News

• TA office hours in lab for P2/H2 questions next week
  • Mon 3-5 (Shailen)
  • Tue 3:30-5 (Kai)
  • Wed 3-5 (Shailen)
  • Thu 3-5 (Kai)
  • Fri 2-4 (Garrett)

• again - start **now**, do not put off until late in break!
Review: Component Color

- component-wise multiplication of colors
  - \((a_0, a_1, a_2) \times (b_0, b_1, b_2) = (a_0b_0, a_1b_1, a_2b_2)\)

- why does this work?
  - must dive into light, human vision, color spaces
Basics Of Color

- elements of color:

  - Illumination
  - Reflectance
  - Perception
Basics of Color

• physics
  • illumination
    • electromagnetic spectra
  • reflection
    • material properties
    • surface geometry and microgeometry
      • polished versus matte versus brushed

• perception
  • physiology and neurophysiology
  • perceptual psychology
Light Sources

• common light sources differ in kind of spectrum they emit:
  • continuous spectrum
    • energy is emitted at all wavelengths
      • blackbody radiation
      • tungsten light bulbs
      • certain fluorescent lights
      • sunlight
      • electrical arcs
  • line spectrum
    • energy is emitted at certain discrete frequencies
Blackbody Radiation

• black body
  • dark material, so that reflection can be neglected
  • spectrum of emitted light changes with temperature
    • this is the origin of the term “color temperature”
      • e.g. when setting a white point for your monitor
    • cold: mostly infrared
    • hot: reddish
    • very hot: bluish
  • demo:
    http://www.mhhe.com/physsci/astronomy/applets/Blackbody/frame.html
Electromagnetic Spectrum
White Light

• sun or light bulbs emit all frequencies within visible range to produce what we perceive as "white light"
Sunlight Spectrum

- spectral distribution: power vs. wavelength
Continuous Spectrum

- sunlight
- various “daylight” lamps
Line Spectrum

- ionized gases
- lasers
- some fluorescent lamps
White Light and Color

• when white light is incident upon an object, some frequencies are reflected and some are absorbed by the object

• combination of frequencies present in the reflected light that determines what we perceive as the color of the object
Hue

- hue (or simply, "color") is dominant wavelength/frequency

- integration of energy for all visible wavelengths is proportional to intensity of color
Saturation or Purity of Light

- how washed out or how pure the color of the light appears
  - contribution of dominant light vs. other frequencies producing white light
  - saturation: how far is color from grey
    - pink is less saturated than red
    - sky blue is less saturated than royal blue
Intensity vs. Brightness

- intensity: physical term
  - measured radiant energy emitted per unit of time, per unit solid angle, and per unit projected area of the source (related to the luminance of the source)

- lightness/brightness: perceived intensity of light
  - nonlinear
Perceptual vs. Colorimetric Terms

• Perceptual
  • Hue
  • Saturation
  • Lightness
    • reflecting objects
  • Brightness
    • light sources

• Colorimetric
  • Dominant wavelength
  • Excitation purity
  • Luminance
  • Luminance
Physiology of Vision

- the retina
  - rods
    - b/w, edges
  - cones
    - 3 types
    - color sensors
  - uneven distribution
    - dense fovea
Physiology of Vision

- Center of retina is densely packed region called the **fovea**.
  - Cones much denser here than the **periphery**

![Diagram showing the density of cones in the retina.](Image)
Foveal Vision

- hold out your thumb at arm’s length
Tristimulus Theory of Color Vision

• Although light sources can have extremely complex spectra, it was empirically determined that colors could be described by only 3 primaries

• Colors that look the same but have different spectra are called metamers
Trichromacy

- three types of cones
  - L or R, most sensitive to red light (610 nm)
  - M or G, most sensitive to green light (560 nm)
  - S or B, most sensitive to blue light (430 nm)

- color blindness results from missing cone type(s)
Metamers

- A given perceptual sensation of color derives from the stimulus of all three cone types.

- Identical perceptions of color can thus be caused by very different spectra.

- Demo

http://www.cs.brown.edu/exploratories/freeSoftware/catalogs/color_theory.html
Color Spaces

• three types of cones suggests color is a 3D quantity. how to define 3D color space?

• idea: perceptually based measurement
  • shine given wavelength (\(\lambda\)) on a screen
  • user must control three pure lights producing three other wavelengths
    • used R=700nm, G=546nm, and B=436nm
  • adjust intensity of RGB until colors are identical
    • this works because of metamers!
    • experiments performed in 1930s
Negative Lobes

- sometimes need to point red light to shine on target in order to match colors
  - equivalent mathematically to "removing red"
    - but physically impossible to remove red from CRT phosphors
- can’t generate all other wavelengths with any set of three positive monochromatic lights!
- solution: convert to new synthetic coordinate system to make the job easy
CIE Color Space

• CIE defined 3 “imaginary” lights X, Y, Z
  • any wavelength $\lambda$ can be matched perceptually by positive combinations

Note that:
X $\sim$ R
Y $\sim$ G
Z $\sim$ B
Measured vs. CIE Color Spaces

- measured basis
  - monochromatic lights
  - physical observations
  - negative lobes

