Rasterization & The Graphics Pipeline

Fast Approximations for Real-Time Graphics

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Introduction

Why Rasterization?

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Valorant - 120 FPS Gaming

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Up - 30 hours per frame

- **Real-time constraint:** Games need 60-120 FPS

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- **Trade-off:** Sacrifice physical accuracy for speed

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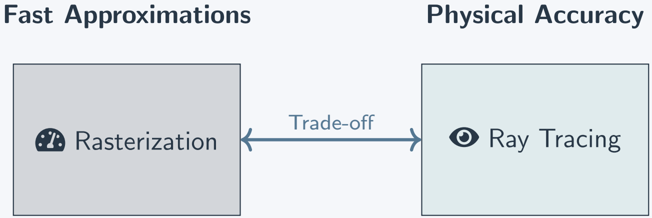
Up - 30 hours per frame

- **Real-time constraint:** Games need 60-120 FPS
- **Interactive experience:** User input must feel responsive
- **Trade-off:** Sacrifice physical accuracy for speed
- **Goal:** Images that look good enough, delivered fast enough

Rasterization vs Ray Tracing: The Fundamental Choice



Rasterization:

- 60-240 FPS
- Clever approximations
- Hardware optimized
- "Good enough" quality

Ray Tracing:

- ≈ 0 FPS
- Physical simulation
- Computationally heavy
- Photorealistic

The Real-Time Graphics Challenge

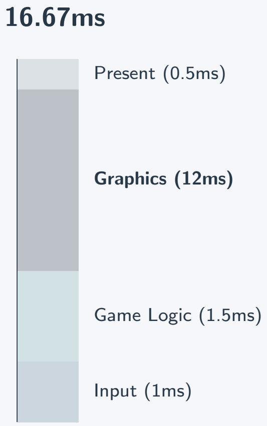
Time Budget at 60 FPS

$\frac{1}{60} = 16.67$ milliseconds per frame

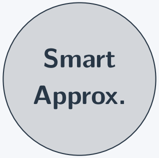
What needs to happen:

- Process input
- Update game logic
- Render graphics
- Present to screen

Graphics budget: $\sim$10-12ms



How Rasterization Achieves Speed



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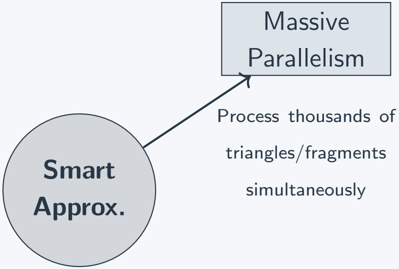

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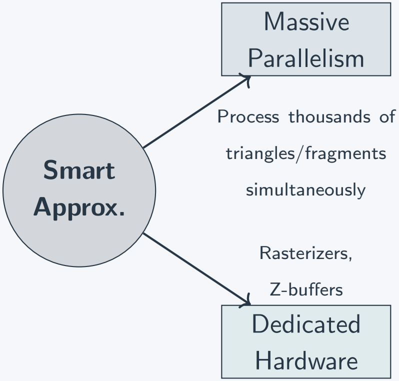

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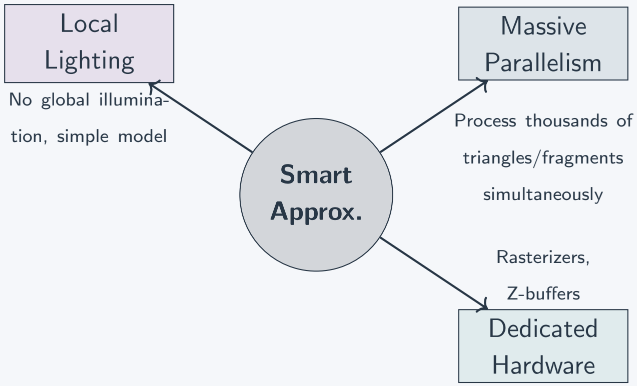
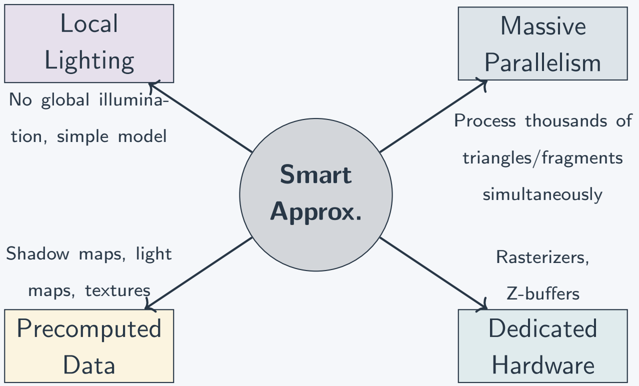

