CS770/870 Spring 2017 Color

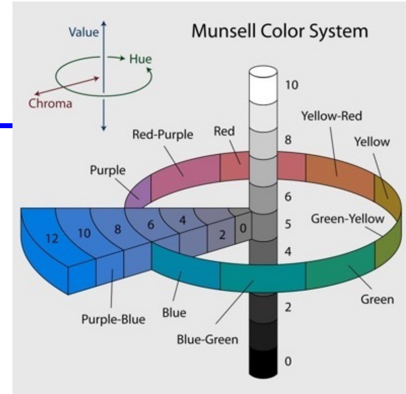
Chromatic color
Psychophysics
CIE Chromaticity Diagram
Color models
Color usage guidelines

Based on Hill and Kelley: Ch. 11, Foley, van Dam et al. and other sources; color images from Wikipedia

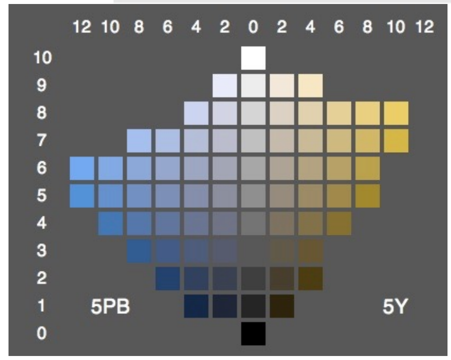
Chromatic Color Terms

- *Hue*: identifies what we think of as "color"
  - Also, called the *dominant wavelength*
- *Saturation*: how far color is from a gray of equal intensity
  - Also, *excitation purity*
- *Intensity* terms
  Lightness: perceived intensity of reflecting objects
  Brightness: perceived intensity of self-luminous objects
  Luminance: physically measured intensity of reflecting and self-luminous objects

Munsell Color System



- Munsell <u>color-ordering</u> system — standard color samples viewed under standard lighting conditions, ordered in order to have equal *perceived* distances from neighbors in color space.
  - Created in early 1900's
  - Books still published with 100's of pages of sample colors

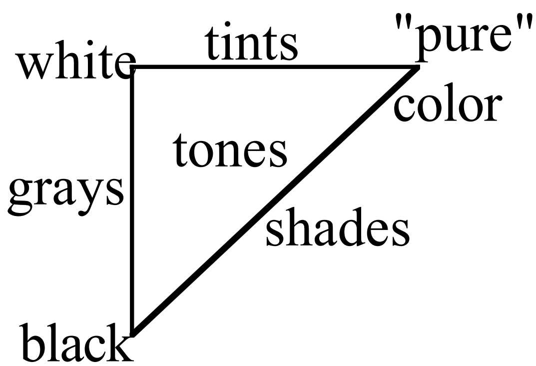


Pantone Color Matching System

- Pantone <u>matching</u> system used in printing and graphic design
  - Standardizes color reproduction
  - 1113 standard colors defined by specified amounts 13 base colors
  - Heavily used in printing industry based primarily on CMYK model: Cyan, Magenta, Yellow, Black
  - Most Pantone colors cannot be generated from CMYK
  - Just recently (2007?) came up with mappings to RGB and LUV for mapping colors to monitors.

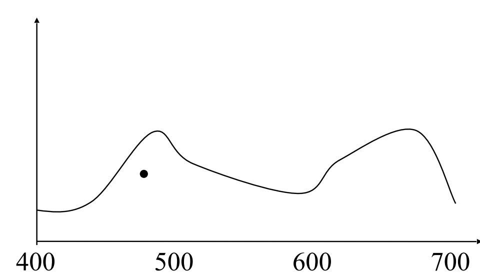
Artist-Oriented System

- *tints* — add white to "pure" fully saturated colors
- *shade* — add black to "pure" fully saturated colors
- *tones* — add both black and white



