Homework 1 due on Tuesday, Feb 9
- Submit pdf via moodle or printout in class

Late day policy
- 3 days total (use wisely)
- No credit for homework beyond late days

Honors section will meet in CS 142 @ 4pm today

Recap of last lecture
Color
- Spectral basis of light
- Color perception in the human eye
- Tristimulus theory and color spaces
- Color phenomena

Sergey Prokudin-Gorskii (1863-1944)
- Photographs of the Russian empire (1909-1916)
Homework 1: fix this by aligning the channels

Basic idea for alignment

• Fix one channel (say red). For the homework we will assume that channels are only translated, i.e., no rotation, scaling, etc.

• For each shift: \( x \in (-15,15), y \in (-15,15) \)

• Measure similarity, e.g. angle between the vectors (reshape image to a vector)

• Pick the shift that maximizes similarity

• Repeat for the blue channel

Digital camera

• A digital camera replaces the film with a sensor array

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

• Two common types
  - Charge Coupled Device (CCD)
  - Complementary Metal Oxide Semiconductor (CMOS)


Color sensing in the camera

Color filter array

Bayer grid

Estimate missing components from neighboring values (demosaicing)

Why more green?

Human luminance sensitivity function
**Demosaicing**

- Red
- Green
- Blue

**Interpolation**

- Nearest neighbor: copy one of your neighbors
- Linear interpolation: average values of your neighbors
- Adaptive gradient: average based on local structure
  
  - If $|gt-gb| > |gl-gr|$
  - Else

**Homework 1:** implement nearest neighbor

**Questions?**

- Recap of last lecture
- Color perception
  - Spectral basis of light
  - Color perception in the human eye
  - Tristimulus theory and color spaces
  - Color phenomena
What is color?

• “Color is the result of interaction between 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

Newton’s theory of light

Newton’s sketch of his crucial experiment in which light from the sun is refracted through a prism. One color is then refracted through a second prism to show that it undergoes no further change. Light is then shown to be composed of the colors refracted in the second prisms. Image credit: Warden and Fellows

The electromagnetic spectrum

[Diagram showing the electromagnetic spectrum with labels for different wavelength ranges including visible light and relative sensitivity function.]
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.

Some examples of the spectra of light sources:

A. Ruby Laser
B. Gallium Phosphide Crystal
C. Tungsten Lightbulb
D. Normal Daylight

Reflectance Spectra of Surfaces:

- Reflected color is the result of interaction between the light source spectrum and the reflection surface reflectance.
Interaction of light and surfaces

• What is the observed color of any surface under monochromatic light?

Room for one color, Olafur Eliasson

The eye

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

Rods and cones, fovea

• 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
• There are about 5 million cones and 100 million rods in each eye

Demonstration of visual acuity

With one eye shut, at the right distance, all of these letters should appear equally legible (Glassner, 1.7).
Blind spot

With left eye shut, look at the cross on the left. At the right distance, the circle on the right should disappear (Glassner, 1.8).

Rod/cone sensitivity

Why can’t we read in the dark?

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

Physiology of color vision: fun facts

- “M” and “L” pigments are encoded on the X-chromosome
- That’s why men are more likely to be color blind
- “L” gene has high variation, so some women may be tetra-chromatic
- Some animals have one (night animals), two (e.g. dogs), four (fish, birds), five (pigeons, some reptiles/amphibians), or even 12 (mantis shrimp) types of cones

http://www.mezzmer.com/blog/how-animals-see-the-world/

http://en.wikipedia.org/wiki/Color_vision
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! A lot of the information is lost
  • As a result, two different spectra may appear indistinguishable
    • Such spectra are known as metamers

Color perception

How insects see

Spectra of some real-world surfaces
We would like to understand which spectra produce the same color sensation in people under similar viewing conditions.

Color matching experiments

---

**Color matching experiment 1**

- We would like to understand which spectra produce the same color sensation in people under similar viewing conditions.
- Color matching experiments.
Color matching experiment 1

The primary color amounts needed for a match

Source: W. Freeman 37

Color matching experiment 2

Source: W. Freeman 38

Color matching experiment 2

Source: W. Freeman 39

Color matching experiment 2

Source: W. Freeman 40
Color matching experiment 2

We say a “negative” amount of $p_2$ was needed to make the match, because we added it to the test color’s side.

The primary color amounts needed for a match:

$$p_1 \quad p_2 \quad p_3$$

Source: W. Freeman

Grassman’s Laws (1853)

- Color matching appears to be linear
- If two test lights can be matched with the same set of weights, then they match each other:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$. Then $A = B$.
- If we mix two test lights, then mixing the matches will match the result:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$. Then $A + B = (u_1+v_1) P_1 + (u_2+v_2) P_2 + (u_3+v_3) P_3$.
- If we scale the test light, then the matches get scaled by the same amount:
  - Suppose $A = u_1 P_1 + u_2 P_2 + u_3 P_3$.
  - Then $kA = (ku_1) P_1 + (ku_2) P_2 + (ku_3) P_3$.

