

Advanced Computer Graphics (Fall 2009)

CS 294, Rendering Lecture 7:
High Quality Real-Time Rendering

Ravi Ramamoorthi

<http://inst.eecs.berkeley.edu/~cs294-13/fa09>

Motivation

- Today, we create photorealistic computer graphics
 - Complex geometry, realistic lighting, materials, shadows
 - Computer-generated movies/special effects (difficult to tell real from rendered...)



- *But algorithms are very slow (hours to days)*

Real-Time Rendering

- Goal is interactive rendering. Critical in many apps
 - Games, visualization, computer-aided design, ...
- So far, focus on complex geometry



- *Chasm between interactivity, realism*

Evolution of 3D graphics rendering

Interactive 3D graphics pipeline as in OpenGL

- Earliest SGI machines (Clark 82) to today
- Most of focus on more geometry, texture mapping
- Some tweaks for realism (shadow mapping, accum. buffer)



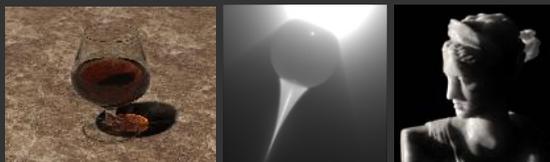
SGI Reality Engine 93
(Kurt Akeley)

Offline 3D Graphics Rendering

Ray tracing, radiosity, global illumination

- High realism (global illum, shadows, refraction, lighting,...)
- But historically very slow techniques

"So, while you and your children's children are waiting for ray tracing to take over the world, what do you do in the meantime?" Real-Time Rendering 1st ed.



Pictures courtesy Henrik Wann Jensen

New Trend: Acquired Data

- Image-Based Rendering: Real/precomputed images as input
- Also, acquire geometry, lighting, materials from real world
- Easy to obtain or precompute lots of high quality data. But how do we represent and reuse this for (real-time) rendering?



10 years ago

- High quality rendering: ray tracing, global illum., image-based rendering (This is what a rendering course would cover)
- Real-Time rendering: Interactive 3D geometry with simple texture mapping, maybe fake shadows (OpenGL, DirectX)
- Complex environment lighting, real materials (velvet, satin, paints), soft shadows, caustics often omitted in both
- *Realism, interactivity at cross purposes*

Today

- Vast increase in CPU power, modern instrs (SSE, Multi-Core)
 - Real-time raytracing techniques are possible
- 4th generation of graphics hardware is *programmable*
 - (First 3 gens were wireframe, shaded, textured)
 - Modern nVidia, ATI cards allow vertex, fragment shaders
- Great deal of current work on acquiring and rendering with realistic lighting, materials... [Especially at Berkeley]
- *Focus on quality of rendering, not quantity of polygons, texture*

Goals

- Overview of basic techniques for high-quality real-time rendering
- Survey of important concepts and ideas, but do not go into details of writing code
- Some pointers to resources, others on web
- One possibility for assignment 2, will need to think about some ideas on your own

Outline

- *Motivation and Demos*
- Programmable Graphics Pipeline
- Shadow Maps
- Environment Mapping

High quality real-time rendering

- Photorealism, not just more polygons
- Natural lighting, materials, shadows



Interiors by architect Frank Gehry. Note rich lighting, ranging from localized sources to reflections off vast sheets of glass.

High quality real-time rendering

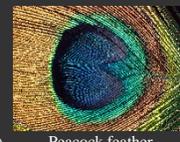
- Photorealism, not just more polygons
- Natural lighting, materials, shadows



Glass Vase



Glass Star (courtesy Intel)



Peacock feather

Real materials diverse and not easy to represent by simple parametric models. Want to support measured reflectance.

High quality real-time rendering

- Photorealism, not just more polygons
- Natural lighting, materials, shadows



small area light, sharp shadows
Agrawala et al. 00



soft and hard shadows
Ng et al. 03

Natural lighting creates a mix of soft diffuse and hard shadows.

Programmable Graphics Hardware



Precomputation-Based Methods

- Static geometry
- Precomputation
- Real-Time Rendering (relight all-frequency effects)
- Involves sophisticated representations, algorithms

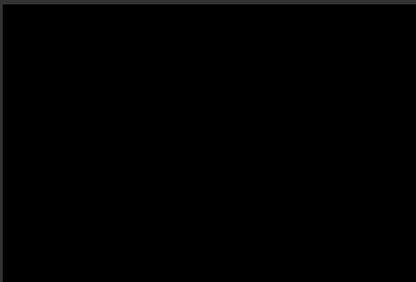


Relit Images



Ng, Ramamoorthi, Hanrahan 04

Video: Real-Time Relighting



Followed by demo with real-time relighting with caustics

Interactive RayTracing

Advantages

- Very complex scenes relatively easy (hierarchical bbox)
- Complex materials and shading for free
- Easy to add global illumination, specularities etc.

