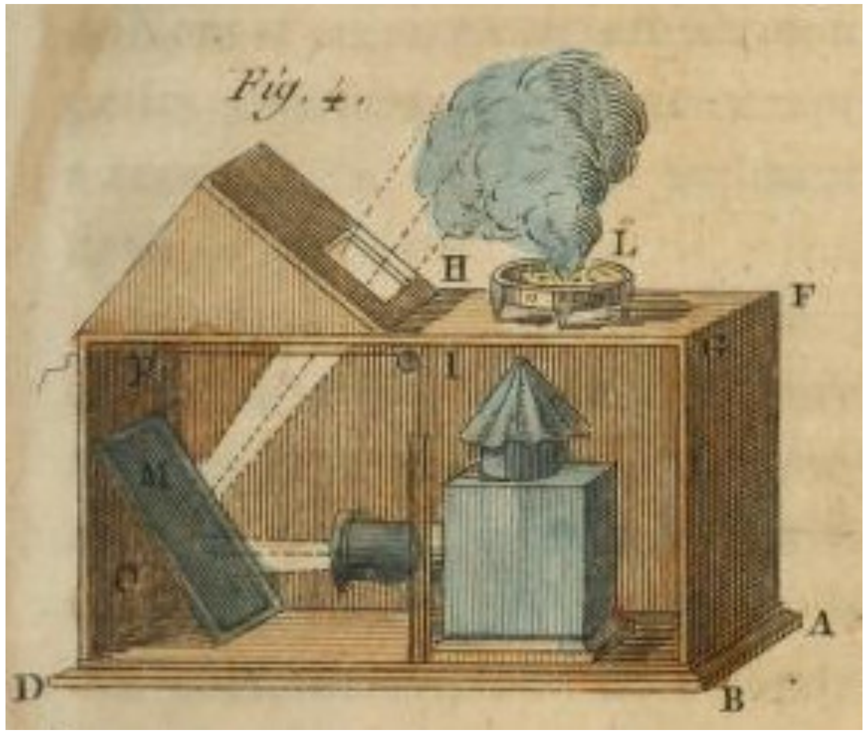
Intro to OpenGL & Rasterization

Computer Graphics
CMU 15-462/662

Graphics APIs

- Graphics APIs perform many common rendering tasks for you
  - Important: **you don't need a graphics API to do graphics**!
  - Generally Graphics APIs are used for **realtime rendering**
- Why use a Graphics API instead of writing it yourself?
  - Graphics hardware is designed around them (huge speedup!)
    - **Graphics drivers** translate standard graphics API calls to specialized GPU hardware instructions
  - Standardization of Graphics APIs allows for the creation of better debugging and tooling
    - This is why DirectX is so popular!
  - It takes way less time

Realtime Rendering as Smoke & Mirrors



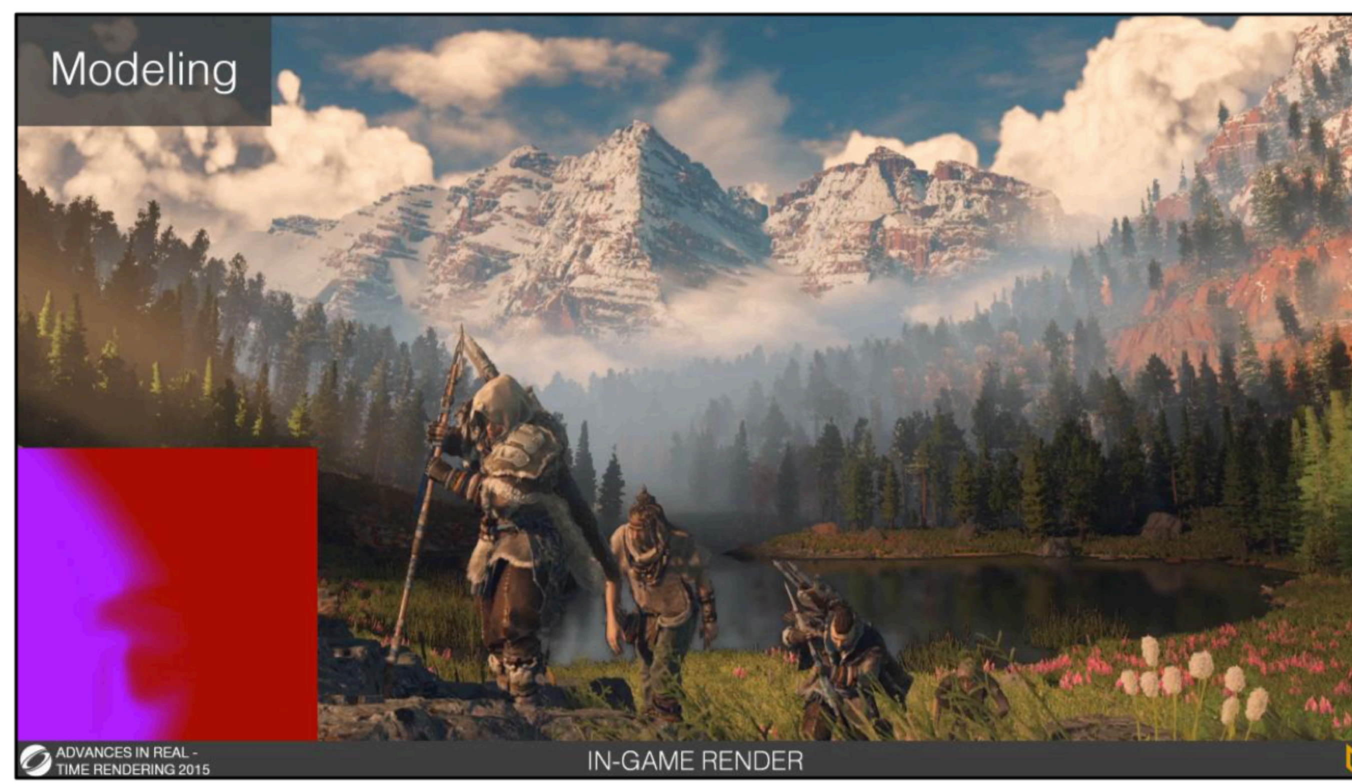
“Phantasmagoria” in Theatre

“Potemkin Villages”

