Dieter Schmalstieg

The Graphics Pipeline

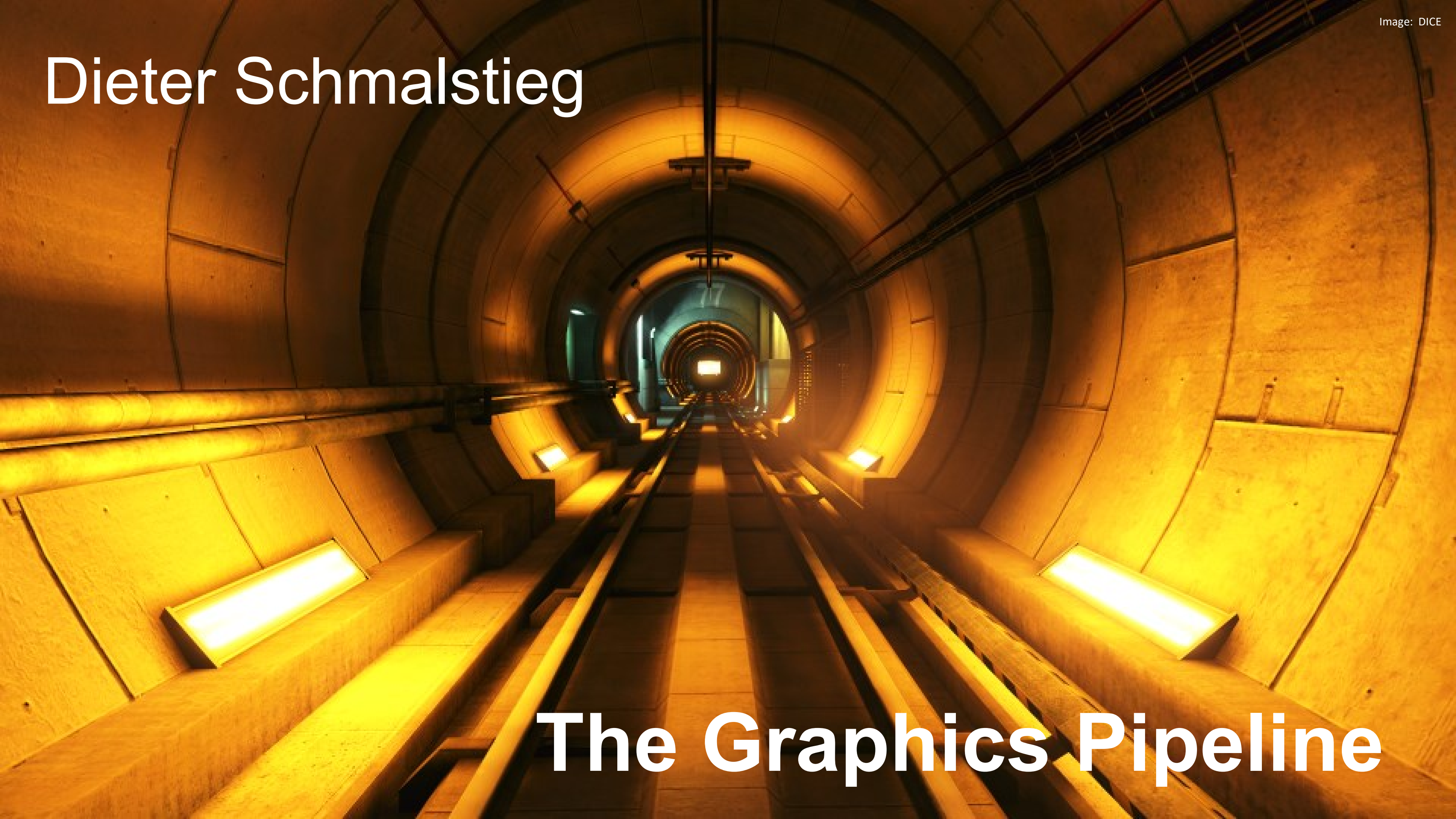


Image: DICE

What do we want?

- Computer-generated imagery (CGI) of complex 3D scenes in real-time
- Computationally extremely demanding
  - Full HD at 60 Hz:

    $$1920 \times 1080 \times 60\ \text{Hz} = 124\ \text{Mpx/s}$$
  - And that's just output data!
- Requires specialized hardware

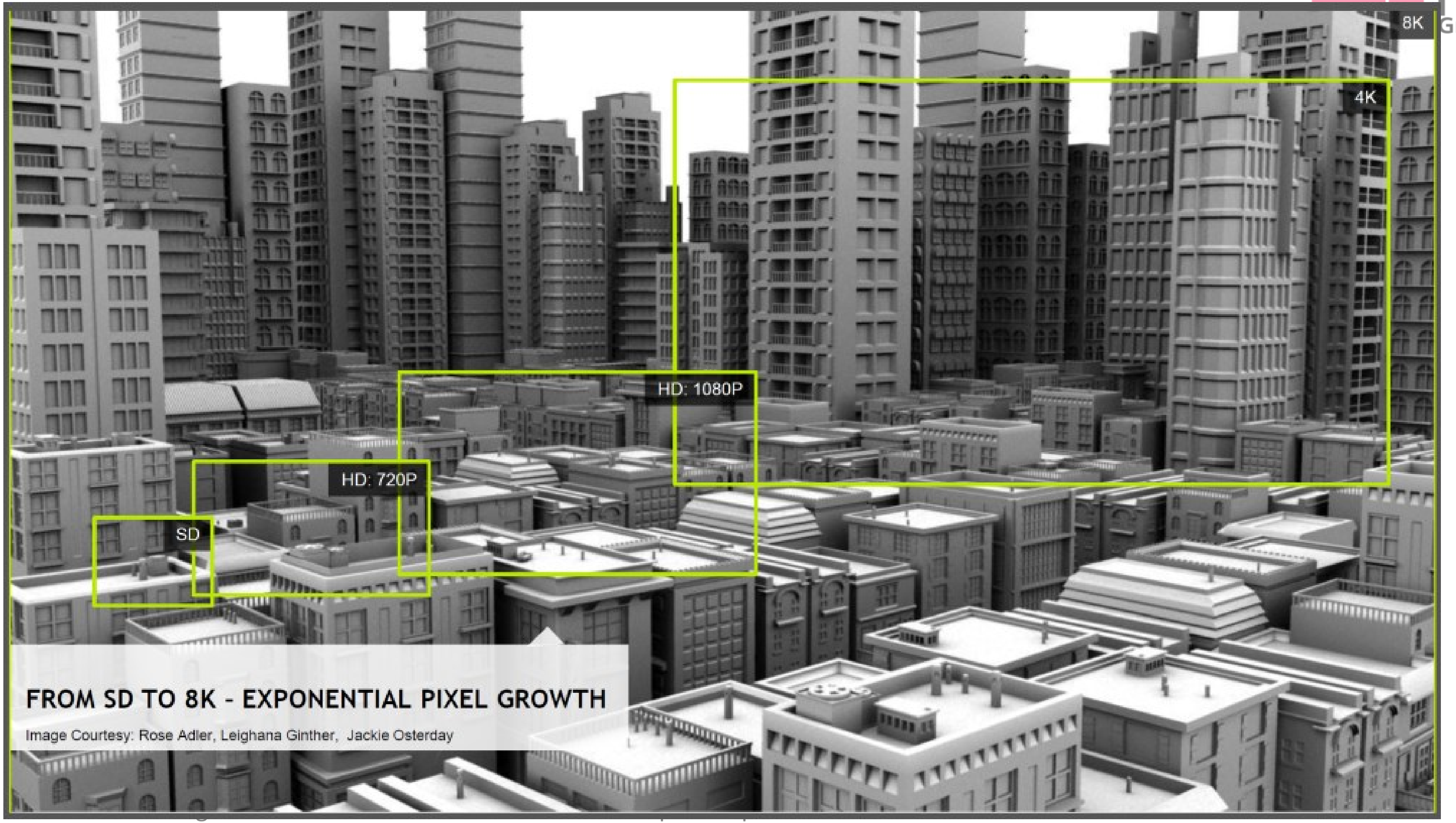
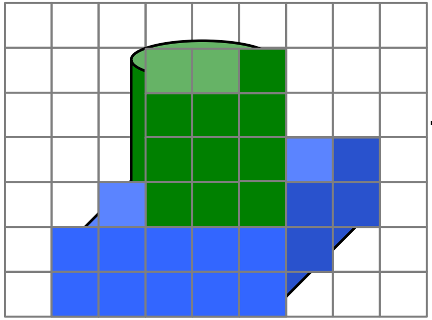

8K
4K
HD: 1080P
HD: 720P
SD
FROM SD TO 8K - EXPONENTIAL PIXEL GROWTH
Image Courtesy: Rose Adler, Leighana Ginther, Jackie Osterday