Disadvantages

- Hard to access data in memory-coherent way
- Many samples for complex lighting and materials
- Global illumination possible but expensive

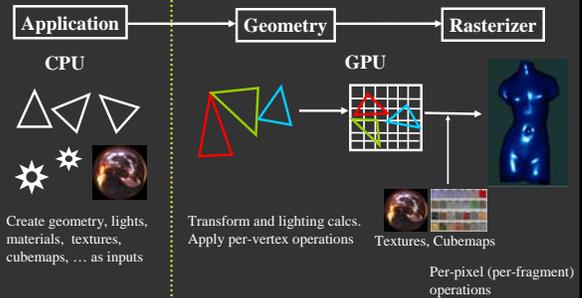
Modern developments: Leverage power of modern CPUs, develop cache-aware, parallel implementations

Demo <http://www.youtube.com/watch?v=blfxUlcVOzU>

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- Motivation and Demos
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Basic Hardware Pipeline



Geometry or Vertex Pipeline



These fixed function stages can be replaced by a general per-vertex calculation using vertex shaders in modern programmable hardware

Pixel or Fragment Pipeline



These fixed function stages can be replaced by a general per-fragment calculation using fragment shaders in modern programmable hardware

Shading Languages

- Vertex / Fragment shading described by small program
- Written in language similar to C but with restrictions
- Long history. Cook's paper on Shade Trees, Renderman for offline rendering
- Stanford Real-Time Shading Language, work at SGI
- Cg from NVIDIA, HLSL
- GLSL directly compatible with OpenGL 2.0 (So, you can just read the OpenGL Red Book to get started)

Shader Setup

```

    GLhandleARB phongVS, phongFS, phongProg; // handles to objects

    // Step 1: Create a vertex & fragment shader object
    phongVS = glCreateShaderObjectARB(GL_VERTEX_SHADER_ARB);
    phongFS = glCreateShaderObjectARB(GL_FRAGMENT_SHADER_ARB);

    // Step 2: Load source code strings into shaders
    glShaderSourceARB(phongVS, 1, &phongVS_String, NULL);
    glShaderSourceARB(phongFS, 1, &phongFS_String, NULL);

    // Step 3: Compile the vertex, fragment shaders.
    glCompileShaderARB(phongVS);
    glCompileShaderARB(phongFS);

    // Step 4: Create a program object
    phongProg = glCreateProgramObjectARB();

    // Step 5: Attach the two compiled shaders
    glAttachObjectARB(phongProg, phongVS);
    glAttachObjectARB(phongProg, phongFS);

    // Step 6: Link the program object
    glLinkProgramARB(phongProg);

    // Step 7: Finally, install program object as part of current state
    glUseProgramObjectARB(phongProg);
    
```

Cliff Lindsay web.cs.wpi.edu/~rich/courses/imgd4000-d09/lectures/gpu.pdf

Phong Shader: Vertex

This Shader Does

- Gives eye space location for v
- Transform Surface Normal
- Transform Vertex Location

```

varying vec3 N;
varying vec3 v;

void main(void)
{
    v = vec3(gl_ModelViewMatrix * gl_Vertex);
    N = normalize(gl_NormalMatrix * gl_Normal);
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
                
```

Created For Use Within Frag Shader

(Update OpenGL Built-in Variable for Vertex Position)

Cliff Lindsay web.cs.wpi.edu/~rich/courses/imgd4000-d09/lectures/gpu.pdf

Phong Shader: Fragment

```

-varying vec3 N;
-varying vec3 v;
void main (void)
{
    // we are in Eye Coordinates, so EyePos is (0,0,0)
    vec3 L = normalize(gl_LightSource[0].position.xyz - v);
    vec3 E = normalize(-v);
    vec3 R = normalize(-reflect(L,N));

    //calculate Ambient Term:
    vec4 lamb = gl_FrontLightProduct[0].ambient;

    //calculate Diffuse Term:
    vec4 ldiff = gl_FrontLightProduct[0].diffuse * max(dot(N,L), 0.0);

    // calculate Specular Term:
    vec4 lspec = gl_FrontLightProduct[0].specular
        * pow(max(dot(R,E),0.0), gl_FrontMaterial.shininess);

    // write Total Color:
    gl_FragColor = gl_FrontLightModelProduct.sceneColor + lamb + ldiff + lspec;
}
                
```

Passed in From VS

Cliff Lindsay web.cs.wpi.edu/~rich/courses/imgd4000-d09/lectures/gpu.pdf

Outline

- Motivation and Demos
- Programmable Graphics Pipeline
- *Shadow Maps*
- Environment Mapping

