Radiometry and reflectance

http://graphics.cs.cmu.edu/courses/15-463

15-463, 15-663, 15-862
Computational Photography
Fall 2020, Lecture 17
Course announcements

• Homework 4 is due tonight.
  - See Piazza announcement for submission guidelines.
  - Any questions?

• Homework 5 will be posted tonight.

• Project proposals were due on Friday.
  - Please make sure to sign up for equipment in the spreadsheet posted on Piazza:
    https://docs.google.com/spreadsheets/d/1CVg7nUbl701pvZFPX3BR0uzKB76Y6PEI3tXmq1UF4AU/edit#gid=1109741985
Overview of today’s lecture

- Appearance phenomena.
- Measuring light and radiometry.
- Reflectance and BRDF.
- Light sources.
Slide credits

Most of these slides were adapted from:

• Srinivasa Narasimhan (16-385, Spring 2014).
• Todd Zickler (Harvard University).
• Steven Gortler (Harvard University).
Appearance
Our challenge: Invent computational representations of shape, lighting, and reflectance that are efficient: simple enough to make inference tractable, yet general enough to capture the world’s most important phenomena.
Example application: Photometric Stereo
Why study the physics (optics) of the world?

Let's see some pictures!
Light and Shadows
Reflections
Refractions
Interreflections
Mies Courtyard House with Curved Elements
Scattering
More Complex Appearances
Measuring light and radiometry
The **solid angle** subtended by a small surface patch with respect to point O is the area of its central projection onto the unit sphere about O.

Depends on:
- orientation of patch
- distance of patch
Solid angle

The *solid angle* subtended by a small surface patch with respect to point $O$ is the area of its central projection onto the unit sphere about $O$.

This depends on:
- orientation of patch
- distance of patch

One can show:

\[ d\omega = \frac{dA \cos \theta}{r^2} \]

Units: steradians [sr]
The solid angle subtended by a small surface patch with respect to point O is the area of its central projection onto the unit sphere about O.

Depends on:
- orientation of patch
- distance of patch

One can show: “surface foreshortening”

\[ d\omega = \frac{dA \cos \theta}{r^2} \]

Units: steradians [sr]
Solid angle

To calculate solid angle subtended by a surface $S$ relative to $O$ you must add up (integrate) contributions from all tiny patches (nasty integral)

$$\Omega = \int \int \frac{\vec{r} \cdot \hat{n}}{|\vec{r}|^3} dS$$

One can show: "surface foreshortening"

$$d\omega = \frac{dA \cos \theta}{r^2}$$

Units: steradians [sr]
Question

Suppose surface $S$ is a hemisphere centered at $O$. What is the solid angle it subtends?
Question

 Suppose surface $S$ is a hemisphere centered at $O$. What is the solid angle it subtends?

 Answer: $2\pi$ (area of sphere is $4\pi r^2$; area of unit sphere is $4\pi$; half of that is $2\pi$)
Quantifying light: flux, irradiance, and radiance

- Imagine a sensor that counts photons passing through planar patch X in directions within angular wedge W.
- It measures radiant flux [watts = joules/sec]: rate of photons hitting sensor area.
- Measurement depends on sensor area |X|.

\[ \Phi(W, X) \]

* shown in 2D for clarity; imagine three dimensions
Quantifying light: flux, irradiance, and radiance

- **Irradiance**: A measure of incoming light that is independent of sensor area \(|X|\).
- Units: watts per square meter [W/m\(^2\)]
Quantifying light: flux, irradiance, and radiance

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Quantifying light: flux, irradiance, and radiance

- **Irradiance**: A measure of incoming light that is independent of sensor area $|X|$
- Units: watts per square meter [W/m$^2$]
- Depends on sensor direction normal.

\[
\Phi(W, X) \over |X| \quad \text{or} \quad \lim_{x \to x} E_\hat{n}(W, x)
\]