Local Lighting
No global illumination, simple model
Massive Parallelism
Process thousands of triangles/fragments simultaneously
Smart Approx.
Rasterizers, Z-buffers
Dedicated Hardware

How Rasterization Achieves Speed


Smart Approx.
Local Lighting
No global illumination, simple model
Massive Parallelism
Process thousands of triangles/fragments simultaneously
Precomputed Data
Shadow maps, light maps, textures
Dedicated Hardware
Rasterizers, Z-buffers

The Clever Approximations

What We Skip

- **Global illumination:** No light bouncing
- **Perfect shadows:** Use shadow maps
- **Perfect reflections:** Use environment maps
- **Complex materials:** Simplified BRDFs

What We Gain

- **Predictable performance:** Linear with triangle count
- **Hardware optimization:** Purpose-built silicon
- **Real-time interaction:** Immediate feedback
- **Scalable quality:** Adjust for performance

The GPU Evolution

A Brief History

1970s-1980s → 1990s → 2000s → 2010s+

1970s-1980s — Software Rendering

- Everything done on CPU
- Frame rates: 1-10 FPS
- Wireframe graphics

1990s — Fixed-Function GPUs

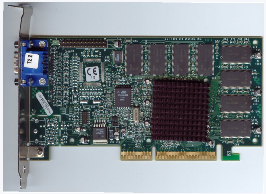
- 3dfx Voodoo, NVIDIA Riva
- Hardware rasterization
- Fixed pipeline stages

2000s — Programmable Shaders

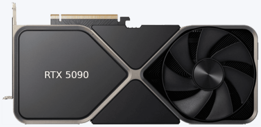
- DirectX 8.0, OpenGL
- Vertex & Fragment shaders
- Creative freedom

2010s+ — Unified Architecture

- CUDA, OpenCL
- Compute shaders
- General-purpose



3dfx Voodoo 3 - 1999



NVIDIA GeForce 5090 - 2025

Why GPUs Dominate Graphics

CPU

4-16 complex cores
Large caches
Branch prediction
Out-of-order execution

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Complex logic
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Parallel Tasks

Simple operations
Same instruction
High throughput

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Simple operations
Same instruction
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Perfect Match: Graphics + GPU

Graphics pipeline stages process thousands of vertices/fragments *independently*

$\Rightarrow$ Ideal for massively parallel GPU architecture

Modern GPU: The Graphics Powerhouse

Hardware Implementation

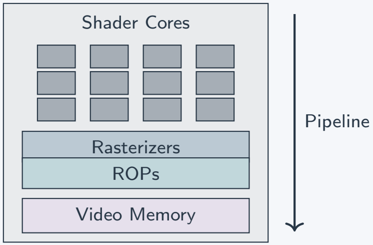
GPU handles entire pipeline:

- **Vertex processing:** Shader cores
- **Rasterization:** Fixed-function units
- **Fragment processing:** Shader cores
- **Memory operations:** ROPs

GPU Driver handles:

- Command submission
- State management
- Resource allocation

GPU Chip



The Modern Graphics Pipeline

Why a Graphics Pipeline?

