Layers are Available

```
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"
		// "VK_KHR_swapchains"
};

// see what device layers are available:

uint32_t  layerCount;
vkEnumerateDeviceLayerProperties(PhysicalDevice, &layerCount, (VkLayerProperties *)nullptr);

VkLayerProperties * deviceLayers = new VkLayerProperties[layerCount];

result = vkEnumerateDeviceLayerProperties( PhysicalDevice, &layerCount, deviceLayers);
```

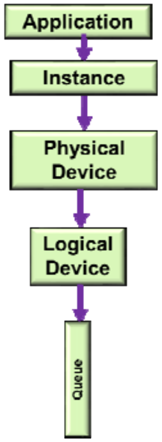
Looking to See What Device Extensions are Available


```
// 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'
```

Vulkan: Creating a Logical Device




```
float   queuePriorities[1] =
{
                1.
};
VkDeviceQueueCreateInfo  vdqci;
        vdqci.sType = VK_STRUCTURE_TYPE_DEVICE_QUEUE_CREATE_INFO;
        vdqci.pNext = nullptr;
        vdqci.flags = 0;
        vdqci.queueFamiltyIndex = 0;
        vdqci.queueCount = 1;
        vdqci.pQueueProperties = queuePriorities;
```

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

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

Vulkan: Creating the Logical Device's Queue


```
// get the queue for this logical device:

vkGetDeviceQueue( LogicalDevice, 0, 0,  OUT &Queue );              // 0, 0 = queueFamilyIndex, queueIndex
```

Oregon State University Computer Graphics

Introduction to the Vulkan Computer Graphics API

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