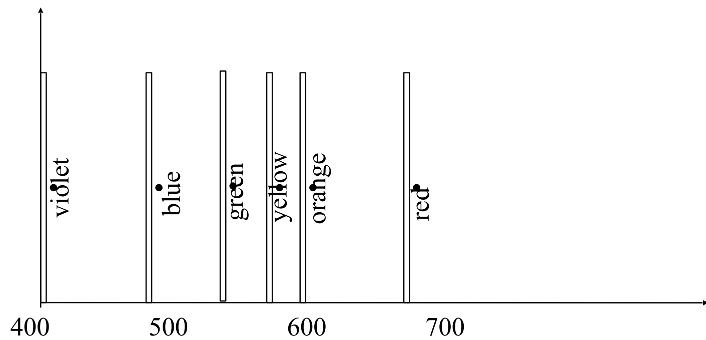
Physics-based Color

- *colorimetry* — physical specification via wavelength.
  - *dominant wavelength* (hue) is still a perceived phenomenon.
  - *excitation purity* is saturation,
  - *luminance* is amount of intensity
- *spectral energy distribution,* (a.k.a. *spectral density*)
  - most light contains a wide range of wavelengths of different power levels
  - total power is area under the curve



Spectral Density for Pure Colors

- "pure" colored light (laser light) only emits a single very narrow range of wavelengths



Vision-based Color

- How do we perceive a particular spectrum?
- Human eye appears to have 3 different cones that respond based on wavelength. These are called S (short), M (middle), and L (long), based on the relative wavelengths they respond to
  - S is most sensitive to light at 440 nm (nearly blue),
  - M peaks at 545nm (we call it green, but green is 510nm)
  - L peaks at 580nm (which is yellow, but we call it red)
- Leads to *tri-stimulus* model for color perception

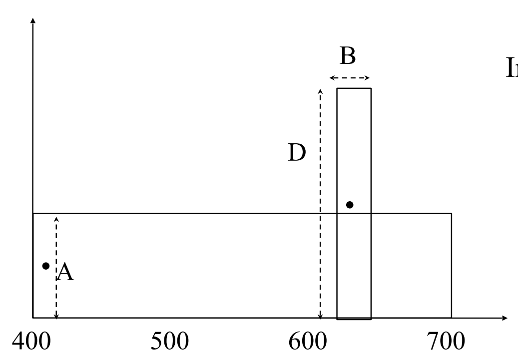
Human Color Perception

- Our visual system can't possibly distinguish all spectra
  - it simplifies by triple integration: one for each kind of cone
  - lots of different spectra trigger identical perception
    - called *metamers*
    - some *metamers* have very different distributions
- The *tristimulus* nature of our visual hardware can be modeled in many different 3-parameter ways
  - many different sets of 3 different colors work
  - can collapse "color" into a single *hue*, or *dominant wavelength* and add 2 other parameters to model other aspects of the color

Online demos at http://www.cs.brown.edu/exploratories

Dominant Wavelength

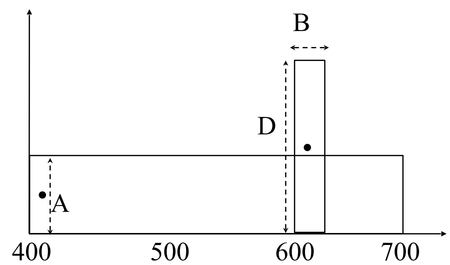
- A good model for our visual system is based on the idea that we eventually integrate the entire color spectrum down to the perception of a single *dominant wavelength* plus a *purity* measure and a total power (luminance). This is a simple spectrum



Interpretation:
- peak is perceived "hue"
- narrower B implies narrower freq range
- horizontal line is "white" light
- the less white, the ***purer*** the color (the higher the ***saturation***)
- the more total energy (area under curve), the brighter the light (more ***luminance***)

Luminance and Saturation

- Hill/Kelley definitions:
  - *luminance*, L, is total power of the light, or the area under the spectral curve
  - *saturation (purity)* is % of luminance that is in the dominant component
- Formulas derived from definitions:
  - L = (700-400)A + (D-A)B
  - P = DB/L