Image Synthesis

Object Order
Go through all objects

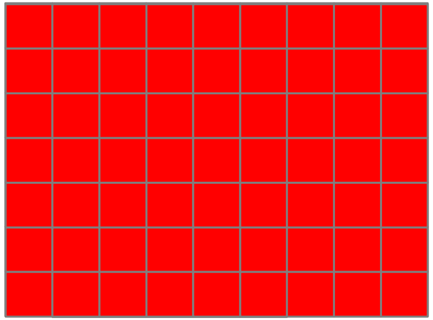
Image Order
Go through all pixels

„What do I see where“



→Rasterization

„Where do I see what“

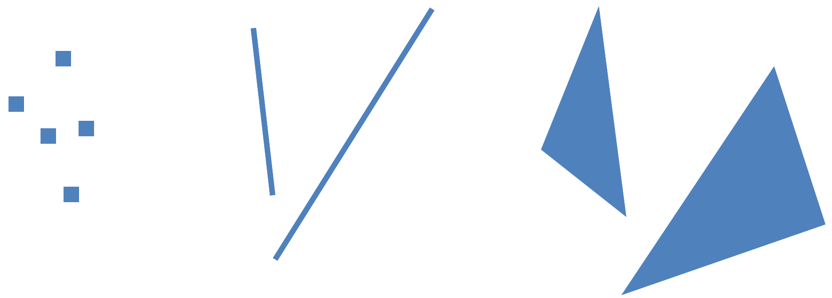


→Raytracing

Rasterization Hardware

Most of real-time graphics is based on

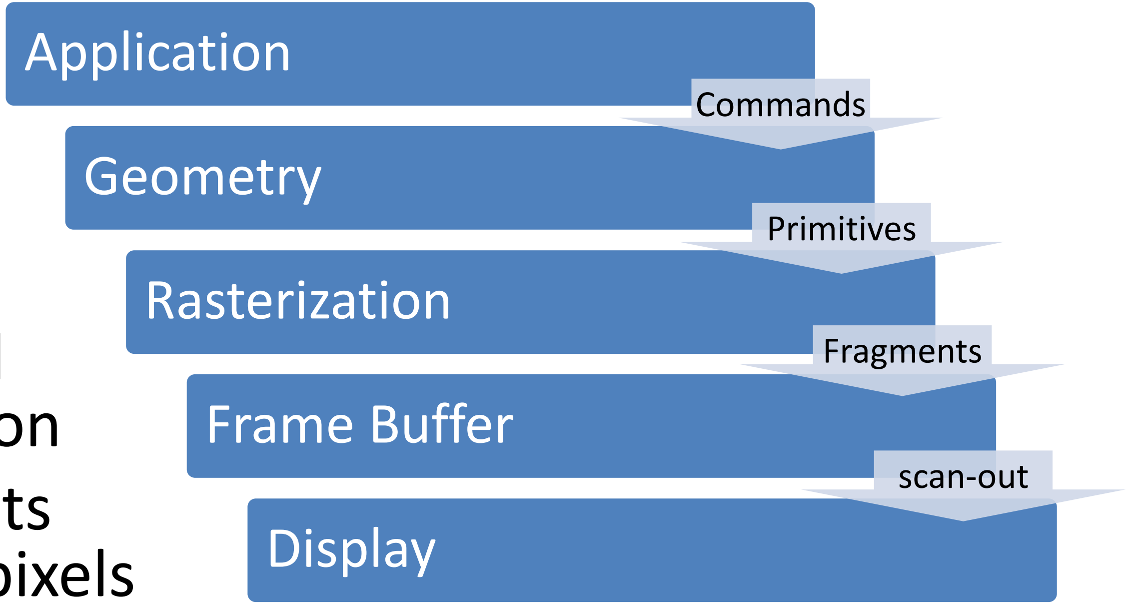
- Rasterization of graphic *primitives*
  - Points
  - Lines
  - Triangles
  - ...



- Implemented in hardware
  - *Graphics processing unit* (GPU)

The Graphics Pipeline

- High-level view:
- "Fragment":
  - Sample produced during rasterization
  - Multiple fragments are *merged* into pixels



Application Stage

- Generate database
  - Usually only once
  - Load from disk or generate algorithmically
  - Build acceleration structures (hierarchy, …)
- Repeat main loop
  - Input event handlers
  - Simulation → modify data structures
  - Database traversal → issue **graphics commands**
- Until exit

Graphics Commands

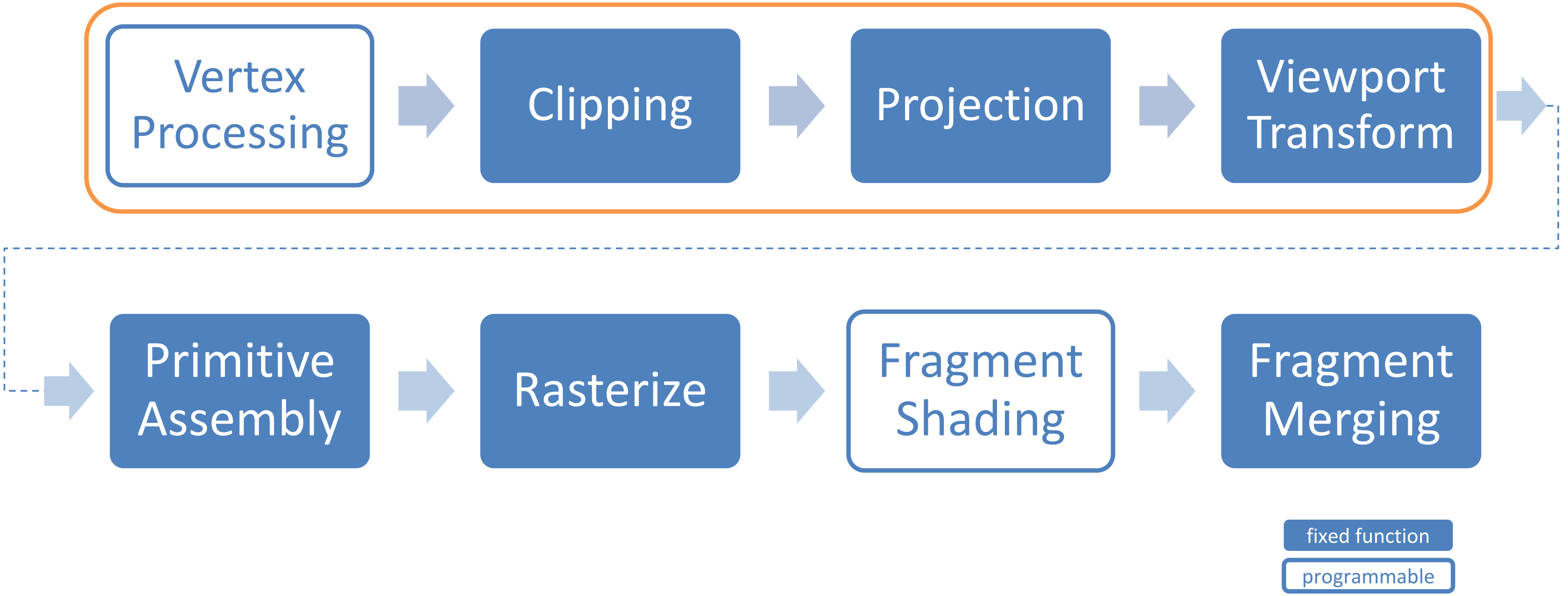
- Graphics command stream from CPU to GPU
  - Specify primitives
  - Manage resources
  - Modify GPU state
- Commands are abstracted as Graphics API
  - OpenGL, DirectX, Vulkan, Metal

Graphics Driver

- Graphics hardware is shared resource
- Large user mode graphics driver
  - Prepares command buffers
- Graphics kernel subsystem
  - Schedule access to hardware
- Small kernel mode graphics driver
  - Submit command buffers to hardware

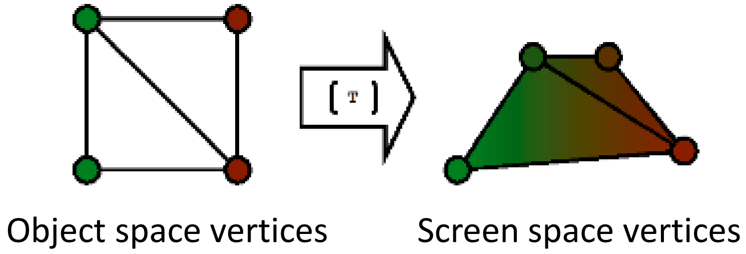
This is were new APIs
(Apple Metal, DirextX 12, Vulkan)
try to be more efficient

Geometry Stage



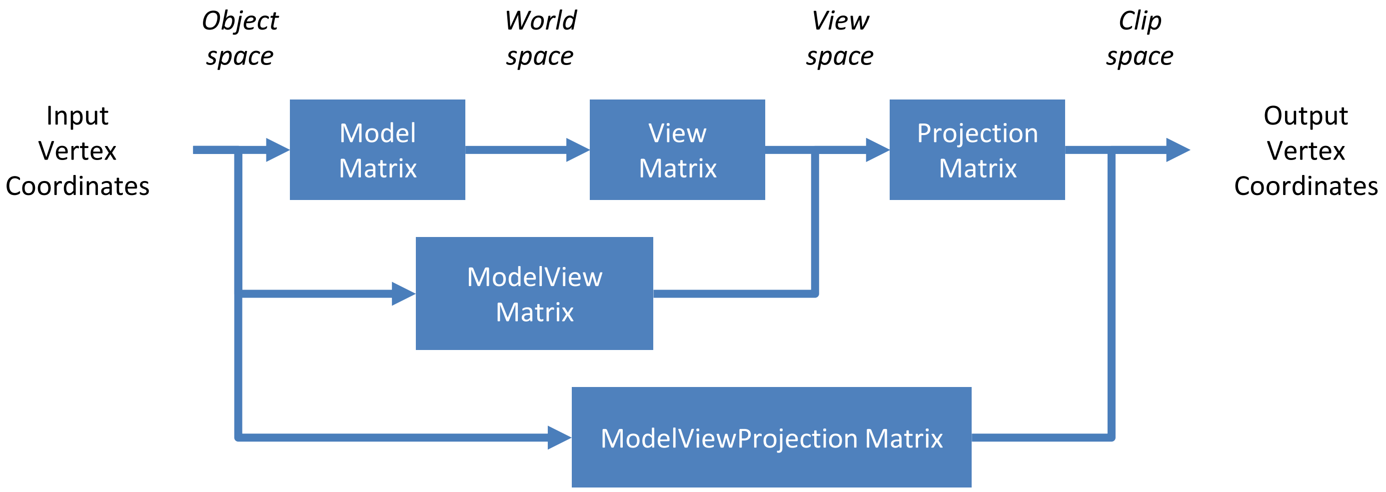
Vertex Processing

- Input vertex stream
  - Composed of arbitrary *vertex attributes* (position, color, …)
- Is transformed into stream of vertices mapped onto the screen
  - Composed of their *clip space* coordinates and additional user-defined attributes (color, texture coordinates, …)
  - Clip space: homogeneous coordinates
- By the *vertex shader*
  - GPU program that implements this mapping
  - Historically, “shaders” were small programs performing lighting calculations



