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 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

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 distinguish 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 (\(\lambda\)) 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:
- Idea: any wavelength \(\lambda\) can be matched perceptually by positive combinations of X,Y,Z
- CIE created table of XYZ values for all visible colors

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

Additive (RGB)

Subtractive (CMYK)

Remove components from white

- 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
- \( H = \text{Hue} \)
- \( S = \text{Saturation} \)
- \( V = \text{Value (or brightness)} \)
- 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:

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

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 \(\gamma\) 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 \(\gamma\) so that \(I\) becomes linearly related to \(N\)
Gamma Correction

- Typical gamma values in range \([1.7 \text{ – } 2.3]\)
- 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

References

- Hill, chapter 12