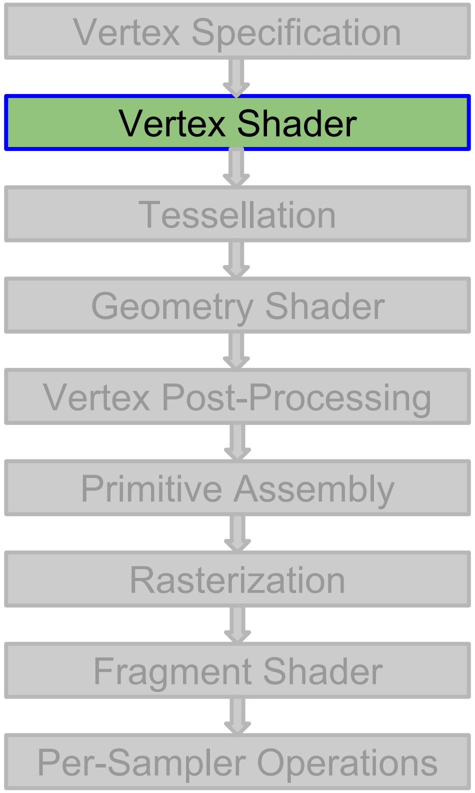
Game Architecture
Graphics II

Attack of the Matrices

Recap

- We’ve described our world using **triangles**.
- Triangles are made up of **vertices**.
- We’ve specified vertex data in **buffers** of a particular **vertex format**.
- We’ve issued a **draw call** to draw the geometry.
- Now what?

Programmable Pipeline



Scene Representation

- How do we describe objects in the scene?
- How do we describe scene topology?
- How do we describe where things are?
- How do we describe how we see things?

Scene Representation

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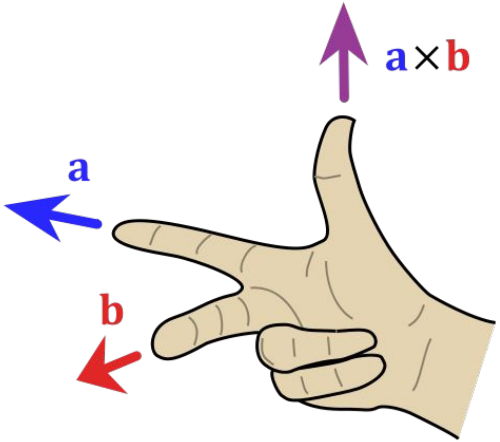
- How do we describe scene topology?
- **How do we describe where things are?**
- How do we describe how we see things?

Coordinate Systems

- Handedness
- World space
- Model space
- View space

Coordinate Systems

- **Handedness**
- World space
- Model space
- View space



Handedness determines the direction of the cross product result.

Assuming positive x to the right, and positive y up…

- In a right-handed system, the z-axis comes out of the screen.
- In a left-handed system, the z-axis goes into the screen.

Image courtesy of Wikipedia

Coordinate Systems

- Handedness
- **World space**
- Model space
- View space

World space is the highest order coordinate system which describes absolute positions for all objects in the game.

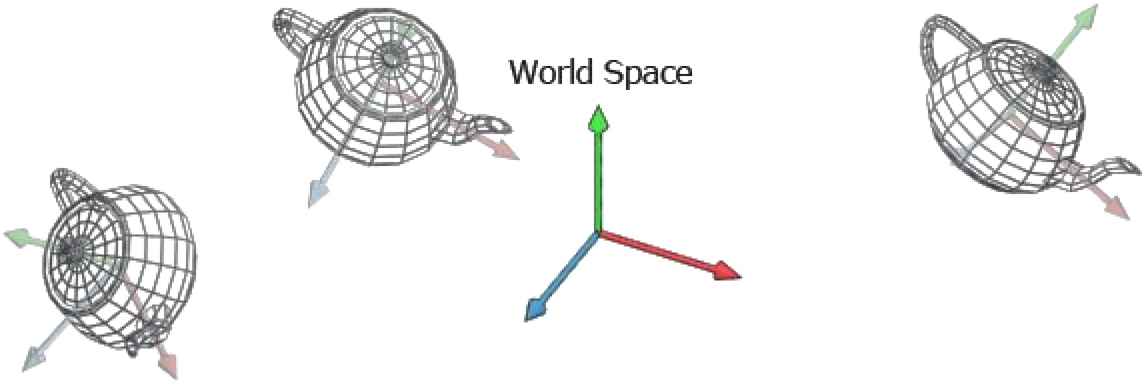


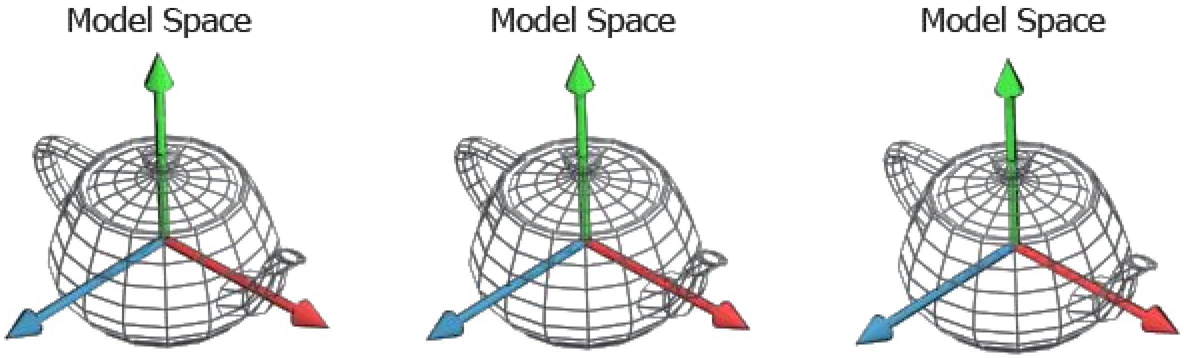
Image courtesy of Marco Alamia via Coding Labs

Coordinate Systems

- Handedness
- World space
- **Model space**
- View space

Model space is the coordinate system local to a single object in the game world.

