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Advanced OpenGL[®] for the Java[™] Platform

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Presentation Goal

Demonstrate the latest 3D graphics techniques available through the OpenGL[®] API and the Java[™] programming language

Speakers' Qualifications

- **Kenneth Russell** works on the Java HotSpot™ Virtual Machine at Sun Microsystems and has nine years of 3D graphics experience
- **Christopher Kline** is a lead programmer for Irrational Games, makers of System Shock II and Freedom Force, and has over six years of 3D graphics experience
- **Gerard Ziemski** works on the graphics libraries for the Java™ platform at Apple Computer and has over four years of 3D graphics experience

Real-time Graphics in Transition

We are finally leaving behind the stone age of real-time 3D graphics programming.

Agenda

- What's new in real-time graphics?
- OpenGL interfaces for the Java™ platform
- Demos and Tutorials
 - Fixed-function pipeline
 - Programmable pipeline
 - Shadows
 - High-level shading languages

Real-time 3D Graphics Timeline

- Early 1990s: SGI and E&S pioneer dedicated (and expensive!) graphics hardware
- Late 1990s: VGA controllers make way for more powerful, mass-market GPUs
- GPU Generation 1 (< 1998): basic rasterization and texturing
- GPU Generation 2 (1999–2000): hardware T&L, better blending and texturing options
- GPU Generation 3 (2001): programmable (but limited) vertex and pixel shaders
- GPU Generation 4 (2002): floating point framebuffers, lengthy vertex and pixel shaders

Trend: Increasing Programmability

- Trend from *configurability* to *programmability*:
 - Fixed blending modes: limited configurability
 - Register combiners: more configurable
 - Vertex and fragment programs: finally, assembly-level control of transformation and shading
 - Now high-level languages and compilers
 - Soon: a unified data model; hardware support for loops and conditionals

What Does This Mean for Programmers?

- In the future, graphics programming will focus less on data management and configuration
- Innovation will be in the area of sophisticated visual effects algorithms
- Pixar and ILM-caliber effects are within the reach of the desktop
- Latest features are now available to the Java™ platform

OpenGL Interfaces for the Java™ Platform

- Several bindings available
 - “OpenGL, for Java™ Technology” (abbreviated “gl4java”)
 - LWJGL (Lightweight Java™ Game Library)
 - Magician
 - Jungle
- Brief discussion of each

OpenGL Interfaces for the Java™ Platform

- “OpenGL, for Java™ Technology”
(abbr. “gl4java”)
 - One of the oldest and most popular bindings
 - Runs on nearly every platform
 - Integrates with AWT and Swing
 - Supports, but not designed for, New I/O
 - Open source
 - Supports only up to OpenGL 1.3, but exposes vendor extensions
 - API is complex
 - Difficult to maintain and enhance

OpenGL Interfaces for the Java™ Platform

- LWJGL (Lightweight Java™ Game Library)
 - Supports latest features (OpenGL 1.4 with vendor extensions)
 - Innovative organization of extensions
 - Designed for New I/O
 - Additional support for audio (OpenAL) and game input devices
 - Supports full-screen rendering
 - Open source
 - Does not support AWT and Swing integration
 - Exposes pointers as longs
 - Destroys type safety

OpenGL Interfaces for the Java™ Platform

- Magician
 - Clean API
 - Integrated with AWT and Swing
 - Innovative composable pipeline (e.g., DebugGL)
 - Did not support New I/O
 - Defunct (no longer being developed or shipped)
 - Was never open source

OpenGL Interfaces for the Java™ Platform

- Jungle
 - New OpenGL interface for the Java™ platform
 - Supports OpenGL 1.4 and vendor extensions
 - Integrates with AWT and Swing
 - Designed for New I/O
 - Clean, minimalist API
 - Supports composable pipeline (e.g., DebugGL)
 - Open source
 - Written almost entirely in Java™ programming language
 - AWT Native Interface, WGL and GLX bound into Java™ programming language using GlueGen

OpenGL Interfaces for the Java™ Platform

- GlueGen
 - Parses C header files using ANTLR
 - Generates intermediate representation expressing primitive types, function prototypes, structs, unions and function pointers
 - Autogenerates Java™ programming language and JNI code
 - Powerful enough to bind AWT Native Interface back into Java programming language
 - Enabled Jungle to be written in Java programming language instead of C
 - Open source; part of Jungle package

