Capturing Light… in man and machine

15-463: Computational Photography
Alexei Efros, CMU, Fall 2010
Etymology

PHOTOGRAPHY

- light
- drawing / writing
Image Formation

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

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

One complete frame using progressive scanning

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

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
Rod / Cone sensitivity

The famous sock-matching problem…
Distribution of Rods and Cones

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
The Physics of Light

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.

# Photons (per ms.)

Wavelength (nm.)
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>Red</td>
<td>![Red Spectra]</td>
</tr>
<tr>
<td>Yellow</td>
<td>![Yellow Spectra]</td>
</tr>
<tr>
<td>Blue</td>
<td>![Blue Spectra]</td>
</tr>
<tr>
<td>Purple</td>
<td>![Purple Spectra]</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

# Photons

Wavelength

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The Psychophysical Correspondence

Area ↔ Brightness

# Photons vs. 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

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

Slide by Steve Seitz
**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?
HSV

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):
    \[ ssd(u, v) = \sum_{(x, y) \in N} [I(u + x, v + y) - P(x, y)]^2 \]
  - Normalized Correlation (NCC):
    \[ ncc(u, v) = \frac{\sum_{(x, y) \in N} [I(u + x, v + y) - \bar{I}] [P(x, y) - \bar{P}]}{\sqrt{\sum_{(x, y) \in N} [I(u + x, v + y) - \bar{I}]^2 \sum_{(x, y) \in N} [P(x, y) - \bar{P}]^2}} \]
Image Pyramids (preview)

Idea: Represent NxN image as a “pyramid” of 1x1, 2x2, 4x4,…, $2^k \times 2^k$ images (assuming N=$2^k$)

- Known as a **Gaussian Pyramid** [Burt and Adelson, 1983]
  - In computer graphics, a *mip map* [Williams, 1983]
  - A precursor to *wavelet transform*
  - *Can use imresize in Matlab*