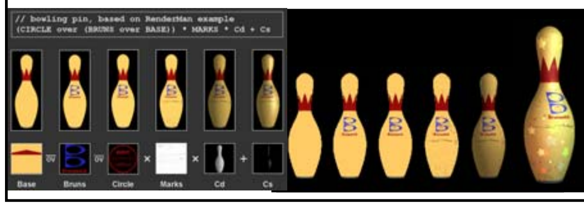
Modern Graphics Hardware

MIT EECS 6.837
Frédo Durand and Barb Cutler
Slides and demos from
Hanrahan & Akeley, Gary McTaggart NVIDIA, ATI

MIT EECS 6.837, Cutler and Durand 1

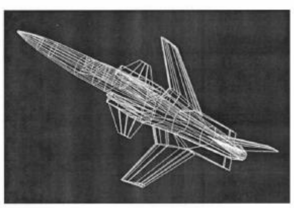
Modern graphics hardware

- Hardware implementation of the rendering pipeline
- Programmability & "shaders"
  - Recent, last few years
  - At the vertex and pixel level



First Generation - Wireframe

Vertex:	transform, clip, and project
Rasterization:	color interpolation (points, lines)
Fragment:	overwrite
Dates:	prior to 1987



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Second Generation - Shaded Solids

Vertex:	lighting calculation
Rasterization:	depth interpolation (triangles)
Fragment:	depth buffer, color blending
Dates:	1987 - 1992

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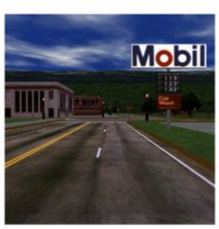
Third Generation - Texture Mapping

Vertex:	texture coordinate transformation
Rasterization:	texture coordinate interpolation
Fragment:	texture evaluation, antialiasing
Dates:	1992 - 2000



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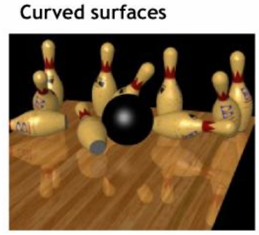
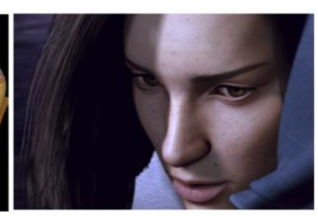
Fourth Generation - Programmability

Programmable shading
Image-based rendering
Convergence of graphics and media processing
Curved surfaces





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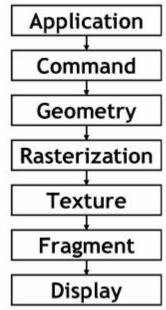
Questions?

Modern Graphics Pipeline



Forward-Algorithm

A trip down the graphics pipeline

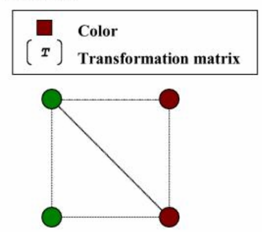
Application

- Simulation
- Input event handlers
- Modify data structures
- Database traversal
- Primitive generation
- Utility functions

Command

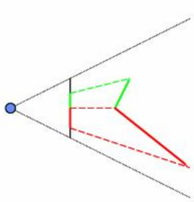
- Command buffering
- Command interpretation
- Unpack and perform format conversion
- Maintain graphics state

```
glLoadIdentity( );
glMultMatrix( T );
glBegin( GL_TRIANGLE_STRIP );
glColor3f ( 0.0, 0.5, 0.0 );
glVertex3f( 0.0, 0.0, 0.0 );
glColor3f ( 0.5, 0.0, 0.0 );
glVertex3f( 1.0, 0.0, 0.0 );
glColor3f ( 0.0, 0.5, 0.0 );
glVertex3f( 0.0, 1.0, 0.0 );
glColor3f ( 0.5, 0.0, 0.0 );
glVertex3f( 1.0, 1.0, 0.0 );
…
glEnd( );
```



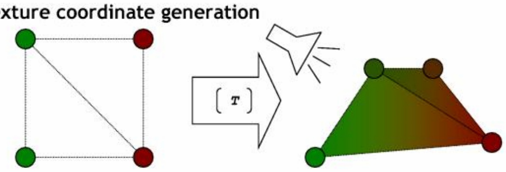
Geometry

- Evaluation of polynomials for curved surfaces
- Transform and projection
- Clipping, culling and primitive assembly



Geometry

- Evaluation of polynomials for curved surfaces
- Transform and projection (object -> image space)
- Clipping, culling and primitive assembly
- Lighting (light sources and surface reflection)
- Texture coordinate generation



