Capturing Light… in man and machine

Some figures from Steve Seitz, Steve Palmer, Paul Debevec, and Gonzalez et al.

15-463: Computational Photography
Alexei Efros, CMU, Fall 2006
Image Formation

Film

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

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

- Ganglion axons
- Ganglion cell layer
- Bipolar cell layer
- Receptor layer

Cross section of retina

- 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?
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

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

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The Psychophysical Correspondence

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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Mean ↔ Hue

# Photons

Wavelength

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Variance ↔ Saturation

# Photons

Wavelength

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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?
- Are there 3?
More Spectra

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
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?
HSV

Hue, Saturation, Value (Intensity)
- RGB cube on its vertex

Decouples the three components (a bit)
Use rgb2hsv() and hsv2rgb() in Matlab
Programming Assignment #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):
    \[
    ncc(u, v) = \frac{\sum_{(x, y) \in N} [I(u + x, v + y) - \bar{I}] \cdot [P(x, y) - \bar{P}]}{\sqrt{\sum_{(x, y) \in N} [I(u + x, v + y) - \bar{I}]^2 \sum_{(x, y) \in N} [P(x, y) - \bar{P}]^2}}
    \]
Image Pyramids (preview)

Known as a **Gaussian Pyramid** [Burt and Adelson, 1983]
- In computer graphics, a *mip map* [Williams, 1983]
- A precursor to *wavelet transform*
White Balance

White World / Gray World assumptions
Image Formation

\[ f(x,y) = \text{reflectance}(x,y) \times \text{illumination}(x,y) \]

Reflectance in \([0,1]\), illumination in \([0,\infty]\)

**FIGURE 2.15** An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.
Problem: Dynamic Range

The real world is high dynamic range.
Is Camera a photometer?

Image

\[ \text{pixel (312, 284) = 42} \]

42 photos?
Long Exposure

Real world

High dynamic range

Picture

$10^{-6}$

$10^{-6}$

0 to 255

$10^6$
Short Exposure

Real world

Picture

High dynamic range

$10^{-6}$ to $10^{6}$

0 to 255
Image Acquisition Pipeline

Camera is NOT a photometer!
Varying Exposure
What does the eye see?

Figure 1: The range of luminances in the natural environment and associated visual parameters. After Hood (1986).
"Every light is a shade, compared to the higher lights, till you come to the sun; and every shade is a light, compared to the deeper shades, till you come to the night."

— John Ruskin, 1879
Cornsweet Illusion
Sine wave

Campbell-Robson contrast sensitivity curve
Metamers

Eye is sensitive to changes
(more on this later…)

Craik-O’Brien Cornsweet Effect

Actual Luminance Profile  Perceived Luminance Profile