Realtime Computer Graphics on GPUs

Speedup Techniques, Other APIs

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Optimizations Intro

Performance Bottlenecks I

- Most of the applications require steady framerate – What can slow down rendering?
- Too much geometry rendered
  - CPU/GPU can process only limited amount of data per second
  - Render only what is visible and with adequate details
- Lighting/shading computation
  - Use simpler material model
  - Limit number of generated fragments
- Data transfers between CPU/GPU
  - Try to reuse/cache data on GPU
  - Use async transfers

Performance Bottlenecks II

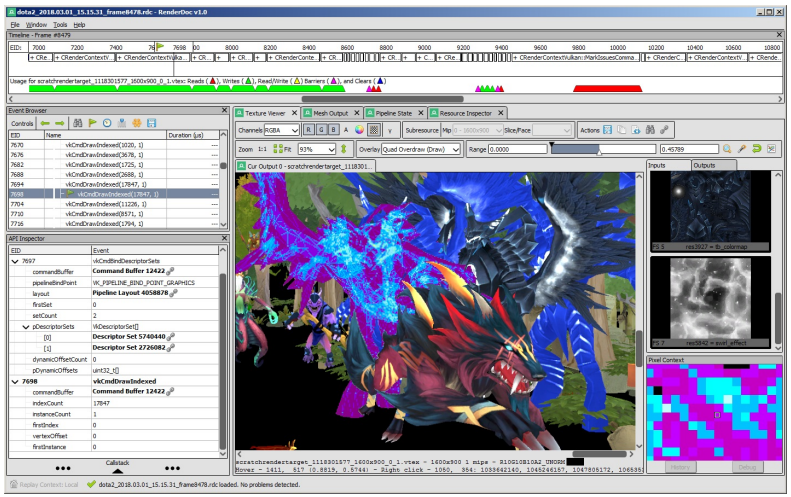
- State changes
  - Bundle object by materials
  - Use UBOs (uniform buffer objects)
- GPU idling – cannot generate work fast enough
  - Multithreaded task generation
  - Not everything must be done in every frame – reuse information (temporal consistency)
- CPU/Driver hotspots
  - Bindless textures
  - Instanced rendering
  - Indirect rendering

Different Needs

- Large open world
  - Rendering lots of objects
  - Not so many details needed for distant sections
- Indoors scenes
  - Often lots of same objects – instaced rendering
  - Only small portion of the scene visible – occluded by walls, ...
- CAD, molecular biology, ...
  - All geometry visible at once
  - Lots of self-occlusions
  - Switching levels of detail

PROFILING

- Three rules of profiling:
  - Measure!
  - Measure!
  - Measure!
- How to measure?
  - Code instrumentation
  - Sampling profilers
  - HW event counters
- Profiling influences performance
- Tools for GPU:
  - NVIDIA Nsight
  - Radeon GPU Profiler
  - RenderDoc
  - apitrace
  - CodeXL



Scene Graph

- Boundary volume hierarchies (BVH)
- Spatial partitioning
  - Binary space partitioning
  - Quadtrees, octrees
  - Grids
- Additional meta-objects:
  - Occluders
  - Collision geometry

Standard Rendering Procedure

1. Analyze world view
2. Transfer data on GPU
   - Upload/reuse geometry in VBOs
   - Upload/reuse textures
3. Issue draw commands

Optimize Rendering

Query Objects

- How to use:

```
glGenQueries(GLsizei n, GLuint * ids);
glBeginQuery(GLenum target, GLuint id);
   // ...
glEndQuery(GLenum target);
```

- Example queries:

  `GL_SAMPLES_PASSED`

  `GL_ANY_SAMPLES_PASSED`

  `GL_PRIMITIVES_GENERATED`

  ...

