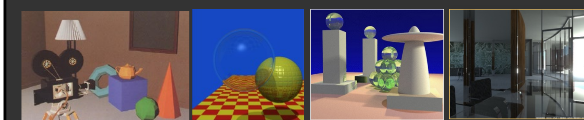
Computer Graphics II: Rendering

CSE 168 [Spr 25], Lectures 18/19: Real-Time Rendering
Ravi Ramamoorthi

http://viscomp.ucsd.edu/classes/cse168/sp25



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To Do

- Final Projects due Jun 10
- PLEASE FILL OUT SET EVALUATIONS!!
- KEEP WORKING HARD

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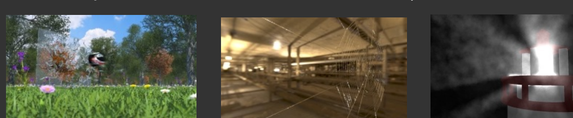
Motivation

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



  - CSE 168 images from rendering competition (2011)
- ***But algorithms were very slow (hours to days)***

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Real-Time Rendering

- Goal: interactive rendering. Critical in many apps
  - Games, visualization, computer-aided design, …
- Until 15-20 years ago, focus on complex geometry

- ***Chasm between interactivity, realism***

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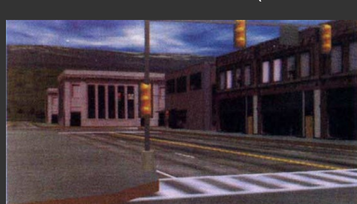
Evolution of 3D graphics rendering

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)

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Offline 3D Graphics Rendering

Ray tracing, radiosity, photon mapping
- 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

Pictures courtesy Henrik Wann Jensen

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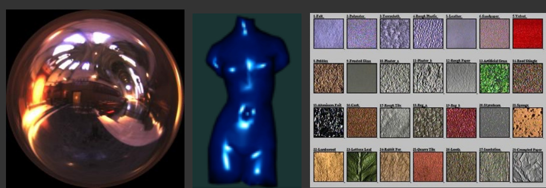
New Trend: Acquired Data

- 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?



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20 years ago

- High quality rendering: ray tracing, global illumination
  - Little change in CSE 168 syllabus, from 2003 to today
- Real-Time rendering: Interactive 3D geometry with simple texture mapping, fake shadows (OpenGL, DirectX)
- Complex environment lighting, real materials (velvet, satin, paints), soft shadows, caustics often omitted in both
- *Realism, interactivity at cross purposes*

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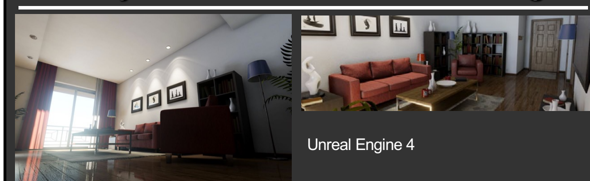
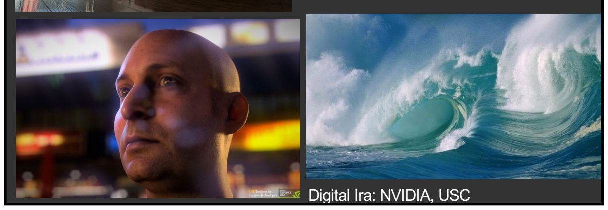
Today: Real-Time Game Renderings



Unreal Engine 4



Digital Ira: NVIDIA, USC

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Today

- Vast increase in CPU power, modern instrs (SSE, Multi-Core)
  - Real-time raytracing techniques are possible (even on hardware: NVIDIA OptiX, RTX Raytracing)
- 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 UCSD]
- *Focus on quality of rendering, not quantity of polygons, texture*

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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 final project, will need to think about some ideas on your own

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Outline

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

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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.

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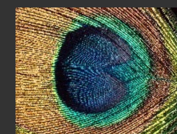
High quality real-time rendering

- 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 parameteric models. Want to support measured reflectance.