Object-space triangles

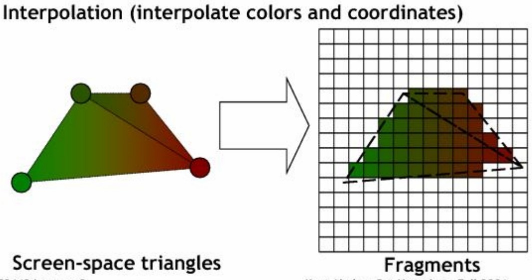
Screen-space lit triangles

Rasterization

Setup (per-triangle)

Sampling (triangle = {fragments})

Interpolation (interpolate colors and coordinates)

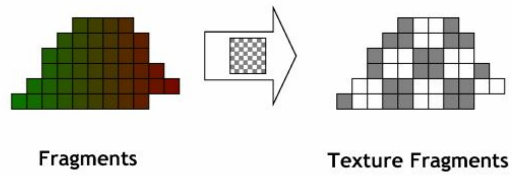


Texture

Texture transformation and projection

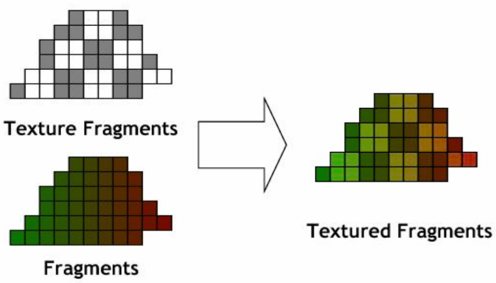
Texture address calculation

Texture filtering



Fragment

Texture combiners



Fragment

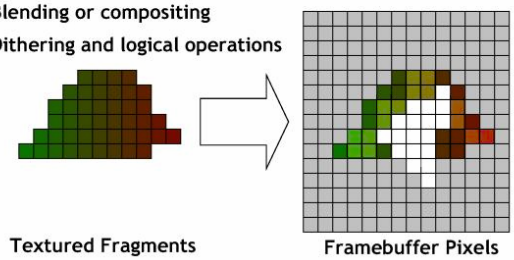
(This part often separated as "raster op")

Texture combiners and fog

Owner, scissor, depth, alpha and stencil tests

Blending or compositing

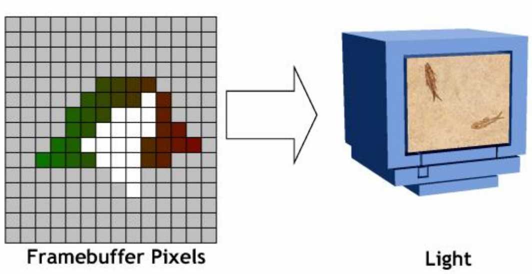
Dithering and logical operations



Display

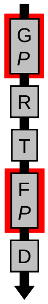
Gamma correction

Analog to digital conversion

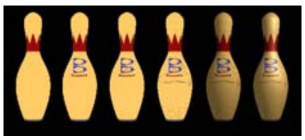


Questions?

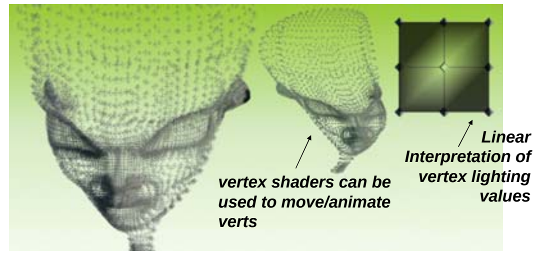
Programmable Graphics Hardware



- Geometry and pixel (fragment) stage become programmable
  - Elaborate appearance
  - More and more general-purpose computation (GPU hacking)



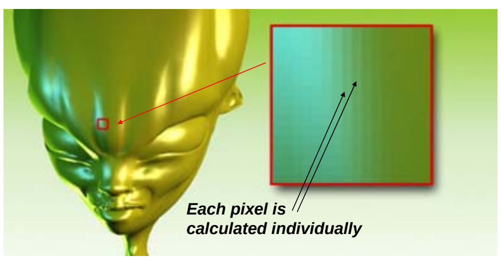
Vertex Shaders



Vertex Shaders are both Flexible and Quick

Slide from NVidia

Pixel Shaders



Pixel shaders have limited or no knowledge of neighbouring pixels

Slide from NVidia

Allows for amazing quality

Rich scene appearance

- Vertex shader
  - Geometry (skinning, displacement)
  - Setup interpolants for pixel shaders
- Pixel shader
  - Visual appearance
  - Also used for image processing and other GPU abuses
- Multipass
  - Render the scene or part of the geometry multiple times
  - E.g. shadow map, shadow volume
  - But also to get more complex shaders

How to program shaders?

