Materials and Surface Appearance

Thanks to Shree Nayar, Ravi Ramamoorthi, Pat Hanrahan
Surface Appearance

Image intensities = \( f(\text{normal, surface reflectance, illumination}) \)

Surface Reflection depends on both the viewing and illumination direction.
BRDF: Bidirectional Reflectance Distribution Function

\[ E_{\text{surface}}(\theta_i, \phi_i) \quad \text{Irradiance at Surface in direction} \quad (\theta_i, \phi_i) \]

\[ L_{\text{surface}}(\theta_r, \phi_r) \quad \text{Radiance of Surface in direction} \quad (\theta_r, \phi_r) \]

\[
\text{BRDF} : f(\theta_i, \phi_i ; \theta_r, \phi_r) = \frac{L_{\text{surface}}(\theta_r, \phi_r)}{E_{\text{surface}}(\theta_i, \phi_i)}
\]
Important Properties of BRDFs

• Rotational Symmetry:

Appearance does not change when surface is rotated about the normal.

BRDF is only a function of 3 variables: \( f(\theta_i, \theta_r, \phi_i - \phi_r) \)

• Helmholtz Reciprocity: (follows from 2\textsuperscript{nd} Law of Thermodynamics)

Appearance does not change when source and viewing directions are swapped.

\[ f(\theta_i, \phi_i; \theta_r, \phi_r) = f(\theta_r, \phi_r; \theta_i, \phi_i) \]
Mechanisms of Surface Reflection

Body Reflection:
- Diffuse Reflection
- Matte Appearance
- Non-Homogeneous Medium
- Clay, paper, etc

Surface Reflection:
- Specular Reflection
- Glossy Appearance
- Highlights
- Dominant for Metals

Image Intensity = Body Reflection + Surface Reflection
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Many materials exhibit both Reflections:
Diffuse Reflection and Lambertian BRDF
Diffuse Reflection and Lambertian BRDF

- Surface appears equally bright from ALL directions! (independent of \( \hat{v} \))

- Lambertian BRDF is simply a constant: 
  \[
  f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{\rho_d}{\pi}
  \]

- Surface Radiance: 
  \[
  L = \frac{\rho_d}{\pi} I \cos \theta_i = \frac{\rho_d}{\pi} I \hat{n} \cdot \hat{s}
  \]

- Commonly used in Vision and Graphics!
Rendered Sphere with Lambertian BRDF

- Edges are dark (N.S = 0) when lit head-on
- See shading effects clearly.
White-out Conditions from an Overcast Sky

CAN’T perceive the shape of the snow covered terrain!

CAN perceive shape in regions lit by the street lamp!!

WHY?
Specular Reflection and Mirror BRDF

- Very smooth surface.
- All incident light energy reflected in a SINGLE direction. (only when $\mathbf{v} = \mathbf{r}$)
- Mirror BRDF is simply a double-delta function:

$$f(\theta_i, \phi_i; \theta_v, \phi_v) = \rho_s \delta(\theta_i - \theta_v) \delta(\phi_i + \pi - \phi_v)$$

- Surface Radiance:

$$L = I \rho_s \delta(\theta_i - \theta_v) \delta(\phi_i + \pi - \phi_v)$$
Specular Reflections in Nature

Compare sizes of objects and their reflections!

The reflections when seen from a lower viewpoint are always longer than when viewed from a higher viewpoint.

It's surprising how long the reflections are when viewed sitting on the river bank.
Specular Reflections in Nature
Glossy Surfaces

• Delta Function too harsh a BRDF model
  (valid only for highly polished mirrors and metals).

• Many glossy surfaces show broader highlights in addition to mirror reflection.

• Surfaces are not perfectly smooth – they show micro-surface geometry (roughness).

• Example Models: Phong model

  Torrance Sparrow model
Blurred Highlights and Surface Roughness
Phong Model: An Empirical Approximation

- How to model the angular falloff of highlights:

\[ L = I \rho_s (R.E)^{n_{\text{shiny}}} \]
\[ R = -S + 2(N.S)N \]
\[ H = (E + S) / 2 \]

Phong Model

Blinn-Phong Model

- Sort of works, easy to compute
- But not physically based (no energy conservation and reciprocity).
- Very commonly used in computer graphics.
Phong Examples

• These spheres illustrate the Phong model as *lighting direction* and $n_{shiny}$ are varied:
Those Were the Days

• “In trying to improve the quality of the synthetic images, we do not expect to be able to display the object exactly as it would appear in reality, with texture, overcast shadows, etc. We hope only to display an image that approximates the real object closely enough to provide a certain degree of realism.”
  – Bui Tuong Phong, 1975
Experiment

Reflections from a shiny floor

From Lafortune, Foo, Torrance, Greenberg, SIGGRAPH 97
Fresnel Reflectance

Metal (Aluminum)

Dielectric (N=1.5)

Gold  \( F(0)=0.82 \)
Silver  \( F(0)=0.95 \)

Glass  \( n=1.5 \)  \( F(0)=0.04 \)
Diamond  \( n=2.4 \)  \( F(0)=0.15 \)

Schlick Approximation

\[ F(\theta) = F(0) + (1 - F(0))(1 - \cos \theta)^5 \]
Reflections on water surfaces - Glittering
Split off-specular Reflections in Woven Surfaces
Why does the Full Moon have a flat appearance?

