Color & Graphics

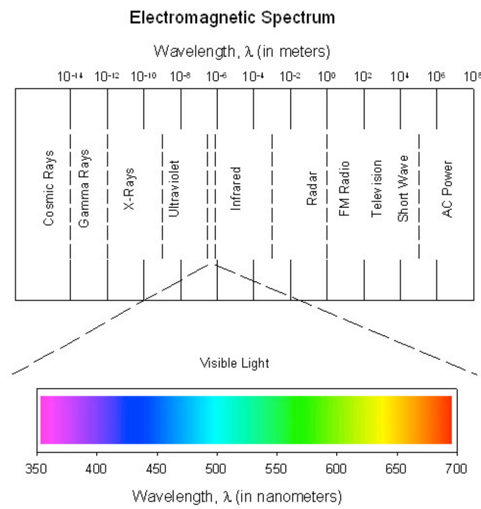
- The complete display system is:
  - Model
  - Frame Buffer
  - Screen
  - Eye
  - Brain

Color & Vision

- We'll talk about:
  - Light
  - Visions
  - Psychophysics, Colorimetry
  - Color
    - Perceptually based models
    - Hardware models

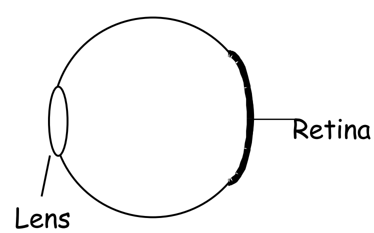
Light

- Vision = perception of electromagnetic energy
- Very small portion of EM spectrum is visible



Vision: The Eye

- A dynamic, biological camera!
  - a lens
  - a focal length
  - an equivalent of film



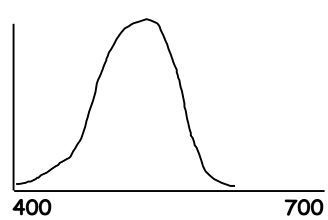
- The lens must focus directly on the retina for perfect vision

Vision: The Retina

- The eye's "film"
- Covered with cells sensitive to light
  - turn light into electrochemical impulses
- Two types of cells
  - rods
  - cones

Vision: Rods

- Sensitive to most wavelengths (brightness)
- About 120 million in eye
- Most outside of fovea (center of retina)
- Used for low light vision
- Absorption function:

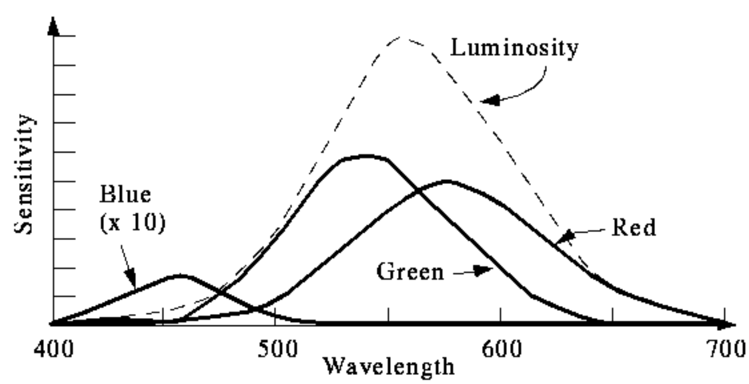


Vision: Cones

- Three kinds
  - R sensitive to long wavelengths
  - G to middle
  - B to short
- About 8 million in eye
- Highly concentrated in fovea
  - B cones more evenly distributed than others
- Used for high detail color vision

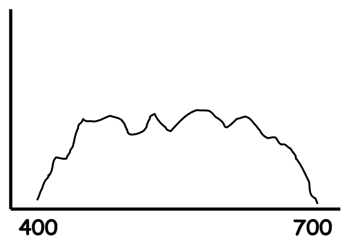
Vision: Cones

- The absorption functions of the cones are:



Psychophysics

- Spectral Energy Distribution
  - measure intensity of light at unit wavelength intervals of electromagnetic spectrum from ~400 nm to ~700 nm

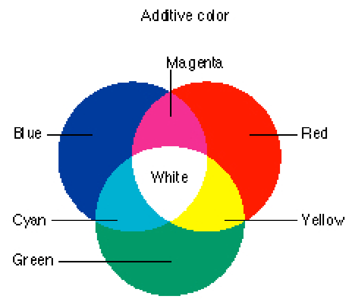


Psychophysics

- Dominant Wavelength ≅ hue
- Excitation Purity ≅ saturation
- Luminance ≅ intensity
  - Lightness: luminance from a reflecting object
  - Brightness: luminance from a light source
- To mix colors
  - mix power distributions!