The origin is the origin point of the model, and is typically user defined. It could be the exact center, a corner, the bottom center; anywhere.



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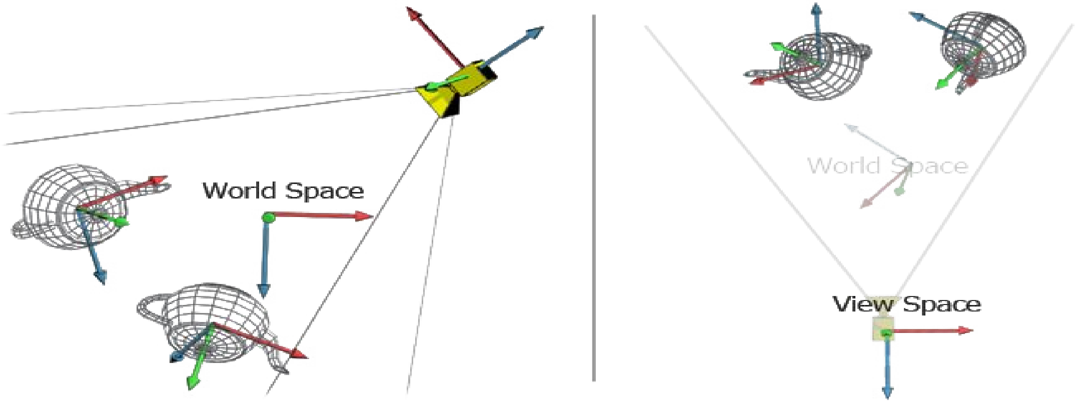
Coordinate Systems

- Handedness
- World space
- Model space
- **View space**

View space describes the coordinate system of the camera, with the origin being the position of the camera.

Transforming into view space is an essential part of the graphics pipeline.



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Scene Representation

- How do we describe objects in the scene?
- How do we describe scene topology?
- How do we describe where things are?
- **How do we describe how we see things?**

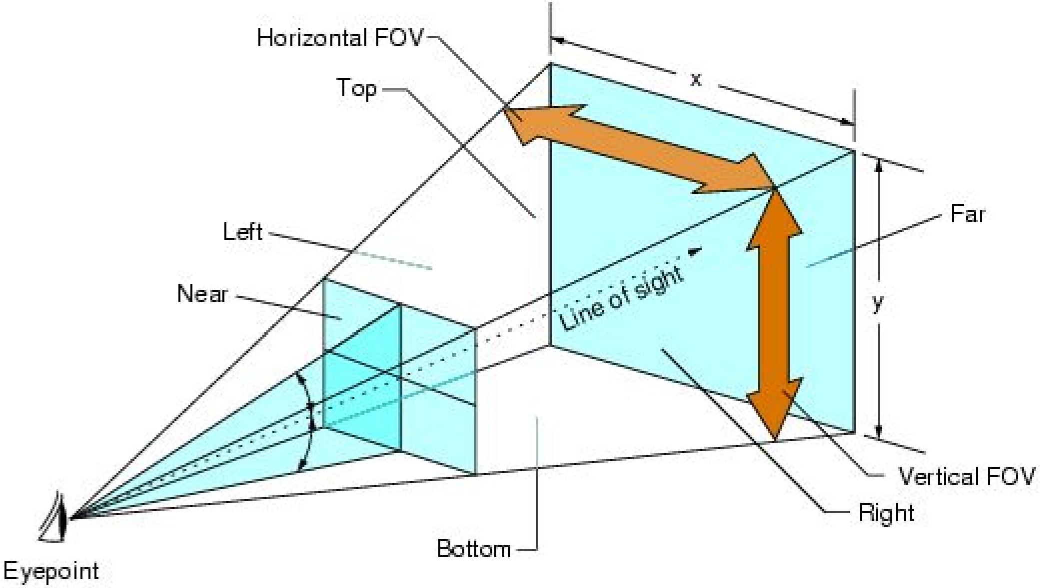
Virtual Camera

- A virtual camera can be created with three components:
    - A position.
    - A forward, or ‘look-at’ vector.
    - An up vector.
- It also needs a frustum.
    - A frustum defines the bounds that the camera can see.
    - To define the frustum, we also need...

Virtual Screen

- The screen is defined by dimensions, and therefore aspect ratio.
  - 1280x720 - 16:9
  - 1920x1080 - 16:9
  - 1920x1200 - 16:10
  - 1024x768 - 4:3
- The screen dimensions define the near plane of the frustum.
  - The near plane is defined to be a certain distance from the camera position.
  - The far plane as well.
  - The field-of-view angles defines the rest of the frustum planes.
  - Note that vertical or horizontal field-of-view can be calculated using one another and the aspect ratio.

Example Frustum



$$\text{Aspect Ratio} = \frac{y}{x} = \frac{\tan(\text{vertical FOV}/2)}{\tan(\text{horizontal FOV}/2)}$$

Image courtesy of Northeastern University

Transformations

- Our goal is to get something from the world to the screen. How?
- We need a series of transformations (matrices)
  - Model - Transform from model into world space.
  - View - Transform from world space into view space.
  - Projection - Transform from view space into clip space.
  - *Viewport - Transform from NDC to screen space.*
    - This is done in the hardware.

