BBM 413
Fundamentals of Image Processing

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Color Perception and Color Spaces
Review - image formation

• What determines the brightness of an image pixel?
A digital camera replaces film with a sensor array

• Each cell in the array is light-sensitive diode that converts photons to electrons

Review – digital images

FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.
Review - digital images

- **Sample** the 2D space on a regular grid
- **Quantize** each sample (round to nearest integer)

Image thus represented as a matrix of integer values.

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Slide credit: K. Grauman, S. Seitz
Review – image representation

• **Digital image:** 2D discrete function $f$
• **Pixel:** Smallest element of an image $f(x,y)$
Outline

• Perception of color and light
• Color spaces
Why does a visual system need color?
Why does a visual system need color? (an incomplete list...)

• To tell what food is edible.
• To distinguish material changes from shading changes.
• To group parts of one object together in a scene.
• To find people’s skin.
• Check whether a person’s appearance looks normal/healthy.
What is color?

• Color is the result of interaction between physical light in the environment and our visual system.

• Color is a psychological property of our visual experiences when we look at objects and lights, *not* a physical property of those objects or lights (S. Palmer, *Vision Science: Photons to Phenomenology*)
Brightness perception

http://web.mit.edu/persci/people/adelson/illusions_demos.html
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Edward Adelson
Brightness perception
Color perception

Look at blue squares  Look at yellow squares

Content © 2008 R.Beau Lotto
http://www.lottolab.org/articles/illusionsoflight.asp
Color perception

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Color perception
Reading Assignment #2

• Watch Beau Lotto’s TED talk on “Optical illusions show how we see” [link available on course webpage]

• Prepare a 1-page summary of the talk

• Due on 8th of November
Color and light

• **Color of light** arriving at camera depends on
  – Spectral reflectance of the surface light is leaving
  – Spectral radiance of light falling on that patch

• **Color perceived** depends on
  – Physics of light
  – Visual system receptors
  – Brain processing, environment

• Color is a phenomenon of human perception; it is **not** a universal property of light

Slide credit: K. Grauman, S. Marschner
Color

White light: composed of about equal energy in all wavelengths of the visible spectrum

Newton 1665

4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Slide credit: B. Freeman, A. Torralba, K. Grauman
Electromagnetic spectrum

• Light is electromagnetic radiation
  – exists as oscillations of different frequency (or, wavelength)

Slide credit: A. Efros
The Physics of light

Any source of light can be completely described physically by its spectrum: the amount of energy emitted (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

Slide credit: A. Efros
The Physics of light

Some examples of the reflectance spectra of surfaces

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<th>% Light Reflected</th>
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<tr>
<td>400</td>
<td>Blue</td>
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<tr>
<td>700</td>
<td>Purple</td>
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Slide credit: A. Efros
Color mixing

Cartoon spectra for color names:

- **Red**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

- **Green**
  - 400 nm
  - 500 nm
  - 600 nm

- **Cyan**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

- **Magenta**
  - 400 nm
  - 500 nm
  - 600 nm

- **Yellow**
  - 400 nm
  - 500 nm
  - 600 nm
  - 700 nm

Credit: W. Freeman
Additive color mixing

Colors combine by adding color spectra

Light adds to black.

Credit: W. Freeman
Examples of additive color systems

Cathode Ray Tube
- Picture tube
- Electron guns
- Color signals
- Electron beams
- Shadow Mask
- Screen
- Phosphor dots

CRT phosphors

multiple projectors

Slide credit: K. Grauman

http://www.jegsworks.com
http://www.crtprojectors.co.uk/
Subtractive color mixing

Colors combine by multiplying color spectra.

Pigments remove color from incident light (white).

Credit: W. Freeman
Examples of subtractive color systems

- Printing on paper
- Crayons
- Photographic film
Interaction of light and surfaces

- Reflected color is the result of interaction of light source spectrum with surface reflectance.

[Graphs and images related to the content above]
Reflection from colored surface

Object \times \text{Incandescent Light} = \text{Color 1}

Object \times \text{Daylight} = \text{Color 2}

Slide credit: S. Marschner
The Eye

• **Iris** - colored annulus with radial muscles
• **Pupil** - the hole (aperture) whose size is controlled by the iris
• **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
• **Retina** - photoreceptor cells

Slide credit: S. Seitz
The eye as a measurement device

- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
  - its optics are much like a camera
  - its detection mechanism is also much like a camera

- Light is measured by the photoreceptors in the retina
  - they respond to visible light
  - different types respond to different wavelengths

- The human eye is a camera!
Layers of the retina

Slide credit: S. Ullman
Receptors Density - Fovea

Slide credit: S. Ullman
Receptors Density - Fovea

Slide credit: S. Ullman
Human Photoreceptors

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.