Realtime Rendering as Smoke & Mirrors

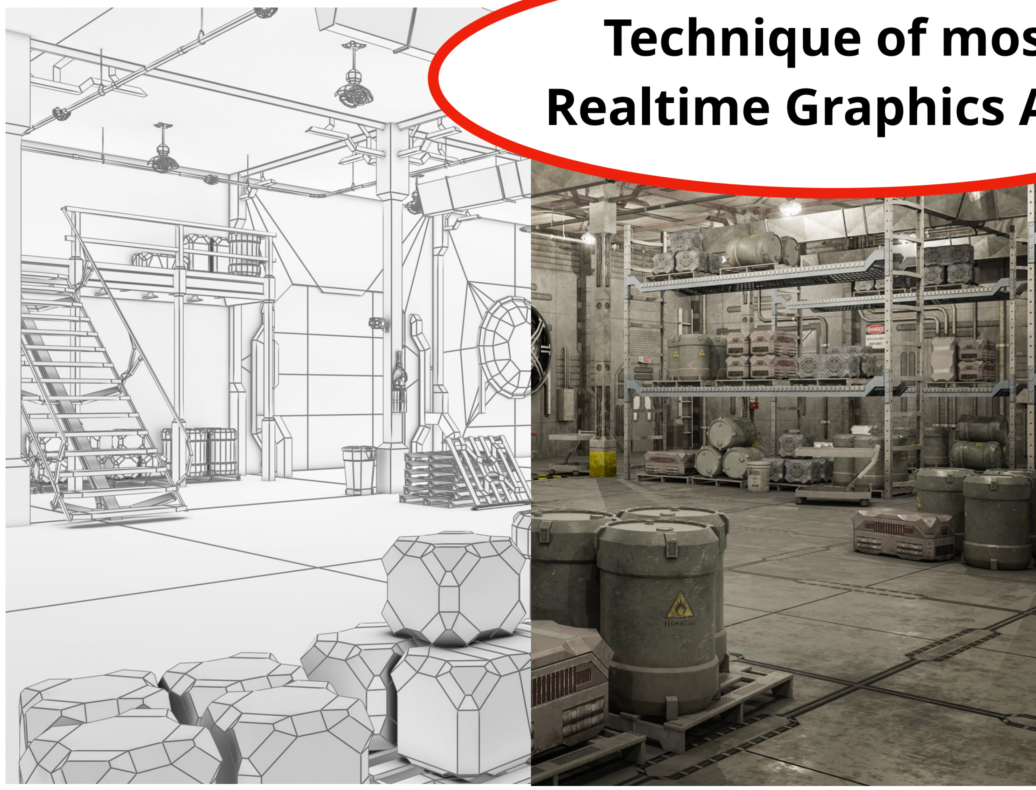
Billboarding in Mario 64

Rim Lighting
(http://blog.wolfire.com/2009/09/character-rim-lighting/)



“The Realtime Volumetric Cloudscapes of Horizon Zero Dawn,” Guerrilla Games @ SIGGRAPH 2015

Rasterization vs Pathtracing



Technique of most Realtime Graphics APIs

Rasterization

Transform scene geometry via matrix operations to screen space, then use triangle fill algorithm.

Optimized for performance

DrawSVG (A1)

Pathtracing

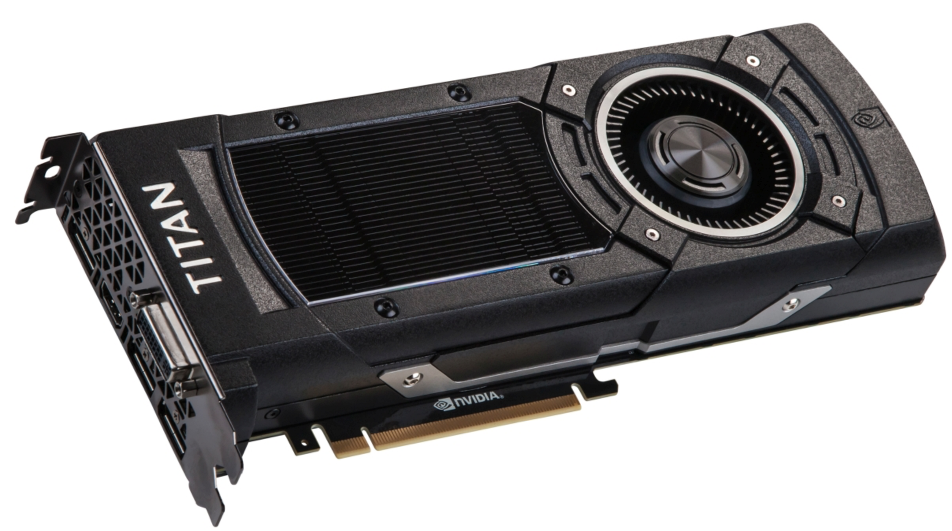
Bounce simulated rays of light throughout your scene randomly for each pixel, and illuminate if it eventually intersects a light.

Optimized for realism

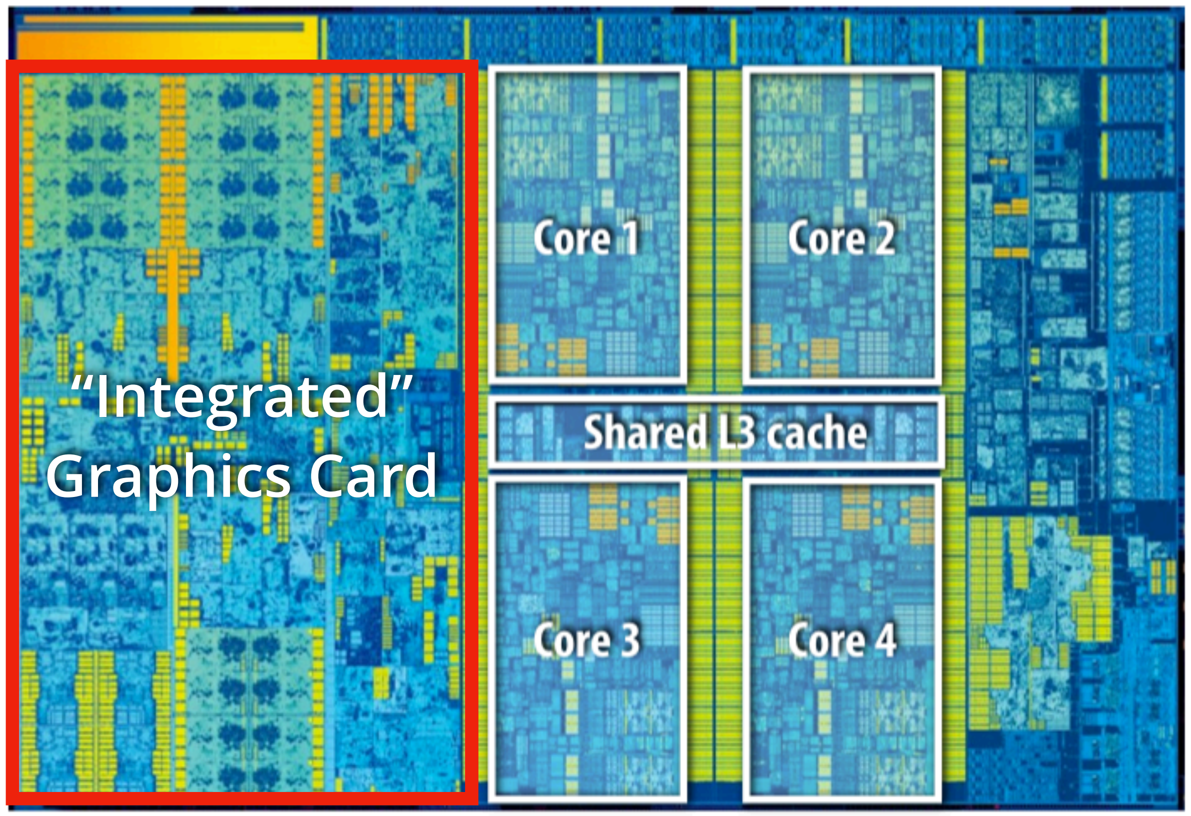
Pathtracer (A3)

The GPU

- The the *GPU* (Graphics Processing Unit) in your computer is designed to accelerate rasterization
  - CPU: ~4-16 “smart” cores
    - Handle branching well, but lower throughput for math
  - GPU: Many (thousands) of “dumb” compute units
    - Bad at branching, very fast at math, great parallelism
- Upshot: GPUs are very good at matrix / vector operations, and bad at handling branching (if statements, nontrivial loops, etc)
- **We will generally not use the GPU in this class** (see 15-418!)