Color Matching

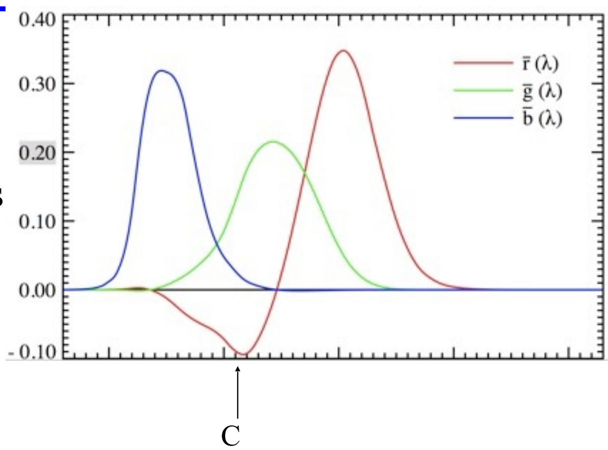
- Perceptually based color systems are all based on color matching experiments
  - Given a sample color generated by a spectral density, S(λ), match the color with proportions of 3 “primary” colors with spectral densities: A(λ), B(λ), C(λ)
  - That is, find a, b, c, such that (a user says that):
    S(λ) = T(λ) where T(λ) = aA(λ) + bB(λ) + cC(λ)
  - Even though S and T can have very different spectral densities, experiments show that if S(λ) = T(λ) :
    - S(λ) + N(λ) = T(λ) + N(λ)
    - aS(λ) = aT(λ) for any scalar a > 0
- Hence, we can define a *vector algebra* for color space

Color Space Algebra

- Any color, C, can be defined as a linear combination of 3 primary colors, such as R, G, B:
  C = rR + gG + bB
- Any 3 colors can be primaries as long as none can be expressed as combination of the other 2.
- How good are R, G, and B?
  - Perceptual experiments tested how people could match “all” pure visible colors with combinations of pure R, G, and B.
  - Let r(λ), g(λ), b(λ) be the spectral densities of pure red, green and blue and let mono(λ) be an arbitrary pure color
  - Goal is to find R,G,B such that :
    mono(λ) = Rr(λ) + Gg(λ) + Bb(λ) for lots of λ

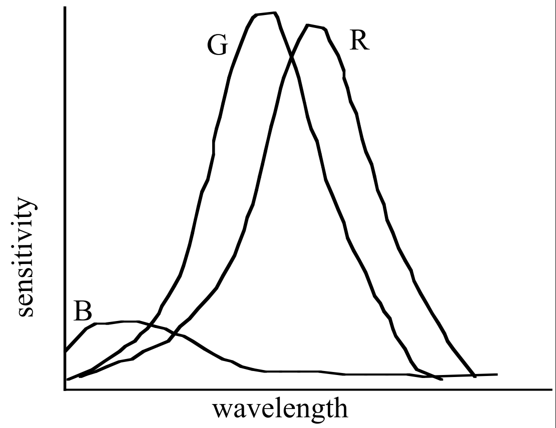
RGB Color Matching

- Results:
  - Some colors need minus red!!! How do we do that?
  - Consider a color C that needs negative red
    C = -0.1R + 0.2G + 0.05B
  - Can write this as
    C + 0.1R = 0.2G + 0.05B
  - So, if subject can make this match, we know the right representation for C in RGB



Luminous Efficiency Function

- Relative sensitivity of the eye to different light:
  – keep luminance constant
  – vary the dominant wavelength
- Perception of blue cone is much lower than the others (.02 vs .2).



Color Gamuts

- A color *gamut* defines a set of color ranges that can be perceived by an organism or generated by a particular rendering technology
  – different species can have dramatically different color perception gamuts
    - different individuals in a species can have different gamuts
  – different display devices can have dramatically different gamuts
    - different examples of the same technology can have different gamuts
- How well does display technology match human vision abilities?

Color Gamut Matching

- Given red, green and blue colors, can we mix quantities (additively) to get all visible colors?
  - No. That is shown by the RGB color matching
- There are some visible colors that can only be represented by combinations of red, green, and blue that have <u>negative</u> values for red
  - of course, you can't take away light that isn't there!

