Tutorial 5: Programming Graphics Hardware

Introduction to the Hardware Graphics Pipeline

Cyril Zeller

Overview of the Tutorial: Morning

8:30	Introduction to the Hardware Graphics Pipeline Cyril Zeller
9:30	Controlling the GPU from the CPU: the 3D API Cyril Zeller
10:15	Break
10:45	Programming the GPU: High-level Shading Languages Randy Fernando
12:00	Lunch

Overview of the Tutorial: Afternoon

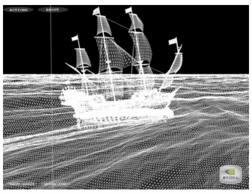
12:00	Lunch
14:00	Optimizing the Graphics Pipeline Matthias Wloka
14:45	Advanced Rendering Techniques Matthias Wloka
15:45	Break
16:15	General-Purpose Computation Using Graphics Hardware Mark Harris
17:30	End

Overview

- Concepts:
  - Real-time rendering
  - Hardware graphics pipeline
- Evolution of the PC hardware graphics pipeline:
  - 1995-1998: Texture mapping and z-buffer
  - 1998: Multitexturing
  - 1999-2000: Transform and lighting
  - 2001: Programmable vertex shader
  - 2002-2003: Programmable pixel shader
  - 2004: Shader model 3.0 and 64-bit color support
- PC graphics software architecture
- Performance numbers

Real-Time Rendering

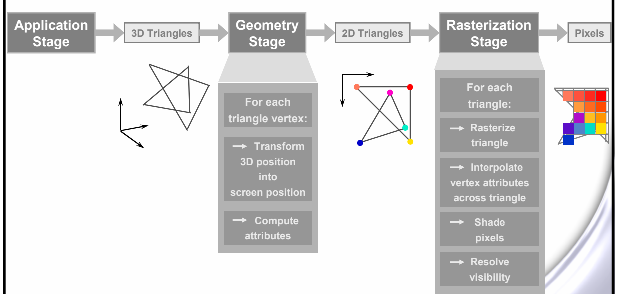
- Graphics hardware enables real-time rendering
- Real-time means display rate at more than 10 images per second



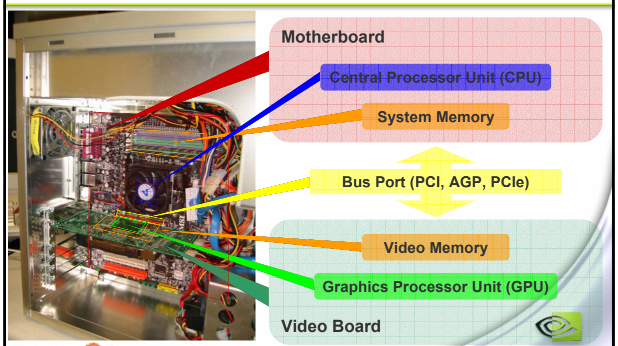
3D Scene = Collection of 3D primitives (triangles, lines, points)