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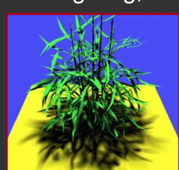
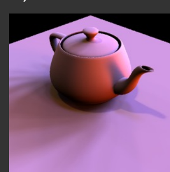
High quality real-time rendering

- 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.

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Today: Full Global Illumination

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Applications

- Entertainment: Lighting design
- Architectural visualization
- Material design: Automobile industry
- Realistic Video games
- Electronic commerce



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Programmable Graphics Hardware

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Programmable Graphics Hardware

NVIDIA a new dawn demo (may need to type URL)

- https://www.youtube.com/watch?v=bI1_quVr_3w

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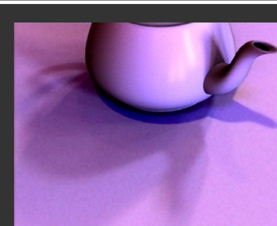
Precomputation-Based Methods

- Static geometry
- Precomputation



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

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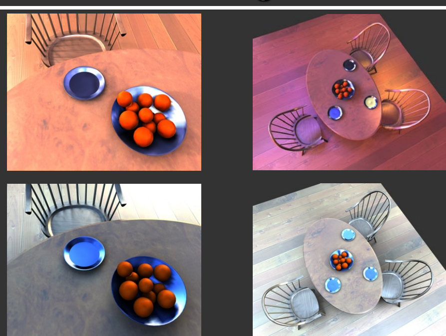
Relit Images



Ng, Ramamoorthi, Hanrahan 04

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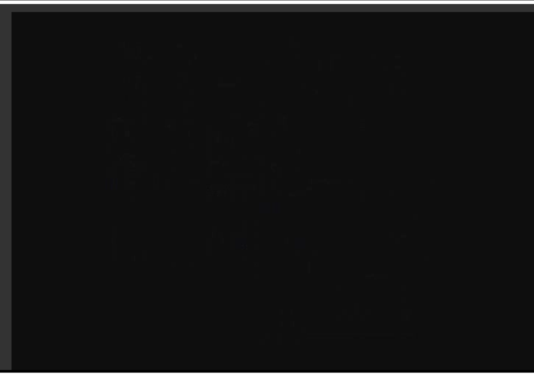
Video: Real Time Relighting



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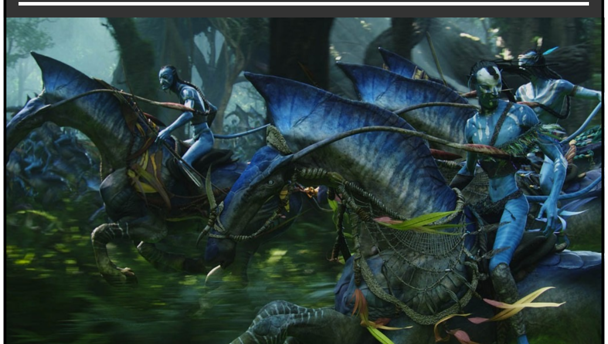
Spherical Harmonic Lighting



Avatar 2010, based on Ramamoorthi and Hanrahan 01, Sloan 02

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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

Recent developments make real-time raytracing mainstream (NVIDIA OptiX 5 in 2017, RTX chips in 2018, denoise, DLSS)

https://www.youtube.com/watch?v=kcP1NzB49zU

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NVIDIA RTX Real-Time RayTracing

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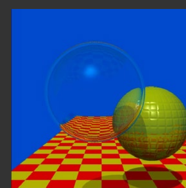
Impact: Real-Time

- Extend AAF, FSF, MAAF: Predict Filter based on Deep Learning (sample and AI-based denoising)
- NVIDIA software (OptiX 2017), hardware (RTX 2018)
- 40-year journey: ray tracing curiosity to every pixel


Whitted 79 (74 min 512x512)


