Reflectance
Lights, Surfaces, and Cameras

- Light sources emit photons
- Surfaces reflect & absorb photons
- Cameras measure photons
Light at Surfaces

Many effects when light strikes a surface -- could be:
- Absorbed, reflected, scattered, and travel along the surface and leave at some other points
Reflectance

- *Reflectance* is all about the way light interacts with surfaces
- It is an entire field of study on its own
- The most important quantity is the BRDF…
The BRDF

- **Assumption:**
  - No fluoresce, light emission
  - All the light leaving a point depends ONLY on the light arriving at that point

\[ \rho(\omega_o, \omega_i) \]

**Bi-directional Reflectance Distribution Function (BRDF)**
Fluorescence
The BRDF

- Given the incoming ray, it describes how reflected lights are distributed
- This distribution changes when the incoming ray changes

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plot a BRDF as a function of $\omega_o$ for a fixed $\omega_i$; the radius along each direction is set to the radiance of the reflected light at that direction.
Questions?
Rendering Equation

\[ L_o(\omega_o) = \rho_{bd}(\omega_o, \omega_i) L_i(\omega_i) \cos \theta_i \]

- Reflected Radiance (Pixel Intensity)
- BRDF
- Incident radiance (from light source)
- Cosine of Incident angle
Rendering Equation

\[ L_o(\omega_o) = \sum_i \rho_{bd}(\omega_o, \omega_i) L_i(\omega_i) \cos \theta_i \]

Reflected Radiance (Pixel Intensity)  BRDF  Incident radiance (from light source)  Cosine of Incident angle
Replace sum with integral

\[ L_o(\omega_o) = \int_{\Omega} \rho_{bd}(\omega_o, \omega_i) L_i(\omega_i) \cos \theta_i d\omega_i \]

Reflected Radiance (Pixel Intensity)  BRDF  Incident radiance (from light source)

Cosine of Incident angle
Radiometric Image Analysis

the rendering equation:
determine pixel values from shape, lighting, or reflectance

the radiometric image analysis:
recover shape, lighting, or reflectance from intensity values
Radiometric Image Analysis

Typical simplification assumptions:
- Single point light source
- No inter-reflection
- Simplified BRDF models (more details later)

\[ L_o(\omega_o) = \rho_{bd}(\omega_o, \omega_i)L_i(\omega_i)\cos\theta_i \]
Questions?
Diffuse & Specular Reflection

• Diffuse reflection:
  – The surface look the same from all directions (many vision algorithms depend on this!)
  – Matte surfaces
• Specular reflection:
  – The surface look different from different directions (causes troubles to many vision algorithms)
  – Shiny surfaces
Diffuse & Specular Reflection

- Diffuse reflection:
  - has the same color as the object surface
  - is unpolarized
- Specular reflection:
  - has the same color as the light source
  - has the same polarization as the light source
Questions?
Common BRDF Models

Lambert’s Model

Torrance-Sparrow
Lambert’s Model

Empirical mathematic model for diffuse reflection

• Assume the BRDF is a constant
  \[ \rho(\omega_o, \omega_i) = \rho \]

• Observed Pixel intensity should be
  \[ I_o = I_i \rho \cos \theta_i = I_i \rho \mathbf{N} \cdot \mathbf{L} \]

Features of this model:

• Named after Johann H. Lambert
• A pixel’s brightness does not depend on viewing direction
• Brightness *does* depend on direction of illumination
• This is the model most commonly used in computer vision

\[ \mathbf{N}, \mathbf{L}, \mathbf{V} \] are unit vectors

\[ I_i, I_o \] are intensity of incoming and outgoing light
Lambert’s Model

plot a BRDF as a function of $\omega_o$ for a fixed $\omega_i$
Questions?
Mathematic model for specular reflection

- Assume light is concentrated on the “mirrored direction”
- Intensity of light falls off by cosine law
- Observed Pixel intensity should be

\[ L_r = L_i (V \cdot R)^n \]

\[ R = 2(N \cdot L)N - L \]

Features of this model:

- Named after Bui Tuong Phong
- A pixel’s brightness depends on viewing direction
- This is an empirical model, not physically correct! (e.g. violate energy conservation)
Phong Model

Shininess $n$ controls the size of the highlight spot.

$$\cos^n \sigma$$

$\theta$ ranges from $-90^\circ$ to $90^\circ$.
Linear combination of Lambert’s model and Phong Model

\[ L_o = k_d N \cdot L + k_s (V \cdot R)^n \]
Phong Model

plot a BRDF as a function of $\omega_o$ for a fixed $\omega_i$
Phong Model

plot a BRDF as a function of $\omega_o$ for a fixed $\omega_i$

$k_d = 0.7$

$k_s = 0.4$

$n = 15$
Cook-Torrance Model

Mathematic model for specular reflection
  • Assume the surface consists of small facets
  • Derive the reflectance as the overall behavior of facets

Features of this model:
  • Named after Robert Cook and Kenneth Torrance
  • Also known as Torrance-Sparrow model
  • Assume surface consists of microfacets
  • Assume each facet is a perfect mirror
Cook-Torrance Model
Questions?
Measuring the BRDF

• Capture the BRDF by moving a camera + light source
• Need careful control of illumination, environment
Acquisition

• A spherically homogeneous sample of the material can make the acquisition simpler
  – A sphere contains all kinds of normals
  – So a single image contains many BRDF samples
Represent Measured Data

• Measure-then-fit analytic models
  – Fitting can reduce noise but also is limited by the model
  – Non-obvious error metric for fitting – often biased to specular which has large values
  – Difficult optimization – nonlinear; depends on initial guess

• Tabulated BRDF
  – 4D table
  – Not editable
Acquisition

130 materials were scanned; 100 of them shown here

MERL BRDF database, freely available online
Tabulated BRDF

- nickel
- hematite
- gold paint
- pink fabric
Questions?
Example-based Photometric Stereo

Aaron Hertzmann
University of Toronto

Steven M. Seitz
University of Washington
Shiny things

“Orientation consistency”: points of similar orientation have similar intensity
One to many mapping…
Normal at this pixel cannot be determined by referring to the sphere
Let's get multiple images....
Virtual views
Velvet
Virtual Views
Brushed Fur
Salem Specialty Ball Company

Quality Control, Phone & Fax, Addresses, E-mail Directory, Methods of Payment

Salem Specialty Ball supplies industrial grade balls that are used in bearings, pumps, valves and other commercial applications. We can supply balls in just about any size that is machinable. We have produced precision balls from .002" all the way up to 12.0" and beyond. We can also produce these balls in any material. A most important exception, if the material exists, we can make it into a ball. Not only do we specialize in hard to find materials, we also carry standard materials such as chrome steel and stainless steel. We stock an extensive inventory of ready to ship balls. Most orders are shipped the same day. And if it is in stock we can make it for you in matter of days. In addition, you will find that our prices are very competitive.

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Questions?
BRDF Symmetries

Isotropic vs. anisotropic

\[ \rho(\theta_o, \varphi_o, \theta_i, \varphi_i) = \rho(\theta_o, \theta_i, \varphi_o - \varphi_i) \]

Reciprocity and isotropy

\[ \rho(\theta_o, \theta_i, \varphi_o - \varphi_i) = \rho(\theta_o, \theta_i, \varphi_i - \varphi_o) = \rho(\theta_o, \theta_i, |\varphi_i - \varphi_o|) \]

Most of real materials are isotropic
Examples

[Westin et al. 92]