- Usualy used with one frame lag

Occlusion Culling

- Do not render objects hidden behind others
- Helper objects – occluders
- CPU processing
  - Analyze scene graph + occluders to filter rendered geometry
- GPU processing
  - Z-buffer pre-render
  - Render occluders to Z-buffer
  - Occlusion queries
  - Temporal consistency – Z-buffer reprojection

Conditional Rendering

- GL version is 3.0 or greater
- Render cheap object
- Use occlusion query to see if any of it is visible
- If it isn't, skip rendering of expensive object

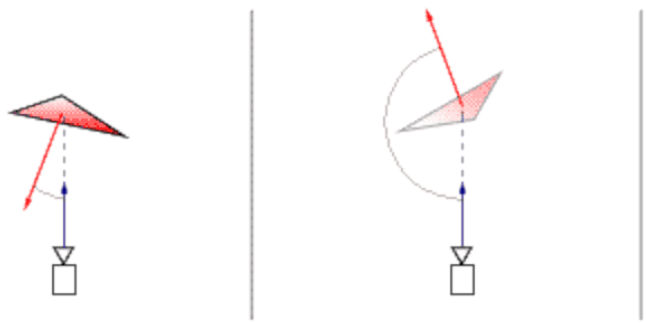
```
glBeginConditionalRender(GLuint id, GLenum mode);
glEndConditionalRender();
```

Z-buffer Optimizations

- Early Z-test:
  - Fragment shader cannot modify depth value
  - Front-to-back rendering (rough sort)
  - Double speed Z-only:
    - First pass depth (stencil) only, write z-buffer – faster when no color buffer present
    - Second pass color writes, z-buffer read-only
  - Optimizations:
    - Z-pass for major occluders
- Deffered shading

Backface Culling

- Good closed meshes
  - No need for triangle back-side rasterization
- GPU can filter (face cull) according to vertex order:
  - glEnable(GL_CULL_FACE);
  - glFrontFace(GL_CCW);
  - glCullFace(GL_BACK); // draw front faces only



Clipping Planes

- Objects outside of the view frustum are not rendered
- Set far-plane reasonable close (also increases z-buffer precision)
- Harsh end of all geometry
  - Render background geometry
  - Hide the far plane in fog (glFog())
  - More sophisticated effect in fragment shader/deffered shading

Level of Detail (LoD)

- Optimal rendering efficiency:
  - details of distant objects (pixel size) need not be drawn
  - the closest objects (and/or user focus) need the best available visual quality
- dynamic level of detail
  - rendering system adjusts individual rendering accuracy
  - global parameter definition (e.g. total approximate number of drawn triangles)
  - advance data preparation: discrete LoD levels / continuous LoD pre-processing..

Discrete LoD

- fixed LoD levels are prepared in advance
  - shape approximations with different accuracy
  - can come from the finest model – generalization (can be time consuming)
- rendering – choosing appropriate LoD level:
  - according to object-camera distance
  - according to bounding object projection size or even exact object projection – errors perpendicular to viewing direction are most noticeable
  - object importance, “player focus”, ..
  - global balancing (declared number of triangles to draw)

Continuous LoD

- Progressive meshes (Hoppe)
  - Hierarchy of simplifying operations
  - Smooth transition between differetn LoDs
  - High memory consuption
  - Problematic to implement on parallel architectures (GPUs)
- LoD streaming:
  - Analyze required LoD levels
  - Stream missing geometry and required operations to GPU
  - Temporal coherence