Image = Array of pixels

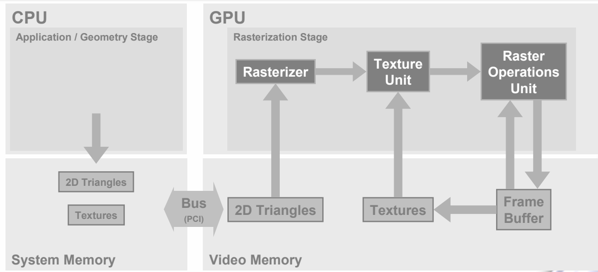
Hardware Graphics Pipeline



PC Architecture

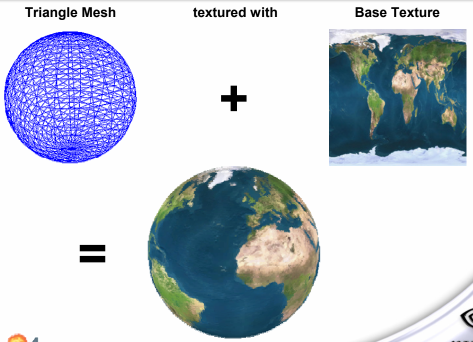


1995-1998: Texture Mapping and Z-Buffer

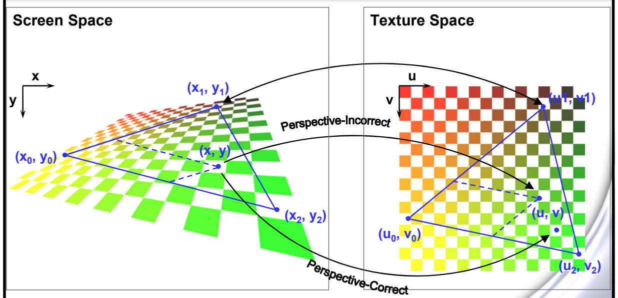


- PCI: Peripheral Component Interconnect
- 3dfx's Voodoo

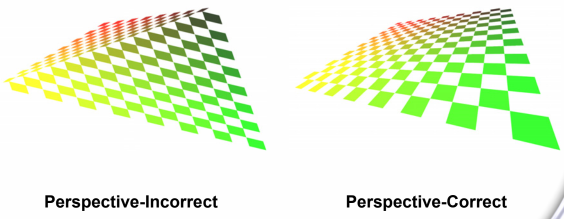
Texture Mapping



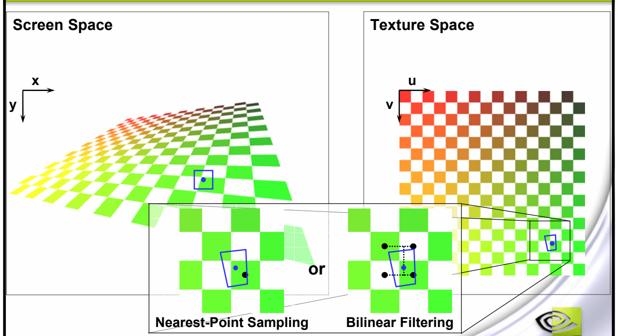
Texture Mapping: Texture Coordinates Interpolation

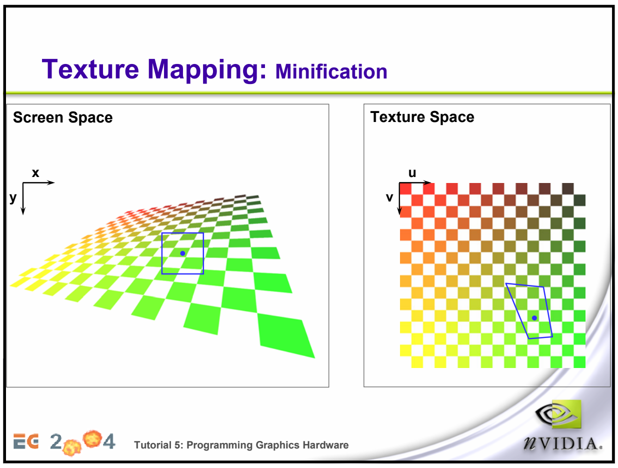


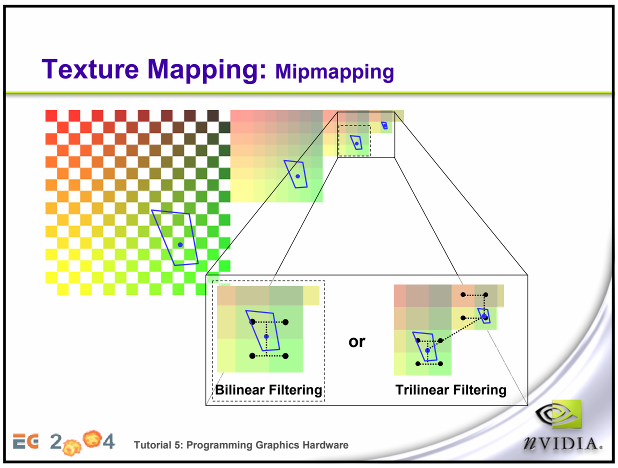
Texture Mapping: Perspective-Correct Interpolation

