上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

1896 1935 1987 2006

游戏设计与开发

GPU实时图形管线

GPU: Real-time Graphics Pipelines

上海交通大学软件学院
数字艺术实验室
Digital ART LAB

Outline

- Real Time Requirement
- A Conceptual Rendering Pipeline
- Evolution of GPU
  - —Hardware
  - —APIs
  - —Shaders

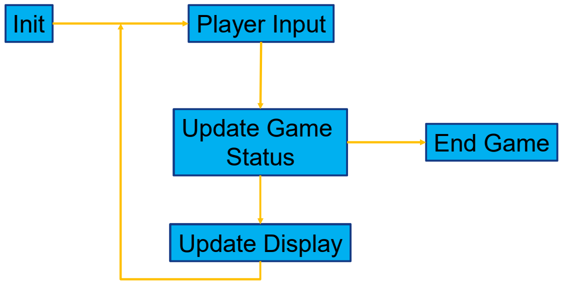
REAL TIME REQUIREMENT

Building A Game

- Background Scene (e.g. sky, terrain)
- Static Objects
- Movement of Objects
- Users' Control
- Collision and Response
- Others

3D Game Loop

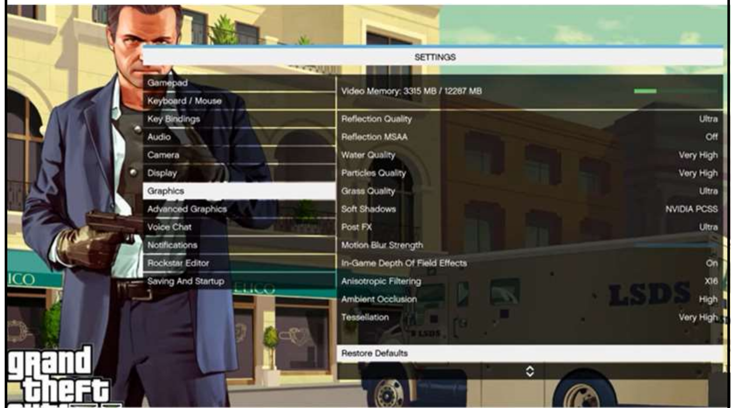
- **The “Game Loop” (Main Event Loop) :**



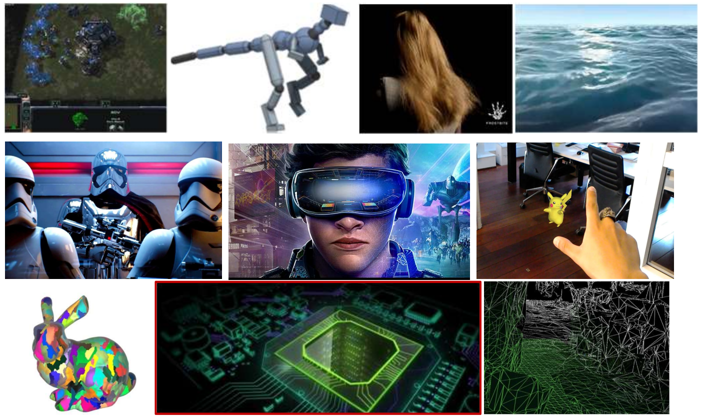
How Fast Does my Game Loop Need to Run?

- ANSWER: *“It depends…”*
  - Visual displays: 25-30 Hz or higher，90~120Hz for VR display
  - Head-tracking for HMDs: 60 Hz, but even only 2-5ms of latency yields *display lag*, which often quickly causes users to lose their lunch…
  - Haptic displays: much higher update rates (500 - 1000 Hz)
  - Multitasking / Multiprocessing: allows for different update rates for different types of output displays
- Main requirement: Real Time 3D Graphics

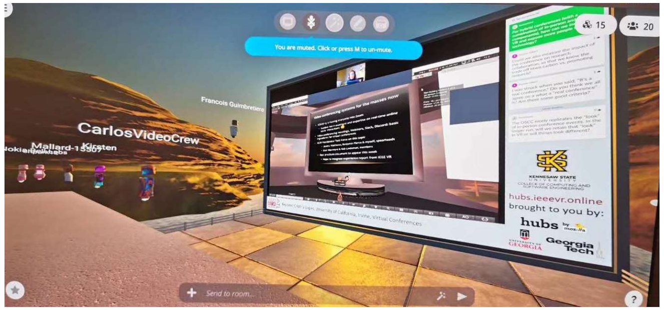
E.g. Game Graphics Setting



Game Programming Techniques



VR in VR (IEEE VR 2020, Mar.23-26)



ACM A.M. Turing Award (2019)

- **PIONEERS OF MODERN COMPUTER GRAPHICS: 3D CGIs**

Patrick M. Hanrahan

- Volume rendering; light field rendering
- RenderMan Shading Language: Shader, →GLSL
- Brook (a language for GPUs) → Nvidia's CUDA
- GPU enabled:
  - CGI for animated films and games
  - VR/AR
  - high performance computing
  - machine learning for AI

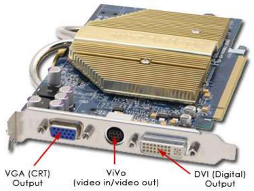
Edwin E. Catmull

Curved patches displaying
Z-Buffering
Texture Mapping
Catmull-Clark Subdivision

Lucas Films → Pixar (1986)

