Introduction
Acknowledgements

First of all, thanks to the inaugural class of 19 students who braved new, unrefined, and just-in-time course materials to take the first Vulkan class at Oregon State University – Winter Quarter, 2018. Thanks for your courage and patience!

Second, thanks to NVIDIA! The GeForce 1080ti cards are what made this course possible.

Third, thanks to Kathleen Mattson and the Khronos Group for the great laminated Vulkan Quick Reference Cards! (Look at those happy faces in the photo holding them.)
What Prompted the Move to Vulkan?

1. Performance
2. Performance
3. Performance

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

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

As an aside, the Vulkan development effort was originally called glNext, which created the false impression that this was a replacement for OpenGL. It’s not.
OpenGL 4.2 Pipeline Flowchart
Why is it so important to keep the GPU Busy?

<table>
<thead>
<tr>
<th>NVidia Titan V Specs vs. Titan Xp, 1080 Ti</th>
</tr>
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<tr>
<td><strong>Titan V</strong></td>
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<tr>
<td><strong>GPU</strong></td>
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<tr>
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<tr>
<td><strong>Fab Process</strong></td>
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<tr>
<td><strong>CUDA Cores / Tensor Cores</strong></td>
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<tr>
<td><strong>TMUs</strong></td>
</tr>
<tr>
<td><strong>ROPs</strong></td>
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<td><strong>Total Power Budget (&quot;TDP&quot;)</strong></td>
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<td><strong>Release Date</strong></td>
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<td><strong>Release Price</strong></td>
</tr>
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The NVidia Titan V graphics card is not targeted at gamers, but rather at scientific and machine/deep learning applications. That does not, however, mean that the card is incapable of gaming, nor does it mean that we can't extrapolate future key performance metrics for Volta. The Titan V is a derivative of the earlier-released GV100 GPU, part of the Tesla accelerator card series. The key differentiator is that the Titan V ships at $3000, whereas the Tesla V100 was available as part of a $10,000 developer kit. The Tesla V100 still offers greater memory capacity by 4GB – 16GB HBM2 versus 12GB HBM2 – and has a wider memory interface, but other core features remain matched or nearly matched. Core count, for one, is 5120 CUDA cores on each GPU, with 640 Tensor cores (used for Tensorflow deep/machine learning workloads) on each GPU.
Who was the original Vulcan?

From WikiPedia:

“Vulcan is the god of fire including the fire of volcanoes, metalworking, and the forge in ancient Roman religion and myth. Vulcan is often depicted with a blacksmith's hammer. The **Vulcanalia** was the annual festival held August 23 in his honor. His Greek counterpart is Hephaestus, the god of fire and smithery. In Etruscan religion, he is identified with Sethlans. Vulcan belongs to the most ancient stage of Roman religion: Varro, the ancient Roman scholar and writer, citing the Annales Maximi, records that king Titus Tatius dedicated altars to a series of deities among which Vulcan is mentioned.”

Why Name it after the God of the Forge?
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

PROMOTER MEMBERS

Over 140 members worldwide
Any company is welcome to join

[Image of various company logos]

Oregon State
University
Computer Graphics
Who’s Been Specifically Working on Vulkan?
Vulkan

- Largely derived from AMD’s *Mantle* API
- Also heavily influenced by Apple’s *Metal* API and Microsoft’s *DirectX 12*
- Goal: much less driver complexity and overhead than OpenGL has
- Goal: much less user hand-holding – Vulkan can crash
- Goal: higher single-threaded performance than OpenGL can deliver
- Goal: able to do multithreaded graphics
- Goal: able to handle tiled rendering
Vulkan Differences from OpenGL

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

• Screen coordinate system is Y-down

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

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

• You must manage your own transformations.

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

• Shaders are pre-”half-compiled” outside of your application. The compilation process is then finished during the pipeline-building process.
The Basic OpenGL Computer Graphics Pipeline, OpenGL-style

Vertex, Normal, Color

Model Transform

ModelViewMatrix, ProjectionMatrix, ModelViewProjectionMatrix

View Transform

Per-vertex Lighting

Projection Transform

Per-vertex Lighting

Fragment Processing, Texturing, Per-fragment Lighting

Rasterization

Framebuffer

MC = Model Vertex Coordinates
WC = World Vertex Coordinates
EC = Eye Vertex Coordinates
The Basic Computer Graphics Pipeline, Shader-style

Vertex Shader:
- **Per-vertex in variables:** gl_Vertex, gl_Normal, gl_Color
- **Uniform Variables:** gl_ModelViewMatrix, gl_ProjectionMatrix, gl_ModelViewProjectionMatrix
- **Per-vertex out variables:** gl_Position