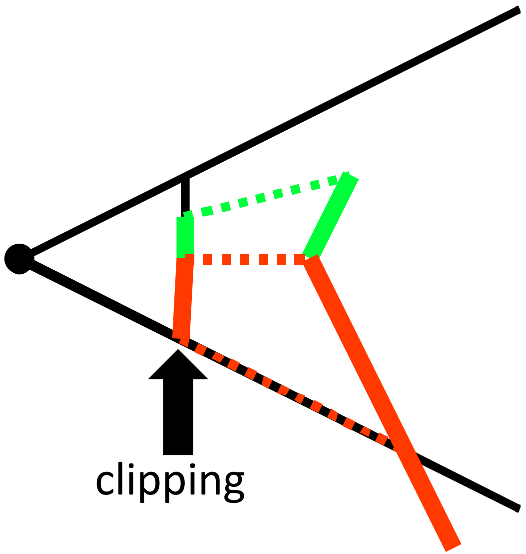
Vertex Coordinate Transformation

Common model in rasterization-based 3D graphics

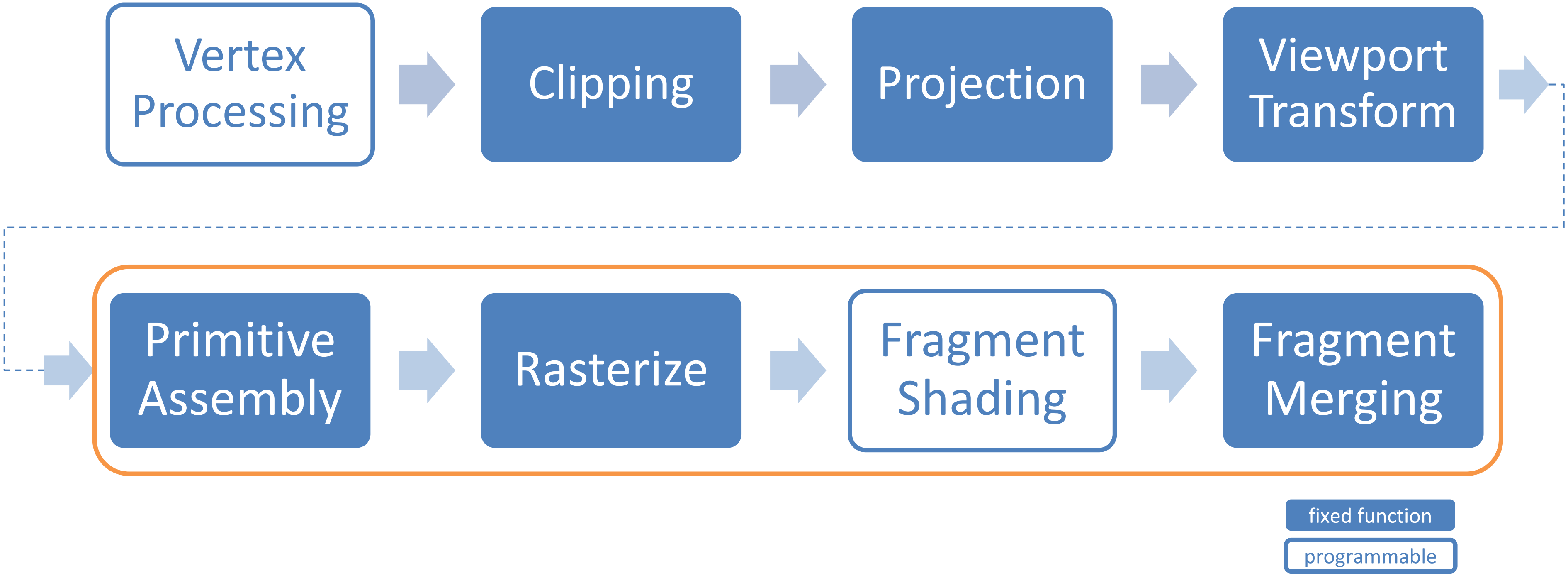


Geometry Stage Tasks

- Clipping
  - Primitives not entirely in view are clipped to avoid projection errors
- Projection
  - Projects clip space coordinates to the image plane
  - Primitives in *normalized device coordinates*
- Viewport Transform
  - Maps resolution-independent normalized device coordinates to a rectangular window in the frame buffer, the *viewport*
  - Primitives in window (pixel) coordinates

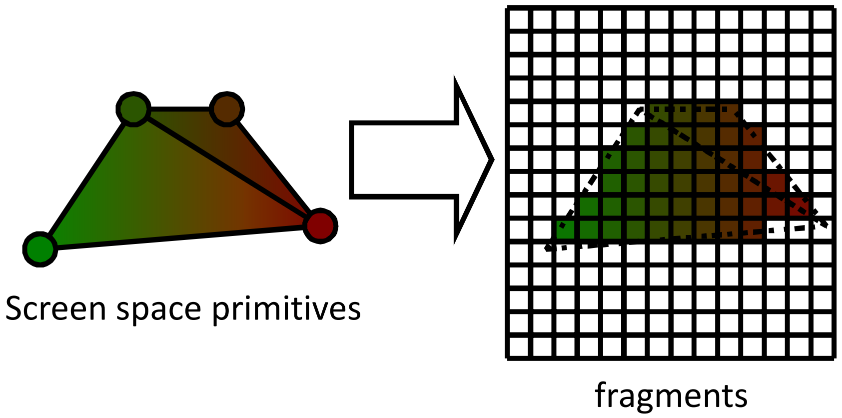


Rasterization Stage

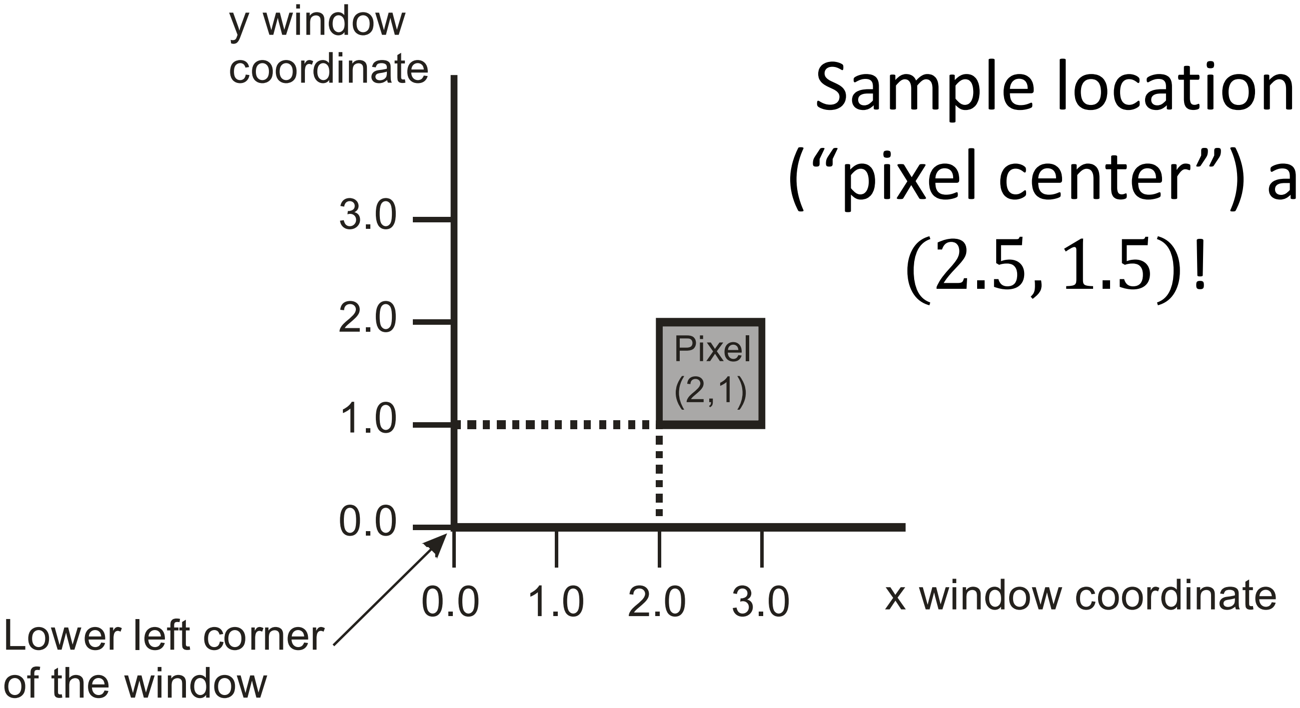


Rasterization Stage Tasks

- Primitive assembly
  - Backface culling
  - Setup primitive for traversal
- Rasterization (“primitive traversal”, “scan conversion”)
  - Sampling (triangle → fragments)
  - Interpolation of vertex attributes (depth, color, …)
- Fragment shading
  - Compute fragment colors
- Fragment merging
  - Compute pixel colors from fragments
  - Depth test, blending, …