- Assembly code
- Higher-level language and compiler (e.g. Cg, HLSL, GLSL)
- Send to the card like any piece of geometry
- Is usually modified/optimized by the driver
- We won’t talk here about other dirty driver tricks

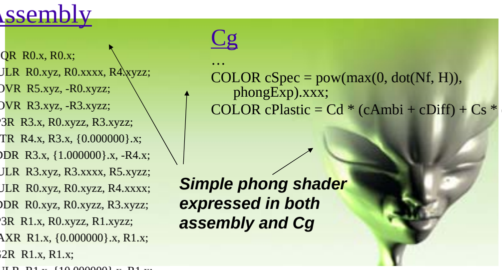
What Does Cg look like?

Assembly

```
…
RSQR  R0.x, R0.x;
MULR  R0.xyz, R0.xxxx, R4.xyzz;
MOVR  R5.xyz, -R0.xyzz;
MOVR  R3.xyz, -R3.xyzz;
DP3R  R3.x, R0.xyzz, R3.xyzz;
SLTR  R4.x, R3.x, {0.000000}.x;
ADDR  R3.x, {1.000000}.x, -R4.x;
MULR  R3.xyz, R3.xxxx, R5.xyzz;
MULR  R0.xyz, R0.xyzz, R4.xxxx;
ADDR  R0.xyz, R0.xyzz, R3.xyzz;
DP3R  R1.x, R0.xyzz, R1.xyzz;
MAXR  R1.x, {0.000000}.x, R1.x;
LG2R  R1.x, R1.x;
MULR  R1.x, {10.000000}.x, R1.x;
EX2R  R1.x, R1.x;
MOVR  R1.xyz, R1.xxxx;
MULR  R1.xyz, {0.900000, 0.800000, 1.000000}.xyzz, R1.xyzz;
DP3R  R0.x, R0.xyzz, R2.xyzz;
MAXR  R0.x, {0.000000}.x, R0.x;
```

Cg

```
…
COLOR cSpec = pow(max(0, dot(Nf, H)),
    phongExp).xxx;
COLOR cPlastic = Cd * (cAmbi + cDiff) + Cs * cSpec;
```



Simple phong shader expressed in both assembly and Cg

Cg Summary

- C-like language – expressive and efficient
- HW data types
- Vector and matrix operations
- Write separate vertex and fragment programs
- Connectors enable mix & match of programs by defining data flows
- Will be supported on any DX9 hardware
- Will support future HW (beyond NV30/DX9)

Brushed Metal

- Procedural texture
- Anisotropic lighting

Melting Ice

- Procedural, animating texture
- Bumped environment map

Toon & Fur

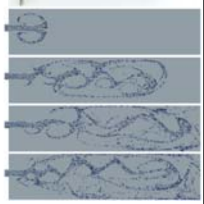
Vegetation & Thin Film

Translucence
Backlighting

Example of custom lighting
Simulates iridescence

General Purpose-computation on GPUs

- Hundreds of Gigaflops
  - Moore's law cubed
- Becomes programmable
  - Code executed for each vertex or each pixel
- Use for general-purpose computation
  - But tedious, low level, hacky
- Performances not always as good as hoped for

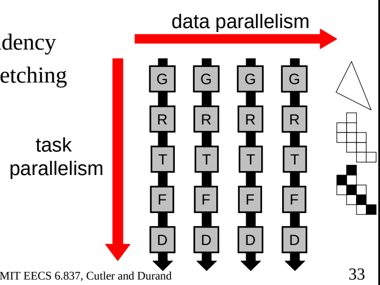


Navier-Stokes on GPU [Bolz et al.]

Questions?

Graphics Hardware

- High performance through
  - Parallelism
  - Specialization
  - No data dependency
  - Efficient pre-fetching



Modern Graphics Hardware

- A.k.a Graphics Processing Units (GPUs)
- Programmable geometry and fragment stages
- 600 million vertices/second, 6 billion texels/second
- In the range of tera operations/second
- Floating point operations only
- Very little cache

Modern Graphics Hardware

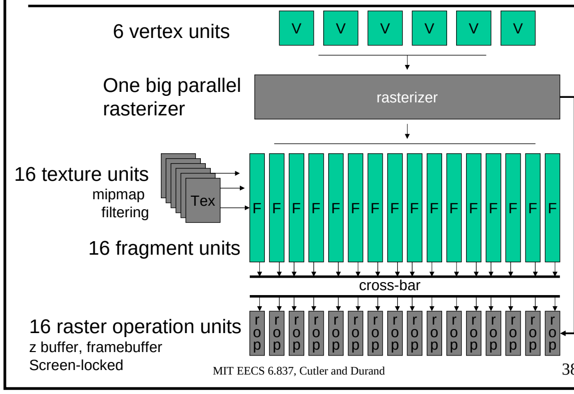
- About 4-6 geometry units
- About 16 fragment units
- Deep pipeline (~800 stages)
- Tiling of screen (about 4x4)
  - Early z-rejection if entire tile is occluded
- Pixels rasterized by quads (2x2 pixels)
  - Allows for derivatives
- Very efficient texture pre-fetching
  - And smart memory layout

Why is it so fast?