- We keep track of the normal because a planar sensor with distinct orientation would converge to a different limit.
- In the literature, notations $n$ and $W$ are often omitted, and values are implied by context.
Quantifying light: flux, irradiance, and radiance

- **Radiance:**
  A measure of incoming light that is independent of sensor area $|X|$, orientation $n$, and wedge size (solid angle) $|W|$
- **Units:** watts per steradian per square meter $[W/(m^2 \cdot sr)]$

\[
\frac{E_{\hat{n}}(W, x)}{|W|} \quad \text{and} \quad \frac{L_{\hat{n}}(\hat{\omega}, x)}{|W|}
\]

- Has correct units, but still depends on sensor orientation
- To correct this, convert to measurement that would have been made if sensor was perpendicular to direction $\omega$
Quantifying light: flux, irradiance, and radiance

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  A measure of incoming light that is independent of sensor area $|X|$, orientation $n$, and wedge size (solid angle) $|W|$

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\[
E_n(W, x) = \frac{L_n(\hat{\omega}, x)}{|W|}
\]

\[
\lim_{W \to \hat{\omega}} E_n(W, x)
\]

\[
\cos \theta = \frac{\Box/2}{|X|/2}
\]

\[
\rightarrow \Box = |X| \cos \theta
\]

“foreshortened area”
Quantifying light: flux, irradiance, and radiance

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```
\[
\begin{align*}
E_n(W, x) &= \frac{W}{|W|} \\
L_n(\hat{\omega}, x) &= \frac{L(\hat{\omega}, x)}{\cos \theta}
\end{align*}
\]
```

- Has correct units, but still depends on sensor orientation
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Quantifying light: flux, irradiance, and radiance

- Attractive properties of radiance:
  - Allows computing the radiant flux measured by *any* finite sensor
Quantifying light: flux, irradiance, and radiance

○ Attractive properties of radiance:
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\[
\Phi(W, X) = \int_X \int_W L(\hat{\omega}, x) \cos \theta d\omega dA
\]
Quantifying light: flux, irradiance, and radiance

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\[
\Phi(W, X) = \int_X \int_W L(\hat{\omega}, x) \cos \theta d\omega dA
\]

- Constant along a ray in free space

\[
L(\hat{\omega}, x) = L(\hat{\omega}, x + \hat{\omega})
\]
Quantifying light: flux, irradiance, and radiance

- Attractive properties of radiance:
  - Allows computing the radiant flux measured by *any* finite sensor
    \[ \Phi(W, X) = \int_X \int_W L(\omega, x) \cos \theta d\omega dA \]
  - Constant along a ray in free space
    \[ L(\omega, x) = L(\omega, x + \omega) \]
  - A camera measures radiance (after a **one-time radiometric calibration**). So RAW pixel values are proportional to radiance.
    - “Processed” images (like PNG and JPEG) are not linear radiance measurements!!
Question

๏ Most light sources, like a heated metal sheet, follow Lambert’s Law

\[
J(\hat{\omega}) = J_o \langle \hat{\omega}, \hat{n} \rangle = J_o \cos \theta
\]

“Lambertian area source”

๏ What is the radiance \( L(\hat{\omega}, x) \) of an infinitesimal patch [W/sr \( \cdot \) m\(^2\)]?
Question

๏ Most light sources, like a heated metal sheet, follow Lambert’s Law

\[ J(\hat{\omega}) = J_0 \langle \hat{\omega}, \hat{n} \rangle = J_0 \cos \theta \]

“Lambertian area source”

๏ What is the radiance \( L(\hat{\omega}, x) \) of an infinitesimal patch \([W/\text{sr} \cdot \text{m}^2]\)?

Answer: \( L(\hat{\omega}, x) = J_0/|X| \) (independent of direction)
Question