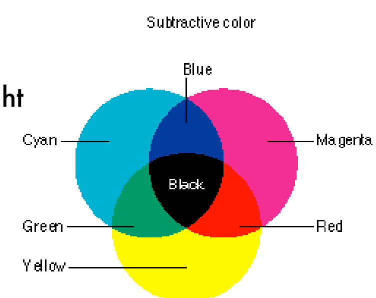
Color Mixing: Additive

- Luminous objects emit s.e.d.
- Linearly add s.e.d.'s
- Primaries: red green blue
- Complements: cyan magenta yellow
- e.g. Monitors, lights



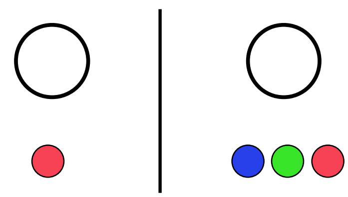
Color Mixing: Subtractive

- Reflective objects absorb (or filter) light
- Can't subtract s.e.d.'s
  - Filters: transmission functions
  - Pigment: suspension, scattering of light
- Primaries: cyan magenta yellow
- Complements: red green blue
- E.g., ink, film, paint, dye



Colorimetry

- Based on matching colors using additive color mixing

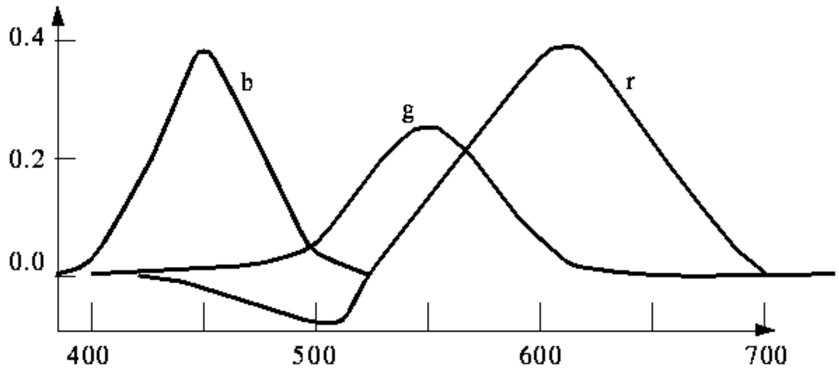


- Tristimulous Values
- Metamers
  - Different s.e.d.'s that appear the same
  - Same tristimulous values

Colorimetric Color Models

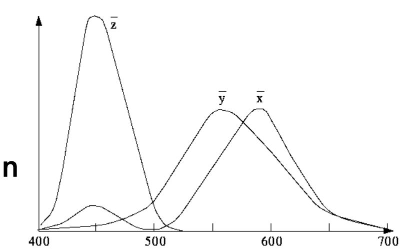
- Generated color match functions
  - match each wavelength, multiple people
  - some colors require negative red!
- CIE produced two device independent models:
  - 1931: Measured on 10 subjects (!) on samples subtending 2 (!) degrees of the field of view
  - 1964: Measured on larger number of subjects subtending 10 degrees of field of view

Color Match Functions



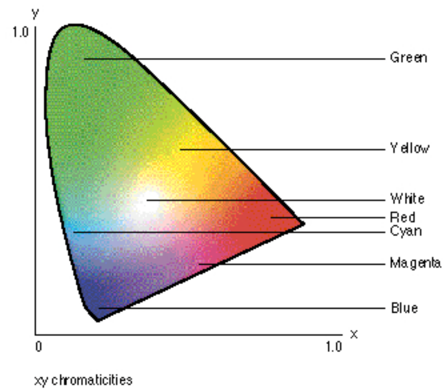
CIE 1931 Imaginary Primaries

- Defines three new primary "colors"
  - X, Y and Z
  - Mixtures positive valued
  - Y's fcn corresponds to luminance-efficiency function
- To define a color
  - weights x,y,z for the X,Y,Z primaries (e.g. color = xX + yY + zZ)



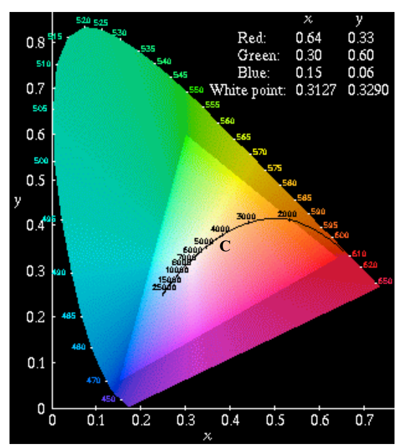
CIE 1931 Chromaticity

- X, Y and Z form a three dimensional color volume
  - Y is luminance, others aren't intuitive
- Factor luminance by normalizing x+y+z = 1
- *Chromaticity* values:
  - x' = x/(x+y+z)
  - y' = y/(x+y+z)
  - z' = 1 - x' - y'



CIE 1931 Chromaticity Diagram

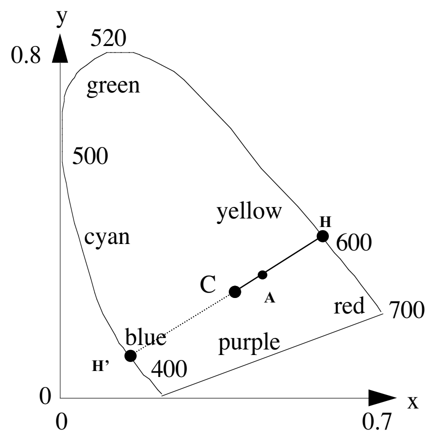
- Chromaticity diagram
  - Plot of x' vs. y'
- Additive color mixing
  - linear interpolation
- Color gamuts
  - range of possible colors for a device
  - convex hull of primary colors