- All transistors do computation, little cache
- Parallelism
- Specialization (rasterizer, texture filtering)
- Arithmetic intensity
- Deep pipeline, latency hiding, prefetching
- Little data dependency
- In general, memory-access patterns

Questions?

Architecture



Total: 250 operations per vertex
150operations per fragment

520Mhz

160-220 Mtransistors

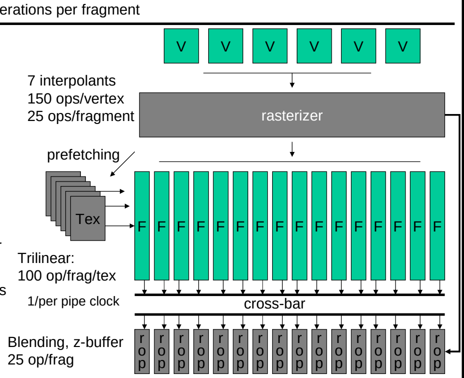
Peak pixel fill: 8.3GPixel/sec

Peak texture: 8.3GTexel/sec

-> 120GFlops

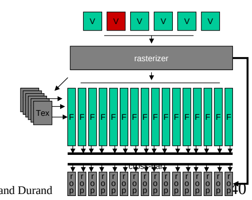
+ 41.6 GFlops in Fragment shader

Memory: 256 bit, 1.2GHz ->36GB/s



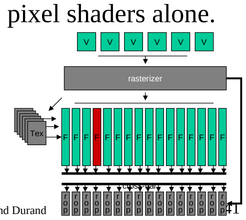
Vertex shading unit (ATI X800)

- One 128-bit vector ALU and one 32-bit scalar ALU.
- Total of 12 instructions per clock
- 28GFlops for the six units



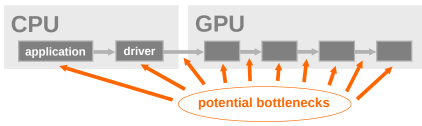
Pixel shading unit (ATI X800)

- Two vector ALU & two scalar ALUs + texture addressing unit.
- Up to five floating-point instructions per cycle
- In total (16 units) 80 floating-point ops per clock, or 41.6Gflops/sec from the pixel shaders alone.



Questions?

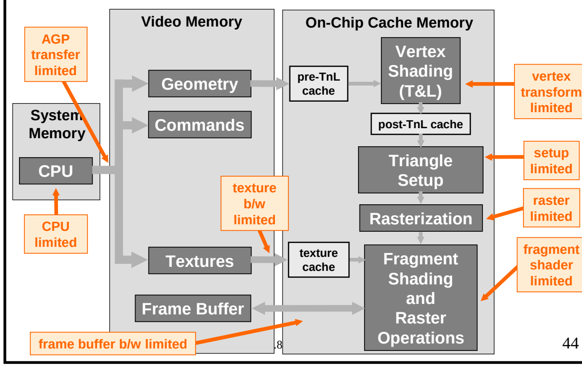
Bottlenecks?



- The bottleneck determines overall throughput
- In general, the bottleneck varies over the course of an application and even over a frame
- For pipeline architectures, getting good performance is all about finding and eliminating bottlenecks

Slide from NVidia

Potential Bottlenecks



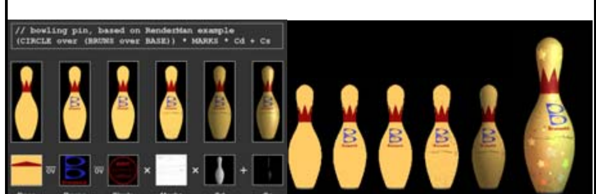
Rendering pipeline bottlenecks

- The term "transform/vertex/geometry bound" often means the bottleneck is "anywhere before the rasterizer"
- The term "fill/raster bound" often means the bottleneck is "anywhere after setup for rasterization" (computation of edge equations)
- Can be both transform and fill bound over the course of a single frame!