- transformed basis
  - “imaginary” lights
  - all positive, unit area
  - Y is luminance, no hue
  - X,Z no luminance
CIE and Chromaticity Diagram

• X, Y, Z form 3D shape
• project X, Y, Z on X+Y+Z=1 plane for 2D color space
  • chromaticity diagram
    • separate color from brightness
    • x = X / (X+Y+Z)
    • y = Y / (X+Y+Z)
CIE “Horseshoe” Diagram Facts

- all visible colors lie inside the horseshoe
  - result from color matching experiments
- spectral (monochromatic) colors lie around the border
  - straight line between blue and red contains purple tones
- colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space
CIE “Horseshoe” Diagram Facts

• can choose a point C for a white point
  • corresponds to an illuminant
  • usually on curve swept out by black body radiation spectra for different temperatures
Blackbody Curve

- illumination:
  - candle 2000K
  - A: Light bulb 3000K
  - sunset/sunrise 3200K
  - D: daylight 6500K
  - overcast day 7000K
  - lightning >20,000K
CIE “Horseshoe” Diagram Facts

• can choose a point C for a white point
  • corresponds to an illuminant
  • usually on curve swept out by black body radiation spectra for different temperatures
• two colors are complementary relative to C when are
  • located on opposite sides of line segment through C
  • so C is an affine combination of the two colors
• find dominant wavelength of a color:
  • extend line from C through color to edge of diagram
  • some colors (i.e. purples) do not have a dominant wavelength, but their complementary color does
Color Interpolation, Dominant & Opponent Wavelength

Complementary wavelength
Device Color Gamuts

- gamut is polygon, device primaries at corners
  - defines reproducible color range
  - X, Y, and Z are hypothetical light sources, no device can produce entire gamut
Display Gamuts

Projector Gamuts
Gamut Mapping

• how to handle colors outside gamut?
  • one way: construct ray to white point, find closest displayable point within gamut
RGB Color Space (Color Cube)

- define colors with \((r, g, b)\) amounts of red, green, and blue
  - used by OpenGL
  - hardware-centric

- RGB color cube sits within CIE color space
  - subset of perceivable colors
  - scale, rotate, shear cube
HSV Color Space

- more intuitive color space for people
  - H = Hue
    - dominant wavelength, “color”
  - S = Saturation
    - how far from grey/white
  - V = Value
    - how far from black/white
    - also: brightness B, intensity I, lightness L
HSI/HSV and RGB

- HSV/HSI conversion from RGB not expressible in matrix
  - H=hue same in both
  - V=value is max, I=intensity is average

\[
H = \cos^{-1}\left[\frac{1}{2} \left( \frac{(R - G) + (R - B)}{\sqrt{(R - G)^2 + (R - B)(G - B)}} \right) \right]
\]

if (B > G),

\[
H = 360 - H
\]

HSI: \[
S = 1 - \frac{\min(R,G,B)}{I}
\]

\[
I = \frac{R + G + B}{3}
\]

HSV: \[
S = 1 - \frac{\min(R,G,B)}{V}
\]

\[
V = \max(R,G,B)
\]
**YIQ Color Space**

- color model used for color TV
  - Y is luminance (same as CIE)
  - I & Q are color (not same I as HSI!)
  - using Y backwards compatible for B/W TVs
- conversion from RGB is linear
  - expressible with matrix multiply
    \[
    \begin{bmatrix}
    Y \\
    I \\
    Q
    \end{bmatrix} =
    \begin{bmatrix}
    0.30 & 0.59 & 0.11 \\
    0.60 & -0.28 & -0.32 \\
    0.21 & -0.52 & 0.31
    \end{bmatrix}
    \begin{bmatrix}
    R \\
    G \\
    B
    \end{bmatrix}
    \]
  - green is much lighter than red, and red lighter than blue
Luminance vs. Intensity

- **luminance**
  - Y of YIQ
  - \(0.299R + 0.587G + 0.114B\)
  - captures important factor

- **intensity/brightness**
  - I/V/B of HSI/HSV/HSB
  - \(0.333R + 0.333G + 0.333B\)
  - not perceptually based

Opponent Color

- definition
  - achromatic axis
  - R-G and Y-B axis
  - separate lightness from chroma channels
- first level encoding
  - linear combination of LMS
  - before optic nerve
  - basis for perception
  - “color blind” = color deficient
    - degraded/no acuity on one axis
    - 8%-10% men are red/green deficient
vischeck.com

- simulates color vision deficiencies

Normal vision  Deuteranope  Protanope  Tritanope
Color/Lightness Constancy

- color perception depends on surrounding
  - colors in close proximity
  - simultaneous contrast effect

- illumination under which the scene is viewed
Color/Lightness Constancy

Image courtesy of John McCann
Color/Lightness Constancy

Image courtesy of John McCann
Color Constancy

- automatic “white balance” from change in illumination
- vast amount of processing behind the scenes!
- colorimetry vs. perception

From Color Appearance Models, fig 8-1
Stroop Effect

- red
- blue
- orange
- purple
- green
Stroop Effect

- blue
- green
- purple
- red
- orange

- interplay between cognition and perception