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Answer: \( L(\hat{\omega}, x) = J_o / |X| \) (independent of direction)

“Looks equally bright when viewed from any direction”
Appearance
“Physics-based” computer vision (a.k.a. “inverse optics”)
Reflectance and BRDF
Reflectance

- Ratio of outgoing energy to incoming energy at a single point
- Want to define a ratio such that it:
  - converges as we use smaller and smaller incoming and outgoing wedges
  - does not depend on the size of the wedges (i.e. is intrinsic to the material)
Reflectance

- Ratio of outgoing energy to incoming energy at a single point
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\[
\begin{align*}
fx, \hat{n}(W_{in}, \hat{w}_{out}) &= \lim_{W_{in} \to \hat{w}_{in}} \frac{L_{out}(x, \hat{w}_{out})}{E_{\hat{n}}^{in}(W_{in}, x)} \\
\end{align*}
\]

- Notations x and n often implied by context and omitted; directions \( \omega \) are expressed in local coordinate system defined by normal \( n \) (and some chosen tangent vector)
- Units: sr\(^{-1}\)
- Called Bidirectional Reflectance Distribution Function (BRDF)
BRDF: Bidirectional Reflectance Distribution Function

\[ E_{\text{surface}}^{\text{surface}}(\theta_i, \phi_i) \quad \text{Irradiance at Surface in direction} \ (\theta_i, \phi_i) \]
\[ L_{\text{surface}}^{\text{surface}}(\theta_r, \phi_r) \quad \text{Radiance of Surface in direction} \ (\theta_r, \phi_r) \]

\[ \text{BRDF} : f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{L_{\text{surface}}^{\text{surface}}(\theta_r, \phi_r)}{E_{\text{surface}}^{\text{surface}}(\theta_i, \phi_i)} \]
Reflectance: BRDF

- Units: sr\(^{-1}\)

- Real-valued function defined on the double-hemisphere

- Has many useful properties
Important Properties of BRDFs

- Conservation of Energy:

\[ \forall \hat{\omega}_{\text{in}}, \quad \int_{\Omega_{\text{out}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) \cos \theta_{\text{out}} d\hat{\omega}_{\text{out}} \leq 1 \]

Why smaller than or equal?
Property: “Helmholtz reciprocity”

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

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

\[ f_r(\vec{\omega}_{\text{in}}, \vec{\omega}_{\text{out}}) = f_r(\vec{\omega}_{\text{out}}, \vec{\omega}_{\text{in}}) \]
Common assumption: Isotropy

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

Bi-directional Reflectance Distribution Function (BRDF)
Can be written as a function of 3 variables: \( f(\theta_i, \theta_r, \phi_i - \phi_r) \)

\[ f_r(\vec{\omega}_{\text{in}}, \vec{\omega}_{\text{out}}) \]
Reflectance: BRDF

- Units: sr$^{-1}$
- Real-valued function defined on the double-hemisphere
- Has many useful properties
- Allows computing output radiance (and thus pixel value) for any configuration of lights and viewpoint

$$L_{\text{out}}(\hat{\omega}) = \int_{\Omega_{\text{in}}} f(\hat{\omega}_{\text{in}}, \hat{\omega}_{\text{out}}) L_{\text{in}}(\hat{\omega}_{\text{in}}) \cos \theta_{\text{in}} d\hat{\omega}_{\text{in}}$$

Why is there a cosine in the reflectance equation?
Derivation of the Reflectance Equation

From the definition of BRDF:

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

From the definition of BRDF:

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

Write Surface Irradiance in terms of Source Radiance:

\[ L_{\text{surface}}(\theta_r, \phi_r) = L_{\text{src}}(\theta_i, \phi_i) f(\theta_i, \phi_i; \theta_r, \phi_r) \cos \theta_i d\omega_i \]