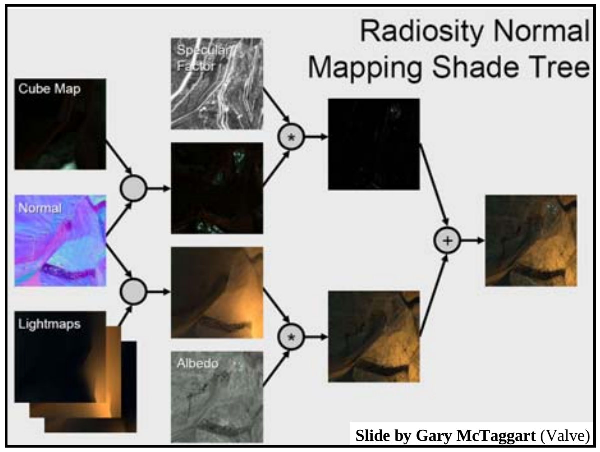
Questions?

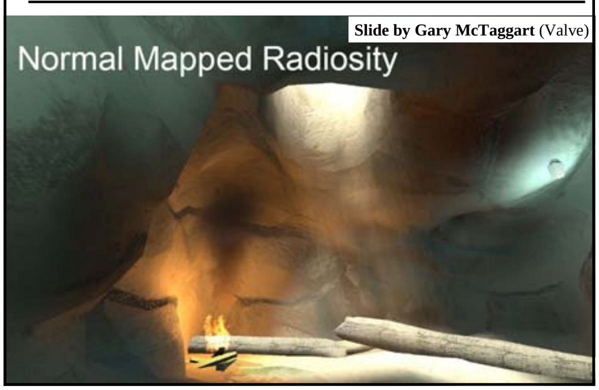
Shader zoo

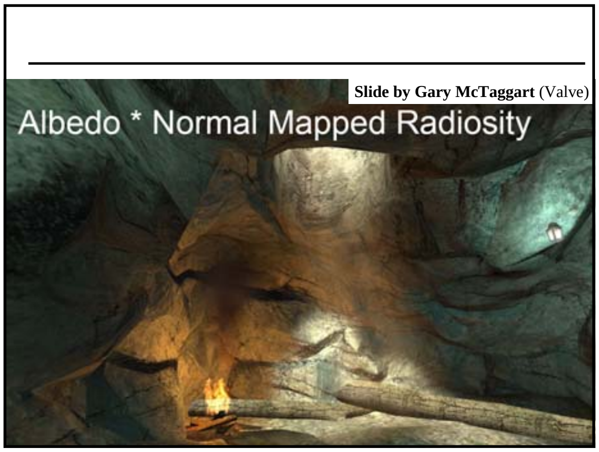
Layering

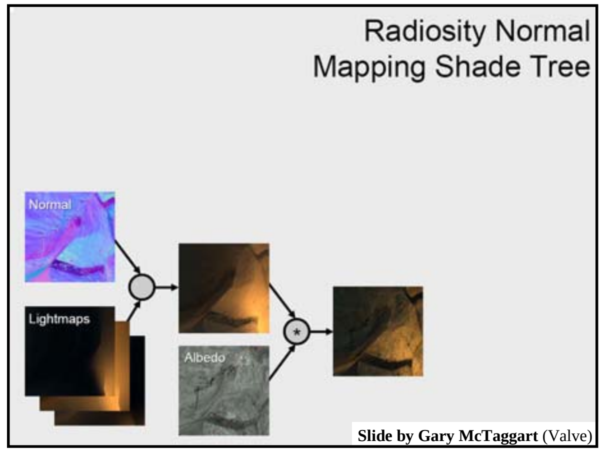


From Half Life 2 (Valve)



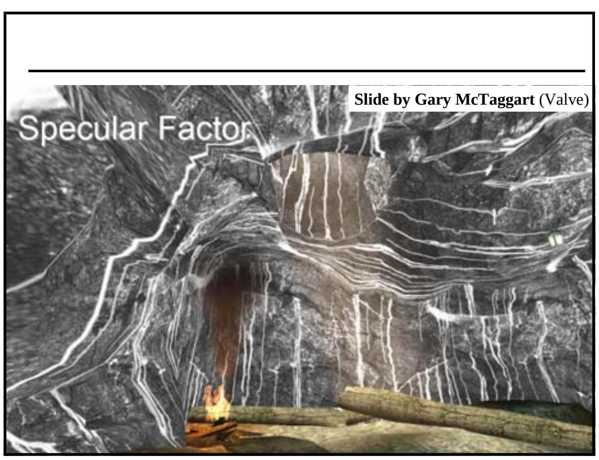



Slide by Gary McTaggart (Valve)
Albedo * Normal Mapped Radiosity

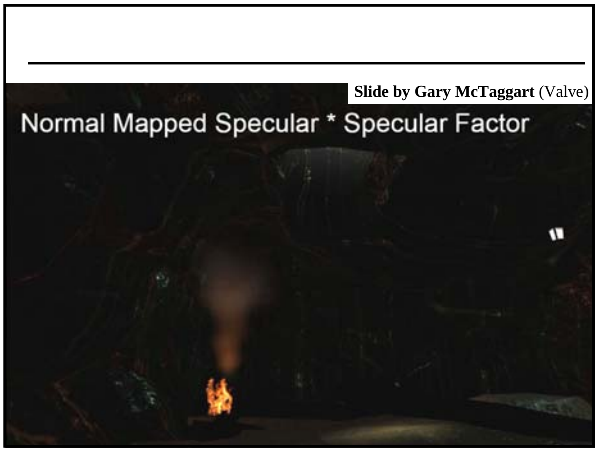

Radiosity Normal
Mapping Shade Tree
Normal
Lightmaps
Albedo
*
Slide by Gary McTaggart (Valve)

