CS 4731: Computer Graphics
Lecture 24: Color Science

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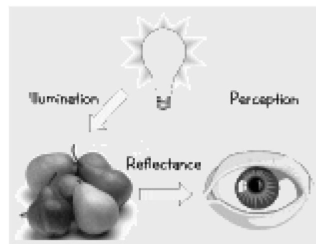
Basics Of Color

- Elements of color:



What is color?

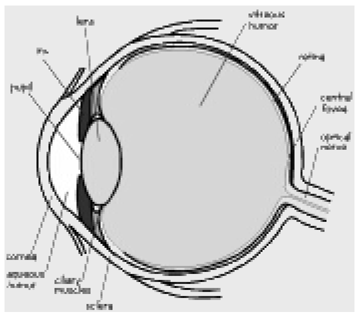
- Color is defined many ways
- Physical definition
  - Wavelength of photons
  - Electromagnetic spectrum: infra-red to ultra-violet
- But so much more than that…
  - Excitation of photosensitive molecules in eye
  - Electrical impulses through optical nerves
  - Interpretation by brain

Introduction

- Color description: Red, greyish blue, white, dark green…
- Computer Scientist:
  - Hue: dominant wavelength, color we see
  - Saturation
    - how pure the mixture of wavelength is
    - How far is the color from gray (pink is less saturated than red, sky blue is less saturated than royal blue)
  - Lightness/brightness: how intense/bright is the light

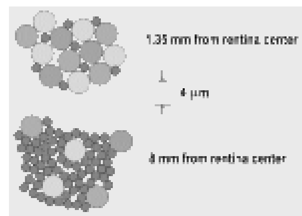
The Human Eye

- The eye:
- The retina
  - Rods
  - Cones
    - Color!



The Human Eye

- The center of the retina is a densely packed region called the *fovea*.
  - Eye has about 6- 7 million cones
  - Cones much denser here than the *periphery*

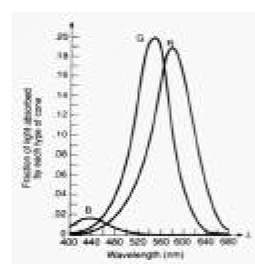


The Human Eye

- Rods:
  - relatively insensitive to color, detail
  - Good at seeing in dim light, general object form
- Human eye can distinguish
  - 128 different hues of color
  - 20 different saturations of a given hue
- Visible spectrum: about 380nm to 720nm
- Hue, luminance, saturation useful for describing color
- Given a color, tough to derive HSL though

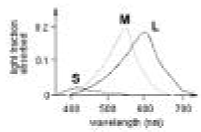
Tristimulus theory

- 3 types of cones
  - Loosely identify as R, G, and B cones
- Each is sensitive to its own spectrum of wavelengths
- Combination of cone cell stimulations give perception of **COLOR**



The Human Eye: Cones

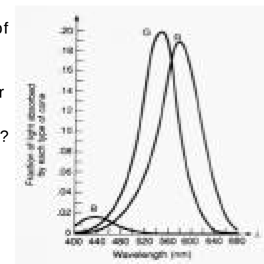
- Three types of cones:
  - **L** or **R**, most sensitive to red light (610 nm)
  - **M** or **G**, most sensitive to green light (560 nm)
  - **S** or **B**, most sensitive to blue light (430 nm)



  - Color blindness results from missing cone type(s)

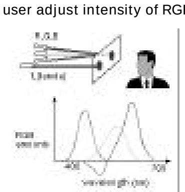
The Human Eye: Seeing Color

- The tristimulus curve shows overlaps, and different levels of responses
- Eyes more sensitive around 550nm, can distinquish smaller differences
- What color do we see the best?
  - Yellow-green at 550 nm
- What color do we see the worst?
  - Blue at 440 nm



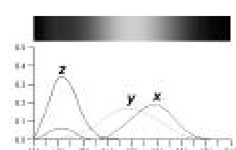
Color Spaces

- Three types of cones suggests color is a 3D quantity.
- How to define 3D color space?
- Color matching idea:
  - shine given wavelength (λ) on a screen
  - Mix three other wavelengths (R,G,B) on same screen.
  - Have user adjust intensity of RGB until colors are identical:



CIE Color Space

- *CIE* (Commission Internationale d'Eclairage) came up with three hypothetical lights X, Y, and Z with these spectra:

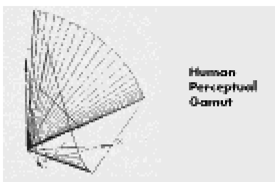


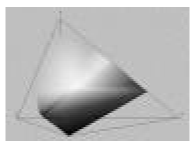
Note that:
X ~ R
Y ~ G
Z ~ B

- Idea: any wavelength λ can be matched perceptually by *positive* combinations of X,Y,Z
- CIE created table of XYZ values for all *visible* colors

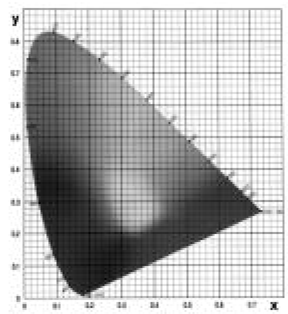
CIE Color Space

- 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
•Also normalize

X'+Y'+Z'=1
X'' = X' / (X'+Y'+Z')
Y'' = Y' / (X'+Y'+Z')
Z'' = 1 – X'' – Y''

• **Note:** Inside horseshoe visible, outside invisible to eye

CIE uses

- Find complementary colors:
  - equal linear distances from white in opposite directions
- Measure hue and saturation:
  - extend line from color to white till it cuts horseshoe (hue)
  - Saturation is ratio of distances color-to-white/hue-to-white
- Define and compare device color gamut (color ranges)
- Problem: not perceptually uniform:
  - Same amount of changes in different directions generate perceived difference that are not equal
  - CIE LUV - uniform

Color Spaces

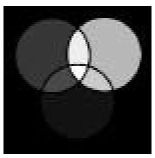
- CIE very exact, defined
- Alternate lingo may be better for other domains
- Artists: tint, tone shade
- CG: Hue, saturation, luminance
- Many different color spaces
  - RGB
  - CMY
  - HLS
  - HSV Color Model
  - And more…..

