Real-Time Rendering

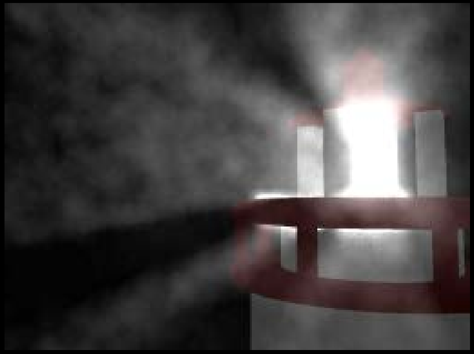
COS 526: Advanced Computer Graphics

PRINCETON UNIVERSITY

Slide credits: Ravi Ramamoorthi

Motivation

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



- ***But algorithms are slow (minutes, hours, days)***

Real-Time Rendering

- Goal: interactive rendering. Critical in many apps
  - Games, visualization, computer-aided design, …
- Until 10-15 years ago, 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)

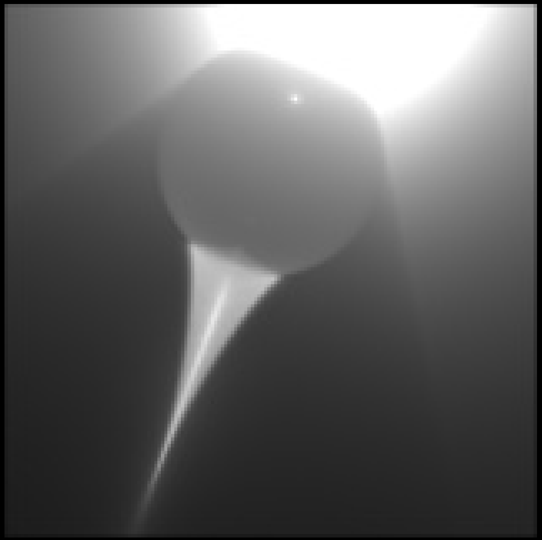
SGI Reality Engine 93
(Kurt Akeley)

Offline 3D Graphics Rendering

Ray tracing, radiosity, photon mapping

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

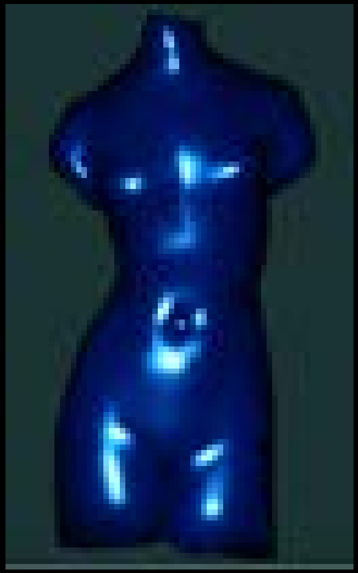
"So, while you and your children's children are waiting for ray tracing to take over the world, what do you do in the meantime?" Real-Time Rendering


Pictures courtesy Henrik Wann Jensen

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?



15 years ago

- High quality rendering: ray tracing, global illumination
  - Little change in COS 426 syllabus over the past 15 years
- 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*

Today: Real-Time Game Renderings

Unreal Engine 4
https://www.youtube.com/watch?v=gtHamLNPXyk#t=33

Digital Ira: NVIDIA, USC

Today

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

Goals

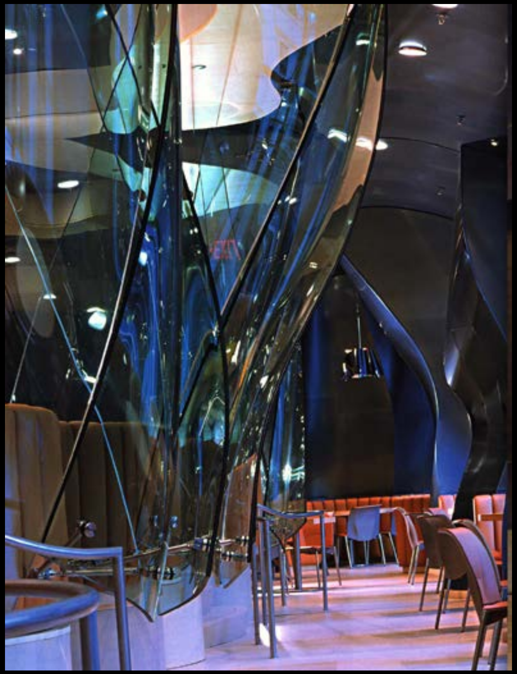
- Overview of basic techniques for high-quality real-time rendering
- Survey of important concepts and ideas, but do not go into details of writing code
- Some pointers to resources, others on web

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



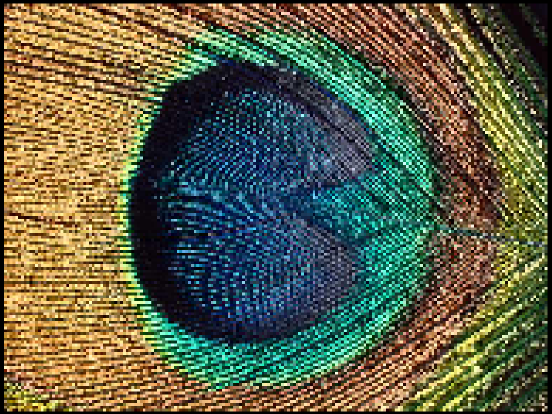
Interiors by architect Frank Gehry. Note rich lighting, ranging from localized sources to reflections off vast sheets of glass.

High quality real-time rendering

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


Glass Vase

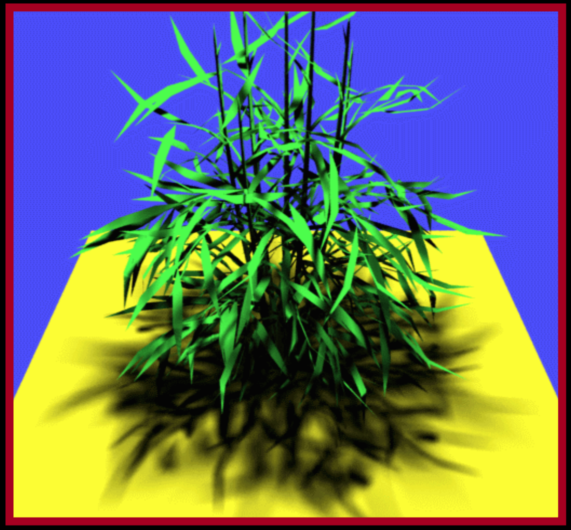

Glass Star (courtesy Intel)


Peacock feather

Real materials diverse and not easy to represent by simple parameteric 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.

Today: Full Global Illumination

Applications

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



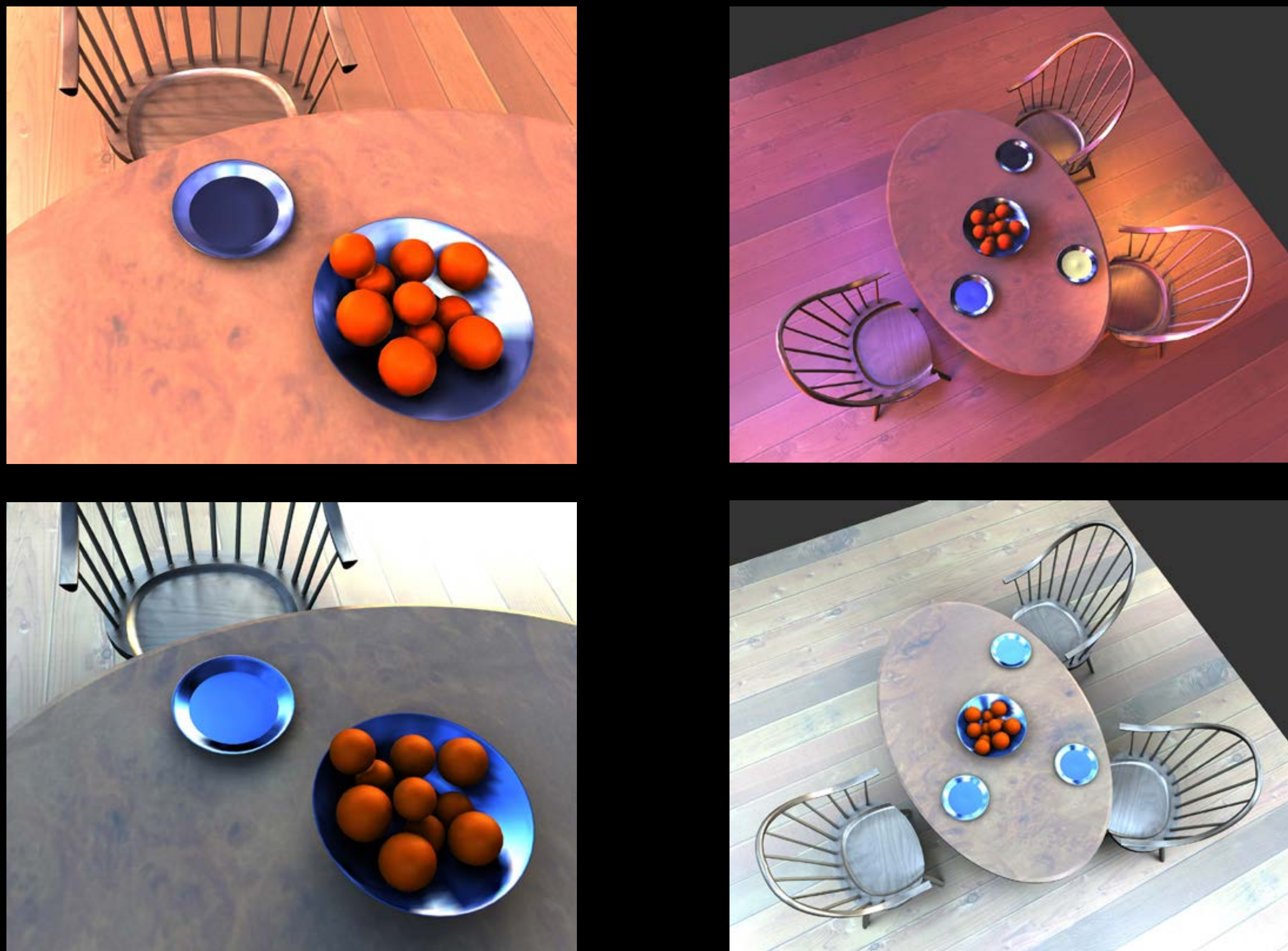
Programmable Graphics Hardware (circa 2008)