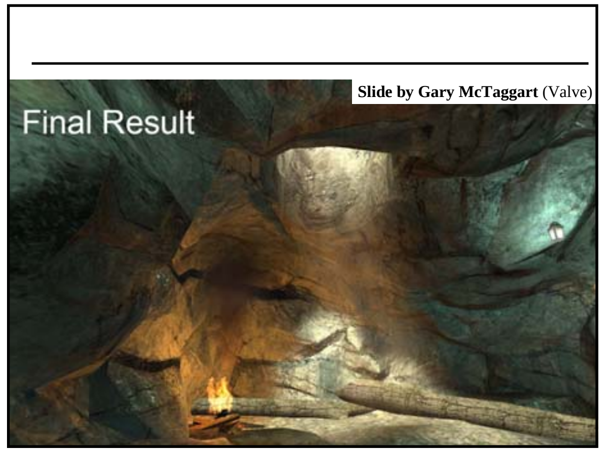

Slide by Gary McTaggart (Valve)
Cube Map Specular

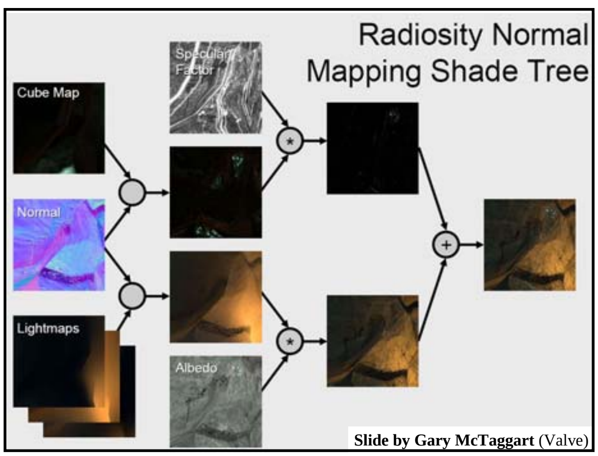

Slide by Gary McTaggart (Valve)
Normal Mapped Specular

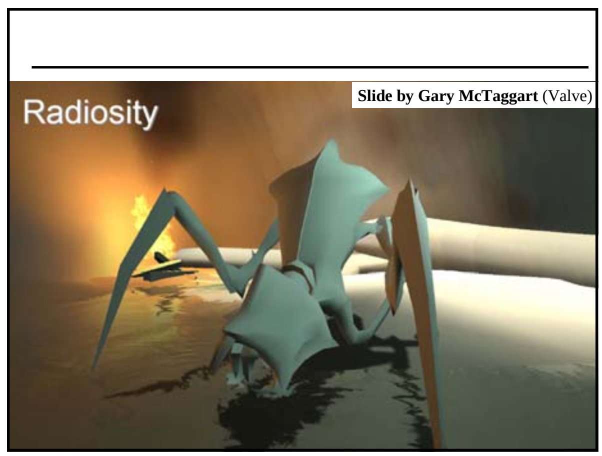

Slide by Gary McTaggart (Valve)
Specular Factor

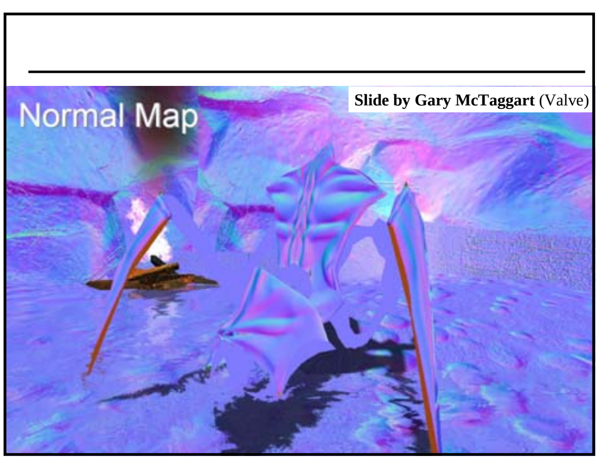

Slide by Gary McTaggart (Valve)
Normal Mapped Specular


Slide by Gary McTaggart (Valve)
Normal Mapped Specular * Specular Factor


Slide by Gary McTaggart (Valve)
Final Result


Radiosity Normal Mapping Shade Tree
Cube Map
Normal
Lightmaps
Specular Factor
Albedo
Slide by Gary McTaggart (Valve)