Combining Colors: Additive and Subtractive

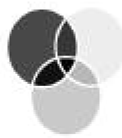
Add components

Remove components from white

Additive (RGB)



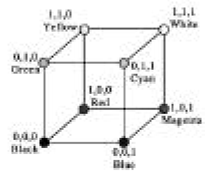
Subtractive (CMYK)

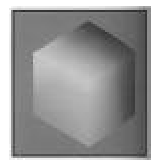


- Some color spaces are additive, others are subtractive
- Examples: Additive (light) and subtractive (paint)

RGB Color Space

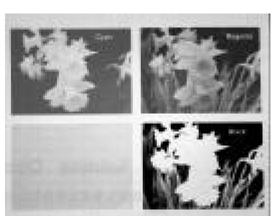
- Define colors with (r, g, b) amounts of red, green, and blue
- Most popular
- Additive





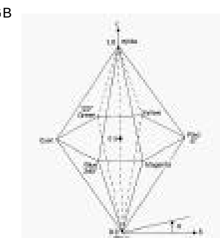
CMY

- Subtractive
- For printing
- Cyan, Magenta, Yellow
- Sometimes black (K) is also used for richer black
- (c, m, y) means subtract the c, m, y of the compliments of C (red) M (green) and Y (blue)



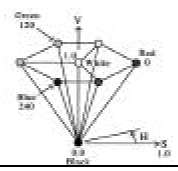
HLS

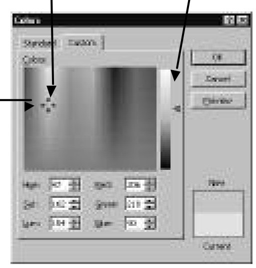
- Hue, Lightness, Saturation
- Based on warped RGB cube
- Look from (1,1,1) to (0,0,0) or RGB cube
- All hues then lie on hexagon
- Express hue as angle in degrees
- 0 degrees: red



HSV Color Space

- A more intuitive color space
  - H = Hue
  - S = Saturation
  - V = Value (or brightness)
- Based on artist Tint, Shade, Tone
- Similar to HLS in concept





Converting Color Spaces

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

$$[R \quad G \quad B] = [X \quad Y \quad Z] \begin{bmatrix} 2.739 & -1.110 & 0.138 \\ -1.145 & 2.029 & -0.333 \\ -0.424 & 0.033 & 1.105 \end{bmatrix}$$

Color Quantization

- True color can be quite large in actual description
- Sometimes need to reduce size
- Example: take a true-color description from database and convert to web image format
- Replace true-color with "best match" from smaller subset
- Quantization algorithms:
  - Uniform quantization
  - Popularity algorithm
  - Median-cut algorithm
  - Octree algorithm

Gamma Correction

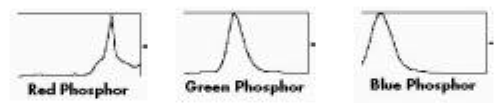
- Color spaces, RGB, HLS, etc are all linear.
- E.g. (0.1,0.1,0.1) in RGB is half the intensity of (0.2,0.2,0.2)
- However, CRT Intensity: $I = kN^{\gamma}$
  - N is no. of electrons hitting screen (voltage), related to pixel value
  - k and γ are constants for each monitor
- Intensity-voltage relationship is non-linear, different min/max N for different devices
- Gamma correction: make relationship linear, match up intensity on different devices
- How? Invert above equation so that $N = (I/k)^{1/\gamma}$
- Choose k and γ so that I becomes linearly related to N

Gamma Correction

- Typical gamma values in range [1.7 – 2.3]
- E.g. NTSC TV standard in US defines gamma = 2.2
- Some monitors perform the gamma correction in hardware (SGI's)
- Others do not (most PCs)
- Tough to generate images that look good on both platforms (i.e. images from web pages)

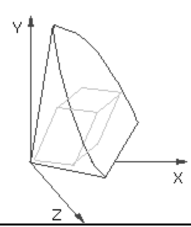
Device Color Gamuts

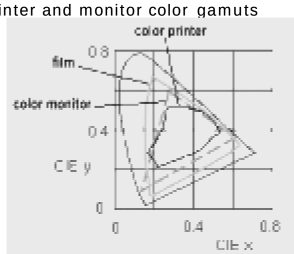
- Since X, Y, and Z are hypothetical light sources, no real device can produce the entire gamut of perceivable color
- Depends on physical means of producing color on device
- Example: R,G,B phosphors on CRT monitor



Device Color Gamuts

- The RGB color cube sits within CIE color space
- We can use the CIE chromaticity diagram to compare the gamuts of various devices
- E.g. compare color printer and monitor color gamuts





References

- Hill, chapter 12