Integrate over entire hemisphere of possible source directions:

\[ L_{\text{surface}}(\theta_r, \phi_r) = \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} L_{\text{src}}(\theta_i, \phi_i) f(\theta_i, \phi_i; \theta_r, \phi_r) \cos \theta_i \sin \theta_i d\theta_i d\phi_i \]
\[ \int f(w) \, dw = \int_{0}^{2\pi} \int_{0}^{\pi} f(\theta, \phi) \, \sin \theta \, d\theta \, d\phi \]

\[ \int f(\omega) \, d\omega = \int_{0}^{\pi} \int_{0}^{2\pi} f(\theta, \phi) \, \sin \theta \, d\theta \, d\phi \]

\[ \vec{\omega} \cdot \vec{\nu} = \cos \theta \]

\[ \vec{\omega} = (x, y, z) \]

\[ \begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \cos \theta \\
\begin{bmatrix} \frac{x}{R} \\ \frac{y}{R} \end{bmatrix} = \sin \theta \cos \phi \\
y = \sin \theta \sin \phi \]

Z: azimuthal direction
Differential Solid Angles

\[ dA = (r \, d\theta)(r \sin \theta \, d\phi) = r^2 \sin \theta \, d\theta \, d\phi \]

\[ d\omega = \frac{dA}{r^2} = \sin \theta \, d\theta \, d\phi \]

\[ S = \int_0^\pi \int_0^{2\pi} \sin \theta \, d\theta \, d\phi = 4\pi \]
Bi-directional Reflectance Distribution Function (BRDF)
BRDF

Lambertian (diffuse) BRDF: energy equally distributed in all directions

What does the BRDF equal in this case?

$f_r(\vec{\omega}_{in}, \cdot)$

$f_r(\vec{\omega}_{in}, \vec{\omega}_{out})$

Bi-directional Reflectance Distribution Function (BRDF)
Diffuse Reflection and Lambertian BRDF

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

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

- Most commonly used BRDF in Vision and Graphics!

\[
0 \leq \rho_d \leq 1
\]

\[
\int f(\mathbf{w}_i, \mathbf{w}_o) \cos \theta_o \, d\omega_o \leq 1
\]
BRDF

Specular BRDF: all energy concentrated in mirror direction

What does the BRDF equal in this case?

$f_r(\omega_{in}, \omega_{out})$

Bi-directional Reflectance Distribution Function (BRDF)
Specular Reflection and Mirror BRDF

- Source intensity $I$
- Incident direction $(\theta_i, \phi_i)$
- Normal $n$
- Viewing direction $(\theta_v, \phi_v)$
- Specular/mirror direction $r (\theta_r, \phi_r)$
- Specular albedo $f(\theta_i, \phi_i; \theta_v, \phi_v) = \frac{\rho_s}{\cos \theta_i} \delta(\theta_i - \theta_v) \delta(\phi_i + \pi - \phi_v)$

- Valid for very smooth surfaces.
- All incident light energy reflected in a SINGLE direction (only when $v = r$).
- Mirror BRDF is simply a double-delta function:

$$\int S(x) f(x) dx = f(x_0)$$

Term canceling out foreshortening
\[ \int s(x-x_0) f(x) dx = f(x_0) \]

\[ L_0(w_0) = \rho L_i(w_i, \mu) \]

\[ L(f(w_0, \mu)) = \int \frac{F(w_i, w_0, \mu) \cos \theta_i L_i(w_i)}{H^2} \text{d}w_i \]

\[ = \int \frac{\rho \delta(w_i - w_i \mu) \cos \theta_i L_i(w_i)}{H^2} \text{d}w_i \]

\[ = \rho L(w_i, \mu) \cos \theta_i \pi \]

\[ f(w_i, w_0, \mu) = \rho \frac{S(...)}{\cos \theta_i} \]
Example Surfaces

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

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

Many materials exhibit both Reflections:
BRDF

Glossy BRDF: more energy concentrated in mirror direction than elsewhere

\[ f_r(\vec{\omega}_{\text{in}}, \cdot) \]

\[ f_r(\vec{\omega}_{\text{in}}, \vec{\omega}_{\text{out}}) \]

Bi-directional Reflectance Distribution Function (BRDF)
Trick for dielectrics (non-metals)

• BRDF is a sum of a Lambertian diffuse component and non-Lambertian specular components

• The two components differ in terms of color and polarization, and under certain conditions, this can be exploited to separate them.