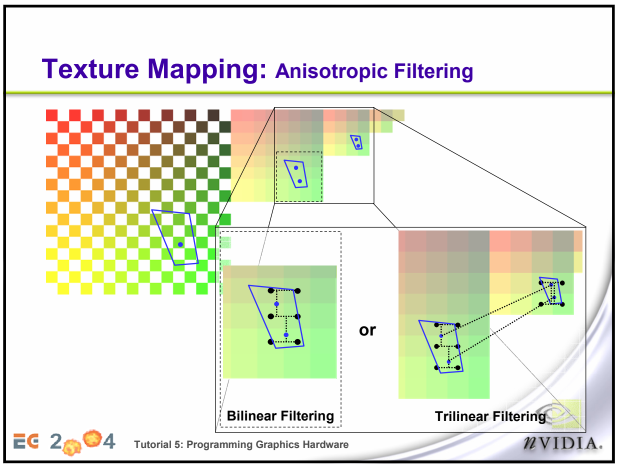


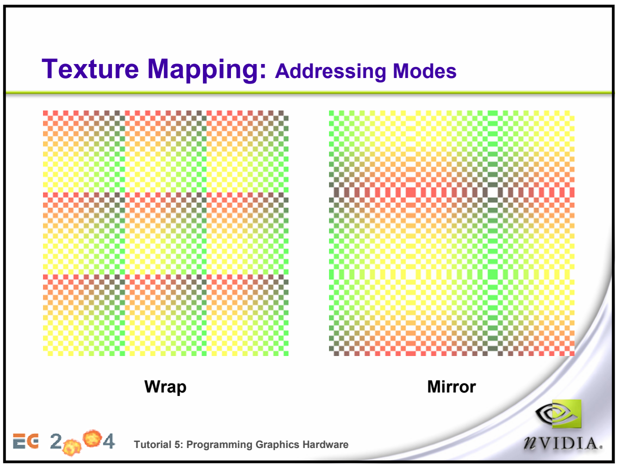
Texture Mapping: Magnification

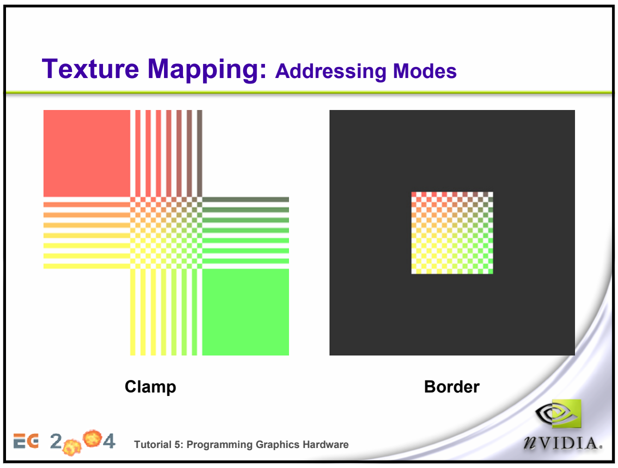


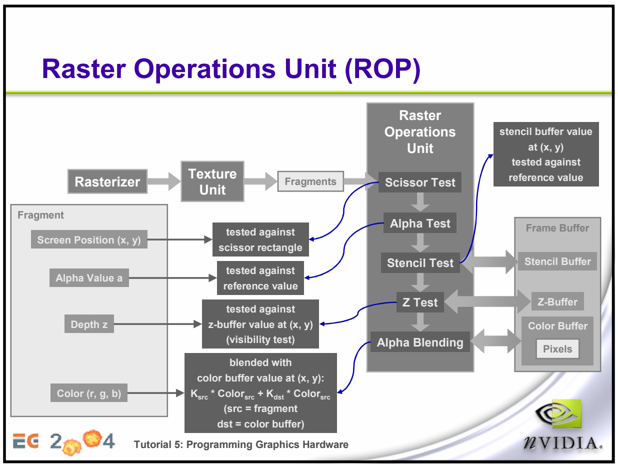

Texture Mapping: Minification
Screen Space
x
y
Texture Space
u
v
EG 2004
Tutorial 5: Programming Graphics Hardware
NVIDIA


Texture Mapping: Mipmapping
or
Bilinear Filtering
Trilinear Filtering
EG 2004
Tutorial 5: Programming Graphics Hardware
NVIDIA