The Rasterization Process

- GPU process vast numbers of **vertices** and **pixels** every frame (millions per second)

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- The operations can be divided into **stages**

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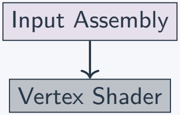
The Graphics Pipeline

The graphics pipeline is a sequence of stages that process vertices and fragments in parallel, transforming 3D models into 2D images.

Pipeline Stages at a Glance

Input Assembly: Pull vertex data (positions, normals, UVs) into the pipeline.

Pipeline Stages at a Glance



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Vertex Shader: `Programmable stage` — transform each vertex from model to clip space.

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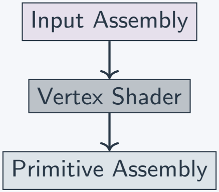

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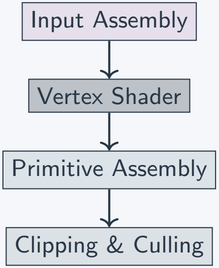

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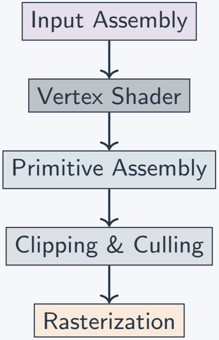

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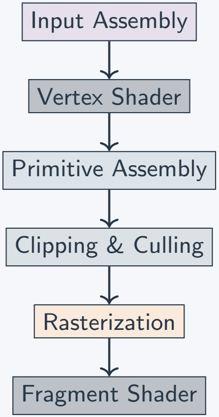

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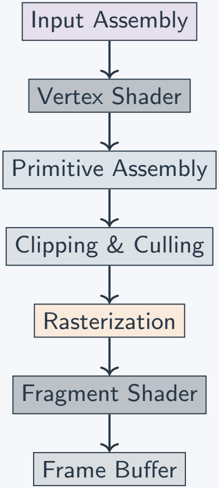

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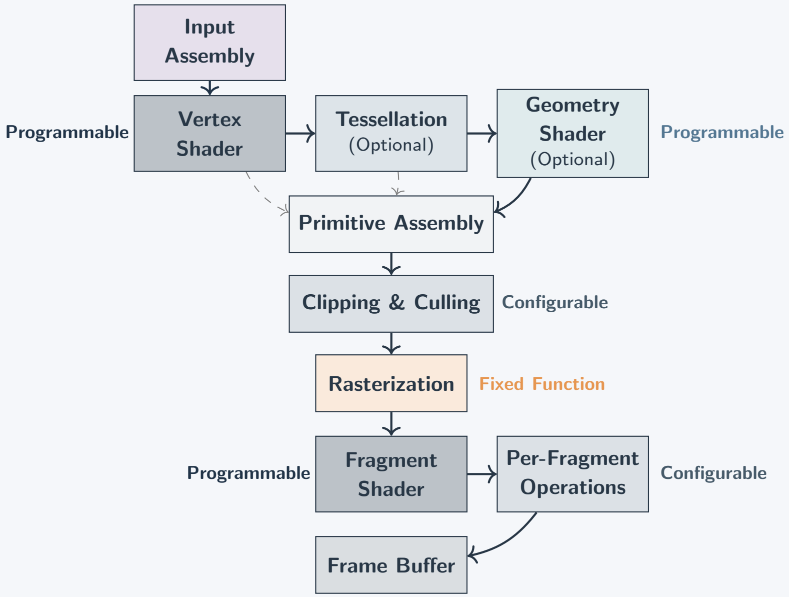
Fragment Shader: `Programmable stage` — compute final color of each fragment.

Frame Buffer: Blend, depth-test, and write pixels to the screen.