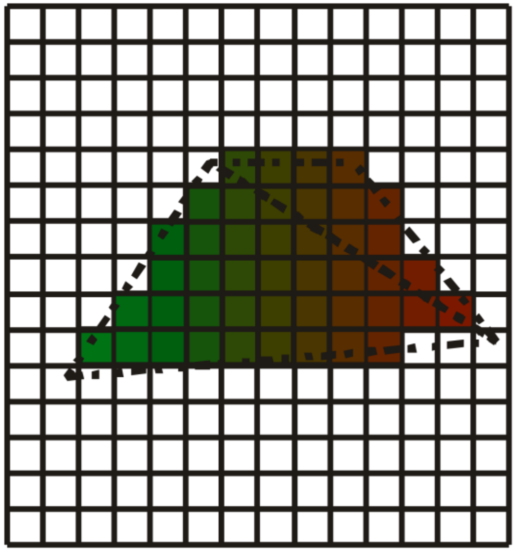
Rasterization – Coordinates



Sample location ("pixel center") at $(2.5, 1.5)$!

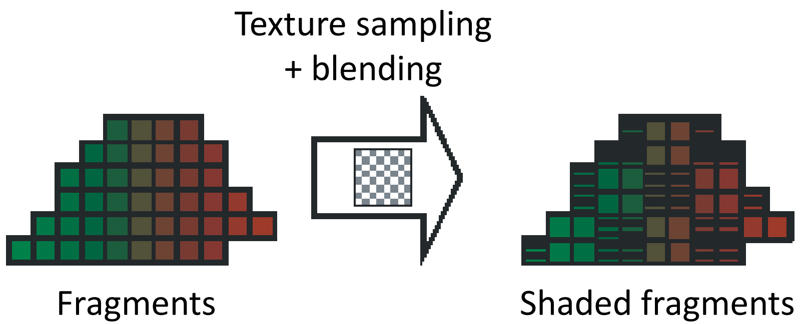
Rasterization – Rules

- Different rules apply for each primitive type
  - “Fill convention”
- Non-ambiguous!
  - Avoids artifacts
- Polygons
  - Pixel center contained in polygon
  - Pixels on edge: only one rasterized



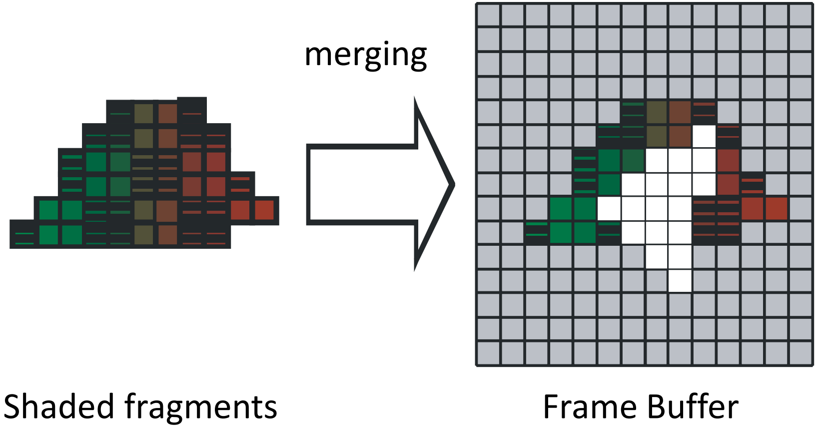
Fragment Shading

- Aka *pixel shader*
- Given the interpolated vertex attributes
  - Output by the vertex shader
- The *fragment shader* computes color values for each fragment
  - Apply textures
  - Lighting calculations
  - …

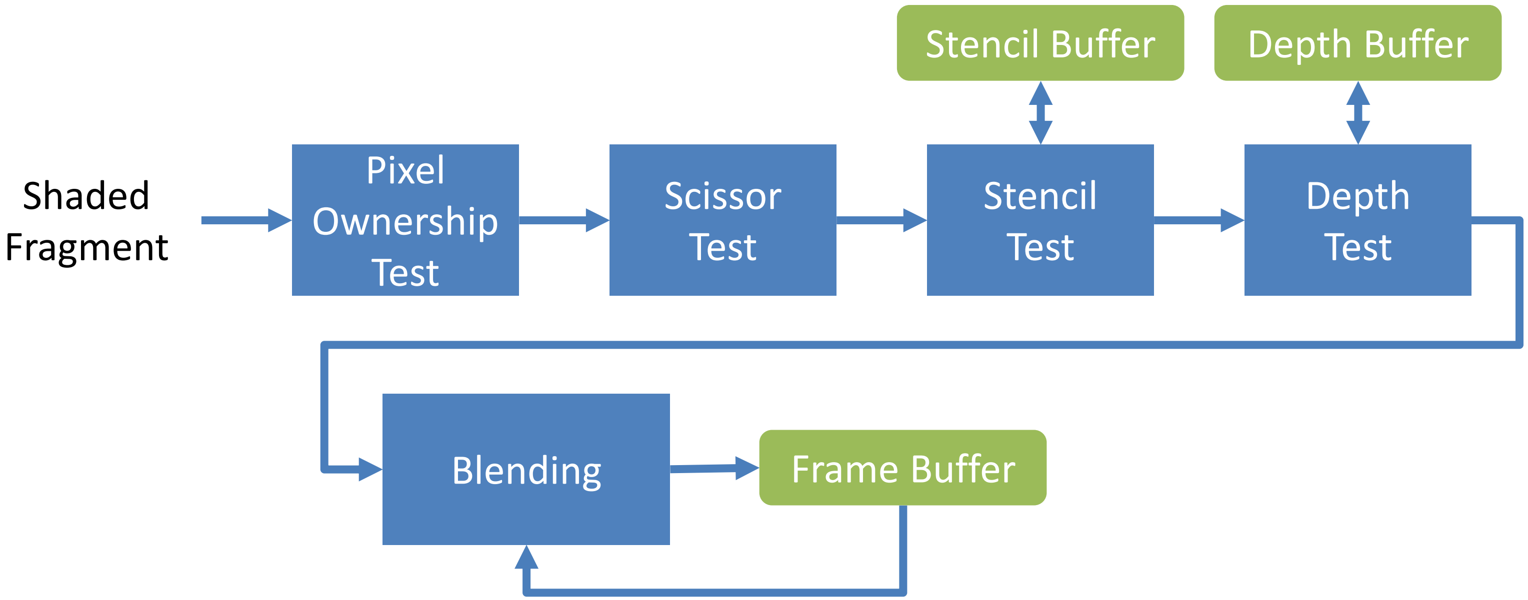


Fragment Merging

- Also known as “raster operations” (ROP)
- Multiple primitives can cover the same pixel
- Their fragments need to be composed to form the final pixel values
  - Blending
  - Resolve visibility via depth buffering

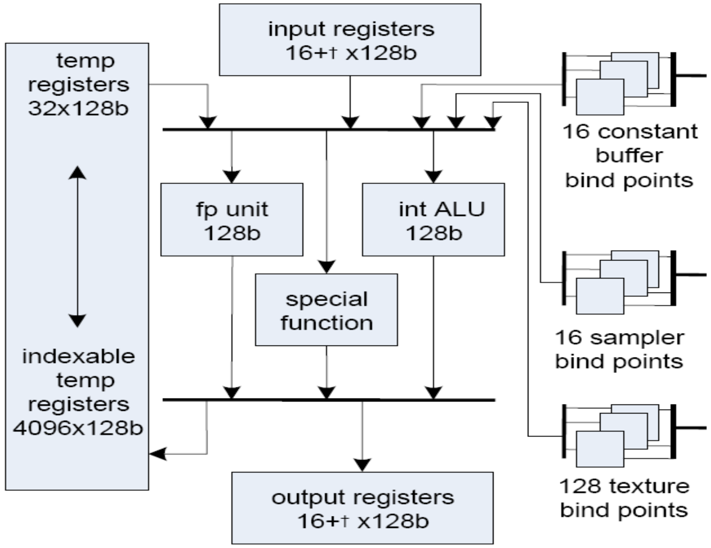


Fragment Merging Workflow



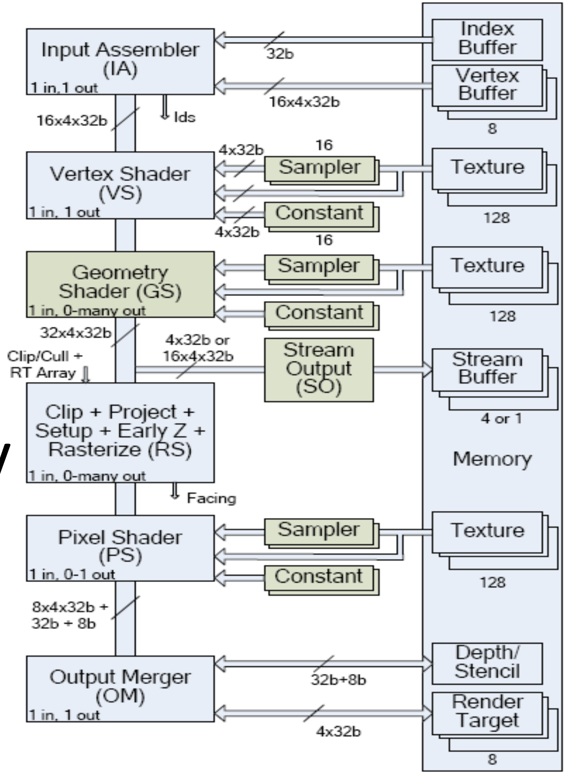
Unified Shader Model

- Same instruction set and capabilities for all shaders
- Dynamic load balancing between vertex and fragement shaders
- IEEE-754 floating point
- Enables new GPGPU languages like CUDA