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

Spherical Harmonic Lighting

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

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

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

Sparse Sampling, Reconstruction

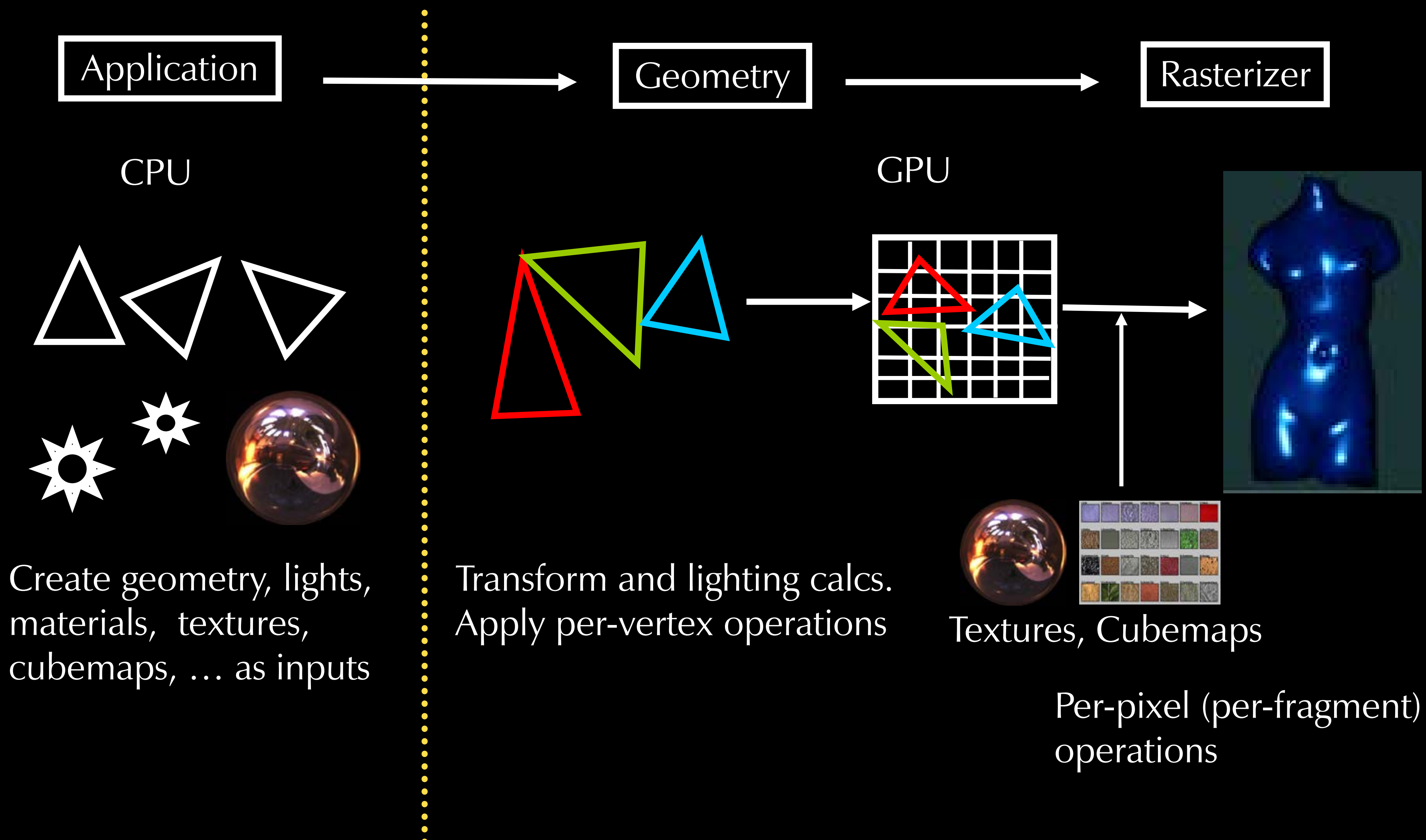
- Same algorithm as offline Monte Carlo rendering
- But with smart sampling and filtering (current work)

Sparse Sampling, Reconstruction

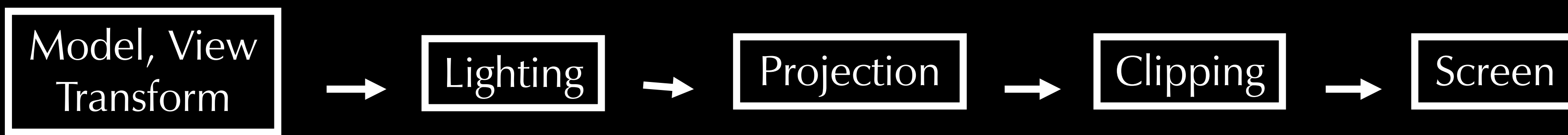
Outline

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

Basic Hardware Pipeline

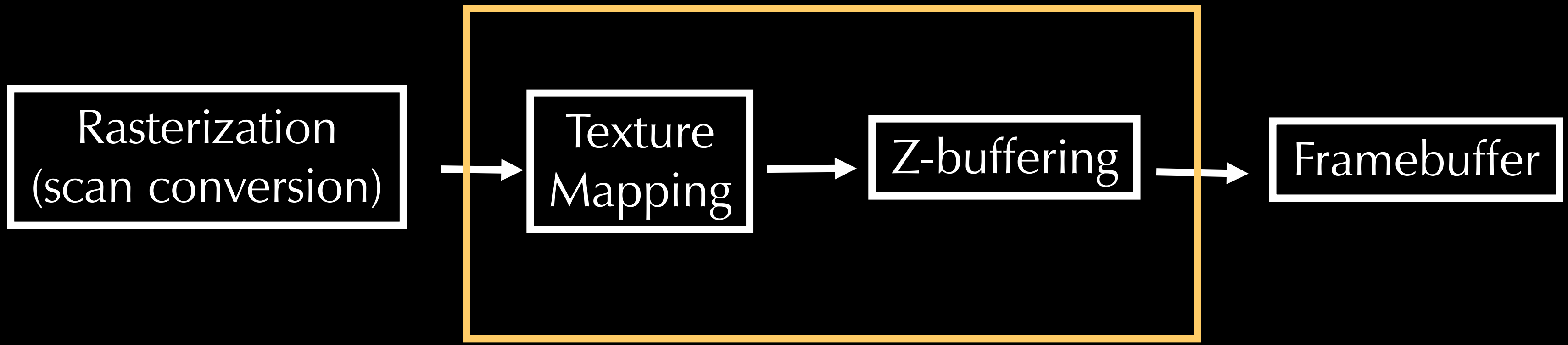


Geometry or Vertex Pipeline



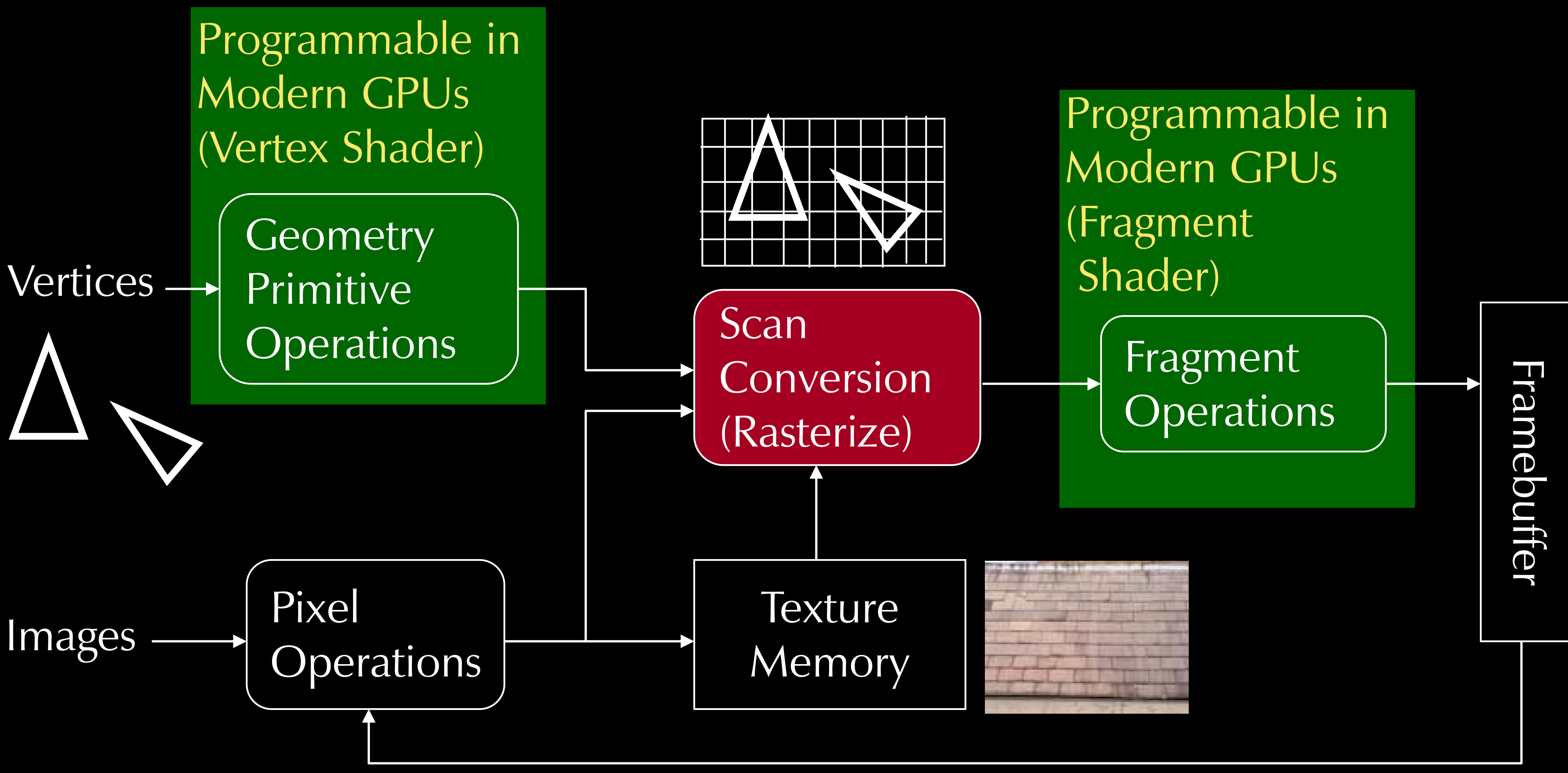
These fixed function stages can be replaced by a general per-vertex calculation using vertex shaders in modern programmable hardware

Pixel or Fragment Pipeline



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

OpenGL Rendering Pipeline



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

Simplified OpenGL Pipeline

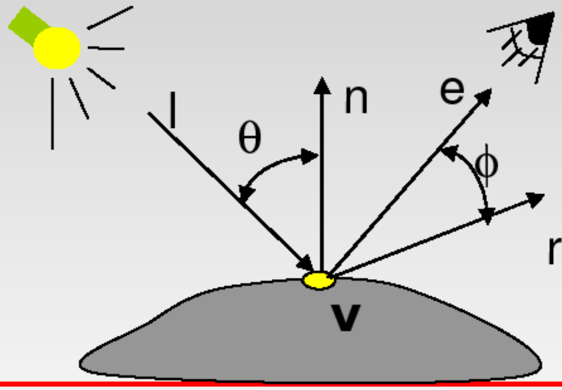
- User specifies vertices (vertex buffer object)
- For each vertex in parallel
  - OpenGL calls user-specified vertex shader: Transform vertex (ModelView, Projection), other ops
- For each primitive, OpenGL rasterizes
  - Generates a *fragment* for each pixel the fragment covers
- For each fragment in 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