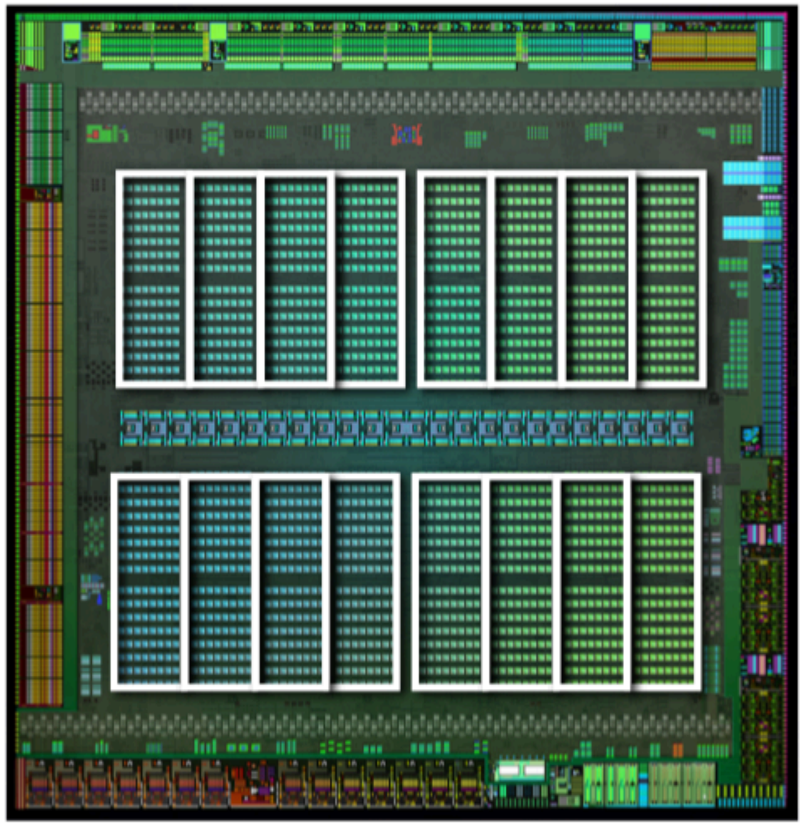


Multi-core examples



Intel "Skylake" Core i7 quad-core CPU
(2015)

Each core is sophisticated, out-of-order processor



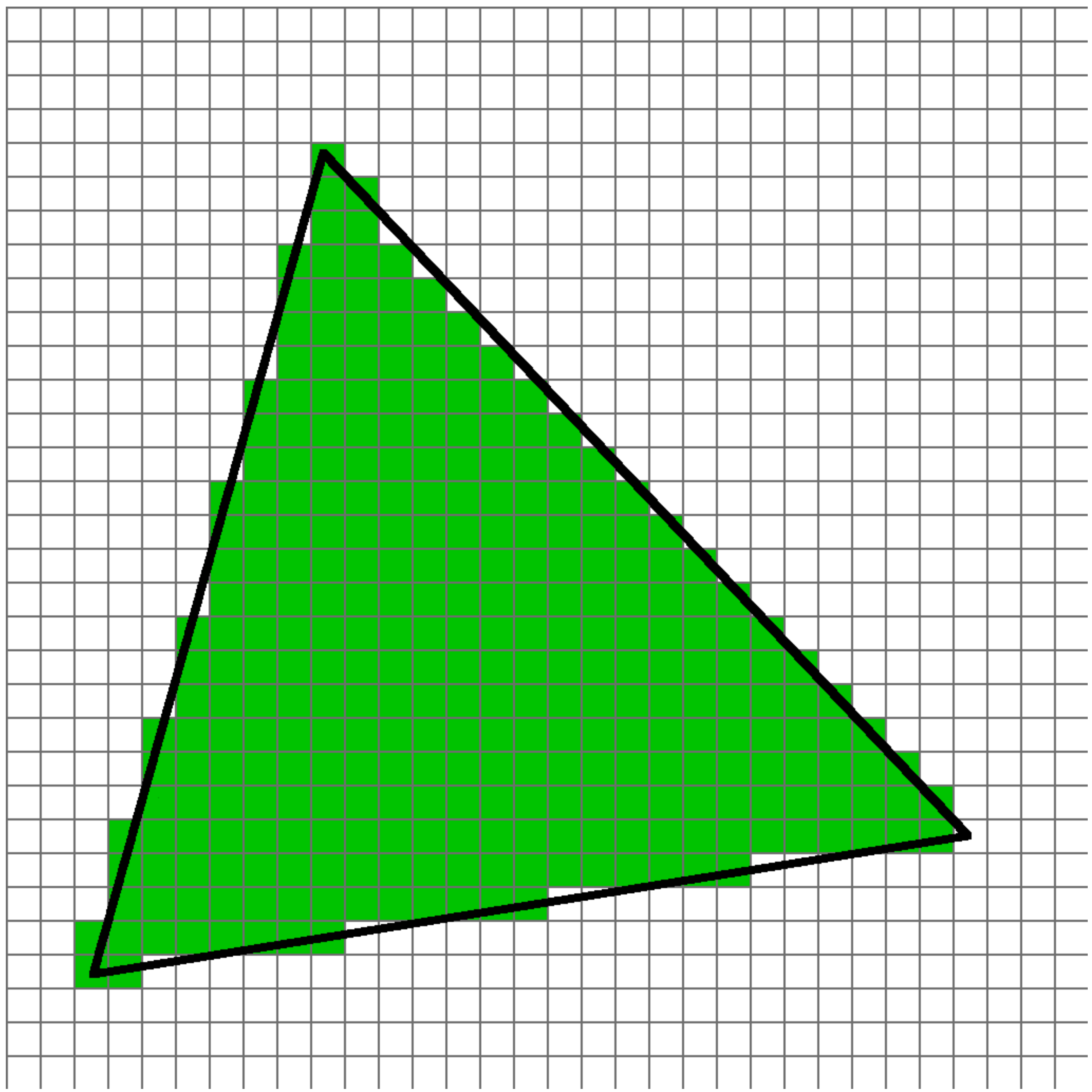
NVIDIA GTX 980 GPU
16 replicated processing cores ("SM")
(2014)

Each core processors vectors of data

Check out 15-418!