CIE XYZ Color Model

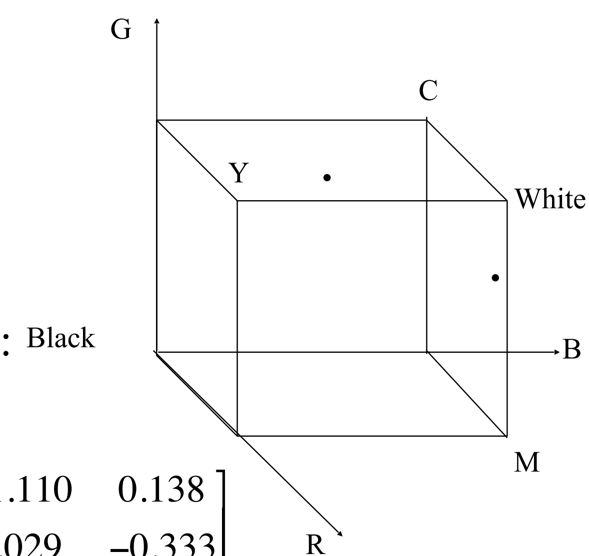
- 1931 Commission Internationale de l'Eclairage (CIE) adopted the XYZ color model.
  - X,Y,Z are chosen so that all visible colors can be expressed as *positive* factors of X,Y, and Z.
  - Color matching functions are identified as x_λ, y_λ, z_λ
  - Y's color matching function exactly matches the luminous-efficiency function as perceived by a *standard observer* intended to represent the perception of an average human. 1931 CIE, so it extracts non-color luminance.

Color Models

- Since color is a 3d space, many color models can be defined by a coordinate frame transformation (a new set of basis vectors)
- RGB: most common for monitors
- XYZ: traditional foundation
- CMY: Cyan, Magenta, Yellow
- CMYK: in practice a *subtractive* process
- YIQ: television transmission
- HSV: Hue, Saturation, Value
- HLS: Hue, Lightness, Saturation
- CIE Lab and CIE Luv: attempts at a perceptually uniform color model

RGB Color Model

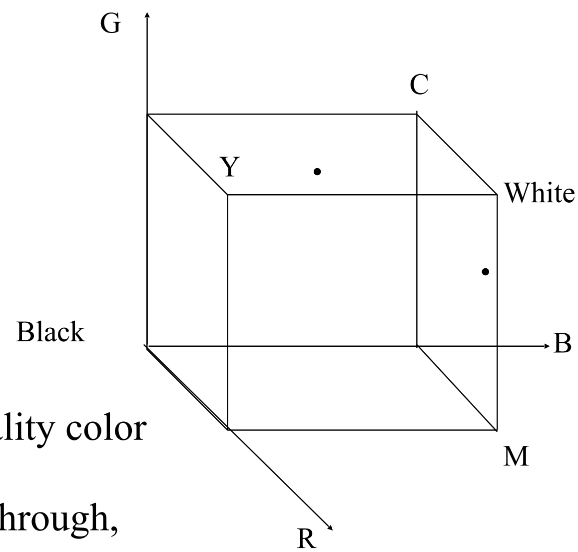
- RGB is an additive color model
  - components, r,g,b are added together to get color
- Given a specified "white" point, can create a matrix transform from XYZ to rgb:



$$\begin{bmatrix} r & g & b \end{bmatrix} = \begin{bmatrix} x & y & z \end{bmatrix} \begin{bmatrix} 2.739 & -1.110 & 0.138 \\ -1.145 & 2.029 & -0.333 \\ -0.424 & 0.033 & 1.105 \end{bmatrix}$$

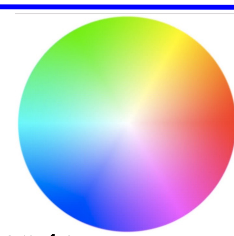
CMY Color Model

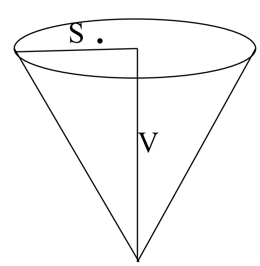
- CMY is a subtractive color model.
  - Subtract values from *white*
  - Acts like a filter
    - Cyan filter removes red
    - Magenta filter removes green
    - Yellow filter removes blue
  - (r,g,b)=(1,1,1) - (c,m,y)
- CMYK (CMY + blacK)
  - principal model for high-quality color offset printing
  - inks are filters, light passes through, bounces back off white paper



