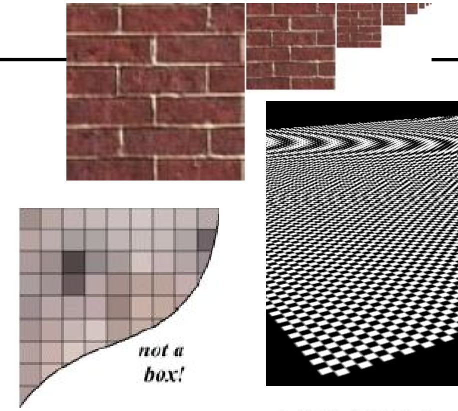
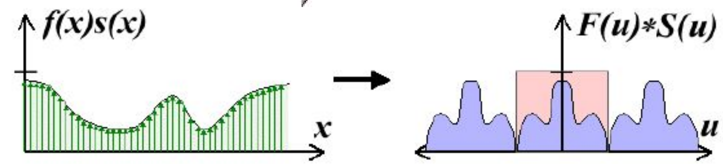
Subsurface Scattering & Complex Material Properties

Last Time?

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





Reading for Today:

- "Correlated Multi-Jittered Sampling", Andrew Kensler, Pixar Technical Memo, 2013

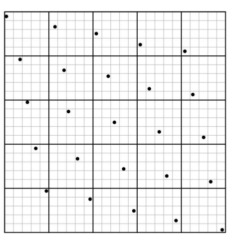


Figure 1: The canonical arrangement. Heavy lines show the boundaries of the 2D jitter cells. Light lines show the horizontal and vertical substrata of N-rooks sampling. Samples are jittered within the subcells.

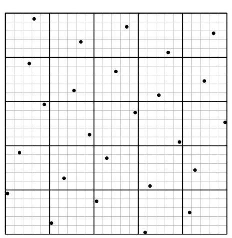


Figure 3: With correlated shuffling.

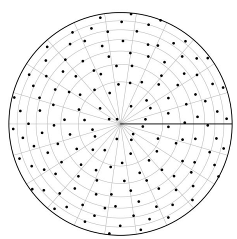


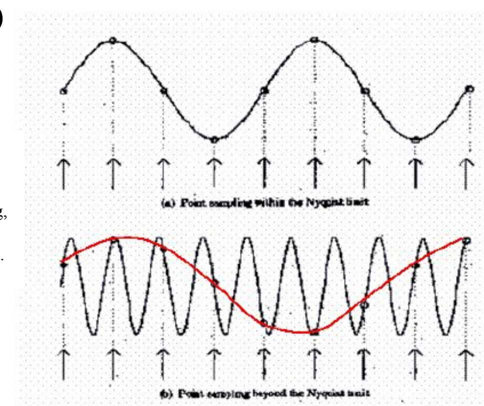
Figure 9: Polar warp with $m = 22$, $n = 7$.

[9] G. J. Ward and P. S. Heckbert. Irradiance gradients. In *Third Eurographics Rendering Workshop*, pages 85–98, May 1992.

Optional Reading for Today

- If we insufficiently sample the signal, it may be mistaken for something simpler during reconstruction (that's aliasing!)

Image from Robert L. Cook, "Stochastic Sampling and Distributed Ray Tracing", An Introduction to Ray Tracing, Andrew Glassner, ed., Academic Press Limited, 1989.



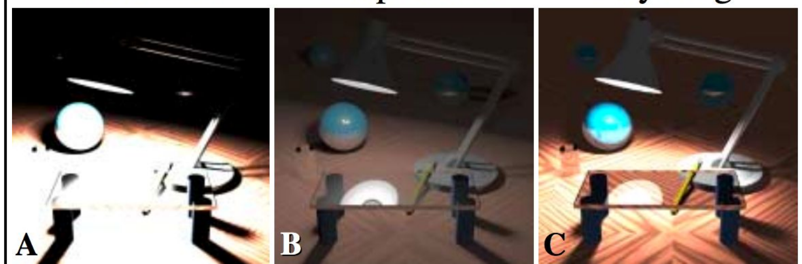
Reading for Today:

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

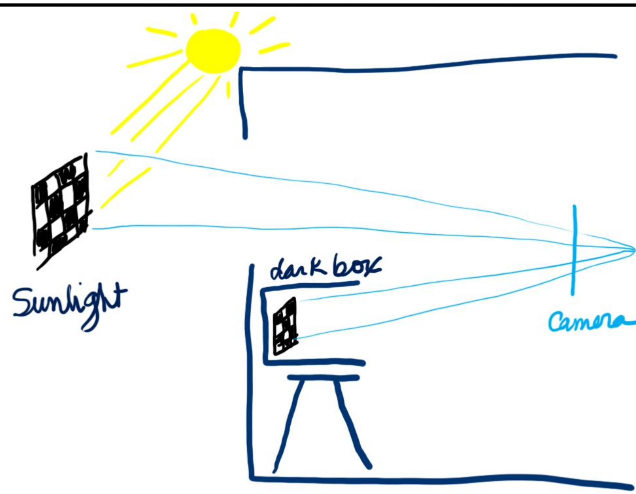
Optional Reading for Today:

"Two Methods for the Display of High Contrast Images", Tumblin, Hodgins, & Guenter, ACM Trans on Graphics 1999

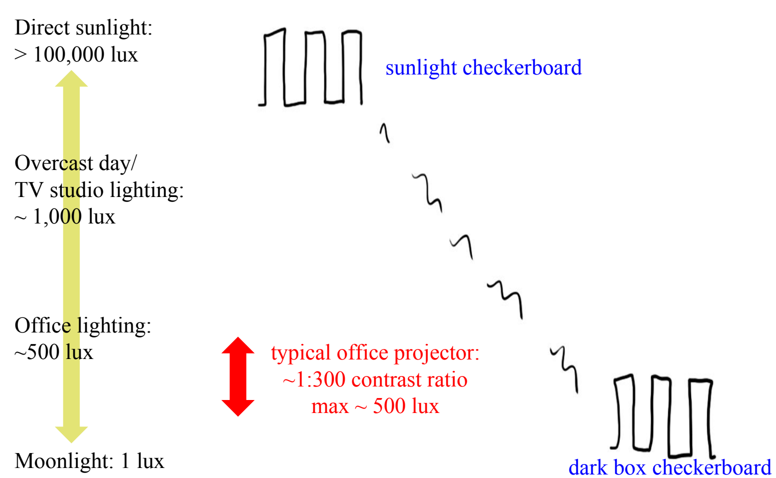
Truncation | Compression | "Layering"



High Dynamic Range Example:



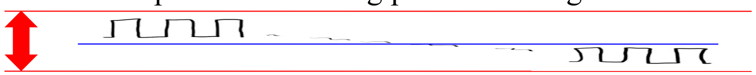
Illuminance & typical Lux values:



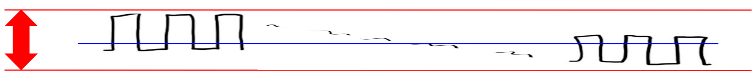
Tone Mapping

- 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:

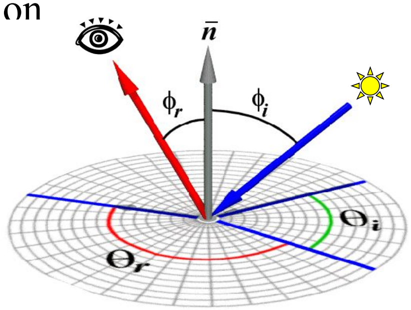


Today

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

BRDF

- Ratio of light coming from one direction that gets reflected in another direction
- Bidirectional Reflectance Distribution Function
  - 4D
  - $R(\theta_i, \varphi_i; \theta_r, \varphi_r)$
  - Note: BRDF for *isotropic* materials is 3D