\[ f(\vec{\omega}_i, \vec{\omega}_o) = f_d + f_s(\vec{\omega}_i, \vec{\omega}_o) \]
Trick for dielectrics (non-metals)

- BRDF is a sum of a Lambertian diffuse component and non-Lambertian specular components

- The two components differ in terms of color and polarization, and under certain conditions, this can be exploited to separate them.

\[ f(\omega_i, \omega_o) = f_d + f_s(\omega_i, \omega_o) \]

Often called the *dichromatic BRDF*:
- Diffuse term varies with wavelength, constant with polarization
- Specular term constant with wavelength, varies with polarization
Trick for dielectrics (non-metals)

- In this example, the two components were separated using linear polarizing filters on the camera and light source.
Trick for dielectrics (non-metals)

\[ I_\parallel = \frac{1}{2} I_{\text{diffuse}} + I_{\text{specular}} \]

\[ I_\perp = \frac{1}{2} I_{\text{diffuse}} \]
Tabulated 4D BRDFs (hard to measure)

[Ngan et al., 2005]
Low-parameter (non-linear) BRDF models

- A small number of parameters define the (2D,3D, or 4D) function
- Except for Lambertian, the BRDF is non-linear in these parameters
- Examples:

Lambertian: \( f(\omega_i, \omega_o) = \frac{a}{\pi} \)

Phong: \( f(\omega_i, \omega_o) = \frac{a}{\pi} + b \cos^c (2\langle \omega_i, n \rangle \langle \omega_o, n \rangle - \langle \omega_i, \omega_o \rangle) \)

Blinn: \( f(\omega_i, \omega_o) = \frac{a}{\pi} + b \cos^c b(\omega_i, \omega_o) \)

Lafortune: \( f(\omega_i, \omega_o) = \frac{a}{\pi} + b(-\omega_i^\top A\omega_o)^k \)

Ward: \( f(\omega_i, \omega_o) = \frac{a}{\pi} + \frac{b}{4\pi c^2 \sqrt{\langle n, \omega_i \rangle \langle n, \omega_o \rangle}} \exp \left( -\frac{\tan^2 b(\omega_i, \omega_o)}{c^2} \right) \)

\( \alpha \) is called the albedo
Reflectance Models

Reflection: An Electromagnetic Phenomenon

Two approaches to derive Reflectance Models:

– Physical Optics (Wave Optics)
– Geometrical Optics (Ray Optics)

Geometrical models are approximations to physical models
But they are easier to use!
Reflectance that Require Wave Optics
References

Basic reading:
• Szeliski, Section 2.2.
• Gortler, Chapter 21.
  This book by Steven Gortler has a great introduction to radiometry, reflectance, and their use for image formation.

Additional reading:
  These two thesis are foundational for modern computer graphics. Among other things, they include a thorough derivation (starting from wave optics and measure theory) of all radiometric quantities and associated integro-differential equations. You can also look at them if you are interested in physics-based rendering.
  A book discussing modeling and simulation of other appearance effects beyond single-bounce reflectance.
  A very thorough review of everything that has to do with modeling and measuring BRDFs.
  This paper has a great review of physics-based models for reflectance and refraction.
  This thesis introduced the largest measured dataset of 4D reflectances. It also provides detailed discussion of many topics relating to modelling reflectance.
  These two papers discuss the isotropy and other properties of common BRDFs, and how one can take advantage of them using alternative parameterizations.
  The paper introducing the dichromatic reflectance model.
• Levin et al., “Fabricating BRDFs at high spatial resolution using wave optics,” SIGGRAPH 2013.
  These three papers describe reflectance effects that can only be modeled using wave optics (and in particular diffraction).