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

Phong Shader: Vertex



<u>This Shader Does</u>

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

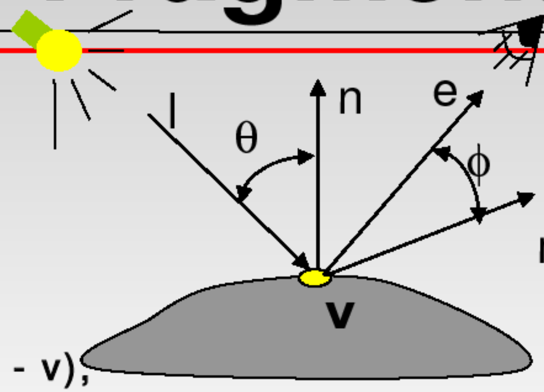
```
varying vec3 N;
varying vec3 v;

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)

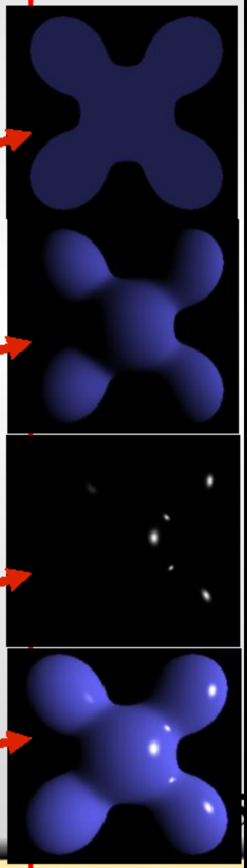
Cliff Lindsay web.cs.wpi.edu/~rich/courses/imgd4000-d09/lectures/gpu.pdf

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 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

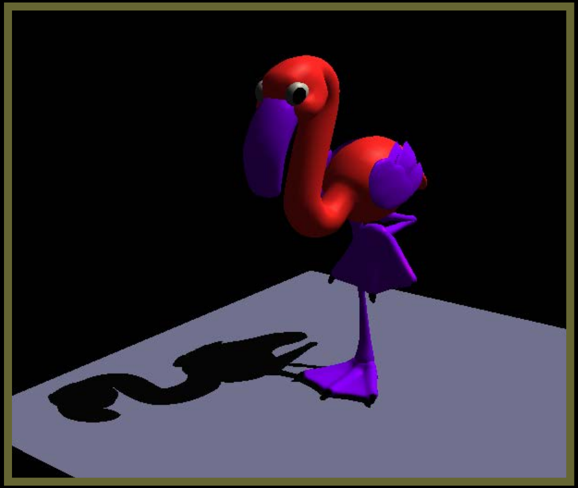
Outline

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

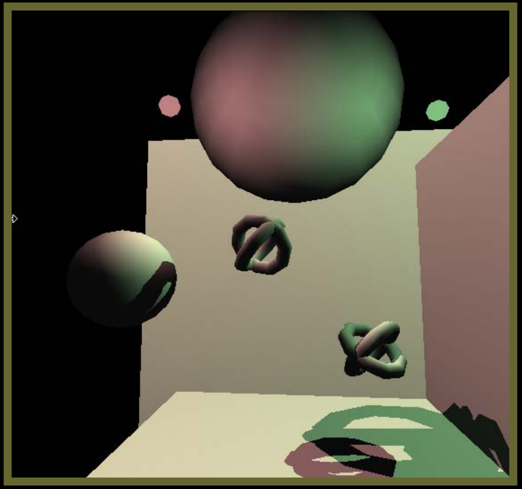
Shadow and Environment Maps

- Basic methods to add realism to interactive rendering
- Shadow maps: image-based way 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

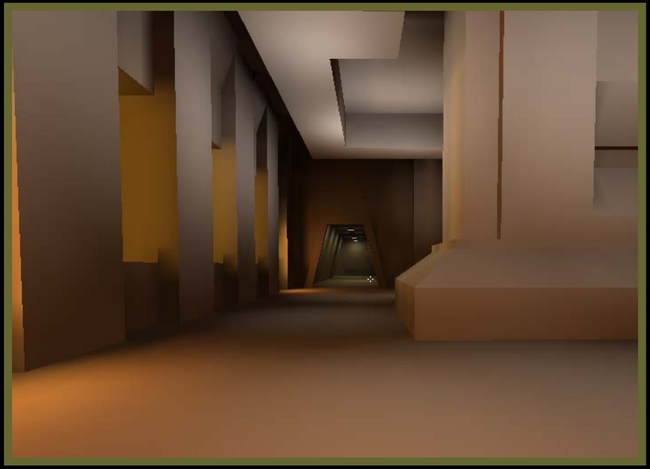
Common Real-time Shadow Techniques



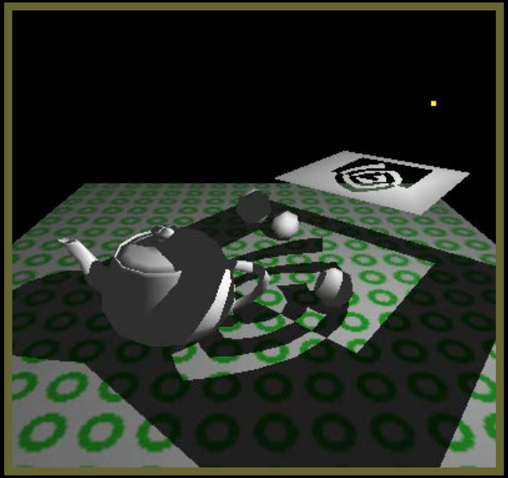
Projected planar shadows



Shadow volumes