NVIDIA RTX 2018, OptIX: Pixar real-time previewer

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From SIGGRAPH 18


Real Photo: Speaker and Turner Whitted at SIGGRAPH 18

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Outline

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

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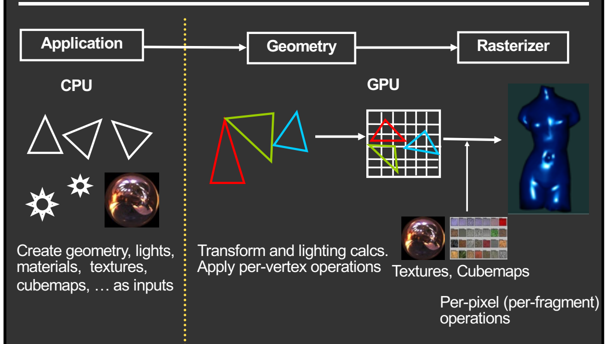
Basic Hardware Pipeline



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Geometry or Vertex Pipeline

Model, View Transform → Lighting → Projection → Clipping → Screen

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

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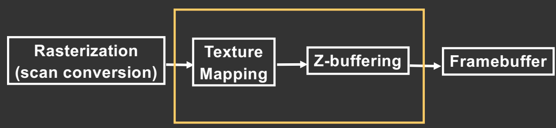
Pixel or Fragment Pipeline



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

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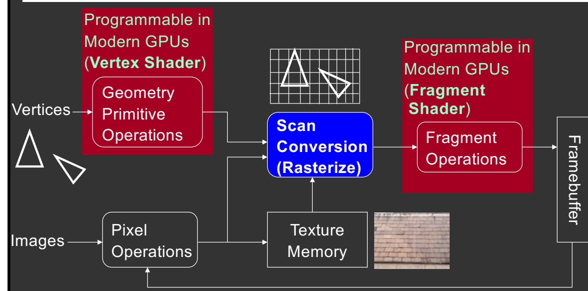
OpenGL Rendering Pipeline



Traditional Approach: Fixed function pipeline (state machine)
New Development (2003-): Programmable pipeline

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Simplified OpenGL Pipeline

- User specifies vertices (vertex buffer object)
- For each vertex in parallel
  - OpenGL calls user-specified vertex shader: Transform vertex (ModelView, Projection), other ops
- For each primitive, OpenGL rasterizes
  - Generates a *fragment* for each pixel the fragment covers
- For each fragment in parallel
  - OpenGL calls user-specified fragment shader: Shading and lighting calculations
  - OpenGL handles z-buffer depth test unless overwritten
- Modern OpenGL is "lite" basically just a rasterizer
  - "Real" action in user-defined vertex, fragment shaders

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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)

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Shader Setup

- Initializing (shader itself discussed later)

1. Create shader (Vertex and Fragment)
2. Compile shader
3. Attach shader to program
4. Link program
5. Use program

- Shader source is just sequence of strings
- Similar steps to compile a normal program

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Shader Initialization Code

```
GLuint initshaders (GLenum type, const char *filename) {
  // Using GLSL shaders, OpenGL book, page 679
  GLuint shader = glCreateShader(type) ;
  GLint compiled ;
  string str = textFileRead (filename) ;
  GLchar * cstr = new GLchar[str.size()+1] ;
  const GLchar * cstr2 = cstr ; // Weirdness to get a const char
  strcpy(cstr,str.c_str()) ;
  glShaderSource (shader, 1, &cstr2, NULL) ;
  glCompileShader (shader) ;
  glGetShaderiv (shader, GL_COMPILE_STATUS, &compiled) ;
  if (!compiled) {
    shadererrors (shader) ;
    throw 3 ;
  }
  return shader ;
}
```

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Linking Shader Program

```
GLuint initprogram (GLuint vertexshader, GLuint fragmentshader)
{
  GLuint program = glCreateProgram() ;
  GLint linked ;
  glAttachShader(program, vertexshader) ;
  glAttachShader(program, fragmentshader) ;
  glLinkProgram(program) ;
  glGetProgramiv(program, GL_LINK_STATUS, &linked) ;
  if (linked) glUseProgram(program) ;
  else {
    programerrors(program) ;
    throw 4 ;
  }
  return program ;
}
```

