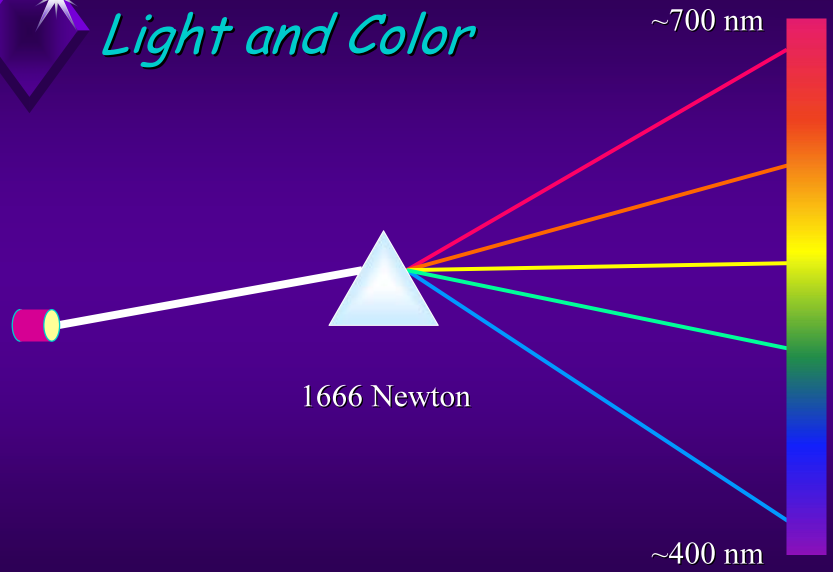
Introduction to:

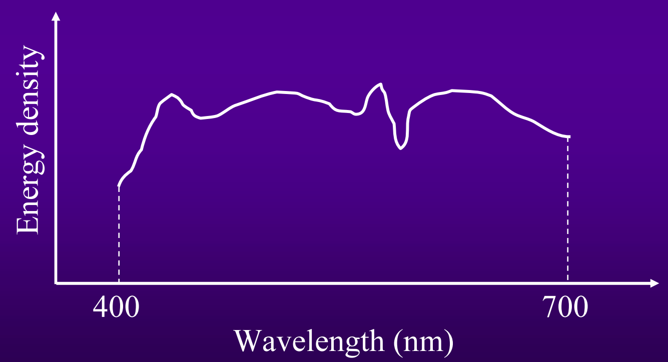
Color

- The physical nature of color.
- The perception of color.
- Color matching and reproduction.
- Common color spaces.

Light and Color

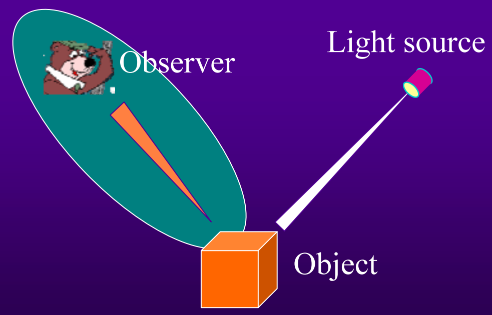


Typical spectral energy distribution of a light:

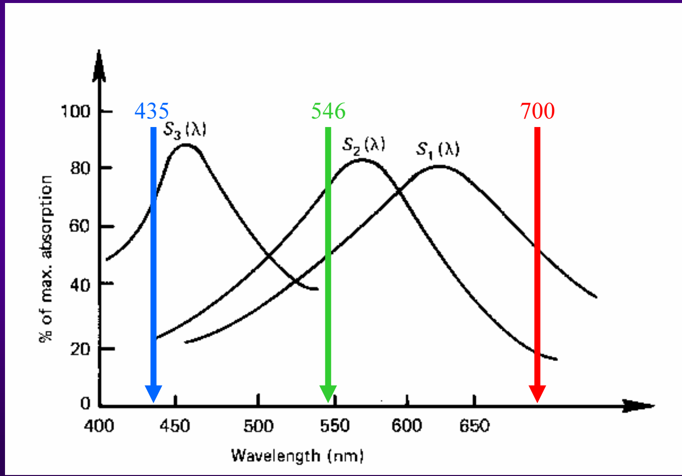


What is color to a human?

