Measuring Material Appearance: BRDF, BSSRDF, BTF

Computer Graphics, Fall 2009

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Images Courtest Ben-Ezra et al

Thanks to Steve Marschner, Shree Nayar, Ravi Ramamoorthi, Szymon Rusinkiewicz, Marc Levoy, Pat Hanrahan, Kristin Dana, Ken Perlin, Debevec, Matusik
A variety of material appearances
Methods Relying on Surface Reflectance

Shape from Shading

Photometric Stereo

Texture Modeling

Reflection Separation
Mechanisms of Reflection

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

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

Image Intensity = Body Reflection + Surface Reflection
Mechanisms of Reflection

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Surface Reflection:
- Specular Reflection
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Many materials exhibit both Reflections:
Image intensities \( = f(\text{normal, surface reflectance, illumination}) \)

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

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

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

\[ \text{BRDF} : f(\theta_i, \phi_i ; \theta_r, \phi_r) = \frac{L_{\text{surface}}(\theta_r, \phi_r)}{E_{\text{surface}}(\theta_i, \phi_i)} \]
Derivation of the Scene Radiance Equation

From the definition of BRDF:

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

- Rotational Symmetry:
  
  BRDF 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 2nd Law of Thermodynamics)
  
  BRDF does not change when source and viewing directions are swapped.
  
  \[ f(\theta_i, \phi_i; \theta_r, \phi_r) = f(\theta_r, \phi_r; \theta_i, \phi_i) \]
Specular Reflection and Mirror BRDF

- Very smooth surface.

- All incident light energy reflected in a SINGLE direction. (only when $V = R$)

- 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
Diffuse Reflection and Lambertian BRDF

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

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

- Surface Radiance: 
  $$L = \frac{\rho_d}{\pi} I \cos \theta_i = \frac{\rho_d}{\pi} I \mathbf{n} \cdot \mathbf{s}$$

- Commonly used in Vision and Graphics!
Diffuse Reflection and Lambertian BRDF
White-out Conditions from an Overcast Sky

CAN’T perceive the shape of the snow covered terrain!
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**.
View Dependence of Matte Surfaces - Key Observation

- Overall brightness increases as the angle between the source and viewing direction decreases. WHY?

- Pixels have finite areas. As the viewing direction changes, different mixes between dark and bright are added up to give pixel brightness.
Slope Distribution Model

- Model the distribution of slopes as Gaussian.
- Mean is Zero, Variance represents ROUGHNESS.

\[ \rho_\alpha (\alpha) = \frac{1}{\sqrt{2\pi \sigma_\alpha}} e^{-\frac{\alpha^2}{2\sigma_\alpha^2}}. \]
• Take into account two light bounces (reflections).

• Hard to solve analytically, so they find a functional approximation.
Lambertian model is simply an extreme case with roughness equal to zero.
Surface Roughness Causes Flat Appearance

Actual Vase
Lambertian Vase
Surface Roughness Causes Flat Appearance

Increasing surface roughness

Lambertian model

Valid for only SMOOTH MATTE surfaces.

Bad for ROUGH MATTE surfaces.
Rendered Sphere with Lambertian BRDF

- Edges are dark (N.S = 0) when lit head-on
- See shading effects clearly.
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
Oren-Nayar Model – Main Points

• Physically Based Model for Diffuse Reflection.

• Explains view dependent appearance in Matte Surfaces

• Lambertian model is simply an extreme case with roughness equal to zero.
Fig. 7. (a-c) Real image of a cylindrical clay vase compared with images rendered using the Lambertian and proposed models. Illumination is from the direction \( \theta_i = 0^\circ \). (d) Comparison between image brightness along the cross-sections of the three vases.
• 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:

\[ L = I \, \rho_s \, (R.E)^{n_{shiny}} \]

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 $n_{\text{shiny}}$ 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
Many surfaces may be rough and show both diffuse and surface reflection.
Many surfaces may be rough and show both diffuse and surface 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

0º/45º
Diffuse Measurement

45º/45º
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°
BRDF Measurements

- Next step up in complexity: measure BRDF in plane of incidence (1- or 2-D)
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
Ward’s BRDF Measurement Setup

- Collect reflected light with hemispherical mirror
Ward’s BRDF Measurement Setup

- Result: each image captures light at all exitant angles
Image-Based BRDF Measurement