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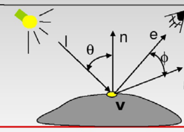
Phong Shader: Vertex

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

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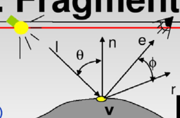
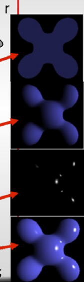
Phong Shader: Fragment

```
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 Iamb = gl_FrontLightProduct[0].ambient;

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

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

  // write Total Color:
  gl_FragColor = gl_FrontLightModelProduct.sceneColor + Iamb + Idiff + Ispec;
}
```

Passed In From VS





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

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Fragment Shader Compute Lighting

```
vec4 ComputeLight (const in vec3 direction, const in vec4
   lightcolor, const in vec3 normal, const in vec3 halfvec, const
   in vec4 mydiffuse, const in vec4 myspecular, const in float
   myshininess) {

     float nDotL = dot(normal, direction)  ;
     vec4 lambert = mydiffuse * lightcolor * max (nDotL, 0.0) ;

     float nDotH = dot(normal, halfvec) ;
     vec4 phong = myspecular * lightcolor * pow (max(nDotH, 0.0),
   myshininess) ;

     vec4 retval = lambert + phong ;
     return retval ;
}
```

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Outline

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

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Shadow and Environment Maps

- Basic methods to add realism to interactive rendering
- Shadow maps: image-based way 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 (some covered in course)
- Together, give most of realistic effects we want
  - **But cannot be easily combined!!**
  - See Annen 08 [real-time all-frequency shadows dynamic scenes] for one approach: convolution soft shadows

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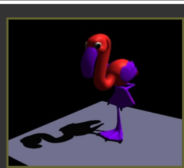
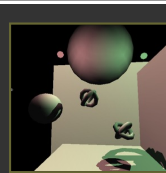
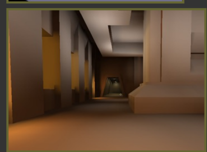
Common Real-time Shadow Techniques



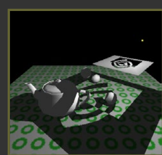
Projected planar shadows



Shadow volumes



Light maps



Hybrid approaches

This slide, others courtesy Mark Kilgard

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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

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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.

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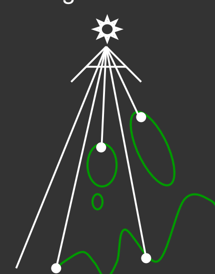
Phase 1: Render from Light

- Depth image from light source



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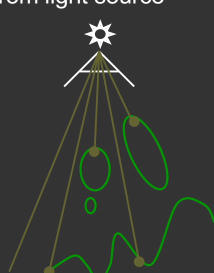
Phase 1: Render from Light

- Depth image from light source



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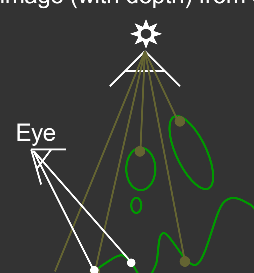
Phase 2: Render from Eye

- Standard image (with depth) from eye



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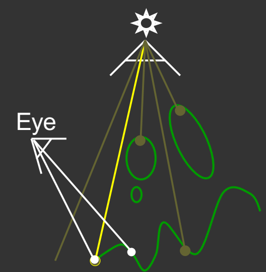
Phase 2+: Project to light for shadows

- Project visible points in eye view back to light source



(Reprojected) depths match for light and eye. VISIBLE

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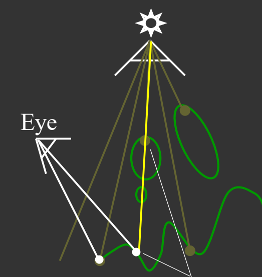
Phase 2+: Project to light for shadows

- Project visible points in eye view back to light source



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

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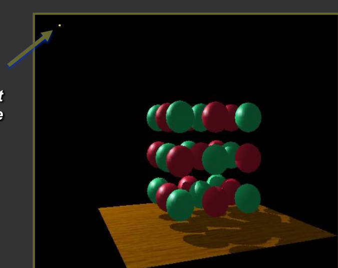
Visualizing Shadow Mapping

