Subsurface Scattering &
Complex Material Properties

Today

• Measuring BRDFs
• 3D Digitizing & Scattering
• Complex Material Properties
• Importance of Participating Media
• BSSRDFs
• Other Complex Materials

How Do We Obtain BRDFs?

• Gonioreflectometer
  – 4 degrees of freedom

Source: Greg Ward

Last Time?

• What is a Pixel?
• Aliasing
• Fourier Analysis
• Sampling & Reconstruction
• Mip maps

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

BRDFs in the Movie Industry

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

Not just a BRDF…

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

Materials – BRDF & BTDF

Measuring Materials

Today

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

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?

Reading for Today:


Today

• Measuring BRDFs
• 3D Digitizing & Scattering
• Complex Material Properties
• Importance of Participating Media
• BSSRDFs
• Other Complex Materials

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

What makes a Rainbow?

From “Color and Light in Nature” by Lynch and Livingstone

Pink Floyd, The Dark Side of the Moon
### 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.

![Image of light reflection](image_url)

### Light Rays in a Dusty Room

Image by Henrik Wann Jensen

### Ray Tracing Participating Media

- Measuring BRDFs
- 3D Digitizing & Scattering
- Complex Material Properties
- Importance of Participating Media
- BSSRDFs
- Other Complex Materials
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”
Jensen, Marschner, Levoy, & Hanrahan, SIGGRAPH 2001

<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>$\psi(\theta,\phi,\gamma)$</td>
<td>-</td>
<td>Angular distribution of scattering</td>
</tr>
<tr>
<td>Extinction Coeff.</td>
<td>$\sigma_e$</td>
<td>(length)$^{-1}$</td>
<td>$\sigma_a + \sigma_s$</td>
</tr>
<tr>
<td>(Scattering) Albedo</td>
<td>$A$</td>
<td>-</td>
<td>$\int_0^\pi \sigma_e \text{d} \theta$</td>
</tr>
<tr>
<td>Optical Depth</td>
<td>$\tau(0,\theta)$</td>
<td>-</td>
<td>$e^{-\tau(0,\theta)}$</td>
</tr>
<tr>
<td>Transmittance</td>
<td>$t(0,\theta)$</td>
<td>-</td>
<td>$e^{-\tau(0,\theta)}$</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
Today

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

Measuring BSSRDF by Dilution

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

Measuring Hair

Black hair  Blond hair  Synthetic (wig)

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

Rendering Hair

Old Method  New Method  Photo

"Light Scattering from Human Hair Fibers"
Marschner et al., SIGGRAPH 2003
Reading for Friday:

- “Ray Tracing on Programmable Graphics Hardware Purcell”, Buck, Mark, & Hanrahan SIGGRAPH 2002