Modern Advanced Pipeline



Data Flow Through the Pipeline

Input Data

3D Vertices

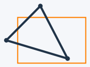
Data Flow Through the Pipeline

Input Data

3D Vertices

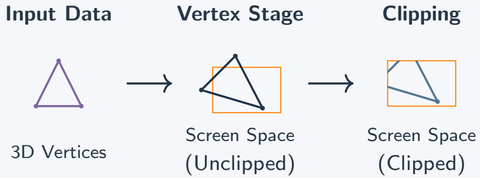
$\longrightarrow$

Vertex Stage



Screen Space (Unclipped)

Data Flow Through the Pipeline



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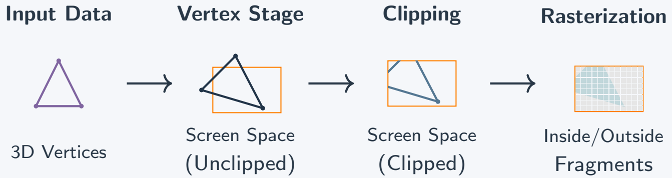

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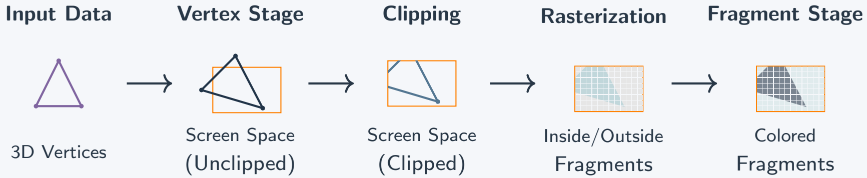

Programmable vs Fixed Function Stages

Programmable Stages

You write the code:

- **Vertex Shader:** Transform positions, compute lighting
- **Tessellation:** Subdivide surfaces adaptively
- **Geometry Shader:** Generate/modify primitives
- **Fragment Shader:** Compute final pixel colors

Maximum flexibility

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Fixed Function Stages

Hardware handles it:

- **Primitive Assembly:** Group vertices into triangles
- **Clipping:** Remove off-screen geometry
- **Rasterization:** Convert triangles to pixels
- **Depth Testing:** Z-buffer comparisons

Maximum performance

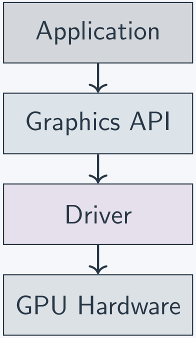
APIs & Shading Languages

Graphics APIs Overview

What is a Graphics API?

An **Application Programming Interface** that provides:

- Commands to control the GPU
- Abstraction over hardware differences
- Standard interface for graphics operations



Major Graphics APIs

OpenGL

Open Graphics Library
Perhaps the most widely used and most beginner-friendly graphics API. OpenGL was designed to be a cross-platform standard for rendering 2D and 3D graphics.

- Stable APIs
- High-level abstraction
- 🐧, 🤖, ⊞ Support
- Two modes -
  - **Immediate Mode** - Deprecated, fixed function (Used by iGraphics)
  - **Retained Mode** - Modern OpenGL, uses shaders

Major Graphics APIs

Vulkan

Low-overhead, Cross-platform Graphics API
Developed by the Khronos Group as a modern successor to OpenGL. Designed for high-performance, multi-threaded rendering.

- Low-level control over GPU
- Better CPU-GPU parallelism
- Explicit memory and resource management
- 🐧, 🤖, 🪟 Support
- Support via MoltenVK

Major Graphics APIs

DirectX (Direct3D)

Microsoft's Graphics API for Windows and Xbox

A powerful API suite used primarily for game development on Windows platforms.

- Direct3D for 3D rendering
- Deep integration with Windows OS and drivers
- High performance with hardware vendor optimizations
- ⊞, Ⓧ Support only

Major Graphics APIs

Metal

Apple's Low-level Graphics API
Designed to maximize performance on Apple devices, replacing OpenGL on Apple platforms.