Calculating the View Matrix

- The view matrix transforms the world into camera space.
- This essentially means applying the inverse of the camera's transform.
  - Translation
  - Orientation
- Translation is easy:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -x & -y & -z & 1 \end{bmatrix}$$

Calculating the View Matrix

- Orientation is a little trickier.
- Recall that rows (or columns) of a transformation matrix are orthogonal vectors representing an orientation.
- Find them for the camera!
  - Given **direction (z)** (eye - at) and **up** vector…
  - Cross **direction** and **up** to get **right (x)**.
  - Cross **right (x)** and **direction (z)** to get an accurate **up (y)**.
  - Then stick ‘em in a matrix:

$$\begin{bmatrix} x_x & x_y & x_z & 0 \\ y_x & y_y & y_z & 0 \\ z_x & z_y & z_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Calculating the View Matrix

- But wait!
  - That describes a transformation from the camera space to world space.
  - We want world space to camera space.
- Solution: invert the matrix.
  - It’s orthogonal, so the inverse is just the transpose.
- Finally, combine with translation.
  - The translation is pre-multiplied with the orientation.

Calculating the View Matrix

- So, given:
  - Camera position (eye)
  - Right vector (x)
  - Up vector (y)
  - Forward vector (z)

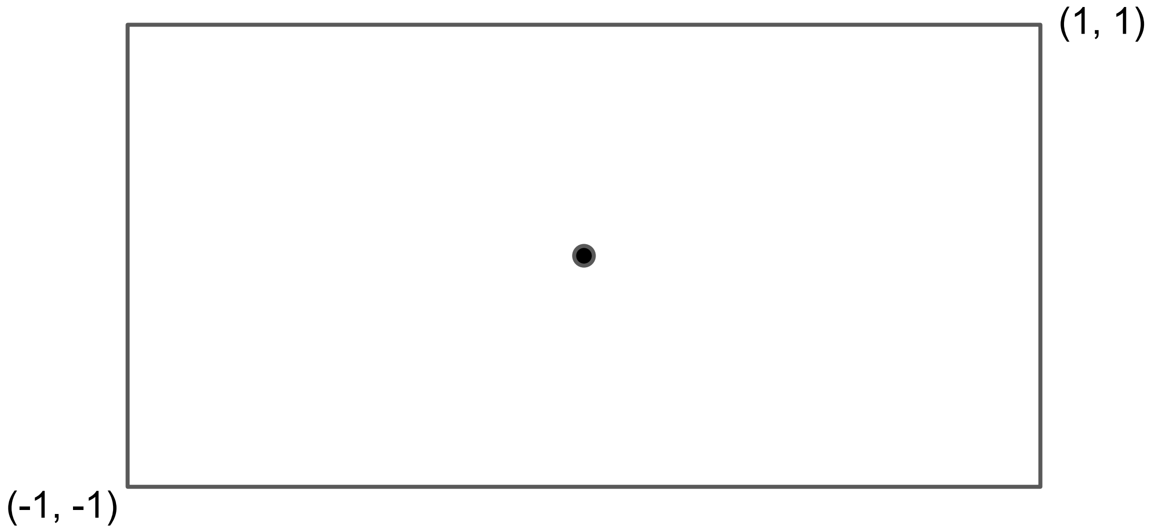
$$\begin{bmatrix} x_x & y_x & z_x & 0 \\ x_y & y_y & z_y & 0 \\ x_z & y_z & z_z & 0 \\ -dot(eye, x) & -dot(eye, y) & -dot(eye, z) & 1 \end{bmatrix}$$

Calculating the Projection Matrix

- The projection matrix takes a point in the frustum and prepares it for a transformation to a point on a plane.
  - Basically flattening the 3D scene onto a 2D plane.
- The destination is typically a rectangle.
  - Output screen
  - Texture
  - GUI minimap

Normalized Device Coordinates

- Abbreviated NDC
- Describe the screen as a square from (-1, -1) to (1, 1)
  - Origin at (0, 0)



