Capturing Light… in man and machine

15-463: Computational Photography
Alexei Efros, CMU, Fall 2007
Image Formation

Digital Camera

The Eye
A digital camera replaces film with a sensor array

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

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

**FIGURE 2.16** Generating a digital image: (a) Continuous image. (b) A scan line from $A$ to $B$ in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.
Interlace vs. progressive scan

1st field: Odd field
2nd field: Even field
One complete frame using interlaced scanning

One complete frame using progressive scanning


Slide by Steve Seitz
Progressive scan

Interlace

The Eye

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**
The Retina

Cross-section of eye

Cross section of retina

Pigmented epithelium

Ganglion axons

Ganglion cell layer

Bipolar cell layer

Receptor layer

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
The famous sock-matching problem...
Night Sky: why are there more stars off-center?
Electromagnetic Spectrum

Human Luminance Sensitivity Function

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.
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
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>Red</td>
</tr>
<tr>
<td>700</td>
<td>Yellow</td>
</tr>
<tr>
<td>400</td>
<td>Blue</td>
</tr>
<tr>
<td>700</td>
<td>Purple</td>
</tr>
</tbody>
</table>

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There is no simple functional description for the perceived color of all lights under all viewing conditions, but ……

A helpful constraint:
Consider only physical spectra with normal distributions

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<th># Photons</th>
</tr>
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<tbody>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
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<tr>
<td>600</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
</tbody>
</table>

area

mean

variance

Wavelength (nm.)

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The Psychophysical Correspondence

Mean ↔ Hue

# Photons

Wavelength

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Area Brightness

# Photons

Wavelength

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Three kinds of cones:

- Why are M and L cones so close?
- Are there 3?
More Spectra

[Graph showing reflectance vs. wavelength for different flowers and a group labeled as metamers]
Color Sensing in Camera (RGB)

3-chip vs. 1-chip: quality vs. cost
Why more green?

Why 3 colors?

http://www.cooldictionary.com/words/Bayer-filter.wikipedia

Slide by Steve Seitz
Practical Color Sensing: Bayer Grid

Estimate RGB at ‘G’ cells from neighboring values

http://www.cooldictionary.com/words/Bayer-filter.wikipedia

Slide by Steve Seitz
RGB color space

RGB cube

- Easy for devices
- But not perceptual
- Where do the grays live?
- Where is hue and saturation?
Hue, Saturation, Value (Intensity)

- RGB cube on its vertex

Decouples the three components (a bit)
Use rgb2hsv() and hsv2rgb() in Matlab
Programming Project #1

• How to compare R,G,B channels?
• No right answer
  • Sum of Squared Differences (SSD):
    \[
    ssd(u, v) = \sum_{(x,y) \in N} \left[ I(u + x, v + y) - P(x, y) \right]^2
    \]
  • Normalized Correlation (NCC):
    \[
    ncc(u, v) = \frac{\sum_{(x,y) \in N} \left[ I(u + x, v + y) - \bar{I} \right] \left[ P(x, y) - \bar{P} \right]}{\sqrt{\sum_{(x,y) \in N} \left[ I(u + x, v + y) - \bar{I} \right]^2 \sum_{(x,y) \in N} \left[ P(x, y) - \bar{P} \right]^2}}
    \]