Rasterization & The Graphics Pipeline

Fast Approximations for Real-Time Graphics

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Introduction

Why Rasterization?

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- **Goal:** Images that look good enough, delivered fast enough

Rasterization vs Ray Tracing: The Fundamental Choice

Fast Approximations | **Physical Accuracy**

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

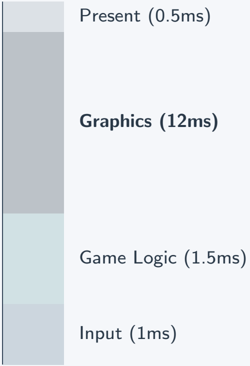
$\frac{1}{60} = 16.67$ milliseconds per frame

What needs to happen:

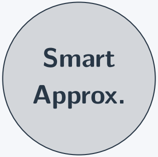
- Process input
- Update game logic
- Render graphics
- Present to screen

Graphics budget: $\sim$10-12ms

16.67ms



How Rasterization Achieves Speed



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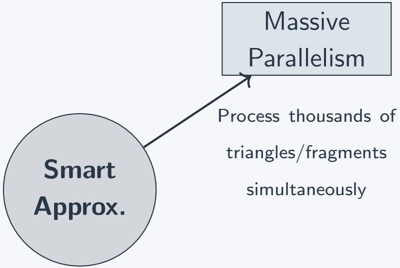

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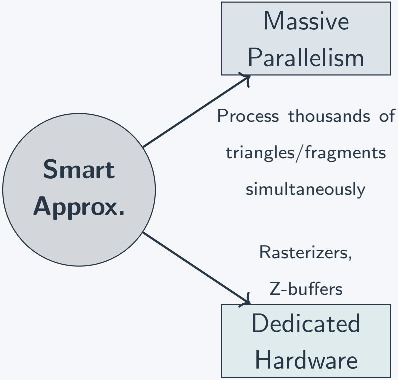

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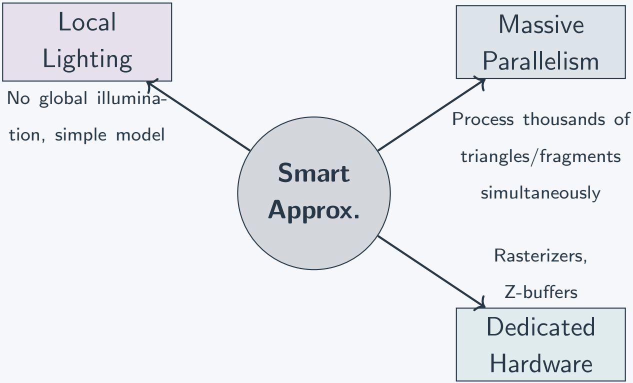

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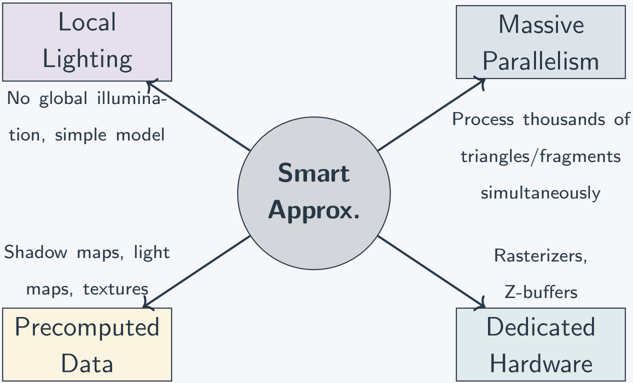


The Clever Approximations

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

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

1990s

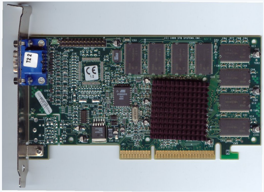
Fixed-Function GPUs
- 3dfx Voodoo, NVIDIA Riva
- Hardware rasterization
- Fixed pipeline stages

2000s

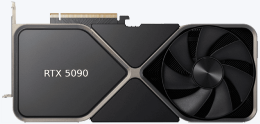
Programmable Shaders
- DirectX 8.0, OpenGL
- Vertex & Fragment shaders
- Creative freedom

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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Same instruction
High throughput

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Parallel Tasks

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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

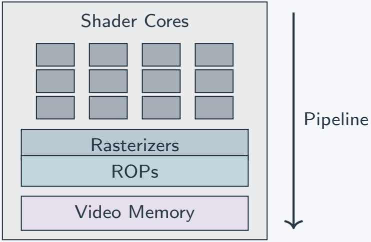
GPU handles entire pipeline:

- **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 Graphics Pipeline

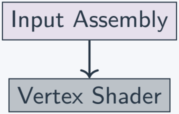
The graphics pipeline is a sequence of stages that process vertices and fragments in parallel, transforming 3D models into 2D images.