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

- Any object with known geometry

Marschner et al.
Image-based measurement of skin

Marschner et al. 2000
Measurement

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

- Turntable
  - Kaidan MD-19
  - Computer-controlled

- Dark Room
  - Walls painted with flat black paint

- Spherical Samples
Calibration

- Geometric calibration
  - Contact digitizer
    - Faro Arm
  - Intrinsic & extrinsic camera parameters
  - Sphere center & radius
  - Light Position
    - parameterized on a circle in 3D
Measurement

- 20-80 million reflectance measurements per material
- Each tabulated BRDF entails 90x90x180x3 = 4,374,000 measurement bins
Rendering from Tabulated BRDFs

- These BRDFs are immediately useful
- Direct renderings from measurements
Measurement Process

1. Measure BRDFs

2. Find Compact Basis

3. Optimize Sampling

Course 10: Realistic Materials in Computer Graphics

Wojciech Matusik
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

\[ \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \ldots = \]

Course 10: Realistic Materials in Computer Graphics
Wojciech Matusik
BRDFs as Vectors in High Dimensional Space

- Each tabulated BRDF is a vector in 90x90x180x3 = 4,374,000 dimensional space
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

Course 10: Realistic Materials in Computer Graphics

Wojciech Matusik
Representing Physical Processes

Steel Oxidation

Course 10: Realistic Materials in Computer Graphics
Wojciech Matusik
Next Step in the Appearance Food Chain

Textures

Spatially Varying BRDFs

CURET Database – [Dana, Nayar 96]
Few slides about BTF here – from Kristin Dana’s slides
### 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
Measurement Methods
Measurement Methods

Illumination Directions

(xs, zs, ys)
Texture-mapping using BTF

standard texture-mapping

texture-mapping with the BTF
Texture-mapping using BTF

standard texture-mapping

texture-mapping with the BTF
Next Step in the Appearance Food Chain

Why bother about measuring patches or spheres?
Why not measure the scenes themselves directly?

• Change only lighting (for Relighting)
• Change only viewpoint (Light Fields)
• Change both lighting and viewpoint
Debevec et al. Siggraph 2000
VIDEO and DEMO for relighting
Time-Varying BRDFs

Bo Sun
Kalyan Sunkavalli
Ravi Ramamoorthi
Peter Belhumeur
Shree Nayar

Columbia University
Materials Change with Time
Previous Work

- Time-Varying Spatial Albedo Patterns
  - [J. Dorsey et al., 96]
  - [J. Dorsey et al., 99]
  - [J. Lu et al., 05]
  - [S. Enrique et al., 05]

- Paints, Wet Surfaces and Dust
  - [C. J. Curtis., 97]
  - [J. W. Jensen et al., 99]
  - [E. Nakamae et al., 96]
  - [S. Hsu et al., 96]
Our Goals

• Efficient TVBRDF Acquisition

• Underlying Temporal Trend Analysis

• Developing Analytic TVBRDF Models
Acquisition System
Acquisition System
Acquisition System
Acquisition System
Acquisition System
Acquisition System

12 seconds / scan, 360 color images / camera, 0.2~32 millisecond exposures
Acquisition - Sampling
## TVBRDF Samples

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41 samples and three time-varying effects
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<td></td>
<td></td>
</tr>
<tr>
<td>Krylon Spray Paint</td>
<td>White Plaster</td>
<td>Household Dust</td>
<td></td>
</tr>
<tr>
<td>Flat / White</td>
<td>Cement</td>
<td>Electric Red Paint</td>
<td></td>
</tr>
<tr>
<td>Satin / Green</td>
<td></td>
<td>Satin / Red Spray</td>
<td></td>
</tr>
<tr>
<td>Glossy / Blue</td>
<td></td>
<td>Satin / Dove-Teal</td>
<td></td>
</tr>
<tr>
<td>Glossy / Blue</td>
<td></td>
<td>Flat / Yellow Spray</td>
<td></td>
</tr>
<tr>
<td>Satin / Dove-Teal</td>
<td></td>
<td>Almas Red Fabric</td>
<td></td>
</tr>
<tr>
<td>Rust-Oleum Spray</td>
<td>White Plaster</td>
<td>Green Grey Paint</td>
<td></td>
</tr>
<tr>
<td>Flat / Yellow</td>
<td>Terracotta Clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daler-Rowney Oil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prussian Green</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prussian Red</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Green</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium Yellow</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Measurement

Flat Yellow Spray Paint (Top Camera, Blue Channel)

Drying Cement (Top Camera, Blue Channel)