Light maps



Hybrid approaches

This slide, others courtesy Mark Kilgard

Problems

Mostly tricks with lots of limitations

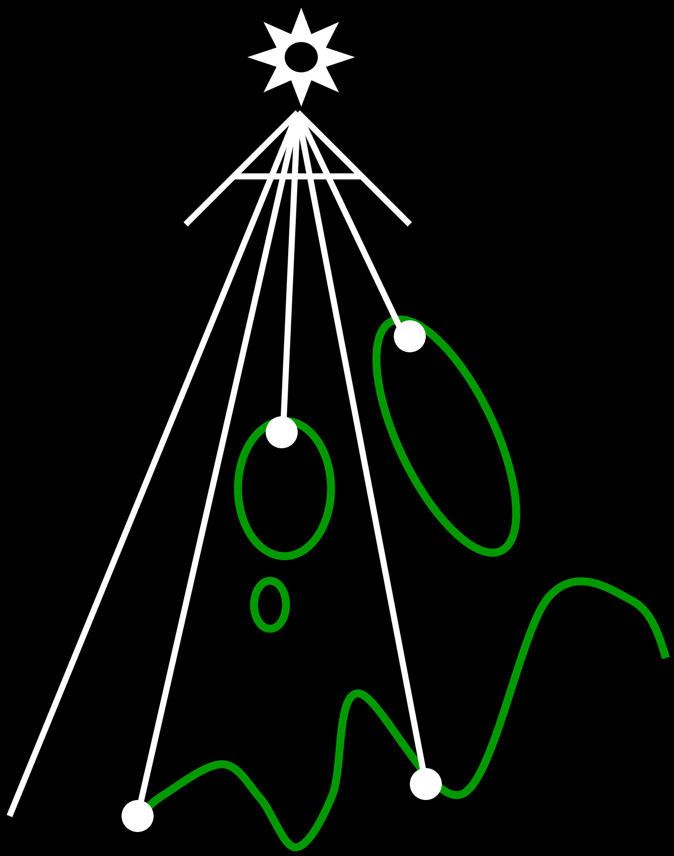
- Projected planar shadows
  works well only on flat surfaces
- Stenciled shadow volumes
  determining the shadow volume is hard work
- Light maps
  totally unsuited for dynamic shadows
- In general, hard to get everything shadowing everything

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.

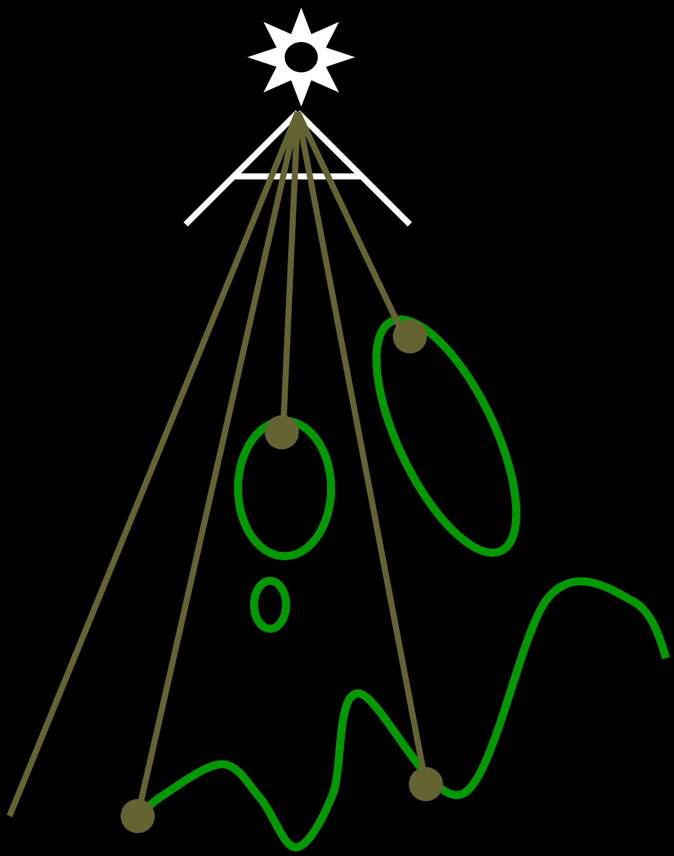
Phase 1: Render from Light

- Depth image from light source



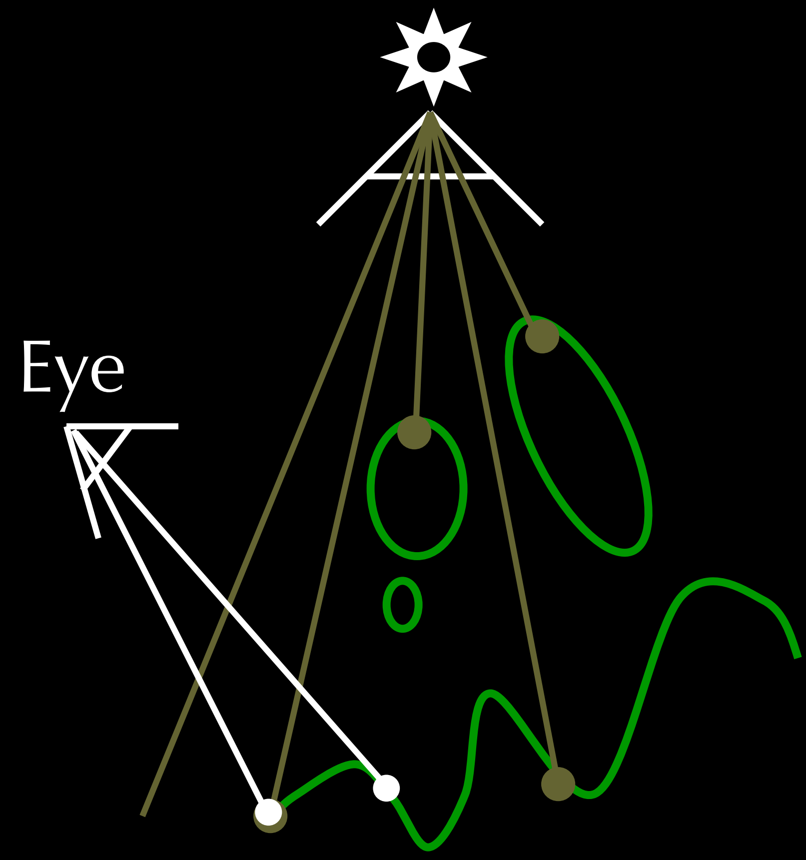
Phase 1: Render from Light

- Depth image from light source



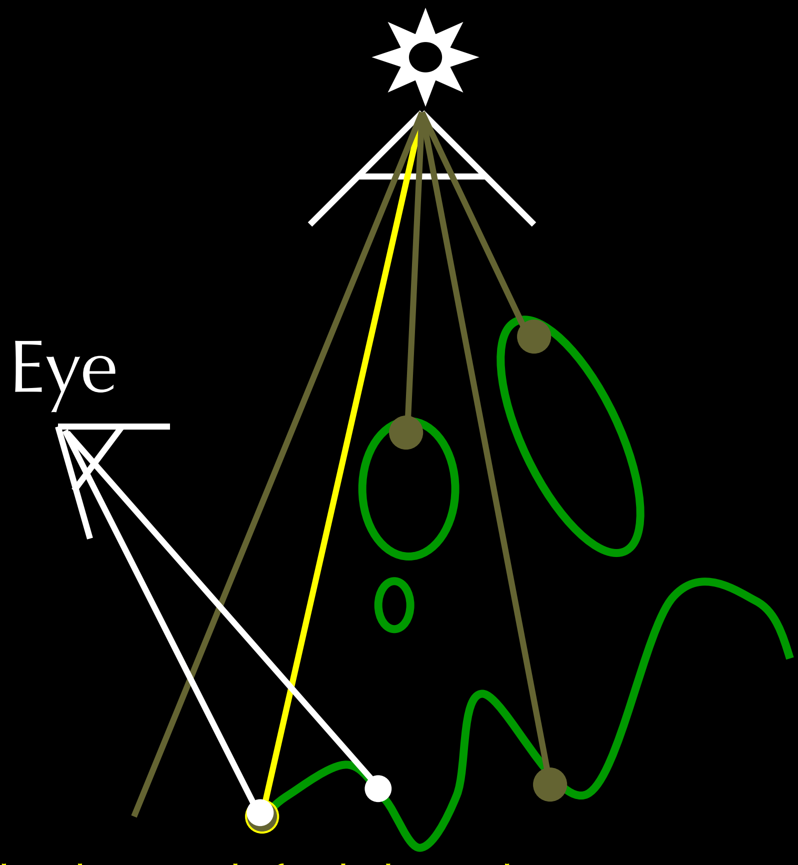
Phase 2: Render from Eye

- Standard image (with depth) from eye



Phase 2+: Project to light for shadows

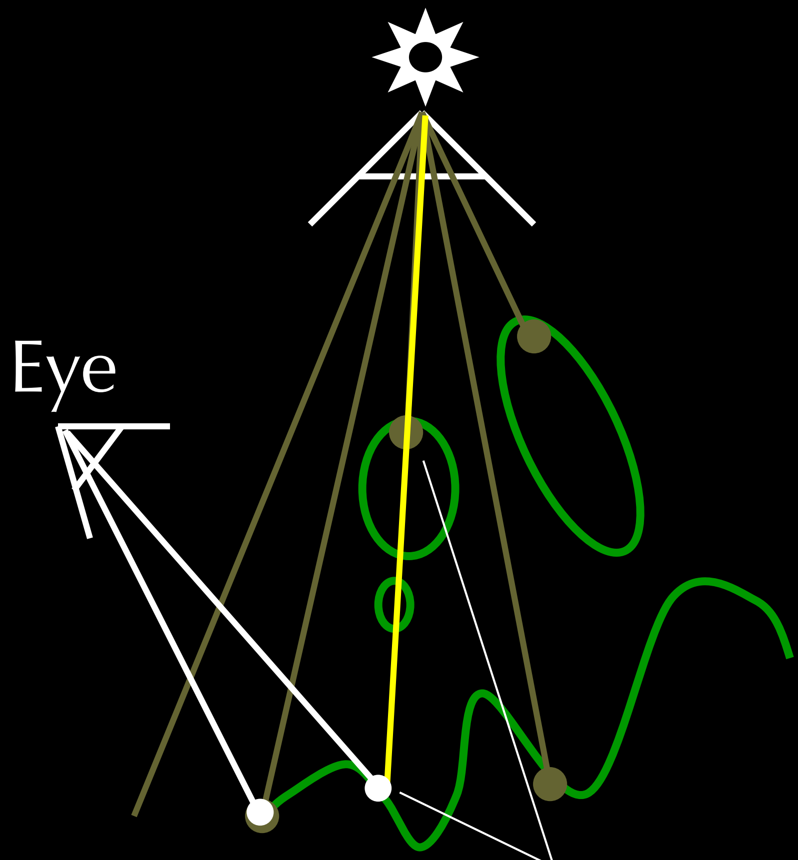
- Project visible points in eye view back to light source



(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