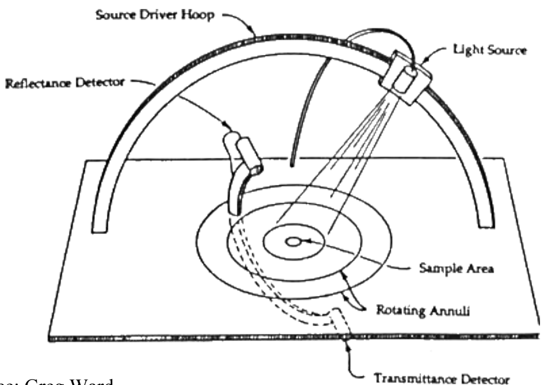
BRDFs in the Movie Industry

- 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

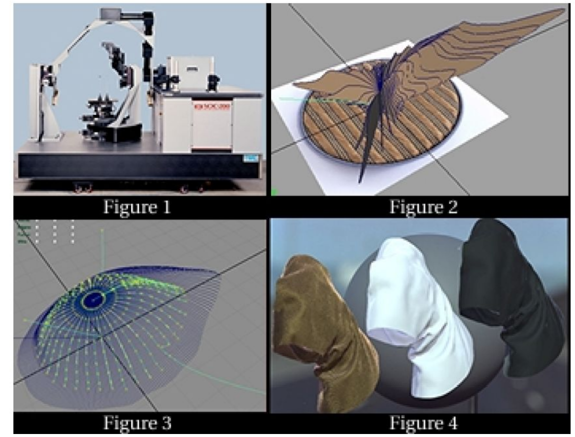
How Do We Obtain BRDFs?

- 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

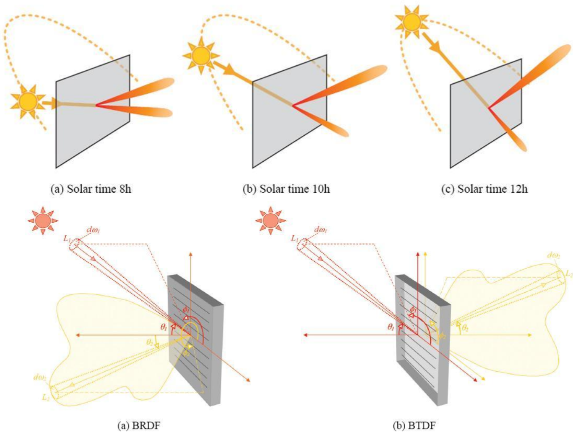
BRDFs in the Movie Industry

Photo CG Photo CG

Not just a BRDF…

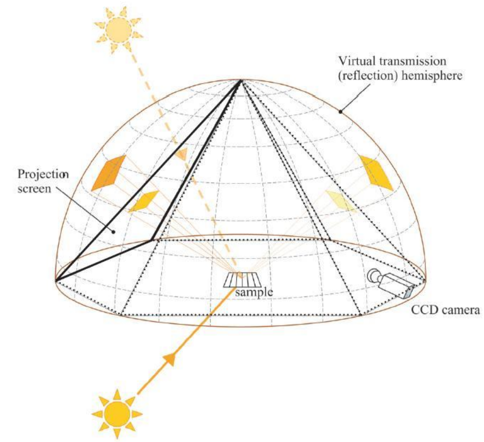
Realistic human face rendering for "The Matrix Reloaded"
Borshukov & Lewis, SIGGRAPH 2003 Sketches & Applications

Materials – BRDF & BTDF



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

Measuring Materials



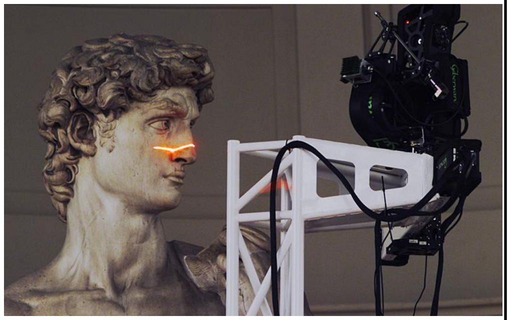
M. Andersen, "Innovative bi-directional video-goniophotometer for advanced fenestration systems", 2004.

Today

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

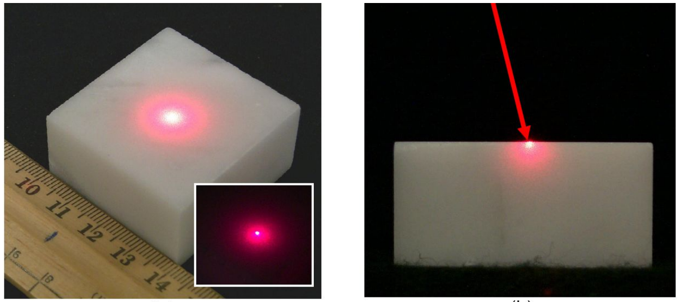
3D Digitizing

Cyberware



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

Scattering & Scanning



(a) (b)

