Subsurface Scattering & Complex Material Properties

Last Time?
- What is a Pixel?
- Aliasing
- Fourier Analysis
- Sampling & Reconstruction
- Mip maps
High Dynamic Range Example:

Illuminance & typical Lux values:

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Lux Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct sunlight</td>
<td>&gt; 100,000 lux</td>
</tr>
<tr>
<td>Office lighting</td>
<td>~500 lux</td>
</tr>
<tr>
<td>Overcast day/TV studio</td>
<td>~1,000 lux</td>
</tr>
<tr>
<td>Lighting</td>
<td></td>
</tr>
<tr>
<td>Moonlight</td>
<td>1 lux</td>
</tr>
</tbody>
</table>

sunlight checkerboard

typical office projector:
~1:300 contrast ratio
max ~ 500 lux

dark box checkerboard
Tone Mapping

• Convert high dynamic range ( HDR) data to low dynamic range ( LDR)
  – Linear Scale: loss of contrast & precision
  – Nonlinear Scale: preserve more contrast & precision in important/interesting/prominent ranges
  – Spatially-varying Scaling:

Readings for Friday: (pick one)


Truncation  Compression  "Layering"
Readings for Friday: (pick one)

"Fast Bilateral Filtering for the Display of High-Dynamic Range Images", Durand & Dorsey, SIGGRAPH 2002

Today

- Measuring BRDFs
- 3D Digitizing & Scattering
- Complex Material Properties
- Importance of Participating Media
- BSSRDFs
- Other Complex Materials
BRDFs in the Movie Industry

- Agent Smith’s clothes are CG, with measured BRDF

Measured BRDF in film production: realistic cloth appearance for “The Matrix Reloaded”
Borshukov, SIGGRAPH 2003 Sketches & Applications

How Do We Obtain BRDFs?

- Gonioreflectometer
  - 4 degrees of freedom

Source: Greg Ward
BRDFs in the Movie Industry

Measured BRDF in film production: realistic cloth appearance for “The Matrix Reloaded”
Borshukov, SIGGRAPH 2003 Sketches & Applications
Not just a BRDF…

Realistic human face rendering for "The Matrix Reloaded"
Borshukov & Lewis, SIGGRAPH 2003 Sketches & Applications

Materials – BRDF & BTDF

Measuring Materials


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3D Digitizing

The Digital Michelangelo Project: 3D Scanning of Large Statues, Levoy et al., SIGGRAPH 2000

Scattering & Scanning

Figure 1: Diffusion in a sample of Carrara Statuario marble.

Questions?

Today

• Measuring BRDFs
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Anisotropic BRDFs

- Surfaces with strongly oriented microgeometry
- Examples:
  - brushed metals, hair, fur, cloth, velvet

Source: Westin et.al 92

What makes a Rainbow?

- Refraction is wavelength-dependent
  - Refraction increases as the wavelength of light decreases
  - violet and blue experience more bending than orange and red
- Usually ignored in graphics
- Rainbow is caused by
  refraction + internal reflection + refraction

Pink Floyd, *The Dark Side of the Moon*

From “Color and Light in Nature” by Lynch and Livingstone
Amount of Reflection

- Traditional ray tracing (hack)
  - Constant reflectionColor
- More realistic:
  - Fresnel reflection term (more reflection at grazing angle)
  - Schlick’s approximation: \( R(\theta) = R_0 + (1 - R_0)(1 - \cos \theta)^5 \)

Dusty Surfaces & Retro-Reflection

- Viewed perpendicular to the surface, there is little scattering off dust
- At grazing angles, there is increased scattering with the dust making the surface appear brighter
- Similarly, the earth viewed from space appears brighter near the edges, because of increased scattering of the atmosphere.