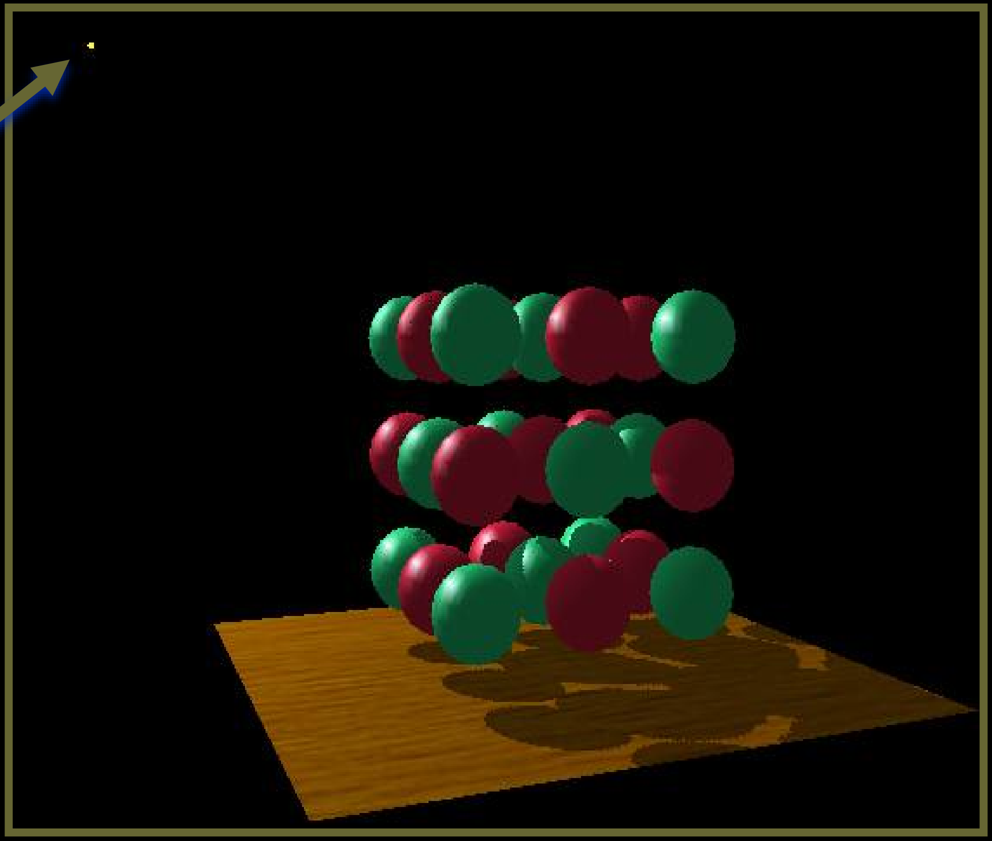


(Reprojected) depths from light, eye not the same. BLOCKED!!

Visualizing Shadow Mapping

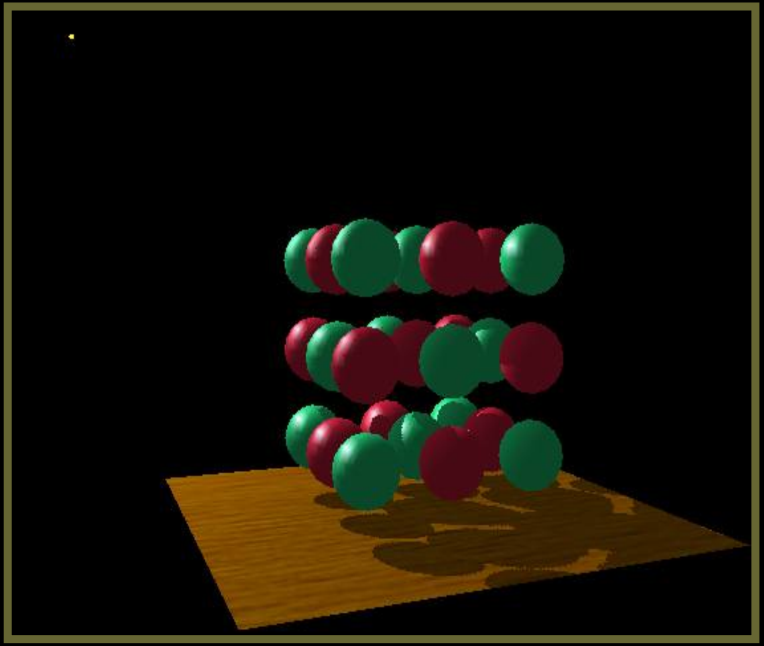
- A fairly complex scene with shadows

the point light source

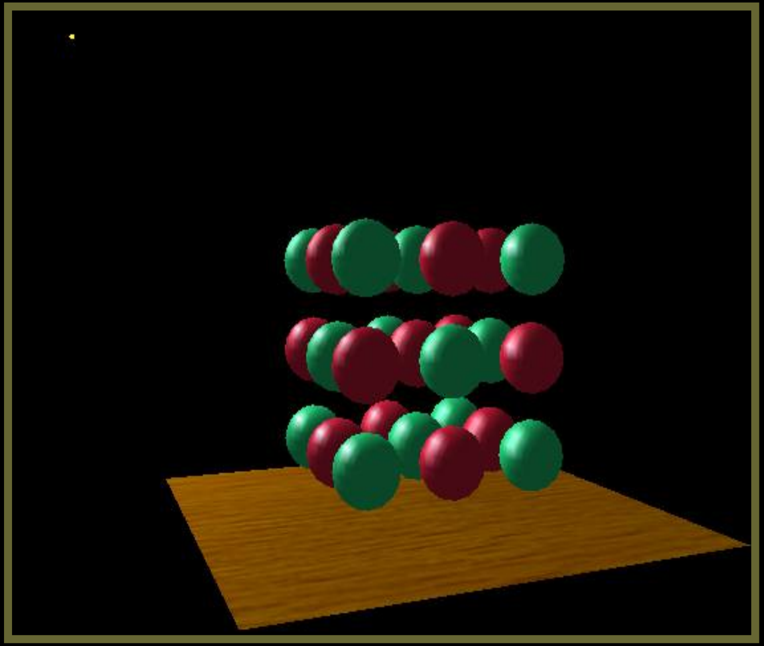


Visualizing Shadow Mapping

- Compare with and without shadows



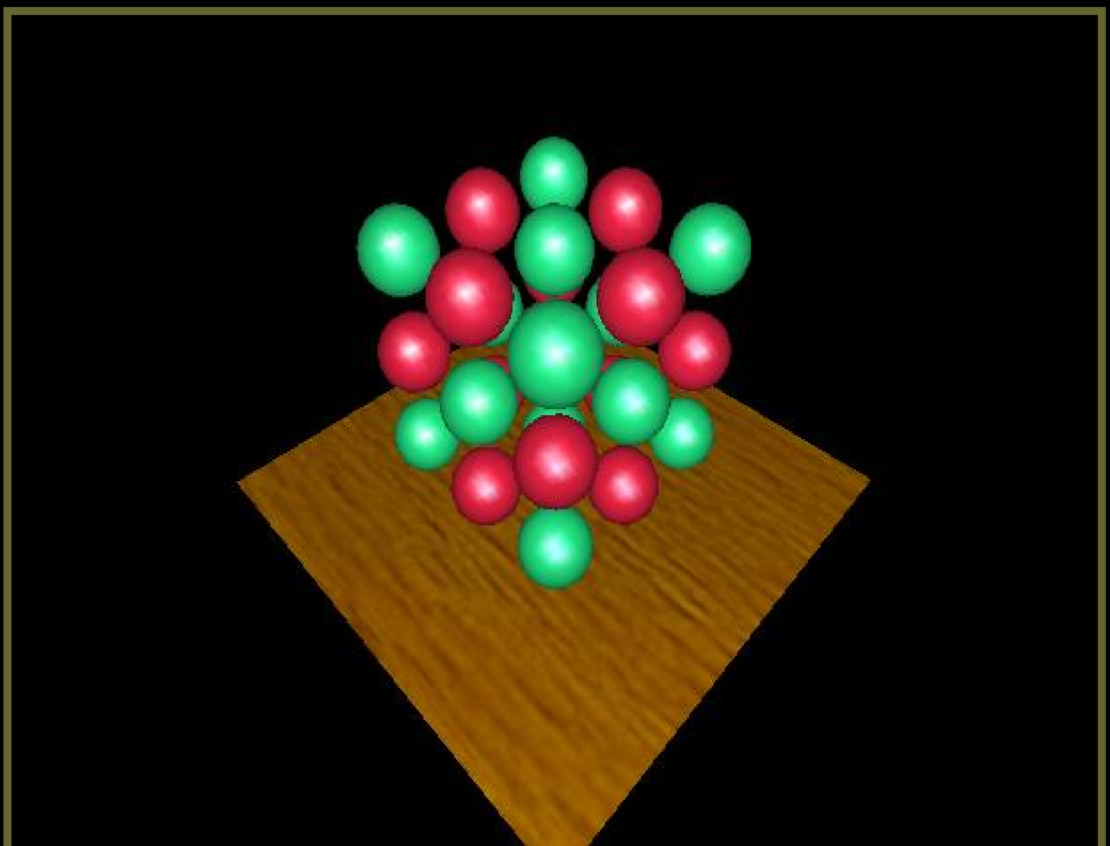
with shadows

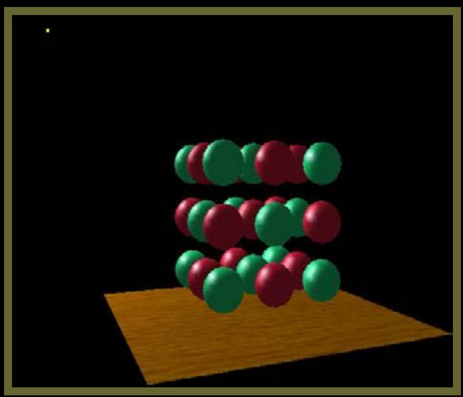


without shadows

Visualizing Shadow Mapping

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

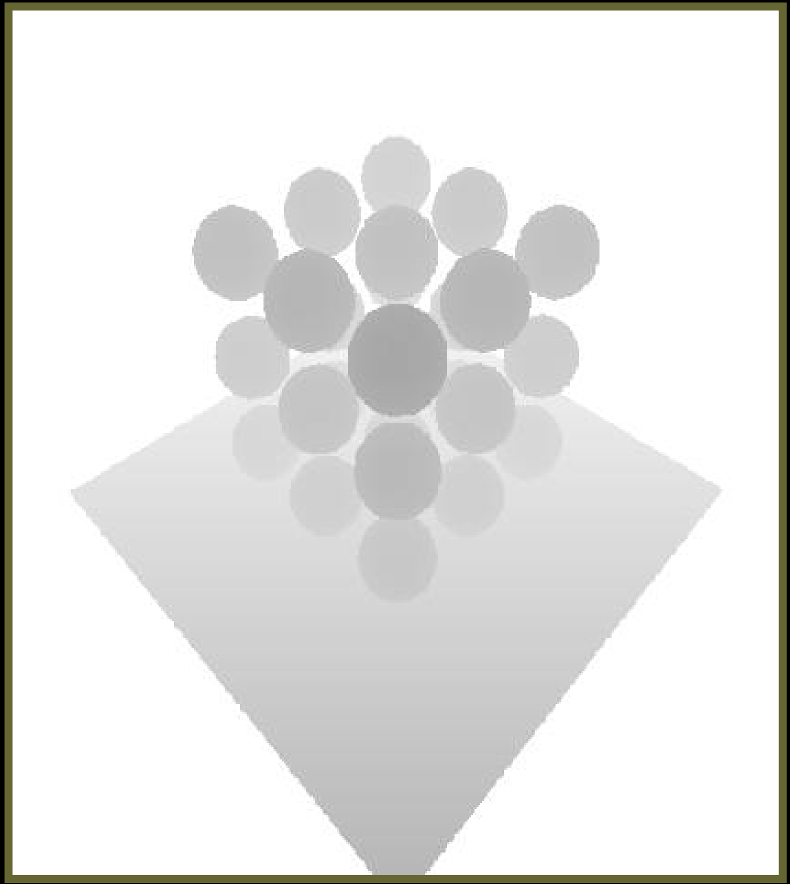


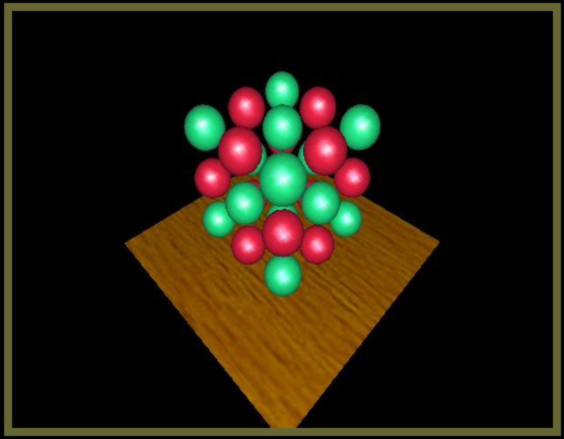


FYI: from the eye's point-of-view again

Visualizing Shadow Mapping

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

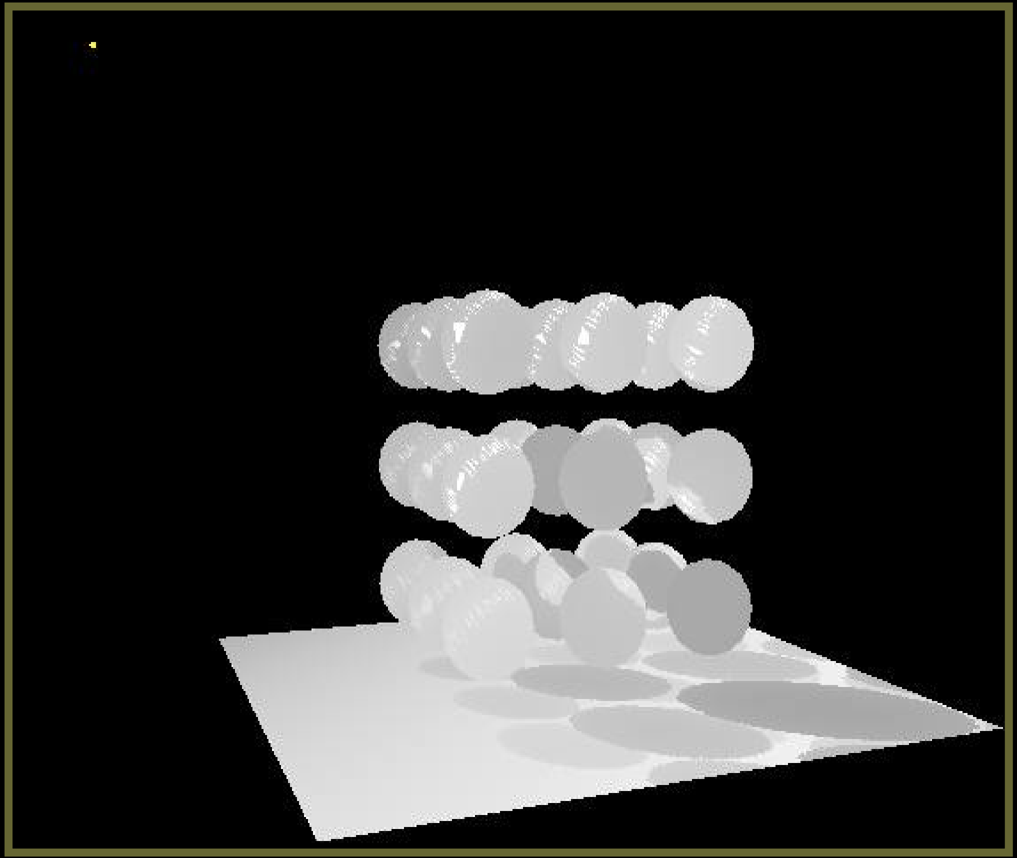


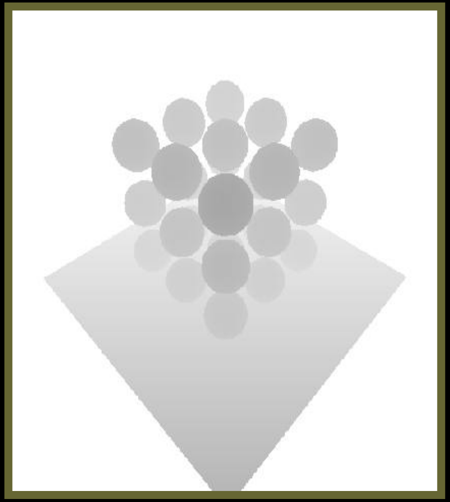


FYI: from the light's point-of-view again

Visualizing Shadow Mapping

- Projecting the depth map onto the eye's view



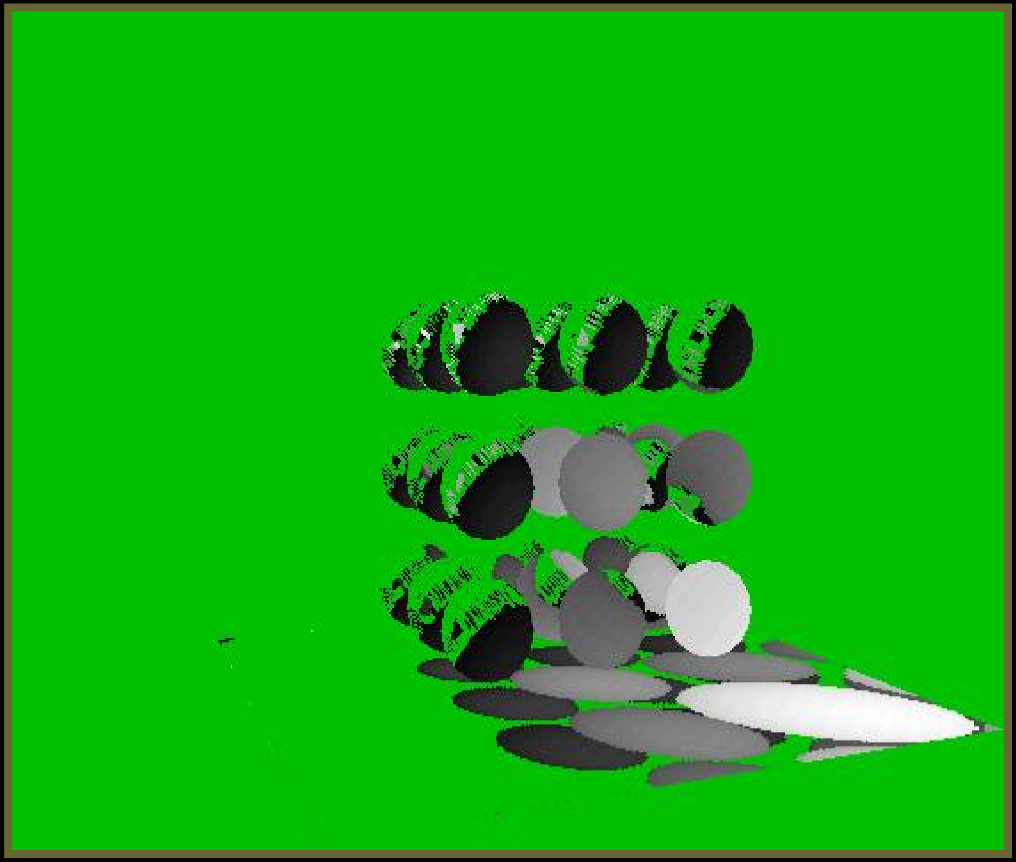