Things GPUs Are Good At: Triangle Fill

- Fact: GPUs can fill in triangles on a 2D image plane quickly

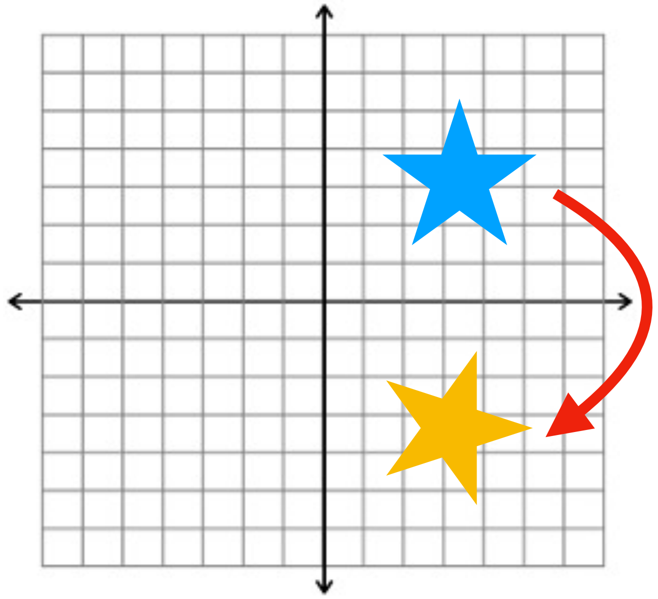


Things GPUs Are Good At: Transformation Matrices

- Consider the matrix: $A = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$
- Question: What happens when you multiply A by a vector?

$$\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} 5 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ -5 \end{bmatrix} \qquad \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 2 \\ -1 \end{bmatrix}$$

- Answer: A represents a 90 degree clockwise rotation about the origin!
  - It turns out you can encode arbitrary rotations in a matrix (even in 3D!)



Things GPUs Are Good At: Transformation Matrices

- We can encode scaling (using 3D vectors here):

$$\begin{bmatrix} 3 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 1/2 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} = \begin{bmatrix} 3 \\ 10 \\ 3/2 \end{bmatrix}$$

- If we cheat a little and add a 4th coordinate set to 1, we can also encode translation:

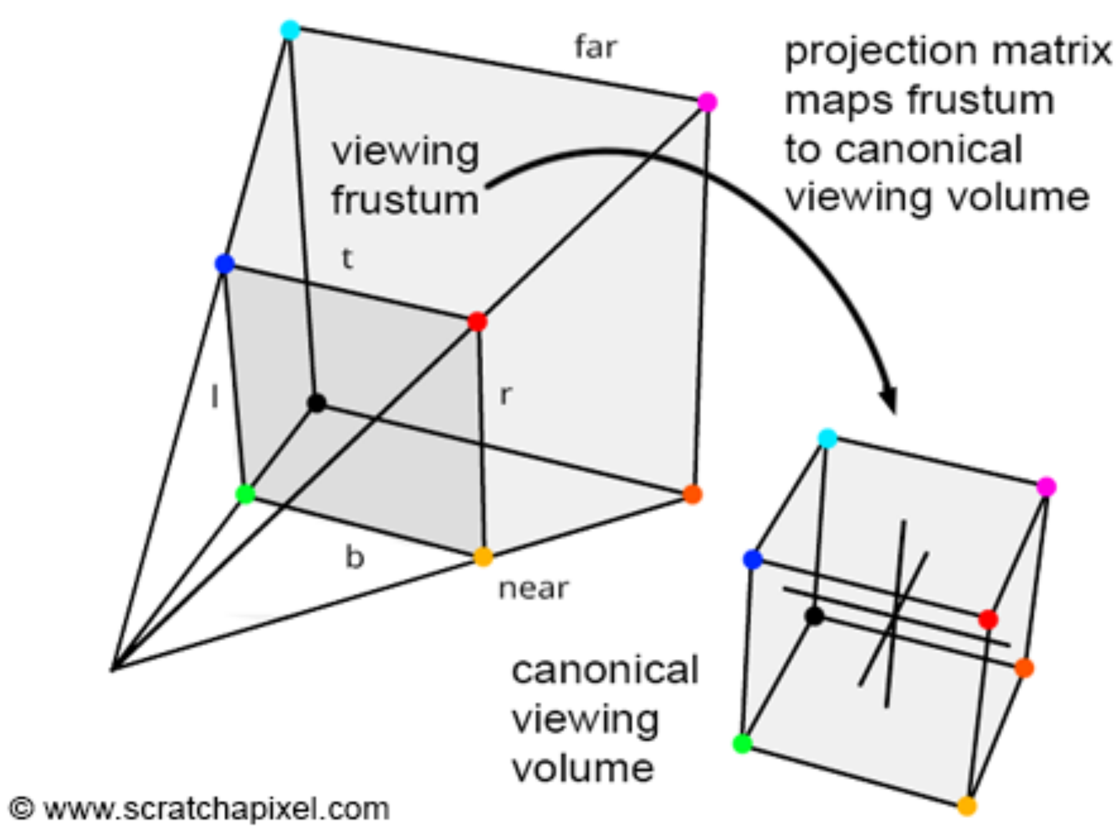
$$\begin{bmatrix} 1 & 0 & 0 & 5 \\ 0 & 1 & 0 & -2 \\ 0 & 0 & 1 & 4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ 3 \\ 1 \end{bmatrix} = \begin{bmatrix} 6 \\ 0 \\ 7 \\ 1 \end{bmatrix}$$

XYZ Coordinates

W Coordinate used for translation

Things GPUs Are Good At: Transformation Matrices

- The *projection matrix* accounts for objects vanishing in the distance due to perspective.
  - After applying the projection matrix, you can throw away the z coordinate.



(technically, perspective projection is a nonlinear operation so we can't shove it in a matrix alone. We need to do some tricks with the W coordinate from earlier. More info to come!)

Things GPUs Are Good At: Transformation Matrices

- We can even combine these matrices into a single matrix: Let T, R, S denote translation / rotation / scale matrices and let $\overrightarrow{v}$ be a point in 3D space.
  - Then $T \times (R \times (S \times (\overrightarrow{v})))$ means "scale $\overrightarrow{v}$ about origin, then rotate result about origin, then translate result"
  - But by associativity of matrix multiplication this is equivalent to $(T \times R \times S) \times \overrightarrow{v}$!
- This is very useful: we can encode arbitrary geometric transformations into a single matrix.

More on this in a later lecture!

