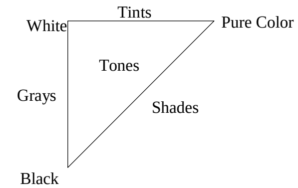
Specifying Color

- 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.

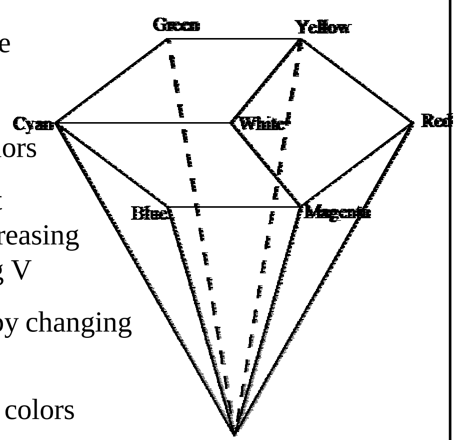
How Do Artists Do It?

- 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



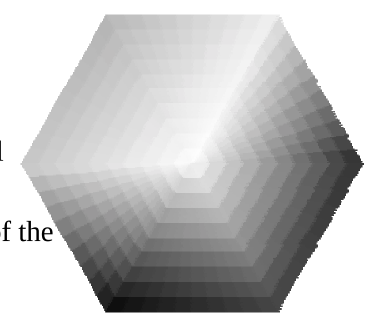
The HSV "hexcone"

- 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

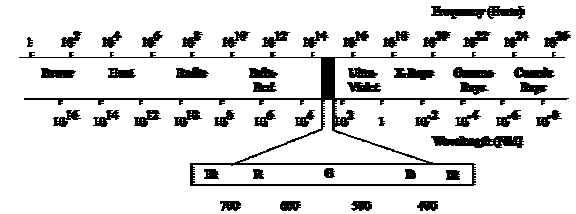
- HSV is an intuitive color space, corresponding to our perceptual notions of tint, shade, and tone
- Hue (H) is the angle around the vertical axis
- Saturation (S) is a value from 0 to 1 indicating how far from the vertical axis the color lies
- Value (V) is the height of the "hexcone"



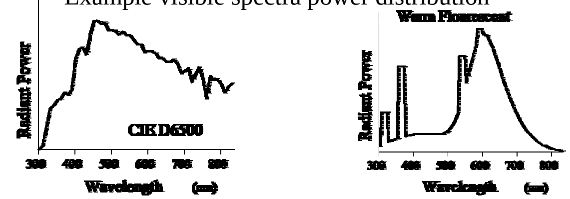
Precise Color Specifications

- 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

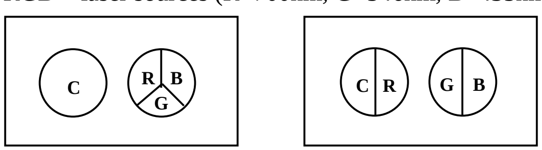


Example visible spectra power distribution



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)

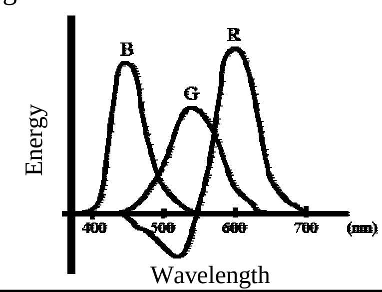


C = R + G + B **C + R = G + B**

- 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:

$$2C = 2R + 2G + 2B$$

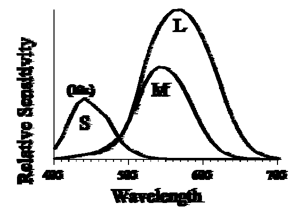
2. To match a color formed by adding two colors, add the primaries for each color:

$$C_1 + C_2 = (R_1 + R_2) + (G_1 + G_2) + (B_1 + B_2)$$

Human Color Vision

- Humans have 3 light sensitive pigments in their cones, called L, M, and S
- Each has a different *spectral response curve*:

$$L = \int L(\lambda)E(\lambda)d\lambda$$
$$M = \int M(\lambda)E(\lambda)d\lambda$$
$$S = \int S(\lambda)E(\lambda)d\lambda$$