FYI: depth map for light's point-of-view again

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

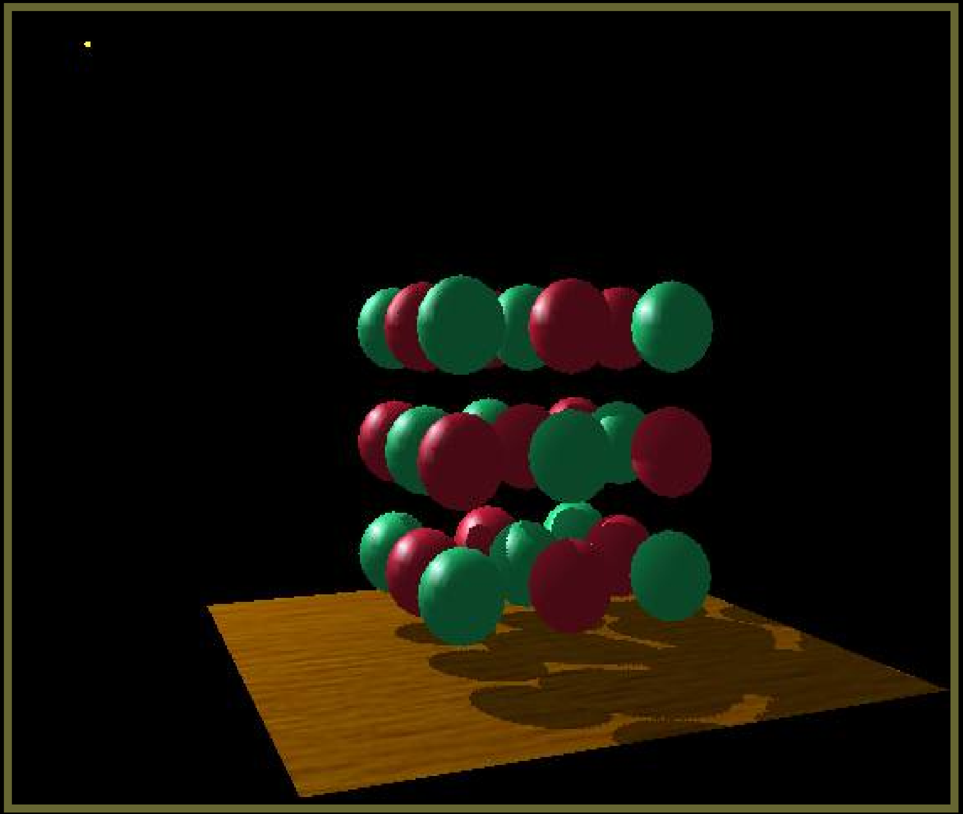


Non-green is where shadows should be

Visualizing Shadow Mapping

- Scene with shadows

Notice how specular highlights never appear in shadows



Notice how curved surfaces cast shadows on each other

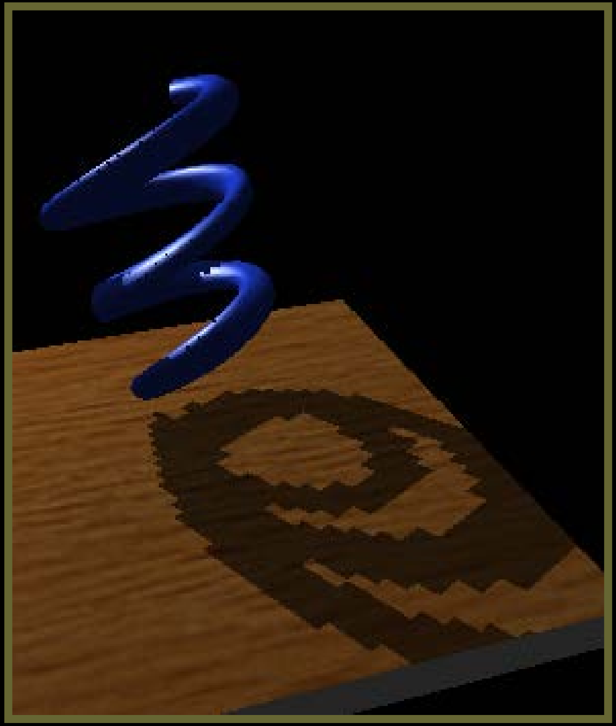
Hardware Shadow Map Filtering

"Percentage Closer" filtering

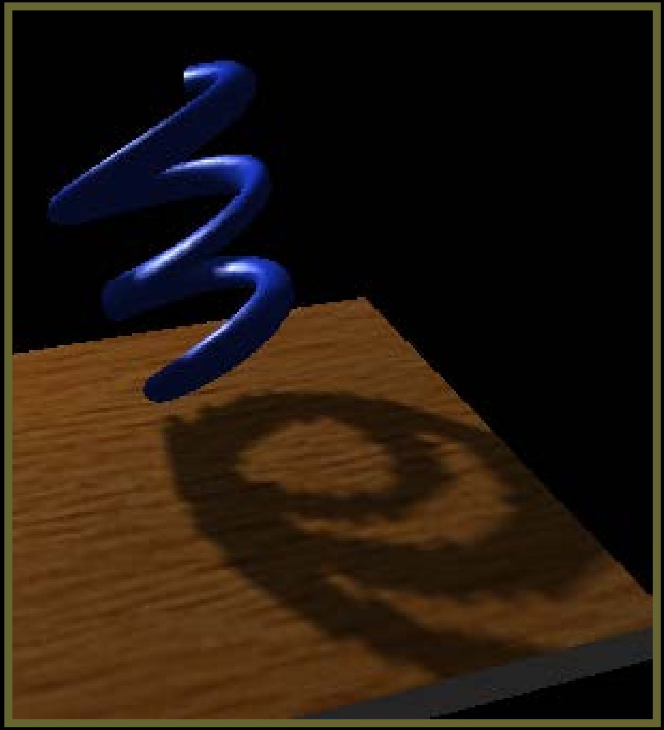
- Normal texture filtering just averages color components
- Averaging depth values does NOT work
- Solution [Reeves, SIGGARPH 87]
  - Hardware performs comparison for each sample
  - Then, averages results of comparisons
- Provides anti-aliasing at shadow map edges
  - Not soft shadows in the umbra/penumbra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

Hardware Shadow Map Filtering

GL_NEAREST: blocky



GL_LINEAR: antialiased edges

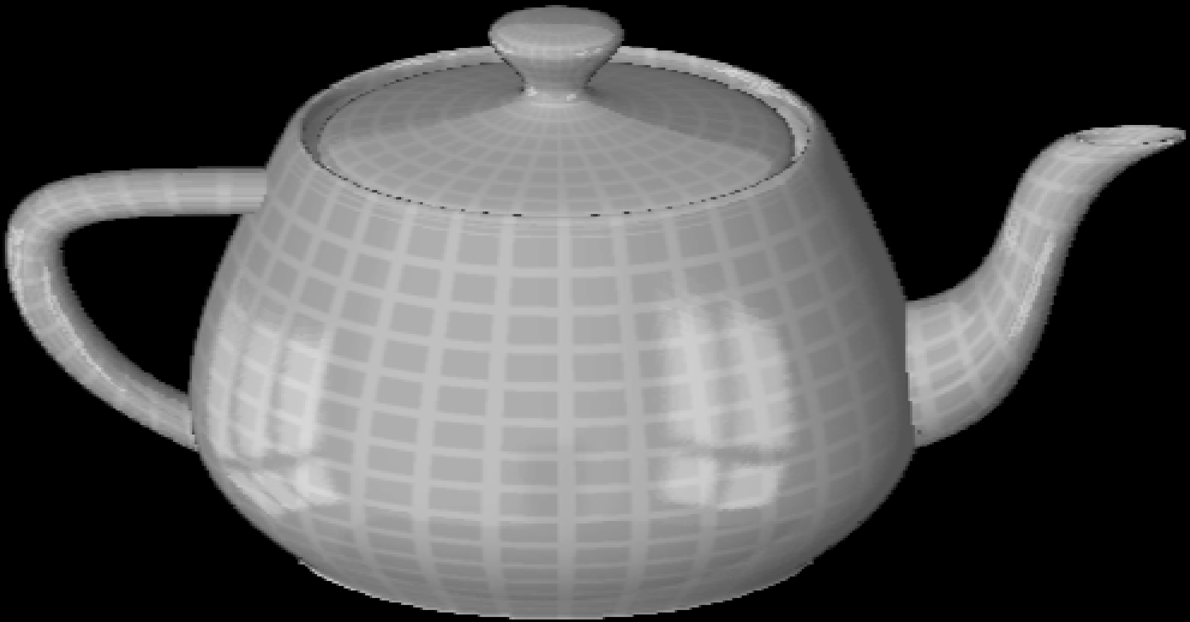


Low shadow map resolution