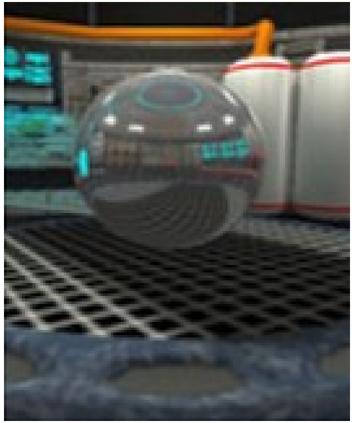
Geometry Shader

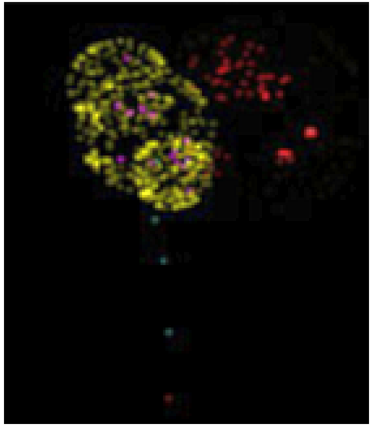
- Between vertex and pixel shader
- Can generate primitives dynamically
- Procedural geometry
  - E.g., growing plants
- Geometry shader can write to memory
  - Called „stream output"
  - Enables multi-pass for geometry



Geometry Shader Examples 1

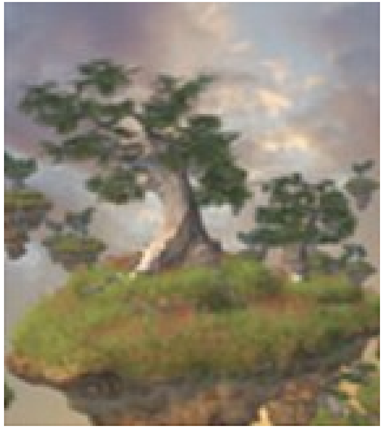
Cube Map: GS instances every triangle 6x





Particles produced by GS as stream-out

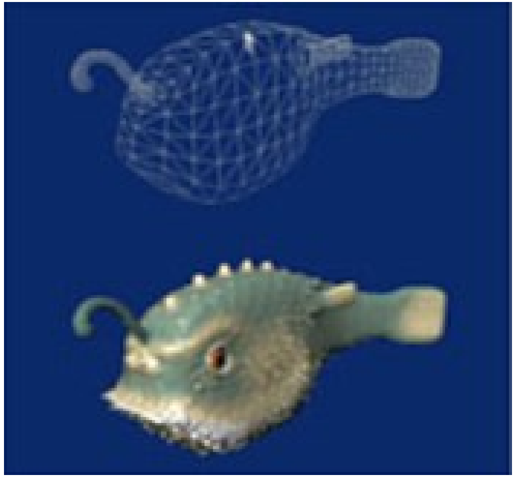
Plants created as parameterized instances



Geometry Shader Examples 2

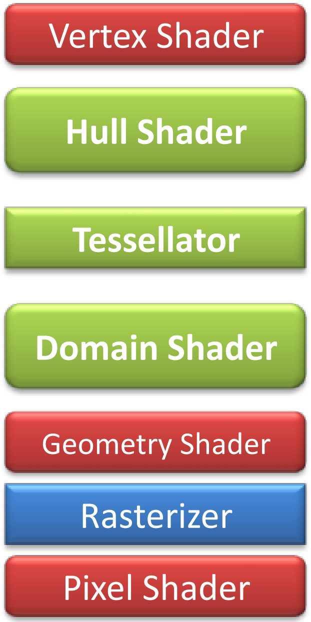
Shadow volume created by GS extrusion

Displacements created by GS



Tesselation Shader

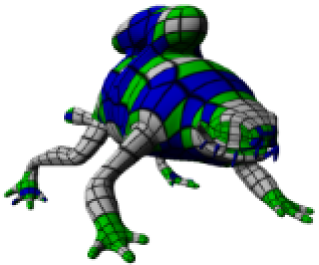
- Since DirectX11
- New shader stage: Tessellation
- Input: low-detail mesh
- Output: high-detail mesh



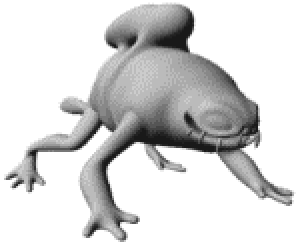
https://www.youtube.com/watch?v=p_VpAMaxwpY