C = standard illuminant, approximates sunlight

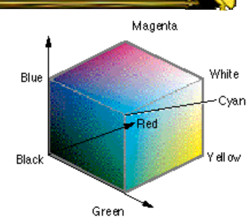
CIE 1931 Chromaticity Diagram

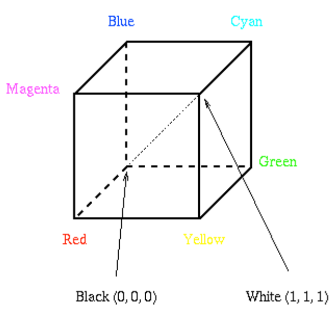
- Dominant Wavelength/Hue:
  - inscribe line from C through color (A) to edge of diagram (H)
- Saturation
  - distance C-A / distance C-H
- Complements
  - inscribe line through C to the edge of the diagram (H')
- What if edge is bottom?



Hardware Models: RGB (Additive Color)

- (red, green, blue)
- Parameters vary between 0 and 1





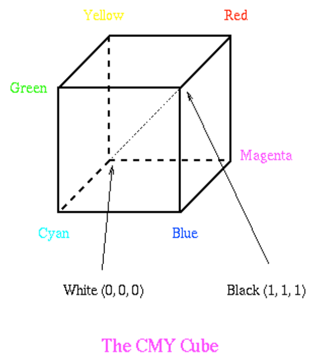
The RGB Cube

Hard to achieve intuitive effects:

- Hue is defined by the one or two largest parameters
- Saturation controlled by varying the collective minumum value of R, G and B
- Luminance controlled by varying magnitudes while keeping ratios constant

Hardware Models: CMY, CMYK (Subtractive Color)

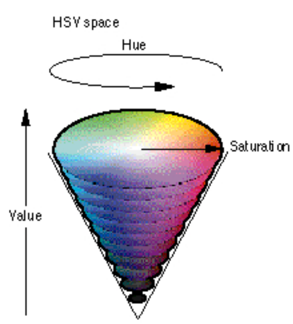
- (cyan, magenta, yellow, +blacK)
- All parameters vary between 0 and 1



- K = min (C,M,Y)
- subtract K from each

Intuitive Hardware Models: HSV

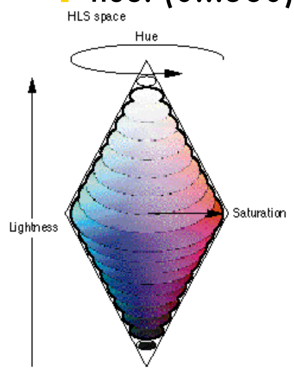
- (hue, saturation, value)
  - value roughly luminance
  - hue: (0...360), saturation/value: (0...1)



- Simple xform of RGB
- What do hexagonal and triangle cross sections look like?

Intuitive Hardware Models: HLS

- (hue, lightness, saturation)
  - lightness roughly luminance
  - hue: (0...360), saturation/value: (0...1)



- saturated colors at l=0.5
- *tints* above, *shades* below
- What do hexagonal and triangle cross sections look like?

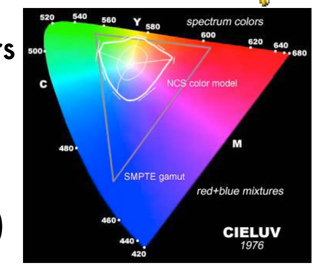
Problem: V/L != Luminance

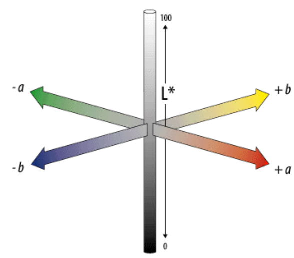
- Fully saturated colors (same v/l) have far different Y values in XYZ (Sun 17" monitor, 1991):

Colour	RGB	XYZ	Chromaticity
White	1 1 1	0.951 1.000 1.088	0.313 0.329
Red	1 0 0	0.589 0.290 0.000	0.670 0.330
Green	0 1 0	0.179 0.605 0.068	0.210 0.710
Blue	0 0 1	0.183 0.105 1.020	0.140 0.080
Cyan	0 1 1	0.362 0.710 1.088	0.168 0.329
Magenta	1 0 1	0.772 0.395 1.020	0.363 0.181
Yellow	1 1 0	0.768 0.895 0.068	0.444 0.517

Problem: None of these models are perceptually uniform

- Perceived distance between two colors not proportional to linear distance
- Uniform Color Spaces
  - Non-linear deformations
  - OSA Uniform Color Space (limited range)
  - CIELUV
  - CIELAB





Issue: Device-independent color

- Must use CIEXYZ
  - ie. Apple Colorsync
- RGB = (0.3,0.2,0.55) tells you what computer generates, not what the monitor will display!
  - Depends on phosphors, room lighting, monitor adjustment
- Moving between devices (and media)
  - Go through XYZ
  - Must know properties of devices