- Color is our ***perceptual*** sensation of light in the visible range (~400..700 nm) incident upon the retina.



Human Visual System Response to Color



Cone Responses:

$$red(C) = \int_{\lambda\min}^{\lambda\max} S_1(\lambda)C(\lambda)d\lambda$$

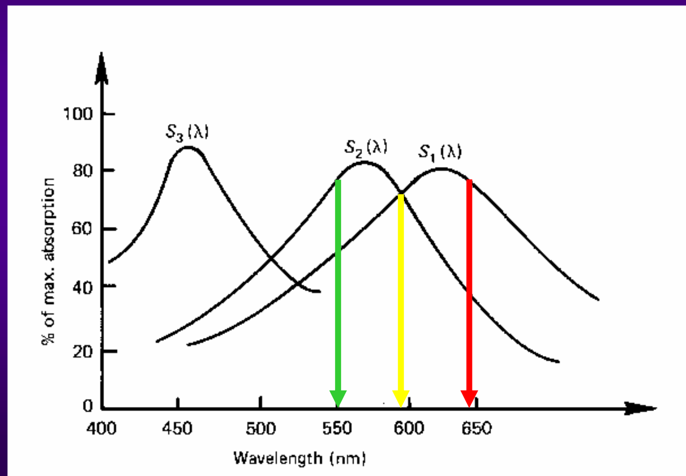
$$green(C) = \int_{\lambda\min}^{\lambda\max} S_2(\lambda)C(\lambda)d\lambda$$

$$blue(C) = \int_{\lambda\min}^{\lambda\max} S_3(\lambda)C(\lambda)d\lambda$$

Metamers and Color Matching

- Two light sources (emitting or reflecting) with *spectral energy densities* of C_1 and C_2 will have the same perceived color if:
  - *Red(C_1) = Red(C_2)*
  - *Green(C_1) = Green(C_2)*
  - *Blue(C_1) = Blue(C_2)*
- C_1 is called a *metamer* of C_2

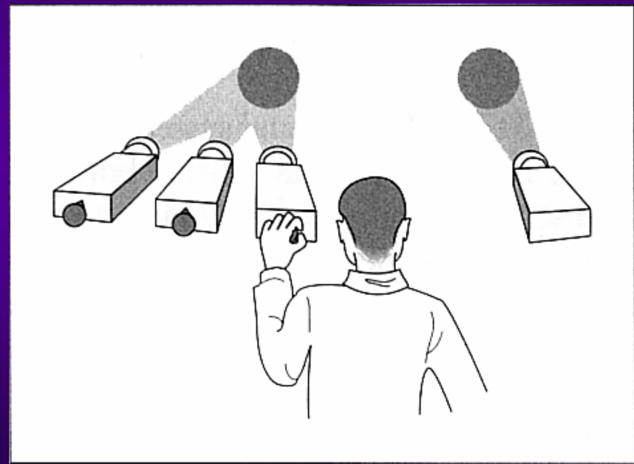
Possible causes of "yellow" perceived color:



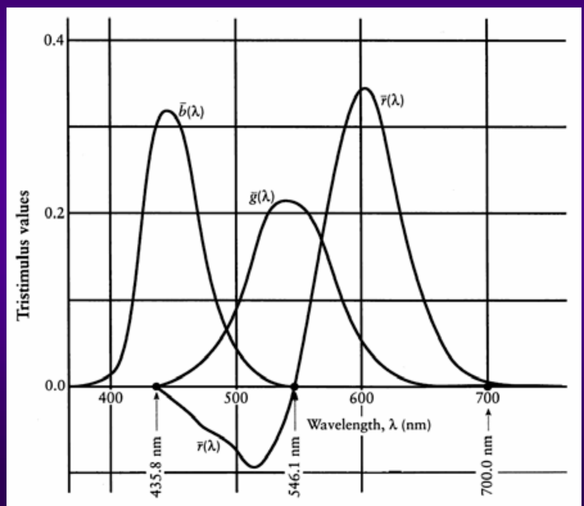
Color Spaces

- CIE - RGB space.
- CIE - XYZ space.
- HSV space.
- L*a*b* space.
- YUV, YIQ
- CMY, CMYK