Graphics Hardware and APIs

- **GPU(Graphics Processing Unit):**
  - **Nvidia, AMD, Intel**



- **API:**
  - **Microsoft: DirectX 9, DirectX 10, DirectX 11,…**
  - **OpenGL ARB: OpenGL 1.0, 2.0, 3.0, 4.0,…**

3D Graphics Software Tools

- Low-level 3D graphics APIs:
  - hardware-independent, transparent access
    - window-system and OS independent
    - network-transparent
  - Commonly-Used 3D Graphics APIs:
    - Realtime: OpenGL, Direct3D (*part of* **DirectX**), Vulkun
    - Offline: Renderman
- High-level 3D graphics tools:
  - — 3D Graphics Engine: OGRE, OpenSceneGraph, VTK
  - — 3D Game Engine: Unity, Unreal

OpenGL vs. Vulkan

Vulkan: lower-level; multi-core; parallel tasking
- lower overhead
- more direct control over the GPU
- and lower CPU usage

OpenGL	Vulkan
One single global state machine	Object-based with no global state
State is tied to a single context	All state concepts are localized to a command buffer
Operations can only be executed sequentially	Multi-threaded programming is possible
GPU memory and synchronization are usually hidden	Explicit control over memory management and synchronization
Extensive error checking	Vulkan drivers do no error checking at runtime; there is a validation layer for developers

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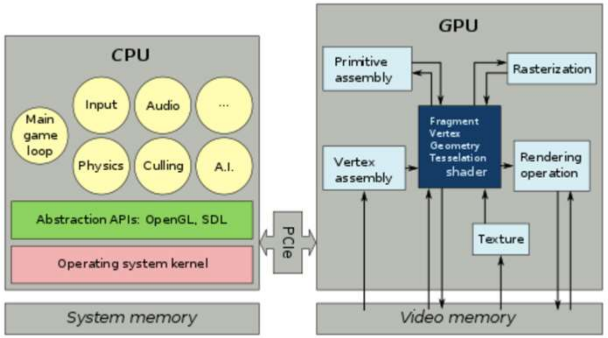
CPU-GPU Cooperation



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GPU vs. CPU

- **GPU**
  - —Data Parallelism
  - —More cores, but low clock speed
  - —VRAM, fast but small size
  - —Low cache memory
- **CPU**
  - —Task parallelism
  - —Less cores, but high clock speed
  - —External RAM, slow but large in size
  - —High cache memory

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Graphics Computations on CPU

- **Vertices to pixels:**
  - —Transformations done on CPU
  - —Compute each pixel in series…slow!
- **Example:**
  - 1 million triangles
  - x 100 pixels per triangle
  - x 10 lights
  - x 4 cycles per light computation

= 4 billion cycles

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Flynn's Taxonomy

- A taxonomy of computer architecture
  - —Micheal Flynn in 1966
- Based on two things:
  - —Instructions
  - —Data

	Single instruction	Multiple instruction
Single data	SISD	MISD
Multiple data	SIMD	MIMD

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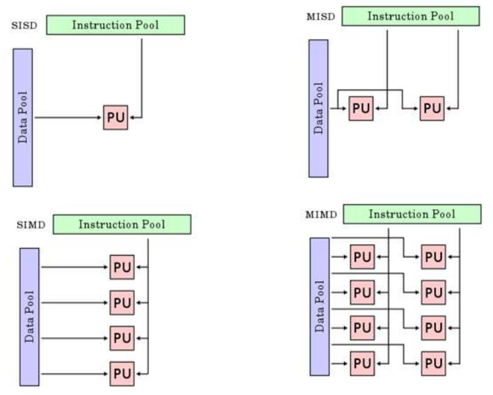
Which one is closest to GPU?



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A CONCEPTUAL RENDERING PIPELINE

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The Graphics Rendering Pipeline

- *rendering pipeline* or *the pipeline*
  - The core component of real time graphics
  - main function: generate, or render, a 2D image, given a virtual camera, 3D objects, light sources, lighting models, textures, and more.

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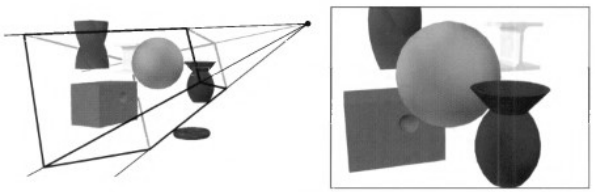
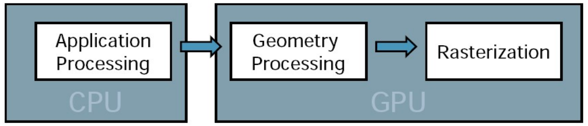
Using the pipeline

- Object (model, color, texture, material)
- Camera/view
- Light source



The Basic Construction

- A conceptual rendering pipeline
- 3 conceptual stages:



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High-Level Pipeline

Application	Geometry (a.k.a. "vertex pipeline")	Rasterization (a.k.a. "pixel pipeline" or "fragment pipeline")
Handle input	Transform	Rasterize (fill pixels)
Simulation & AI	Lighting	Interpolate vertex parameters
		Look up/filter textures
Culling	Skinning	Z- and stencil tests
LOD selection	Calculate texture coords	Blending
Prefetching		

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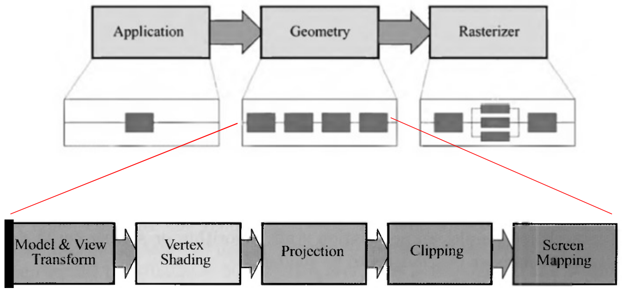
Substages of Geometry Stage