Figure 5: Showing retroreflection from a very rough surface (left). Only areas with normals close to the light direction are well lit, so there is a strong retroreflective peak. On the right, we see a corner reflector (the inside corner of 3 planes is the 3D analog) which produces the same effect.
Light Rays in a Dusty Room

Ray Tracing Participating Media

primary ray (traditional ray casting)

shadow rays (sample the volume)
Participating Media

Image by Henrik Wann Jensen

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Reading for Tuesday

BRDF vs. BSSRDF

Images from "A Practical Model for Subsurface Light Transport" Jensen, Marschner, Levoy, & Hanrahan SIGGRAPH 2001

Sampling a BSSRDF

Figure 7: (a) Sampling a BRDF (traditional sampling), (b) sampling a BSSRDF (the sample points are distributed both over the surface as well as the light).

Images from "A Practical Model for Subsurface Light Transport" Jensen, Marschner, Levoy, & Hanrahan SIGGRAPH 2001
Subsurface Scattering Variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering Coeff.</td>
<td>$\sigma_s$</td>
<td>(length)$^{-1}$</td>
<td>Probability of scattering per unit length</td>
</tr>
<tr>
<td>Absorption Coeff.</td>
<td>$\sigma_a$</td>
<td>(length)$^{-1}$</td>
<td>Probability of absorption per unit length</td>
</tr>
<tr>
<td>Phase Function</td>
<td>$p(x, \omega', \omega)$</td>
<td>(length)$^{-1}$</td>
<td>Angular distribution of scattering</td>
</tr>
<tr>
<td>Extinction Coeff.</td>
<td>$\sigma_t$</td>
<td>(length)$^{-1}$</td>
<td>$\sigma_a + \sigma_s$</td>
</tr>
<tr>
<td>(Scattering) Albedo</td>
<td>$A$</td>
<td></td>
<td>$\int d \omega' \sigma_t d \omega$</td>
</tr>
<tr>
<td>Optical Depth</td>
<td>$\tau(0, d)$</td>
<td></td>
<td>$e^{-\tau(0, d)}$</td>
</tr>
<tr>
<td>Transmittance</td>
<td>$t(0, d)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Albedo**: first approximation of BRDF, % of light reflected off the surface
  - When the albedo = 1, no absorption occurs and light is only transmitted or scattered. This is an ok approximation for snow or clouds.

BSSRDF Measurement

Images from "A Practical Model for Subsurface Light Transport"
Jensen, Marschner, Levoy, & Hanrahan
SIGGRAPH 2001
Single Scattering

Figure 4: Single scattering occurs only when the refracted incoming and outgoing rays intersect, and is computed as an integral over path length s along the refracted outgoing ray.

Images from "A Practical Model for Subsurface Light Transport"  
Jensen, Marschner, Levoy, & Hanrahan  SIGGRAPH 2001

Dipole Approx. for Diffuse Scattering

Figure 3: An incoming ray is transformed into a dipole source for the diffusion approximation.

Images from "A Practical Model for Subsurface Light Transport"  
Jensen, Marschner, Levoy, & Hanrahan  SIGGRAPH 2001
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(option for Tuesday reading)

- "Digital Face Cloning", Jensen, SIGGRAPH Sketch 2003
- "Light Diffusion in Multi-Layered Translucent Materials" Donner & Jensen, SIGGRAPH 2005
Measuring BSSRDF by Dilution

“Acquiring Scattering Properties of Participating Media by Dilution”
Narasimhan et al. SIGGRAPH 2006

Measuring Hair (option for Tuesday reading)

"Light Scattering from Human Hair Fibers"
Marschner et al., SIGGRAPH 2003
Rendering Hair  *(option for Tuesday reading)*

<table>
<thead>
<tr>
<th>Old Method</th>
<th>New Method</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Old Method Image]</td>
<td>![New Method Image]</td>
<td>![Photo Image]</td>
</tr>
</tbody>
</table>

*Figure 12: A comparison of Kajiya and Key’s model (left) under a single point source, our proposed model (center) with the same lighting, and the hair from the photograph in Figure 11 (removed from context to simplify the comparison). The Kajiya model’s diffuse term results in a flat appearance, while the secondary highlight in our model correctly captures the colored shading of the real hair.*

"Light Scattering from Human Hair Fibers"
Marschner et al., SIGGRAPH 2003