Orthographic vs. Perspective

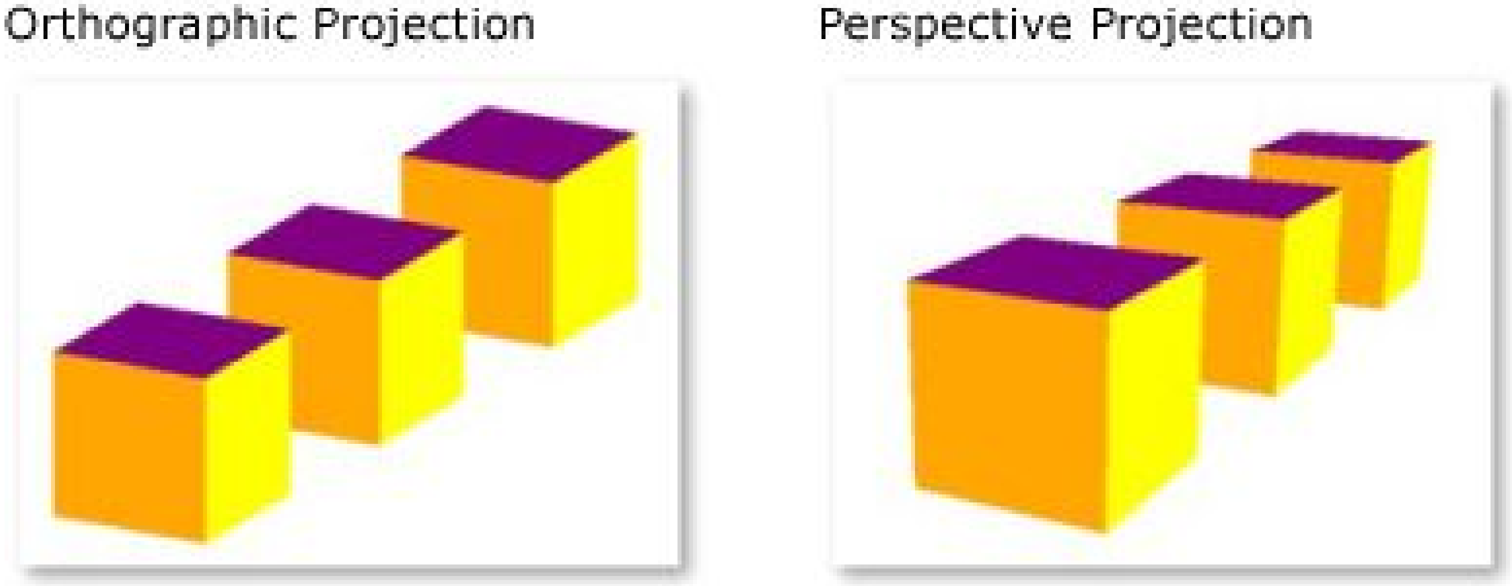
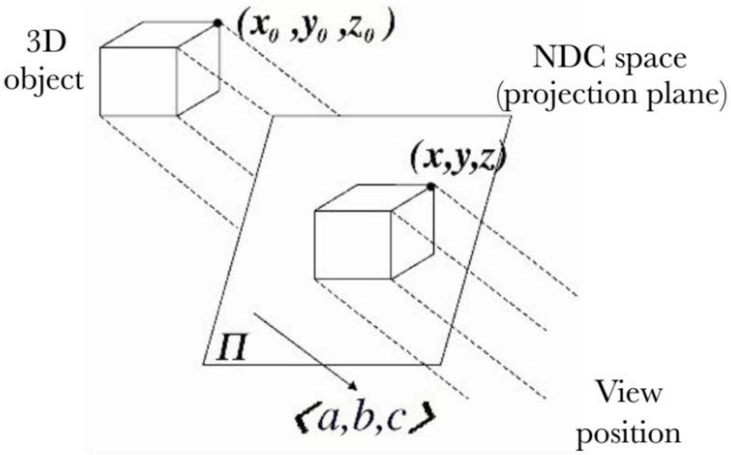
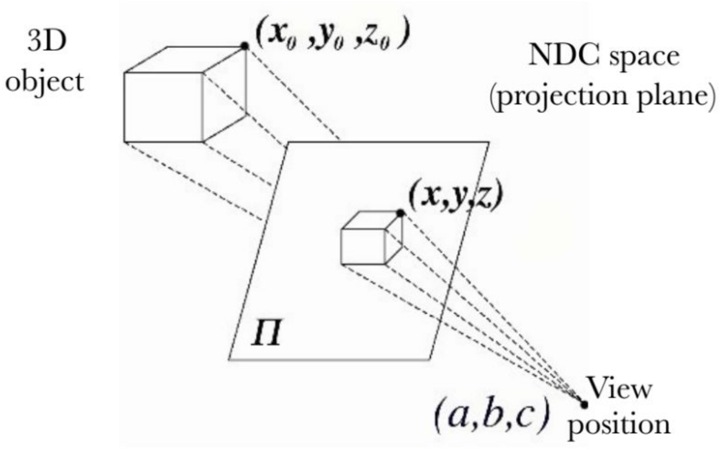