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

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

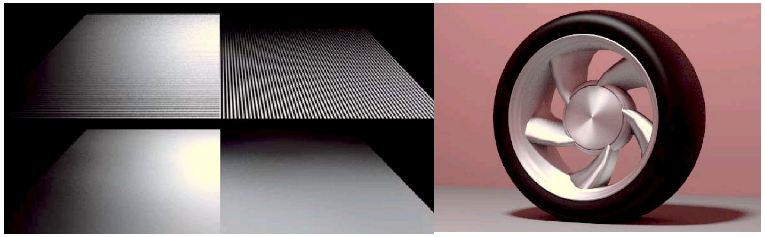
Questions?

Today

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

Anisotropic BRDFs

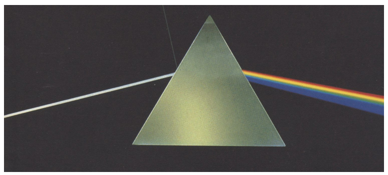
- Surfaces with strongly oriented microgeometry
- Examples:
  - brushed metals, hair, fur, cloth, velvet



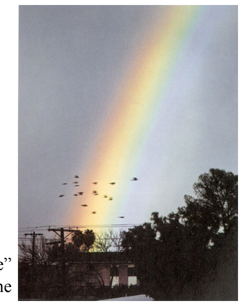
Source: Westin et.al 92

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



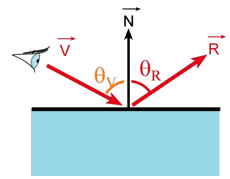
Pink Floyd, *The Dark Side of the Moon*

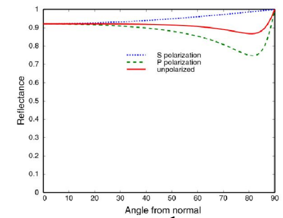


From "Color and Light in Nature" by Lynch and Livingstone

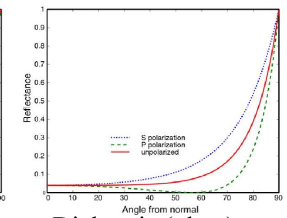
Amount of Reflection

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





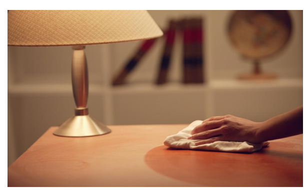
metal

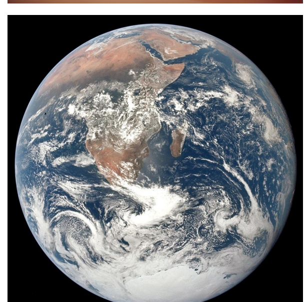


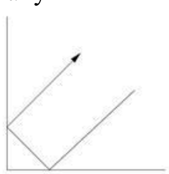
Dielectric (glass)

Dusty Surfaces & Retro-Reflection

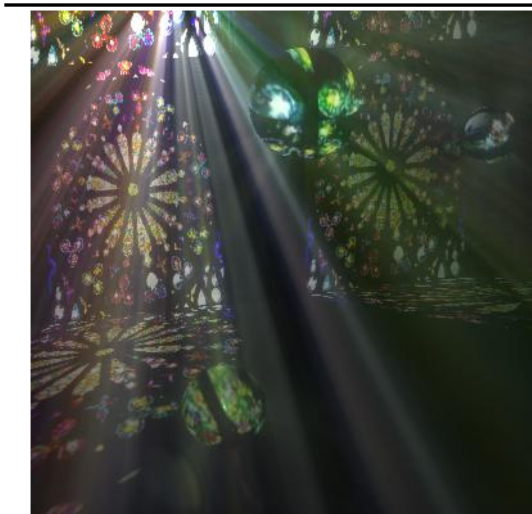
- Viewed perpendicular to the surface, there is little scattering off dust
- At grazing angles, there is increased scattering with the dust making the surface appear brighter
- Earth viewed from space appears brighter near the edges, due to increased atmospheric scattering
- Road paint is intentionally retro-reflective (so drivers see road markings illuminated by their own headlights)





