Reflectance, Lights and on to photometric stereo

And if that 120MP Camera was cool

- Large Synoptic Survey Telescope
- 3.2Gigapixel camera
- 189 CCD’s, each with 16 megapixels
- Pixels are 10μm
- Filter wheel
- 6200 lbs
- https://www.lsst.org/about/camera
Announcements

• HW1 due Tuesday

BRDF

With assumptions in previous slide
• Bi-directional Reflectance Distribution Function
  \[ \rho(\theta_{\text{in}}, \phi_{\text{in}}; \theta_{\text{out}}, \phi_{\text{out}}) \]
• Ratio of emitted radiance to incident irradiance (units: sr\(^{-1}\))
• In local coordinate system at \(x\)
  – Incoming light direction: \(\theta_{\text{in}}, \phi_{\text{in}}\)
  – Outgoing light direction: \(\theta_{\text{out}}, \phi_{\text{out}}\)

\[
\rho(x; \theta_{\text{in}}, \phi_{\text{in}}; \theta_{\text{out}}, \phi_{\text{out}}) = \frac{L_o(x; \theta_{\text{out}}, \phi_{\text{out}})}{L_i(x; \theta_{\text{in}}, \phi_{\text{in}}) \cos \theta_{\text{in}} \, d\omega}
\]

Where \(\rho\) is sometimes denoted \(f_r\).
Properties of BRDFs

1. Non-negative: $\rho(\theta_{in}, \phi_{in}; \theta_{out}, \phi_{out}) \geq 0$

2. Helmholtz Reciprocity Principle:
   
   $\rho(\theta_{in}, \phi_{in}; \theta_{out}, \phi_{out}) = \rho(\theta_{out}, \phi_{out}; \theta_{in}, \phi_{in})$

3. Total energy leaving a surface must be less than total energy arriving at the surface

\[
\int_{\Omega_i} L_i(x, \theta_i, \phi_i) \cos \theta_i d\omega_i \geq \int_{\Omega_o} \left[ \int_{\Omega_i} \rho(\theta_i, \phi_i; \theta_o, \phi_o) L_i(x, \theta_i, \phi_i) \cos \theta_i d\omega_i \right] \cos \theta_o d\omega_o
\]
Important class of BRDFs: Isotropic BRDF

\[ \rho(\theta_i, \phi_i; \theta_o, \phi_o) = \rho_r(\theta_i, \theta_o, \phi_i - \phi_o) \]

Isotropic BRDF’s are symmetric about the surface normal. If the surface is rotated about the normal for the same incident and emitting directions, the value of the BRDF is the same.

Anisotropic BRDF

\[ \rho(\theta_i, \phi_i; \theta_o, \phi_o) \] is an arbitrary function
Lambertian (Diffuse) Surface

- BRDF is a constant called the albedo. \( \rho (\omega_i, \omega_o, \theta_{inc}, \theta_{em}, \phi_{inc}, \phi_{em}) = K \)
- Emitted radiance is NOT a function of outgoing direction – i.e. constant in all directions.
- For lighting coming in single direction \( \omega_i \), emitted radiance is proportional to cosine of the angle between normal and light direction

\[
L_r = K \hat{N} \cdot \omega_i
\]
Specular Reflection: Smooth Surface

\[ \omega_o = 2(\omega_i \cdot N)N - \omega_i \]

- \( N, \omega_i, \omega_o \) are coplanar
- \( \theta_i = \theta_o \)

Speculum – Latin for “Mirror”

Rough Specular Surface

Symmetric V-shaped grooves – ‘microfacets’
Phong Model

\[ L_r(\omega_o) = k_a L_a + k_d (N \cdot \omega_i) + k_s (\omega_o \cdot R) s \]

where \( R = 2(\omega_i \cdot N)N - \omega_i \)

Non-Lambertian reflectance
Lots of BRDF Models

**Common Models**

- Lambertian
- Phong
- Physics-based
  - Specular
    - [Blinn 1977], [Cook-Torrance 1982], [Ward 1992]
  - Diffuse
    - [Hanrahan, Kreuger 1993]
  - Generalized Lambertian
    - [Oren, Nayar 1995]
  - Thoroughly Pitted Surfaces
    - [Koenderink et al 1999]
- Phenomenological
  - [Koenderink, Van Doorn 1996]

**Arbitrary Reflectance**

- Non-parametric model
- Anisotropic
- Non-uniform over surface
- BRDF Measurement
  - [Dana et al, 1999], [Marschner]

**Specialized**

- Hair, skin, threads, paper [Jensen et al]