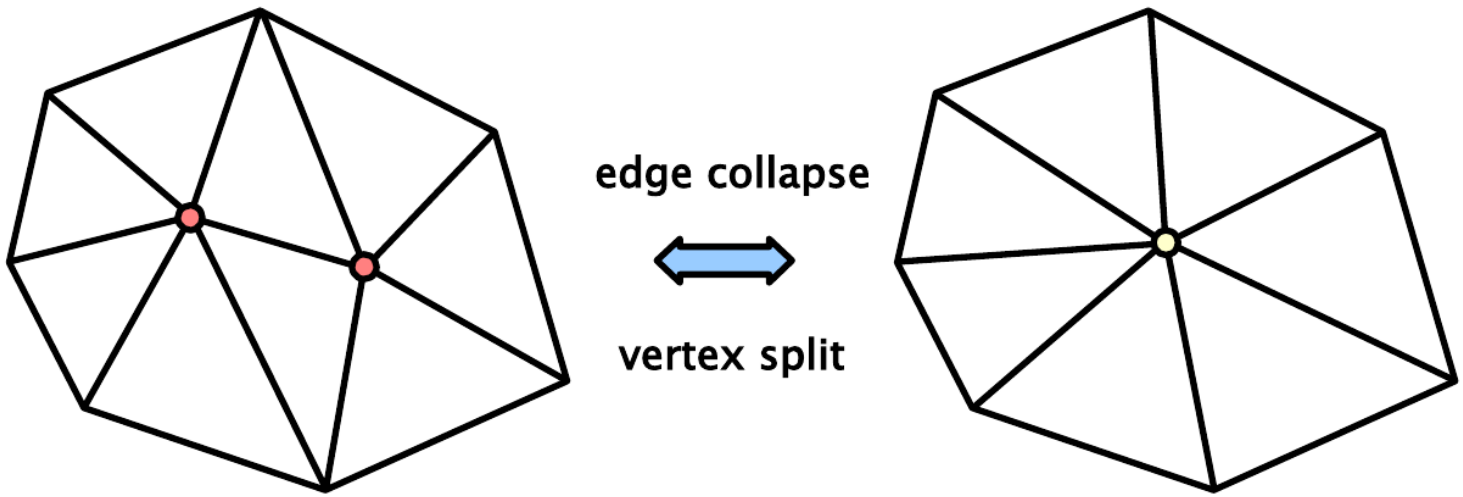
LoD Transitions

- simple switching
  - hysteresis must be introduced (against unwanted ”popping”)
- blending neighboring LoD levels
  - drawing both neighboring levels using transparency
  - linear combination (blending, “transition”)
  - another option
    - current LoD level is opaque
    - additional semitransparent new LoD (“over” a operation)
    - “z-writing” enabled only for the current LoD level

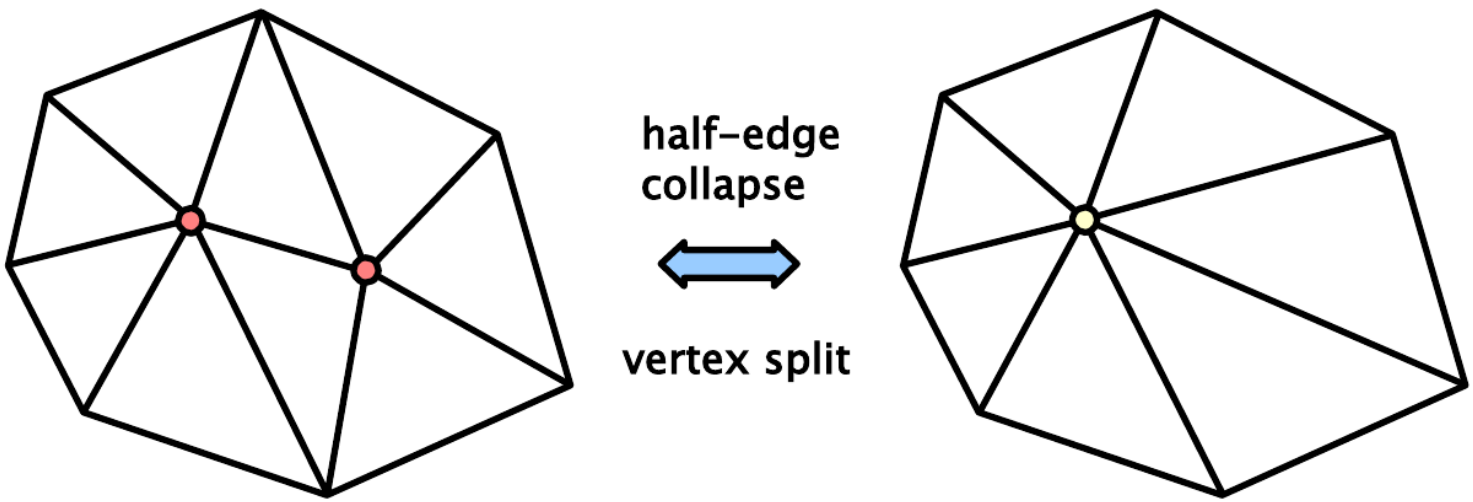
Generating LoDs

- top-down approach
  - based on the simplest shape representation (low-poly), additional details are introduced
  - less frequent (subdivision surfaces..)
- bottom-up
  - starts with detailed (most accurate) model
  - gradual simplification / generalization (data reduction)