- A pipeline consists of several stages (N)
  —ideally give a speedup of a factor of N



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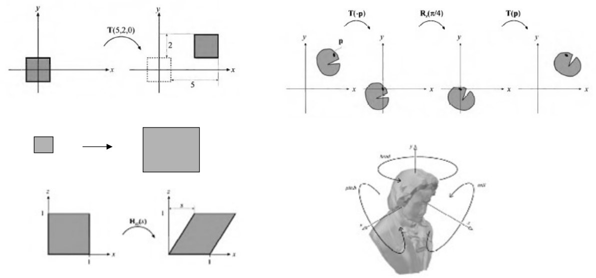
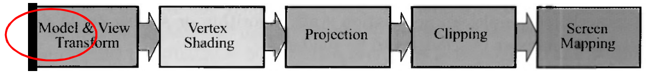
Model Transform

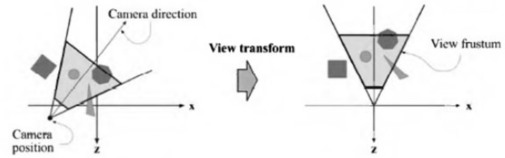
- model transform： model space → world space

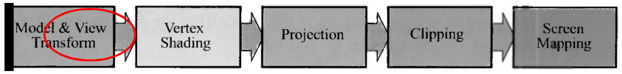




View Transform

- Purpose: place camera at the origin and aim it to look in –z , with y upward, x to the right
- Camera space (or eye space)
- right-hand or left-hand (API specific)





Transform Matrix

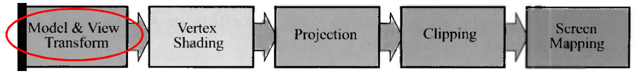
- Both are implemented as 4x4 matrices
  - —Model Transform
  - —View Transform

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & m \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x+t_x \\ y+t_y \\ z+t_z \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

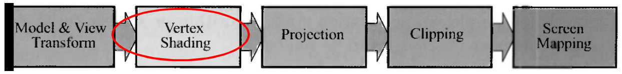
$$\begin{bmatrix} S_x x \\ S_y y \\ S_z z \\ 1 \end{bmatrix} = \begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c & 0 \\ e & f & g & 0 \\ i & j & k & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$



Vertex Shading

- Modeling object appearance:
  - —Object's materials
  - —Effects of light sources
- ***Shading*** :
  - —Determining the effect of a light on a material
  - —By computing ***a shading equation*** at points on the object
    - Per-vertex operation
    - or Per-pixel operation

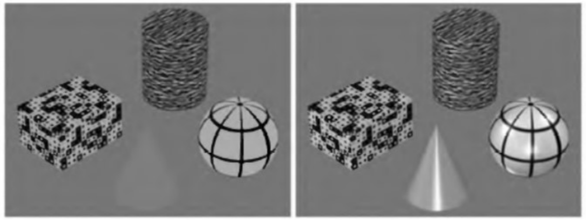


Vertex Shading

- Material data can be stored at each vertex:
  - —Points’ location
  - —A normal
  - —A color
  - —Other numerical information
- Shading can be performed in
  - —World space
  - —Model space
  - —Eye space

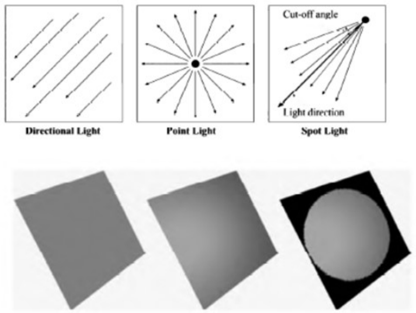
Lighting

- Lighting in fixed-function pipeline



Lighting

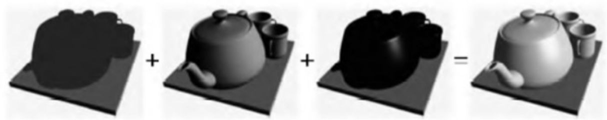
- Light sources



Lighting

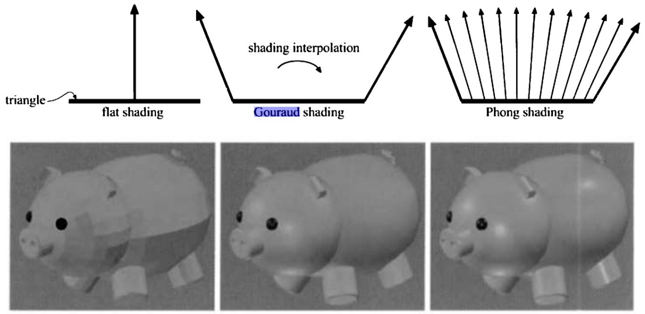
- Lighting Equation in fixed-function pipeline

$$\mathbf{i}_{tot} = \mathbf{i}_{amb} + \mathbf{i}_{diff} + \mathbf{i}_{spec} \qquad (4.14)$$