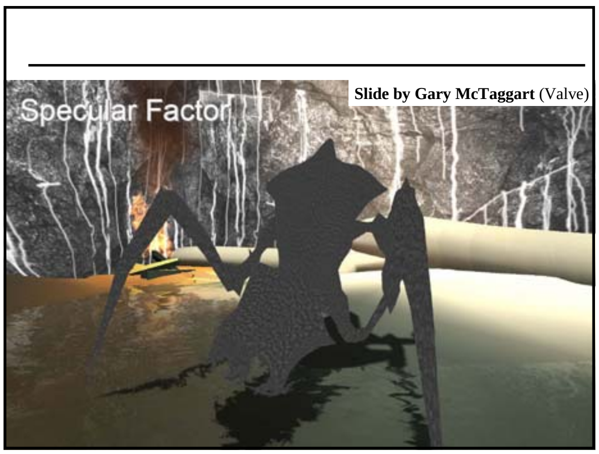

Slide by Gary McTaggart (Valve)
Radiosity


Slide by Gary McTaggart (Valve)
Normal Map


Slide by Gary McTaggart (Valve)
Albedo

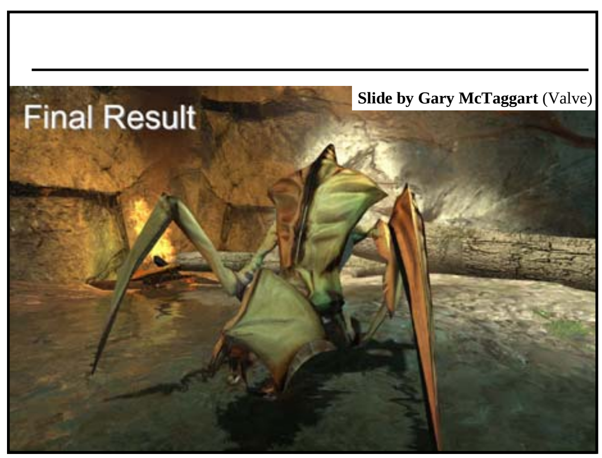

Slide by Gary McTaggart (Valve)
Albedo * Normal Mapped Radiosity


Slide by Gary McTaggart (Valve)
Normal Mapped Specular


Slide by Gary McTaggart (Valve)
Specular Factor


Slide by Gary McTaggart (Valve)
Normal Mapped Specular * Specular Factor


Slide by Gary McTaggart (Valve)
Albedo * Normal Mapped Radiosity

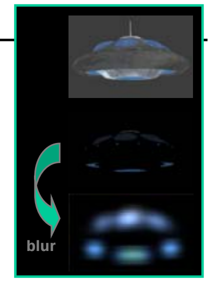

Slide by Gary McTaggart (Valve)
Final Result

Refraction mapping (multipass)

Slide by Gary McTaggart (Valve)

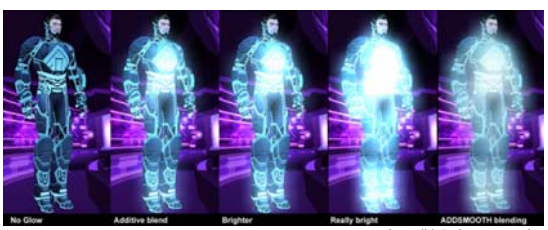
Image processing

- Start with ordinary model
  - Render to backbuffer
- Render parts that are the sources of glow
  - Render to offscreen texture
- Blur the texture
- Add blur to the scene



More glow

- From "Tron"



Assets courtesy of Monolith & Disney Interactive

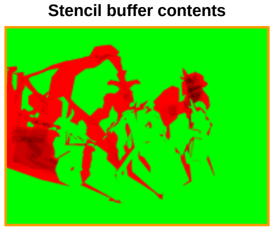
Vertex Shader: Blendshapes (1/2)

- Collected from Maya "Blendshape" node
- 50 faces
  - 30 emotion faces (angry, happy, sad…)
  - 20 modifiers (left eyebrow up, right smirk …)
- Each target stored as difference vector
- A blendshape is a single multiply-add
  - Per *active* blend target
  - Per attribute
  - Result is a weighted sum of all *active* targets
- An *active* blendshape takes vertex attributes
  - 12 * (coodinate)
  - 6 * (coordinate + normal)
  - 4 * (coordinate + normal + tangent)

