Light & Perception
Announcements

• Project 4
  – To be released on Wednesday
  – Groups of 2

• Please submit midterm regrade requests by tomorrow (Tuesday, 4/9) by 11:59pm

• Project 3 artifact voting open until Friday

• Quiz 3 this Wednesday, April 10
  – Will cover topics since the midterm was released (single-view modeling, stereo, two-view geometry / Fundamental matrices, and today’s lecture on light)
Road map

• Finishing up geometry
• Next: deep learning and hot topics in computer vision
Can we determine shape from lighting?

- Are these spheres?
  - Or just flat discs painted with varying albedo?
  - There is ambiguity between *shading* and *reflectance*
  - But still, as humans we can understand the shapes of these objects
What we know: Stereo

Key Idea: use feature motion to understand shape
Next: Photometric Stereo

Key Idea: use pixel brightness to understand shape
Next: Photometric Stereo

Key Idea: use pixel brightness to understand shape
Photometric Stereo

What results can you get?

Input (1 of 12)  Normals (RGB colormap)  Normals (vectors)  Shaded 3D rendering  Textured 3D rendering
Light
by Ted Adelson

Readings
• Szeliski, 2.2, 2.3.2
Light

by Ted Adelson

Readings

• Szeliski, 2.2, 2.3.2
Properties of light

Today

• What is light?
• How do we measure it?
• How does light propagate?
• How does light interact with matter?
Radiometry

What determines the brightness of a pixel?

- Light source properties
- Surface properties
Radiometry

What determines the brightness of a pixel?

@robertwestonbreshears  https://www.instagram.com/p/BtgX55ZBhU-/
Radiometry

What determines the brightness of a pixel?
Radiometry

What determines the brightness of an image pixel?

- Light source properties
- Surface shape
- Surface reflectance properties
- Optics
- Sensor characteristics
- Exposure

Slide by L. Fei-Fei
What is light?

Electromagnetic radiation (EMR) moving along rays in space

- \( R(\lambda) \) is EMR, measured in units of power (watts)
  - \( \lambda \) is wavelength

Light field

- We can describe all of the light in the scene by specifying the radiation (or “radiance” along all light rays) arriving at every point in space and from every direction

\[
R(X, Y, Z, \theta, \phi, \lambda, t)
\]
Color perception

Electromagnetic radiation (EMR) moving along rays in space

- $R(\lambda)$ is EMR, measured in units of power (watts)
  - $\lambda$ is wavelength

Perceiving light

- How do we convert radiation into “color”?
- What part of the spectrum do we see?
Visible light

We “see” electromagnetic radiation in a range of wavelengths
Light spectrum

The appearance of light depends on its power spectrum

- How much power (or energy) at each wavelength

Our visual system converts a light spectrum into “color”

- This is a rather complex transformation
The human visual system

Color perception

- Light hits the retina, which contains photosensitive cells
  - rods and cones
- These cells convert the spectrum into a few discrete values
Density of rods and cones

Rods and cones are non-uniformly distributed on the retina

- Rods responsible for intensity, cones responsible for color
- **Fovea** - Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods).
- Less visual acuity in the periphery—many rods wired to the same neuron
Demonstrations of visual acuity

With one eye shut, at the right distance, all of these letters should appear equally legible (Glassner, 1.7).
Demonstrations of visual acuity

With left eye shut, look at the cross on the left. At the right distance, the circle on the right should disappear (Glassner, 1.8).
Brightness contrast and constancy

The apparent brightness depends on the surrounding region

- **brightness contrast**: a constant colored region seems lighter or darker depending on the surrounding intensity:

  ![Image](image.png)

  [http://www.sandlotscience.com/Contrast/Checker_board_2.htm](http://www.sandlotscience.com/Contrast/Checker_board_2.htm)

- **brightness constancy**: a surface looks the same under widely varying lighting conditions.
Light response is nonlinear

Our visual system has a large *dynamic range*

- We can resolve both light and dark things at the same time
- One mechanism for achieving this is that we sense light intensity on a *logarithmic scale*
  - an exponential intensity ramp will be seen as a linear ramp
- Another mechanism is *adaptation*
  - rods and cones adapt to be more sensitive in low light, less sensitive in bright light.
Visual dynamic range

<table>
<thead>
<tr>
<th>Background</th>
<th>Luminance (candela per square meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizon sky</td>
<td></td>
</tr>
<tr>
<td>Moonless overcast night</td>
<td>0.00003</td>
</tr>
<tr>
<td>Moonless clear night</td>
<td>0.0003</td>
</tr>
<tr>
<td>Moonlit overcast night</td>
<td>0.003</td>
</tr>
<tr>
<td>Moonlit clear night</td>
<td>0.03</td>
</tr>
<tr>
<td>Deep twilight</td>
<td>0.3</td>
</tr>
<tr>
<td>Twilight</td>
<td>3</td>
</tr>
<tr>
<td>Very dark day</td>
<td>30</td>
</tr>
<tr>
<td>Overcast day</td>
<td>300</td>
</tr>
<tr>
<td>Clear day</td>
<td>3,000</td>
</tr>
<tr>
<td>Day with sunlit clouds</td>
<td>30,000</td>
</tr>
<tr>
<td>Daylight fog</td>
<td></td>
</tr>
<tr>
<td>Dull</td>
<td>300–1,000</td>
</tr>
<tr>
<td>Typical</td>
<td>1,000–3,000</td>
</tr>
<tr>
<td>Bright</td>
<td>3,000–16,000</td>
</tr>
<tr>
<td>Ground</td>
<td></td>
</tr>
<tr>
<td>Overcast day</td>
<td>30–100</td>
</tr>
<tr>
<td>Sunny day</td>
<td>300</td>
</tr>
<tr>
<td>Snow in full sunlight</td>
<td>16,000</td>
</tr>
</tbody>
</table>

A piece of white paper can be 1,000,000,000 times brighter in outdoor sunlight than in a moonless night.