Slide Credit: B. Freeman and A. Torralba
Human eye photoreceptor spectral sensitivities

3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.

Two types of light-sensitive receptors

**Cone**s  
cone-shaped  
less sensitive  
operate in high light  
color vision

**Rods**  
rod-shaped  
highly sensitive  
operate at night  
gray-scale vision

Images by Shimon Ullman

Slide credit: A. Efros
Rods and cones

- Rods are responsible for intensity, cones for color perception
- Rods and cones are **non-uniformly** distributed on the retina
  - Fovea - Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods)

Slide credit: S. Seitz
Rod / Cone sensitivity

- Dazzling light; bright sun on snow
- Outdoors in full sunlight
- Outdoors under a tree on a sunny day
- Comfortable indoor illumination; night sports events
- Threshold for perception of color; bright moonlight
- Threshold when dark-adapted

Slide credit: A. Efros
Physiology of Color Vision

Three kinds of cones:

- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

Slide credit: A. Efros
Color perception

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

Q: How can we represent an entire spectrum with 3 numbers?
A: We can’t! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable

Slide credit: S. Seitz
Digital images

- **Sample** the 2D space on a regular grid
- **Quantize** each sample (round to nearest integer)

- Image thus represented as a matrix of integer values.
Color Images: Bayer Grid

• Estimate RGB at ‘G’ cells from neighboring values

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

Slide credit: S. Seitz
Digital color images

Color images, RGB color space

Slide credit: K. Grauman
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
- \( \text{imread(filename)} \) returns a uint8 image (values 0 to 255)
  - Convert to double format (values 0 to 1) with im2double

Slide credit: D. Hoiem
Color spaces

- How can we represent color?
Color spaces: RGB

- Single wavelength primaries
- makes a particular monitor RGB standard
- Good for devices (e.g., phosphors for monitor), but not for perception

Slide credit: K. Grauman, S. Marschner
Color spaces: RGB

Some drawbacks

• Strongly correlated channels
• Non-perceptual


Slide credit: D. Hoiem
Color spaces: CIE XYZ

- Standardized by CIE (Commission Internationale de l’Eclairage, the standards organization for color science)

- Based on three “imaginary” primaries X, Y, and Z
  - imaginary = only realizable by spectra that are negative at some wavelengths
  - separates out luminance: X, Z have zero luminance, so Y tells you the luminance by itself

Slide credit: K. Grauman, S. Marschner
Color spaces: CIE XYZ

- Standardized by CIE (Commission Internationale de l’Eclairage, the standards organization for color science)

- Based on three “imaginary” primaries $X$, $Y$, and $Z$
  - imaginary = only realizable by spectra that are negative at some wavelengths
  - separates out luminance: $X$, $Z$ have zero luminance, so $Y$ tells you the luminance by itself

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix}
0.49 & 0.31 & 0.20 \\
0.17697 & 0.81240 & 0.01063 \\
0.00 & 0.01 & 0.99
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

Slide credit: K. Grauman, S. Marschner
Perceptually organized color spaces

• Artists often refer to colors as *tints*, *shades*, and *tones* of pure pigments
  – tint: mixture with white
  – shade: mixture with black
  – tones: mixture with black and white
  – gray: no color at all (aka. neutral)

• This seems intuitive
  – tints and shades are inherently related to the pure color
    • “same” color but lighter, darker, paler, etc.

[slide credit: S. Marschner]
Perceptual dimensions of color

- **Hue**
  - the “kind” of color, regardless of attributes
  - colorimetric correlate: dominant wavelength
  - artist’s correlate: the chosen pigment color

- **Saturation**
  - the “colorfulness”
  - colorimetric correlate: purity
  - artist’s correlate: fraction of paint from the colored tube

- **Lightness (or value)**
  - the overall amount of light
  - colorimetric correlate: luminance
  - artist’s correlate: tints are lighter, shades are darker

Slide credit: S. Marschner
Color spaces: HSV

• **Hue, Saturation, Value**

• Nonlinear – reflects topology of colors by coding **hue** as an angle

• **Matlab**: `hsv2rgb`, `rgb2hsv`.