used to heighten filtering artifacts

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

Reflection Maps

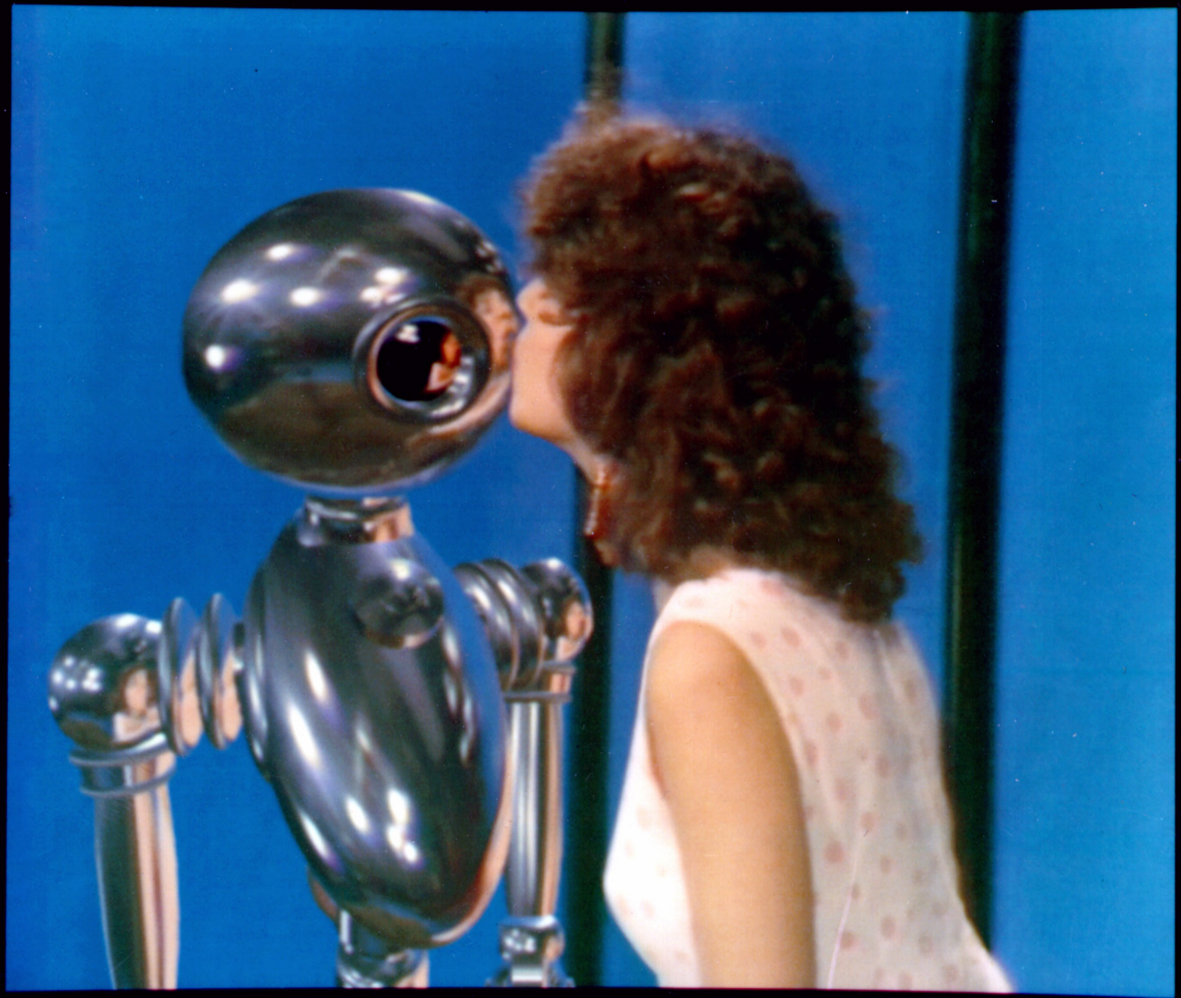


Blinn and Newell, 1976

Environment Maps

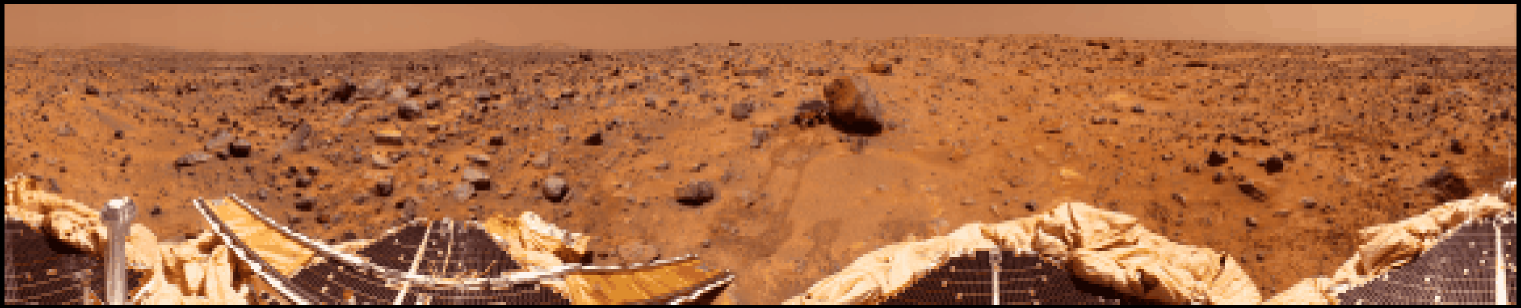
Miller and Hoffman, 1984

Environment Maps

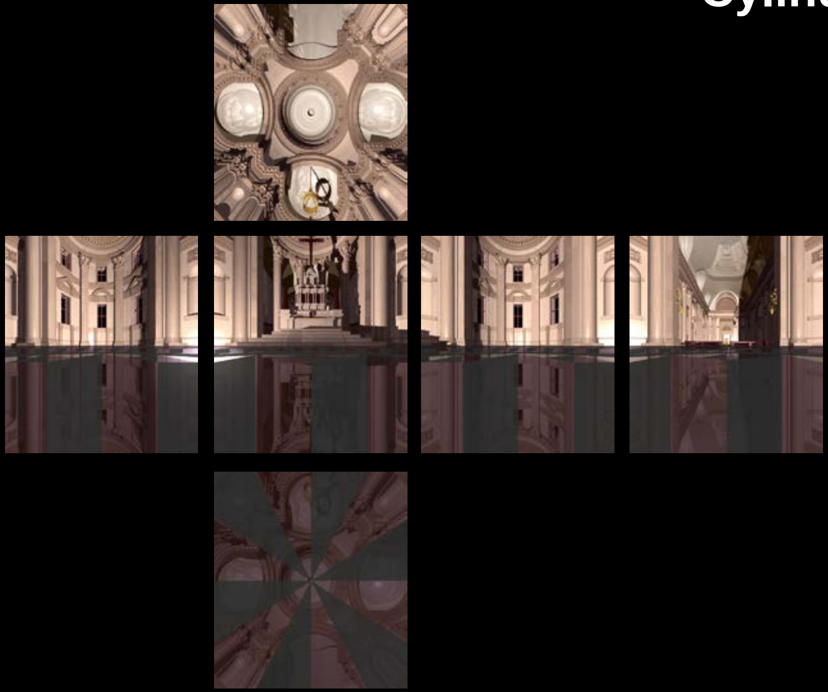


Interface, Chou and Williams (ca. 1985)

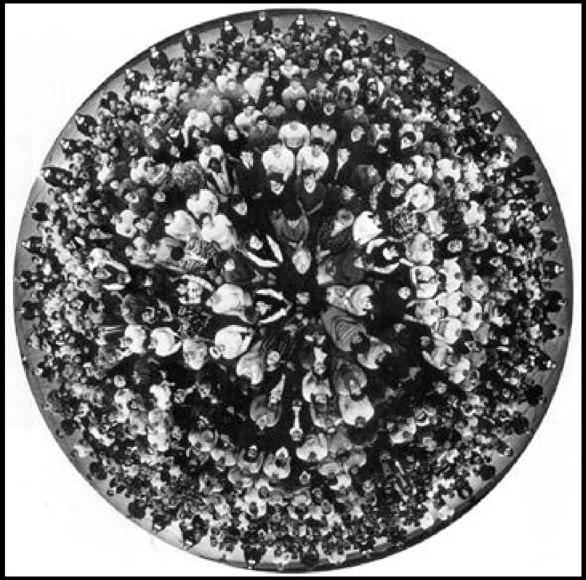
Environment Maps



Cylindrical Panoramas



Cubical Environment Map



180 degree fisheye
Photo by R. Packo

Reflectance Maps

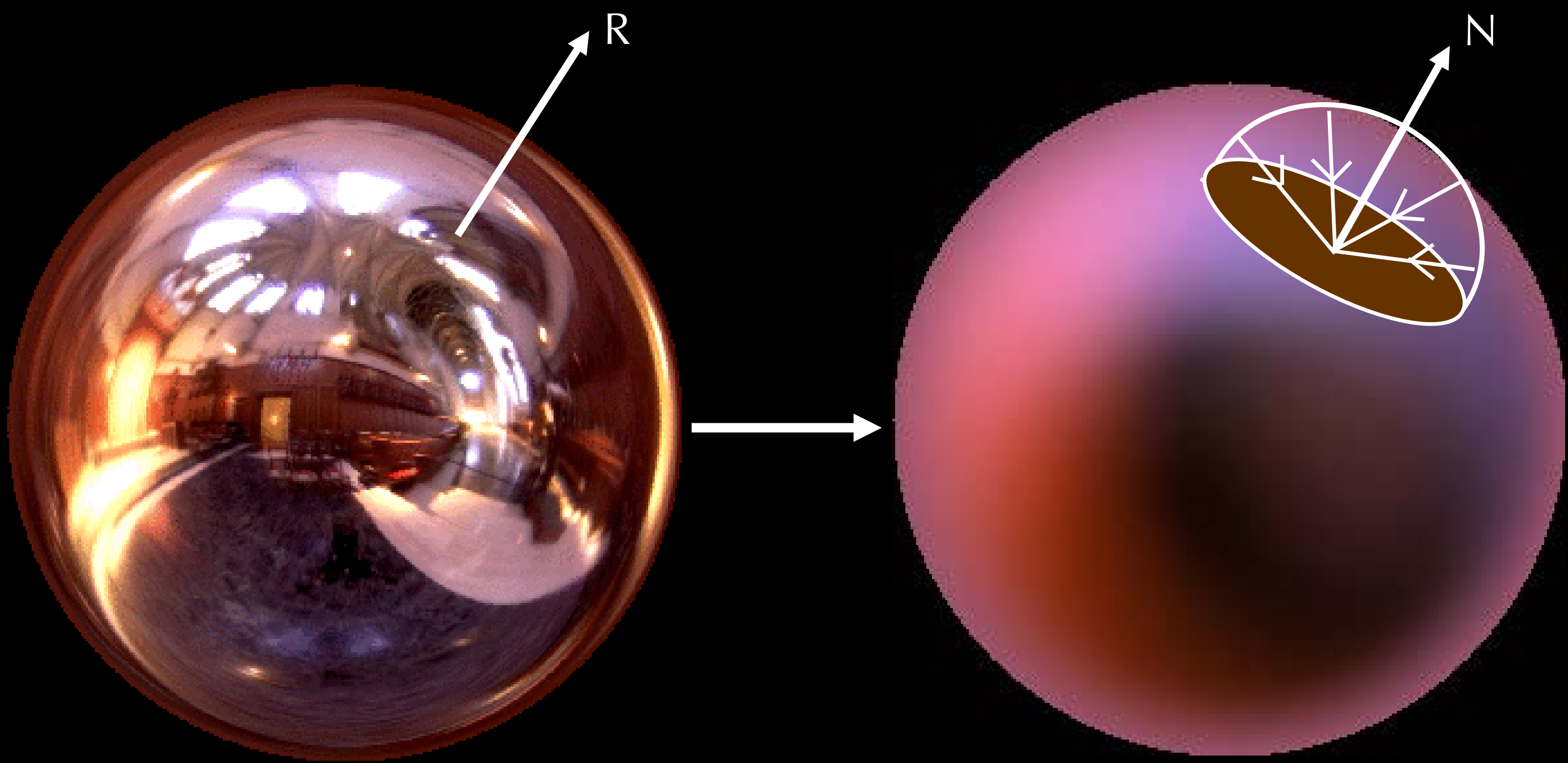
- Reflectance Maps (Index by N)
- Horn, 1977
- Irradiance (N) and Phong (R) Reflection Maps
- Miller and Hoffman, 1984

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

$$B = \rho E$$

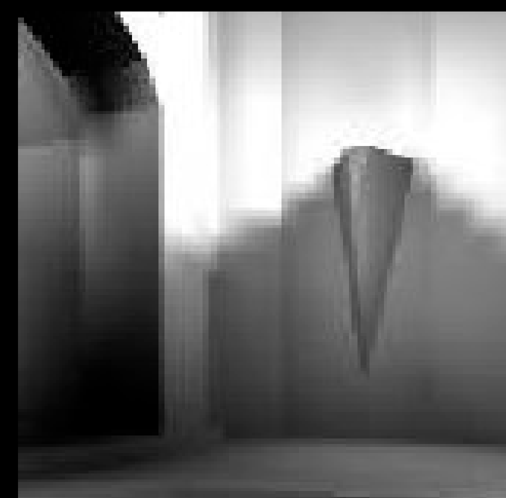
Radiosity
(image intensity)

Reflectance
(albedo/texture)

Irradiance
(incoming light)

$=$

$\times$

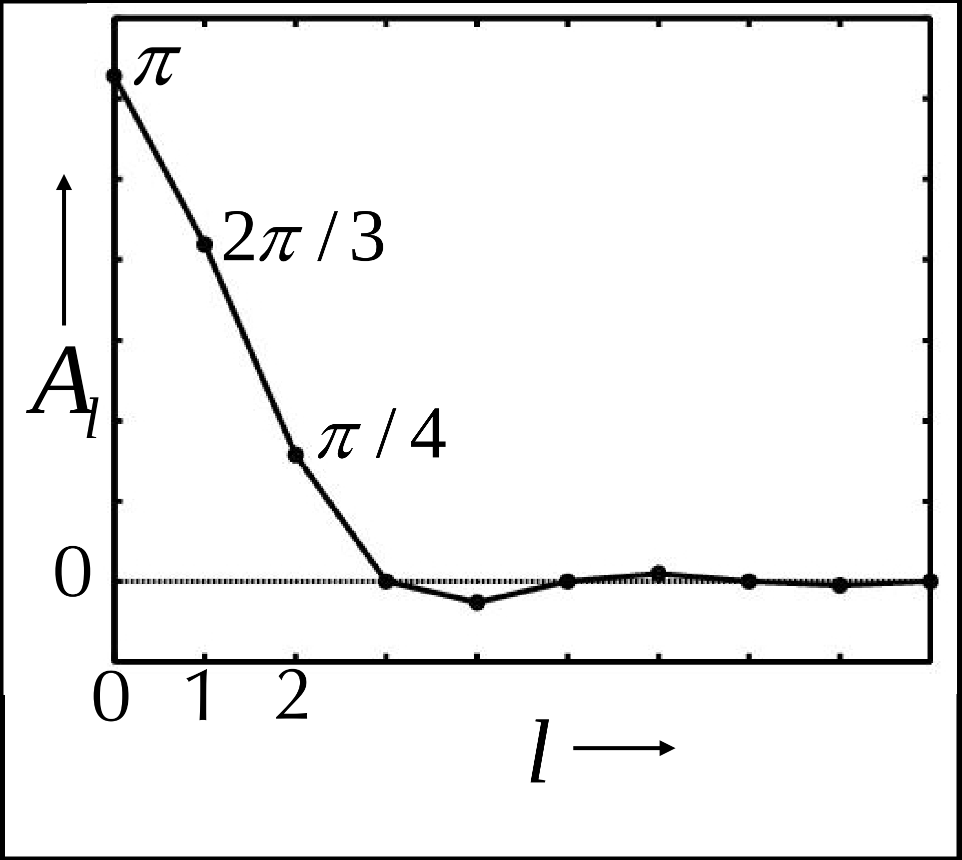


quake light map

Analytic Irradiance Formula