BUT in a given lighting condition, light ranges over only about two orders of magnitude.

**Figure 1.13**
Luminance of everyday backgrounds. Source: Data from Rea, ed., Lighting Handbook 1984 Reference and Application, fig. 3-44, p. 3-24.
Learning to See in the Dark

Chen Chen, Qifeng Chen, Jia Xu and Vladlen Koltun

IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2018

Figure. Extreme low-light imaging by a Sony a7S II camera using ISO 8000, f/5.6, 1/30 second. Dark indoor environment. The illuminance at the camera is <0.1 lux.

http://cchen156.web.engr.illinois.edu/SID.html
Visual dynamic range

If we were sensitive to this whole range all the time, we wouldn’t be able to discriminate lightness levels in a typical scene.

The visual system solves this problem by restricting the ‘dynamic range’ of its response to match the current overall or ‘ambient’ light level.
Color perception

Three types of cones
- Each is sensitive in a different region of the spectrum
  - but regions overlap
  - Short (S) corresponds to blue
  - Medium (M) corresponds to green
  - Long (L) corresponds to red
- Different sensitivities: we are more sensitive to green than red
  - varies from person to person (and with age)
- Colorblindness—deficiency in at least one type of cone
Rods and cones act as filters on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

Q: How can we represent an entire spectrum with 3 numbers?

A: We can’t! Most of the information is lost.

- As a result, two different spectra may appear indistinguishable
  » such spectra are known as metamers
  » [http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/explo
  ratories/applets/spectrum/metamers_guide.html](http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/explo
  ratories/applets/spectrum/metamers_guide.html)
What kind of bulb is it?

Perception summary

The mapping from radiance to perceived color is quite complex!

- We throw away most of the data
- We apply a logarithm
- Brightness affected by pupil size
- Brightness contrast and constancy effects

The same is true for cameras

- But we have tools to correct for these effects
  - (Computational Photography)
Light transport
Light sources

Basic types
- point source
- directional source
  - a point source that is infinitely far away
- area source
  - a union of point sources

More generally
- a light field can describe *any* distribution of light sources

What happens when light hits an object?
Modeling Image Formation

We need to reason about:

• How light interacts with the scene
• How a pixel value is related to light energy in the world

Track a “ray” of light all the way from light source to the sensor
Directional Lighting

- Key property: all rays are parallel
- Equivalent to an infinitely distant point source
Lambertian Reflectance

\[ I = N \cdot L \]

Image intensity \(\propto \cos(\text{angle between } N \text{ and } L)\)
Materials - Three Forms

- Ideal diffuse (Lambertian)
- Ideal specular
- Directional diffuse
Reflectance — Three Forms

Ideal diffuse (Lambertian)

Ideal specular

Directional diffuse

© Kavita Bala. Computer Science, Cornell University
Ideal Diffuse Reflection

• Characteristic of multiple scattering materials
• An idealization but reasonable for matte surfaces
1. Reflected energy is proportional to cosine of angle between L and N (incoming)

2. Measured intensity is viewpoint-independent (outgoing)
Lambertian Reflectance: Incoming

1. Reflected energy is proportional to cosine of angle between L and N
Lambertian Reflectance: Incoming

1. Reflected energy is proportional to cosine of angle between \( L \) and \( N \)
Lambertian Reflectance: Incoming

1. Reflected energy is proportional to cosine of angle between L and N

Light hitting surface is proportional to the cosine
Lambertian Reflectance: Outgoing

1. Radiance (what we see) is viewpoint-independent
Lambertian Reflectance: Outgoing

1. Radiance (what the eye sees) is viewpoint-independent
Lambertian Reflectance: Outgoing

1. Measured intensity is viewpoint-independent
Lambertian Reflectance: Outgoing

1. Measured intensity is viewpoint-independent

\[ \text{Radiance (what eye sees)} \propto B_0 \cos(\theta) \frac{1}{\cos(\theta)} \]
1. Diffuse albedo: what fraction of incoming light is reflected?
   • Introduce scale factor $k_d$
2. Light intensity: how much light is arriving?
   • Compensate with camera exposure (global scale factor)
3. Camera response function
   • Assume pixel value is linearly proportional to incoming energy
     (perform radiometric calibration if not)

$$I = k_d N \cdot L$$
A Single Image: Shape from Shading

\[ I = k_d \mathbf{N} \cdot \mathbf{L} \]

Assume \( k_d \) is 1 for now.

What can we measure from one image?

- \( \cos^{-1}(I) \) is the angle between \( \mathbf{N} \) and \( \mathbf{L} \)
- Add assumptions:
  - Constant albedo
  - A few known normals (e.g. silhouettes)
  - Smoothness of normals

In practice, SFS doesn’t work very well: assumptions are too restrictive, too much ambiguity in nontrivial scenes.
Application: Detecting composite photos

Fake photo

Real photo
Questions?