OpenGL Interfaces for the Java™ Platform

- Jungle
 - Working in collaboration with Java™ Gaming Initiative
 - Has been adopted as JGI's OpenGL binding
 - Now named “Jogl”
 - Open source (modified BSD license)
 - Available from <http://jogl.dev.java.net/>

Demos and Techniques

- Illustrations of latest techniques
 - Demonstrations borrowed from several sources
 - Ported where necessary to Java™ programming language
 - Utilizing Jungle OpenGL interface

Overview of Demos and Tutorials

- Fixed-function pipeline
- Programmable pipeline
- High-level languages
- Larger demos

Fixed-function Pipeline

- Basically a “black box” that generates images according to a standard set of algorithms
- You supply the input data
 - Vertex attributes, connectivity, textures
- You configure the algorithm parameters
 - Transform matrices, blending modes, light colors, data formats, etc.
- No programmability, only configurability

Fixed-function Pipeline

- Why use the fixed-function pipeline?
 - Easy to understand
 - Best availability
 - Only option on legacy hardware
- Core OpenGL 1.3 and earlier
- Still powerful!

Example: The Virtual Fishtank

- Developed by Nearlife, Inc.
<http://www.nearlife.com/>
- Developed in 1998; now at the Boston Museum of Science, with a second installation in the St. Louis Science Center
- Museum exhibit designed to teach children about emergent self-organizing behavior within decentralized rule-based systems

Example: The Virtual Fishtank

- Distributed simulation running 15 networked machines, rendered on 13 large projection screens, simulating a 24,000 gallon aquarium
- Fish migrate from server to server as they swim from screen to screen
- Written entirely in Java™ programming language; Originally used Java™ 3D software, later ported to custom OpenGL-based renderer

Example: The Virtual Fishtank

DEMO



Programmable Pipeline

- What is the programmable pipeline?
 - Allows you to replace “black box” components of FF-pipeline with your own implementation
- What does it replace?
 - Vertex shaders
 - Transformation and lighting of vertices
 - Fragment shaders
 - Texturing, fog, color sum

Programmable Pipeline

- *Program* the rendering process instead of *configuring* it
- Wow, I can do anything I want to?
 - Yes, but if you choose to replace *anything*, you have to implement *everything*
 - Great power at the cost of great responsibility

Programmable Pipeline

- Why use the programmable pipeline?
 - Can be more efficient
 - Higher-quality results with less detailed geometry
 - Don't need multi-pass to accumulate intermediate results
 - Cut corners or customize to your needs
 - Do things that aren't possible with FF pipeline
 - Non-standard lighting models
 - Humans perceive detail by observing how light interacts with a surface
 - More control over light means more impressive graphics

Vertex Shaders

- Calculate all attributes of one particular vertex
 - No access to other vertices!
 - No hand holding: you must code all calculations yourself
 - Vertex position, normal, colors, texture coords, fog depth
- Additional input registers for arbitrary constants:
 - Transform matrices, light information, time, etc.
 - Parameters to your VS “function”

Vertex Shaders

- Output is used as input to fragment shader
 - Interpolated
- Assembly language syntax
 - Can be compiled from high-level language
 - Nvidia Cg
 - OpenGL GLSL
 - Microsoft DX9 HLSL

Vertex Shaders

- Example: 3-Component Normalize

```
#  
# Assume R1 = (nx,ny,nz)  
#  
# Calculate:  
# R0.xyz = normalize(R1)  
# R0.w    = 1/sqrt(nx*nx + ny*ny + nz*nz)  
#  
DP3 R0.w, R1, R1;  
RSQ R0.w, R0.w;  
MUL R0.xyz, R1, R0.w;
```

Vertex Shaders

- Can arbitrarily swizzle components of registers
 - No additional cost
 - Good for vector math operations
 - Save instructions, render faster
 - Impress your friends