Trichromacy

- In color matching experiments, most people can match any given light with three primaries
  - Primaries must be independent
- For the same light and same primaries, most people select the same weights
  - Exception: color blindness
- Trichromatic color theory
  - Three numbers seem to be sufficient for encoding color
  - Dates back to 18th century (Thomas Young)

Example

- Bob walks into a room and sees the following spectra
  - How many tungsten and led bulbs are there?

Spectra of individual light sources

Spectra of combined light

Using linearity of light we have target = $n *$ tungsten + $m *$ led; $n=3$ and $m=2$
Linear color spaces

- Defined by a choice of three **primaries**
- The coordinates of a color are given by the weights of the primaries used to match it

Mixing two lights produces colors that lie along a straight line in color space.

Mixing three lights produces colors that lie within the triangle they define in color space.

45

46

**Color matching function: primary colors**

We know that a monochromatic light $\lambda_i$ of wavelength will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.

And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

$$\tilde{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$

47

48

**Color matching functions: any color**

Store the color matching functions in the rows of the matrix, $C$

$$C = \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ \vdots & \cdots & \vdots \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$

Let the new spectral signal be described by the vector $\tilde{t}$.

$$\tilde{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$

Then the amounts of each primary needed to match $\tilde{t}$ are:

$$\tilde{e} = C\tilde{t}$$

The components $e_1, e_2, e_3$ describe the color of $\tilde{t}$. If you have some other spectral signal, $s$, and $s$ matches $\tilde{t}$ perceptually, then $e_1, e_2, e_3$, will also match $s$ (by Grassman’s Laws).
RGB space

- Primaries are monochromatic lights (for monitors, they correspond to the three types of phosphors)
- **Subtractive matching** required for some wavelengths

- \( p_1 = 645.2 \text{ nm} \)
- \( p_2 = 525.3 \text{ nm} \)
- \( p_3 = 444.4 \text{ nm} \)

Comparison of RGB matching functions with best linear transformation of cone responses

4.20 **COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS.** The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the Stiles and Burch (1959) color-matching functions. The symbols show the matches predicted from the photocurrents of the three types of macaque cones. The predictions included a correction for absorption by the lens and other inert pigments in the eye. Source: Baylor, 1987.

Linear color spaces: CIE XYZ

- Matching functions are positive everywhere
- Y parameter corresponds to brightness or **luminance** of a color
- Z corresponds to blue simulation

Uniform color spaces

- Unfortunately, differences in x,y coordinates do not reflect perceptual color differences
- CIE \( u’v’ \) is a transform of x,y to make the ellipses more uniform

McAdam ellipses: Just noticeable differences in color

Nonlinear color spaces: HSV

- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)
- RGB cube on its vertex

Some early attempts in color spaces

- Philipp Otto Runge’s Farbenkugel (color sphere), 1810
- Munsell’s balanced color sphere, 1900, from A Color Notation, 1905

Color constancy

- The ability of the human visual system to perceive color relatively constant despite changes in illumination conditions

Color constancy

- #1 white and gold
- #2 blue and black

#1 light is blue, so white is tinted blue and gold doesn’t really change

#2 light is yellow, so black reflects the yellow and the blue is unaffected
The visual system changes its sensitivity depending on the luminances prevailing in the visual field
• The exact mechanism is poorly understood
• Adapting to different brightness levels
  • Changing the size of the iris opening (i.e., the aperture) changes the amount of light that can enter the eye
  • Think of walking into a building from full sunshine
• Adapting to different color temperature
  • The receptive cells on the retina change their sensitivity
  • For example: if there is an increased amount of red light, the cells receptive to red decrease their sensitivity until the scene looks white again
  • We actually adapt better in brighter scenes: This is why candlelit scenes still look yellow

When looking at a picture on screen or print, our eyes are adapted to the illuminant of the room, not to that of the scene in the picture
• When the white balance is not correct, the picture will have an unnatural color “cast”
**Film cameras:**
- Different types of film or different filters for different illumination conditions

**Digital cameras:**
- Automatic white balance
- White balance settings corresponding to several common illuminants
- Custom white balance using a reference object

Von Kries adaptation
- Multiply each channel by a gain factor

**Best way:** gray card
- Take a picture of a neutral object (white or gray)
- Deduce the weight of each channel
  - If the object is recorded as \( r_w, g_w, b_w \), use weights \( 1/r_w, 1/g_w, 1/b_w \)

Without gray cards: we need to “guess” which pixels correspond to white objects

Gray world assumption
- The image average \( r_{ave}, g_{ave}, b_{ave} \) is gray
- Use weights \( 1/r_{ave}, 1/g_{ave}, 1/b_{ave} \)

Brightest pixel assumption
- Highlights usually have the color of the light source
- Use weights inversely proportional to the values of the brightest pixels

Gamut mapping
- Gamut: convex hull of all pixel colors in an image
- Find the transformation that matches the gamut of the image to the gamut of a “typical” image under white light
- Use image statistics, learning techniques

Source:
- L. Lazebnik

Further readings and thoughts …

- Color matching applet
  - [http://graphics.stanford.edu/courses/cs178/applets/colormatching.html](http://graphics.stanford.edu/courses/cs178/applets/colormatching.html)

- D.A. Forsyth, A novel algorithm for color constancy
  - Gamut based approach