Fragment Shader:
- **Per-fragment in variables:** gl_FragColor
- **Uniform Variables:**
- **Fragment Processing:**
  - Texturing
  - Per-fragment Lighting

Framebuffer:
- gl_FragColor

**MC** = Model Vertex Coordinates
**WC** = World Vertex Coordinates
**EC** = Eye Vertex Coordinates
The Basic Computer Graphics Pipeline, Vulkan-style

Vertex Shader

Per-vertex \textit{in} variables

Uniform Variables

\texttt{gl\_Position},
Per-vertex \textit{out} variables

Rasterization

Fragment Shader

Per-fragment \textit{in} variables

Uniform Variables

Output color(s)

Framebuffer
## A Complete API Redesign

<table>
<thead>
<tr>
<th><strong>OpenGL</strong></th>
<th><strong>Vulkan</strong></th>
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</thead>
<tbody>
<tr>
<td>Originally architected for graphics workstations with direct renderers and split memory</td>
<td>Matches architecture of modern platforms including mobile platforms with unified memory, tiled rendering</td>
</tr>
<tr>
<td>Driver does lots of work: state validation, dependency tracking, error checking. Limits and randomizes performance</td>
<td>Explicit API – the application has direct, predictable control over the operation of the GPU</td>
</tr>
<tr>
<td>Threading model doesn’t enable generation of graphics commands in parallel to command execution</td>
<td>Multi-core friendly with multiple command buffers that can be created in parallel</td>
</tr>
<tr>
<td>Syntax evolved over twenty years – complex API choices can obscure optimal performance path</td>
<td>Removing legacy requirements simplifies API design, reduces specification size and enables clear usage guidance</td>
</tr>
<tr>
<td>Shader language compiler built into driver. Only GLSL supported. Have to ship shader source</td>
<td>SPIR-V as compiler target simplifies driver and enables front-end language flexibility and reliability</td>
</tr>
<tr>
<td>Despite conformance testing, developers must often handle implementation variability between vendors</td>
<td>Simpler API, common language front-ends, more rigorous testing increase cross vendor functional/performance portability</td>
</tr>
</tbody>
</table>

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Oregon State University
Computer Graphics
Moving part of the driver into the application

Complex drivers lead to driver overhead and cross vendor unpredictability

Error management is always active

Driver processes full shading language source

Separate APIs for desktop and mobile markets

Simpler drivers for low-overhead efficiency and cross vendor portability

Layered architecture so validation and debug layers can be unloaded when not needed

Run-time only has to ingest SPIR-V intermediate language

Unified API for mobile, desktop, console and embedded platforms

Khronos Group

Oregon State University
Computer Graphics
Vulkan Highlights: Command Buffers

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

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

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

• Vulkan forces you to set all your state at once into a “pipeline state object” (PSO) and then invoke the entire PSO whenever you want to use that state combination

• Think of the pipeline state as being immutable.

• Potentially, you could have thousands of these pre-prepared states

• This is a good time to talk about how game companies view Vulkan…
Querying the Number of Things