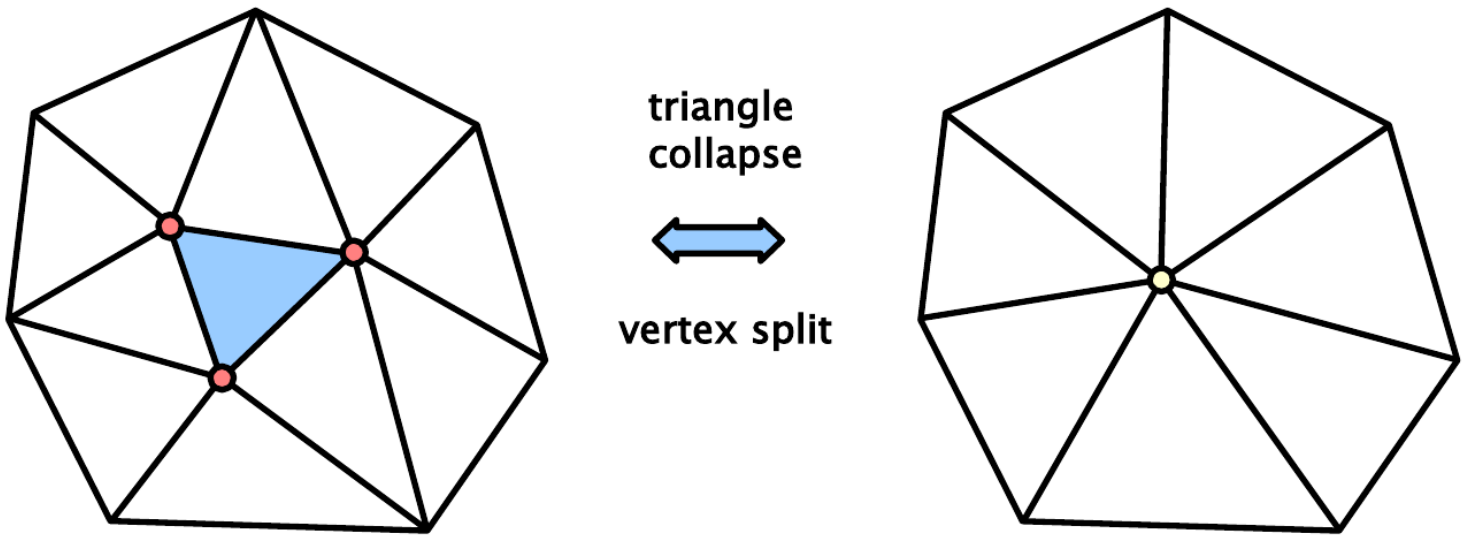
EDGE COLLAPSE VS. VERTEX SPLIT



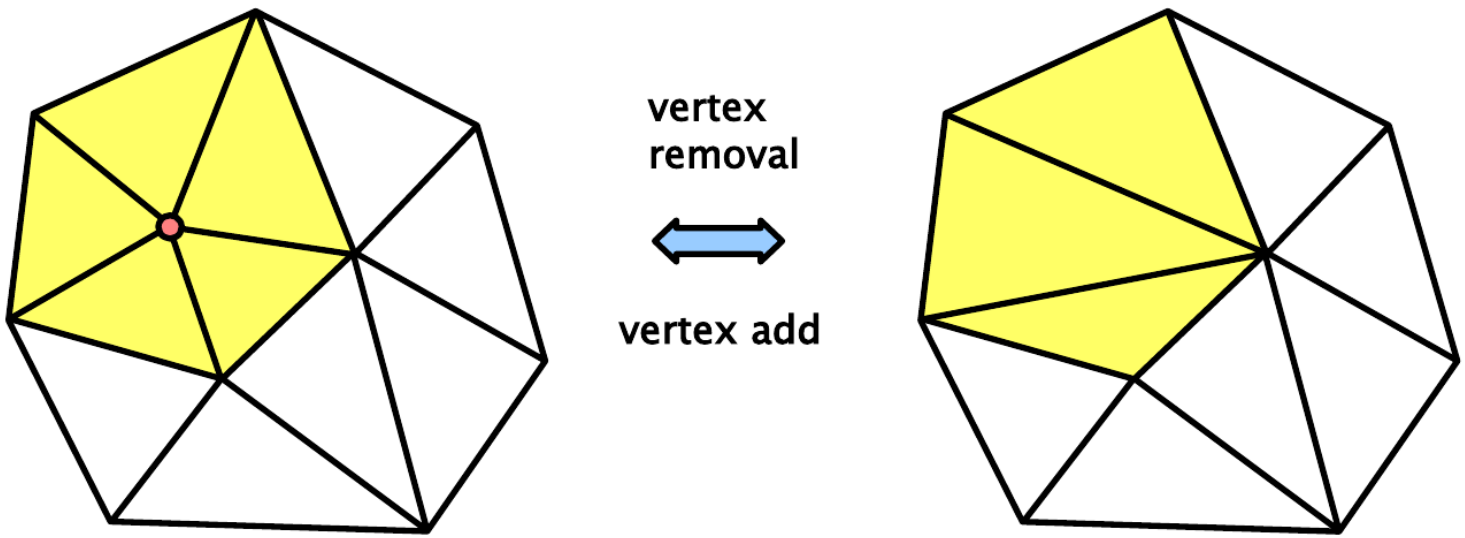
HALF-EDGE COLLAPSE VS. VERTEX SPLIT



TRIANGLE COLLAPSE COLLAPSE VS. VERTEX SPLIT



VERTEX REMOVAL VS. VERTEX ADD



TRIANGLE STRIPS/FANS

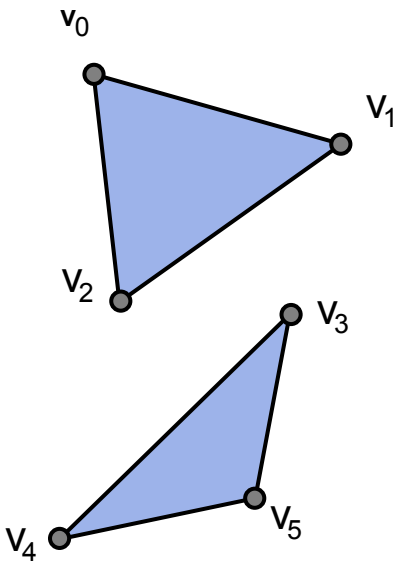


Figure:
GL_TRIANGLES

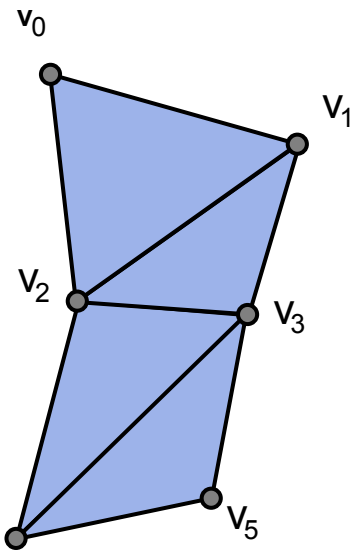


Figure:
GL_TRIANGLE_STRIP

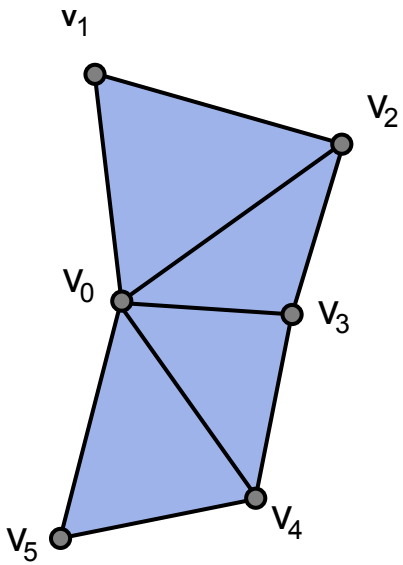


Figure:
GL_TRIANGLE_FAN

Limit Draw Calls

- Instanced rendering
- Multidraw commands – bundle more indexed render calls together

```
void glMultiDrawElements(GLenum mode, const GLsiz
```