Shadow and Environment Maps

- Basic methods to add realism to interactive rendering
- Shadow maps: image-based way to add hard shadows
 - Very old technique. Originally Williams 78
 - Many recent (and older) extensions
 - Widely used even in software rendering (RenderMan)
 - Simple alternative to raytracing for shadows
- Environment maps: image-based complex lighting
 - Again, very old technique. Blinn and Newell 76
 - Huge amount of recent work
- Together, give many of realistic effects we want
 - **But cannot be easily combined!!**

Common Real-time Shadow Techniques

Projected planar shadows

Shadow volumes

Light maps

Hybrid approaches

This slide, others courtesy Mark Kilgard

Problems

Mostly tricks with lots of limitations

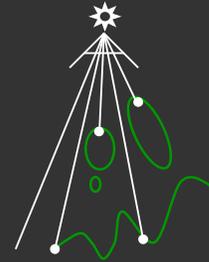
- Projected planar shadows
works well only on flat surfaces
- Stenciled shadow volumes
determining the shadow volume is hard work
- Light maps
totally unsuited for dynamic shadows
- In general, hard to get everything shadowing everything

Shadow Mapping

- Lance Williams: Brute Force in image space (shadow maps in 1978, but other similar ideas like Z buffer, bump mapping using textures and so on)
- Completely image-space algorithm
 - no knowledge of scene's geometry is required
 - must deal with aliasing artifacts
- Well known software rendering technique
 - Basic shadowing technique for Toy Story, etc.

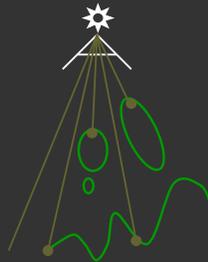
Phase 1: Render from Light

- Depth image from light source



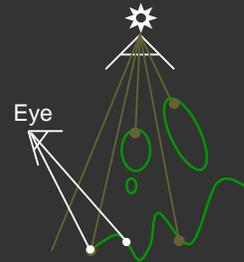
Phase 1: Render from Light

- Depth image from light source



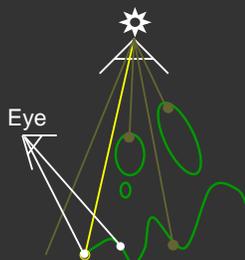
Phase 2: Render from Eye

- Standard image (with depth) from eye



Phase 2+: Project to light for shadows

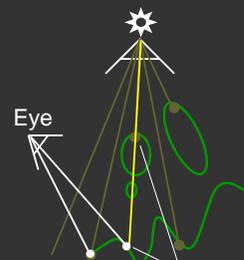
- Project visible points in eye view back to light source



(Reprojected) depths match for light and eye. VISIBLE

Phase 2+: Project to light for shadows

- Project visible points in eye view back to light source



(Reprojected) depths from light, eye not the same. BLOCKED!!

Visualizing Shadow Mapping

- A fairly complex scene with shadows

the point light source

Visualizing Shadow Mapping

with shadows without shadows

Visualizing Shadow Mapping

- The scene from the light's point-of-view

FYI: from the eye's point-of-view again

Visualizing Shadow Mapping

- The depth buffer from the light's point-of-view

FYI: from the light's point-of-view again

Visualizing Shadow Mapping

- Projecting the depth map onto the eye's view

FYI: depth map for light's point-of-view again

Visualizing Shadow Mapping

- Comparing light distance to light depth map

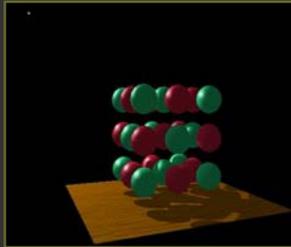
Green is where the light planar distance and the light depth map are approximately equal

Non-green is where shadows should be

Visualizing Shadow Mapping

- Scene with shadows

Notice how specular highlights never appear in shadows



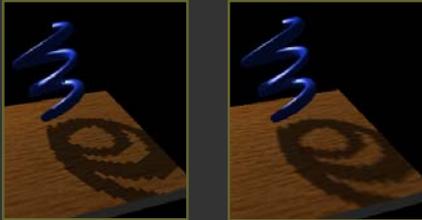
Notice how curved surfaces cast shadows on each other

Hardware Shadow Map Filtering

- Normal texture filtering just averages color components
- Averaging depth values does NOT work
- “Percentage Closer” filtering [Reeves 87]
 - Hardware performs comparison for each sample
 - Then, averages results of comparisons
 - Provides anti-aliasing at shadow map edges
 - Not soft shadows for umbra/penumbra case
 - But often used to fake soft shadows

Hardware Shadow Map Filtering

GL_NEAREST: blocky GL_LINEAR: antialiased edges



Low shadow map resolution used to heighten filtering artifacts

Problems with shadow maps

- Hard shadows (point lights only)
- Quality depends on shadow map resolution (general problem with image-based techniques)
- Involves equality comparison of floating point depth values means issues of scale, bias, tolerance
- Many recent extensions

Outline

- Motivation and Demos
- Programmable Graphics Pipeline
- Shadow Maps
- *Environment Mapping*

Reflection Maps



Blinn and Newell, 1976

Environment Maps




Miller and Hoffman, 1984
 Later, Greene 86, Cabral et al, Debevec 97, ...