Image courtesy of MSDN

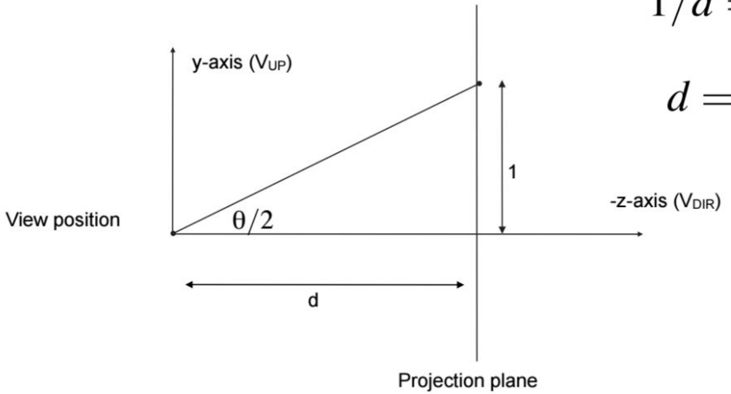
Orthographic vs. Perspective





Field of View

- Related to the location of the projection plane

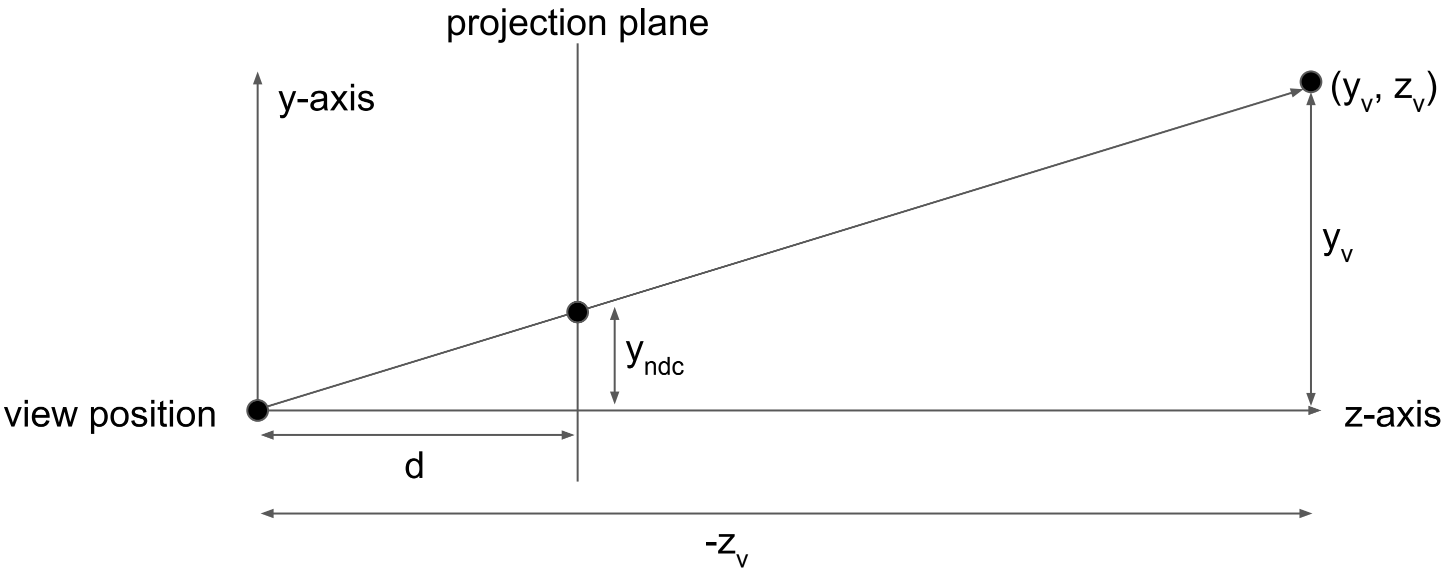


$$1/d = \tan(\theta_{fov}/2)$$

$$d = \frac{1}{\tan(\theta_{fov}/2)}$$

- We'll need this distance next.

Perspective Projection



$$\frac{y_{ndc}}{d} = \frac{y_v}{-z_v} \quad \text{or} \quad y_{ndc} = \frac{dy_v}{-z_v}$$

Perspective Projection

- The target probably isn't a square.
- We need to adjust by the aspect ratio:

$$a = \frac{w_s}{h_s}$$

- If we assume that *y* height is 1, we only need to adjust *x*:

$$x_{ndc} = \frac{dx_v}{-az_v}$$

Perspective Projection

- The further away an object is, the smaller it should appear.
  - Solution is to divide *x* and *y* by the *z* coordinate.
  - Hardware is going to perform division by the *w* component.
  - So we need to move the *z* coordinate into the *w* position.
- Which gives us the homogenous perspective matrix:

$$\begin{bmatrix} \frac{d}{a} & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & -d & -1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Perspective Projection in Action

$$\begin{bmatrix} \frac{d}{a} & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & -d & -1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} x_v & y_v & z_v & w_v \end{bmatrix} \quad \begin{bmatrix} \frac{dx_v}{a} & dy_v & -dz_v & -z_v \end{bmatrix}$$

Projecting the Z Coordinate

- We want to use the z coordinate for depth and sorting.
- It needs to be mapped onto a (-1, 1) range depending on the near and far planes.

$$z_c = \frac{z_v(n+f) + 2nf}{n-f}\left(\frac{1}{-z_v}\right)$$

- For DirectX, the range is (0, 1). Ugh.

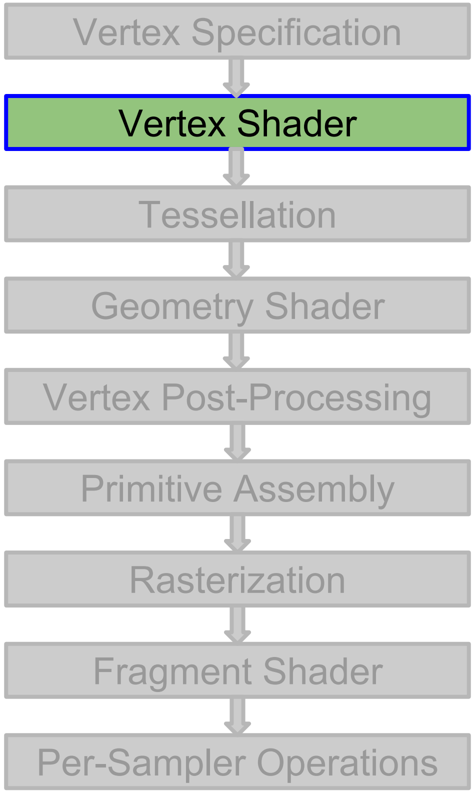
Calculating the Projection Matrix

$$\begin{bmatrix} \frac{d}{a} & 0 & 0 & 0 \\ 0 & d & 0 & 0 \\ 0 & 0 & \frac{n+f}{n-f} & -1 \\ 0 & 0 & \frac{2nf}{n-f} & 0 \end{bmatrix}$$

Order of Multiplication?

- This depends on your matrix layout and multiplication code.
- For A * B:
    - Row major layout and A rows * B columns **or**
    - Column major layout and A columns * B rows
        - Pre-multiplication = local
        - Post-multiplication = world
    - Row major layout and A columns * B rows **or**
    - Column major layout and A rows * B columns
        - Pre-multiplication = world
        - Post-multiplication = local

Programmable Pipeline



Programmable Shaders

- Miniature programs which operate on vertex and fragment data.
  - Vertex shader outputs vertex position in homogenous clip space, and per-vertex values.
    - gl_Position
  - Fragment shader outputs fragment color(s).
    - gl_FragColor
    - And possibly depth information.
- There are many built-in functions for common operations.
  - See the OpenGL or HLSL reference pages for a list.

Shading Languages

- Most shading languages are C-like.
  - GLSL - OpenGL Shading Language
  - HLSL - High Level Shading Language (DirectX)
  - Cg
- They are compiled to bytecode similar to assembly.
- GPU execution units execute the bytecode.