- Indirect rendering
  - GL_DRAW_INDIRECT_BUFFER
  - Fill on GPU

```
void glDrawElementsIndirect()
void glDrawArraysIndirect()
void glMultiDrawElementsIndirect()
```

MULTITHREADING

- Contexts are not thread-safe
- Context can be current only in one thread
  - It can be used in multiple threads, but not in parallel
- Multiple contexts can be used concurrently
  - Enable resource sharing – textures, VBOs, . . .
- Split preparation work between multiple threads (task systems)

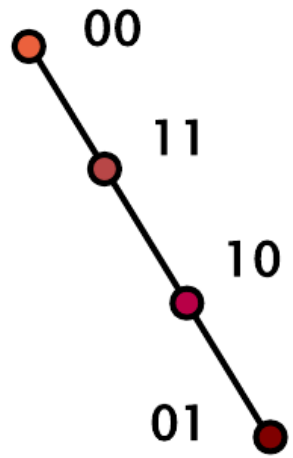
Textures

Texture Access

- Texture accesses expensive
  - Limit number of tex reads per fragment
- Use caching efficiently
  - Textures have spatial caching
  - Neighboring fragments should access neighboring texels
  - Use reasonable sized textures
  - Use mip-mapping

Texture Compression I

- Invention: S3 in DirectX 6 (1998)
  - DXTC, in OpenGL: S3TC, DXT1
- Fixed compression ratio
  - necessary for memory management
  - 4:1 to 6:1 lossy compression
- Decomposition into rectangle tiles (4×4 px)
  - each tile: two 16-bit colors and sixteen 2-bit indices (together – 4 bpp)
    - two extreme colors (R5G6B5), two more in-between colors (or one in-between and black)
    - each pixel is represented by a reference to one color
  - Extensions add alpha compression (128-bit): DXT3, DXT5



Texture Compression II

- NVIDIA VTC (Volume Texture Compression)
  - 3D variant of S3TC
  - data blocks $4 \times 4 \times 1$, $4 \times 4 \times 2$, $4 \times 4 \times 4$
- BPTC Texture Compression:
  - Byte stream
  - Unsigned + float
  - Multiple gradients

Other APIs

OpenGL ES

- OpenGL for Embedded Systems (smartphones, tablet computers, video game consoles)
- Most widely deployed 3D graphics API in history
- Subset of the OpenGL API
- Latest version of OpenGL ES 3.2
  - Adds tesselation and geometry shaders

WebGL

- JavaScript API for rendering interactive 2D and 3D graphics within any compatible web browser without the use of plug-ins
- Control code written in JavaScript and shader code that is written in OpenGL ES Shading Language
- WebGL 1.0 is based on OpenGL ES 2.0, HTML5 canvas element
- WebGL 2.0 is based on OpenGL ES 3.0
- WebAssembly
  - Compile code for virtual architecture
  - Executable in browser + OpenGL ES
- WebGPU – future API based on Vulcan and Metal

DirectX (Direct3D) I

- Available only for Microsoft platforms (Windows, XBox)
- Wraps same hardware – similar principles to OpenGL
- API organization different
  - State machine vs. parameter objects
  - Resources managed by developer
- Component Object Model (COM)
  - MS binary-interface standard for software components
  - Support for interprocess communication, multiple languages
  - Entities (textures, render targets, shaders, . . .) are COM objects
- Shading language HLSL
  - Similar to GLSL (almost 1:1 mapping)
  - Cross compilers available