Authoring without Tessellation

Sub-D modeling

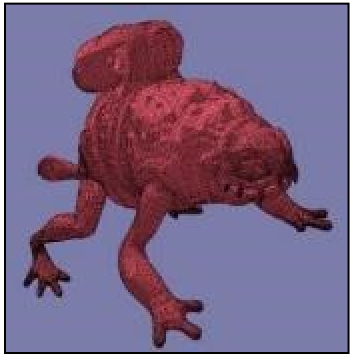


Animation

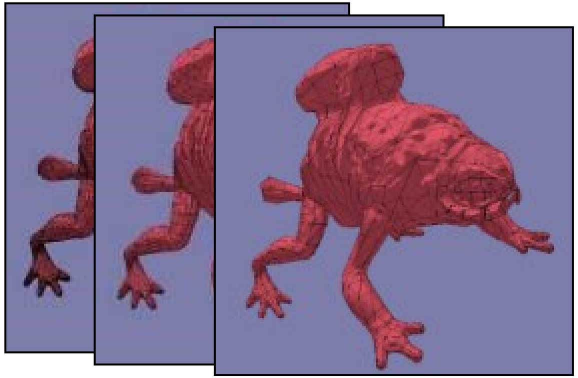


Displacement map

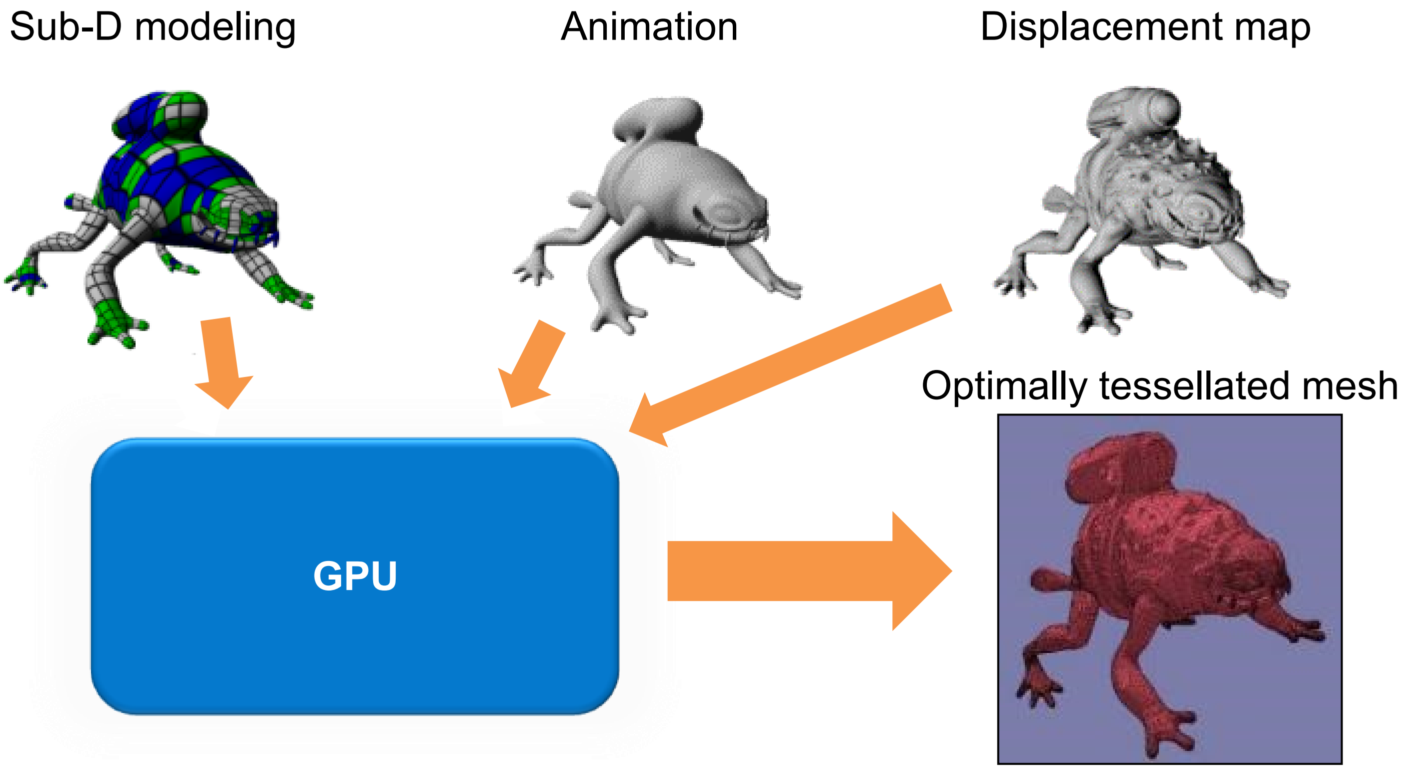
Polygon mesh



Generate LODs

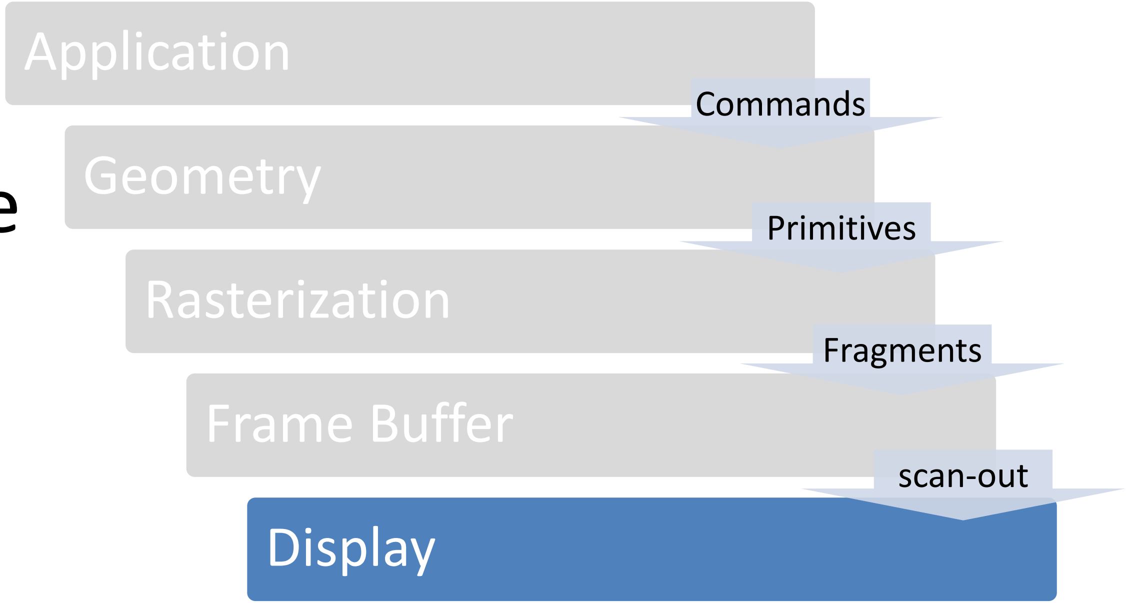


Authoring with Tessellation



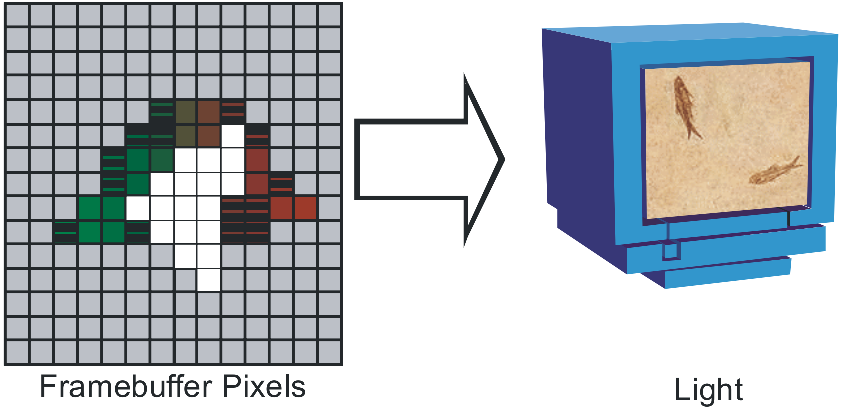
Display Stage

- What happens after fragments are retired to the frame buffer?



Display Stage Tasks

- Gamma correction
- Historically: digital to analog conversion
- Today: digital scan-out, HDMI encryption?

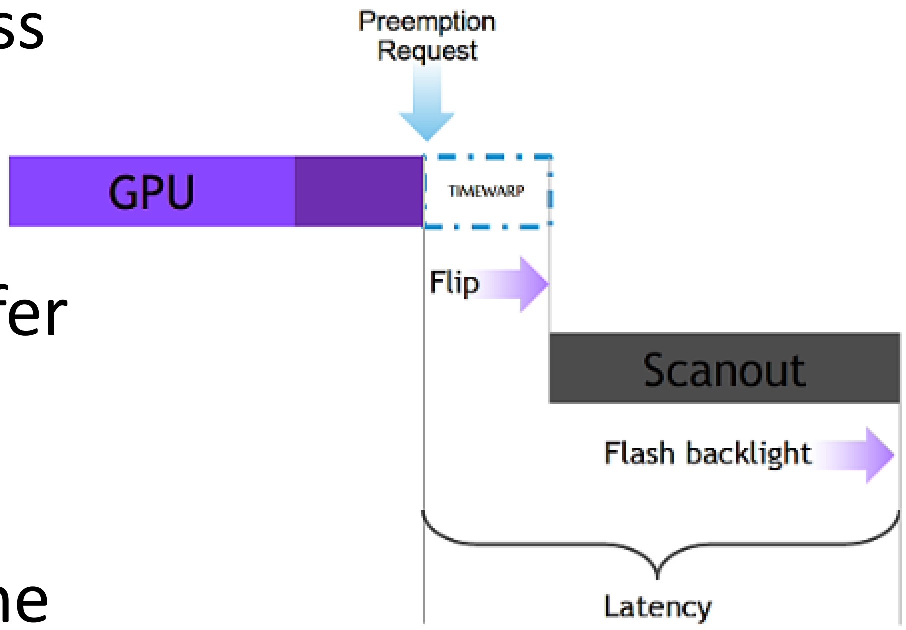


Display Format

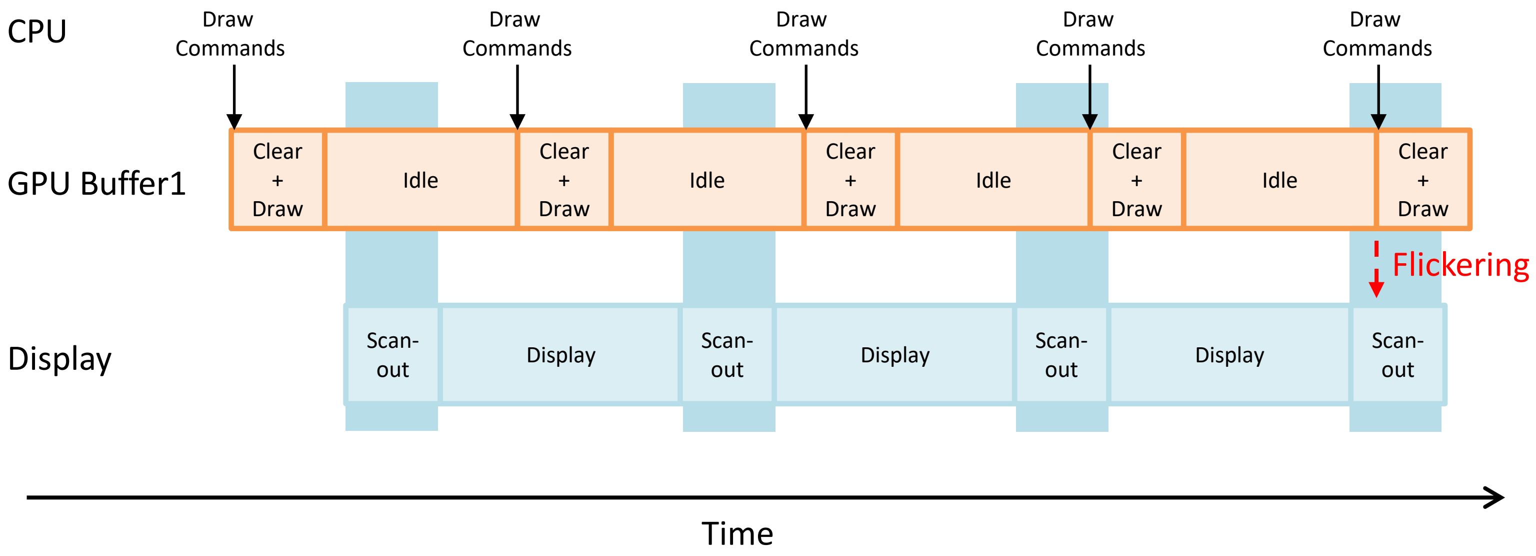
- Frame buffer pixel format:
  RGBA vs. index (obsolete)
- Bits: 16, 32, 64, 128 bit floating point, …
- Double buffering for smooth animation
- Quad-buffering for stereo graphics
- Overlays (extra bitplanes)
- Auxilliary buffers: alpha, stencil, depth

What is Display Synchronization?