Shadow Volumes

Shadowed scene

Stencil buffer contents



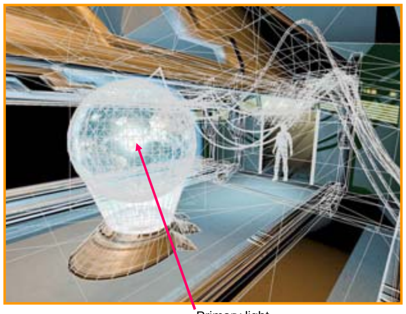
green = stencil value of 0
red = stencil value of 1
darker reds = stencil value > 1

Shadows in a Real Game Scene

CONTRABAND ENTERTAINMENT

Abducted game images courtesy Joe Riedel at Contraband Entertainment

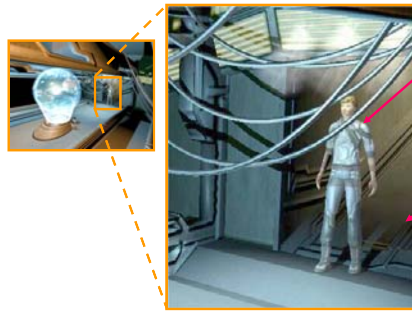
Scene's *Visible* Geometric Complexity



Wireframe shows geometric complexity of visible geometry

Primary light source location

Blow-up of Shadow Detail



Notice cable shadows on player model

Notice player's own shadow on floor

Scene's *Shadow Volume* Geometric Complexity

Wireframe shows geometric complexity of shadow volume geometry

Shadow volume geometry projects away from the light source

Visible Geometry vs. Shadow Volume Geometry

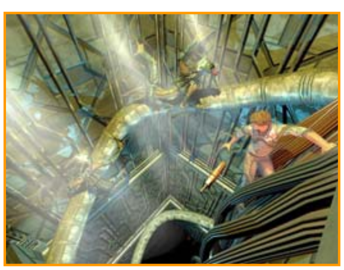
Visible geometry

<<

Shadow volume geometry

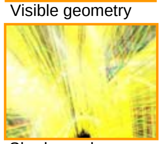
Typically, shadow volumes generate considerably more pixel updates than visible geometry

Other Example Scenes (1 of 2)



Dramatic chase scene with shadows

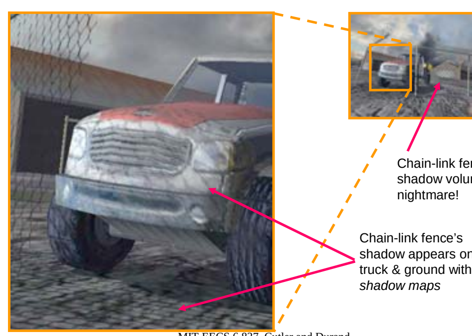
Visible geometry



Shadow volume geometry

Abducted game images courtesy Joe Riedel at Contraband Entertainment

Situations When Shadow Volumes Are Too Expensive



Chain-link fence is shadow volume nightmare!

Chain-link fence's shadow appears on truck & ground with *shadow maps*

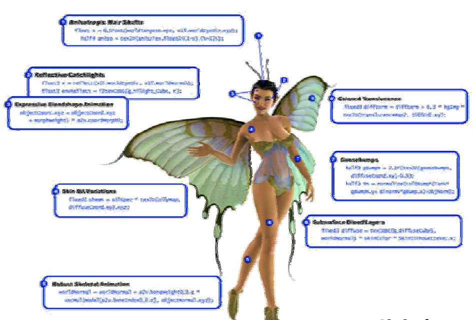
Fuel game image courtesy Nathan d'Obrenan at Firetoad Software

Shadow Volumes vs. Shadow Maps

- Shadow mapping via projective texturing
  - The other prominent hardware-accelerated shadow technique
- Shadow mapping advantages
  - Requires no explicit knowledge of object geometry
  - No 2-manifold requirements, etc.
  - View independent
- Shadow mapping disadvantages
  - Sampling artifacts
  - Not omni-directional

- http://www.graphics.stanford.edu/courses/cs448a-01-fall/
- http://www.ati.com/developer/techpapers.html
- http://developer.nvidia.com/page/documentation.html
  http://download.nvidia.com/developer/SDK/Individual_Samples/samples.html
  http://download.nvidia.com/developer/SDK/Individual_Samples/effects.html
  http://developer.nvidia.com/page/tools.html

Hardware Shading for Artists



Slide from NVidia

Computational Requirements

Application → Command → Geometry → Rasterization → Texture → Fragment → Display

Per-Vertex

ADD	CMP	MUL	DIV	SPE
102	30	108	5	1

Per-Fragment

ADD	CMP	MUL	DIV	SPE
66	9	70	1	3

Rough estimate

CS448 Lecture 2 Kurt Akeley, Pat Hanrahan, Fall 2001