Light and Color

“Empire of Light”, Magritte

Computational Photography
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Slides adopted from Derek Hoiem
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

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

Slide Credit: Efros
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.
Some examples of the spectra of light sources

A. Ruby Laser
B. Gallium Phosphide Crystal
C. Tungsten Lightbulb
D. Normal Daylight

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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>

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More Spectra

metamers
Physiology of Color Vision

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

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

Perceptual equivalents with CIE-XYZ
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

Slide: Forsyth
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

light source

specular reflection

θ

θ

λ

by Richard

by Jeff Petersen
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.

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

Slide credit: S. Savarese
More complicated effects

transparency

light source

refraction

light source
fluorescence

phosphorescence
subsurface scattering

interreflection
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
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

From Koenderink slides on image texture and the flow of light
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

A. For each of the arrows in the above image, name the reasons the pixel near the end of the arrow has its brightness value and explain very briefly. The arrow pointing to milk is pointing to the thin bright line at the edge of the piece of apple; the arrow pointing to the spoon handle is pointing to the bright area on the handle.