- A fairly complex scene with shadows

the point light source



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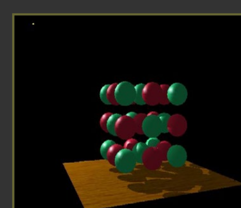
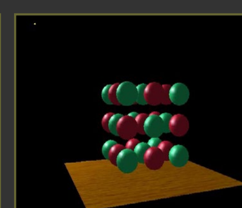
Visualizing Shadow Mapping

- Compare with and without shadows



with shadows



without shadows

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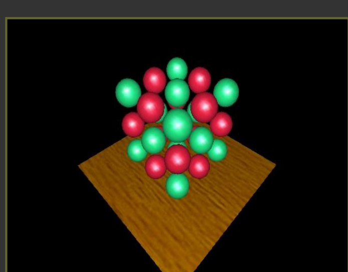
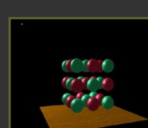
Visualizing Shadow Mapping

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





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

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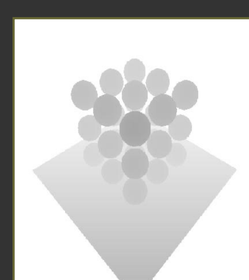
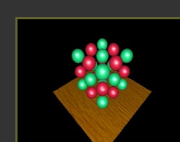
Visualizing Shadow Mapping

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





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

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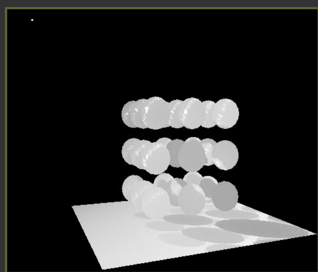
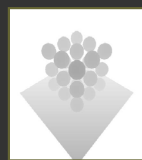
Visualizing Shadow Mapping

- Projecting the depth map onto the eye's view





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

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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

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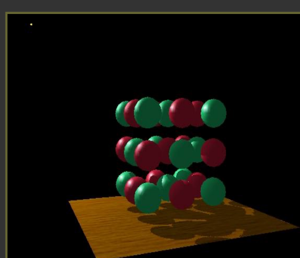
Visualizing Shadow Mapping

- Scene with shadows

Notice how specular highlights never appear in shadows



Notice how curved surfaces cast shadows on each other

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Hardware Shadow Map Filtering

"Percentage Closer" filtering

- Normal texture filtering just averages color components
- Averaging depth values does NOT work
- Solution [Reeves, SIGGRAPH 87]
  - Hardware performs comparison for each sample
  - Then, averages results of comparisons
- Provides anti-aliasing at shadow map edges
  - Not soft shadows in the umbra/penumbra sense

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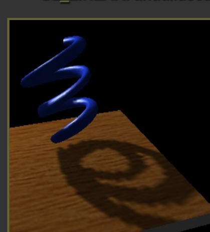
Hardware Shadow Map Filtering

GL_NEAREST: blocky

GL_LINEAR: antialiased edges



Low shadow map resolution used to heighten filtering artifacts

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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

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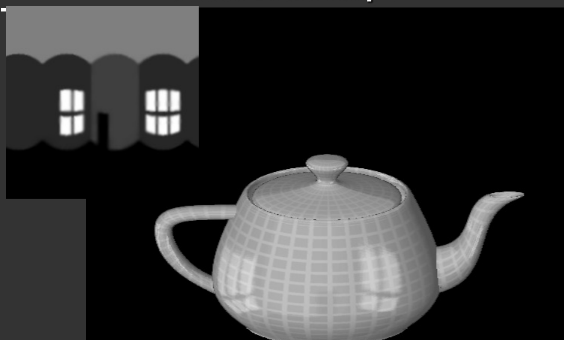
Reflection Maps



