Light and Shading

“Empire of Light”, Magritte

Computer Vision

Derek Hoiem, University of Illinois
Administrative stuff

• Some people waiting to get in

• Tentative office hours
  – Derek: Wed 4pm, 8pm (skype only)
  – Ruiqi: Mon 7pm, Thurs 4pm

• Homework 1 released soon

• Any questions?
How light is recorded
A digital camera replaces film with a sensor array

- Each cell in the array is a light-sensitive diode that converts photons to electrons
- Two common types: Charge Coupled Device (CCD) and CMOS

Slide by Steve Seitz
Sensor Array

FIGURE 2.17  (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.

Each sensor cell records amount of light coming in at a small range of orientations.
The raster image (pixel matrix)
The raster image (pixel matrix)

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Today’s class: Light and Shading

- What determines a pixel’s intensity?
- What can we infer about the scene from pixel intensities?
How does a pixel get its value?

Light emitted

Fraction of light reflects into camera

Lens

Sensor
How does a pixel get its value?

- Major factors
  - Illumination strength and direction
  - Surface geometry
  - Surface material
  - Nearby surfaces
  - Camera gain/exposure
Basic models of reflection

• Specular: light bounces off at the incident angle
  – E.g., mirror

• Diffuse: light scatters in all directions
  – E.g., brick, cloth, rough wood
Lambertian reflectance model

- Some light is absorbed (function of albedo $\rho$)
- Remaining light is scattered (diffuse reflection)
- Examples: soft cloth, concrete, matte paints

![Diagram showing absorption and diffuse reflection](image)
Diffuse reflection: Lambert’s cosine law

Intensity does not depend on viewer angle.

- Amount of reflected light proportional to $\cos(\theta)$
- Visible solid angle also proportional to $\cos(\theta)$

[Equation: $I_0 = \frac{I d\Omega dA}{d\Omega_0 dA_0}$]

[Equation: $I_0 = \frac{I \cos(\theta) d\Omega dA}{d\Omega_0 \cos(\theta) dA_0}$]

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
  - Most surfaces can be modeled with a mixture of diffuse and specular components
Most surfaces have both specular and diffuse components

- Specularity = spot where specular reflection dominates (typically reflects light source)

Photo: northcountryhardwoodfloors.com

Typically, specular component is small
Intensity and Surface Orientation

Intensity depends on illumination angle because less light comes in at oblique angles.

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

• When light hits a typical surface
  – Some light is absorbed \((1-\rho)\)
    • More absorbed for low albedos

  – Some light is reflected diffusely
    • Independent of viewing direction

  – Some light is reflected specularly
    • Light bounces off (like a mirror), depends on viewing direction
Other possible effects

- Transparency
- Light source
- Refraction
\[ \lambda_1 \text{ light source} \]

\[ \lambda_2 \text{ fluorescence} \]

\[ t = 1 \text{ light source} \]

\[ t > 1 \text{ phosphorescence} \]
light source

subsurface
scattering

λ
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

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

• Assume:
  – a set of point sources that are infinitely distant
  – a set of pictures of an object, obtained in exactly the same camera/object configuration but using different sources
  – A Lambertian object (or the specular component has been identified and removed)
Each image is: \[ I_i(x) = S_i \cdot (p(x)N(x)) \]

So if we have enough images with known sources, we can solve for \[ B(x) = p(x)N(x) \]
And the albedo (shown here) is given by:

\[ B(x) = p(x)N(x) \]

And the albedo (shown here) is given by:

\[ p(x) = \sqrt{B(x) \cdot B(x)} \]  
(the normal is a unit vector)
Dynamic range and camera response

• Typical scenes have a huge dynamic range.

• Camera response is roughly linear in the mid range (15 to 240) but non-linear at the extremes—called saturation or undersaturation.
Color

Light is composed of a spectrum of wavelengths

human Luminance Sensitivity Function

Slide Credit: Efros

http://www.yorku.ca/eye/photopik.htm
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
Some examples of the reflectance spectra of surfaces

<table>
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<tr>
<th>Wavelength (nm)</th>
<th>% Photons Reflected</th>
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<tr>
<td>400</td>
<td>Red</td>
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<td>700</td>
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<td>400</td>
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© Stephen E. Palmer, 2002
More spectra

metamers

yellow flower
orange flower
white flower
orange berry
violet flower
blue flower
white petal

reflectance vs wavelength in nm
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

Receptor response of k'th receptor class

\[ \int_{\lambda} \sigma(\lambda) \rho(\lambda) E(\lambda) d\lambda \]

Incoming spectral radiance \( E(\lambda) \)

Outgoing spectral radiance \( E(\hat{\lambda}) \rho(\lambda) \)

Spectral albedo \( \rho(\lambda) \)

Slide: Forsyth
Color Sensing: Bayer Grid

- Estimate RGB at each cell from neighboring values

http://en.wikipedia.org/wiki/Bayer_filter
Color Image
Why RGB?