Household Dust on Satin Paint (Top Camera, Blue Channel)
Analytic BRDF Functions

- The Oren-Nayar diffuse model

\[
\rho_d(\omega_i, \omega_o; \sigma_d, K_d^{r,g,b})
\]

- The Torrance-Sparrow specular model

\[
\rho_s(\omega_i, \omega_o; \sigma_s, K_s)
\]

- The Blinn’s dust model

\[
\rho(\tau) = (1 - T_1(\tau)) \cdot \rho_{dust} + T_2(\tau) \cdot \rho_d + \rho_s(\sigma_s, K_s)
\]
Data Fitting

Maximum RMS Error 3.84%
TVBRDF Database
TVBRDF Database
TVBRDF Database

- Prussian Green Oil Paint
  - 00.0
  - 01.2
  - 02.0
  - 04.0
  - 06.8
  - 09.2 (mins)

- Light Green Oil Paint
  - 00.0
  - 02.0
  - 03.2
  - 04.4
  - 05.2
  - 08.8 (mins)

- Alme Dark Blue Grey
  - 000
  - 020
  - 040
  - 064
  - 106
  - 151 (mins)

- Ideno Beige Fabric
  - 00.0
  - 14.4
  - 26.4
  - 39.6
  - 48.0
  - 57.6 (mins)
TVBRDF Database

- Joint Compound & Electric Red Paint
  - Optical thickness (τ): 0.00, 0.03, 0.10, 0.19, 0.44, 2.76 (τ)
- Joint Compound & Satin Dove Teal
  - Optical thickness (τ): 0.00, 0.01, 0.09, 0.35, 0.63, 2.83 (τ)
- Household Dust & Satin Red Paint
  - Optical thickness (τ): 0.00, 0.11, 0.17, 0.28, 0.99, 2.93 (τ)
- Household Dust & Satin Dove Teal
  - Optical thickness (τ): 0.00, 0.02, 0.22, 0.62, 1.17, 2.96 (τ)
Temporal Trends

$K_s, \sigma_s$: Specular Parameters  $K_d^r, K_d^g, K_d^b$: Diffuse Parameters
Time-Varying Phenomena

- Paints drying on smooth surfaces
- Water drying on rough surfaces
- Dust accumulation
Paints

- Exponential fall-off of specular albedo and roughness
- Diffuse color shifts in a dichromatic plane
Paints

- Exponential fall-off of specular albedo and roughness
- Diffuse color shifts in a dichromatic plane

\[ K_s(t) = (K_{s,wet} - K_{s,dry}) \cdot e^{-\lambda t} + K_{s,dry} \]

\[ \sigma_s(t) = \frac{\sigma_{s,wet} \cdot \sigma_{s,dry}}{(\sigma_{s,dry} - \sigma_{s,wet}) \cdot e^{-\lambda t} + \sigma_{s,wet}} \]
Paints

- Exponential fall-off of specular albedo and roughness
- Diffuse color shifts in a dichromatic plane

\[ \rho_d(t) = \alpha(t) \cdot \rho_{d,\text{surface}} + \beta(t) \cdot \rho_{d,\text{surface}} \]
Paints – Spatial Variations

Captured Blue Watercolor on White Surface
Paints – Effects Transfer

Synthesized Green Watercolor on White Surface
Paints – Effects Transfer

Synthesized Blue Watercolor on Red Surface
Wet Surfaces

- Diffuse color shifts on a straight line
- Sigmoidal change of surface intensity

$$\rho_d(t) = \alpha(t) \cdot \rho_{d, dry} + (1 - \alpha(t)) \cdot \rho_{d, wet}$$
Wet Surfaces

- Diffuse color shifts on a straight line
- Sigmoidal change of surface intensity
Time-Varying Phenomena

- Paints drying on smooth surfaces
- Water drying on rough surfaces
- Dust accumulation
Dust

- Analysis generalizes to other BRDF models
- Exponential fall-off of specular highlights
Dust

• Analysis generalizes to other BRDF models
• Exponential fall-off of specular highlights

\[ \rho(\tau) = (1 - T(\tau)) \cdot \rho_{dust} + T(\tau) \cdot \rho_d + e^{-\lambda \tau} \cdot \rho_s \]

\[ \rho(\tau) = (1 - T_1(\tau)) \cdot \rho_{dust} + T_2(\tau) \cdot \rho_d + \rho_s(\sigma_s, K_s) \]
Dust – Final Example