Navigating Coordinate Frames

- When we want to draw something on screen, it is loaded in via a 3D model file (.obj, .dae etc) with its own *coordinate frame*. We call this coordinate frame **model space**

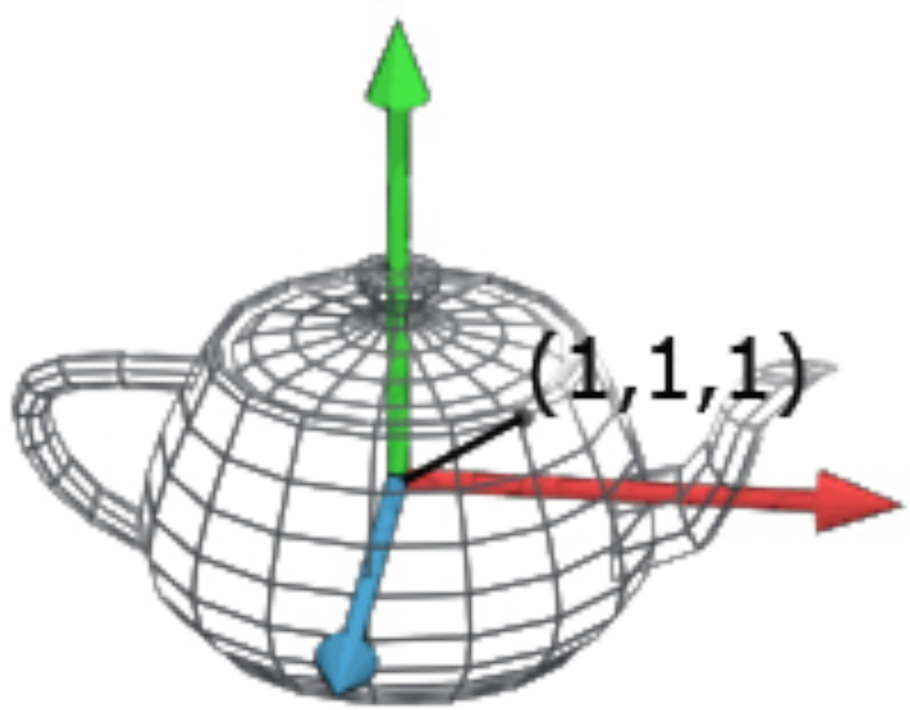


Figure source: http://www.codinglabs.net/article_world_view_projection_matrix.aspx

Navigating Coordinate Frames

- Suppose we wanted to place three of these teapots in a scene, each with their own position, rotation and scale.
  - We can use the translation / rotation / scale (TRS) matrix discussed earlier to move them into **world space**
  - The **model matrix** is applied to each vertex to bring it from model space to world space.

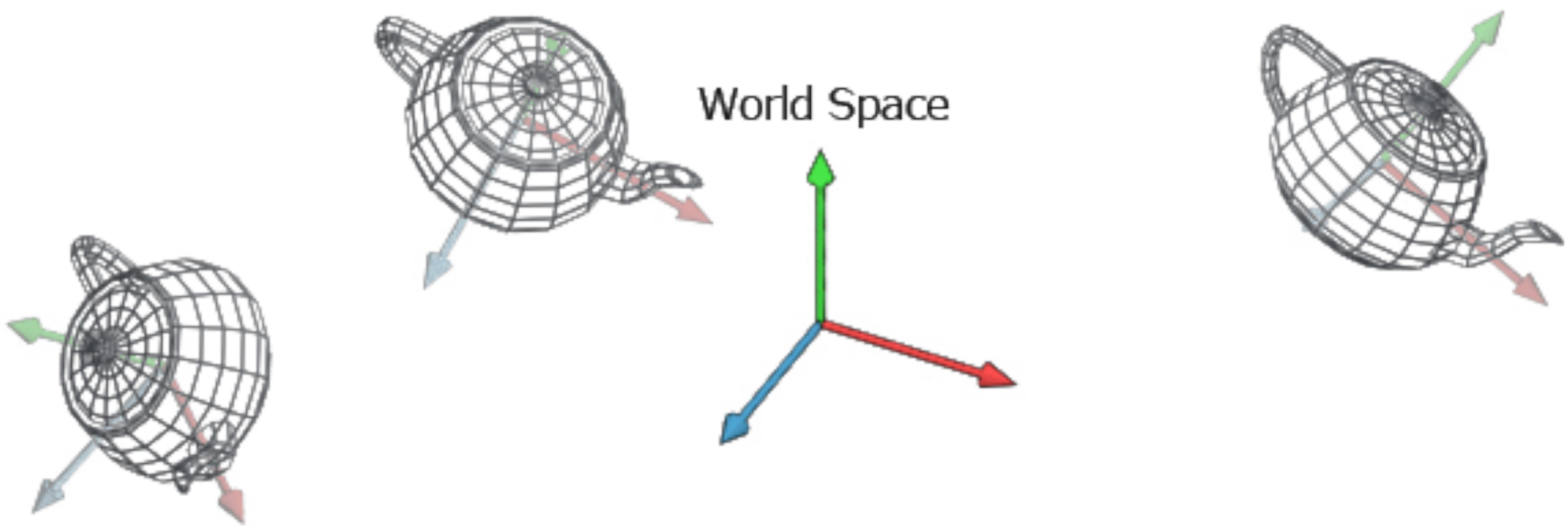


Figure source: http://www.codinglabs.net/article_world_view_projection_matrix.aspx

Navigating Coordinate Frames

- Of course, we also must have a camera that views the scene. We define **view space** to be the frame with the camera position as the origin and the camera direction as the Z- direction.
  - Question: How do we build the **view matrix**, which converts from world space to view space?

