Light and Color

Computational Photography

Derek Hoiem, University of Illinois

“Empire of Light”, Magritte
Announcements

• Project 1 due next Mon (9/18), 11:59pm
  – Choosing cutoff: sigma > 1 (often large)
  – Remember to convert images to double or single
  – Although I showed examples of filtering with FFT, in practice I recommend using `imfilter` unless otherwise stated
  – Don’t use built-in code for pyramids, contrast equalization etc., ask if not sure
Today’s class

• How is incoming light measured by the eye or camera?
Today’s class

• How is incoming light measured by the eye or camera?
• How is light reflected from a surface?
The human eye is a camera!

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- What’s the “film”?
  - photoreceptor cells (rods and cones) in the **retina**
Retina up-close
Two types of light-sensitive receptors

**Cones**
- cone-shaped
- less sensitive
- operate in high light
- color vision

**Rods**
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision
- slower to respond
Rod / Cone sensitivity

Dazzling light; bright sun on snow
Outdoors in full sunlight
Outdoors under a tree on a sunny day
Comfortable indoor illumination; night sports events
Threshold for perception of color; bright moonlight
Threshold when dark-adapted

Distribution of Rods and Cones

Night Sky: why are there more stars off-center?
Electromagnetic Spectrum

Human Luminance Sensitivity Function

Slide Credit: Efros

http://www.yorku.ca/eye/photopik.htm
Visible Light

Why do we see light of these wavelengths?

...because that’s where the Sun radiates EM energy.
Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.

<table>
<thead>
<tr>
<th>Wavelength (nm.)</th>
<th># Photons (per ms.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
</tbody>
</table>
The Physics of Light

Some examples of the spectra of light sources

A. Ruby Laser

B. Gallium Phosphide Crystal

C. Tungsten Lightbulb

D. Normal Daylight

© Stephen E. Palmer, 2002
The Physics of Light

Some examples of the reflectance spectra of surfaces

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>% Photons Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>700</td>
</tr>
<tr>
<td>Red</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td></td>
</tr>
<tr>
<td>Purple</td>
<td></td>
</tr>
</tbody>
</table>

© Stephen E. Palmer, 2002
More Spectra

metamers
Three kinds of cones:

- Why are M and L cones so close?
- Why are there 3?
3 is better than 2...

- “M” and “L” on the X-chromosome
  - Why men are more likely to be color blind

- “L” has high variation, so some women are tetrachromatic

- Some animals have 1 (night animals), 2 (e.g., dogs), 4 (fish, birds), 5 (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp)

http://en.wikipedia.org/wiki/Color_vision
We don’t perceive a spectrum (or even RGB)

• We perceive
  – Hue: mean wavelength, color
  – Saturation: variance, vividness
  – Intensity: total amount of light

• Same perceived color can be recreated with combinations of three primary colors ("trichromacy")
Trichromacy and CIE-XYZ

Perceptual equivalents with RGB

Perceptual equivalents with CIE-XYZ

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix}
0.49 & 0.31 & 0.20 \\
0.17697 & 0.81240 & 0.01063 \\
0.00 & 0.01 & 0.99
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
CIE-XYZ

\[ x = \frac{X}{X + Y + Z} \]

\[ y = \frac{Y}{X + Y + Z} \]

RGB portion is in triangle
Color Sensing: Bayer Grid

Estimate RGB at each cell from neighboring values

http://en.wikipedia.org/wiki/Bayer_filter
Alternative to Bayer: RGB+W

Kodak 2007
How is light reflected from a surface?

Depends on

• Illumination properties: wavelength, orientation, intensity

• Surface properties: material, surface orientation, roughness, etc.
Lambertian surface

- Some light is absorbed (function of albedo)
- Remaining light is reflected in all directions (diffuse reflection)
- Examples: soft cloth, concrete, matte paints
Diffuse reflection

Intensity *does* depend on illumination angle because less light comes in at oblique angles.

\[ I(x) = \rho(x)(S \cdot N(x)) \]

- \( \rho = \) albedo
- \( S = \) directional source
- \( N = \) surface normal
- \( I = \) image intensity
Diffuse reflection

Perceived intensity does not depend on viewer angle.
- Amount of reflected light proportional to $\cos(\theta)$
- Visible solid angle also proportional to $\cos(\theta)$

http://en.wikipedia.org/wiki/Lambert%27s_cosine_law
Specular Reflection

- Reflected direction depends on light orientation and surface normal
- E.g., mirrors are fully specular
Many surfaces have both specular and diffuse components

- Specularity = spot where specular reflection dominates (typically reflects light source)
**BRDF: Bidirectional Reflectance Distribution Function**

- Model of local reflection that tells how bright a surface appears when viewed from one direction when light falls on it from another.

\[
\rho(\theta_i, \phi_i, \theta_e, \phi_e; \lambda) = \frac{L_e(\theta_e, \phi_e)}{E_i(\theta_i, \phi_i) \cos \theta_i d\omega}
\]
More complicated effects

transparency

light source

refraction

light source
fluorescence

\[ \lambda_1 \]

\[ \lambda_2 \]

phosphorescence

\[ t = 1 \]

\[ t > 1 \]
subsurface scattering

light source

λ

interreflection

light source

λ
Inter-reflection is a major source of light
Inter-reflection affects the apparent color of objects

From Koenderink slides on image texture and the flow of light
The color of objects

- Colored light arriving at the camera involves two effects
  - The color of the light source (illumination + inter-reflections)
  - The color of the surface

\[
\int_{\Lambda} \sigma_k(\lambda) \rho(\lambda) E(\lambda) d\lambda
\]
Color constancy

- Interpret surface in terms of albedo or “true color”, rather than observed intensity
  - Humans are good at it
  - Computers are not nearly as good
Color illusions
Color illusions
Color illusions
Color illusions
Color illusions
Color illusions

http://www.echalk.co.uk/amusements/OpticalIllusions/colourPerception/colourPerception.html
Shadows cast by a point source

• A point that can’t see the source is in shadow
• For point sources, the geometry is simple
Area sources

• Examples: diffuser boxes, white walls

• The energy received at a point due to an area source is obtained by adding up the contribution of small elements over the whole source
Area Source Shadows

Area Source

Occluder

Slide: Forsyth
Shading and shadows are major cues to shape and position
1. Why is (2) brighter than (1)? Each points to the asphalt.
2. Why is (4) darker than (3)? 4 points to the marking.
3. Why is (5) brighter than (3)? Each points to the side of the wooden block.
4. Why isn’t (6) black, given that there is no direct path from it to the sun?
Things to remember

• Light has a spectrum of wavelengths
  – Humans (and RGB cameras) have color
    sensors sensitive to three ranges

• Observed light depends on:
  illumination intensities, surface
  orientation, material (albedo, specular
  component, diffuse component), etc.

• Every object is an indirect light source
  for every other

• Shading and shadows are informative
  about shape and position
Take-home questions

Possible factors: albedo, shadows, texture, specularities, curvature, lighting direction