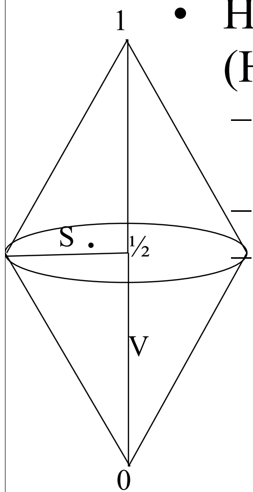
HSV Color Model

- Hue-Saturation-Value model (Smith, 1978)
  - more perceptually oriented, motivated by artists' tint/shade/tone model
  - Hue: based on color wheel; measured as circular angle from red (0) to yellow to green (120) to cyan to blue(240) to magenta
  - Saturation: radially from white (0) at center to fully saturated (1) at outer edge.
  - Value (or Brightness): black (0) at point of cone to white (1) at center of circle

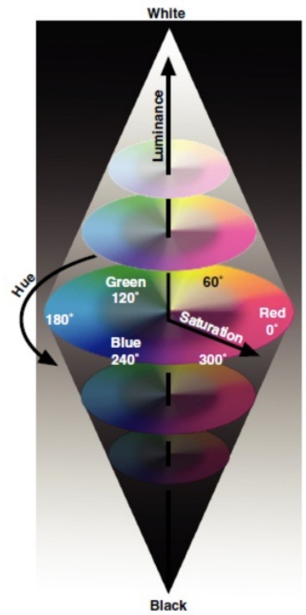




HLS Color Model



- Hue, Lightness, Saturation (HLS or HSL)
  - A variation on HSV that uses a double-ended cone
  - Hue, Saturation same as HSV
  - Lightness goes from Black (0) at the bottom point through ½ at the hue circle center to White (1) at the upper point

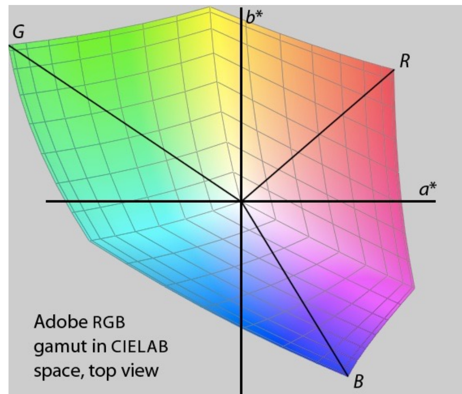


YIQ Color Model

- Model develop in 1920’s to recode RGB to reduce for signal transmission efficiency <u>and</u> to remain compatible with B/W TV signals
  - Y is luminance; IQ encode chromaticity
  - I essentially covers orange/blue range, Q purple/green
- 66% of the signal used to encode Y; visual system most sensitive to intensity!
- 24% signal used for I
- 10% used for Q
- Being phased out as a TV signal

Other Perceptually Based Models

- *Ideal* perceptually-based color model
  - Unit change in any axis anywhere results in a "just noticeable difference" (JND)
- CIELAB (CIE L*a*b*)
  - L* is lightness 0 (black) to 100 (diffuse white)
  - a*: magenta/red (-128±) to green (128±)
  - b*: blue/cyan (-128±) to yellow (128±)
- CIELUV (CIE L*u*v*) is a variant of CIELAB



Color usage guidelines (van Dam)

- **Do**
  - Use families of color to code related items
  - Use a progression of values to code an ordered set
  - Color code for accepted use in specific industry: red means often means stop, but in power industry means go (electricity flowing), In finance means money being lost…
- **Don't**
  - Use red and green for important color coding. Many people (10% men) red-green colorblind.
  - Use similar shades of green and blue for key differentiation. Often confused by viewers
  - Use adjacent small patches of different colors – they will just blend into each other
  - Use rainbow/spectral scale for ordinal coding: we have no sense of whether green is more or less than red…