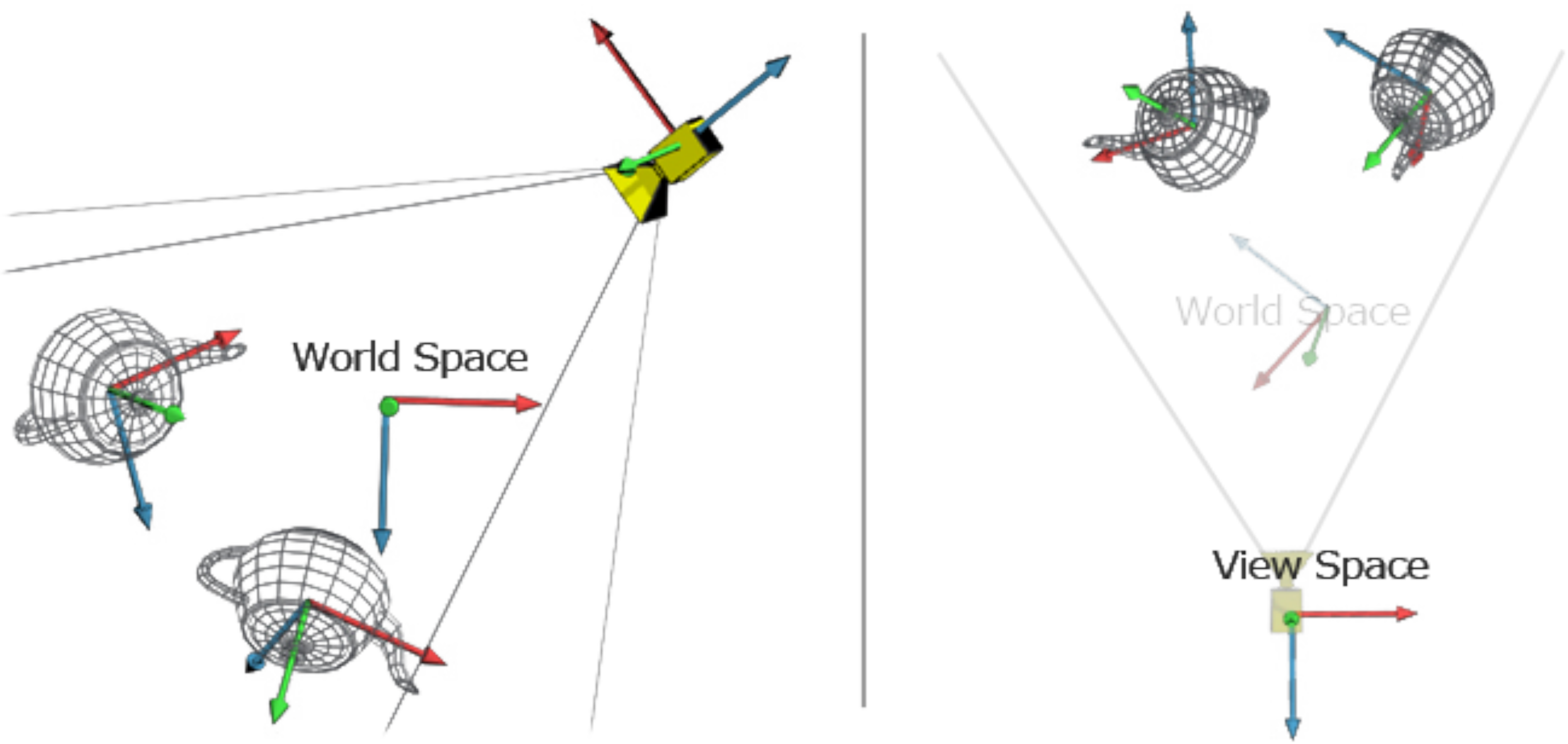
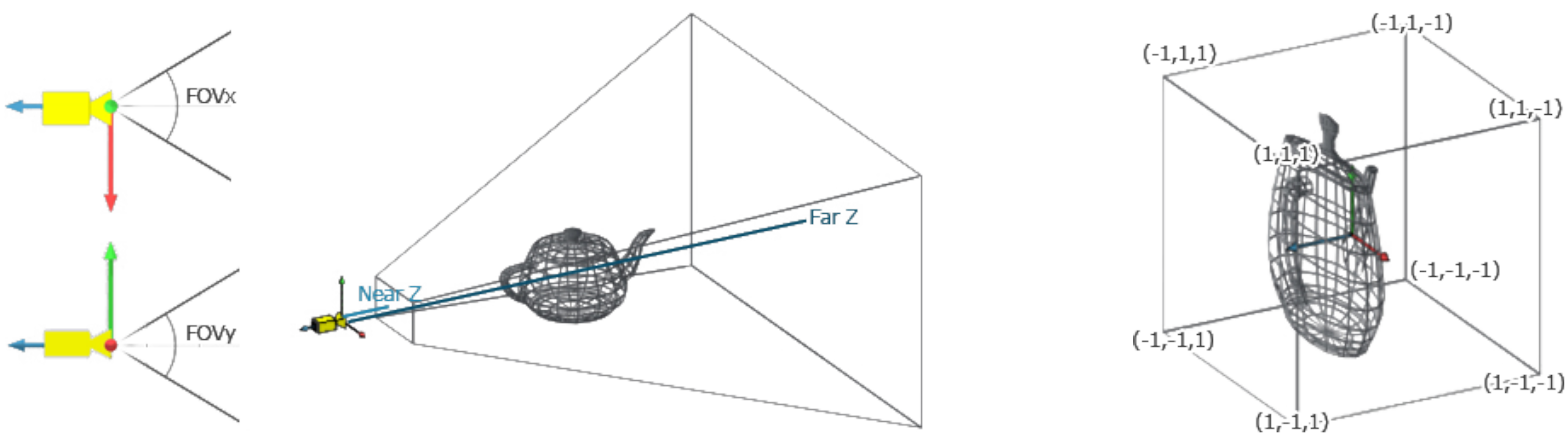


Figure source: http://www.codinglabs.net/article_world_view_projection_matrix.aspx

Navigating Coordinate Frames

- Finally, the **projection matrix** brings us from view space to **screen space** (coordinate frame of the window)
  - Depends on Field of View of the camera
- Now, we just need to run triangle fill in screen space!



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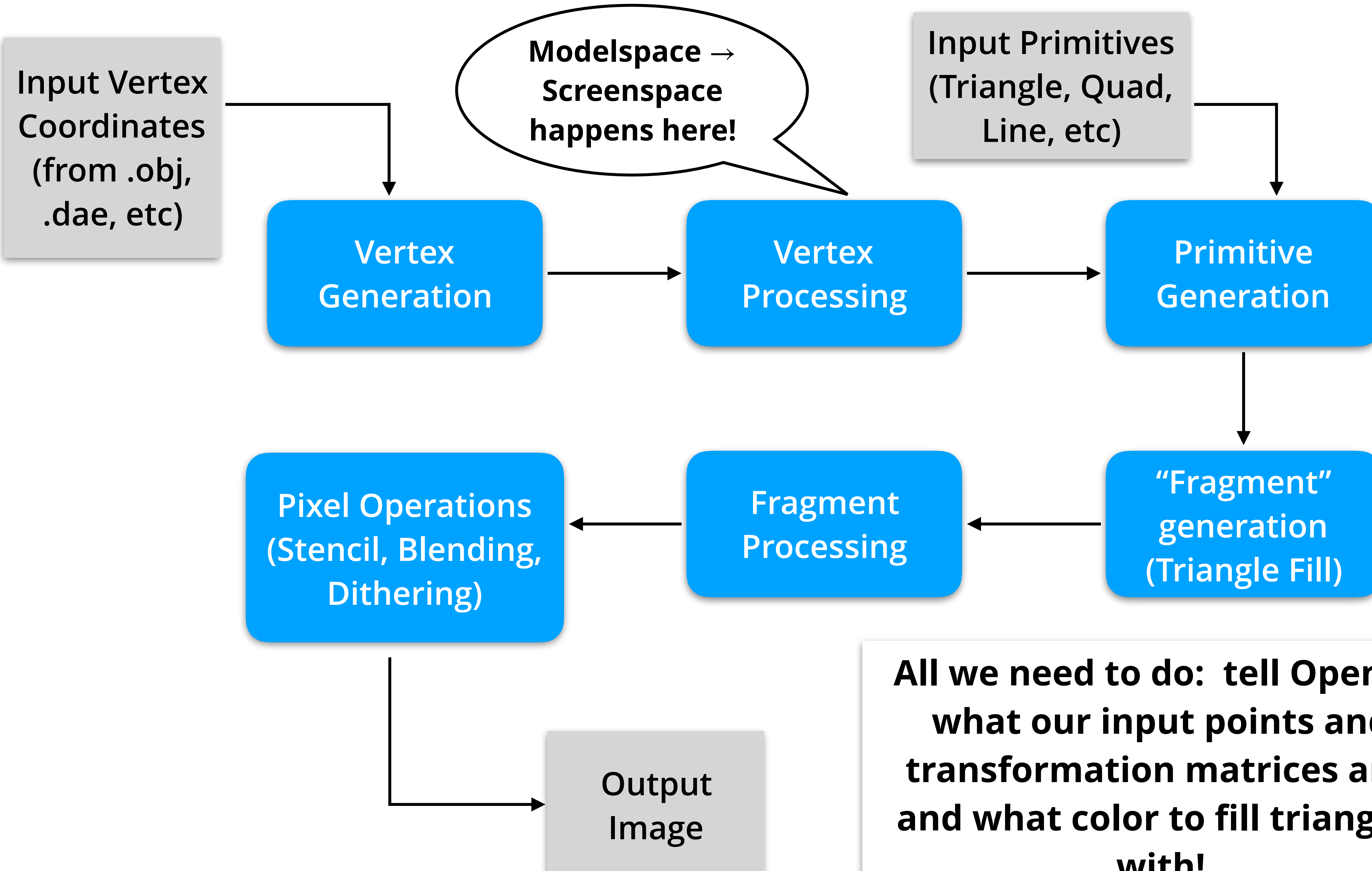
Putting it All Together: Rasterization is a Data Processing Pipeline



All we need to do: tell OpenGL what our input points and transformation matrices are, and what color to fill triangles with!

