Specifying Color

- Color perception usually involves three quantities:
  - **Hue**: Distinguishes between colors like red, green, blue, etc.
  - **Saturation**: How far the color is from a gray of equal intensity
  - **Lightness**: The perceived intensity of a reflecting object
- Sometimes lightness is called **brightness** if the object is emitting light instead of reflecting it.
- In order to use color precisely in computer graphics, we need to be able to specify and measure colors.

How Do Artists Do It?

- Artists often specify color as tints, shades, and tones of saturated (pure) pigments
- **Tint**: Gotten by adding white to a pure pigment, decreasing saturation
- **Shade**: Gotten by adding black to a pure pigment, decreasing lightness
- **Tone**: Gotten by adding white and black to a pure pigment

The HSV "hexcone"

- When V=1, S=1, the colors correspond to an artist’s primary mixing colors
- Adding white paint corresponds to decreasing S without changing V
- Tones are created by changing S and V
- Hard to interpolate colors

Intuitive Color Spaces

- HSV is an intuitive color space, corresponding to our perceptual notions of tint, shade, and tone
- **Hue** (H) is the angle around the vertical axis
- **Saturation** (S) is a value from 0 to 1 indicating how far from the vertical axis the color lies
- **Value** (V) is the height of the "hexcone"
Precise Color Specifications

- Pigment-mixing is subjective --- depends on human observer, surrounding colors, lighting of the environment, etc
- We need an objective color specification
- Light is electromagnetic energy in the 400 to 700 nm wavelength range
- Dominant wavelength is the wavelength of the color we “see”
- Excitation purity is the proportion of pure colored light to white light
- Luminance is the amount (or intensity) of the light

Colored Light and Spectra

Color Matching

- In order to match a color, we can adjust the brightness of 3 overlapping primaries until the two colors look the same.
  - C = color to be matched
  - RGB = laser sources (R=700nm, G=546nm, B=435nm)

\[
\begin{align*}
C &= R + G + B \\
C + R &= G + B
\end{align*}
\]

- Humans have trichromatic color vision

Spectral Matching Functions

- Match each pure color in the visible spectrum (rainbow)
- Record the color coordinates as a function of wavelength
Linear Color Matching

*Grassman’s Laws:*

1. Scaling the color and the primaries by the same factor preserves the match:
   \[ 2C = 2R + 2G + 2B \]

2. To match a color formed by adding two colors, add the primaries for each color:
   \[ C_1 + C_2 = (R_1 + R_2) + (G_1 + G_2) + (B_1 + B_2) \]

Human Color Vision

- Humans have 3 light sensitive pigments in their cones, called L, M, and S.
  - Each has a different *spectral response curve:*
    \[
    L = \int L(\lambda)E(\lambda)\,d\lambda \\
    M = \int M(\lambda)E(\lambda)\,d\lambda \\
    S = \int S(\lambda)E(\lambda)\,d\lambda
    \]
    - This leads to *metamerism* -- two spectral distributions appearing to be the same color

Just Noticeable Differences

- The human eye can distinguish hundreds of thousands of different colors
- When two colors differ only in hue, the wavelength between just noticeably different colors *varies* with the wavelength!
  - More than 10 nm at the extremes of the spectrum
  - Less than 2 nm around blue and yellow
  - Most JND hues are within 4 nm.
- Altogether, the eye can distinguish about 128 fully saturated hues
- Human eyes are less sensitive to hue changes in less saturated light (not a surprise)

Luminance

- Compare color source to a gray source
  - Luminance
    \[ Y = .30R + .59G + .11B \]
  - Color signal on a BW TV
    (Except for gamma)
Chromaticity and the CIE

- Notice that some of the values in the spectral matching functions are negative!
- This means that some colors cannot be represented by adding positive amounts of RGB together.
- This is very inconvenient, so the CIE defined three new standard primaries called X, Y, and Z.
- Not coincidentally, Y was chosen to have a spectral matching function exactly equal to the human response to luminance.

XYZ Matching Functions

- Match all visible colors with only positive weights
- Y matches luminance
- These functions are defined tabularly at 1-nm intervals
- Linear combinations of the R,G,B matching functions

Spectral Locus

Human perceptual gamut

Chromaticity Diagram

Converting from RGB to XYZ is a snap:

Given x, y, and Y, we can recover the X,Y,Z coordinates
Measuring Color

- Colorimeters measure the X, Y, and Z values for any color
- A line between the “white point” of the chromaticity diagram and the measured color intersects the horseshoe curve at exactly the dominant wavelength of the measured color
- A ratio of lengths will give the excitation purity of the color
- Complementary colors are two colors that mix to produce pure white
- Some colors are non-spectral --- their dominant wavelength is defined as the same as their complimentary color, with a “c” on the end

Gamuts

- The chromaticity diagram can be used to define the total set of colors that can be represented on a particular device
- This is why not all colors can be represented by just adding R,G,B
- In fact, you can’t represent all colors by adding any set of visible primaries (why?)

A Problem With XYZ Colors

- If we have two colors C1 and C2, and we add DC to both of them, the differences between the original and new colors will not be perceived to be equal
- This is due to the variation of the just noticeable differences in saturated hues
- XYZ space is not perceptually uniform
- LUV space was created to address this problem

The RGB Color Model

- This is the model used in color CRT monitors
- RGB are additive primaries
- We can represent this space as a unit cube:
More on RGB

- The color gamut covered by the RGB model is determined by the chromaticities of the three phosphors.
- To convert a color from the gamut of one monitor to the gamut of another, we first measure the chromaticities of the phosphors.
- Then, convert the color to XYZ space, and finally to the gamut of the second monitor.
- We can do this all with a single matrix multiply.

The CMY Color Model

- Cyan, magenta, and yellow are the complements of red, green, and blue.
  - We can use them as filters to subtract from white.
  - The space is the same as RGB except the origin is white instead of black.
- This is useful for hardcopy devices like laser printers.
  - If you put cyan ink on the page, no red light is reflected.

\[
\begin{bmatrix}
C \\
M \\
Y
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

CMYK

- Most printers actually add a fourth color, black.
- Use black in place of equal amounts of C, M, and Y.
  \[K = \text{min}(C, M, Y)\]
  \[C = C - K\]
  \[M = M - K\]
  \[Y = Y - K\]
- Why?
  - Black ink is darker than mixing C, M, and Y.
  - Black ink is cheaper than colored ink.

The YIQ Color Model

- YIQ is used to encode television signals.
- Y is the CIE Y primary, not yellow.
  - Remember, Y is luminance, so I and Q encode the chromaticity of the color.
- If we just throw I and Q away, we have black and white TV.

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} =
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
0.596 & -0.275 & -0.321 \\
0.212 & -0.528 & 0.311
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
- This assumes known chromaticities for your monitor.
- Backwards compatibility with black and white TV.
- More bandwidth can be assigned to Y.