- Need to synchronize access to frame buffer between GPU and display
- Cannot change frame buffer during display scan-out
- Need proper buffering in the whole graphics pipeline

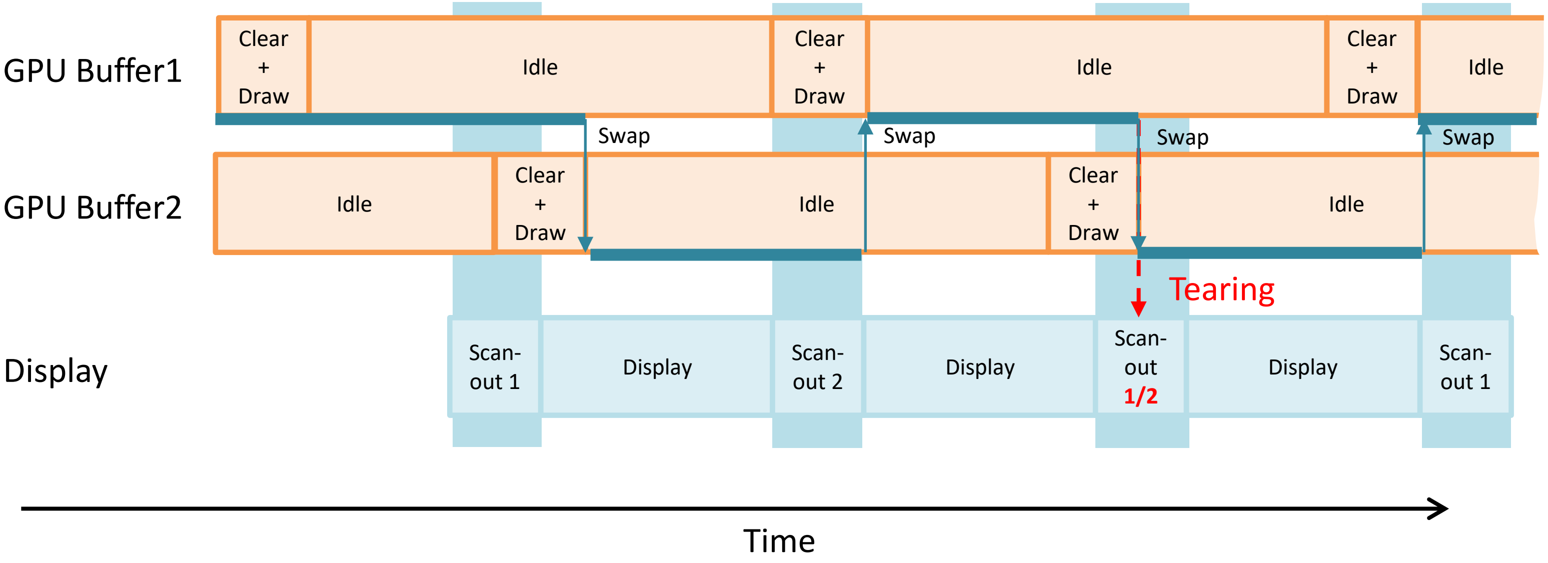


Single Buffering



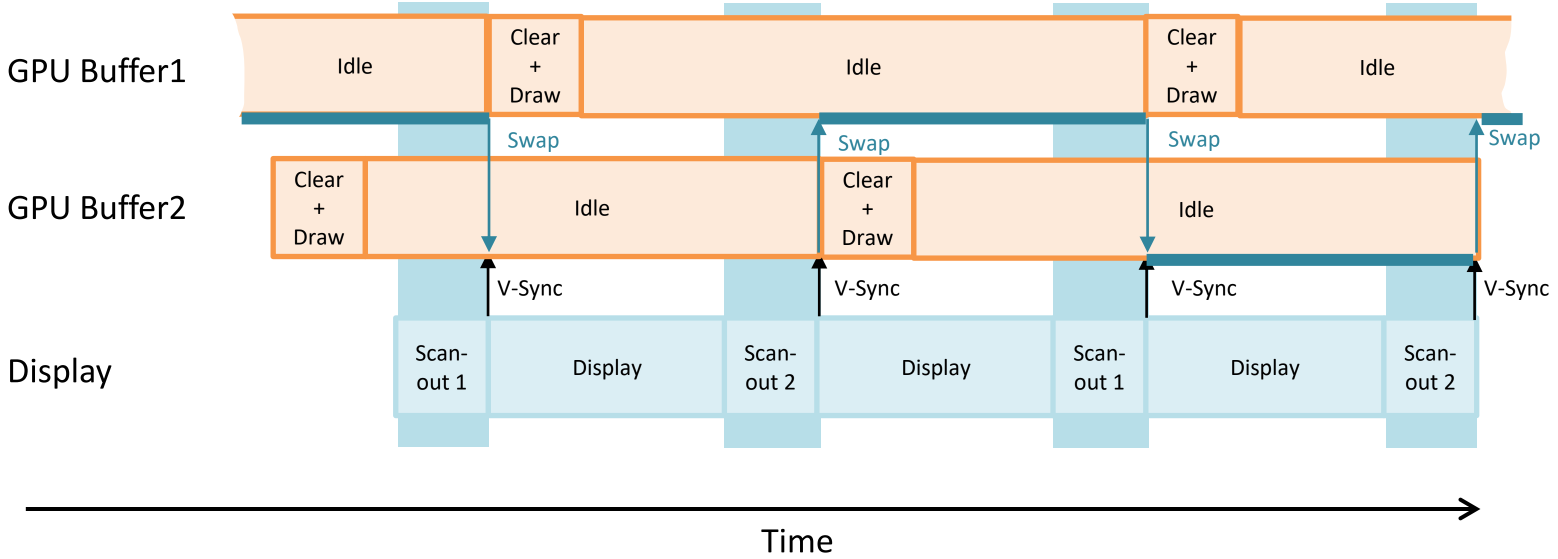
Double Buffering without V-Sync

- Front buffer used for scan-out GPU→display
- SwapBuffers() changes front and back buffer
- No flickering, but tearing artefacts



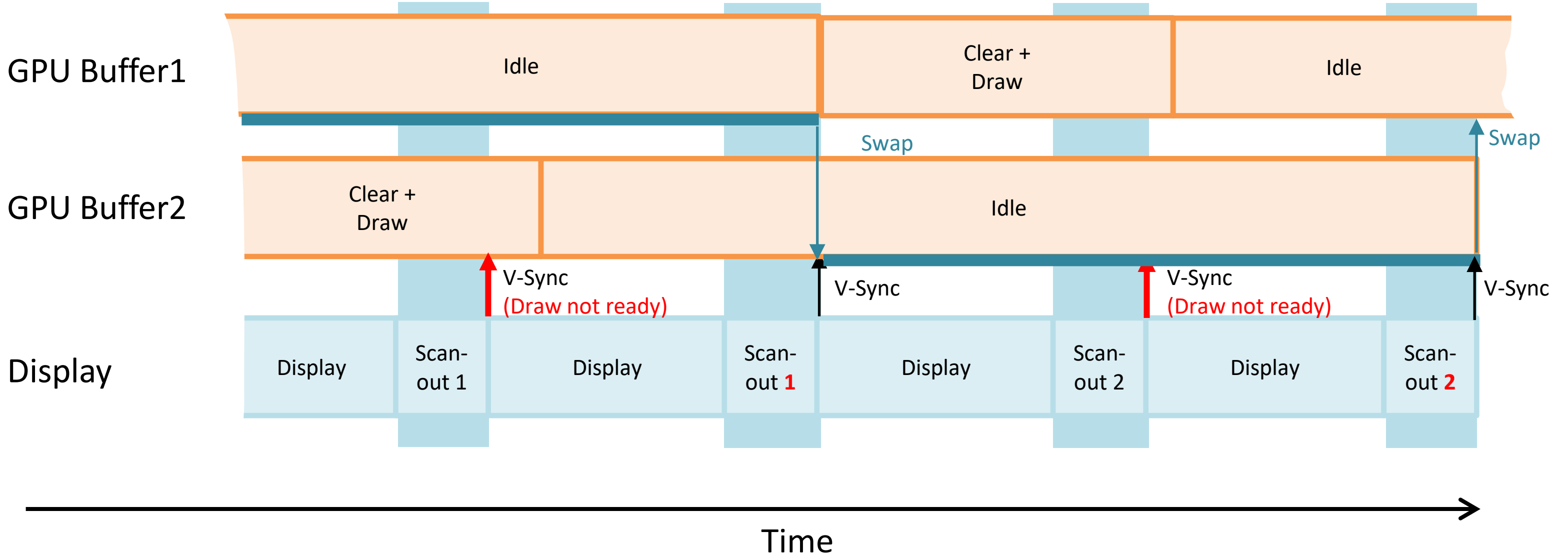
Double Buffering with V-Sync, Fast

- V-Sync means the display is done with frame scan-out from GPU
- When rendering is **fast**, the frame rate is limited by display rate
- Additional latency of max. one frame time