Code!

https://github.com/Flafla2/GLTutorial

(See /checkpoints folder to review later)

Common Realtime Graphics APIs

- **OpenGL**: Runs on all platforms, but old, slow, and falling out of fashion. Mac support ending soon.
  - OpenGL ES: Subset of OpenGL for mobile GPUs
  - GL 1.1 != GL 2.1 != GL 3.3 != GL 4.6
    - **Massive** breaking API changes between GL versions — hard to find tutorials!
    - ... and that's not even counting extensions!
- **Vulkan**: Modern Graphics API, runs on every platform (macOS needs a Metal wrapper)
- **DirectX**: Windows / Xbox only, very popular in Game development due to engine support and tooling
  - DirectX 9: Used on Xbox 360 / WinXP, similar to GL 2.x
  - DirectX 10: Used on Xbox 360 / Vista, similar to GL 3.x
  - DirectX 11: Used on Xbox 360 / Xbox One / Win7, similar to GL 4.x
  - DirectX 12: Used on Xbox One, similar to Vulkan
- **Metal**: Apple's low level graphics API for iOS / Mac

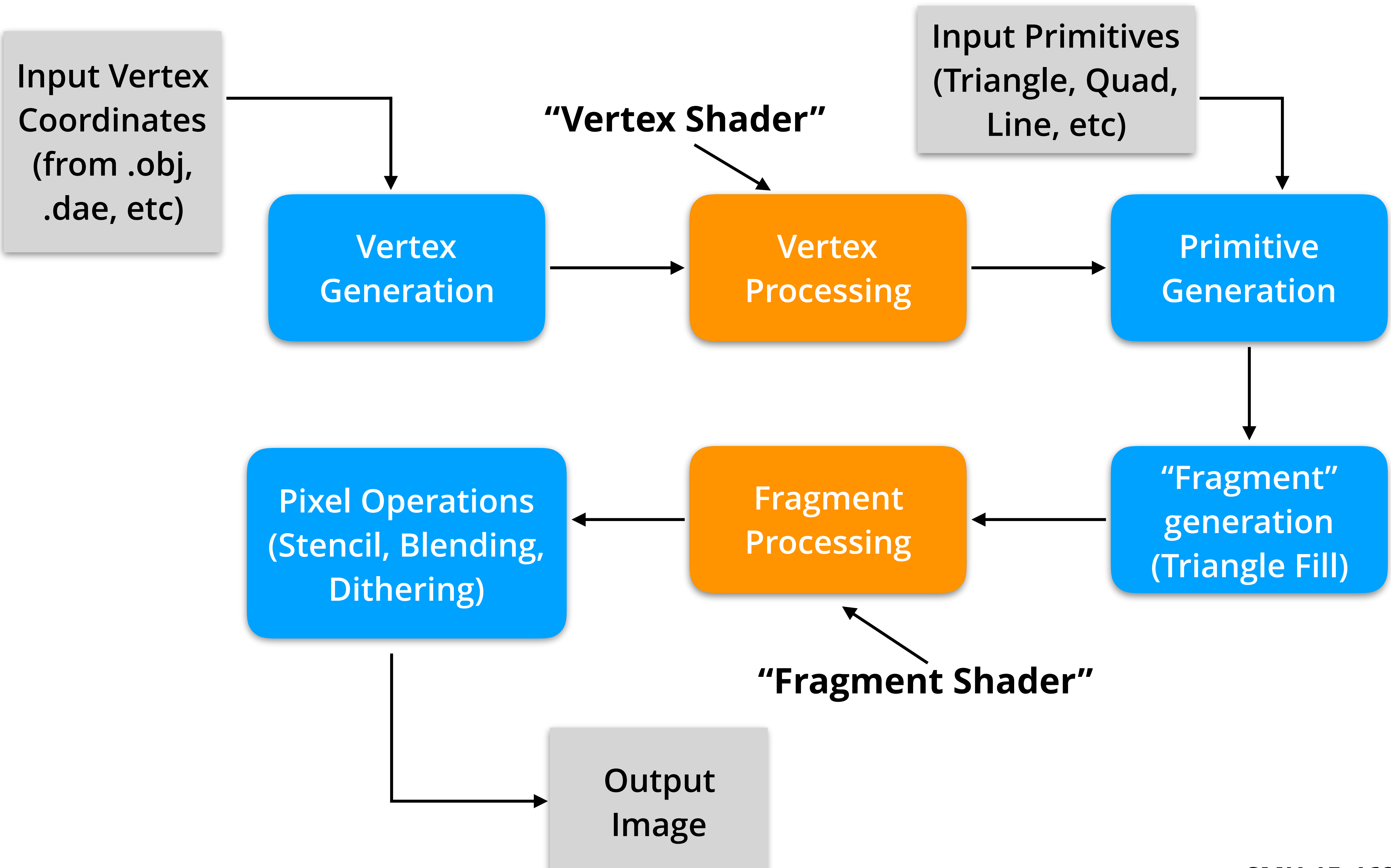
Choosing a Graphics API

- The graphics API you should use depends on:
  - Platform(s) you are publishing on (including OS!)
  - **Example**: On Windows DirectX performs better than OpenGL due to driver support
- Specific API Features
  - **Example**: Vulkan offers lower level control of GPU memory than OpenGL, but may be harder to use
  - Whatever new hotness comes out tends to take a while to arrive to all graphics APIs (*cough raytracing*)
- Your own preference / familiarity
  - Much more important when considering shader languages

DrawSVG

- 5% of the assignment: regurgitate today's demo in `hardware_renderer.cpp`
  - Everything we talked about today, up to blending
- 95% of the assignment: reimplement OpenGL calls on the CPU (using good old C++)!