- Low-overhead, low-level access
- Unified graphics and compute
- Tight integration with Apple hardware
- Support only (macOS, iOS, iPadOS)

Shading Languages

Purpose

Shading languages allow programmers to write code that runs on the GPU for:

- **Vertex processing** (transformations)
- **Fragment processing** (lighting, texturing, effects)
- **Compute operations** (general-purpose GPU computing)

Major Shading Languages:

- **GLSL** (OpenGL)
- **HLSL** (DirectX)
- **MSL** (Metal)
- **SPIR-V** (Vulkan)
  Can be compiled from GLSL or HLSL

GLSL: OpenGL Shading Language

GLSL Characteristics

- C-like syntax
- Built-in vector/matrix types
- Version-specific features

Data Types

- `float, int, bool`
- `vec2, vec3, vec4`
- `mat2, mat3, mat4`
- `sampler2D, samplerCube`

```glsl
#version 330 core
// Vertex shader inputs
layout (location = 0) in vec3 aPos;
layout (location = 1) in vec3 aNormal;
layout (location = 2) in vec2 aTexCoord;
// Outputs to fragment shader
out vec3 FragPos;
out vec3 Normal;
out vec2 TexCoord;
// Uniform variables
uniform mat4 model;
uniform mat4 view;
uniform mat4 projection;

void main() {
    FragPos = vec3(model * vec4(aPos, 1.0));
    Normal = mat3(transpose(inverse(model)))
             * aNormal;
    TexCoord = aTexCoord;

    gl_Position = projection
                * view
                * vec4(FragPos, 1.0);
}
```

GLSL Qualifiers

Storage Qualifiers

- in - Input from previous stage
- out - Output to next stage
- uniform - Buffer from CPU

Layout Qualifiers

Used to explicitly assign indices or binding points to resources.

- location - Attribute/output index
- binding - Texture/uniform buffer slot

```
#version 330 core
// Fragment shader
in vec3 FragPos;
in vec3 Normal;
in vec2 TexCoord;
out vec4 FragColor;
uniform vec3 lightPos;
uniform vec3 viewPos;
uniform sampler2D texture_diffuse1;
void main() {
    vec3 color = texture(texture_diffuse1,
                          TexCoord).rgb;
    // Ambient
    vec3 ambient = 0.1 * color;
    // Diffuse
    vec3 norm = normalize(Normal);
    vec3 lightDir = normalize(
                      lightPos - FragPos);
    float diff = max(dot(norm, lightDir),
                      0.0);
    vec3 diffuse = diff * color;
    // Result
    vec3 result = ambient + diffuse;
    FragColor = vec4(result, 1.0);
}
```

Input Assembly

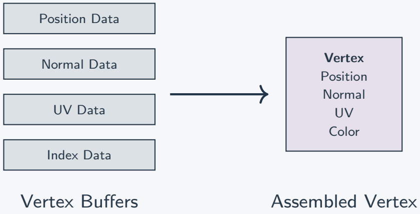
Input Assembly Stage

Input Assembly

Input: Vertex data from application
Output: Organized vertex streams for vertex shader

Purpose:

- Pull vertex data from memory
- Organize data into vertex attributes
- Handle indexed vs non-indexed drawing
- Set up primitive topology



Vertex Attributes

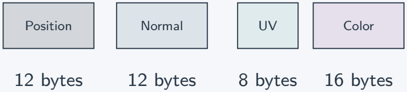
Common Vertex Attributes

- **Position:** 3D coordinates (vec3)
- **Normal:** Surface normal vector (vec3)
- **Texture Coordinates:** UV mapping (vec2)
- **Color:** Vertex color (vec3/vec4)

Vertex Layout Example

$$\text{Vertex} = \begin{cases} \text{Position:} & (x, y, z) \\ \text{Normal:} & (n_x, n_y, n_z) \\ \text{UV:} & (u, v) \\ \text{Color:} & (r, g, b, a) \end{cases} \tag{1}$$

Total size: $3 + 3 + 2 + 4 =$ 12 floats $=$ 48 bytes



Primitive Topology

Primitive Types

Points: Individual vertices

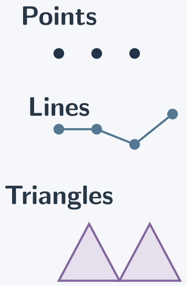
- Used for particle systems
- Point sprites

Lines: Connected line segments

- Wireframe rendering
- Debug visualization

Triangles: Most common primitive

- Standard for 3D surfaces
- Hardware optimized



Indexed vs Non-Indexed Drawing

Non-Indexed Drawing

Direct vertex specification
Each vertex is specified multiple times for shared vertices.