Vertex Shaders

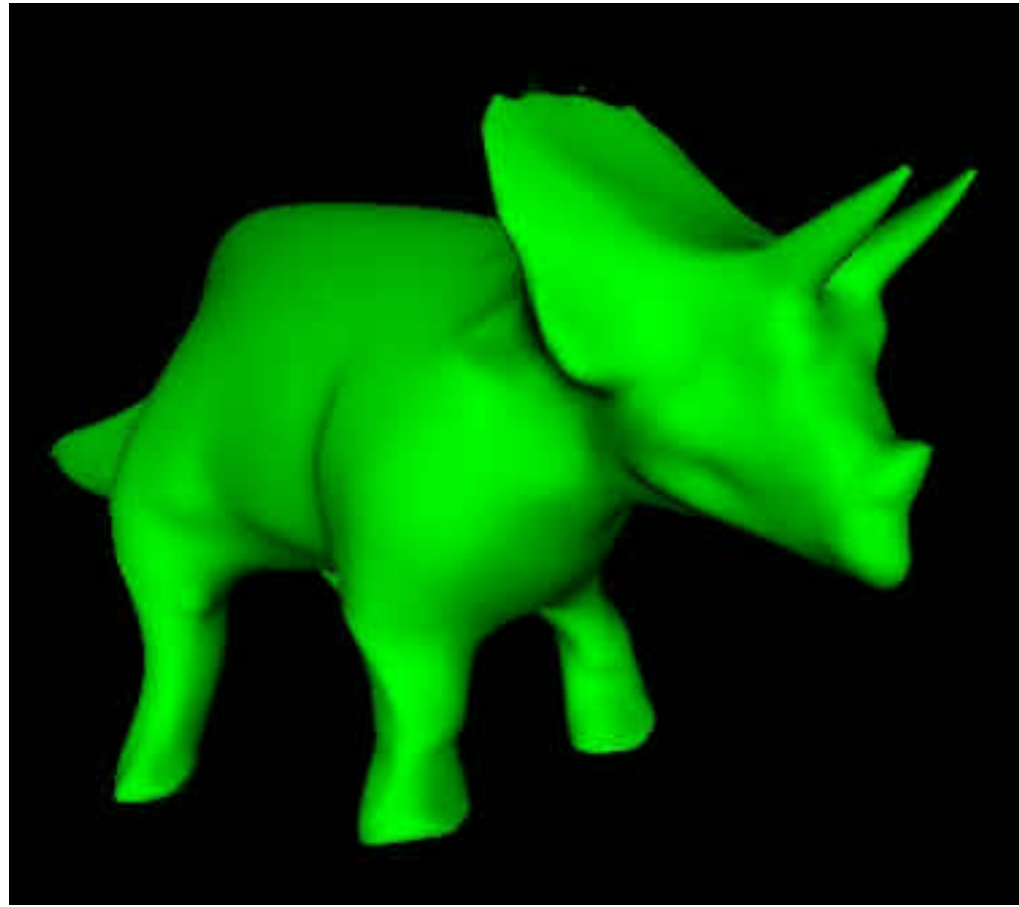
- Example: 3-Component Cross Product

```
# Calculate R2 = R0.cross(R1)
#
# Cross product |   i       j       k   | into R2.
#               | R0.x    R0.y    R0.z |
#               | R1.x    R1.y    R1.z |
#
#   R2.x = (R0.y*R1.z - R0.z*R1.y)
#   R2.y = (R0.z*R1.x - R0.x*R1.z)
#   R2.z = (R0.x*R1.y - R0.y*R1.x)
#
MUL R2,  R0.yzxw, R1.zxyw;      # Swizzle
MAD R2, -R1.yzxw, R0.zxyw, R2;  # Swizzle again
```

Vertex Shaders: vtxprog_warp

DEMO

Nvidia vtxprog_warp



Vertex Shaders: vtxprog_warp

- Several per-vertex distortion effects
 - Wave, fisheye, spherize, ripple, twist
- Static effects compute vertex's distance from center point and scale according to function
- Dynamic effects based mostly on sine waves
 - Computed ***on the GPU*** via Taylor series approximation to $\sin(x)$
- All effects' programs contain small snippet of code implementing diffuse lighting

Vertex Shaders: vtxprog_refract

DEMO

Nvidia vtxprog_refract

Vertex Shaders: vtxprog_refract

- Implements chromatic aberration through multipass rendering
 - Fresnel term determines fraction of light transmitted as opposed to reflected
 - Renders three times with fresnel terms modified for differing wavelengths of red, green and blue light
 - Causes slightly different distortion for each

Vertex Shaders: vtxprog_refract

- Vertex program computes approximation to reflection/refraction based on vertex's relative position and normal to eye
 - Approximation: only takes into account forward-facing triangles, not the depth of the surface
- Resulting rays are transformed into texture coordinates into surrounding cube map
- Provides blended reflection and refraction effects even in single pass and without fragment shaders

