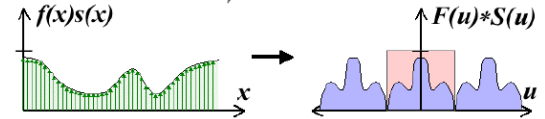
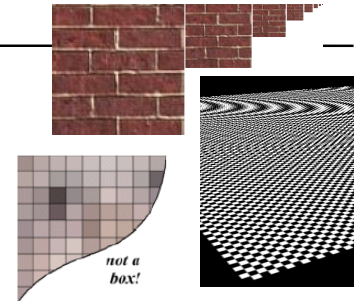


# Subsurface Scattering & Complex Material Properties

## Last Time?

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



## Today

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

## BRDFs in the Movie Industry

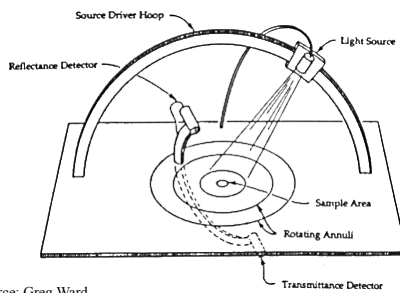
- Agent Smith's clothes are CG, with measured BRDF



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

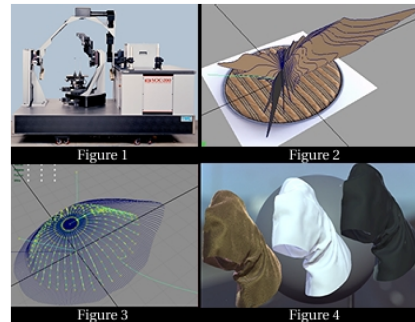
## How Do We Obtain BRDFs?

- Gonioreflectometer  
– 4 degrees of freedom



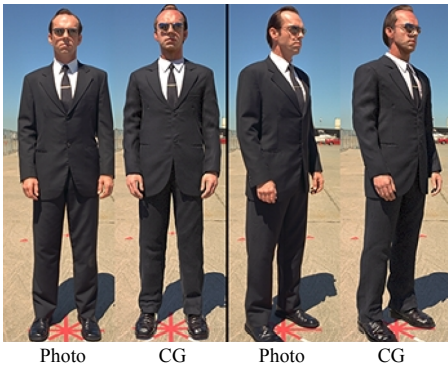
Source: Greg Ward

## BRDFs in the Movie Industry



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

## BRDFs in the Movie Industry

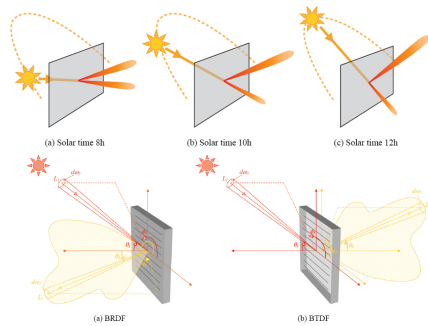


## Not just a BRDF...



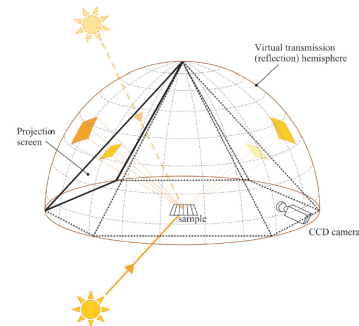
Realistic human face rendering for "The Matrix Reloaded"  
Borshukov & Lewis, SIGGRAPH 2003 Sketches & Applications

## Materials – BRDF & BTDF



M. Andersen, "Innovative bi-directional video-goniophotometer for advanced fenestration systems", 2004.

## Measuring Materials

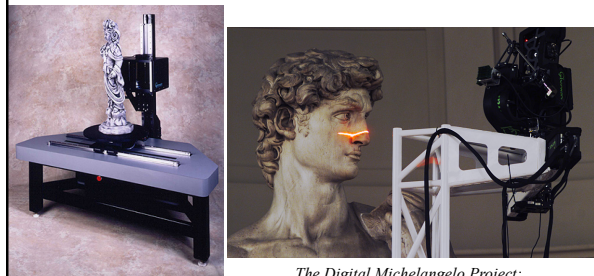


M. Andersen, "Innovative bi-directional video-goniophotometer for advanced fenestration systems", 2004.

## Today

- Measuring BRDFs
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## 3D Digitizing



Cyberware

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

## Scattering & Scanning

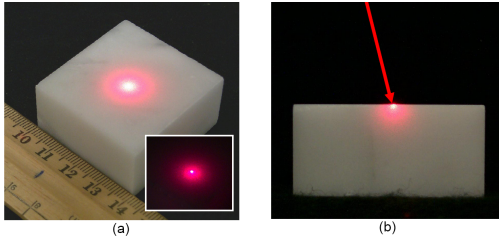


Figure 1: Diffusion in a sample of Carrara Statuario marble.