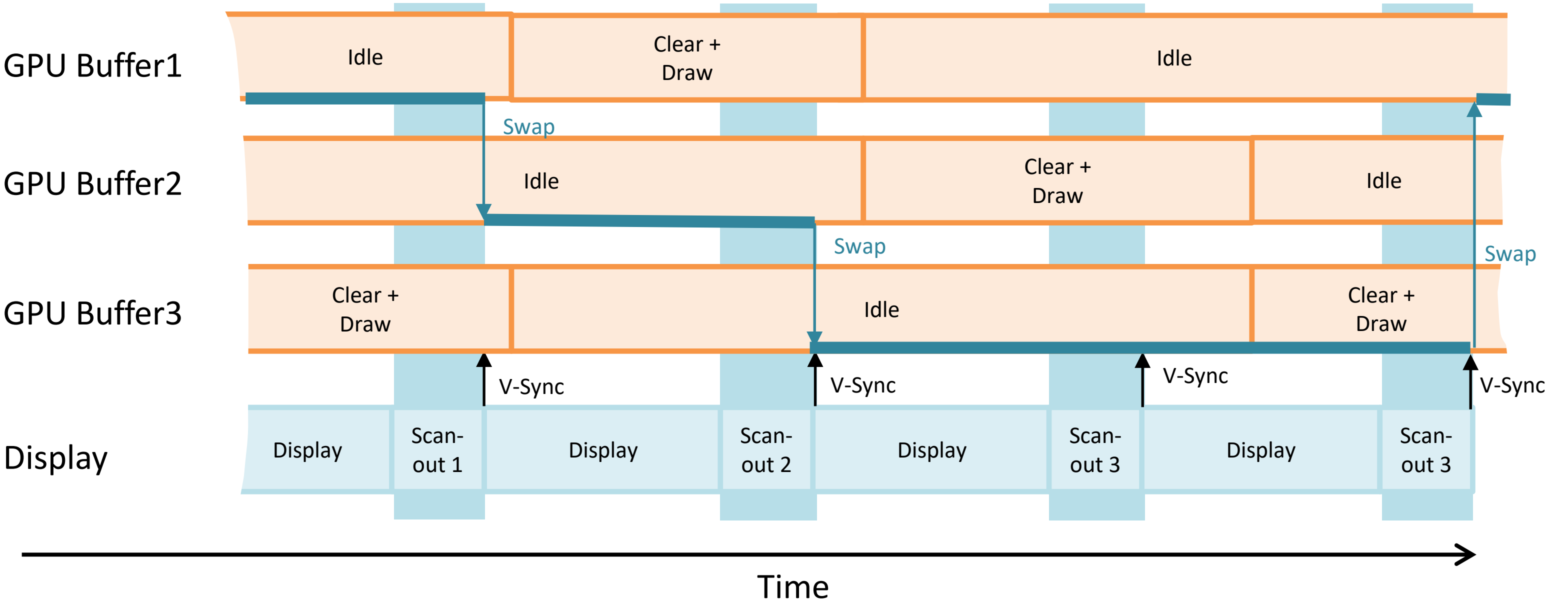
Double Buffering with V-Sync, Slow

- When rendering is **slow**, frame rates can only be integer fractions of display rate
- Display rate 60Hz → frame rates 60, 30, 20, 15, … (but not 59) possible
- Adaptive V-Sync (NVIDIA) turns off V-Sync automatically if rendering is slow



Triple Buffering with V-Sync

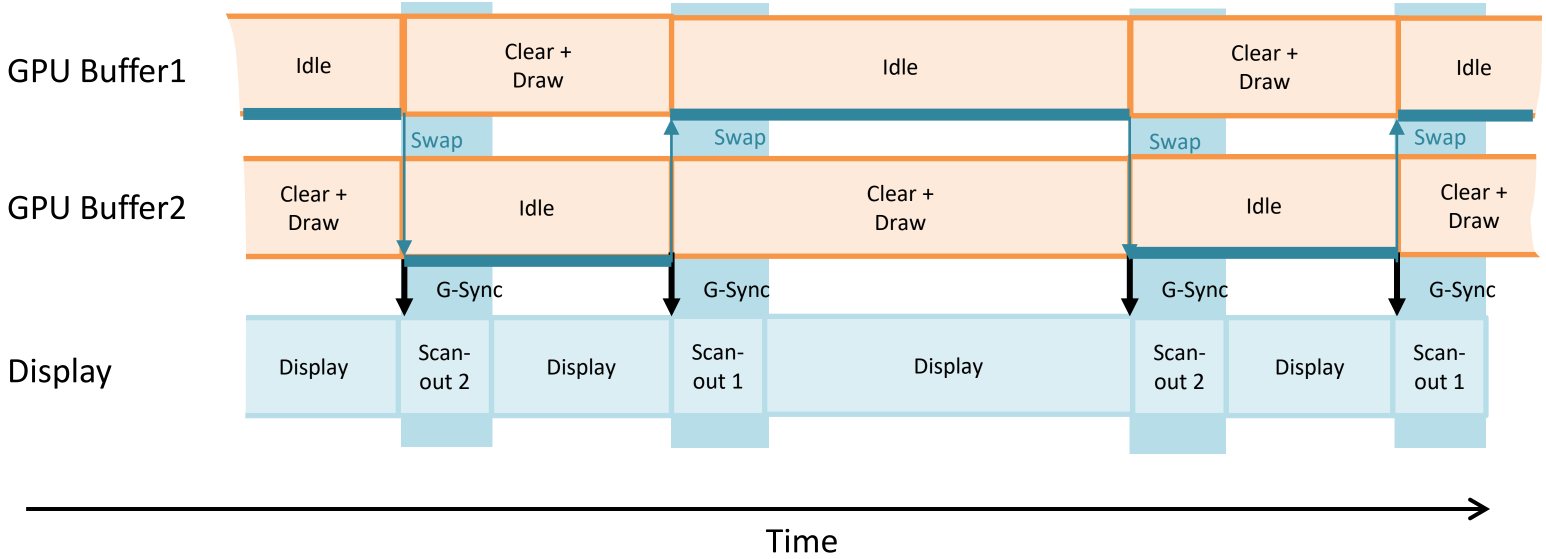
- Triple buffering only makes sense together with V-Sync
- When rendering is **slow**, third buffer allows continuous drawing
- When rendering is **fast**, two back-buffers can be alternated (wasted frames!)



G-Sync / FreeSync

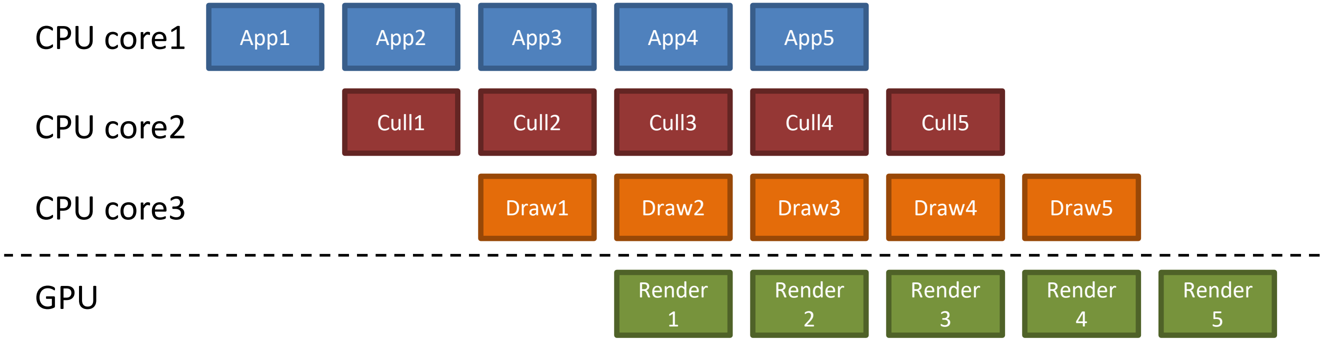
- Display scan-out can be triggered by GPU
- Requires additional display hardware feature
- G-Sync (NVIDIA), FreeSync (AMD)

https://youtu.be/5maHG9Kpjic



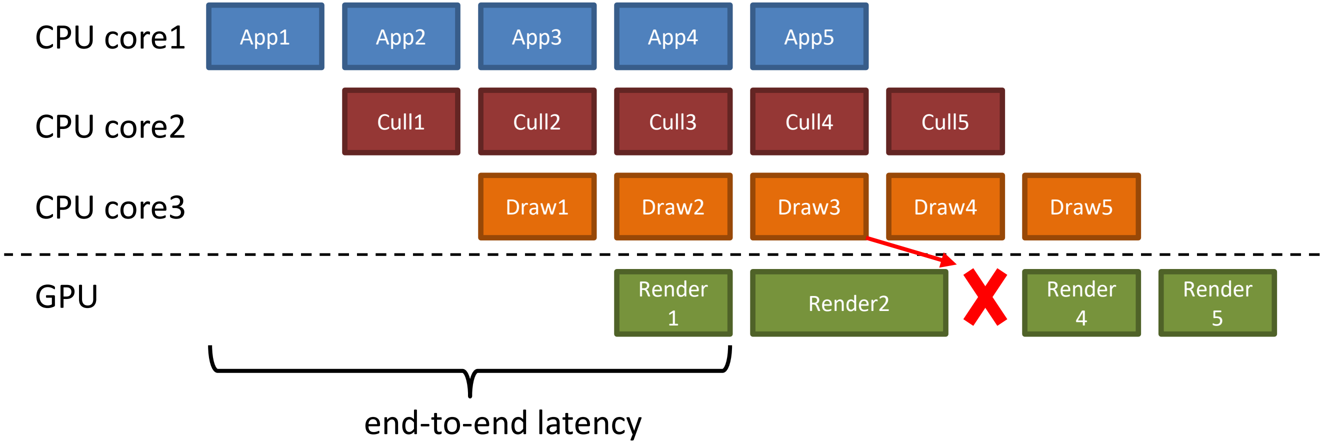
Multi-Threaded Rendering Pipeline

- App stage: simulate 3D world
- Cull stage: determine object in view frustum
- Draw stage: issue OpenGL commands to driver (includes optimizations such as mode sorting)
- Everything must work at target frame rate!



Minimizing Pipeline Latency

- Always aim for minimal latency
- Fixed size buffer from stage to stage
- Never wait for (downstream) consumer!



Thank You!

Questions ?