Vertex Shaders: ProceduralTexturePhysics

DEMO

Nvidia ProceduralTexturePhysics



Vertex Shaders: Procedural Texture Physics

- Performs physical simulation of water entirely on graphics card using texture maps as units of computation
- Every pixel affects its nearest neighbors
- Vertex program transforms vertices and produces initial sets of texture coordinates
- Offset texture coordinates used in conjunction with register combiners to perform approximation to integration of water forces
- Blur (convolution) smooths result

Fragment Shaders

- Calculate final visual appearance of one fragment
 - Operates on a rasterized pixel (a *fragment*)
 - Sometimes called *pixel shaders*
- Input:
 - Interpolated color, tex/fog coords, window position
 - Note: no world-space position, no normal!
 - Additional registers for arbitrary constants
- Output:
 - Color and depth of pixel

Fragment Shaders

- Similar to vertex shaders
 - No access to other pixels
 - Must roll your own shading code
 - Assembly syntax
- But different from vertex shaders
 - Texture sampler assembly instructions
 - No knowledge of geometry

Fragment Shaders

Example:

Modulate diffuse color by texture color

```
# sample texture color and load into R0
TEX R0, fragment.texcoord[0], texture[0], 2D;
# load diffuse color into R1
MOV R1, fragment.color.secondary;
# final color = diffuse * texture
MAD result.color, fragment.color.primary, R0, R1;
```

Fragment Shaders

Why No Standalone FS Demo?

- FS of limited utility without VS support
 - Remember, no knowledge of geometry
 - Can do tricks in normalized device coord space
 - Position-based fades and masks
 - Depth-based color (e.g., fake heat-vision)
 - To do really interesting things, need geometric information
 - Use VS to smuggle geometry data into FS

Combining Vertex and Fragment Shaders

- Work together in unison
 - VS writes geometry data into attributes that PS can access (secondary color, tex/fog coords)
 - PS reads this data to get geometry info
- Share the computational burden
 - VS calculates low-frequency (per vertex) data
 - PS calculates high-frequency (per pixel) data
- Good way to optimize performance

VS + FS Example: Phong Lighting

- Ubiquitous model in computer graphics
 - If it looks like plastic, it's probably Phong
- Simple idea
 - Surface should look shiniest where incident light is reflecting directly into your face
 - Less shiny as angle between reflected light and observer direction increases
 - Easy and efficient to implement
- OpenGL FF-pipeline vertex lighting is Phong variant

VS + FS Example: Phong Lighting

DEMO:

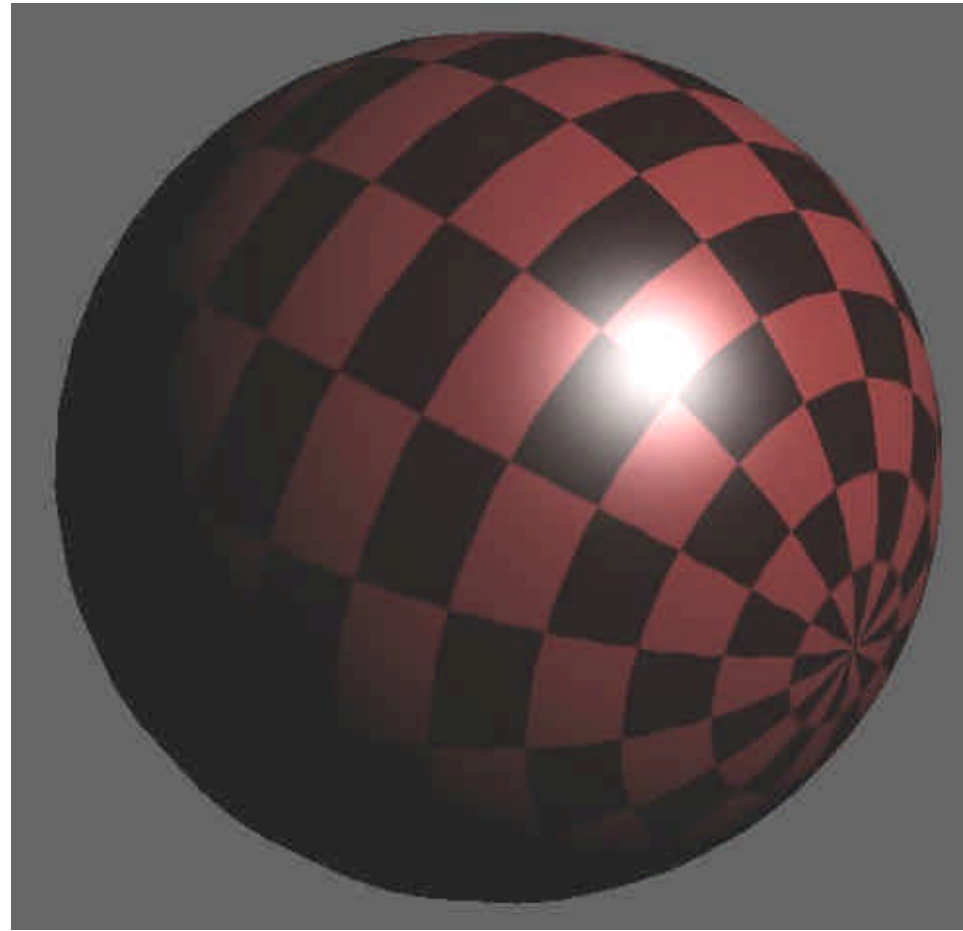
Cg Toolkit OpenGL Phong Lighting

- Vertex shader
 - Calculates vertex position and normal in eye space, stores in texture coordinate sets 0 and 1
- Fragment shader
 - Reads texture coordinates to retrieve (interpolated) eye-space position and normal of fragment
 - Reads light position passed in by program as “arbitrary constant”
 - Compares fragment position and normal with light position to calculate specular highlight intensity

VS + FS Example: Phong Lighting

DEMO

NVidia Cg Toolkit OpenGL
Phong Lighting



Shadows

- Why do we need shadows?
 - 1) Humans use shadows to infer spatial relationships
 - Relative positions of objects
 - Locations of light sources
 - Shape of an object
 - 2) Scene looks natural
 - 3) Scene is easier to understand

Shadows

- Why do we need shadows?

4) Technically speaking, shadows are “groovy”

Shadows

- Two basic categories
 - Render-to-texture
 - Image-space technique
 - Volumetric
 - Geometric technique

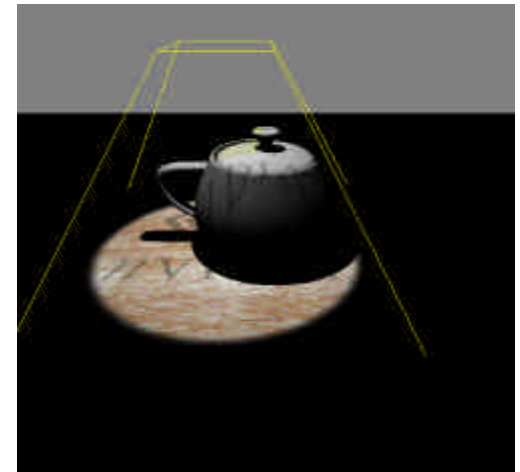
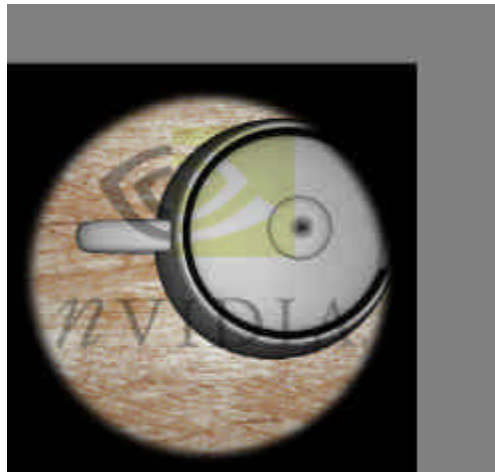
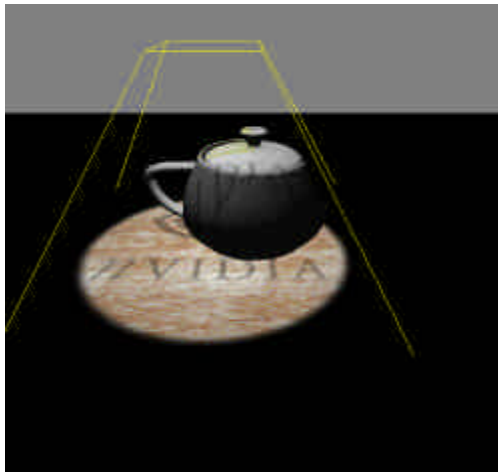
Render-to-texture Shadows

- Render the scene from the light's perspective
- Store depth of rendered scene as texture
- Render scene from the viewer's perspective
- Render the depth texture onto the scene
 - Careful setup of texture transform and texture-coord generation
 - Object's position maps to correct u-v texture coords in depth texture
 - Object's r texture coord maps to distance from the object to the light source
 - If r-value is greater than texture value, pixel is in shadow

Render-to-texture Shadows

DEMO

NVidia Hardware Shadow Mapping



Render-to-texture Shadows

Advantages

- Performance independent of geometric complexity
- No additional cost for animated geometry
- Can take into account alpha-masked geometry (example: a chain-link fence)

Render-to-texture Shadows

Disadvantages:

- Dependent on texture resolution (aliasing)
 - Not good for long projections
- Need special tricks to get self-shadowing to work well
- Older hardware may not support render-to-texture in hardware
 - Fall back to slow framebuffer->texture copy

Volumetric Shadows

Basic idea: Use geometry to calculate volume of space that is in shadow

- Calculate silhouette edge of object, from light's perspective
- Extrude the silhouette away from the light
- Objects inside this volume are in shadow from the light

Volumetric Shadows

Uses stencil buffer for per-pixel in/out test

- Render scene, ambient light only
 - Sets the depth buffer
- Render shadow volumes w/ stencil enabled
 - Render front/back faces separately
 - If pixel passes depth test, adjust stencil value
 - Many adjustment heuristics (z-pass, z-fail)
- If stencil value is 0 afterwards, pixel is not in shadow

Volumetric Shadows

DEMO:

NVidia Infinite Shadow Volumes



Volumetric Shadows

Advantages

- Self-shadowing “just works”
- No aliasing problems
 - Crisp shadows, even at infinite projection distances
 - Good for wide-open spaces

Volumetric Shadows

Disadvantages:

- Performance depends on scene
 - Expensive for complex objects, many lights, or many shadow receivers
 - $N \text{ lights} = N+1 \text{ render passes per shadowed object}$
 - Slow for non-static geometry/non-static lights
 - Silhouettes must be recalculated each frame
- Incorrect shadows cast from alpha-masked geometry
 - Purely geometric technique
- Many subtleties to make it work correctly for all intersections of light, viewer, and shadow volume

Shading Languages

- What is a shading language?
 - High-level language for programming vertex and fragment operations
 - Compiles down to low-level hardware representation (assembly)
 - Analogous to the relationship between C and Assembly

Shading Languages

- Why use a shading language?
 - Create and re-use code libraries
 - Borrow snippets from others
 - Can be platform-independent
 - Compile at run-time for target hardware
 - Cross-platform development, easier porting
 - Compiler is probably better at optimizing than you are

Shading Languages

- Why use a shading language?

It's just plain easier!

Shading Languages

- Many shading languages available today
 - NVidia Cg
 - Microsoft DirectX9 HLSL
 - OpenGL GLSL (soon)
- Derive from lots of prior art
 - Pixar RenderMan
 - Stanford Real-Time Shading Language
 - UNC PixelFlow

Shading Languages: Cg

- What is Cg?
 - Product of NVidia corporation
 - C-like language
 - Hardware-independent
 - Compiles to various forms of assembly for vertex and pixel shaders

Shading Languages: Cg

- Cg example: Phong lighting vertex shader

```
void main(float4 Pobject      : POSITION,
          float3 Nobject      : NORMAL,
          float2 TexUV        : TEXCOORD0,
          float3 diffuse      : TEXCOORD1,
          float3 specular     : TEXCOORD2,
          uniform float4x4 ModelViewProj,
          uniform float4x4 ModelView,
          uniform float4x4 ModelViewIT,

          out float4 HPosition : POSITION,
          out float3 Peye      : TEXCOORD0,
          out float3 Neye      : TEXCOORD1,
          out float2 uv        : TEXCOORD2,
          out float3 Kd         : COLOR0,
          out float3 Ks         : COLOR1) {
    // compute homogeneous position of vertex for rasterizer
    HPosition = mul(ModelViewProj, Pobject);
```

(Cont.)

Shading Languages: Cg

- Cg example: Phong lighting vertex shader

```
// transform position and normal from model-space
// to view-space
Peye = mul(ModelView, Pobject).xyz;
Neye = mul(ModelViewIT, float4(Nobject, 0)).xyz;

// pass uv, Kd, and Ks through unchanged;
// if they are varying per-vertex, however,
// they'll be interpolated before being
// passed to the fragment program.
uv = TexUV;
Kd = diffuse;
Ks = specular;
}
```

Shading Languages: Cg

- Cg Phong vertex shader, compiled:

```
!!ARBvp1.0
# ARB_vertex_program generated by NVIDIA Cg compiler
TEMP R0;
ATTRIB v26 = vertex.texcoord[2];
ATTRIB v25 = vertex.texcoord[1];
ATTRIB v24 = vertex.texcoord[0];
ATTRIB v18 = vertex.normal;
ATTRIB v16 = vertex.position;
PARAM c8[4] = { program.local[8..11] };
PARAM c4[4] = { program.local[4..7] };
PARAM c0[4] = { program.local[0..3] };
    MOV result.texcoord[2].xy, v24;
    MOV result.color.front.primary.xyz, v25;
    MOV result.color.front.secondary.xyz, v26;
    DP4 result.position.x, c0[0], v16;
    DP4 result.position.y, c0[1], v16;
    DP4 result.position.z, c0[2], v16;
    DP4 result.position.w, c0[3], v16;
```

(Cont.)

Shading Languages: Cg

- Cg Phong vertex shader, compiled:

```
DP4 result.texcoord[0].x, c4[0], v16;  
DP4 result.texcoord[0].y, c4[1], v16;  
DP4 result.texcoord[0].z, c4[2], v16;  
MOV R0.xyz, v18.xyzz;  
MOV R0.w, c12.x;  
DP4 result.texcoord[1].x, c8[0], R0;  
DP4 result.texcoord[1].y, c8[1], R0;  
DP4 result.texcoord[1].z, c8[2], R0;
```

END

Shading Languages: Cg

- Why use Cg?
 - OpenGL GLSL not yet available
 - Cg compiles for many different backends
 - OpenGL
 - Both ARB and vendor-specific shader extensions
 - DirectX 8 and 9
 - Cg comes with the Cg Runtime Library
 - Easy to load, compile, and set up your vertex and fragment shaders

Shading Languages: Cg

Demo:

NVidia Cg Bump Mapping Demo



Shading Languages: Cg

Demo:

NVidia Cg Bump Mapping Demo

- Vertex program computes texture coordinates into normal map given surface normal, tangent and binormal per-vertex
- Fragment program takes computed texture coordinates and looks up per-pixel surface normal in normal map
- Lighting done in fragment shader using 2D lookup table given lighting angle and half-angle

Dobie Demonstration

- Developed by the Synthetic Characters Group at The Media Lab, MIT
 - <http://www.media.mit.edu/characters/>
- Autonomous animated dog that can be trained with “clicker training” technique
 - Recognizes and uses utterances as cues for actions
 - Synthesizes new actions from novel paths through motion space
 - Learns through both positive and negative reinforcement

Dobie Demonstration

- Research is in models of motivations, actions and action selection, and learning
 - System written in Java™ programming language
 - Small amount of native code for custom input devices
 - Uses OpenGL as rendering API
 - Recently ported to Jungle
 - Runs on multiple operating systems
 - Macintosh OS X primary development platform

Dobie Demonstration

Demo



High Dynamic Range Rendering

Demo:

NVidia High Dynamic Range Rendering



High Dynamic Range Rendering

- NVidia High Dynamic Range Rendering Demo
 - Courtesy Simon Green, NVidia
- Normal 24-bit RGB images don't have enough *dynamic range* to represent natural scenes
 - 0–255 values can represent brightness variations of factor of 255
 - Natural scenes have brightness variations of factors of 10,000
 - Highlight of Sun on roof of car compared to shadow on asphalt underneath car

High Dynamic Range Rendering

- Represent textures as floating-point RGB values instead of bytes
- Convolution and similar operations in image space become analogues of real-world camera effects like focus
- Can now perform these image-space operations in real time using hardware accelerated offscreen rendering in conjunction with vertex and fragment shaders
 - All of this functionality now accessible from Java programming language
- Future of real-time computer graphics