*An Assessment of Laser Range Measurement of Marble Surfaces, Godin et al, 2001.*

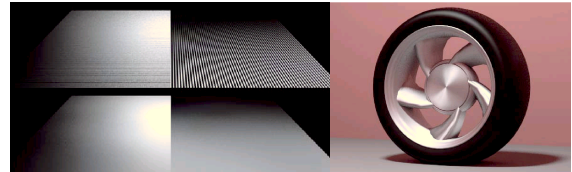
## Questions?

## Today

- Measuring BRDFs
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## Anisotropic BRDFs

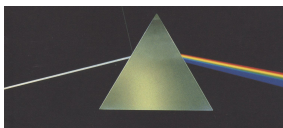
- Surfaces with strongly oriented microgeometry
- Examples:
  - brushed metals, hair, fur, cloth, velvet



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



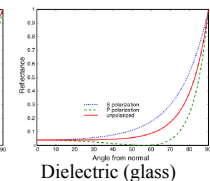
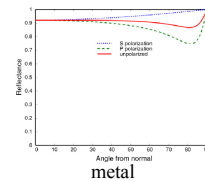
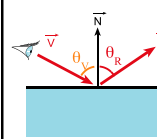
Pink Floyd, *The Dark Side of the Moon*

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.

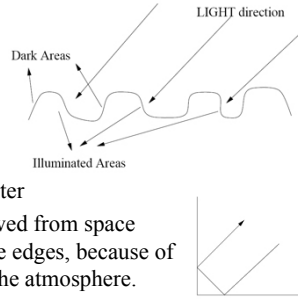
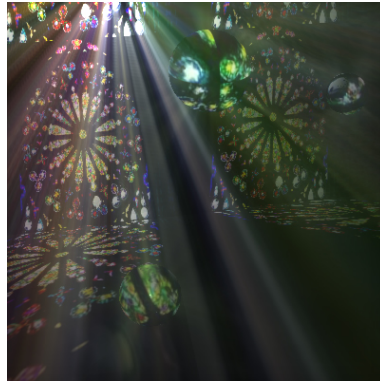


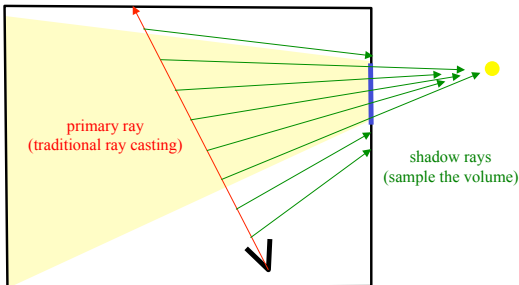
Figure 5: Showing retro-reflection from a very rough surface (left). Only areas with normals close to the light direction are well lit, so there is a strong retro-reflective peak. On the right, we see a corner reflector (the inside corner of 3 planes is the 3D analog) which produces the same effect.

## Light Rays in a Dusty Room



Annie Ding, MIT  
6.837 Final Project  
December, 2004

## Ray Tracing Participating Media



## Participating Media

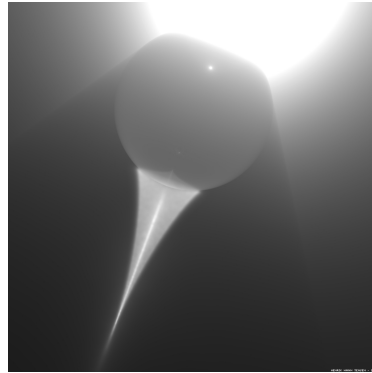


Image by Henrik  
Wann Jensen

## Reading for Today:

- “Radiance Caching for Participating Media”, Jarosz, Donner, Zwicker, & Jensen, 2008.