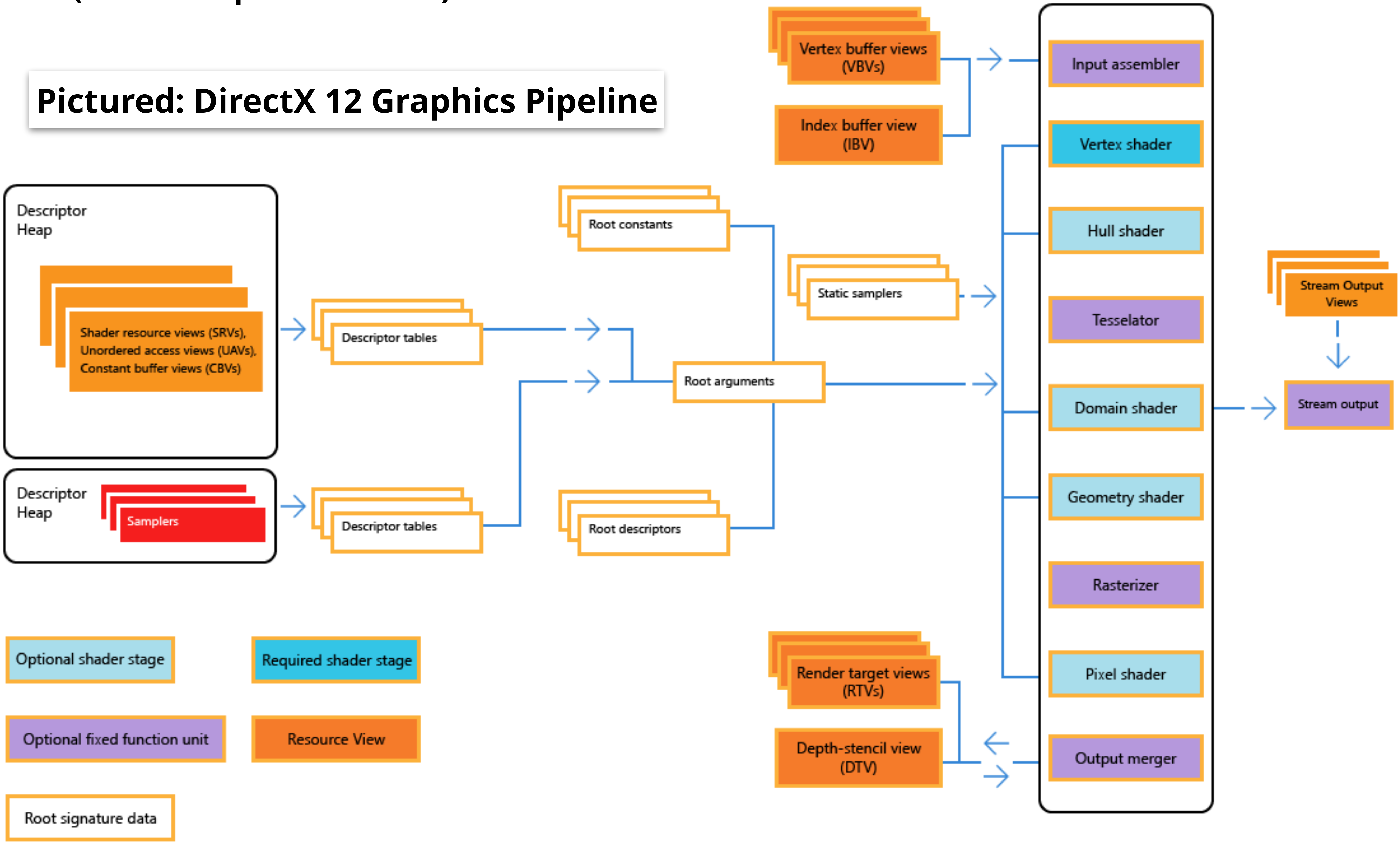
Not discussed:
Shaders are highly parallel GPU programs



Modern Graphics APIs are More Complex

(but more powerful too!)

Pictured: DirectX 12 Graphics Pipeline

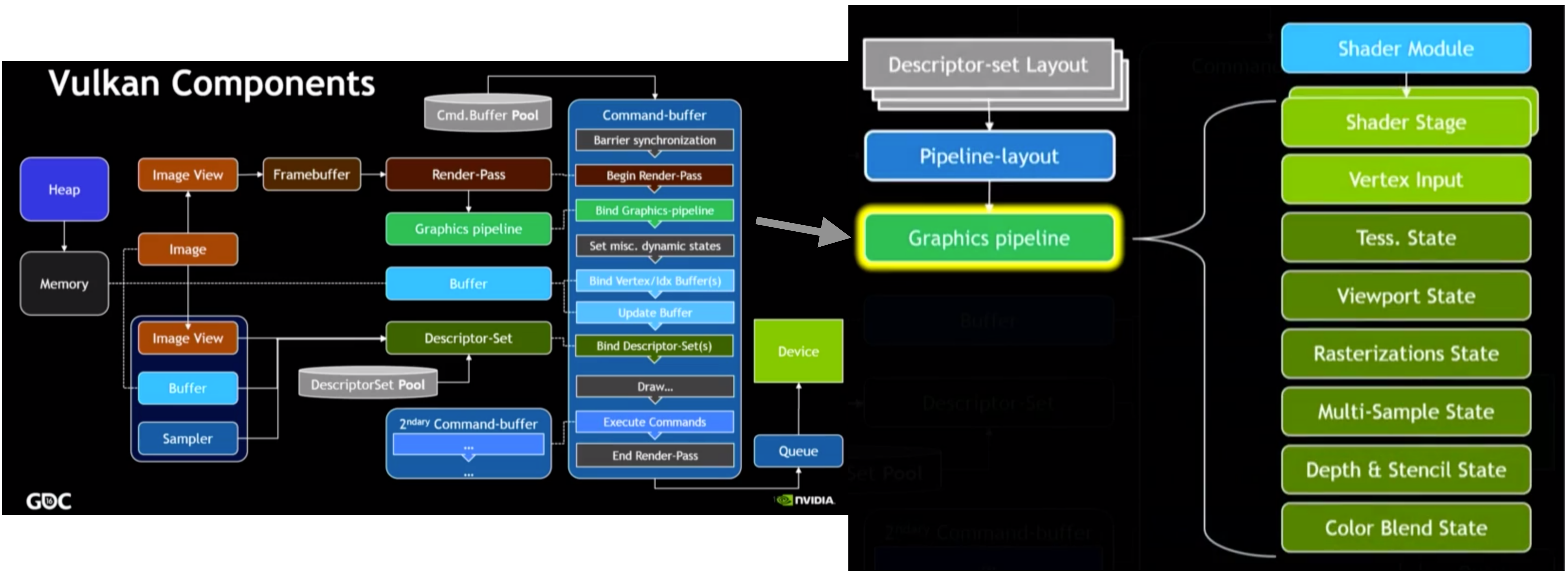


https://docs.microsoft.com/en-us/windows/win32/direct3d12/pipelines-and-shaders-with-directx-12

Modern Graphics APIs are More Complex

(but more powerful too!)

Pictured: Vulkan Graphics Pipeline



https://www.gdcvault.com/play/1023525/Vulkan-and-NVIDIA-The-Essentials

Wrap-up

- OpenGL and similar APIs are the bread and butter of practical computer graphics, so start learning them!
  - Recommend: 15-466 Computer Game Programming which uses OpenGL 3.3
  - Great tutorial for modern OpenGL: http://learnopengl.com
- Check out: Shaders are highly parallel code compiled for the GPU. Modern graphics libraries use shaders to implement many common GL 2.1 “fixed function” effects.
  - http://shadertoy.com (simple example here)
  - There is a shading language for all modern graphics apis