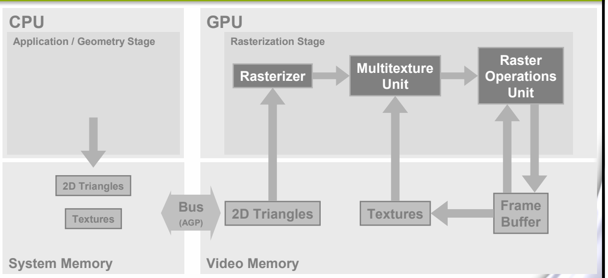

Texture Mapping: Anisotropic Filtering
or
Bilinear Filtering
Trilinear Filtering
EG 2004
Tutorial 5: Programming Graphics Hardware
NVIDIA


Texture Mapping: Addressing Modes
Wrap
Mirror
EG 2004
Tutorial 5: Programming Graphics Hardware
NVIDIA


Texture Mapping: Addressing Modes
Clamp
Border
EG 2004
Tutorial 5: Programming Graphics Hardware
NVIDIA


Raster Operations Unit (ROP)
Rasterizer
Texture Unit
Fragments
Raster Operations Unit
Scissor Test
Alpha Test
Stencil Test
Z Test
Alpha Blending
stencil buffer value at (x, y) tested against reference value
Fragment
Screen Position (x, y)
Alpha Value a
Depth z
Color (r, g, b)
tested against scissor rectangle
tested against reference value
tested against z-buffer value at (x, y) (visibility test)
blended with color buffer value at (x, y): K_{src} * $Color_{src}$ + K_{dst} * $Color_{src}$ (src = fragment dst = color buffer)
Frame Buffer
Stencil Buffer
Z-Buffer
Color Buffer
Pixels
EG 2004
Tutorial 5: Programming Graphics Hardware
NVIDIA

1998: Multitexturing



- AGP: Accelerated Graphics Port
- NVIDIA's TNT, ATI's Rage

AGP

- PCI uses a parallel connection
- AGP uses a serial connection

→ Less pins, simpler protocol → Cheaper, more scalable

- PCI uses a shared-bus protocol
- AGP uses a point-to-point protocol

→ Bandwidth is not shared among devices

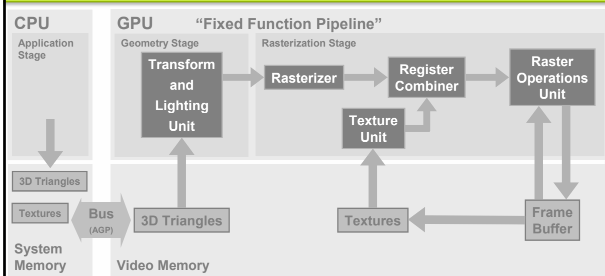
- AGP uses a dedicated system memory called AGP memory or non-local video memory
  - The GPU can lookup textures that resides in AGP memory
- Bandwidth: AGP = 2 x PCI (AGP2x = 2 x AGP, etc.)

Multitexturing

Base Texture modulated by Light Map

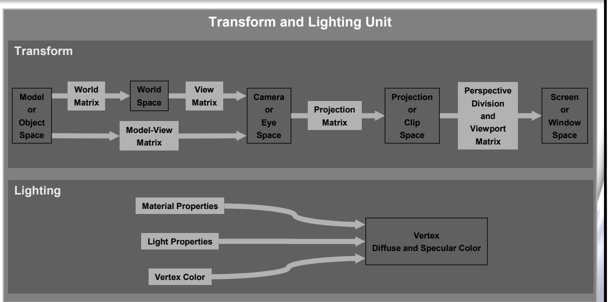
from UT2004 (c)
Epic Games Inc.
Used with permission

1999-2000: Transform and Lighting



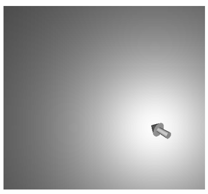
- Register Combiner: Offers many more texture/color combinations
- NVIDIA's GeForce 256 and GeForce2, ATI's Radeon 7500, S3's Savage3D

Transform and Lighting Unit (TnL)



Bump Mapping

- Bump mapping is about fetching the normal from a texture (called a normal map) instead of using the interpolated normal to compute lighting at a given pixel

