University of British Columbia

CPSC 414 Computer Graphics

Color 2

Week 10, Fri 7 Nov 2003

Readings

- Chapter 1.4: color
- plus supplemental reading:
  - A Survey of Color for Computer Graphics, Maureen Stone, SIGGRAPH Course Notes 2001
  - pages 4-24 required
  - http://graphics.stanford.edu/courses/cs448b-02-spring/04cdrom.pdf

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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: Ahbijeet 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

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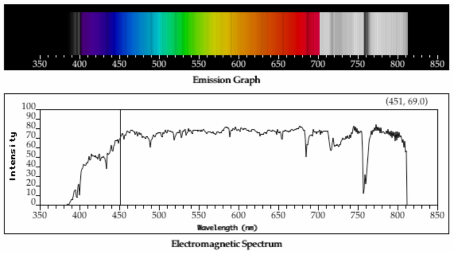
Color recap

Sunlight Spectrum

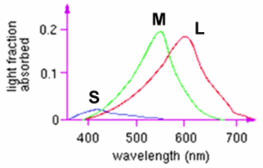


Humans and Light

- when we view a source of light, our eyes respond 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

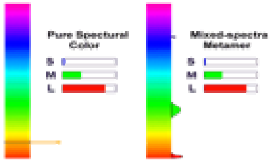
- three types of cones
  - L or R, most sensitive to red light (610 nm)
  - M or G, most sensitive to green light (560 nm)
  - S or B, most sensitive to blue light (430 nm)



  - color blindness results from missing cone type(s)

Metamers

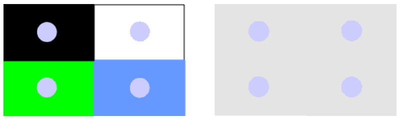
a given perceptual sensation of color derives from the stimulus of all three cone types



- 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



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Color

Bezold Effect

- impact of outlines

Color Constancy

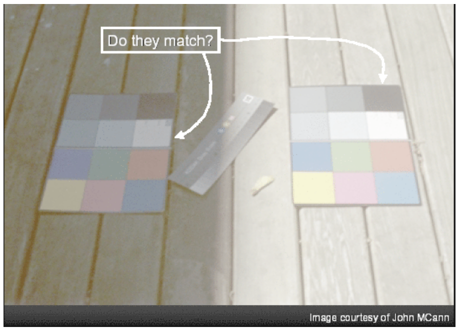


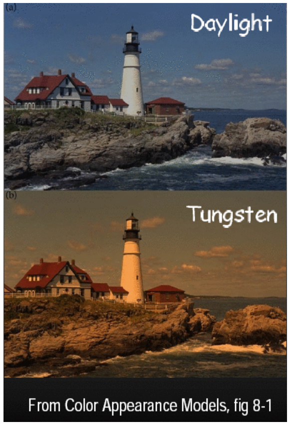
Image courtesy of John MCann

Color Constancy

Color Constancy

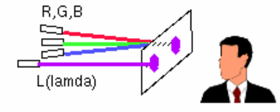
Color Constancy

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



From Color Appearance Models, fig 8-1

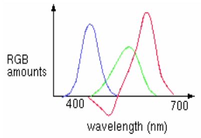
Color Spaces



- Three types of cones suggests color is a 3D quantity. How to define 3D color space?
- Idea:
  - Shine given wavelength (λ) 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

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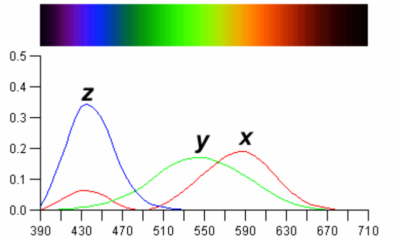
Negative Lobes

- can’t generate all other wavelenths with any set of three positive monochromatic lights!
- solution: convert to new synthetic coordinate system to make the job easy

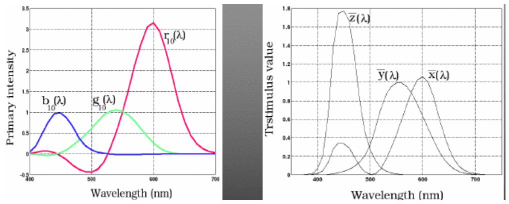
CIE Color Space

- CIE defined three “imaginary” lights X, Y, and Z, any wavelength λ can be matched perceptually by positive combinations



Note that:
X ~ R
Y ~ G
Z ~ B

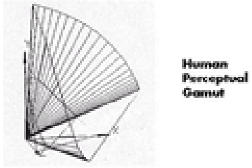
Measured vs. CIE Color Spaces



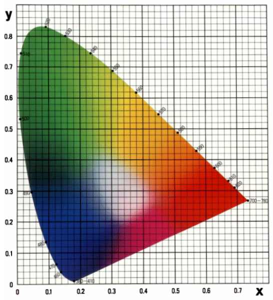
- measured basis
  - monochromatic lights
  - physical observations
  - negative lobes
- transformed basis
  - “imaginary” lights
  - all positive, unit area
  - Y is luminance

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)

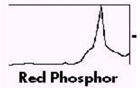


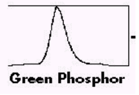
For simplicity, we often project to the 2D plane X’+Y’+Z’=1

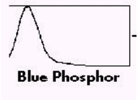
$X' = X' / (X'+Y'+Z')$
$Y' = Y' / (X'+Y'+Z')$
$Z' = 1 - X' - Y'$