If light is a spectrum, why are images RGB?
Human color receptors

- Long (red), Medium (green), and Short (blue) cones, plus intensity rods
- Fun facts
  - “M” and “L” on the X-chromosome
    - That’s why men are more likely to be color blind (see what it’s like: http://www.vischeck.com/vischeck/vischeckURL.php)
  - “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) types of cones

http://en.wikipedia.org/wiki/Color_vision
So far: light $\rightarrow$ surface $\rightarrow$ camera

- Called a local illumination model
- But much light comes from surrounding surfaces

From Koenderink slides on image texture and the flow of light
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
Scene surfaces also cause shadows

- Shadow: reduction in intensity due to a blocked source
Shadows

Point Source

Cast Shadow Boundary

Self Shadow Boundary

Area Source

Occluder

1

2

3
Models of light sources

• Distant point source
  – One illumination direction
  – E.g., sun

• Area source
  – E.g., white walls, diffuser lamps, sky

• Ambient light
  – Substitute for dealing with interreflections

• Global illumination model
  – Account for interreflections in modeled scene
Recap

Possible factors: albedo, shadows, texture, specularities, curvature, lighting direction
What does the intensity of a pixel tell us?

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\[ \text{im}(234, 452) = 0.58 \]
The plight of the poor pixel

- A pixel’s brightness is determined by
  - Light source (strength, direction, color)
  - Surface orientation
  - Surface material and albedo
  - Reflected light and shadows from surrounding surfaces
  - Gain on the sensor

- A pixel’s brightness tells us nothing by itself
And yet we can interpret images...

- Key idea: for nearby scene points, most factors do not change much
- The information is mainly contained in local differences of brightness
Darkness = Large Difference in Neighboring Pixels
What is this?
What differences in intensity tell us about shape

- Changes in surface normal
- Texture
- Proximity
- Indents and bumps
- Grooves and creases

Photos Koenderink slides on image texture and the flow of light
Shadows as cues

From Koenderink slides on image texture and the flow of light
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
One source of constancy: local comparisons
Perception of Intensity

from Ted Adelson
Perception of Intensity

from Ted Adelson
Color Correction

• Simple idea: multiply R, G, and B values by separate constants

\[
\begin{bmatrix}
\tilde{r} \\
\tilde{g} \\
\tilde{b}
\end{bmatrix} =
\begin{bmatrix}
\alpha_r & 0 & 0 \\
0 & \alpha_g & 0 \\
0 & 0 & \alpha_b
\end{bmatrix}
\begin{bmatrix}
r \\
g \\
b
\end{bmatrix}
\]

• How to choose the constants?
  – “White world” assumption: brightest pixel is white
    • Divide by largest value
  – “Gray world” assumption: average value should be gray
    • E.g., multiply r channel by \( \text{avg}(r) / \text{avg}((r+g+b)/3) \)
  – White balancing: choose a reference as the white or gray color
1. Lighting (20%)
   A. Answer the following regarding the above image (photo credit: do/monsaxll from Flickr). Consider shadows, specularities, albedo, surface orientation, light sources, etc. Short answers (several words) are sufficient (8%):
   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?
B. Answer the following using the above illustration. Suppose you have observed the intensities of three points on an object \( (I_1, I_2, I_3) \), which are lit by an infinitely distant point source (the sun). The surface normal at point 2 is exactly perpendicular to the sun. The surface normals of points 1 and 3 differ in only one angle \( (\theta) \), as shown in the cross-section.

a. Suppose the surface has a specular component. Will the observed intensities change as the camera moves (if so why/how)? (4%)

b. Suppose the surface material is Lambertian and has uniform (constant) albedo and that the camera response function is linear (and ignore effects due to interreflections in the scene). Show (with equations for arbitrary observed intensities) how to compute the angles \( \theta_{12}, \theta_{23} \) between surfaces containing points 1 and 2 and points 2 and 3. Then, compute the values of \( \theta_{12}, \theta_{23} \) for the observed intensities \( (0.5, 0.9, 0.8) \). (8%)
Things to remember

• Important terms: diffuse/specular reflectance, albedo, umbra/penumbra

• Observed intensity depends on light sources, geometry/material of reflecting surface, surrounding objects, camera settings

• Objects cast light and shadows on each other

• Differences in intensity are primary cues for shape
Thank you

• Next class: Image Filters