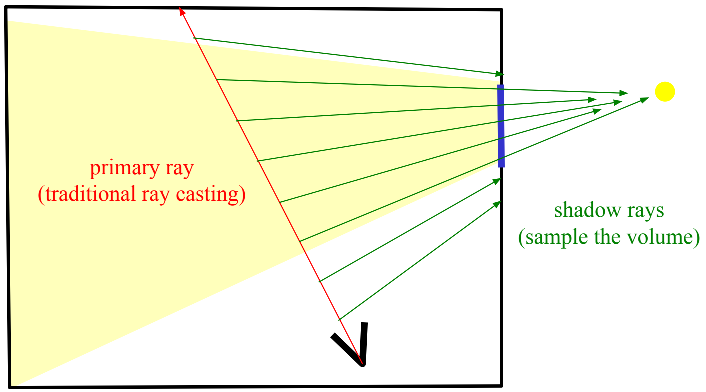


Light Rays in a Dusty Room



Annie Ding, MIT
6.837 Final Project
December, 2004

Ray Tracing Participating Media



Participating Media

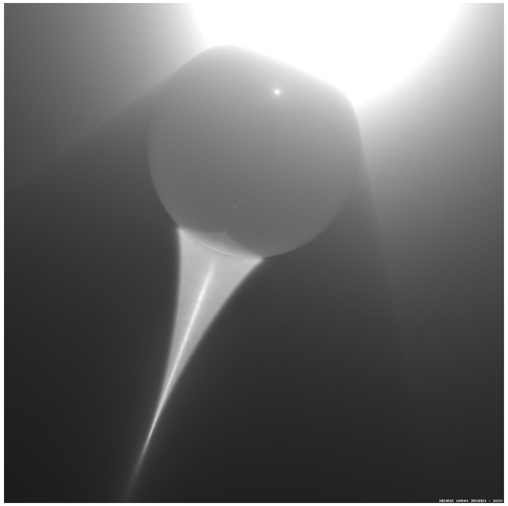


Image by Henrik Wann Jensen

Reading for Today:

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

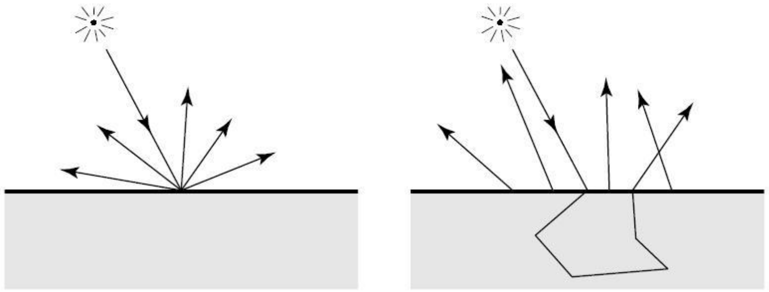
Today

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

Reading for Tuesday

"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

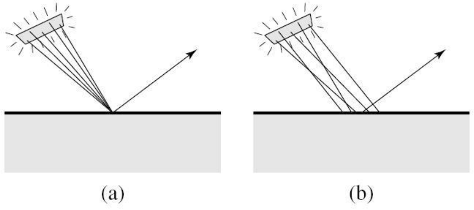


Figure 7: (a) Sampling a BRDF (traditional sampling), (b) sampling a BSSRDF (the sample points are distributed both over the surface as well as the light).

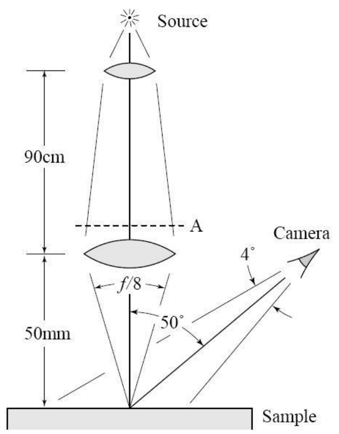
Images from "A Practical Model for Subsurface Light Transport"
Jensen, Marschner, Levoy, & Hanrahan SIGGRAPH 2001

Subsurface Scattering Variables

Name	**Symbol**	**Units**	**Description**
Scattering Coeff.	σ_s	$(\text{length})^{-1}$	Probability of scattering per unit length
Absorption Coeff.	σ_a	$(\text{length})^{-1}$	Probability of absorbtion per unit length
Phase Function	$p(x, \vec{\omega}', \vec{\omega})$		Angular distribution of scattering
Extinction Coeff.	σ_t	$(\text{length})^{-1}$	$\sigma_a + \sigma_s$
(Scattering) Albedo	A		${}^{\sigma_s}/_{\sigma_t}$
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