Problem:

- Vertex duplication
- Increased memory usage
- Inefficient for complex meshes

Indexed Drawing

Vertices referenced by indices
Each vertex is stored once, and indices specify how to connect them.

Benefits:

- No vertex duplication
- Lower memory usage
- Vertex cache friendly

Non-Indexed

Vertices: A, B, C, B, C, D

$$\xrightarrow{\text{33\% less data}}$$

Indexed

Vertices: A, B, C, D

Indices: 0, 1, 2, 1, 2, 3

Vertex Shader

Vertex Shader Stage

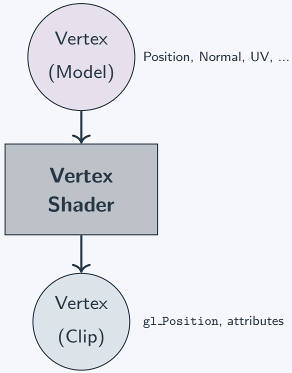
Vertex Shader

Input: Individual vertices with attributes
Output: Transformed vertices in clip space

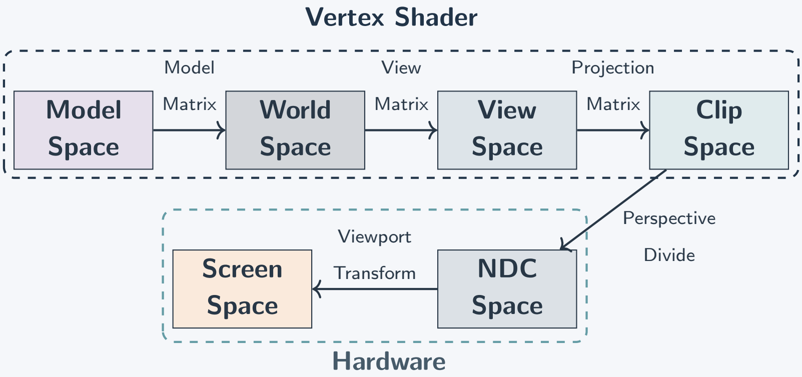
Purpose:

- Transform vertex positions through coordinate spaces
- Pass attributes to next stage
- Optional - Apply animations and deformations
- Optional - Calculate per-vertex lighting (Gouraud shading)

Programmable stage - you write the code!



The Transformation Pipeline



Transformation Matrices

Model Matrix

Purpose: Object-to-world transformation

$$\mathbf{M} = \mathbf{T} \cdot \mathbf{R} \cdot \mathbf{S}$$

- **T**: Translation
- **R**: Rotation
- **S**: Scale

Transforms from model's local coordinates to world coordinates.

View Matrix

Purpose: World-to-camera transformation

$$\mathbf{V} = \text{lookAt}(\mathbf{eye}, \mathbf{target}, \mathbf{up})$$

Transforms from world coordinates to camera/eye coordinates.

Camera is at origin, looking down -Z axis.

Transformation Matrices

Projection Matrix

Purpose: Camera-to-clip space transformation

Perspective:

$$\mathbf{P}_{\text{persp}} = \begin{pmatrix} \frac{1}{\tan(\mathsf{fov}/2)\cdot\mathsf{aspect}} & 0 & 0 & 0 \\ 0 & \frac{1}{\tan(\mathsf{fov}/2)} & 0 & 0 \\ 0 & 0 & \frac{f+n}{n-f} & \frac{2fn}{n-f} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

Orthographic:

$$\mathbf{P}_{\text{ortho}} = \begin{pmatrix} \frac{2}{r-l} & 0 & 0 & -\frac{r+l}{r-l} \\ 0 & \frac{2}{t-b} & 0 & -\frac{t+b}{t-b} \\ 0 & 0 & \frac{-2}{f-n} & -\frac{f+n}{f-n} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Clipping and Perspective Division

Clipping Phase

Purpose: Remove primitives outside the viewing frustum

- Operates in **clip space** (homogeneous coordinates)
- Keeps only geometry inside the cube: $-w \leq x, y, z \leq w$
- Output goes through **perspective division**:

$$\text{NDC} = \left(\frac{x}{w}, \frac{y}{w}, \frac{z}{w}\right)$$

Normalized Device Coordinates (NDC)

Canonical cube from $(-1, -1, -1)$ to $(1, 1, 1)$

- Independent of screen resolution
- Defines final visible region before pixel conversion
- x: left/right, y: bottom/top, z: near/far

Viewport Transformation and Screen Space

Viewport Transformation

Maps NDC coordinates to screen pixels:

$$\text{screen}_x = \left(\frac{\text{ndc}_x + 1}{2}\right) \cdot \text{width} + x_{\text{offset}}$$
$$\text{screen}_y = \left(\frac{\text{ndc}_y + 1}{2}\right) \cdot \text{height} + y_{\text{offset}}$$

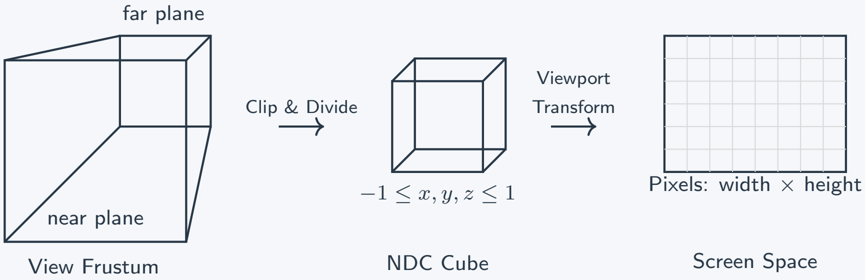
- Converts from $[-1, 1]$ range to pixel coordinates
- Accounts for viewport size and position

Screen Space

Final 2D position used for rasterization

- Measured in pixels
- Used by rasterizer to generate fragments

Frustum $\rightarrow$ NDC $\rightarrow$ Screen Space



Vertex Shader Example

```
#version 330 core
// Vertex shader inputs
layout (location = 0) in vec3 aPos;
layout (location = 1) in vec3 aNormal;
layout (location = 2) in vec2 aTexCoord;
// Outputs to fragment shader
out vec3 FragPos;
out vec3 Normal;
out vec2 TexCoord;
// Uniform variables
uniform mat4 model;
uniform mat4 view;
uniform mat4 projection;

void main() {
    FragPos = vec3(model * vec4(aPos, 1.0));
    Normal = mat3(transpose(inverse(model)))
              * aNormal;
    TexCoord = aTexCoord;

    gl_Position = projection
                * view
                * vec4(FragPos, 1.0);
}
```

Output Variables

`gl_Position` - Clip space position

Gouraud Shading

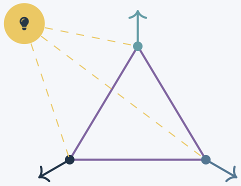
Gouraud (Per-Vertex) Shading

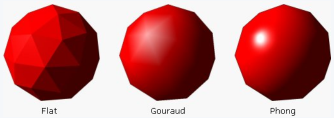
Compute lighting at vertices, interpolate across triangles

Process:

1. Calculate lighting at each vertex
2. Output vertex color
3. Hardware interpolates colors across triangle

Pros: Fast, good for distant objects
Cons: Poor specular highlights, faceted appearance





Questions & Discussion

Questions?

References & Further Reading

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