## Today

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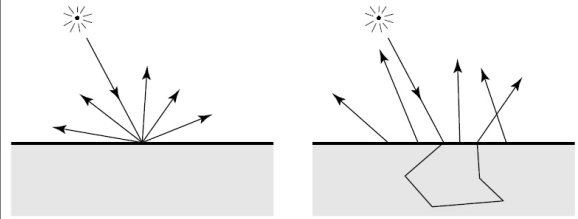


## Reading for Today:

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



## BRDF vs. BSSRDF



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

## Sampling a BSSRDF

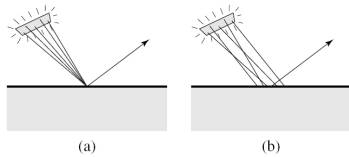


Figure 7: (a) Sampling a BRDF (traditional sampling), (b) sampling a BSSRDF (the sample points are distributed both over the surface as well as the light).

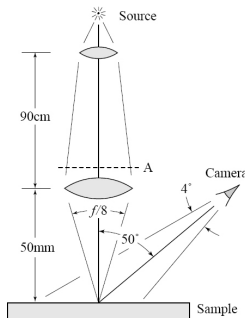
Images from "A Practical Model for Subsurface Light Transport"  
Jensen, Marschner, Levoy, & Hanrahan SIGGRAPH 2001

## Subsurface Scattering Variables

Name	Symbol	Units	Description
Scattering Coeff.	$\sigma_s$	$(\text{length})^{-1}$	Probability of scattering per unit length
Absorption Coeff.	$\sigma_a$	$(\text{length})^{-1}$	Probability of absorption per unit length
Phase Function	$p(x, \vec{\omega}', \vec{\omega})$		Angular distribution of scattering
Extinction Coeff. (Scattering) Albedo	$\sigma_t$ $A$	$(\text{length})^{-1}$	$\sigma_a + \sigma_s$ $\frac{\sigma_s}{\sigma_t}$
Optical Depth	$\tau(0, d)$		$\int_0^d \sigma_t dx$
Transmittance	$t(0, d)$		$e^{-\tau(0, d)}$

- 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

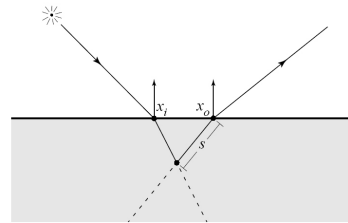


Figure 4: Single scattering occurs only when the refracted incoming and outgoing rays intersect, and is computed as an integral over path length  $s$  along the refracted outgoing ray.

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

## Dipole Approx. for Diffuse Scattering

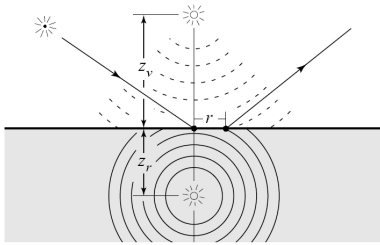


Figure 3: An incoming ray is transformed into a dipole source for the diffusion approximation.

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

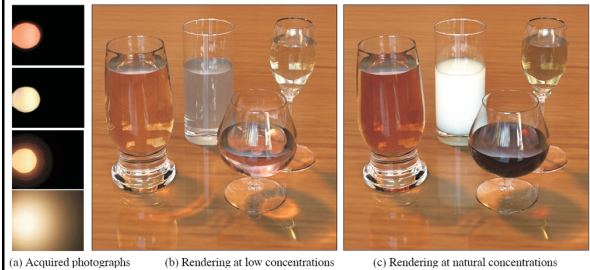
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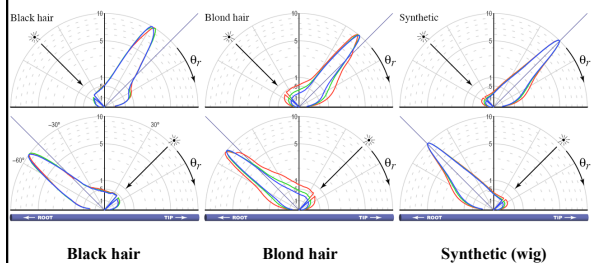


## Measuring BSSRDF by Dilution

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



## Measuring Hair



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

## Rendering Hair



Figure 12: A comparison of Kajiyama and Kay'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 Kajiyama 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

# Reading for Friday:

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