GLSL

- Program variable qualifiers.
  - **in** - A per-element input value, like position.
  - **out** - A per-element output, like fragment color.
  - **uniform** - A per-object constant, like model-view-projection matrix or texture.
- Basic types.
  - C++ like - void, float, int, bool
  - Vectors - vec2, vec3, vec4, ivec2, etc.
  - Matrices - mat2, mat3, mat4
  - Textures - sampler2D
  - Arrays - e.g. float[5]

Vector Types

- Shading language vector types offer different access patterns.
  - { x, y, z, w }, typically used for positions or normals.
  - { r, g, b, a }, typically used for colors.
  - { s, t, p, q }, typically used for texture coordinates.
- Swizzling
  - By definition, rearranging components of a vector.
  - Given vector = vec4(1.0, 2.0, 3.0, 4.0)
    - vector.xxxx = { 1.0, 1.0, 1.0, 1.0 }
    - vector.wzyx = { 4.0, 3.0, 2.0, 1.0 }
    - vector.yyzz = { 3.0, 3.0, 4.0, 4.0 }
    - And so on...

GLSL

- Control flow
  - Mostly the same as C/C++.
  - Notable addition is **discard**, which rejects a current fragment from drawing.
- Built-in functions
  - Trig - sin, cos, tan, asin, acos, atan
  - Math - pow, exp, log, exp2, log2, sqrt, inversesqrt
  - And many more - dot, cross, normalize, clamp, mix, step, reflect, etc.
- Texture lookup
  - texture2D(sampler2D, vec2)
  - There are others, but this is most often used.

Example

```
#version 400

layout (location = 0) in vec3 in_position;

uniform vec3 u_color;

out vec3 out_color;

void main(void)
{
    // Do something with color and position.
    out_color = vec4(1.0, 0.0, 0.0, 1.0);
    // Assign gl_Position as position in homogenous clip space.
}
```

Example: Linking Shaders

Vertex shader declarations:

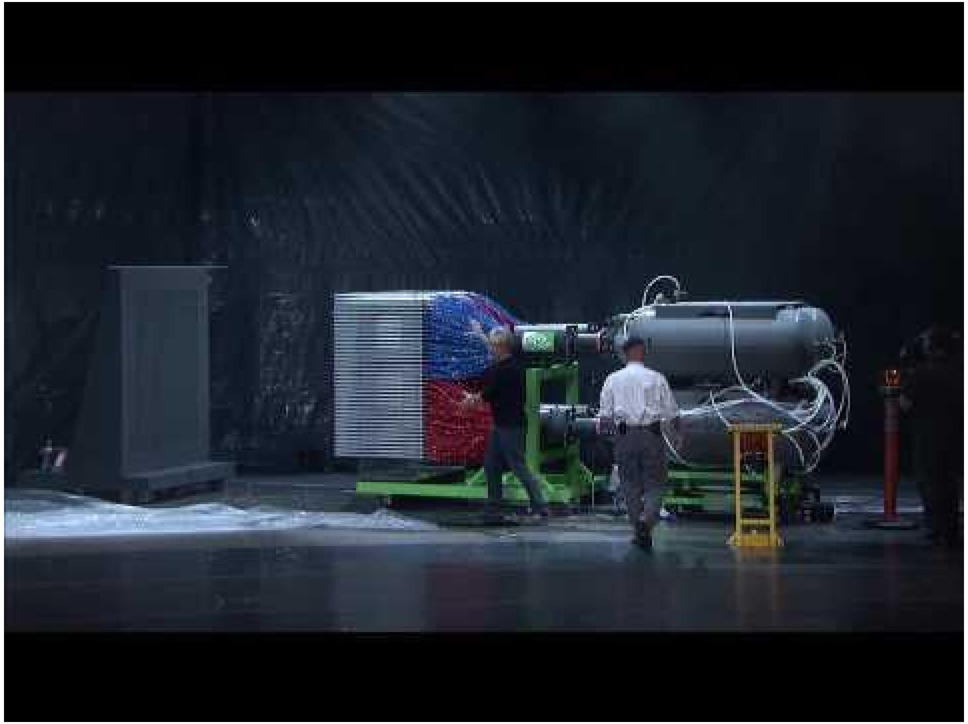
```
layout(location = 0) in vec3 in_position;
layout(location = 1) in vec3 in_color;
layout(location = 2) in vec2 in_texcoord;

out vec3 color;
out vec2 texcoord0;
```

Fragment shader declarations:

```
in vec3 color;
in vec2 texcoord0;
```

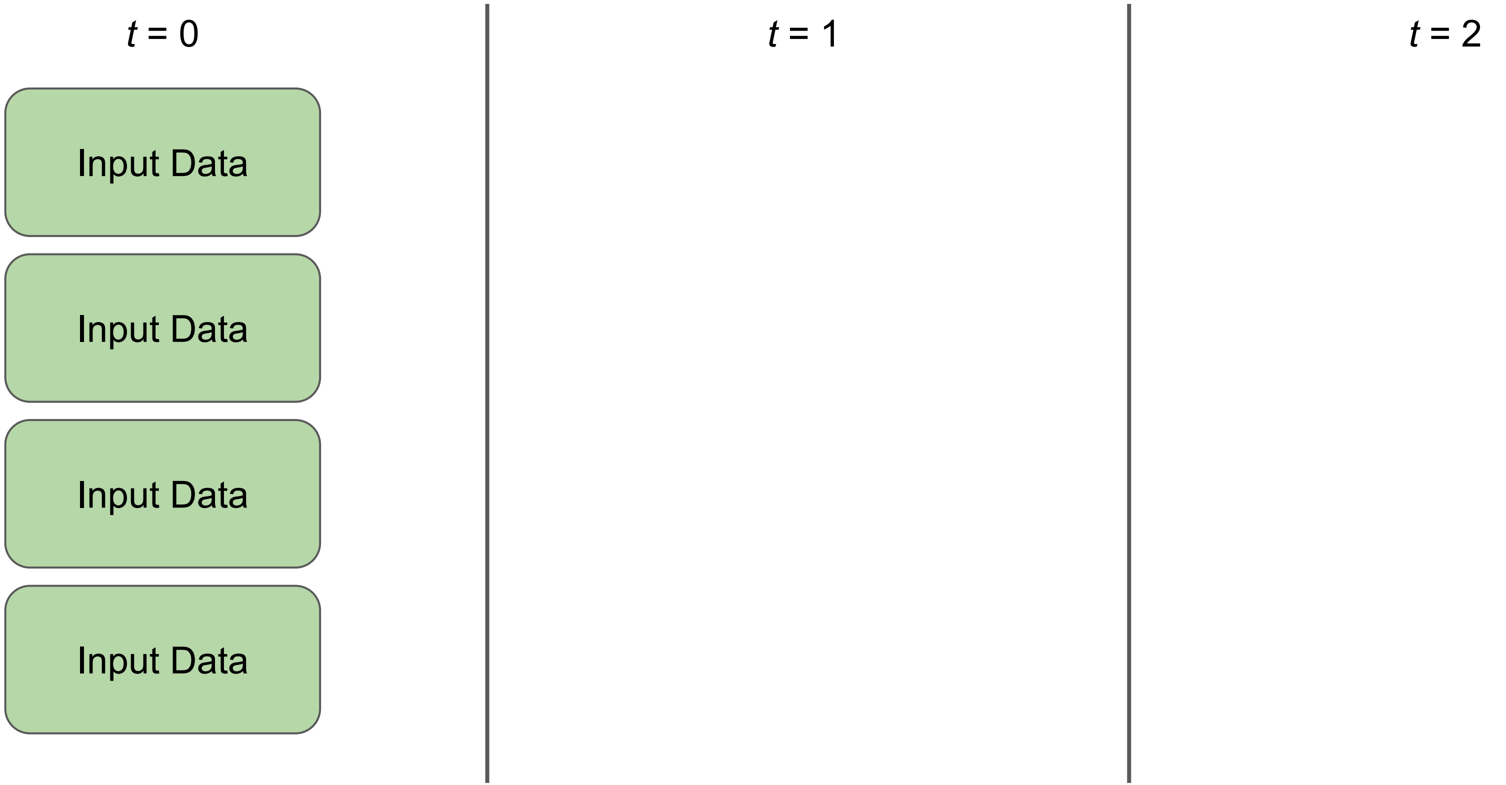
Mythbusters!



