Capturing Light… in man and machine

CS194: Image Manipulation & Computational Photography
Alexei Efros, UC Berkeley, Fall 2017
Etymology

PHOTOGRAPHY

light
drawing
/ writing
Image Formation

**Digital Camera**

**The Eye**

- Scene element
- Imaging system
- (Internal) image plane
- Illumination (energy) source
- Film
FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image 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.
Progressive scan

Interlace

Rolling Shutter

http://en.wikipedia.org/wiki/Rolling_shutter
Saccadic eye movement
Saccadic eye movement
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

Retina up-close

- pigment epithelium
- rods
- cones
- outer limiting membrane
- Müller cells
- horizontal cells
- bipolar cells
- amacrine cells
- ganglion cells
- nerve fiber layer
- inner limiting membrane

Light
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?
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.
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

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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></td>
<td>Red</td>
</tr>
<tr>
<td>400</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
</tr>
<tr>
<td></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
The Psychophysical Correspondence

Mean ↔ Hue

# Photons

Wavelength

blue  green  yellow
The Psychophysical Correspondence

Variance ↔ Saturation

Wavelength

# Photons

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The Psychophysical Correspondence

Area \leftrightarrow 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?
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

- How can we represent an entire spectrum with 3 numbers?
- We can’t! Most of the information is lost
  - As a result, two different spectra may appear indistinguishable
    » such spectra are known as metamers
More Spectra

metamers

- yellow flower
- orange flower
- white flower
- orange berry
- violet flower
- blue flower
- white petal
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).
Color Constancy

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Color Constancy

Do we have constancy over all global color transformations?

60% blue filter

Complete inversion
**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
Green is in!

R | G | B
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
Color Image
Images in Matlab

- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
  - \( \text{im}(1,1,1) \) = top-left pixel value in R-channel
  - \( \text{im}(y, x, b) \) = \( y \) pixels down, \( x \) pixels to right in the \( b \)th channel
  - \( \text{im}(N, M, 3) \) = bottom-right pixel in B-channel
- \text{imread}(\text{filename}) \) returns a uint8 image (values 0 to 255)
  - Convert to double format (values 0 to 1) with \text{im2double}
Color spaces

How can we represent color?

Color spaces: RGB

Default 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
Color spaces: HSV

Intuitive color space

- **H** (S=1, V=1)
- **S** (H=1, V=1)
- **V** (H=1, S=0)
Color spaces: $L^*a^*b^*$

“Perceptually uniform”* color space

\[ L(a=0,b=0) \]
\[ a(L=65,b=0) \]
\[ b(L=65,a=0) \]
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):
    \[ ssd(u,v) = \sum_{(x,y) \in N} [I(u + x, v + y) - P(x, y)]^2 \]
  • Normalized Correlation (NCC):
    \[ ncc(u,v) = \frac{\sum_{(x,y) \in N} [I(u + x, v + y) - \bar{I}] \cdot [P(x, y) - \bar{P}]}{\sqrt{\sum_{(x,y) \in N} [I(u + x, v + y) - \bar{I}]^2 \cdot \sum_{(x,y) \in N} [P(x, y) - \bar{P}]^2}} \]