Capturing Light... in man and machine

15-463: Computational Photography
Alexei Efros, CMU, Fall 2011
Etymology

PHOTOGRAPHY

light
drawing / writing
Image Formation

Film

Digital Camera

The Eye
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

Slide by Steve Seitz
Progressive scan

Interlace

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

Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
Pigmented epithelium

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
Rod / Cone sensitivity

The famous sock-matching problem…
Night Sky: why are there more stars off-center?
3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.
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.

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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

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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

<table>
<thead>
<tr>
<th>Wavelength (nm.)</th>
<th># Photons</th>
<th>mean</th>
<th>area</th>
<th>variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td></td>
<td></td>
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<td>500</td>
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</tbody>
</table>

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Mean ↔ Hue

# Photons

Wavelength

blue green yellow

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Area ↔ Brightness

# Photons

Wavelength

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Physiology of Color Vision

Three kinds of cones:

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

metamers
Color Constancy

The “photometer metaphor” of color perception:
Color perception is determined by the spectrum of light on each retinal receptor (as measured by a photometer).
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Color Constancy

Do we have constancy over all global color transformations?

60% blue filter
Complete inversion

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**Color Constancy**: the ability to perceive the invariant color of a surface despite ecological Variations in the conditions of observation.

Another of these hard inverse problems: Physics of light emission and surface reflection underdetermine perception of surface color.
Camera White Balancing

• **Manual**
  • Choose color-neutral object in the photos and normalize

• **Automatic (AWB)**
  • Grey World: force average color of scene to grey
  • White World: force brightest object to white
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
RGB color space

**FIGURE 6.8** RGB 24-bit color cube.

**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
Prokudin-Gorskii’s Color Photography (1907)
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):

\[
ncc(u, v) = \frac{\sum_{(x,y) \in N} \left[ I(u + x, v + y) - \bar{I} \right] \left[ P(x, y) - \bar{P} \right]}{\sqrt{\sum_{(x,y) \in N} \left[ I(u + x, v + y) - \bar{I} \right]^2 \sum_{(x,y) \in N} \left[ P(x, y) - \bar{P} \right]^2}}
\]