DirectX (Direct3D) II

- Not a standard – more flexible to introduce changes (backward incompatible)
- DirectX 9 $\longleftrightarrow$ OpenGL 2
- DirectX 10 $\longleftrightarrow$ OpenGL 3
- DirectX 11 $\longleftrightarrow$ OpenGL 4
- DirectX 12 $\longleftrightarrow$ Vulkan, Metal

Direct 3D

Basic interfaces:

```
IDXGISwapChain *swapchain;              // the pointer to the swap chain interface
ID3D11Device *dev;                      // the pointer to our Direct3D device interface
ID3D11DeviceContext *devcon;            // the pointer to our Direct3D device context
```

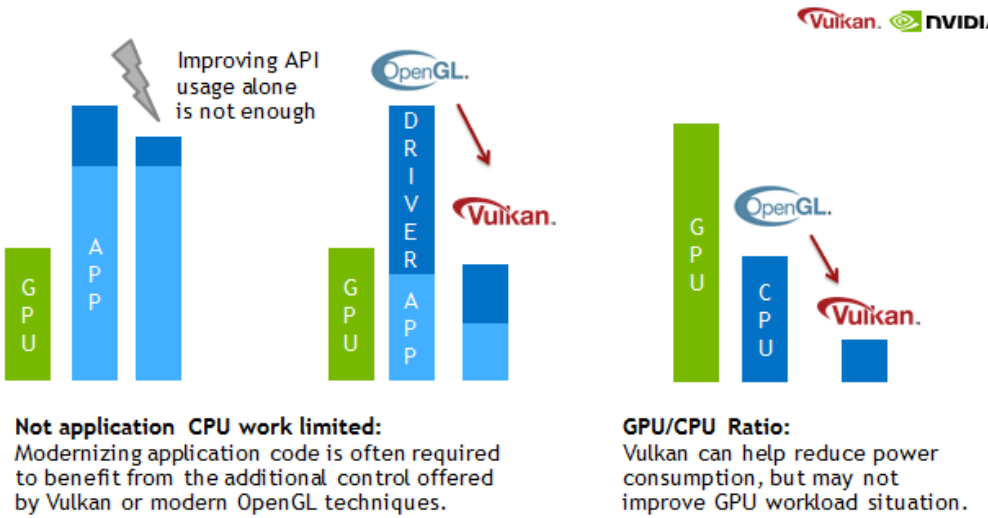
- ID3D11Device thread-safe
  - Can prepare resources in multiple threads
- ID3D11DeviceContext must use some synchronization
  - Draw commands cannot be issued in parallel

New APIs

- Opengl, DirectX (11 and older)
  - Old APIs – designed fo different ecosystems
  - Hotfixed for demands of modern hardware and software architectures
- CPU time in driver – hot spot in lots of modern applications
  - Multicore CPUs cannot efficiently feed command to GPUs
- AMD Mantle $\rightarrow$ Vulkan, Metal (Apple)
  - Explicit command buffer control
  - Multithreaded parallel rendering
  - Lower level API – developers have more control (also more code is needed)
- DirectX 12
  - Added similar features
  - Command queues, feeding from multiple threads

VULKAN

- Managed by Khronos
- Same API for desktop and embedded systems
- Low CPU usage, efficient usage of multi-core systems (thread-safe)
- No global state
- GLSL compiled to SPIR-V (Standard Portable Intermediate Representation)
- OpenCL convergence to Vulkan



Vulcan Usage I

- Create a VkInstance
  - Specify required features, extensions
- Select graphics card (VkPhysicalDevice)
  - Listing cards supporting requested features
- Create a logical device (VkDevice)
- Create queues (VkQueue) from queue families
  - Graphics
  - Compute
  - Memory transfers
- Create a window, window surface and swap chain

Vulcan Usage II

- Wrap the swap chain images into VkImageView
- Create a render pass
  - Specifies the render targets and usage
- Create framebuffers for the render pass
- Set up the graphics pipeline (VkPipeline)
  - Configured in advance
- Allocate and record a command buffer with the draw commands
- Draw frames
  - Acquire images
  - Submit draw commands
  - Return images to swap chain
  - Synchronization required