Lambertian surface acts like low-pass filter

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

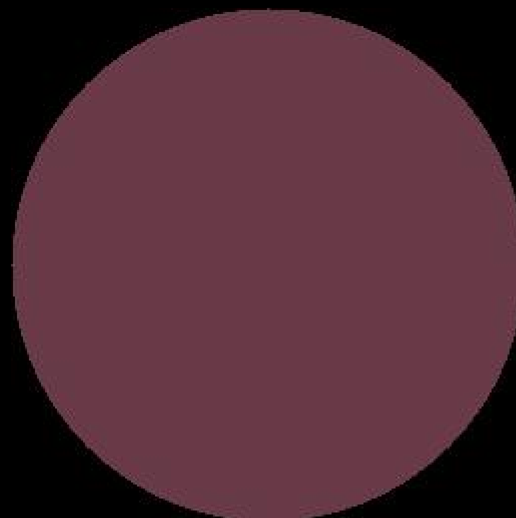


$$A_l = 2\pi \frac{(-1)^{\frac{l}{2}-1}}{(l+2)(l-1)} \left[\frac{l!}{2^l \left(\frac{l}{2}!\right)^2} \right] \qquad l \text{ even}$$

Ramamoorthi and Hanrahan 01
Basri and Jacobs 01

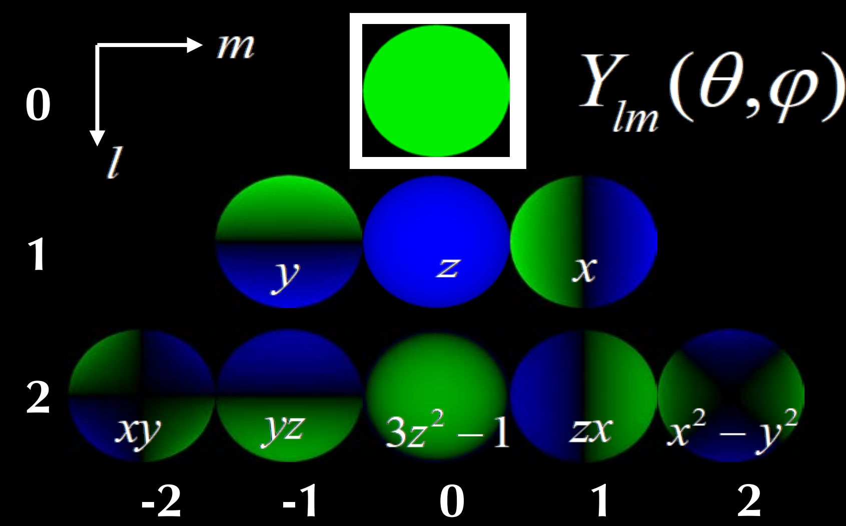
9 Parameter Approximation

Exact image



Order 0
1 term

RMS error = 25 %

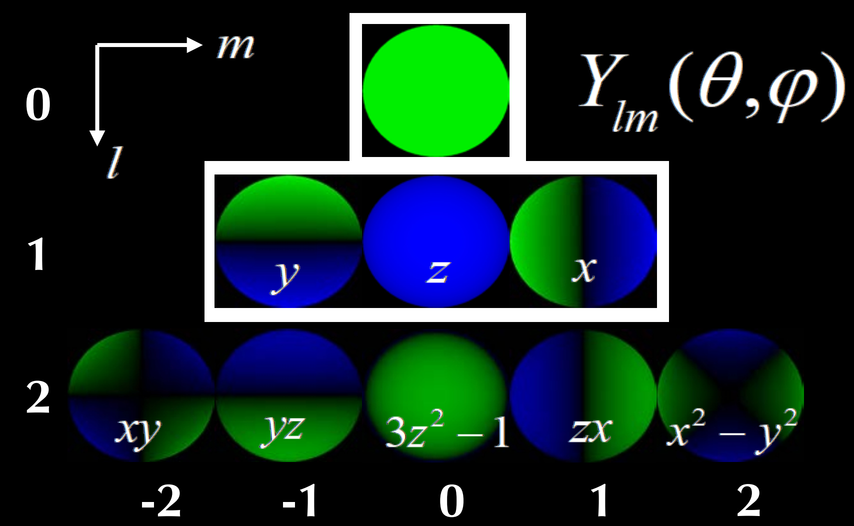


9 Parameter Approximation

Exact image

Order 1
4 terms

RMS Error = 8%



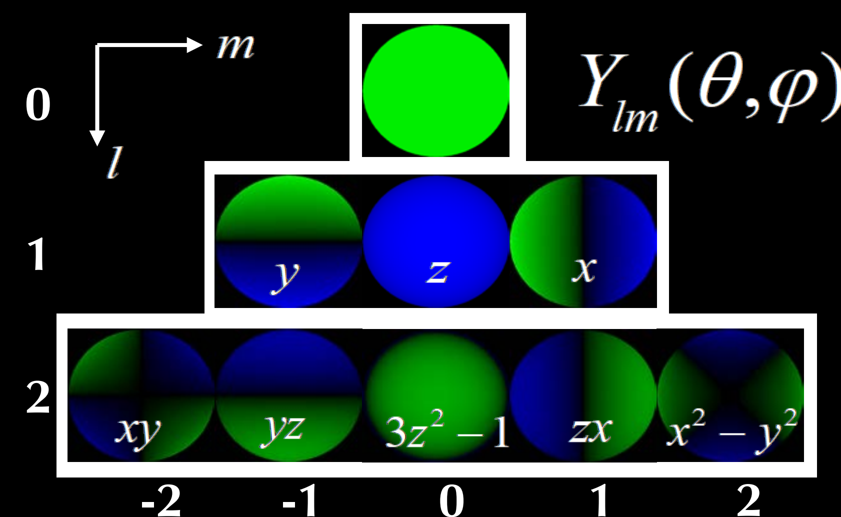
9 Parameter Approximation

Exact image

Order 2
9 terms

RMS Error = 1%

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



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) ;
}
```

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 (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.ucsd.edu/~ravir/papers/envmap
  - Also papers by Heidrich, Cabral, …
- Lots of information available on web…