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

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

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

```
result = vkEnumeratePhysicalDevices( Instance, &count, nullptr );
result = vkEnumeratePhysicalDevices( Instance, &count, physicalDevices );
```
Vulkan Code has a Distinct “Style”

```
VkBufferCreateInfo vbci;
    vbci.sType = VK_STRUCTURE_TYPE_BUFFER_CREATE_INFO;
    vbci.pNext = nullptr;
    vbci.flags = 0;
    vbci.size = << buffer size in bytes >>
    vbci.usage = VK_USAGE_UNIFORM_BUFFER_BIT;
    vbci.sharingMode = VK_SHARING_MODE_EXCLUSIVE;
    vbci.queueFamilyIndexCount = 0;
    vbci.pQueueFamilyIndices = nullptr;

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

VkMemoryRequirements vmr;

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

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

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

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

Vulkan Pipeline Diagram [9]

FROM APPLICATION
- Draw
  - Input Assembler
    - Vertex Shader
      - Tessellation Assembler
        - Tessellation Control Shader
          - Tessellation Primitive Generator
            - Tessellation Evaluation Shader
              - Geometry Assembler
                - Geometry Shader
                  - Primitive Assembler
                    - Rasterization
                      - Per-Fragment Operations
                        - Fragment Assembler
                          - Fragment Shader
                            - Post-Fragment Operations
                              - Color/Blending Operations

FROM APPLICATION
- Indirect Buffer Binding
  - Index Buffer Binding
    - Vertex Buffer Binding
      - Push Constants
        - Descriptor Sets
          - Sampled Image
            - Uniform Texel Buffer
              - Uniform Buffer
                - Storage Image
                  - Storage Texel Buffer
                    - Storage Buffer
                     - Framebuffer
                       - Input Attachment
                         - Depth/Stencil Attachment
                           - Color Attachment
                           - Some Vulkan commands specify geometric objects to be drawn or computational work to be performed, while others specify state controlling how objects are handled by the various pipeline stages, or control data transfer between memory organized as images and buffers. Commands are effectively sent through a processing pipeline, either a graphics pipeline or a compute pipeline.
                           - The heavy black arrows in this illustration show the Vulkan graphics and compute pipelines and indicate data flow:
                             - Fixed function stage
                             - Programmable stage
                             - Buffer
                             - Image
                             - Constants
Vulkan Highlights: Overall Block Diagram

Application
  └ Instance
    ├── Physical Device
    │   └ Logical Device
    │       └ Queue
    │       └ Queue
    ├── Physical Device
    │   └ Logical Device
    │       └ Queue
    │       └ Queue
    ├── Physical Device
    │   └ Logical Device
    │       └ Queue
    │       └ Queue
    └ Physical Device
      └ Logical Device
        └ Queue
          └ Command Buffer
          └ Command Buffer
          └ Command Buffer
Vulkan Highlights: a More Typical Block Diagram
Steps in Creating Graphics using Vulkan

1. Create the 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- …
Vulkan: Creating a Pipeline

VkGraphicsPipelineCreateInfo

- Shader stages
  - VERTEX
  - etc.

- VkSpecializationInfo
  - which stage (VERTEX, etc.)

- VkShaderModule
  - inputRate
  - format

- VkVertexInputBindingDescription
  - binding
  - location

- VkVertexInputAttributeDescription
  - location
  - inputRate

- VkPipelineShaderStageCreateInfo
  - which stage (VERTEX, etc.)

- VkPipelineInputAssemblyStateCreateInfo
  - Topology
  - Offset
  - extent

- VkViewportStateCreateInfo
  - Viewport
  - x, y, w, h, minDepth, maxDepth

- VkPipelineRasterizationStateCreateInfo
  - CullMode
  - PolygonMode

- VkPipelineInputAssemblyStateCreateInfo
  - Topology

- VkPipelineDepthStencilStateCreateInfo
  - StencilTestEnable

- VkPipelineColorBlendStateCreateInfo
  - BlendEnable

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

vkCreateGraphicsPipeline()
Vulkan GPU Memory

- Your application allocates GPU memory for the objects it needs
- You map GPU memory to the CPU address space for access
- Your application is responsible for making sure what you put into that memory is actually in the right format, is the right size, has the right alignment, etc.

From the OpenGL Shader Storage Buffer notes:

```c
glGenBuffers( 1, &posSSbo);
glBindBuffer( GL_SHADER_STORAGE_BUFFER, posSSbo );
glBufferData( GL_SHADER_STORAGE_BUFFER, NUM_PARTICLES * sizeof(struct pos), NULL, GL_STATIC_DRAW );

GLint bufMask = GL_MAP_WRITE_BIT | GL_MAP_INVALIDATE_BUFFER_BIT ;   // the invalidate makes a big difference when re-writing

struct pos *points = (struct pos *) glMapBufferRange( GL_SHADER_STORAGE_BUFFER, 0, NUM_PARTICLES * sizeof(struct pos), bufMask );
```
Vulkan Render Passes

• Drawing is done inside a render pass
• Each render pass contains what framebuffer attachments to use
• Each render pass is told what to do when it begins and ends
• Multiple render passes can be merged
Vulkan Compute Shaders

- Compute pipelines are allowed, but they are treated as something special (just like OpenGL does)
- Compute passes are launched through dispatches
- Compute command buffers can be run asynchronously
Vulkan Synchronization

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

- GLSL is the same as before … almost
- For places it’s not, an implied
  \#define VULKAN 100
  is automatically supplied by the compiler
- You pre-compile your shaders with an external compiler
- Your shaders get turned into an intermediate form known as SPIR-V (Standard Portable Intermediate Representation for Vulkan)
- SPIR-V gets turned into fully-compiled code at runtime
- The SPIR-V spec has been public for months – new shader languages are surely being developed
- OpenCL and OpenGL will be moving to SPIR-V as well

**Advantages:**

1. Software vendors don’t need to ship their shader source
2. Software can launch faster because half of the compilation has already taken place
3. This guarantees a common front-end syntax
4. This allows for other language front-ends
Your Sample2017.zip File Contains This

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