Readings

• Chapter 1.4: color
• plus supplemental reading:
  – pages 4-24 required
  – http://graphics.stanford.edu/courses/cs448b-02-spring/04cdrom.pdf

News

• yet more extra office hours
  – Fri 10-11 (AG lab), 11:30-1:30 (AW, AG xtra)
• I’m at a conference Fri pm – Mon pm
  – guest lecture Monday: Abhijet Ghosh
  – my personal mail response will be slow
  – use newsgroup or email to TAs
    • if can’t post remotely, try unsub/resub or port forward
• homework 1 pickup again end of class

Humans and Light

• when we view a source of light, our eyes respond to
  – hue: the color we see (red, green, purple)
    • dominant frequency
  – saturation: how far is color from grey
    • how far is the color from gray (pink is less saturated than red, sky blue is less saturated than royal blue)
  – brightness: how bright is the color
    • how bright are the lights illuminating the object?
**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

**Adaptation, Surrounding Color**
- color perception is also affected by
  - adaptation (stare at a light bulb... don’t)
  - surrounding color/intensity:
    - simultaneous contrast effect

**Bezold Effect**
- impact of outlines

**Color Constancy**
- Color constancy
Color Constancy

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

Color Spaces

- Three types of cones suggests color is a 3D quantity. How to define 3D color space?
  - Idea:
    - Shine given wavelength (\(\lambda\)) on a screen
    - User must control three pure lights producing three other wavelengths (say R=700nm, G=546nm, and B=436nm)
    - Adjust intensity of RGB until colors are identical
      - this works because of metamers!

Negative Lobes

- Exact target match with phosphors not possible
  - Some red had to be added to target color to permit exact match using "knobs" on RGB intensity output of CRT
  - Equivalently (theoretically), some red could have been removed from CRT output
  - Figure shows that red phosphor must remove some cyan for perfect match
  - CRT phosphors cannot remove cyan, so 500 nm cannot be generated

Negative Lobes

- 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 three "imaginary" lights X, Y, and Z, any wavelength \( \lambda \) can be matched perceptually by positive combinations

Note that:
- \( X \sim R \)
- \( Y \sim G \)
- \( Z \sim B \)

Week 10, Fri 7 Nov 03 © Tamara Munzner

CIE Color Space
- The gamut of all colors perceivable is thus a three-dimensional shape in X, Y, Z
- Color = \( X'X + Y'Y + Z'Z \)

CIE Chromaticity Diagram (1931)
For simplicity, we often project to the 2D plane \( X' + Y' + Z' = 1 \)
- \( X' = X' / (X' + Y' + Z') \)
- \( Y' = Y' / (X' + Y' + Z') \)
- \( Z' = 1 - X' - Y' \)

Device Color Gamuts
- Since X, Y, and Z are hypothetical light sources, no real device can produce the entire gamut of perceivable color
- Example: CRT monitor

Device Color Gamuts
- Use CIE chromaticity diagram to compare the gamuts of various devices
RGB Color Space (Color Cube)

- Define colors with (r, g, b) amounts of red, green, and blue

RGB Color Gamuts

- The RGB color cube sits within CIE color space something like this:

Gamut Mapping

Converting Color Spaces

- Simple matrix operation:

\[
\begin{bmatrix}
R' \\
G \\
B
\end{bmatrix} =
\begin{bmatrix}
X_R & X_G & X_B \\
Y_R & Y_G & Y_B \\
Z_R & Z_G & Z_B
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

- The transformation \( C_2 = M_2 M_1 C_1 \) yields RGB on monitor 2 that is equivalent to a given RGB on monitor 1

YIQ Color Space

- YIQ is the color model used for color TV in America. Y is brightness, I & Q are color
  - Note: Y is the same as CIE’s Y
  - Result: Use the Y alone and backwards compatibility with B/W TV!

Converting Color Spaces

- Converting between color models can also be expressed as such a matrix transform:

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} =
\begin{bmatrix}
0.30 & 0.59 & 0.11 \\
0.60 & -0.28 & -0.32 \\
0.21 & -0.52 & 0.31
\end{bmatrix}
\begin{bmatrix}
R' \\
G \\
B
\end{bmatrix}
\]

- Note the relative unimportance of blue in computing the Y
HSV Color Space

• a more intuitive color space
  – $H =$ Hue
  – $S =$ Saturation
  – $V =$ Value (or brightness)

Perceptually Uniform Color Space

• Color space in which Euclidean distance between two colors in space is proportional to the perceived distance
  – CIE, RGB, not perceptually uniform
  • Example with RGB

Simplified Models

• based on RGB triples
• surface interactions also simplified

The Gamma Problem

• device gamma
  – monitor: $I = A(k_1D + k_2V)^\gamma$
  – typical monitor $\gamma = 2.5$
  – LCD: nearly linear
• OS gamma
  – defined by operating system
  – inverse gamma curve $I^{1/\gamma}$
  – “gamma correction”

Display System Gamma

• product of device and OS curves
  – divide device by OS gamma
  $\gamma_{\text{os}} = \gamma_{D} (1/\gamma_{\text{os}})$
• display system gamma varies
  – different devices, different OS
  – nonlinear
• viewing conditions also affect perception of “gamma”
Intensity Mapping

Pick up Homework 1
- take 3