Environment Maps

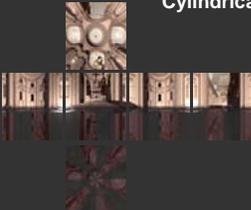
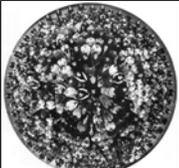


Interface, Chou and Williams (ca. 1985)

Environment Maps



Cylindrical Panoramas

Cubical Environment Map 180 degree fisheye
 Photo by R. Panko

Reflectance Maps

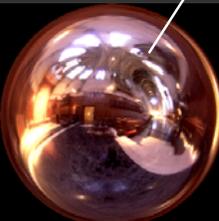
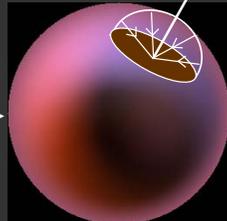
- Reflectance Maps (Index by N)
- Horn, 1977
- Irradiance (N) and Phong (R) Reflection Maps
- Miller and Hoffman, 1984





Mirror Sphere Chrome Sphere Matte Sphere

Irradiance Environment Maps

Incident Radiance (Illumination Environment Map) Irradiance Environment Map

Assumptions

- Diffuse surfaces
- Distant illumination
- No shadowing, interreflection

Hence, Irradiance a function of surface normal

Diffuse Reflection

$$B = \rho E$$

Radiosity (image intensity) Reflectance (albedo/texture) Irradiance (incoming light)

quake light map

Analytic Irradiance Formula

Lambertian surface acts like low-pass filter

$$E_{lm} = A_l L_{lm}$$

$A_l = 2\pi \frac{(-1)^{l+1}}{(l+2)(l-1)} \left[\frac{l!}{2^l (\frac{l}{2}!)^2} \right] \quad l \text{ even}$

Ramamoorthi and Hanrahan 01
Basri and Jacobs 01

9 Parameter Approximation

Exact image Order 0
1 term

RMS error = 25 %

$Y_{lm}(\theta, \varphi)$
 0 l m
 1 y z x
 2 xy yz $3z^2-1$ zx x^2-y^2
 -2 -1 0 1 2

9 Parameter Approximation

Exact image Order 1
4 terms

RMS Error = 8 %

$Y_{lm}(\theta, \varphi)$
 0 l m
 1 y z x
 2 xy yz $3z^2-1$ zx x^2-y^2
 -2 -1 0 1 2

9 Parameter Approximation

Exact image Order 2
9 terms

RMS Error = 1 %

For any illumination, average error < 3% [Basri Jacobs 01]

$Y_{lm}(\theta, \varphi)$
 0 l m
 1 y z x
 2 xy yz $3z^2-1$ zx x^2-y^2
 -2 -1 0 1 2

Real-Time Rendering

$$E(n) = n^t M n$$

Simple procedural rendering method (no textures)

- Requires only matrix-vector multiply and dot-product
- In software or NVIDIA vertex programming hardware

Widely used in Games (AMPED for Microsoft Xbox), Movies (Pixar, Framestore CFC, ...)

```

surface float1 irradat (matrix4 M, float3 v) {
    float4 n = { v, 1 };
    return dot(n, M*n);
}
  
```

Environment Map Summary

- Very popular for interactive rendering
- Extensions handle complex materials
- Shadows with precomputed transfer

- But cannot directly combine with shadow maps
- Limited to distant lighting assumption

Resources

- OpenGL red book (latest includes GLSL)
- Web tutorials: <http://www.lighthouse3d.com/opengl/glsl/>
- Older books: OpenGL Shading Language book (Rost), The Cg Tutorial, ...
- <http://www.realtimerendering.com>
 - Real-Time Rendering by Moller and Haines
- Debevec <http://www.debevec.org/ReflectionMapping/>
 - Links to Miller and Hoffman original, Haeberli/Segal
- <http://www.cs.berkeley.edu/~ravir/papers/envmap>
 - Also papers by Heidrich, Cabral, ...
- Lots of information available on web...