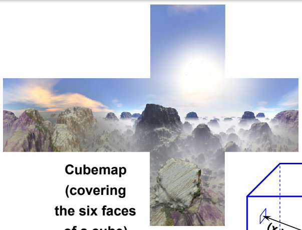


Diffuse light without bump

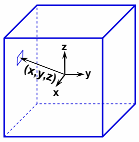
Normal Map

Diffuse light with bumps

Cube Texture Mapping



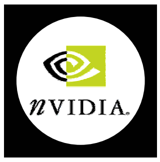
Cubemap (covering the six faces of a cube)



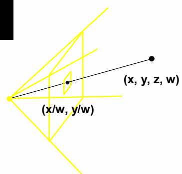
Cubemap lookup (with direction (x, y, z))

Environment Mapping (the reflection vector is used to lookup the cubemap)

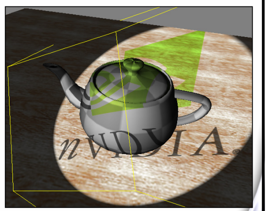
Projective Texture Mapping



Projected Texture

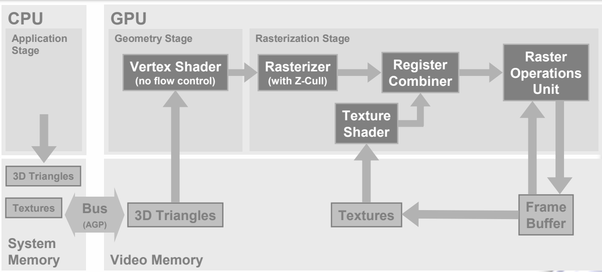


Projective Texture lookup



Texture Projection

2001: Programmable Vertex Shader



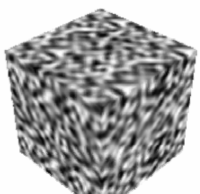
- **Z-Cull**: Predicts which fragments will fail the Z test and discards them
- **Texture Shader**: Offers more texture addressing and operations
- **NVIDIA's GeForce3 and GeForce4 Ti, ATI's Radeon 8500**

Vertex Shader

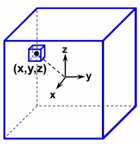
- **A programming processor for any per-vertex computation**

```
void VertexShader(
          // Input per vertex
        in float4 positionInModelSpace,
        in float2 textureCoordinates,
        in float3 normal,

          // Input per batch of triangles
  uniform float4x4 modelToProjection,
  uniform float3 lightDirection,

          // Output per vertex
       out float4 positionInProjectionSpace,
       out float2 textureCoordinatesOutput,
       out float3 color
)
{
  // Vertex transformation
  positionInProjectionSpace = mul(modelToProjection, positionInModelSpace);

  // Texture coordinates copy
  textureCoordinatesOutput = textureCoordinates;

  // Vertex color computation
  color = dot(lightDirection, normal);
}
```

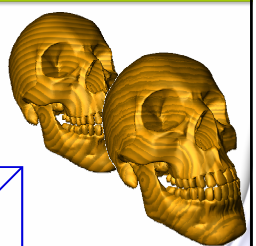

Volume Texture Mapping



Volume Texture (3D Noise)



Volume Texture lookup (with position (x, y, z))

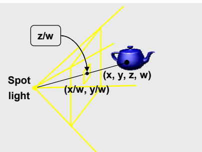


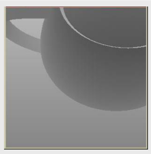
Noise Perturbation

Hardware Shadow Mapping

Shadow Map Computation

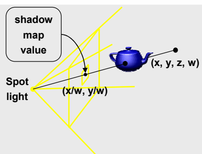
The shadow map contains the depth z/w of the 3D points visible from the light's point of view:

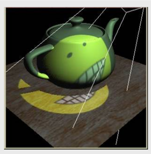




Shadow Rendering

A 3D point (x, y, z, w) is in shadow if:
z/w < value of shadow map at (x/w, y/w)
A hardware shadow map lookup returns the value of this comparison between 0 and 1





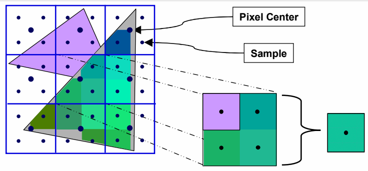
Antialiasing: Definition

- Aliasing: Undesirable visual artifacts due to insufficient sampling of:
  - Primitives (triangles, lines, etc.) → jagged edges
  - Textures or shaders → pixelation, moiré patterns

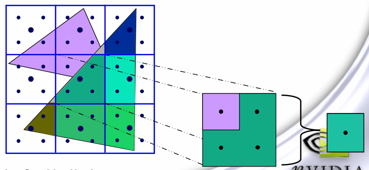
  Those artifacts are even more noticeable on animated images.
- Antialiasing: Method to reduce aliasing
  - Texture antialiasing is largely handled by proper mipmapping and anisotropic filtering
  - Shader antialiasing can be tricky (especially with conditionals)

Antialiasing: Supersampling and Multisampling

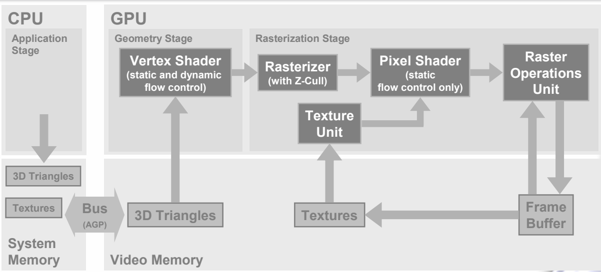
- Supersampling:
  Compute color and Z at higher resolution and display averaged color to smooth out the visual artifacts



- Multisampling:
  Same thing except only Z is computed at higher resolution
  - Multisampling performs antialiasing on primitive edges only



2002-2003: Programmable Pixel Shader



- MRT: Multiple Render Target
- NVIDIA's GeForce FX, ATI's Radeon 9600 to 9800

Pixel Shader

- A programming processor for any per-pixel computation

```
void PixelShader(
        // Input per pixel
        in float2 textureCoordinates,
        in float3 normal,

        // Input per batch of triangles
        uniform sampler2D baseTexture,
        uniform float3 lightDirection,

        // Output per pixel
        out float3 color
)
{
    // Texture lookup
    float3 baseColor = tex2D(baseTexture, textureCoordinates);

    // Light computation
    float light = dot(lightDirection, normal);

    // Pixel color computation
    color = baseColor * light;
}
```

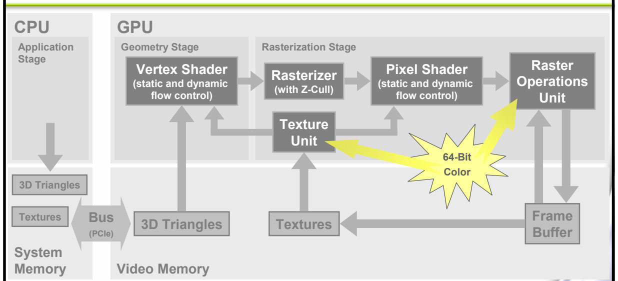

Shader: Static vs. Dynamic Flow Control

```
void Shader(
    ...
        // Input per vertex or per pixel
        in float3 normal,
        // Input per batch of triangles
        uniform float3 lightDirection,
        uniform bool computeLight,
    ...
)
{
    ...
    if (computeLight) {
        ...
        if (dot(lightDirection, normal)) {
            ...
        }
        ...
    }
    ...
}
```

Static Flow Control (condition varies per batch of triangles)

Dynamic Flow Control (condition varies per vertex or pixel)

2004: Shader Model 3.0 and 64-Bit Color Support



- PCIe: Peripheral Component Interconnect Express
- NVIDIA's GeForce 6800

PCIe

- Like AGP:
  - Uses a serial connection → Cheap, scalable
  - Uses a point-to-point protocol → No shared bandwidth
- Unlike AGP:
  - General-purpose (not only for graphics)
  - Dual-channels: Bandwidth is available in both direction
- Bandwidth: PCIe = 2 x AGPx8

Shader Model 3.0

- Shader Model 3.0 means:
  - Longer shaders → More complex shading
  - Pixel shader:
    - Dynamic flow control → Better performance
    - Derivative instructions → Shader antialiasing
    - Support for 32-bit floating-point precision → Fewer artifacts
    - Face register → Faster two-sided lighting
  - Vertex shader:
    - Texture access → Simulation on GPU, displacement mapping

EG 2004 Tutorial 5: Programming Graphics Hardware NVIDIA

64-Bit Color Support

- 64-bit color means one 16-bit floating-point value per channel (R, G, B, A)
- Alpha blending works with 64-bit color buffer (as opposed to 32-bit fixed-point color buffer only)
- Texture filtering works with 64-bit textures (as opposed to 32-bit fixed-point textures only)
- Applications:
  - High-precision image compositing
  - High dynamic range imagery

EG 2004 Tutorial 5: Programming Graphics Hardware NVIDIA

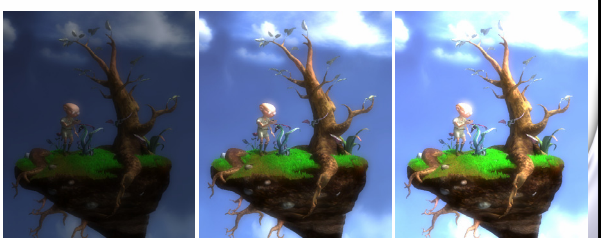
High Dynamic Range Imagery

- The dynamic range of a scene is the ratio of the highest to the lowest luminance
- Real-life scenes can have high dynamic ranges of several millions
- Display and print devices have a low dynamic range of around 100
- Tone mapping is the process of displaying high dynamic range images on those low dynamic range devices
- High dynamic range images use floating-point colors
- OpenEXR is a high dynamic range image format that is compatible with NVIDIA's 64-bit color format

EG 2004 Tutorial 5: Programming Graphics Hardware NVIDIA

Real-Time Tone Mapping

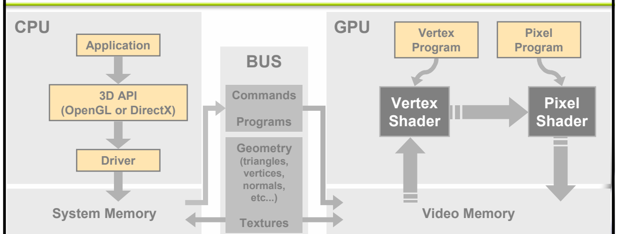
- The image is entirely computed in 64-bit color and tone-mapped for display



From low to high exposure image of the same scene

EG 2004 Tutorial 5: Programming Graphics Hardware NVIDIA

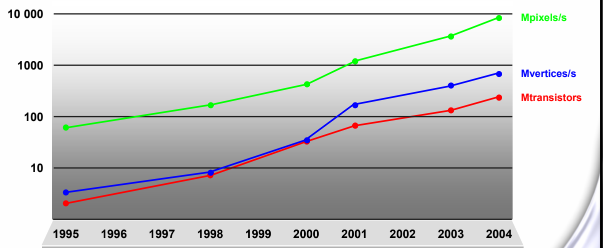
PC Graphics Software Architecture



- The application, 3D API and driver are written in C or C++
- The vertex and pixel programs are written in a high-level shading language (Cg, DirectX HLSL, OpenGL Shading Language)
- Pushbuffer: Contains the commands to be executed on the GPU

EG 2004 Tutorial 5: Programming Graphics Hardware NVIDIA

Evolution of Performance



1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
PCI (133 MB/s)		AGP (266 MB/s)	AGP2x (533 MB/s)	AGP4x (1.06 GB/s)			AGP8x (2.1 GB/s)		PCIe (4 GB/s)
4 MB			32 MB	64 MB	128 MB			256 MB	512 MB
OpenGL 1.1			OpenGL 1.2	DirectX 6	DirectX 7	DirectX 8 OpenGL 1.3	OpenGL 1.4	DirectX 9 OpenGL 1.5	

The Future

- Unified general programming model at primitive, vertex and pixel levels
- Scary amounts of:
  - Floating point horsepower
  - Video memory
  - Bandwidth between system and video memory
- Lower chip costs and power requirements to make 3D graphics hardware ubiquitous:
  - Automotive (gaming, navigation, heads-up displays)
  - Home (remotes, media center, automation)
  - Mobile (PDAs, cell phones)

More Information

- www.realtimerendering.com
- developer.nvidia.com

- Questions: czeller@nvidia.com