• The moon appears matte (or diffuse)

• But still, edges of the moon look bright (not close to zero) when illuminated by earth’s radiance.
Why does the Full Moon have a flat appearance?

Lambertian Spheres and Moon Photos illuminated similarly
Surface Roughness Causes Flat Appearance

Actual Vase  

Lambertian Vase
Rendered Sphere with Lambertian BRDF

- Edges are dark (N.S = 0) when lit head-on.
- See shading effects clearly.
Surface Roughness Causes Flat Appearance

Lambertian model

- Valid for only SMOOTH MATTE surfaces.
- Bad for ROUGH MATTE surfaces.
Modeling Rough Surfaces - Microfacets

- Roughness simulated by Symmetric V-groves at Microscopic level.

- Distribution on the slopes of the V-grove faces are modeled.

- Each microfacet assumed to behave like a perfect lambertian surface.
A Simple Reflection Model - Dichromatic Reflection

Observed Image Color = a \times \text{Body Color} + b \times \text{Specular Reflection Color}

Klinker-Shafer-Kanade 1988

Does not specify any specific model for Diffuse/specular reflection
Measuring BRDFs

Why bother modeling BRDFs?

Why not directly measure BRDFs?

• True knowledge of surface properties

• Accurate models for graphics
Measuring BRDFs

- A full BRDF is 4-dimensional
- Simpler measurements (0D/1D/2D/3D) often useful
- Let's start with simplest and get more complex
Measuring Reflectance

- $0^\circ/45^\circ$ Diffuse Measurement
- $45^\circ/45^\circ$ Specular Measurement
Gloss Measurements

• Standardized for applications such as paint manufacturing

• Example: “contrast gloss” is essentially ratio of specular to diffuse

• “Sheen” is specular measurement at 85°
Gloss Measurements

- “Haze” and “distinctness of image” are measurements of width of specular peak
Gonioreflectometers

- Three degrees of freedom spread among light source, detector, and/or sample
Gonioreflectometers

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Gonioreflectometers

- Can add fourth degree of freedom to measure anisotropic BRDFs
Image-Based BRDF Measurement

• Reduce acquisition time by obtaining larger (e.g. 2-D) slices of BRDF at once
• Idea: Camera can acquire 2D image
• Requires mapping of angles of light to camera pixels
Image-Based BRDF Measurement

- For uniform BRDF, capture 2-D slice corresponding to variations in normals (Marschner et al)
Measurement

- Light Source
  - Hamamatsu SQ Xenon lamp
    - Stable emission output
    - Continuous and relatively constant radiation spectrum
Measurement

- 20-80 million reflectance measurements per material
- Each tabulated BRDF entails $90 \times 90 \times 180 \times 3 = 4,374,000$ measurement bins
Rendering from Tabulated BRDFs

- These BRDFs are immediately useful
- Direct renderings from measurements

Nickel  Hematite  Gold Paint  Pink Felt

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Linear Combinations of BRDFs (LCB)

- Can we find a linear combination of our existing BRDFs that match any new one?
- Requires only estimating 100 coefficients for source BRDFs
- Compute a set of 800 constraints that allow estimating these 100 coefficients robustly

\[ \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \ldots = \]
Linear Analysis (PCA)

- Find optimal linear basis for our data set
- 45 components needed to reduce residue to under measurement error
Navigation Results

Adding Silver Trait
Navigation Results

Adding Specular Trait
Navigation Results

Adding Metallic Trait

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Representing Physical Processes

Steel Oxidation

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Wojciech Matusik
Next Step in the Appearance Food Chain

Textures

Spatially Varying BRDFs
Bi-Directional Texture Distribution Functions (BTF)

CURET Database – [Dana, Nayar 96]
BRDF vs. BTF

coarse-scale ... BRDF

fine-scale ... BTF
Samples for Measurements

61 samples:

- specular  (foil, artificial grass)
- diffuse   (brick, plaster)
- natural   (fur, moss)
- man-made  (velvet, leather)
- isotropic (bread, concrete)
- anisotropic (corn husk, wood)
Measurement Methods

Texture/BTF

Radiance/BRDF
Example images
Measurement Methods
Measurement Methods
Texture-mapping using BTF

standard texture-mapping

texture-mapping with the BTF
Texture-mapping using BTF

standard texture-mapping

texture-mapping with the BTF
Materials Change with Time