Pipeline Stages at a Glance

Input Assembly

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

Pipeline Stages at a Glance



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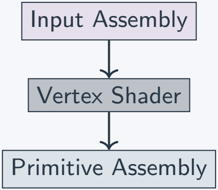

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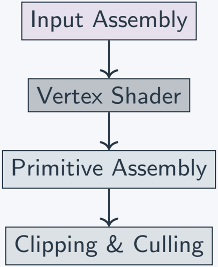

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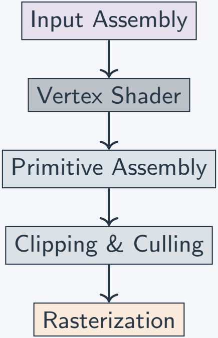

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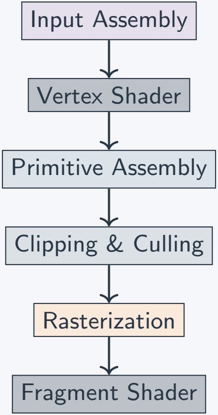

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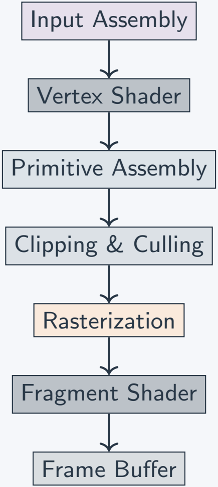

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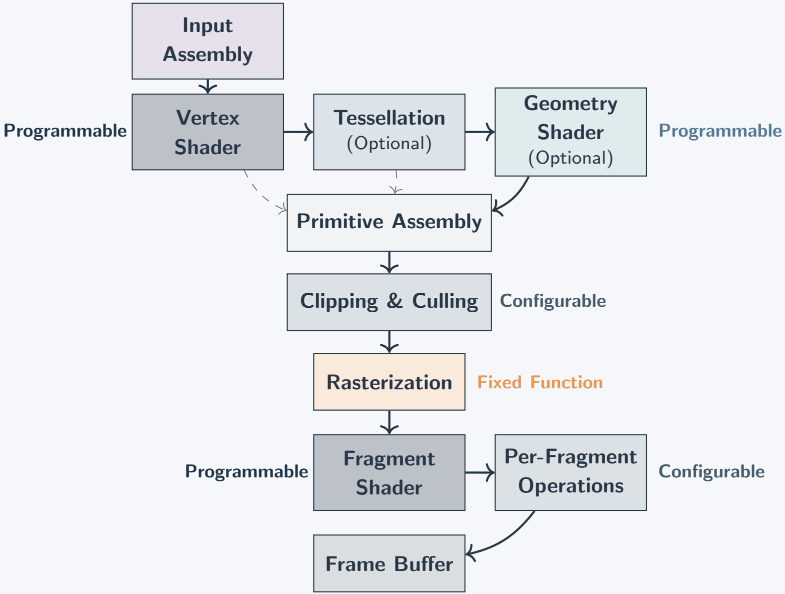
Frame Buffer: Blend, depth-test, and write pixels to the screen.

Modern Advanced Pipeline



Data Flow Through the Pipeline

Input Data

3D Vertices

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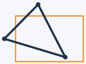
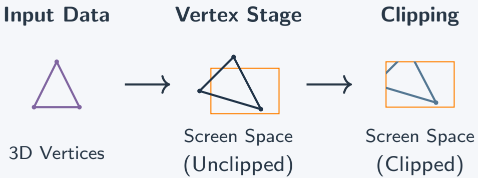
3D Vertices

Vertex Stage



Screen Space (Unclipped)

Data Flow Through the Pipeline



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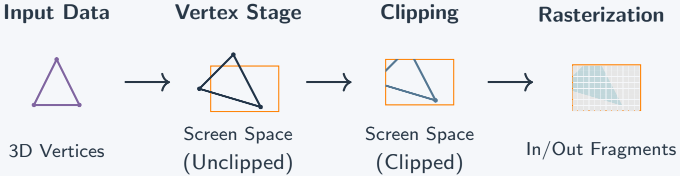

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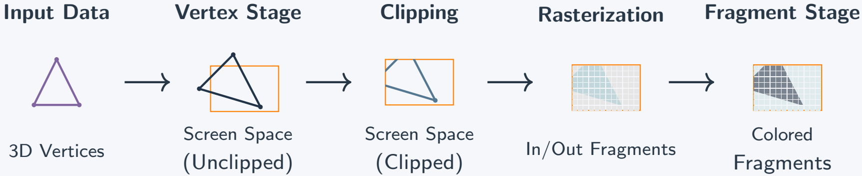

Programmable vs Fixed Function Stages

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

Questions?

References & Further Reading

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