Image from mathworks.com

Slide credit: K. Grauman
Color spaces: HSV

- **Hue**, **Saturation**, **Value**
- Nonlinear – reflects topology of colors by coding hue as an angle
- Matlab: hsv2rgb, rgb2hsv.

Image from mathworks.com

Slide credit: K. Grauman
Color spaces: HSV

Intuitive color space

Slide credit: D. Hoiem
**Color spaces: YCbCr**

Fast to compute, good for compression, used by TV

- $Y=0$
- $Y=0.5$
- $Y=1$

**Y**
- $(Cb=0.5, Cr=0.5)$

**Cb**
- $(Y=0.5, Cr=0.5)$

**Cr**
- $(Y=0.5, Cb=0.5)$

Slide credit: D. Hoiem
Color spaces: YCbCr

Fast to compute, good for compression, used by TV

\[
\begin{bmatrix}
Y' \\
C_b \\
C_r
\end{bmatrix} = \begin{bmatrix}
0.299 & 0.587 & 0.114 \\
-0.168736 & -0.331264 & 0.5 \\
0.5 & -0.418688 & -0.081312
\end{bmatrix} \begin{bmatrix}
R' \\
G' \\
B'
\end{bmatrix} + \begin{bmatrix}
0 \\
128 \\
128
\end{bmatrix}
\]

Slide credit: D. Hoiem
Distances in color space

• Are distances between points in a color space perceptually meaningful?

Slide credit: K. Grauman
Distances in color space

- Not necessarily: CIE XYZ is not a uniform color space, so magnitude of differences in coordinates are poor indicator of color “distance”.

McAdam ellipses:
Just noticeable differences in color

Slide credit: K. Grauman
Uniform color spaces

• Attempt to correct this limitation by remapping color space so that just-noticeable differences are contained by circles $\rightarrow$ distances more perceptually meaningful.

• Examples:
  – CIE $u'v'$
  – CIE Lab

Slide credit: K. Grauman
Perceptually uniform spaces

- Two major spaces standardized by CIE
  - designed so that equal differences in coordinates produce equally visible differences in color
  - by remapping color space so that just-noticeable differences are contained by circles → distances more perceptually meaningful.
  - LUV: earlier, simpler space; $L^*, u^*, v^*$
  - LAB: more complex but more uniform: $L^*, a^*, b^*$
  - both separate luminance from chromaticity
  - including a gamma-like nonlinear component is important

Slide credit: K. Grauman, S. Marschner
Color spaces: L*a*b*

“Perceptually uniform”* color space

Slide credit: D. Hoiem
**Color spaces: L*a*b***

“Perceptually uniform”* color space

\[
L^* = 116f \left( \frac{Y}{Y_n} \right)
\]

\[
f(t) = \begin{cases} 
t^{1/3} & t > \delta^3 \\
t/(3\delta^2) + 2\delta/3 & \text{else}, \end{cases}
\]

\[
a^* = 500 \left[ f \left( \frac{X}{X_n} \right) - f \left( \frac{Y}{Y_n} \right) \right]
\]

\[
b^* = 200 \left[ f \left( \frac{Y}{Y_n} \right) - f \left( \frac{Z}{Z_n} \right) \right]
\]

\((X_n, Y_n, Z_n)\): measured white point

Slide credit: D. Hoiem
Most information in intensity

Only intensity shown – constant color

Slide credit: D. Hoiem
Most information in intensity
Back to grayscale intensity

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Your first programming assignment

• Colorizing the Prokudin-Gorskii photo collection
• A Matlab warm-up exercise

• **Main steps:**
  1. Divide the input image into three equal parts corresponding to RGB channels.
  2. Align the second and the third parts (G and R channels) to the first one (B channel).
Prokudin-Gorskii's Russia in Color

• Russia circa 1900
• One camera, move the film with filters to get 3 exposures

Images from: http://www.loc.gov/exhibits/empire/

Slide credit: F. Durand
Prokudin-Gorskii's Russia in Color

- Digital restoration
Emir Seyyid Mir Mohammed Alim Khan, the Emir of Bukhara, ca. 1910.
Self-portrait on the Karolitskhali River, ca. 1910.
A metal truss bridge on stone piers, part of the Trans-Siberian Railway, crossing the Kama River near Perm, Ural Mountains Region, ca. 1910.
On the Sim River, a shepherd boy, ca. 1910.
Peasants harvesting hay in 1909. From the album "Views along the Mariinskii Canal and river system, Russian Empire", ca. 1910.