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General BRDF: e.g. Velvet

*Portrait of Sir Thomas More*, Hans Holbein the Younger, 1527

[After Koenderink et al, 1998]
Ways to measure BRDFs

Gonioreflectometers

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

Detector

Light source

Sample
Gonioreflectometers

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

• Can add fourth degree of freedom to measure anisotropic BRDFs

• UCSD spherical gantry in CSE has two arms, each with two degrees of freedom.
Ward’s BRDF Measurement Setup

• Collect reflected light with hemispherical (should be ellipsoidal) mirror [SIGGRAPH 92]

Half-silvered dome

Light source

Camera

Sample

Ward’s BRDF Measurement Setup

• Result: each image captures light at all exitant angles
Marschner’s Image-Based BRDF Measurement

- For uniform BRDF, capture 2-D slice corresponding to variations in normals

MERL BRDF Database

- 100 Isotropic materials
- http://www.merl.com/brdf/
- Ver 2, 2006
BRDF Not Always Appropriate

BRDF

BSSRDF captures subsurface scattering

http://graphics.stanford.edu/

(BSSRDF not always appropriate)

(Jensen, Marschner, Levoy, Hanrahan)

Light sources and shading

- A light source emits light instead of reflecting it
- Examples:
  - Laser - a single ray
  - Point source - like a light bulb
  - Line source - fluorescent light bulb
  - Area source
Nearby point source model

Emitted radiance $L$ at $x$

$$L = p_d(x) \frac{1}{|x-s|} \left( N(x) \frac{(x-s)}{|x-s|} \right)$$

- $S$ : Point light source location
- $N$ : Unit surface normal
- $\rho_d$ : Diffuse (Lambertian) albedo

Nearby Line Source

Intensity due to line source varies with inverse distance, if the source is long enough
Distant Point Source Model

• Assume that all points in the model are close to each other with respect to the distance to the source. Then the source vector doesn’t vary much, and the distance doesn’t vary much either, and we can roll the constants together to get:

\[ L = \rho_d(x) N(x) \cdot S(x) \]

• \( N \) is the surface normal
• \( \rho_d \) is diffuse (Lambertian) albedo
• \( S \) is source vector - a vector in source direction, whose length is the intensity term

Lighting at infinity

• Direction is a three vector \( s \), with \(|s| = 1\).
• Described as function on a sphere: radiance as a function of direction \( r(s) \)
• Single point source is a delta function at some direction
• Multiple point sources: sum of delta functions
Diffuse lighting at infinity:
Spherical Harmonics

\[ Y_{lm}(\theta, \phi) \]

Order

\( l=0 \)

\( l=1 \)

\( l=2 \)

\( m=-2 \) \hspace{1cm} m=-1 \hspace{1cm} m=0 \hspace{1cm} m=1 \hspace{1cm} m=2 \)

Green: Positive
Blue: Negative

(Borrowed from: Ramamoorthi, Hanrahan, SIGGRAPH'01)

Shadows cast by a point source

- A point in the scene that can't see the source is in shadow
Area Source Shadows

1. Fully illuminated
2. Penumbra
3. Umbra (shadow)

Shading models

Local shading model
- Surface has incident radiance due only to sources visible at each point
- Advantages:
  - often easy to manipulate, expressions easy
  - supports quite simple theories of how shape information can be extracted from shading
- Used in vision & real time graphics

Global shading model
- Surface radiosity is due to radiance reflected from other surfaces as well as from surfaces
- Advantages:
  - usually very accurate
- Disadvantage:
  - extremely difficult to infer anything from shading values
- Rarely used in vision, often in photorealistic graphics
At the top, geometry of a gutter with triangular cross-section; below, predicted radiosity solutions, scaled to lie on top of each other, for different albedos of the geometry. When albedo is close to zero, shading follows a local model; when it is close to one, there are substantial reflexes.

Irradiance observed in an image of this geometry for a real white gutter.

Figure from “Mutual Illumination,” by D.A. Forsyth and A.P. Zisserman, Proc. CVPR, 1989.
Shape from Shading and Photometric Stereo

Shading reveals 3-D surface geometry
Shape-from-X

• Where X is
  – Shading
  – Photometric stereo
  – Stereo
  – Motion
  – Texture
  – Blur
  – Focus
  – Structured light
  – ....

Two shape-from-X methods that use shading

• Photometric stereo: Single viewpoint, multiple images under different lighting.
  1. Arbitrary known BRDF
  2. Lambertian BRDF, known lighting
  3. Lambertian BRDF, unknown lighting
  4. Unknown arbitrary BRDF, known lighting
Photometric Stereo Rigs: One viewpoint, changing lighting

Because of single viewpoint, a pixel location sees the same point of the scene across all images

An example of photometric stereo

Input Images