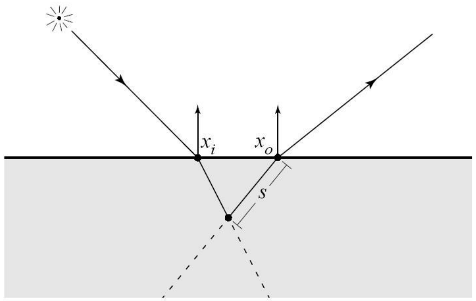


Figure 4: Single scattering occurs only when the refracted incoming and outgoing rays intersect, and is computed as an integral over path length s along the refracted outgoing ray.

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

Dipole Approx. for Diffuse Scattering

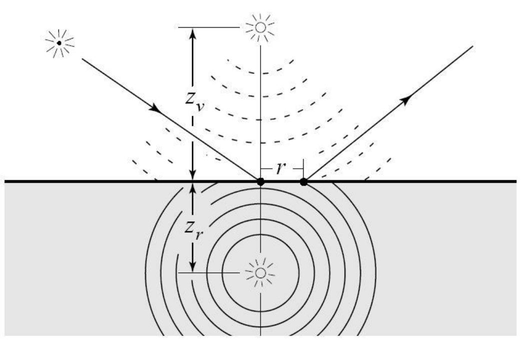


Figure 3: An incoming ray is transformed into a dipole source for the diffusion approximation.

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

Today

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

(option for Tuesday reading)

(a) 3D mesh (close-up of nostril) (b) Color data (c) Diffuse rendering

(d) Oily layer (e) Subsurface scattering (f) Final result

"Digital Face Cloning", Jensen, SIGGRAPH Sketch 2003

"Light Diffusion in Multi-Layered Translucent Materials" Donner & Jensen, *SIGGRAPH 2005*

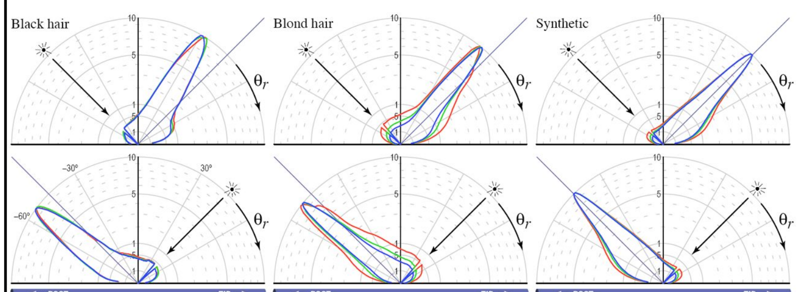
Measuring BSSRDF by Dilution

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

(option for Tuesday reading)

(a) Acquired photographs (b) Rendering at low concentrations (c) Rendering at natural concentrations

Measuring Hair *(option for Tuesday reading)*



Black hair **Blond hair** **Synthetic (wig)**

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

Rendering Hair *(option for Tuesday reading)*

Old Method **New Method** **Photo**

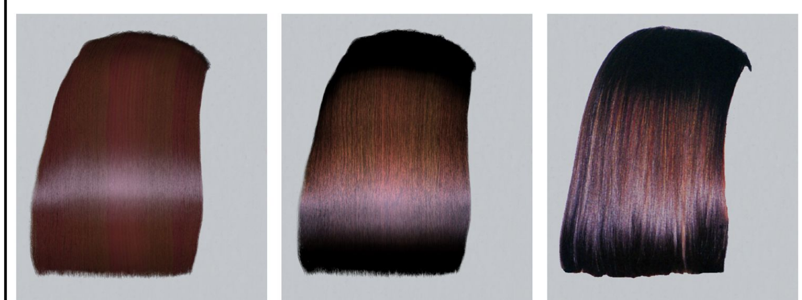


Figure 12: A comparison of Kajiya and Kay's model (left) under a single point source, our proposed model (center) with the same lighting, and the hair from the photograph in Figure 11 (removed from context to simplify the comparison). The Kajiya model's diffuse term results in a flat appearance, while 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