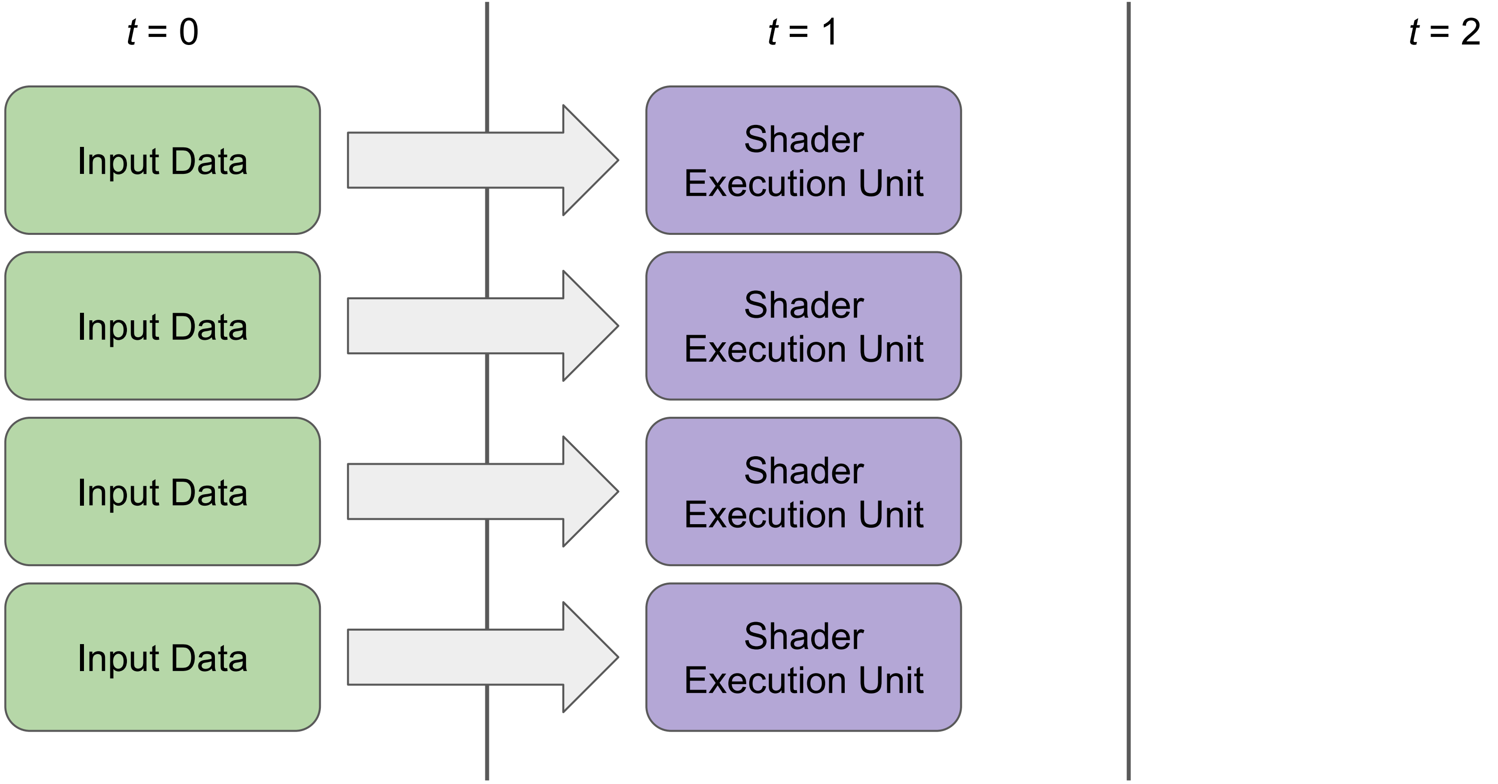
Shader Units

$t = 0$	$t = 1$	$t = 2$

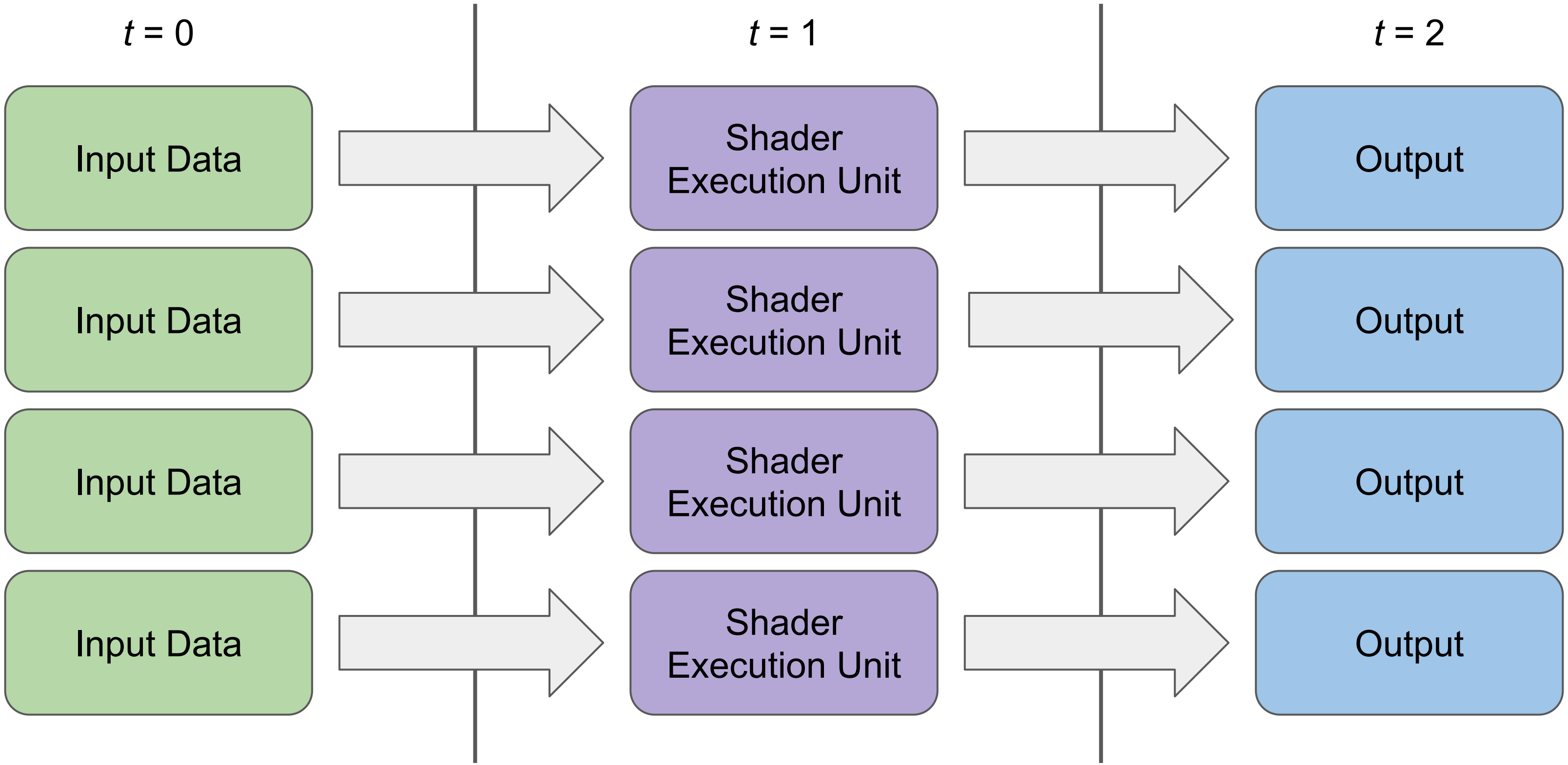
Shader Units



Shader Units



Shader Units



Vertex Shaders

- Modern vertex shaders:
  - Animate vertex positions.
  - Transform vertex positions into homogenous clip space.
  - Pass through (and possibly manipulate) per-vertex attributes.
- And that's really about it…
  - Fragment shaders get more interesting.
- They can be leveraged for optimization.
  - It's possible to use built-in hardware interpolation to your advantage.
    - Perform heavy calculations per vertex, rather than per-fragment.
  - This is really a last-resort optimization.

OpenGL Shaders

- OpenGL manages shaders with **shader objects**.
  - glCreateShader
  - glShaderSource
- Shader **programs** are pairings of vertex and fragment shaders.
  - glCreateProgram
  - glAttachShader
  - glLinkProgram
  - glUseProgram
- Fun fact: shaders are usually not compiled until you actually use them.

End of Lecture

- Homework 3 is now actually assigned.
- It’s due next Thursday, 2/16.
- On Monday, we’ll finish up our trip through the graphics pipeline.