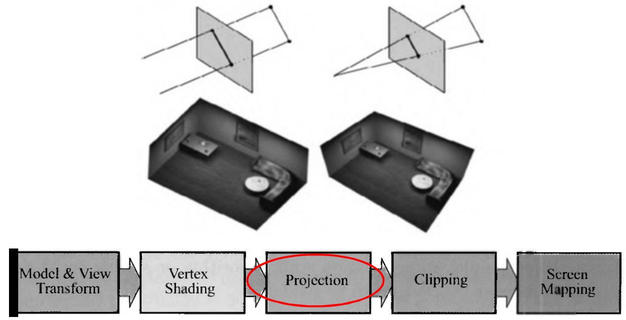
Shading Model

- **Shading Model:**
  - Flat shading, Gouraud shading, Phong Shading (not in fixed)

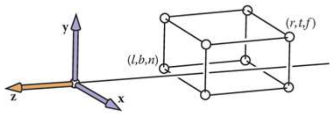


Projection

- View volume → unit cube (-1,-1,-1) and (1,1,1)
- Orthographic projection, perspective projection



Orthographic Projection

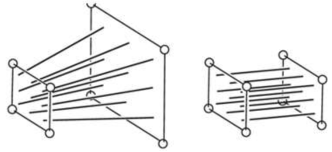


$$\mathbf{M}_{\text{orth}} = \begin{bmatrix} \frac{2}{r-l} & 0 & 0 & -\frac{r+l}{r-l} \\ 0 & \frac{2}{t-b} & 0 & -\frac{t+b}{t-b} \\ 0 & 0 & \frac{2}{n-f} & -\frac{n+f}{n-f} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Orthographic → Perspective

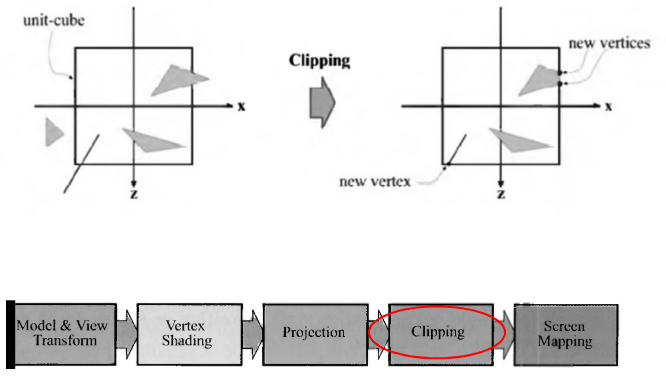
$$\mathbf{M}_{\text{per}} = \mathbf{M}_{\text{orth}}\mathbf{P}$$

$$\mathbf{M}_{\text{orth}} = \begin{bmatrix} \frac{2}{r-l} & 0 & 0 & -\frac{r+l}{r-l} \\ 0 & \frac{2}{t-b} & 0 & -\frac{t+b}{t-b} \\ 0 & 0 & \frac{2}{n-f} & -\frac{n+f}{n-f} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \mathbf{M}_{\text{per}} = \begin{bmatrix} \frac{2n}{r-l} & 0 & \frac{l+r}{l-r} & 0 \\ 0 & \frac{2n}{t-b} & \frac{b+t}{b-t} & 0 \\ 0 & 0 & \frac{f+n}{n-f} & \frac{2fn}{f-n} \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$

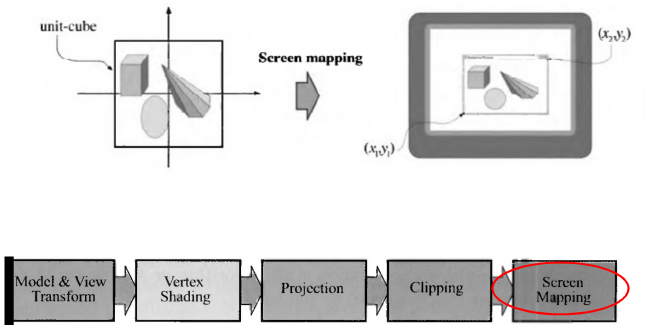


from Fundamentals of Computer Graphics, 4th Edition

Clipping

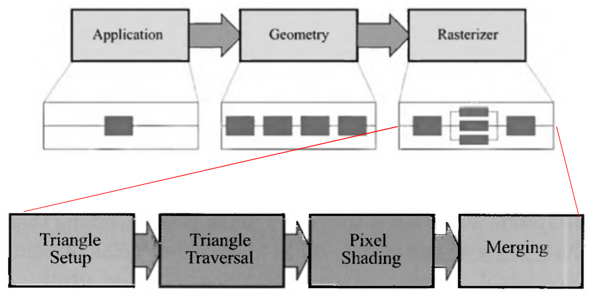


Screen Mapping

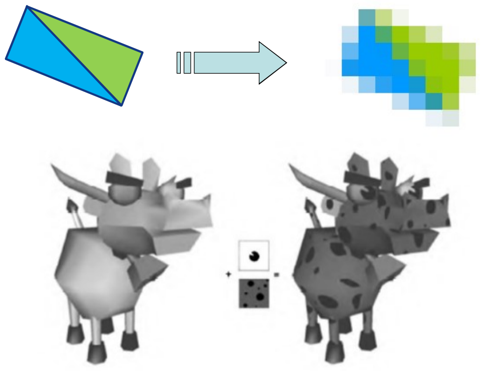


Substages of Rasterizer Stage

- Rasterizer: geometry → fragments
  - Continuous → discrete

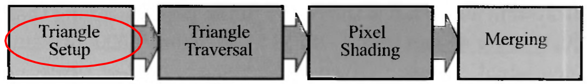


Rasterizer Stage



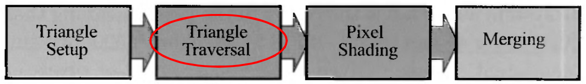
Triangle Setup

- Compute the differentials and other data for the triangle's surfaces
  - —used for scan conversion (next stage)
  - —for interpolation of various shading data produced by the geometry stage (next stages)
- Performed by fixed-operation hardware



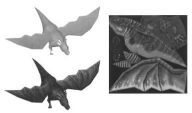
Triangle Traversal

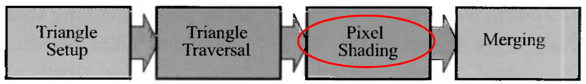
- Also called ***scan conversion***
- Find which samples or pixels are inside a triangle
  - —Check each pixel covered by the triangle
  - —Generate a ***fragment*** for the part of the pixel that overlaps the triangle
  - —Fragment properties: depth, and any shading data from the geometry stage:
    - generated using data interpolated among the 3 triangle vertices
- Performed by fixed-operation hardware



Pixel Shading

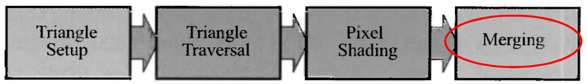
- Do any ***per-pixel shading*** computations
  - —Input: the interpolated shading data
  - —Output: one or more colors to be passed to next stage
- Executed by programmable GPU cores
- Many techniques can be employed here, e.g.
  - —Texturing: "glue" an image (1D,2D or 3D) onto the object





Merging

- Combine the fragment color produced with the color currently stored in color buffer
  - — *color buffer* : 2D array store color info for each pixel (e.g. RGB)
- Not fully programmable, but highly configurable (enable SFXs)
- Also resolving visibility: mostly depth test using Z-buffer (same size as the color buffer, store depth value)
  - — Depth test：compare z-value before rendering to a pixel → update Z-buffer and color buffer if closer
  - — Order-independent for opaque object, but need back-to-front for transparent object (major weakness of Z-buffer)



Merge stage: more buffers and operations

- *Color buffer*: colors
- *Z-buffer*: z-values (*depth test)*
- *Alpha channel* (color buffer): opacity values
  - *alpha test* (==, >=, …) optional before the *depth test*
  - *E.g. ensure fully transparent fragments not affect z-buffer*
- *Stencil buffer*
  - *Record locations of the rendered primitive*
  - *offscreen buffer (typically 8 bits/pixel)*
  - *Control rendering into the color buffer and Z-buffer*
  - *Powerful tool for SFXs: e.g. a circle window*
  - *Raster operations (ROP) or blend operations*
- *Frame buffer (all the buffers, or color + Z-buffer)*
- *Accumulation buffer (images accumulated using a set of ROP)*
  - *e.g. motion blur, depth of field, antialiasing, soft shadows, …*
- *Double buffering:* front buffer & back buffer, swapped during *vertical retrace* (avoid seeing uncompleted screen)

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Various Pipelines

- *Real-time rendering pipelines:* decades of API and GPU evolution for real-time rendering applications
  - *fixed-function pipeline (e.g. Nitendo's Wii, maybe the last)*
    - *On-off configuration*
  - *Programmable GPUs (the modern way!)*
    - *Program exactly operations in substages*
- *Offline rendering pipelines*: different evolution paths
  - Film rendering: commonly *micropolygon pipelines*
  - Academic, and predictive rendering applications (Pre-Viz): *ray tracing renderers*

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EVOLUTION OF GPU HARDWARE

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Graphics Processing Unit (GPU)

- Evolution of hardware graphics accelerations:
  - Started at the end of the pipeline
  - Worked back up the pipeline
  - Hardware accelerator for higher-level application-stage algorithms
- 1999, NVIDIA GeForce256, coined the term GPU (vs. AMD VPU)
  - Hardware T&L (CPU vs. GPU) ➔ 3D FPS Game Card (bad for 2D apps)
  - 4 pixel pipelines: each has 4 pixel units + 1 texture unit
  - Triangle throughput: 15 Million/sec
  - Pixel throughput: 480 Million/sec
  - 2300 transistors (> Pentium III)
  - 0.22 micro process (heat problem vs. 0.18)
  - 256-bit display architecture
  - GeForce256 vs. Quadro

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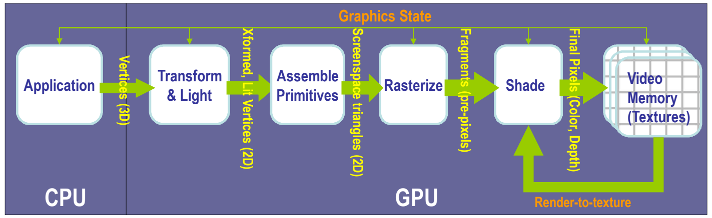
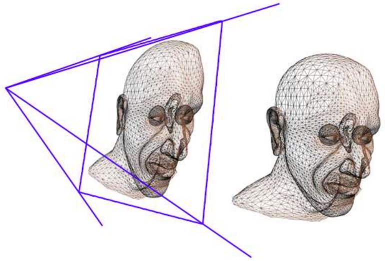
The Fixed-function Graphics Pipeline



- A simplified fixed-function graphics pipeline

Fixed-function GPU Pipeline: Transform

- Transform & light (a.k.a. vertex processor)
  - Transform from “world space” to “image space”
  - Compute per-vertex lighting



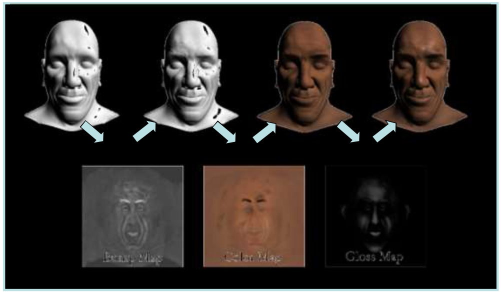
Courtesy Mark Harris

Fixed-function GPU Pipeline: Rasterize

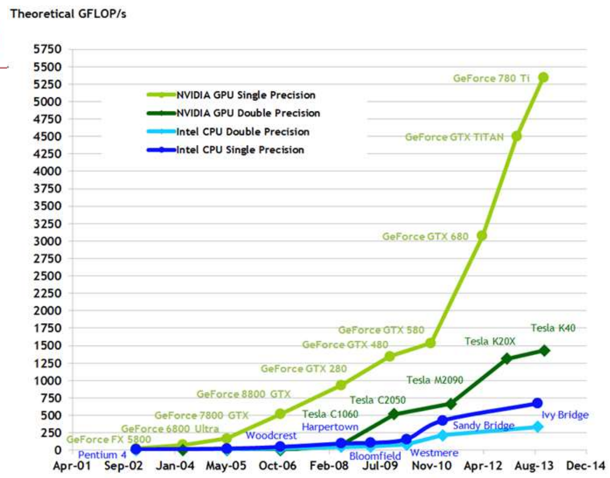
- Rasterizer
  - Convert geometric rep. (vertex) to image rep. (fragment)
    - Fragment = image fragment
      - Pixel + associated data: color, depth, stencil, etc.
  - Interpolate per-vertex quantities across pixels

Fixed-function GPU Pipeline: Shade

- Fragment processors (multiple in parallel)
  - Compute a color for each pixel
  - Optionally read colors from textures (images)

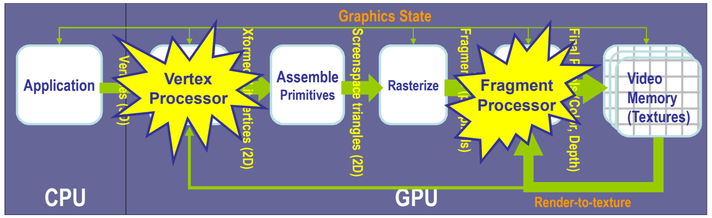


Courtesy Mark Harris



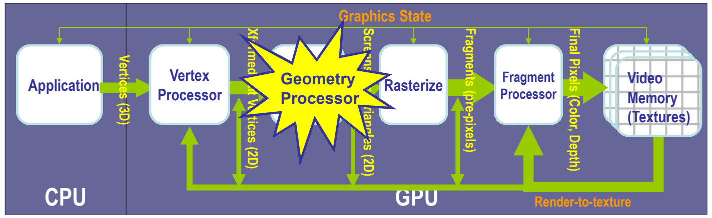
Floating-Point Operations per Second - Nvidia CUDA C Programming Guide
Version 6.5 - 24/9/2014 - copyright Nvidia Corporation 2014

The Modern Graphics Pipeline



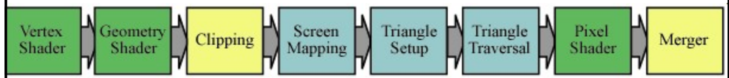
- Programmable vertex processor!
- Programmable pixel processor !

The Modern Graphics Pipeline



- Programmable primitive assembly!
- More flexible memory access!

Modern GPU implementation of rendering pipeline



green : fully programmable
yellow: configurable but not programmable
blue: completely fixed in their function

Vertex Shader (fully programmable)
- Model and View Transform
- Vertex Shading
- Projection

- Geometry shader (optional) - (fully programmable)
  - Operate on the vertices of a primitive (point, line, or triangle)
- Clipping, screen mapping, triangle setup, triangle traversal stages (fixed)
- Pixel Shading - (fully programmable)
  - Pixel shading function
- Merge Stage (highly configurable)
  - Modifying the color
  - Z-buffer blend, stencil, and other buffers

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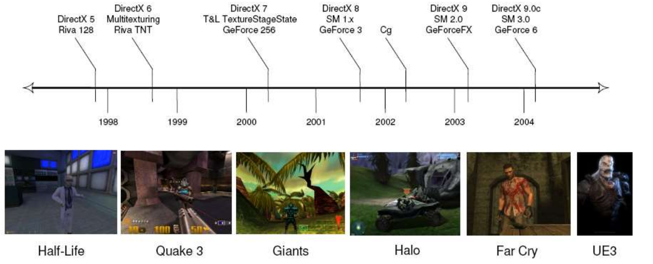
DirectX Shader Model Timeline



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Earlier GPU Architecture Evolution

	Product	New Features	OpenGL Version	Direct3D Version
2000	GeForce 256	Hardware transform & lighting, configurable fixed-point shading, cube maps, texture compression, anisotropic texture filtering	1.3	DX7
2001	GeForce3	Programmable vertex transformation, 4 texture units, dependent textures, 3D textures, shadow maps, multisampling, occlusion queries	1.4	DX8
2002	GeForce4 Ti 4600	Early Z culling, dual-monitor	1.4	DX8.1
2003	GeForce FX	Vertex program branching, floating-point fragment programs, 16 texture units, limited floating-point textures, color and depth compression	1.5	DX9
2004	GeForce 6800 Ultra	Vertex textures, structured fragment branching, non-power-of-two textures, generalized floating-point textures, floating-point texture filtering and blending	2.0	DX9c
2005	GeForce 7800 GTX	Transparency antialiasing	2.0	DX9c

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DirectX 5 / OpenGL 1.0 and Before

- Hardwired pipeline
  - Simple API inputs
  - Small set of operations
- Example Hardware
  - NVIDIA RIVA 128
  - 3dfx Voodoo
  - S3 Virge
- Rigid data flow
  - No read-back from frame buffer

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DirectX 6 / OpenGL 1.2

- Released 1998
- New Features
  - Multitexturing (in OpenGL since 1.3)
- Example Hardware
  - NVIDIA RIVA TNT
  - ATI Rage 128

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DirectX 7 / OpenGL 1.3

- Released 1999
- More work outsourced to GPU
  - Hardware Transformation and Lighting (T&L, Direct3D only)
- New Features
  - Texture Compression in OpenGL
- Example Hardware
  - NVIDIA GeForce 256
  - ATI Radeon 7200

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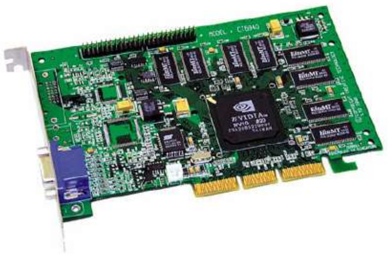
Example: GeForce 256 (1999)



- Graphics Core:
  - 256-bit
- Memory Interface:
  - 128-bit
- Triangles/s:
  - 15 Million
- Pixels/s:
  - Up to 480 Million
- Memory:
  - Up to 128MB

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DirectX 8

- Released 2000
- Introduction of Shader Model 1.1
  - Shaders are GPU-run programs that manipulate Vertices or Pixels
  - Enables a plethora of new visual effects
  - Adds programmable processors to the graphics pipeline
- Example Hardware:
  - NVIDIA GeForce 3
  - ATI Radeon 9000

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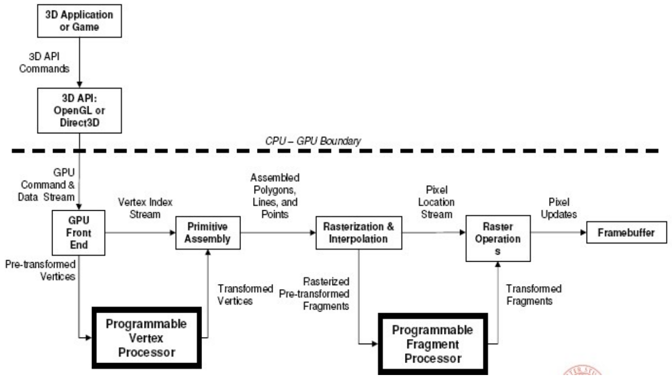
Adding Programmability

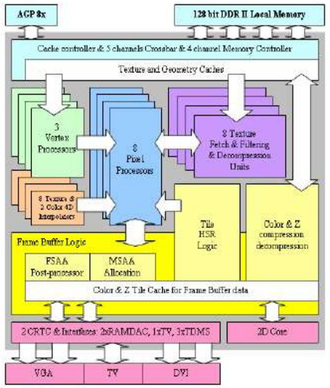


DirectX 9

- Released 2002
- Much more general programming paradigm
  - Branching
  - Floating point fragment programming
- Shader Model 3.0 (in 9.0c, 2004)
  - Big feature increment
- Example Hardware
  - NVIDIA GeForceFX (9.0)
  - NVIDIA GeForce 6200 (9.0c)

Example: Geforce FX (2003)

- **Vertex processor:**
  - execute vertex shaders
  - emulate T&L
- **Pixel processor:**
  - execute pixel shaders
  - emulate 2 integer or 1 float operations
  - Perform 2 Texture accesses
- **Texture & color interpolators**
  - interpolate texture coordinates and color values



OpenGL 2.0

- Released 2005
- OpenGL Shading Language (GLSL)
  - Vertex and fragment shaders
  - GLSL ties shaders to OpenGL API
- Point sprites
  - Particle effects
- Many more features

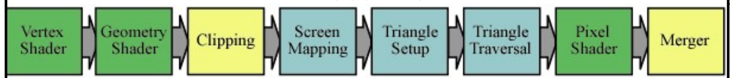
DirectX 10

- Released 2006
- Aligned with Windows Vista
- New Features
  - Geometry shaders; Streaming output; Arrays of surfaces and resource views; State encapsulation
- Break with Past
  - User mode drivers, even for DX9
  - Drivers do not implement Shader Models <4.0
  - No more fixed function (compiles legacy API calls to shaders)

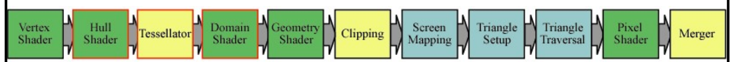
DirectX 11

- Direct3d 11, Released 2009
  - Windows Vista(With Patch)/Windows 7
  - Shader Model 5.0
  - Tessellation, Multithreaded rendering, Compute shaders, supported by hardware and software running Direct3D 9/10/10.1
- Direct3D 11.1
  - —Windows 8, Stereoscopic 3D Rendering, GPGPU
- Direct3D 11.2
  - —Windows 8.1, Tiled resources, GPGPU

DirectX 10



DirectX 11

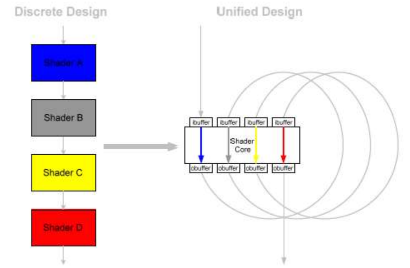


DirectX 12

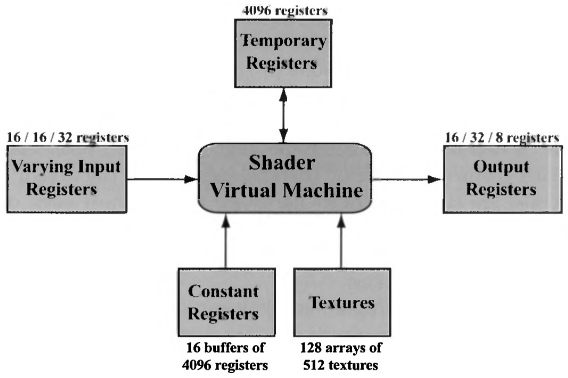
- July 2015
- Windows 10, Xbox One
- reduce driver overhead: “console-level efficiency”
- a lower level of hardware abstraction
  - —enabling future games to significantly improve multithreaded scaling and (decrease) CPU utilization
- claimed to be better than DirectX 11:
  - —50-70% faster
  - —>50% reduction in power consumption

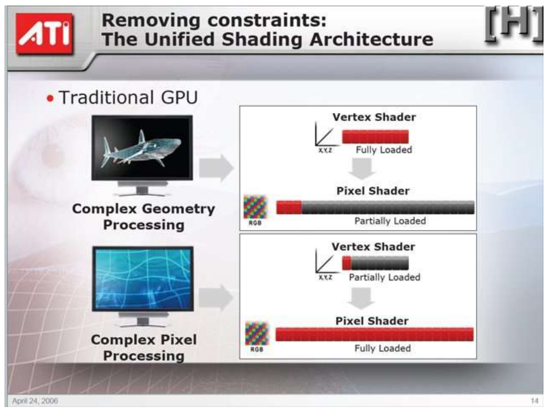
Unified Shader Design

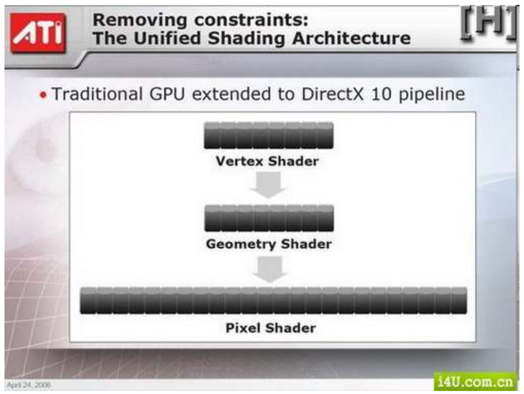
- Rendering pipeline no longer visible in hardware
- Unified shader cores process both vertices and pixels
- Shader Virtual Machine



Common Shader Core Virtual Machine





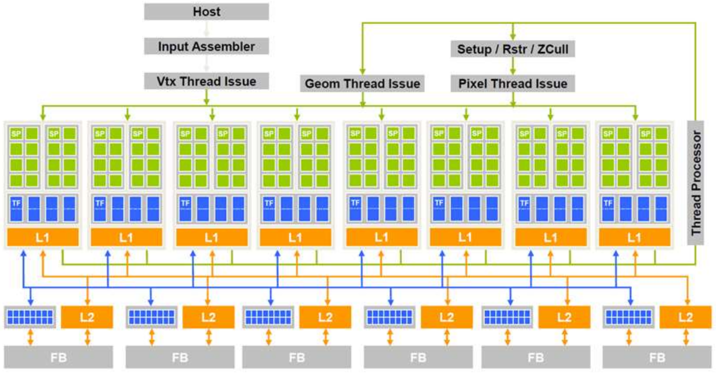


Impact of Unified Shaders

- All shading processes performed by a unified set of processors
- Fewer bottle-necks (i.e. in case of vertex or pixel dominant scenes)
- Better hardware utilization
- Hardware architecture no longer reflects the graphics pipeline
- Greater flexibility makes GPUs eligible for non-graphics applications (game physics, scientific applications)

→ Basically makes the GPU a massively parallel stream multiprocessor!

Example of GPU Architecture



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Programmable Shader Stage

- ***Common-shader core (API) (after DX10)***
  - ***Vertex, pixel and geometry shaders share a programming model***
  - ***Functional description seen by the application programmer***
- ***Unified shaders (GPU architecture)***
  - ***A GPU architecture that maps well to the common-shader core***
- ***Programming model:***
  - ***Shaders are programmed using C-like shading languages (e.g. Cg, HLSL, GLSL)***

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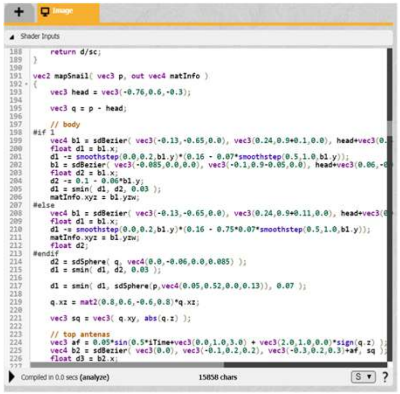
ShaderToy Snail



- **GLSL pixel shader (~800 line codes)**
- **Procedural modeling and procedural lighting**
- **Raymatching**
- **distancefield**

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