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

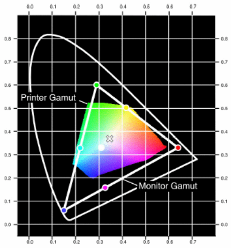

Red Phosphor

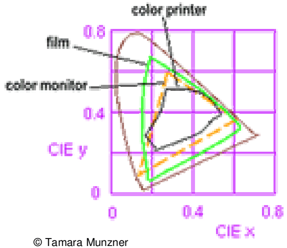

Green Phosphor


Blue Phosphor

Device Color Gamuts

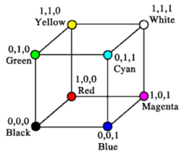
- use CIE chromaticity diagram to compare the gamuts of various devices





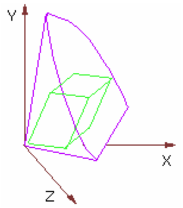
RGB Color Space (Color Cube)

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

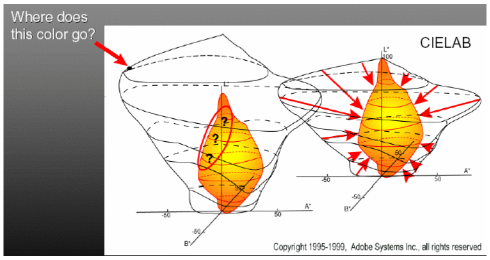


RGB Color Gamuts

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



Gamut Mapping



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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 $\mathbf{C}_2 = \mathbf{M}^{-1}{}_2\, \mathbf{M}_1\, \mathbf{C}_1$ 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

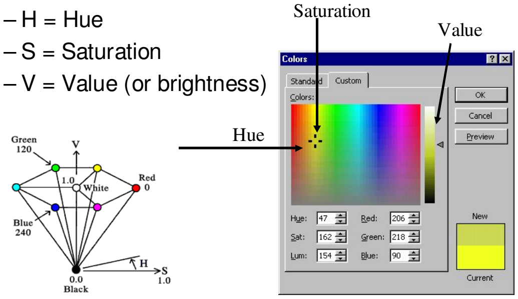
- Converting between color models can also be expressed as such a matrix transform:

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

- Note the relative unimportance of blue in computing the Y

HSV Color Space

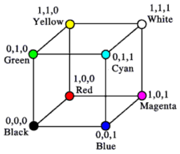
- a more intuitive color space
  - H = Hue
  - S = Saturation
  - V = Value (or brightness)



Hue: 47
Sat: 162
Lum: 154
Red: 206
Green: 218
Blue: 90

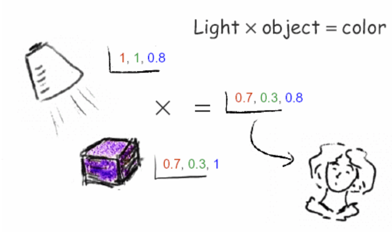
Perceptually Uniform Color Space

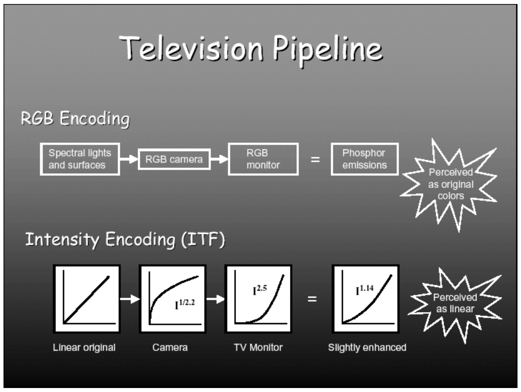
- Color space in which Euclidean distance between two colors in space is proportional to the perceived distance
  - CIE, RGB, not perceptually uniform
    - Example with RGB



Simplified Models

- based on RGB triples
- surface interactions also simplified





Television Pipeline

RGB Encoding

Spectral lights and surfaces → RGB camera → RGB monitor = Phosphor emissions

Perceived as original colors

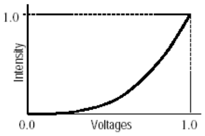
Intensity Encoding (ITF)

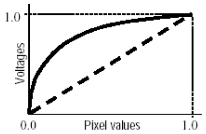
Linear original → Camera ($I^{1/2.2}$) → TV Monitor ($I^{2.5}$) = Slightly enhanced ($I^{1.14}$)

Perceived as linear

The Gamma Problem

- device gamma
  - monitor: $\mathtt{I}= A(k_1 D+k_2 V)^{\gamma}$
  - typical monitor γ=2.5
  - LCD: nearly linear
- OS gamma
  - defined by operating system
  - inverse gamma curve $\mathtt{I}^{1/\gamma}$
  - “gamma correction”





Display System Gamma

- product of device and OS curves
  - divide device by OS gamma

$$\gamma_{DS} = \gamma_D \, (1/\gamma_{OS})$$

- display system gamma varies
  - different devices, different OS
  - nonlinear
- viewing conditions also affect perception of “gamma”

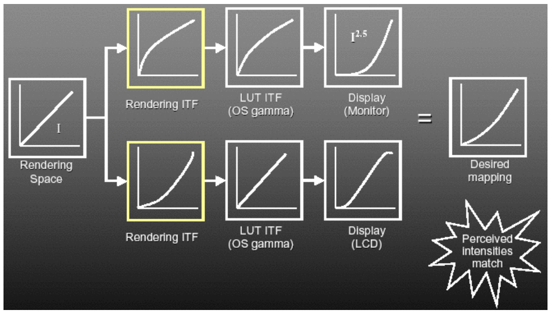
PC	Mac	SGI
1.0	1.4	1.7

Default OS Gamma

PC	Mac	SGI
2.2	1.6	1.3

Default DS Gamma

Intensity Mapping



Pick up Homework 1

- take 3