Blinn and Newell, 1976

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Environment Maps

Miller and Hoffman, 1984

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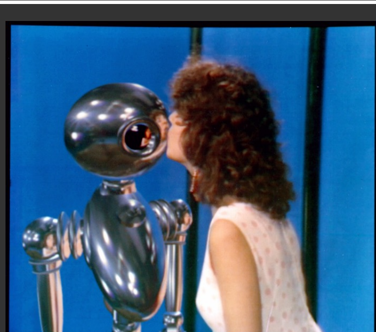
Environment Maps



Interface, Chou and Williams (ca. 1985)

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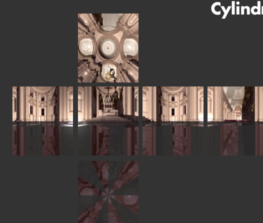
Environment Maps

Cylindrical Panoramas



Cubical Environment Map

180 degree fisheye
Photo by R. Packo

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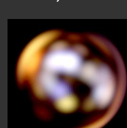
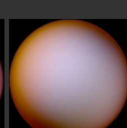
Reflectance Maps

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

Mirror Sphere



Chrome Sphere



Matte Sphere

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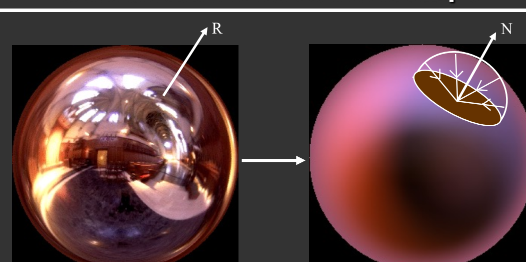
Irradiance Environment Maps



Incident Radiance
(Illumination Environment Map)

Irradiance Environment Map

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Assumptions

- Diffuse surfaces
- Distant illumination
- No shadowing, interreflection

Hence, Irradiance a function of surface normal

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Diffuse Reflection

$$B = \rho E$$

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

quake light map

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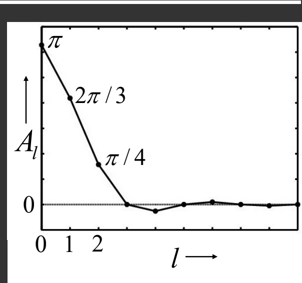
Analytic Irradiance Formula

Lambertian surface acts like low-pass filter

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



Ramamoorthi and Hanrahan 01
Basri and Jacobs 01

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

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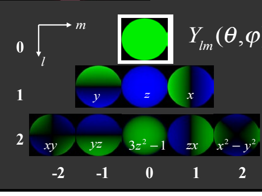
9 Parameter Approximation

Exact image

Order 0
1 term

RMS error = 25 %



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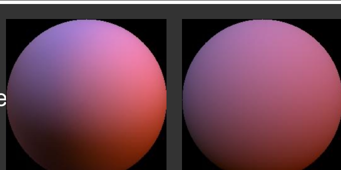
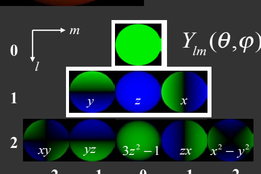
9 Parameter Approximation

Exact image



Order 1
4 terms

RMS Error = 8%



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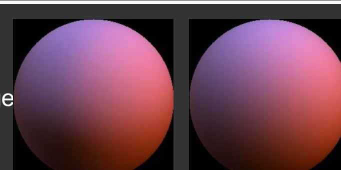
9 Parameter Approximation

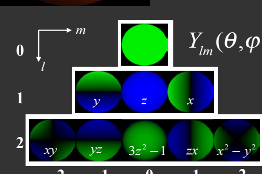
Exact image



Order 2
9 terms

RMS Error = 1%

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



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

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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

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Resources

- OpenGL red book (latest includes GLSL)
- Web tutorials: http://www.lighthouse3d.com/tutorials/
- 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.ucsd.edu/~ravir/papers/envmap
  - Also papers by Heidrich, Cabral, …
- Lots of information available on web…
- Look at resources from CSE 274 website (Wi, Fa 15)

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