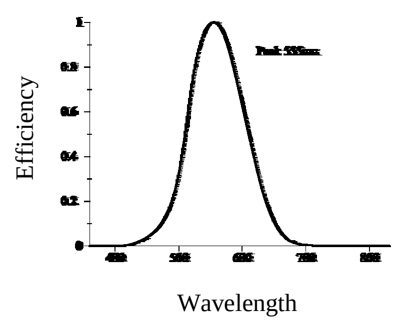


- This leads to *metamerism* -- two spectral distributions appearing to be the same color

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

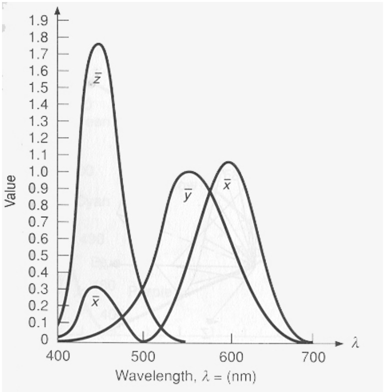
Color signal on a BW TV
(Except for gamma)

Chromaticity and the CIE

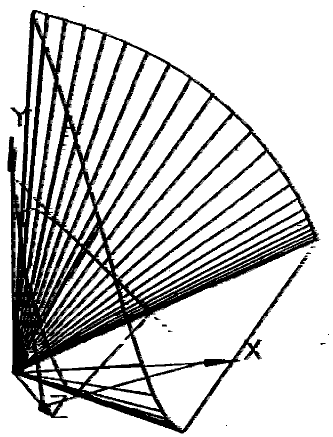
- Notice that some of the values in the spectral matching functions are negative!
- This means that some colors cannot be represented by adding positive amounts of RGB together.
- This is very inconvenient, so the *CIE* defined three new standard primaries called **X, Y,** and **Z**.
- Not coincidentally, **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

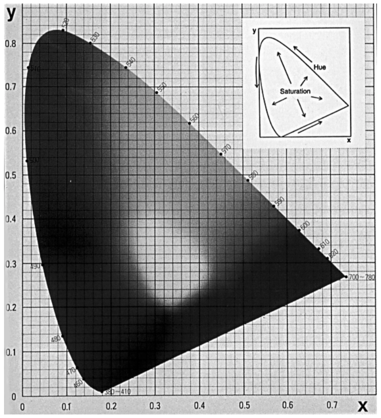


Spectral Locus



Human perceptual gamut

Chromaticity Diagram



Converting from RGB to XYZ is a snap:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.77 & 1.75 & 1.13 \\ 1.00 & 4.59 & 0.06 \\ 0.00 & 0.57 & 5.59 \end{bmatrix} \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix}$$

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

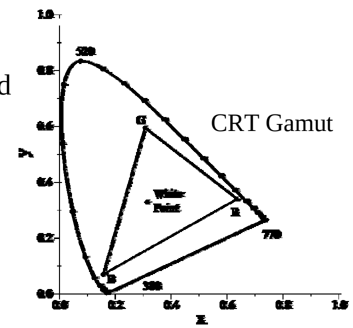
Given *x*, *y*, and **Y**, we can recover the **X**,**Y**,**Z** coordinates

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?)

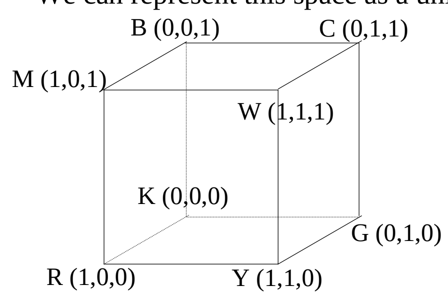


A Problem With XYZ Colors

- 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 chromaticites 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

CS148 Lecture 10 slide 21

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

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

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CMYK

- Most printers actually add a fourth color, black
- Use black in place of equal amounts of C, M, and Y

$$\begin{aligned} K &= \min(C, M, Y) \\ C &= C - K \\ M &= M - K \\ Y &= Y - K \end{aligned}$$

- Why?
  - Black ink is darker than mixing C, M, and Y
  - Black ink is cheaper than colored ink

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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

CS148 Lecture 10 slide 24