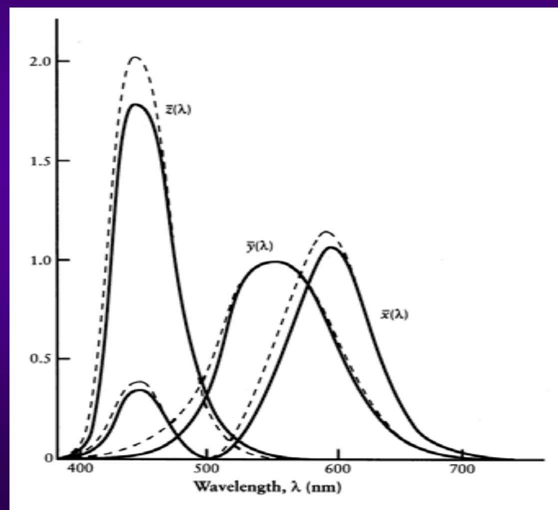
The CIE Color Matching Experiment:



CIE-RGB Matching Functions:



The CIE-XYZ Matching Functions:



From Spectrum to XYZ:

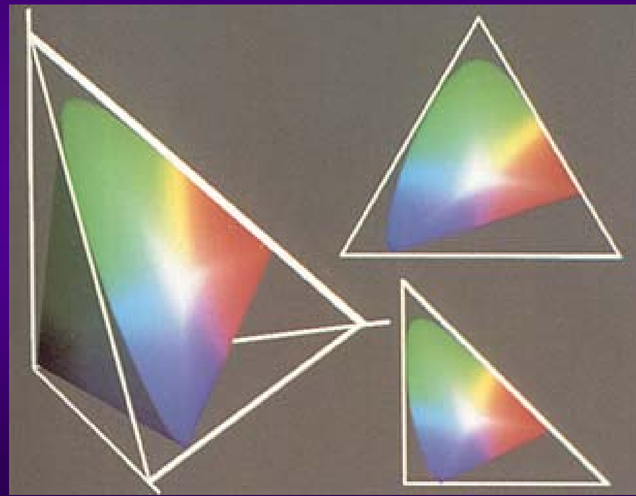
$$X(C) = k \int_{\lambda \min}^{\lambda \max} x(\lambda) C(\lambda) d\lambda$$

$$Y(C) = k \int_{\lambda \min}^{\lambda \max} y(\lambda) C(\lambda) d\lambda$$

$$Z(C) = k \int_{\lambda \min}^{\lambda \max} z(\lambda) C(\lambda) d\lambda$$

$$k = \frac{100}{\int_{\lambda \min}^{\lambda \max} y(\lambda) W(\lambda) d\lambda}$$

The CIE XYZ Color Space



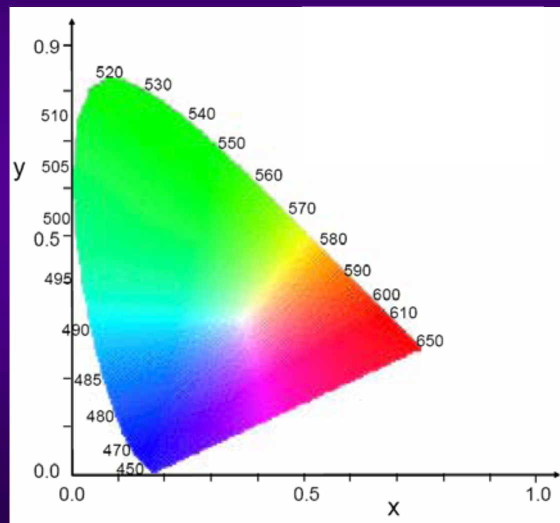
Color Chromaticity

- The chromaticity of a color is defined as:

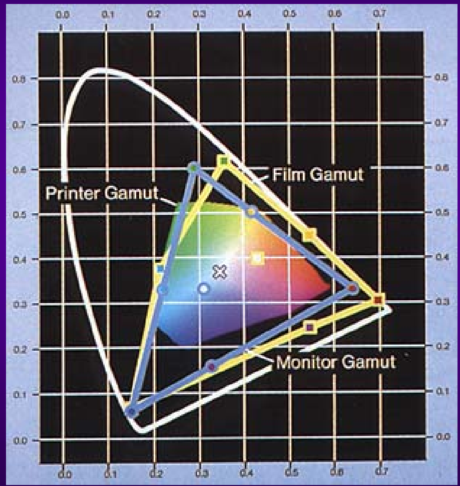
$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}$$

- Since z = 1-x-y, only two components are needed to describe the hue and saturation.
- The original XYZ triplet can be restored from x,y, and Y: $X = \frac{x}{y} Y, \quad Y = Y, \quad Z = \frac{z}{y} Y$

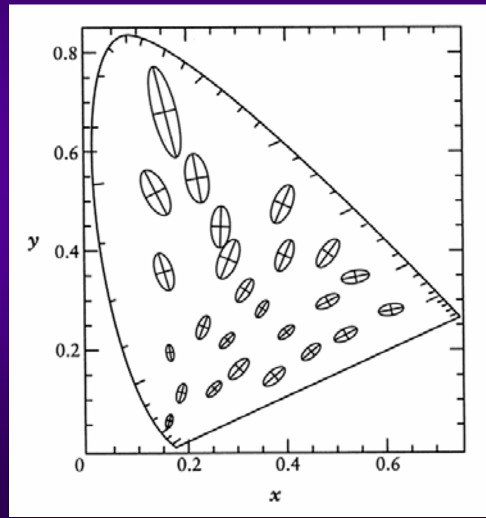
CIE Chromaticity Diagram



Color Gamuts



XYZ Non-Uniformity



L*a*b* Space

- Non-linear model.
- More perceptually uniform then CIE-XYZ : ellipses are much closer to circles. As a result, Euclidean distance is useful.
- L* - Lightness.
- a* - Red-green content.
- b* - yellow-blue content.

L*a*b* Space

$$L^* = 116\left(\frac{Y}{Y_0}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right]$$

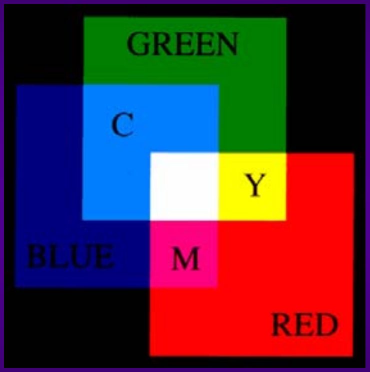
$$b^* = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

X_0, Y_0, Z_0 are reference white tri-stimulus values.

Hardware-Oriented Color Spaces

- RGB - mainly for use with color CRT and LCD monitors
- YIQ - for use in the broadcast TV (NTSC) color system
- CMY(K) - used in many color printers

Additive Color Space: RGB



- There is a linear transformation (3x3 matrix) to convert between RGB and XYZ

RGB to XYZ conversion

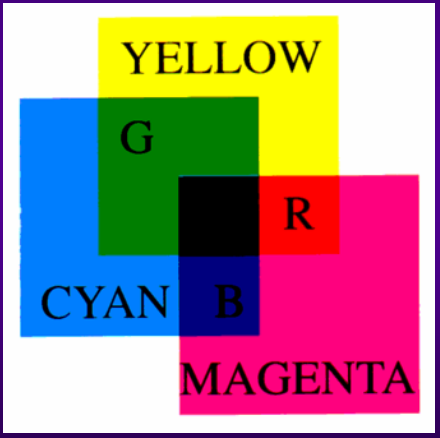
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_r C_r & x_g C_g & x_b C_b \\ y_r C_r & y_g C_g & y_b C_b \\ z_r C_r & z_g C_g & z_b C_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- where x,y,z of r, g, and b are the chromaticities of the red, green, and blue phosphors, and $C_r = X_r + Y_r + Z_r$

$$C_g = X_g + Y_g + Z_g$$

$$C_b = X_b + Y_b + Z_b$$

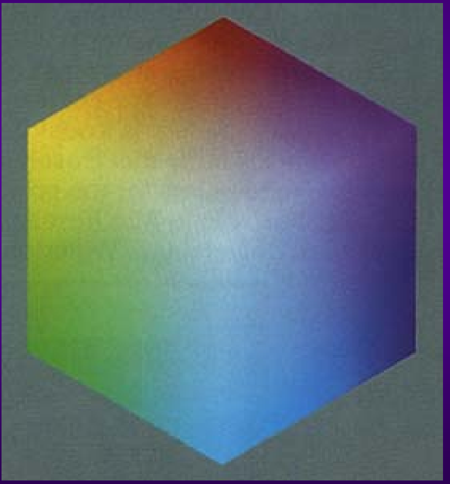
Subtractive Color Space: CMY



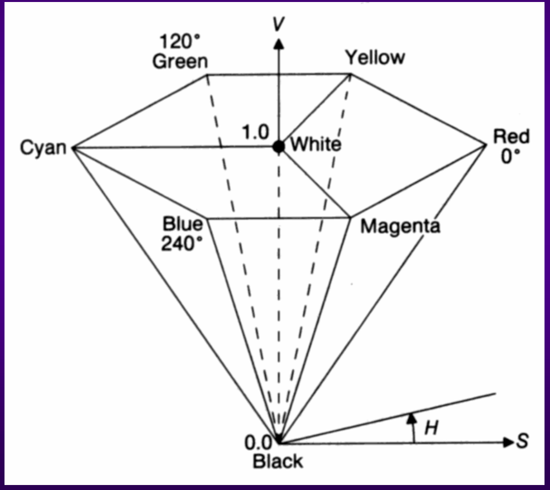
CMYK

- Replace as much of the (C,M,Y) color as possible by black ink:
  - K := min(C,M,Y)
  - C := C - K
  - M := M - K
  - Y := Y - K
- The substitution improves contrast, and saves colored ink.

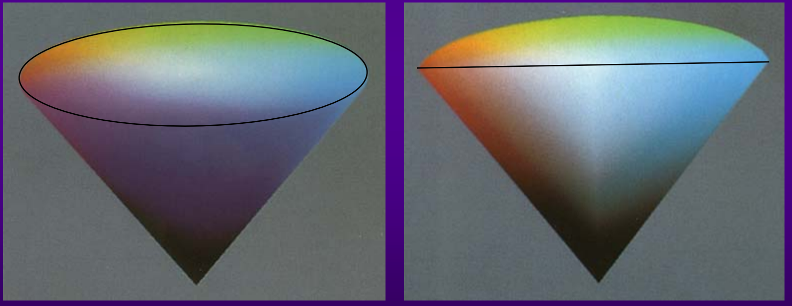
The RGB Color Cube:



The HSV Color Cone:



The HSV Color Cone



RGB to HSV

- Min = min(r,g,b); V = max(r,g,b);
- if (V > 0) then S = (V - Min)/V;
- else { S = 0; H = Undefined; }
- if (r == V) then H = (g - b)/(V - Min)
- if (g == V) then H = 2 + (b - r)/(V - Min)
- if (b == V) then H = 4 + (r - g)/(V - Min)
- H = H * 60
- if (H < 0) then H = H + 360

Color Picking User Interfaces: