COSE436

Lecture 13: Colors

Oct 24, 2024

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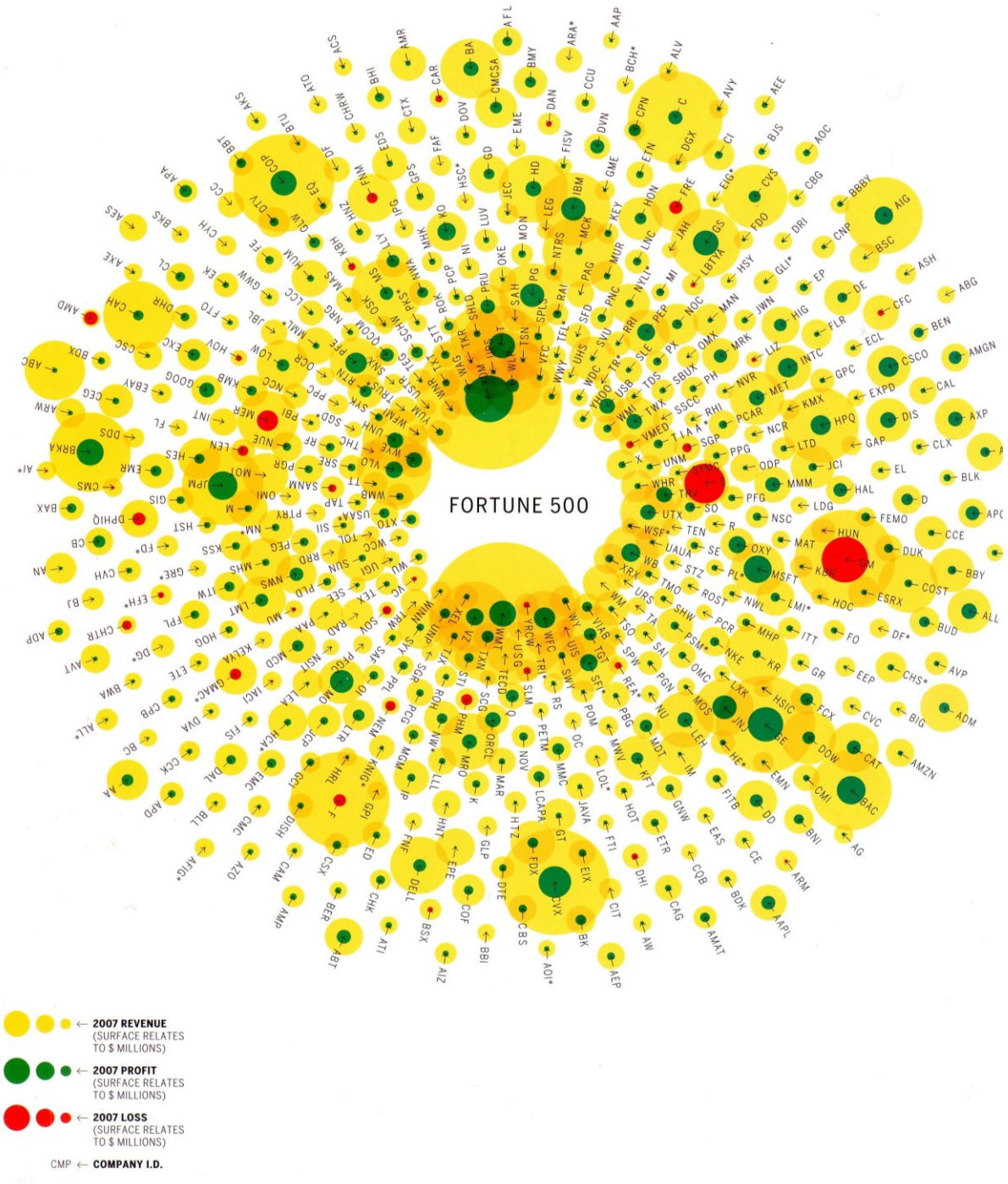
Outline

- Properties of light and colors
- Color models



catalogtree, fortune 500

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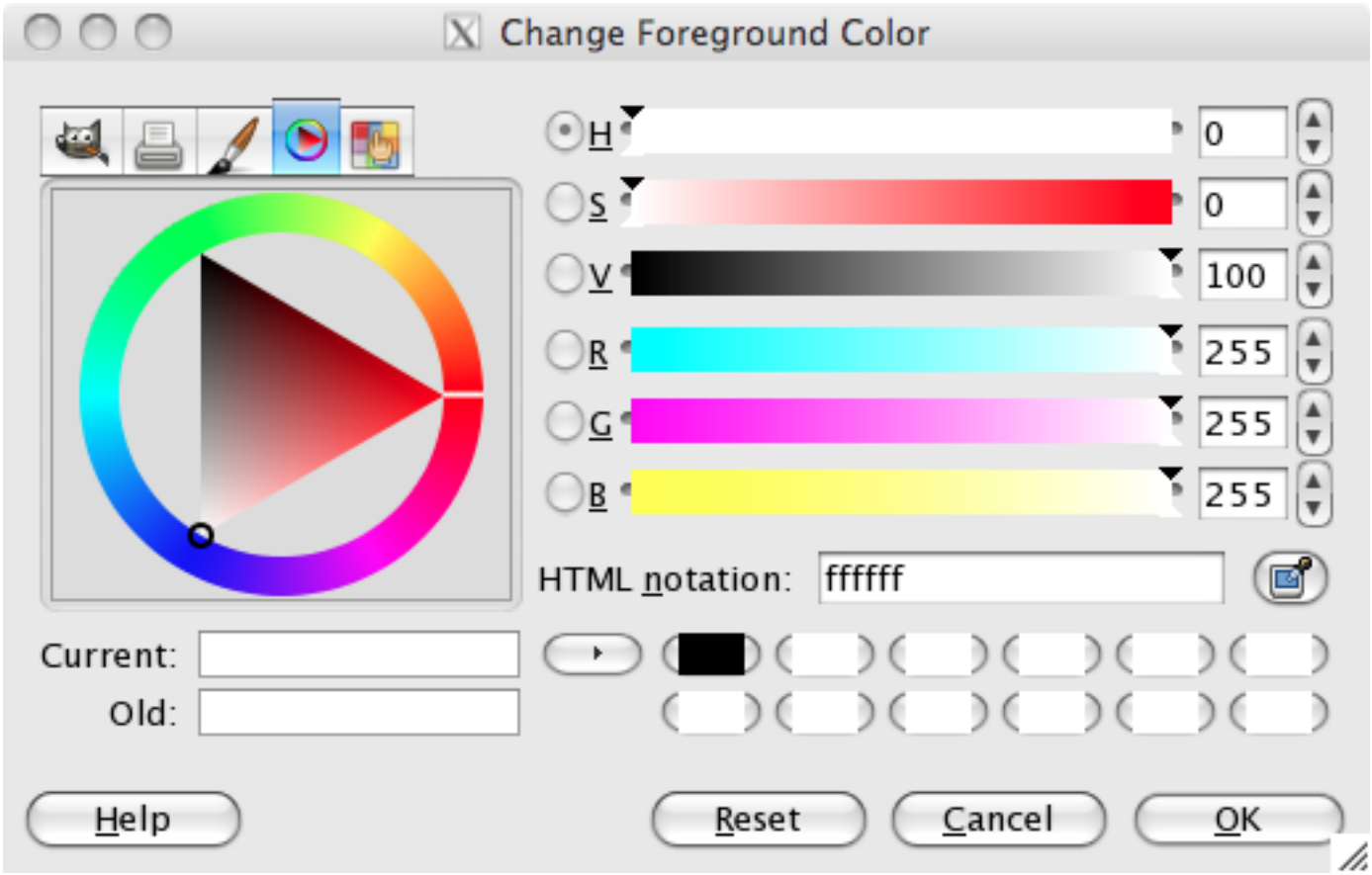

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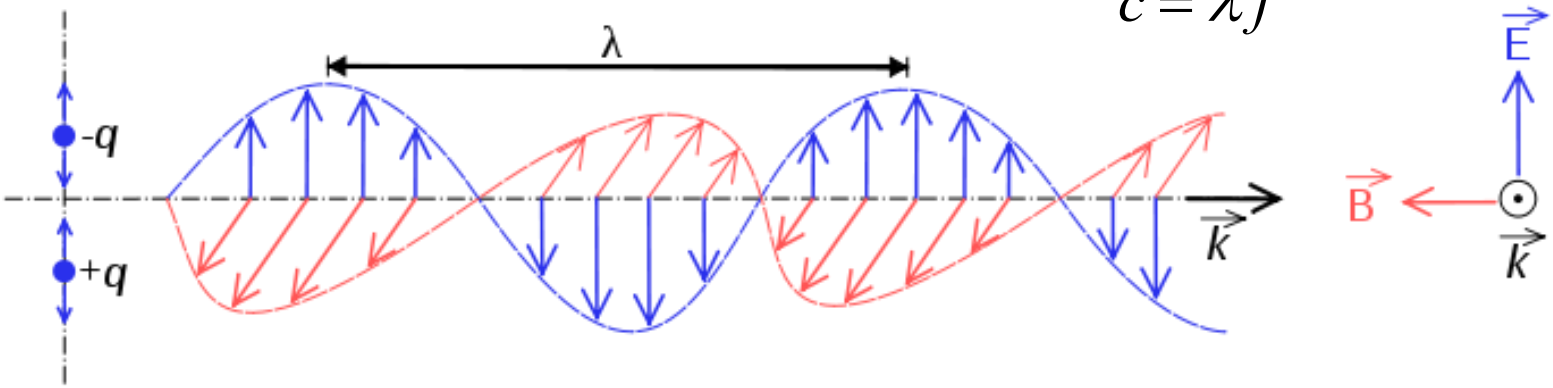
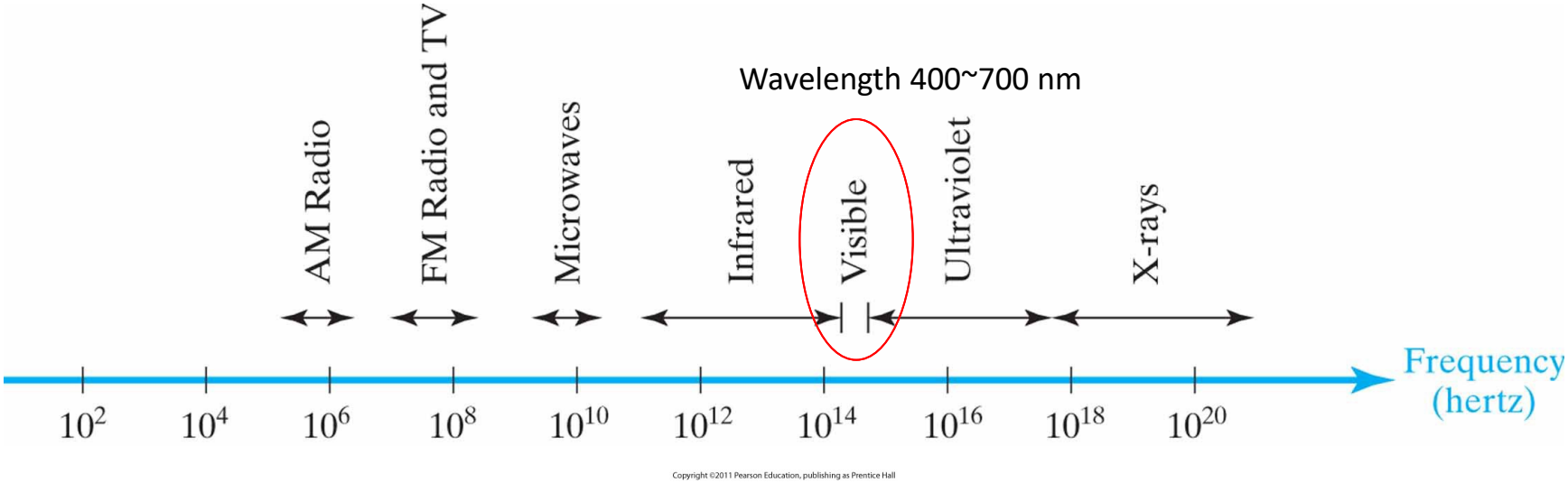
Electromagnetic Spectrum

$$c = \lambda f$$





λ : wavelength, f : frequency, c : speed of light
Wavelength unit is easier to use for visible spectrum.
We use wavelength in vacuum.

Image courtesy of Hearn

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Spectral Color

- Each frequency (wavelength) in visible spectrum corresponds to a single color

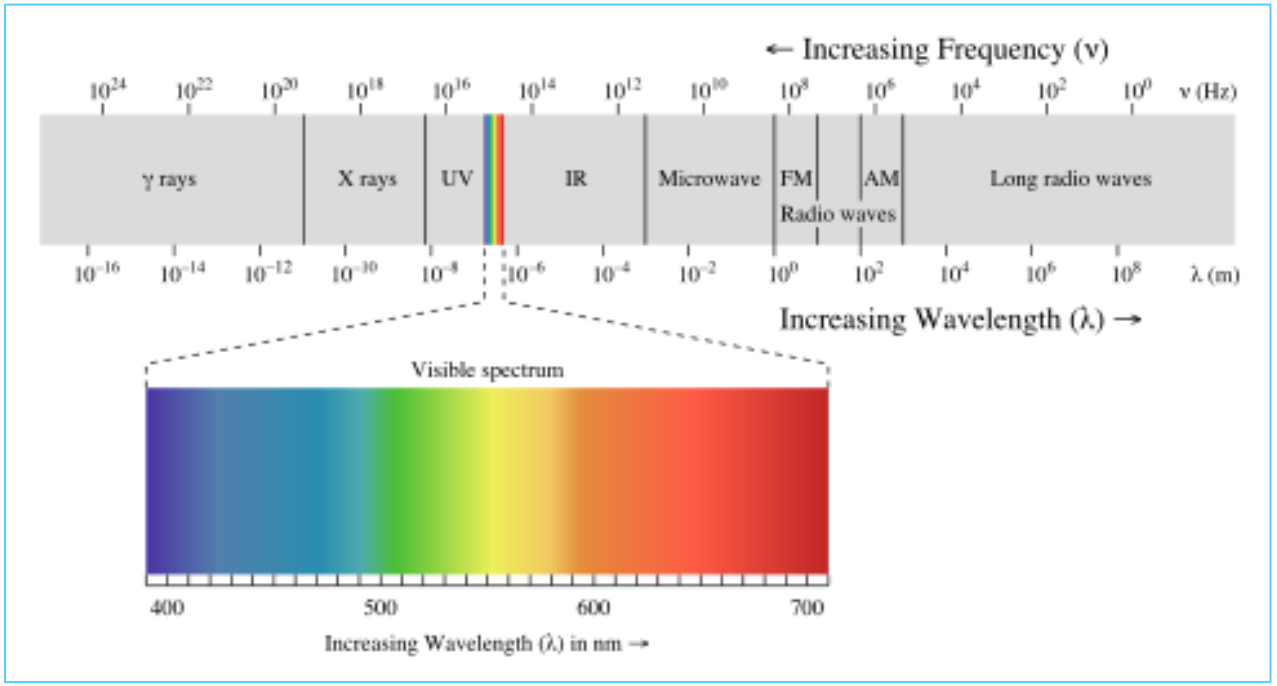
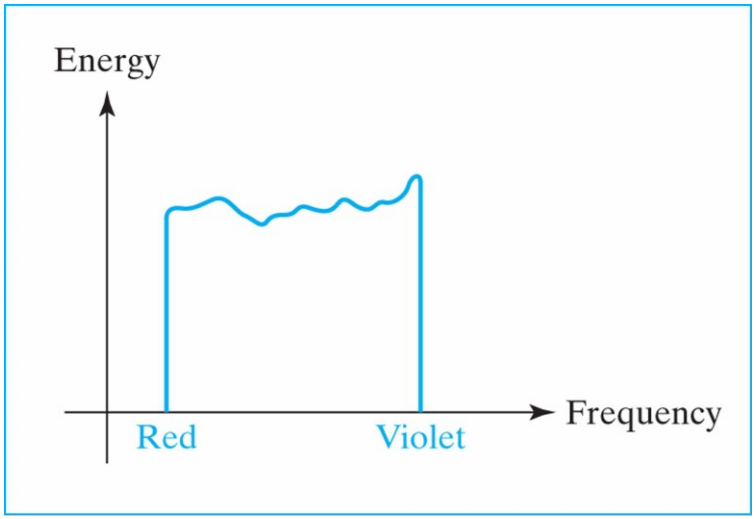


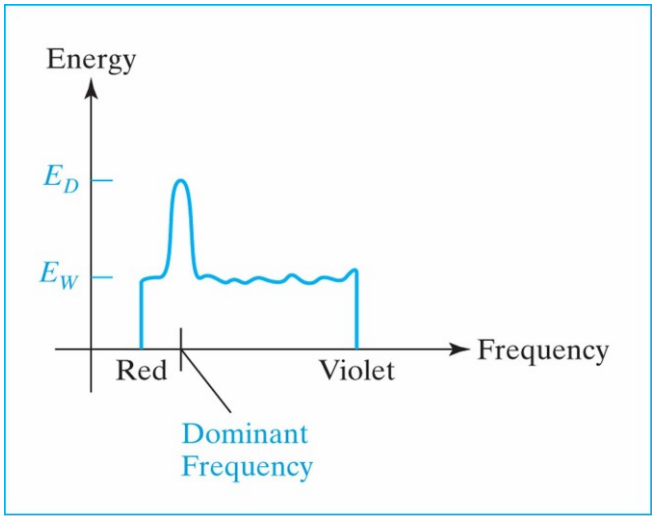
Image courtesy of Hearn

Color of Light

- Light source emits all frequencies within visible range
- Dominant frequency determines the color of light



white light



red light

Image courtesy of Hearn

Color Characteristics

- Hue (color)
  - Dominant frequency
- Brightness (luminance)
  - Total energy of the light
- Saturation (purity)
  - How close to a pure spectral color
- Chromaticity
  - Hue & Saturation

Color Characteristics

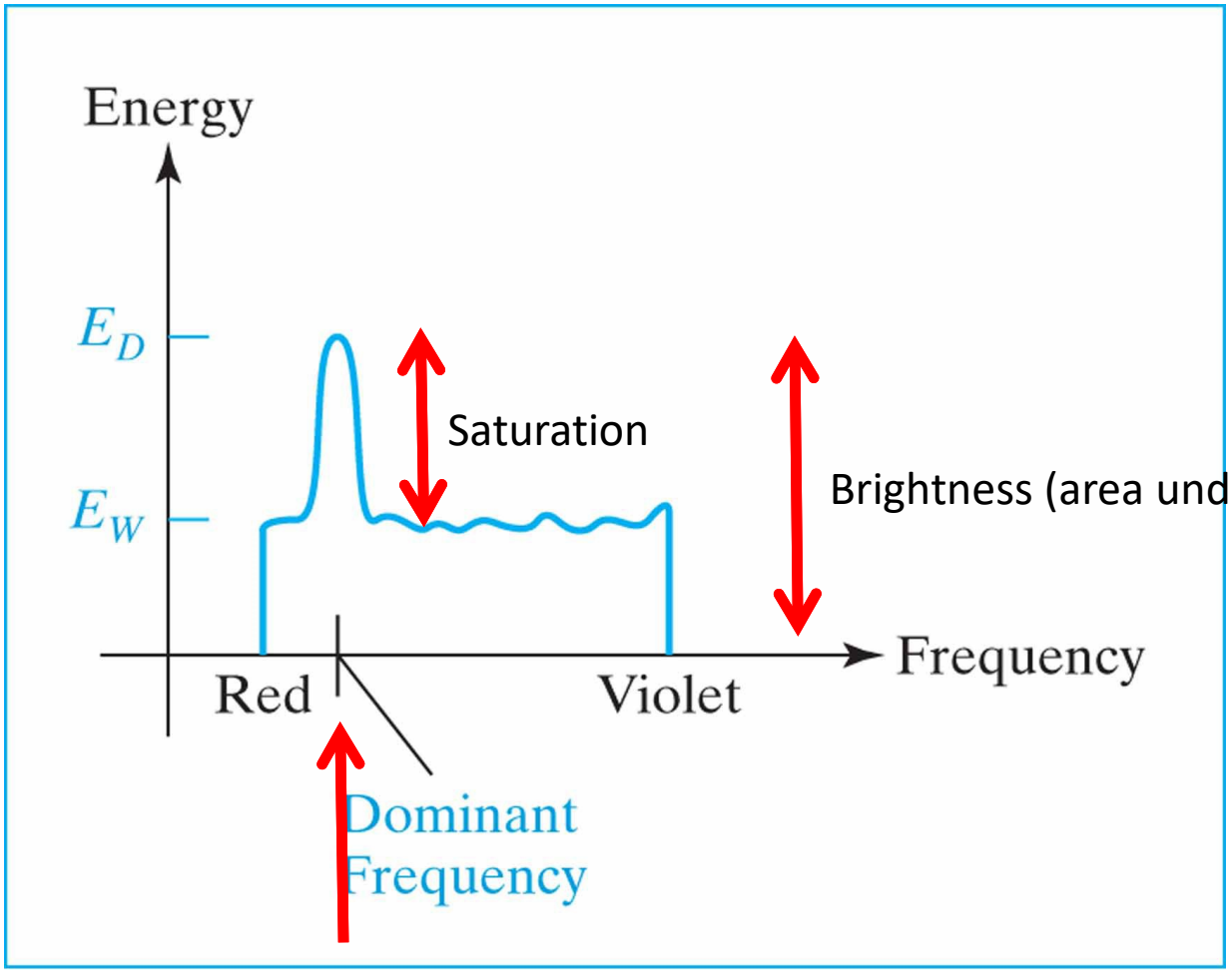


Image courtesy of Hearn

Perceiving Colors

- Interaction between light and materials
  - Reflection
    - Red apple reflects red spectrum of light
  - Transmission
    - Green glass transmits green spectrum of light
- Photoreceptors in the eye
  - Retina (rods & cones)

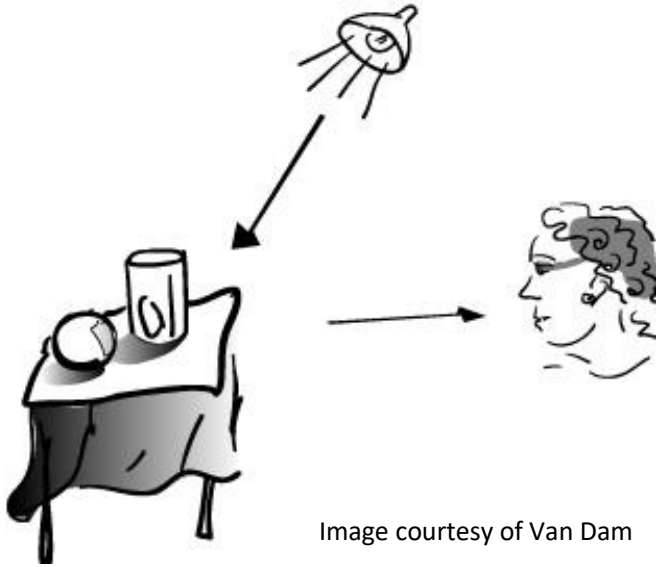
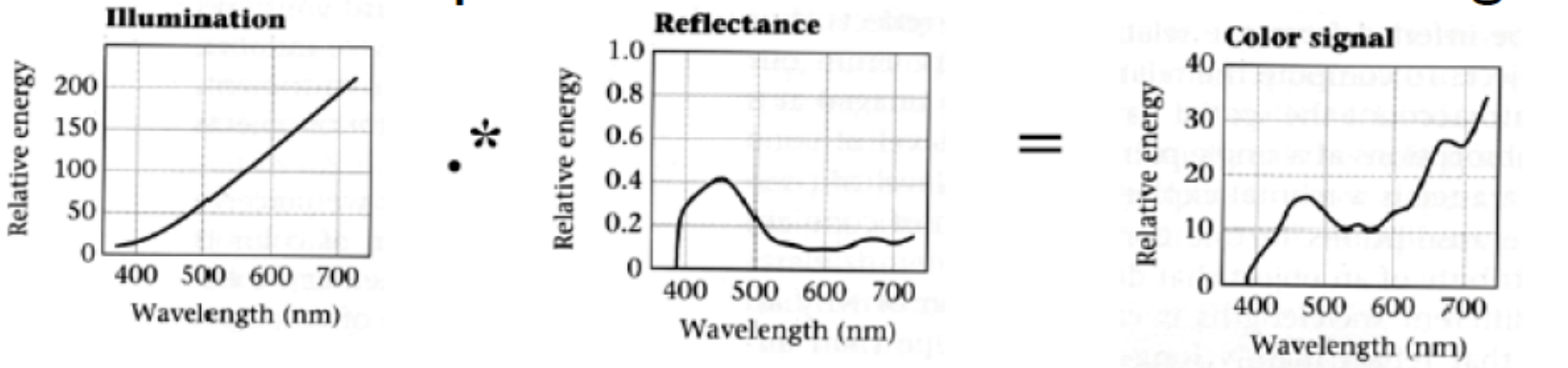


Image courtesy of Van Dam

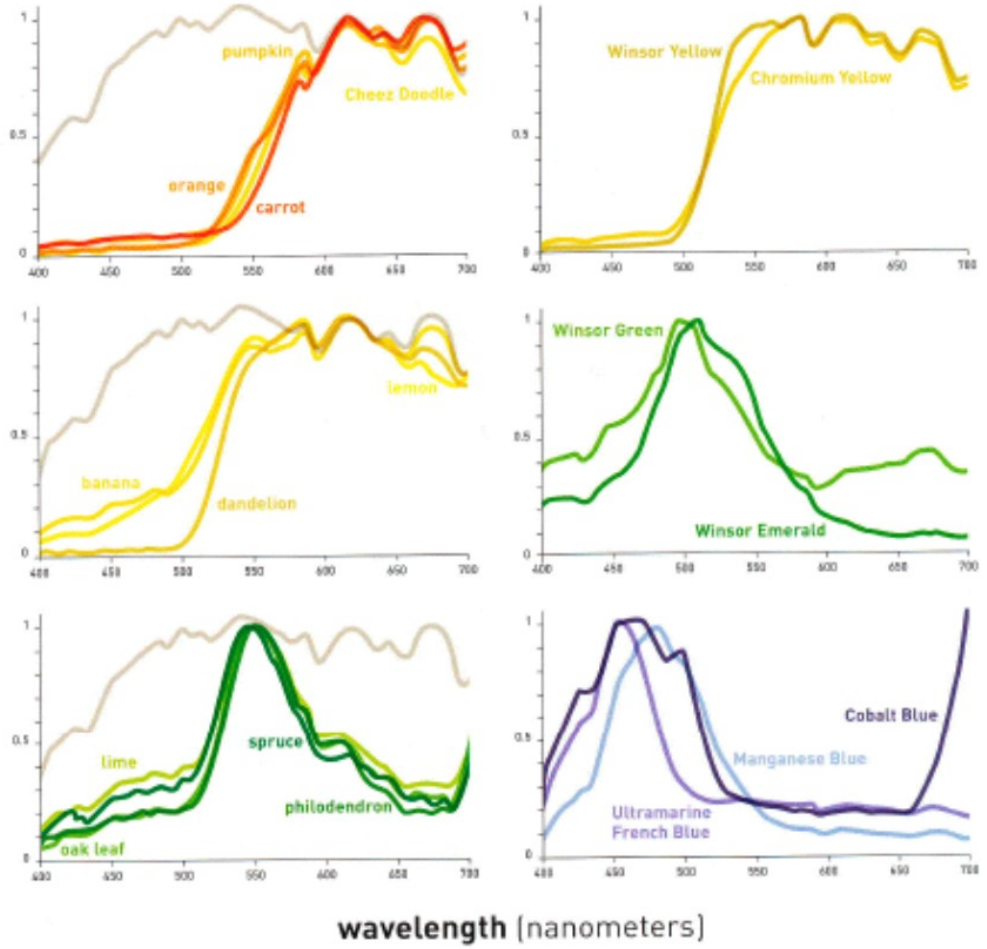
Reflectance Spectra

Wavelength-by-wavelength Multiplication

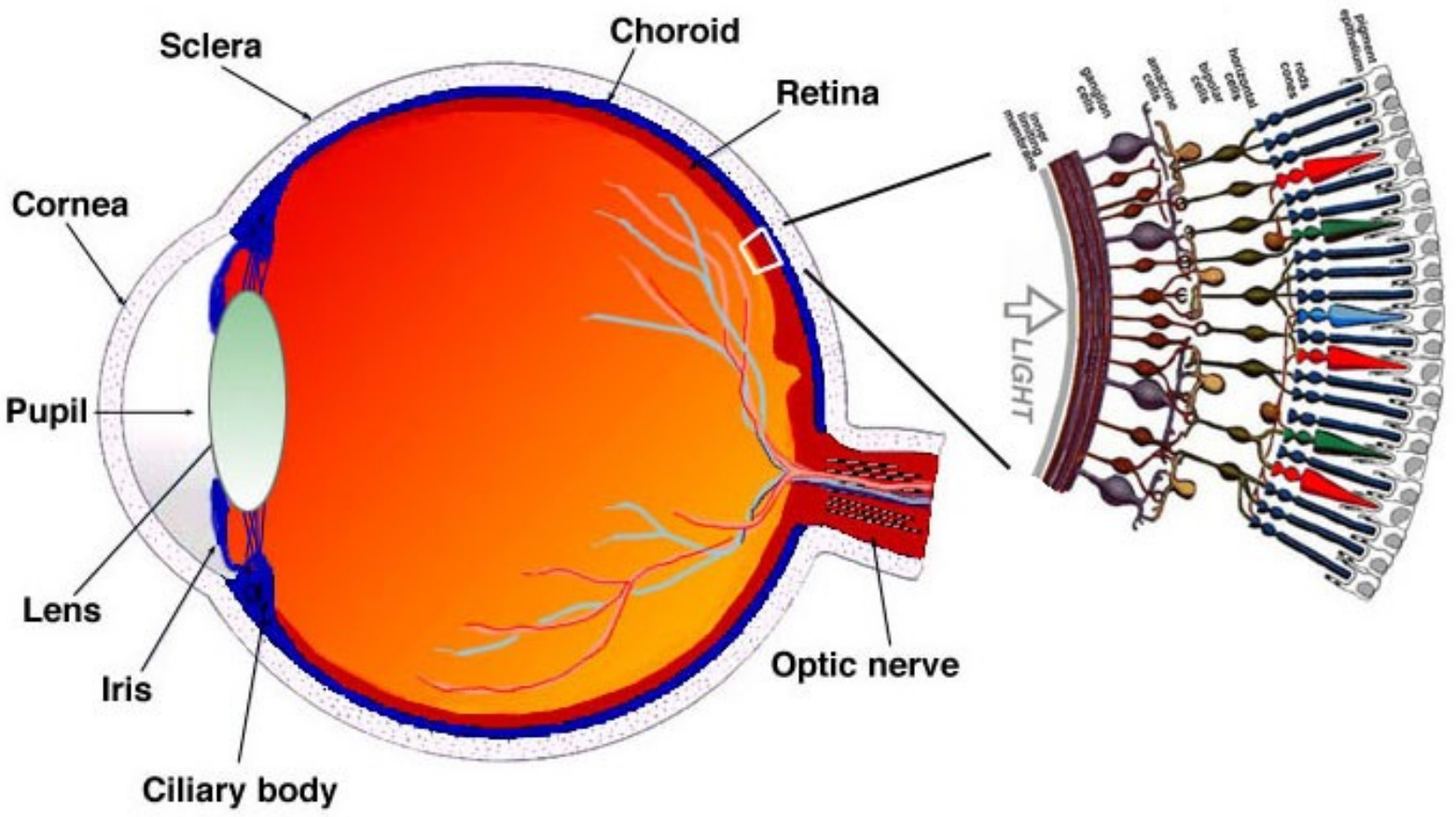
Spectrum of Reflected Light



Reflectance Spectra

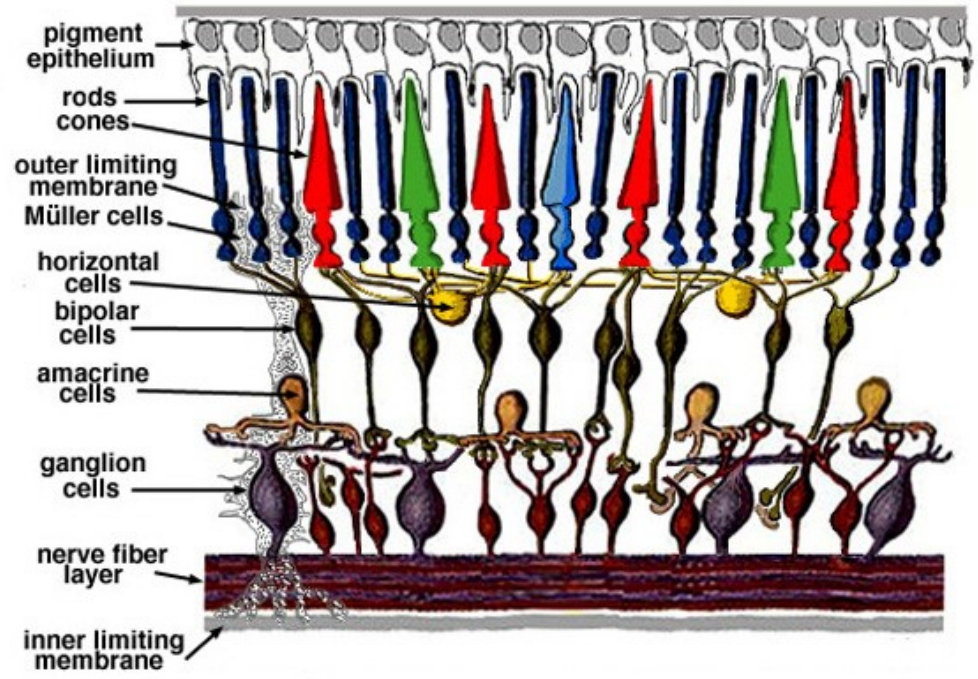


The Eye

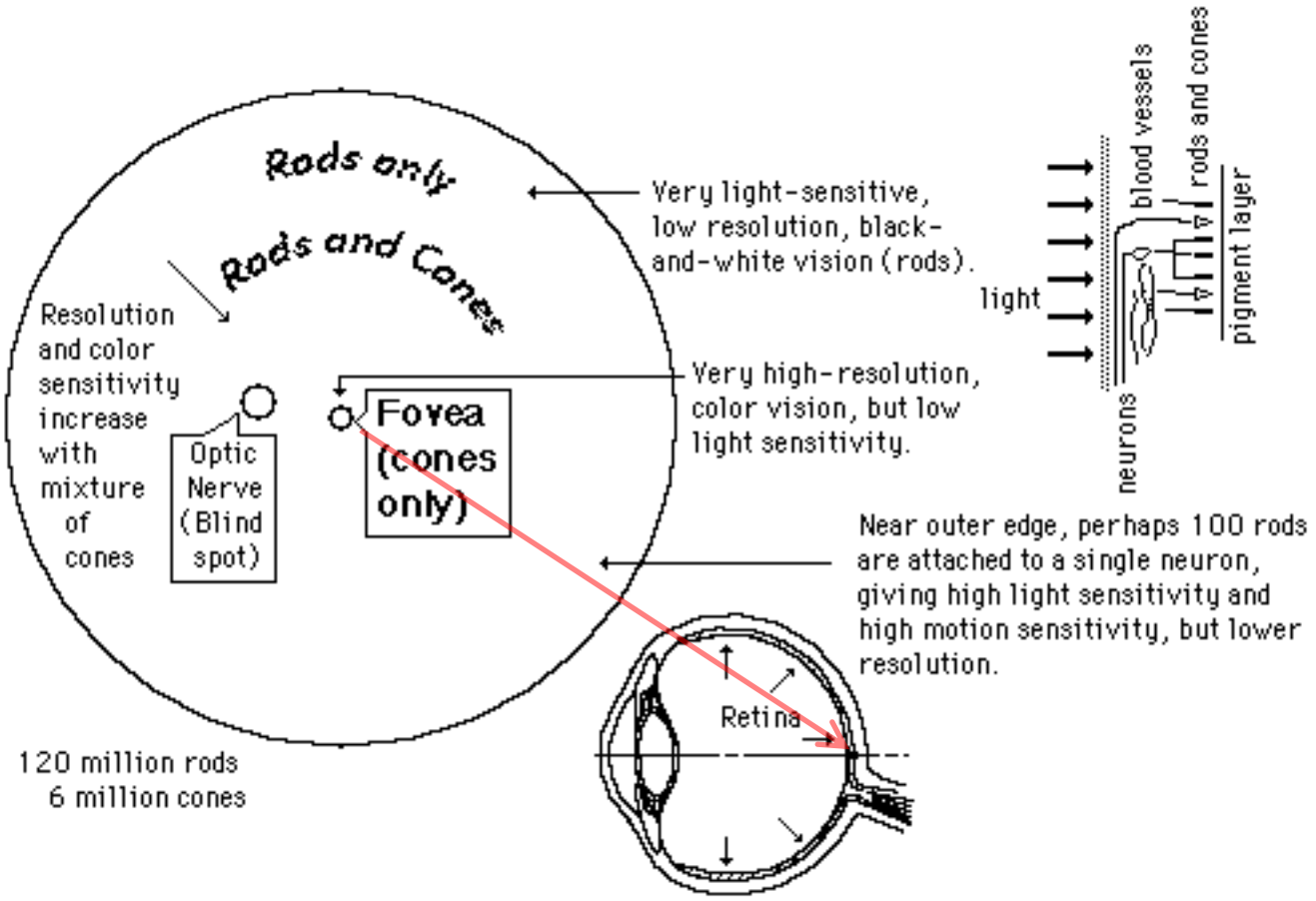

Sclera
Choroid
Retina
Cornea
Pupil
Lens
Iris
Ciliary body
Optic nerve
LIGHT

Rods and Cones

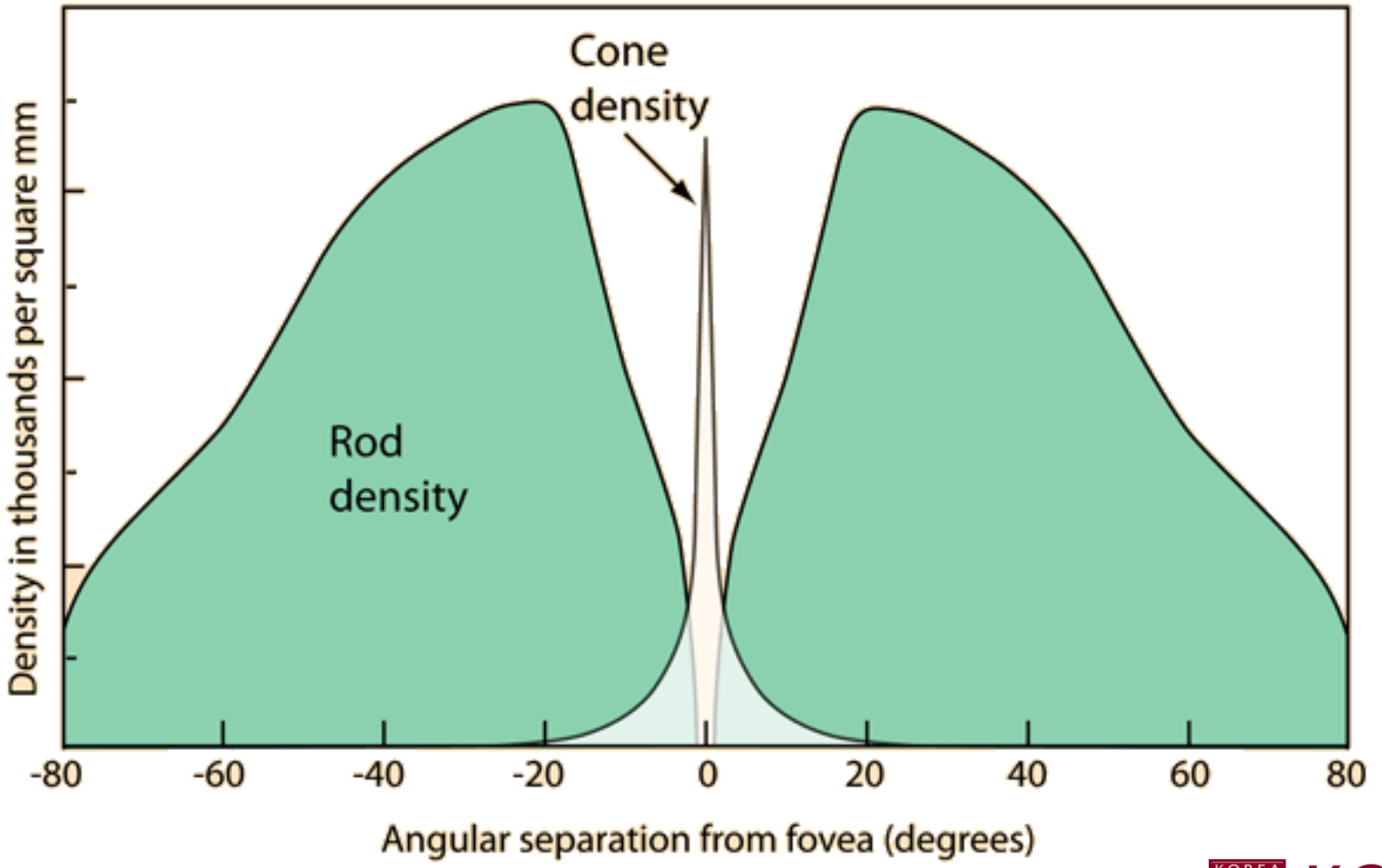
- Rods
  - 120 million cells
  - Monochromatic, night vision
- Cones
  - 6~7 million cells
  - Color sensitive
  - Three types of cones
    - Red (64%)
    - Green (32%)
    - Blue (2%)



The Retina



Rod and Cone Density

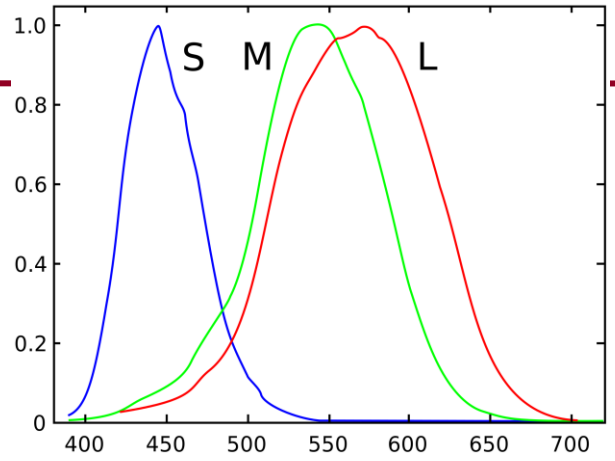


http://hyperphysics.phy-astr.gsu.edu

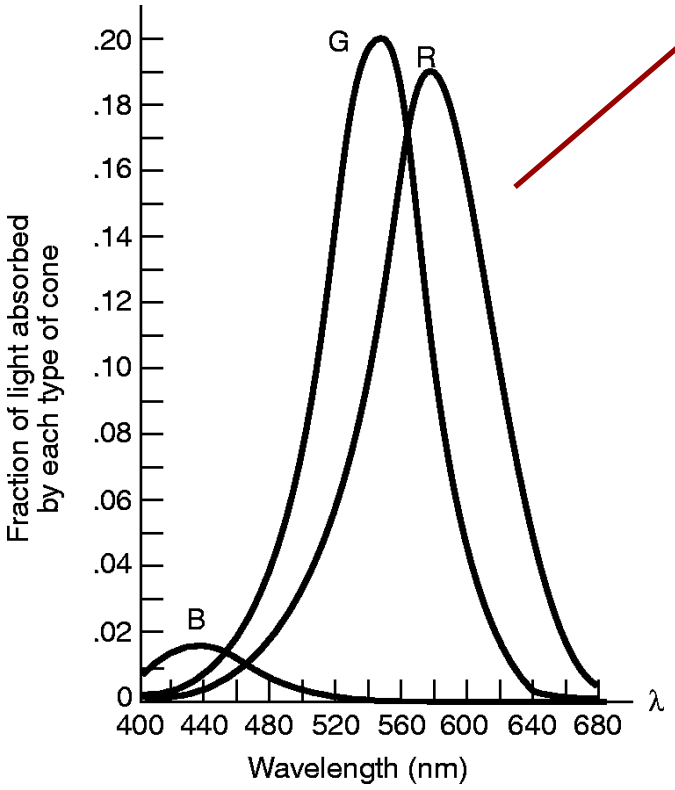
Primary Colors

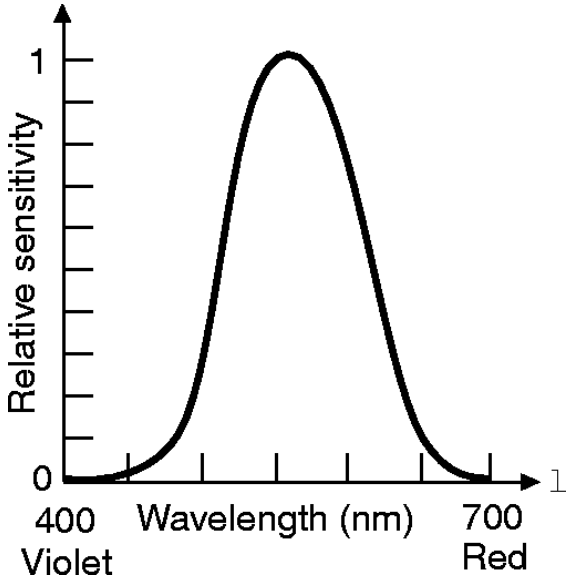
- Tristimulus theory
  - Three types of cone

Short, Middle, Long wavelength types



Normalization





Luminous-Sensitivity of human eye

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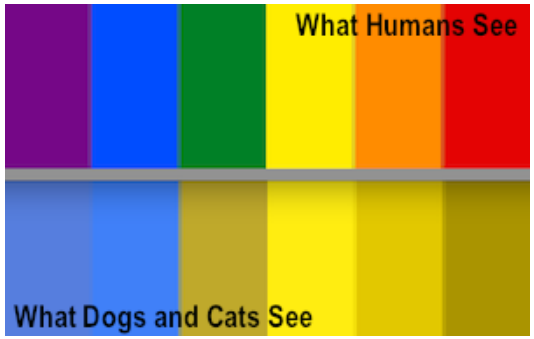
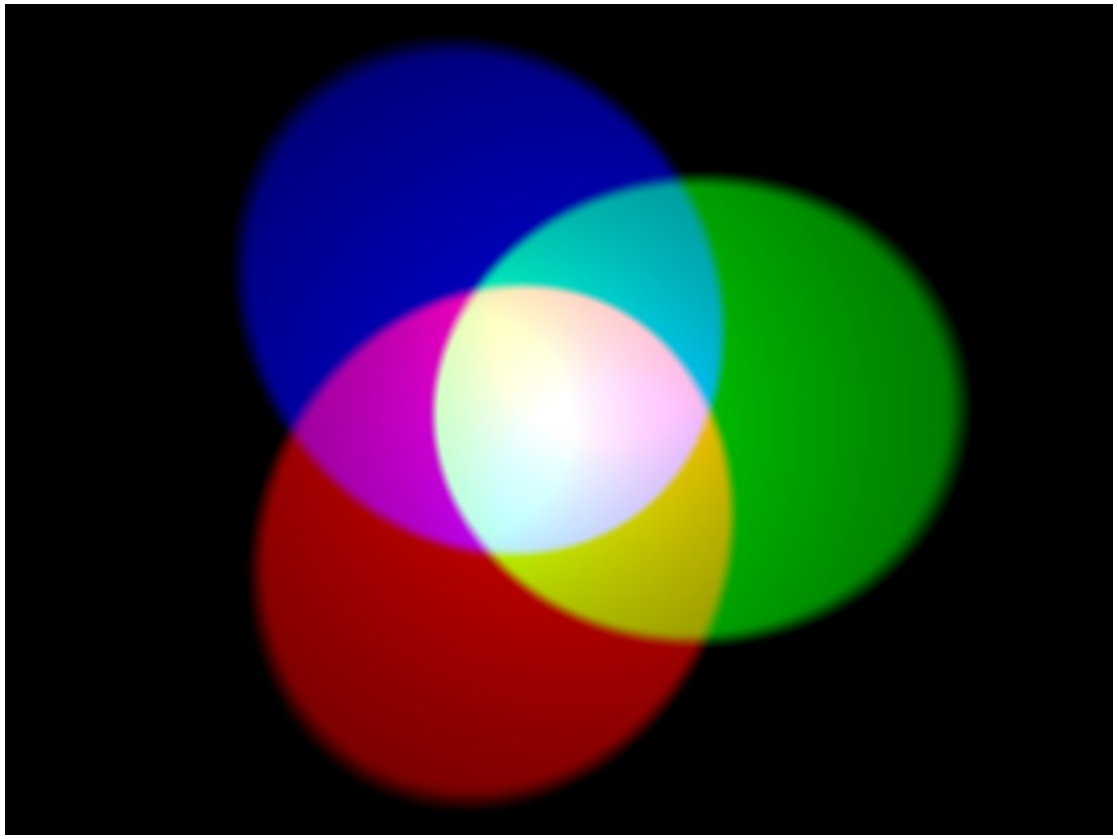
Hunters vs. Gatherer



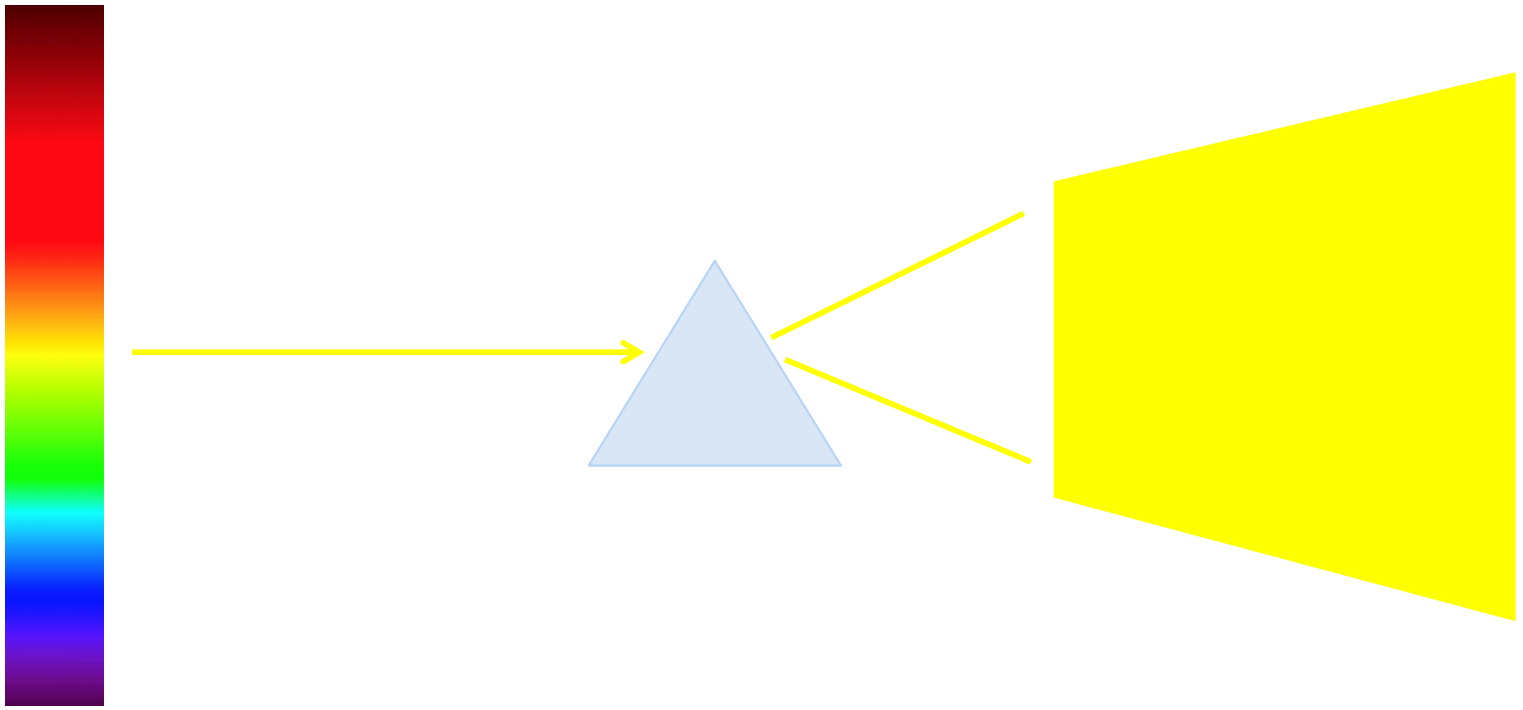
Color Mixing

- Yellow = Red + Green



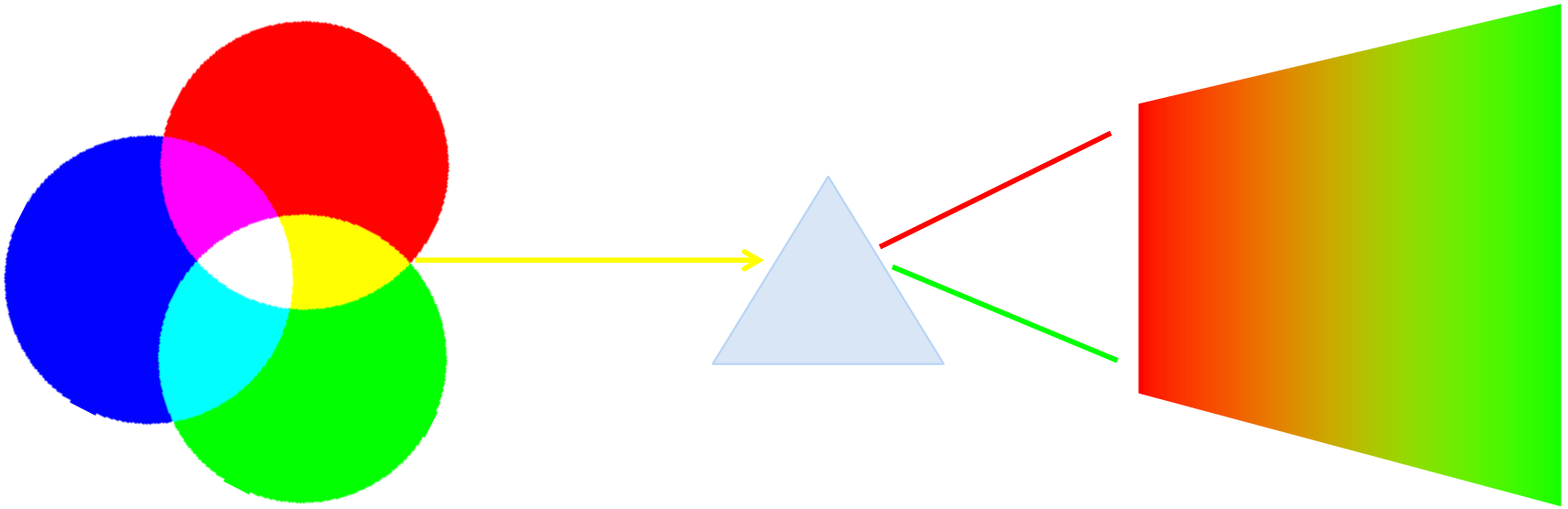
Color Mixing

- Spectral Yellow



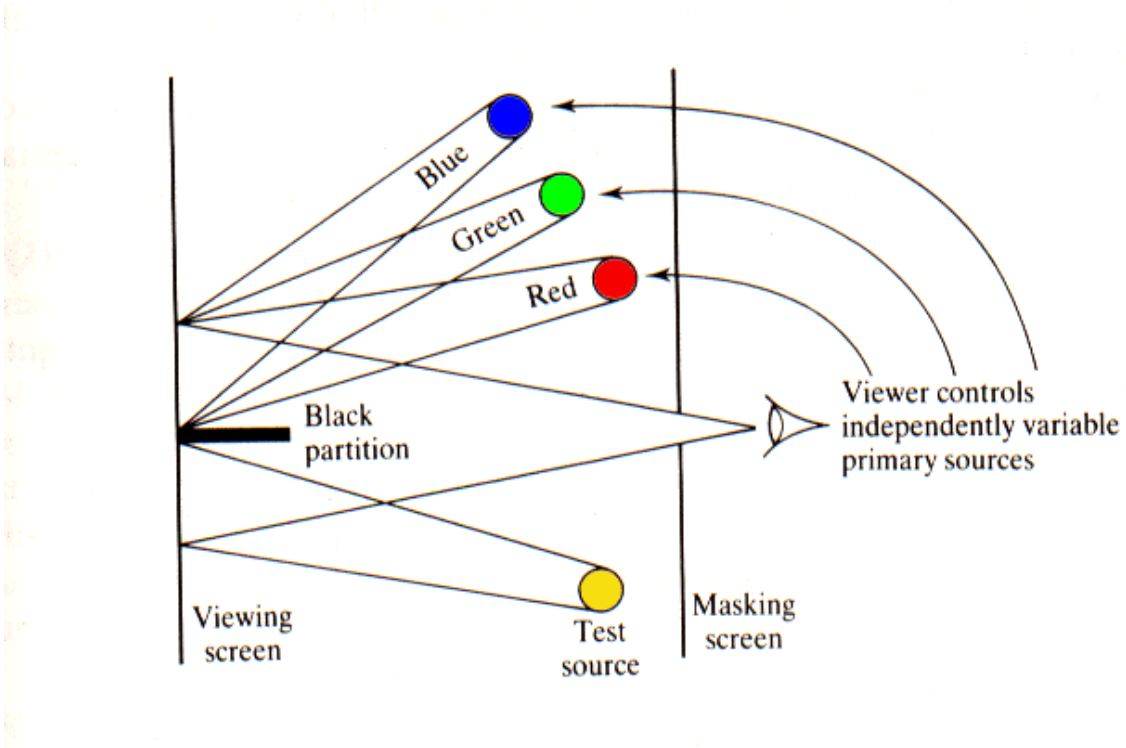
Color Mixing

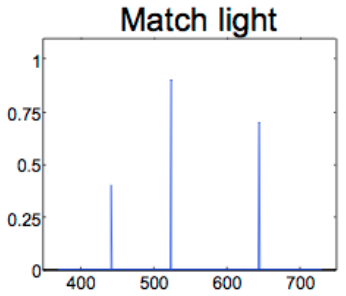
- Yellow as Red & Green mixture

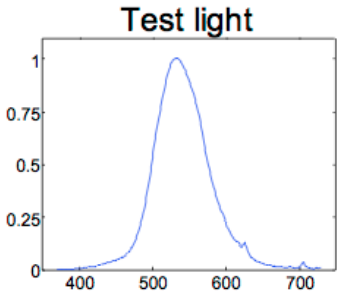


Color Matching Experiment

- Need a precise way to describe colors
  - Use monochromatic (single wavelength) primaries
    - 700nm (red), 546.1nm(green), 435.8nm(blue)



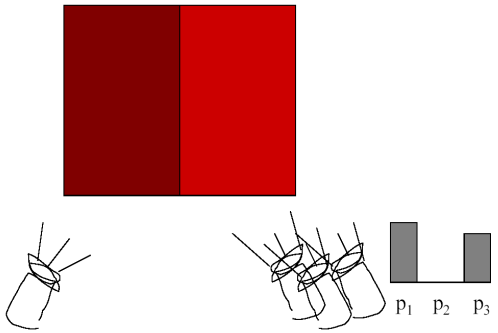




Find matching parameters for each spectral color!

Color Matching Experiment

- Not all visible colors can be expressed using R/G/B primary colors
  - -R required



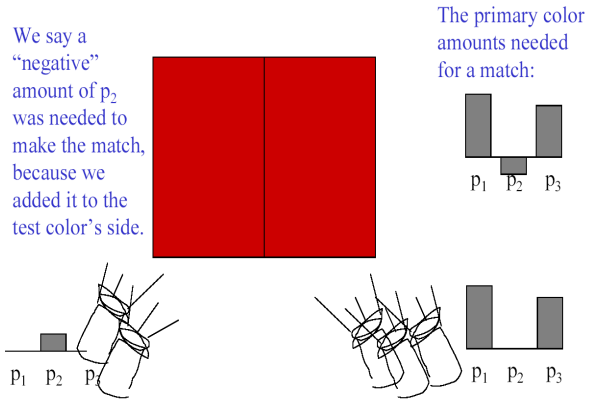


Image courtesy of Van Dam

RGB Color Matching Functions

- **R** (700 nm), **G** (546.1 nm), **B** (435.8 nm)

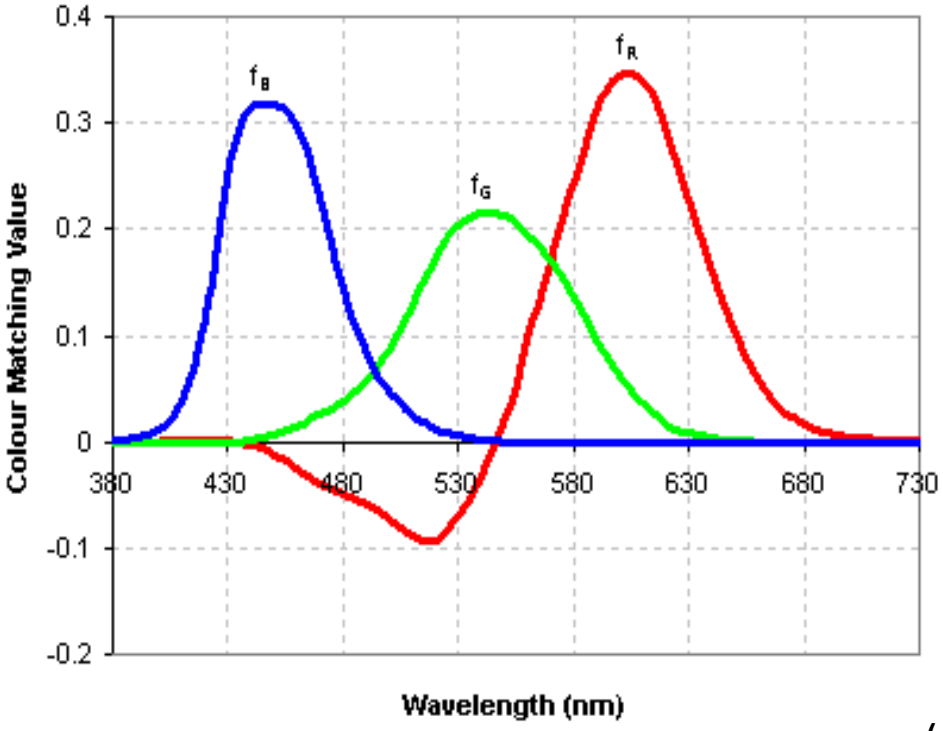


Image courtesy of Van Dam

$$R = k\int I(\lambda) f_R(\lambda) d\lambda$$

$$G = k\int I(\lambda) f_G(\lambda) d\lambda$$

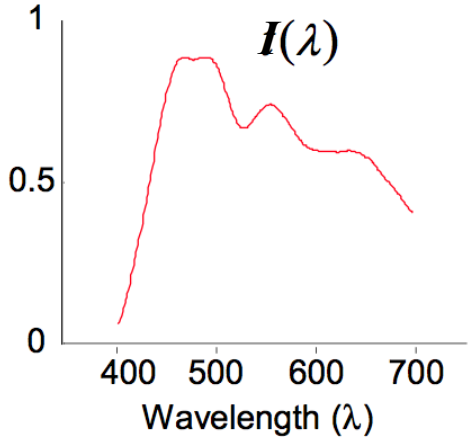
$$B = k\int I(\lambda) f_B(\lambda) d\lambda$$

$$C(\lambda) = R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$$

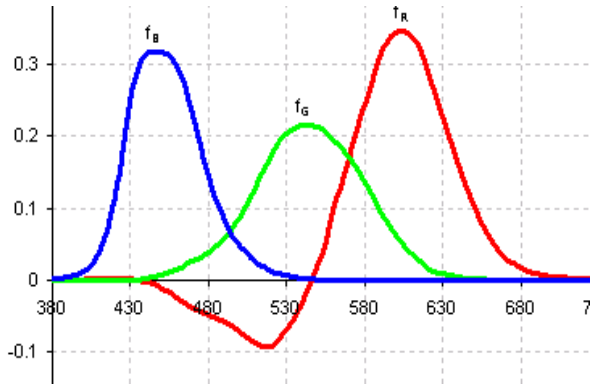
(R,G,B) is uniquely defined per primary

RGB Color Matching Function

- Inner product of spectral radiance function and color matching function



dot product



$$=$$

$$R = k\int I(\lambda) f_R(\lambda) d\lambda$$

$$G = k\int I(\lambda) f_G(\lambda) d\lambda$$

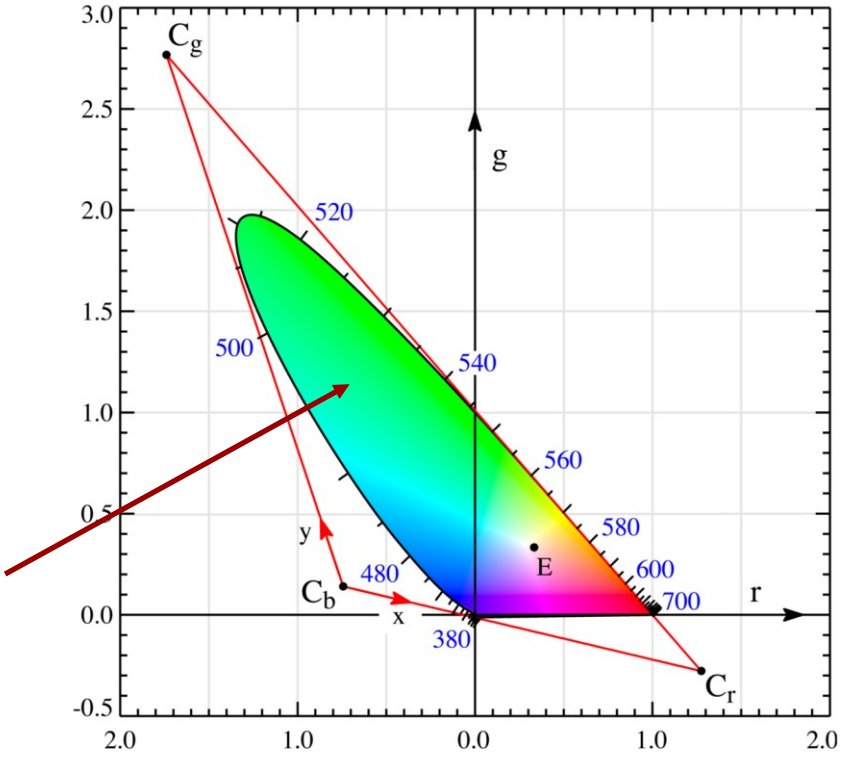
$$B = k\int I(\lambda) f_B(\lambda) d\lambda$$

$$C(\lambda) = R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$$

CIE rg Chromaticity Space

$$r = \frac{R}{R+G+B},$$
$$g = \frac{G}{R+G+B},$$
$$b = \frac{B}{R+G+B}.$$

Outside of triangle [1,0][0,0],[0,1]
(negative weight)



- Can we design new primaries?

Construction of XYZ Color Space

- New primaries X, Y, Z (and normalized x, y, z)
- Goals
  - New color matching functions should be non-negative everywhere
    - Historical reason, positive computations are easier
  - Y represents photopic luminous efficient function
    - Perceived brightness over different wavelength
  - White point : x = y = z = 1/3
  - All visible colors should be within the x-y triangle of [1,0],[0,0],[0,1]

CIE Standard Primaries

- XYZ system
  - Coordinate transform
  - Synthetic primaries

$$C(\lambda) = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

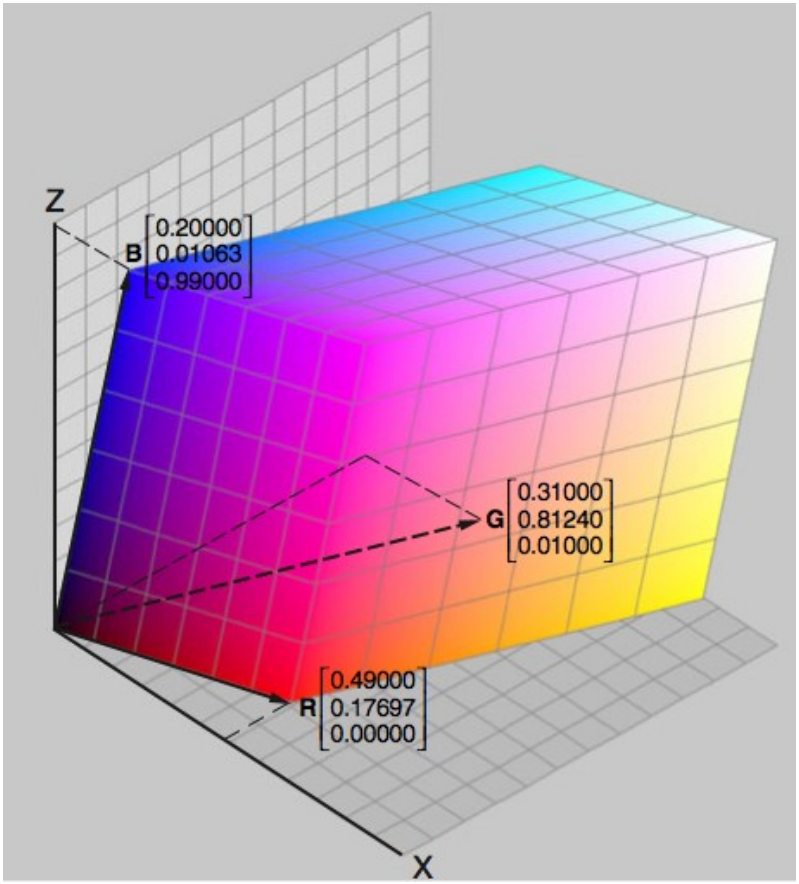
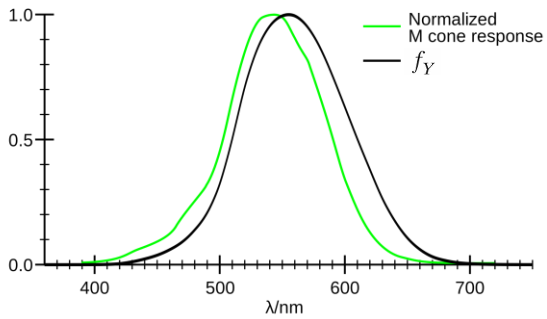


Image courtesy of Hoffmann

CIE Primary Matching Functions

- Positive matching functions
- XYZ color model
  - xy (chromatic) & Y(luminance)



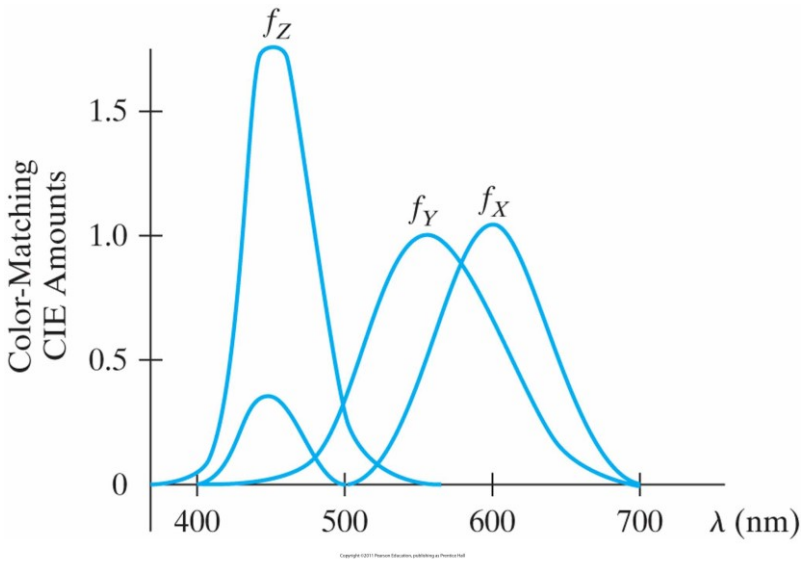


Image courtesy of Hearn

$$X = k\int I(\lambda) f_X(\lambda) d\lambda$$

$$Y = k\int I(\lambda) f_Y(\lambda) d\lambda$$

$$Z = k\int I(\lambda) f_Z(\lambda) d\lambda$$

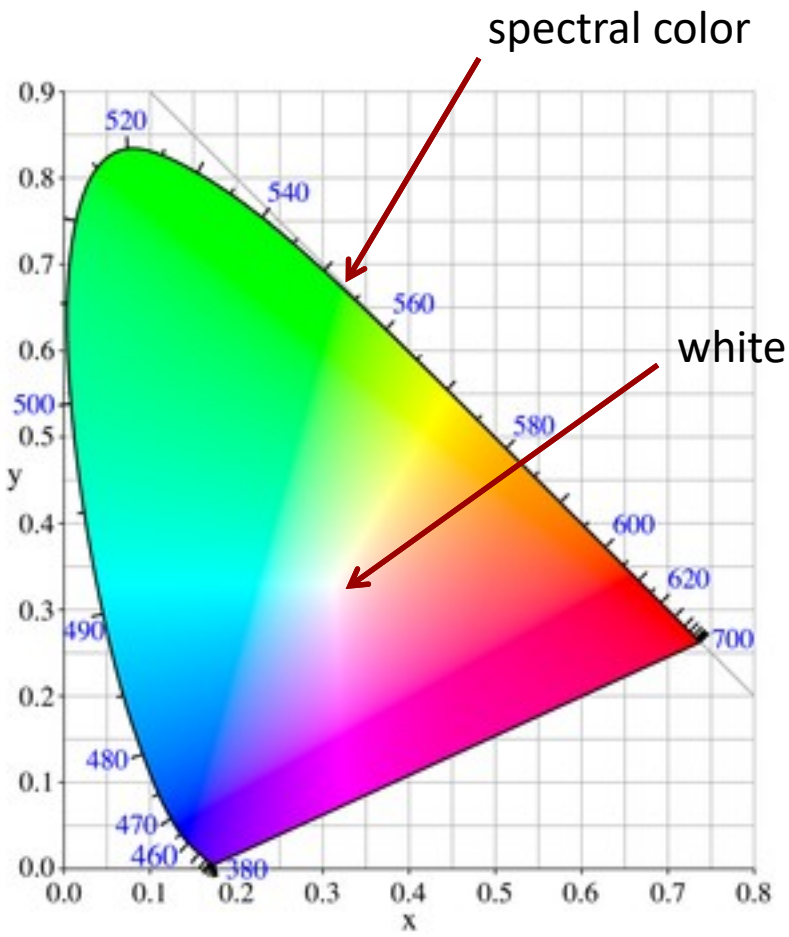
$$C(\lambda) = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$$

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

$$X = \frac{x}{y}Y,\ Z = \frac{z}{y}Y,\ z = 1 - x - y$$

CIE Chromaticity Diagram

- 2D x/y plot
- No luminance
  - Colors with same chromaticity map to same point
- Useful for
  - Comparing color gamut for different primaries
  - Identifying complementary colors
  - Determine purity and dominant wavelength for a given color



Color Gamut

- Range of color represented by primaries
- Straight line or polygon

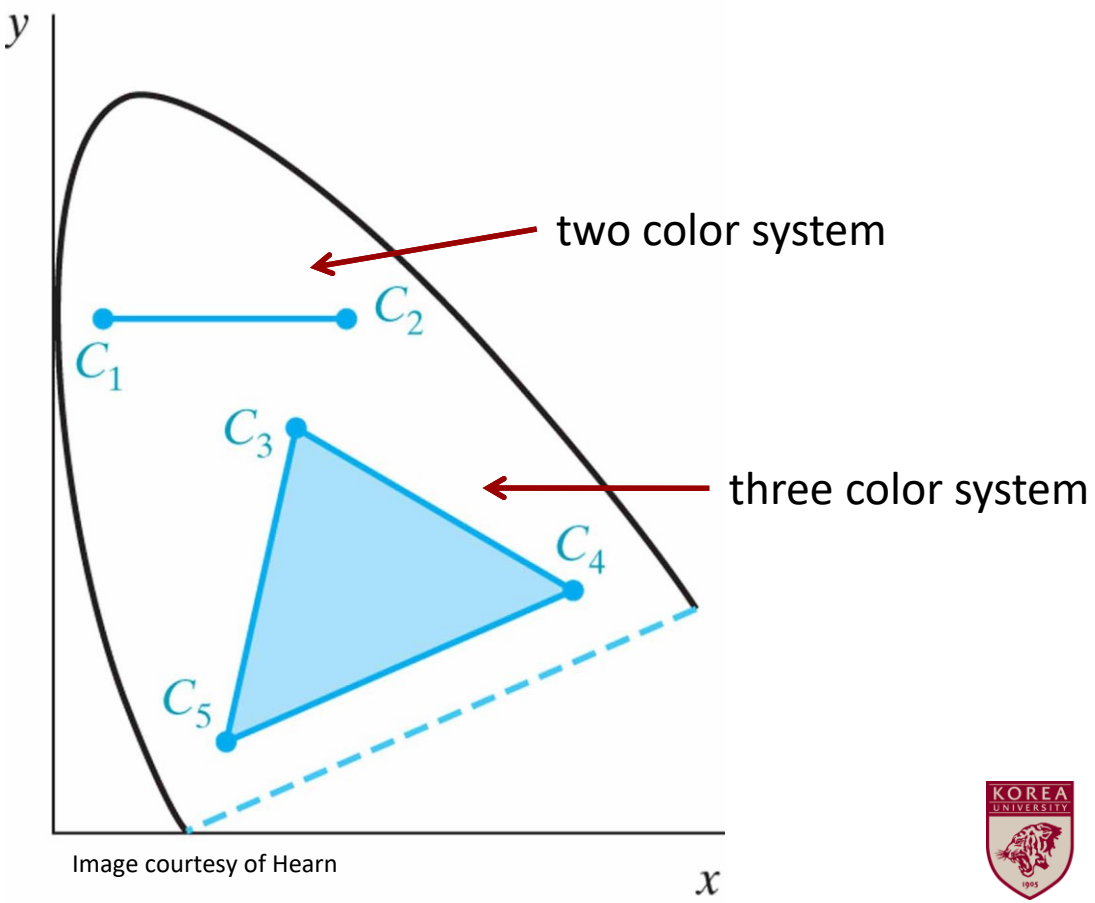


Image courtesy of Hearn

Complementary Colors

- Two colors collinear with white

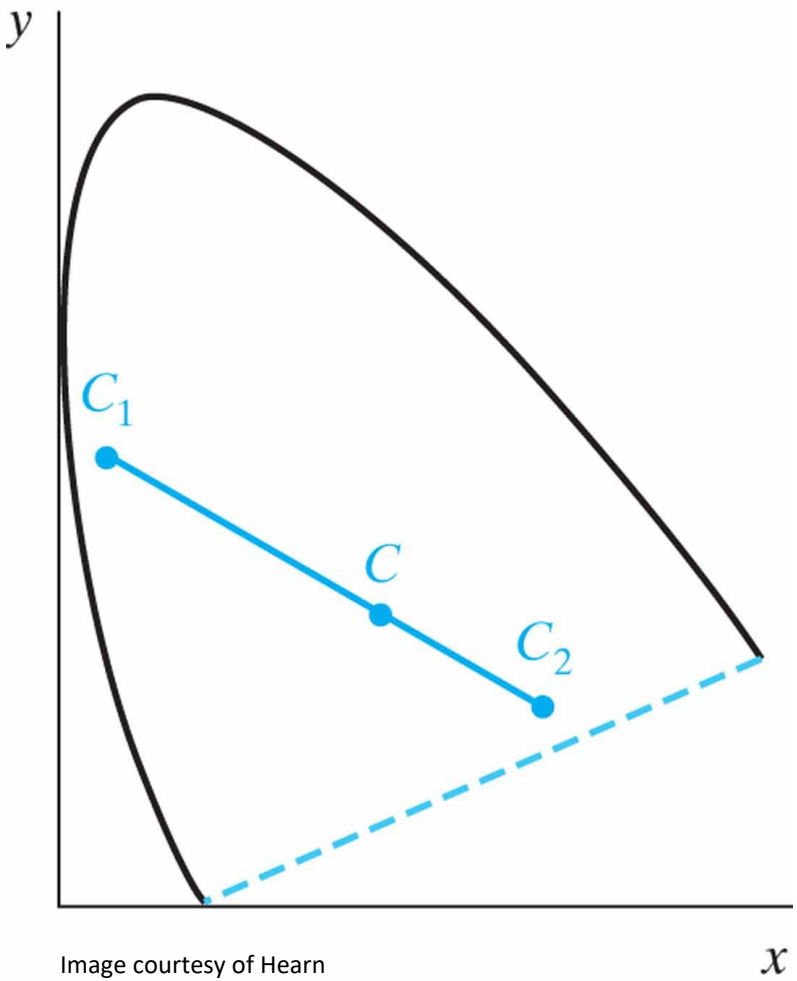
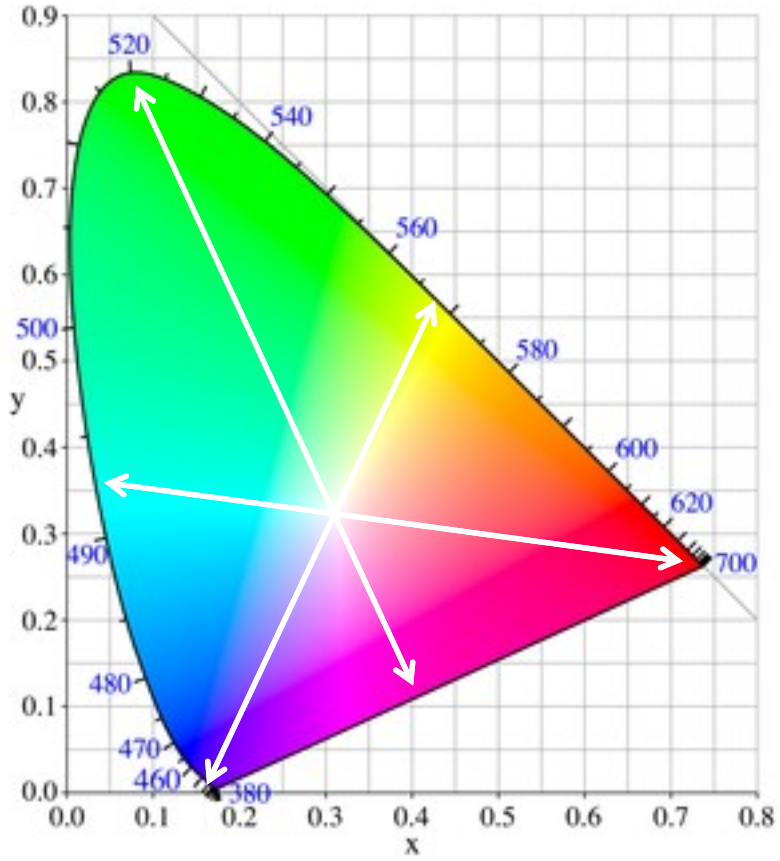
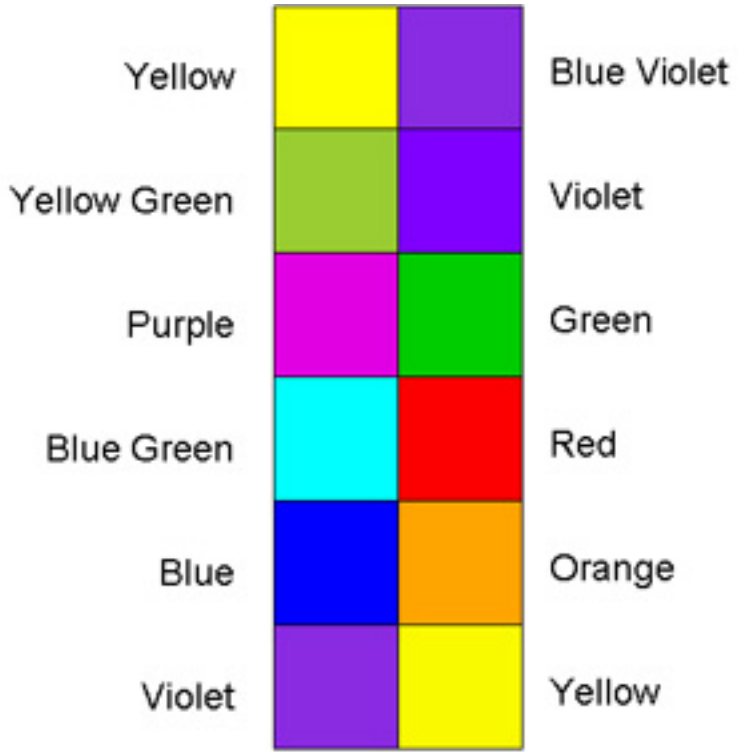


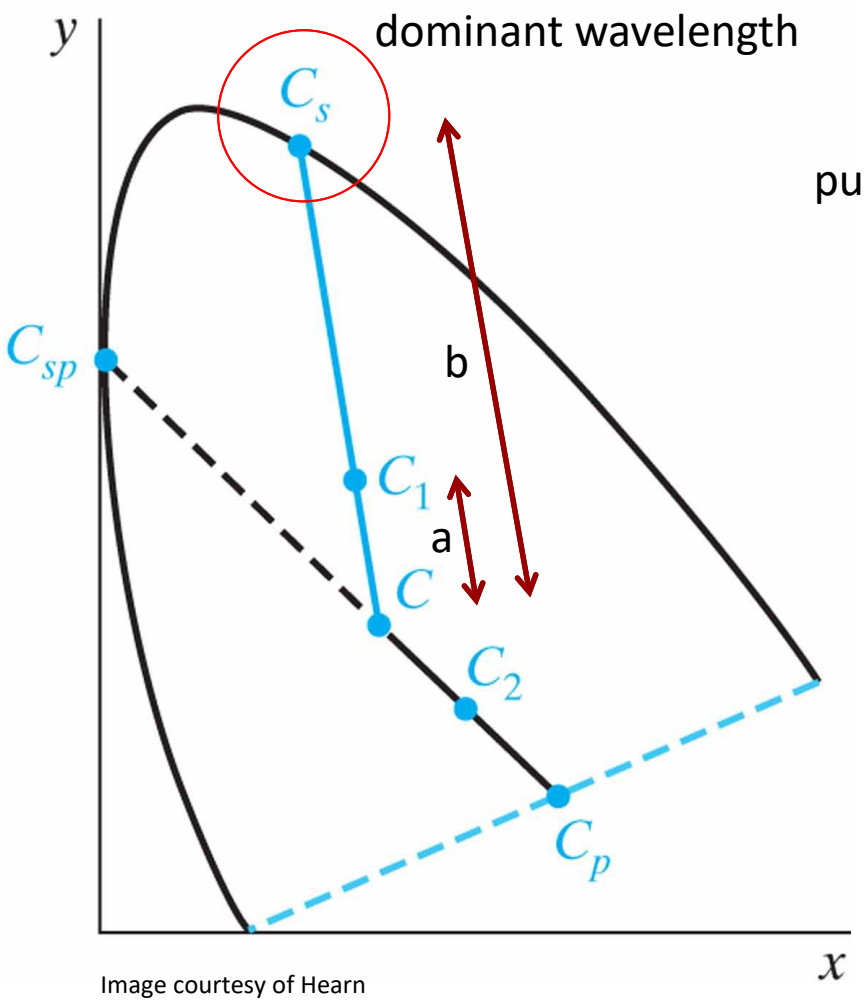
Image courtesy of Hearn

Complementary Colors





Dominant Wavelength and Purity



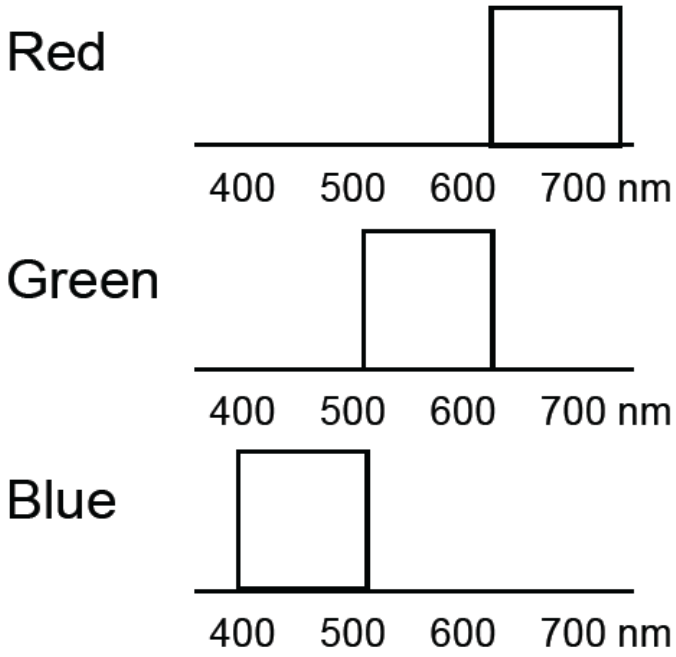
purity of C1 = a/b

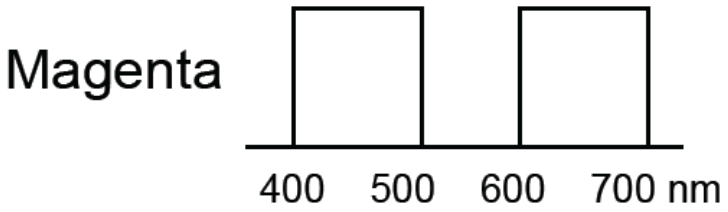
Image courtesy of Hearn

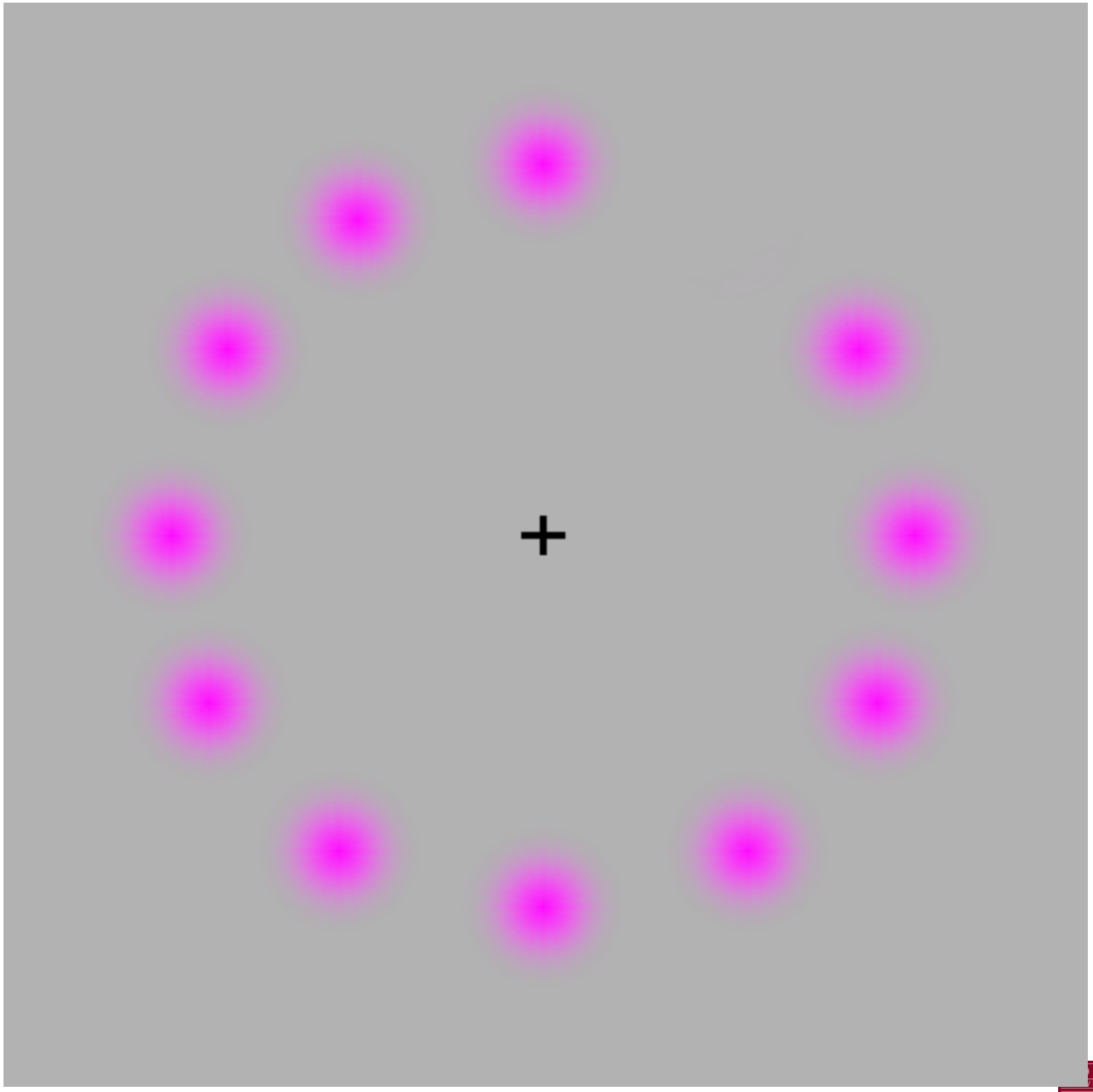
C2: Since there is no wavelength for Cp, take complementary (Csp) to compute dominant wavelength

Magenta (Pink)

- Not a spectral color
  - No corresponding single wavelength
  - (Full spectrum (white) - green spectrum) = addition of red and blue spectra

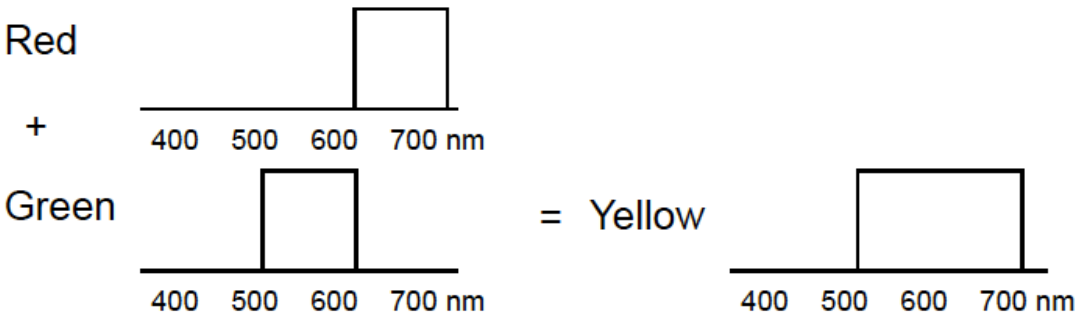






Additive Colors

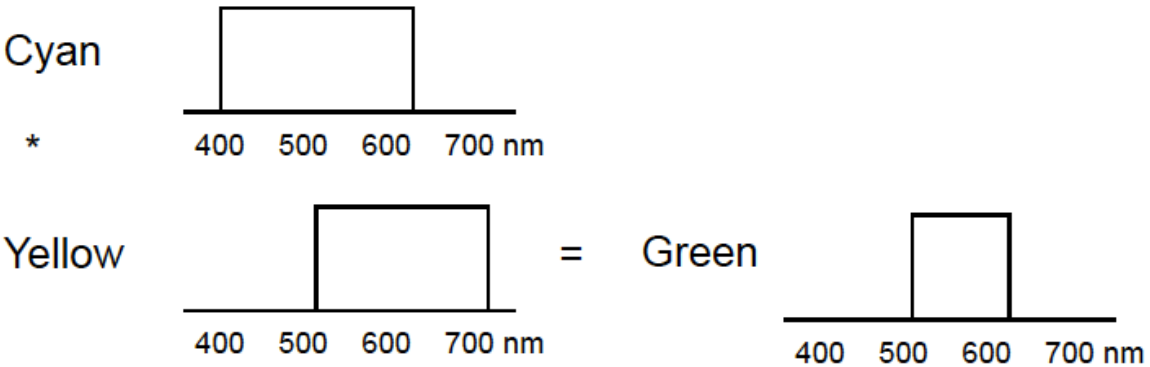
- Colors are combined by adding their spectra
- Light



RGB

Subtractive Colors

- Colors are combined by multiplying their spectra
- Ink, paint



CMYK

RGB Color Model

- Additive

$$C(\lambda) = R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$$

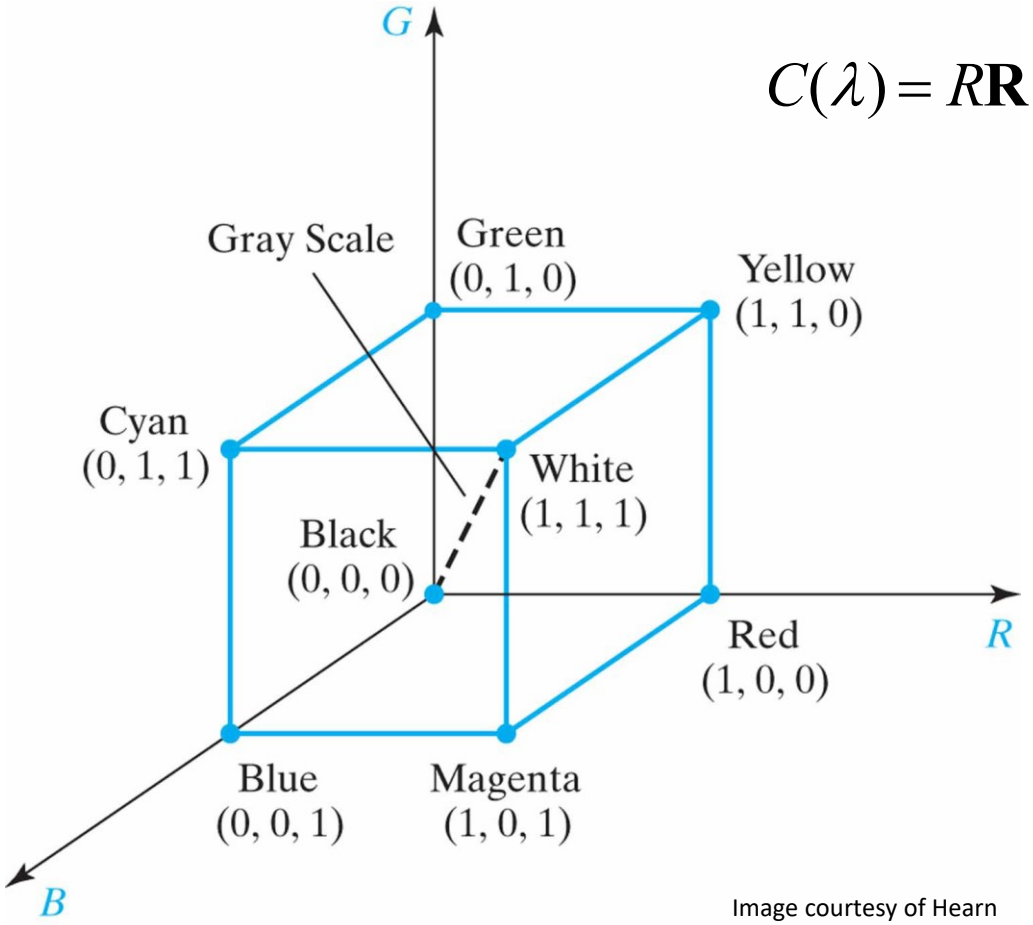


Image courtesy of Hearn

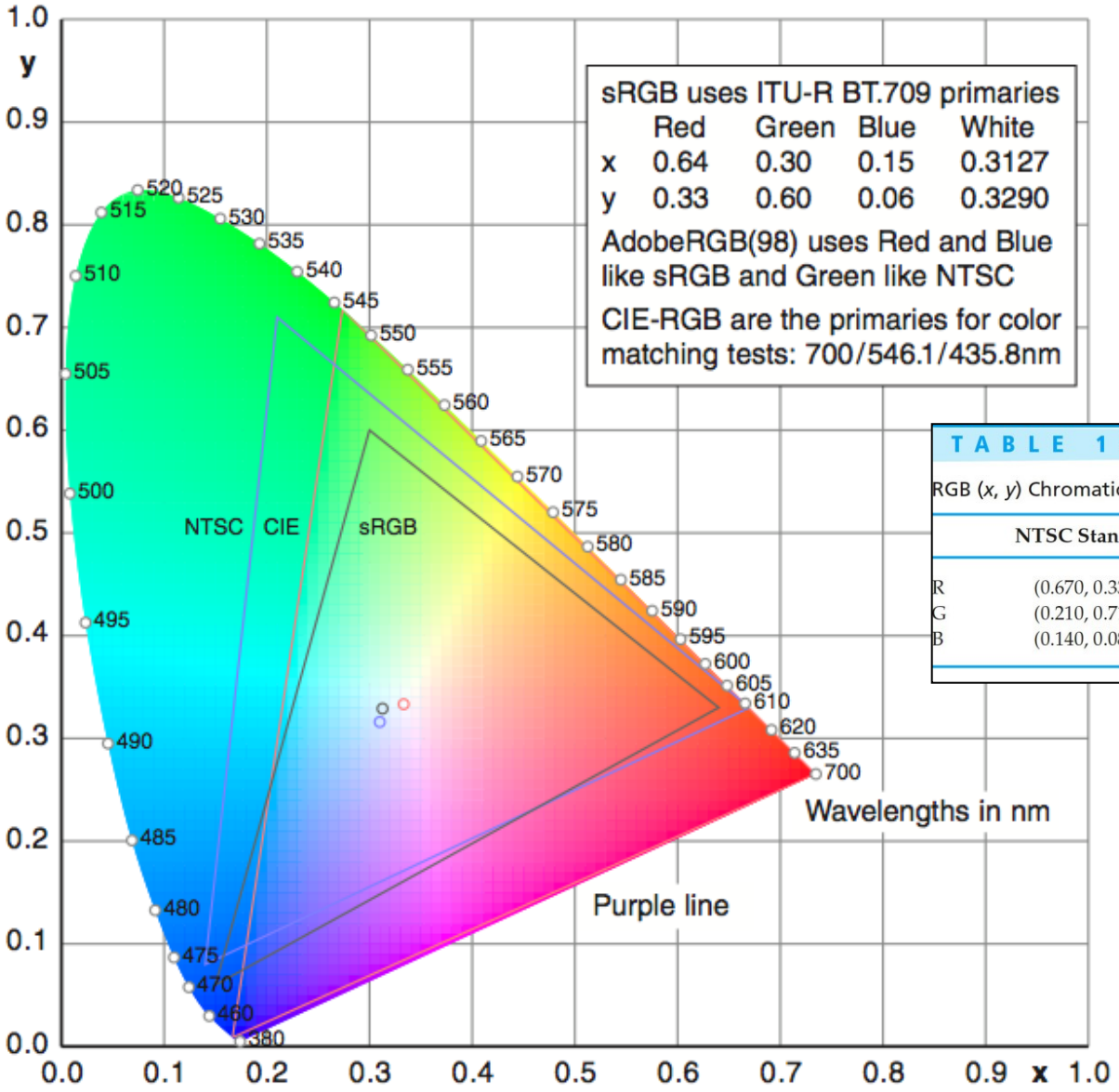


TABLE 19-1

RGB (*x*, *y*) Chromaticity Coordinates

	NTSC Standard	CIE Model
R	(0.670, 0.330)	(0.735, 0.265)
G	(0.210, 0.710)	(0.274, 0.717)
B	(0.140, 0.080)	(0.167, 0.009)

Image courtesy of Hoffmann & Hearn

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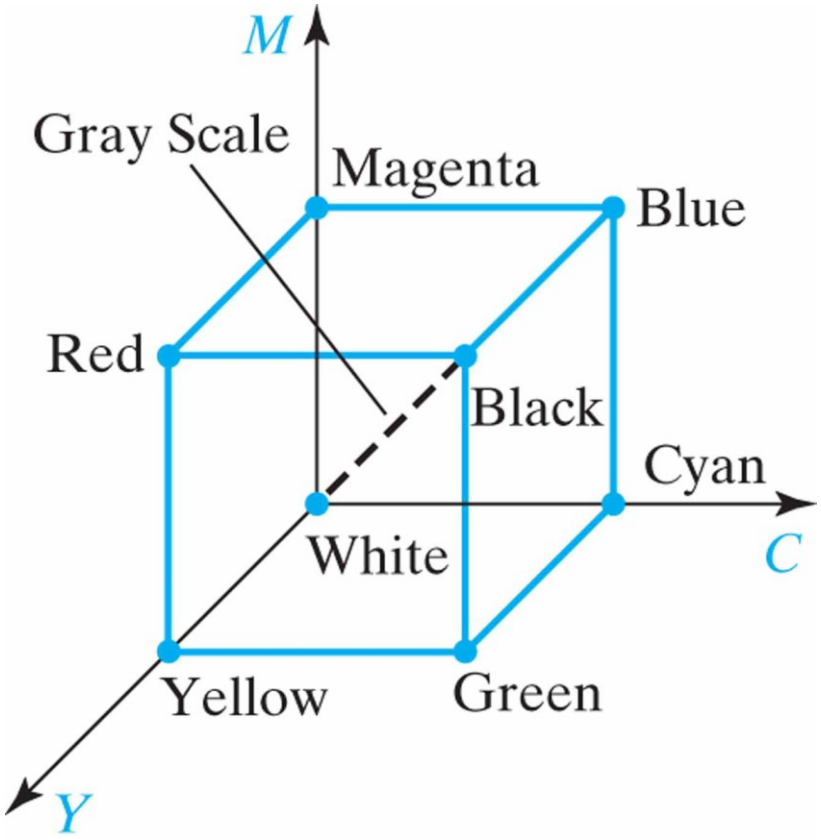
CMY Color Model

- Subtractive



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

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

Image courtesy of Hearn

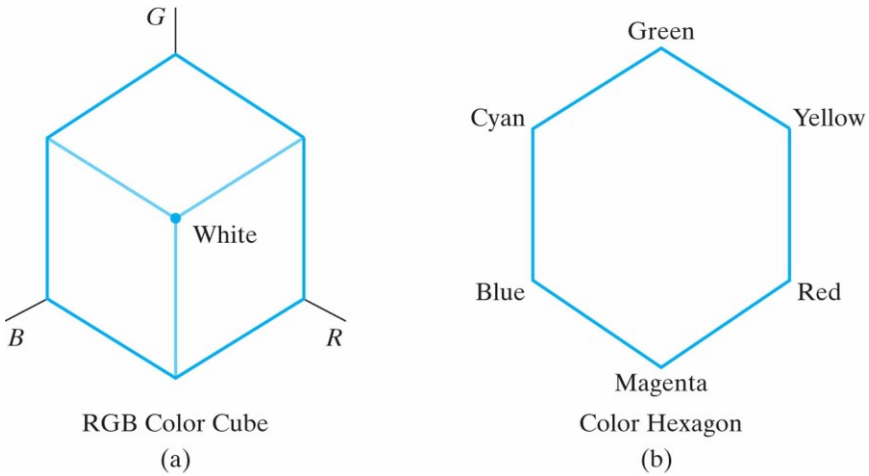
CMYK Color Model

- Use K for richer black
  - Black by CMY is dark gray
  - Use less ink

- K = min(C, M, Y)
  C' = C – K
  M' = M – K
  Y' = Y – K
  (one of C', Y', M' will be 0)

HSV Color Model

- Intuitive color selection
  - Hue, saturation, value (brightness)
  - Rearrangement of RGB



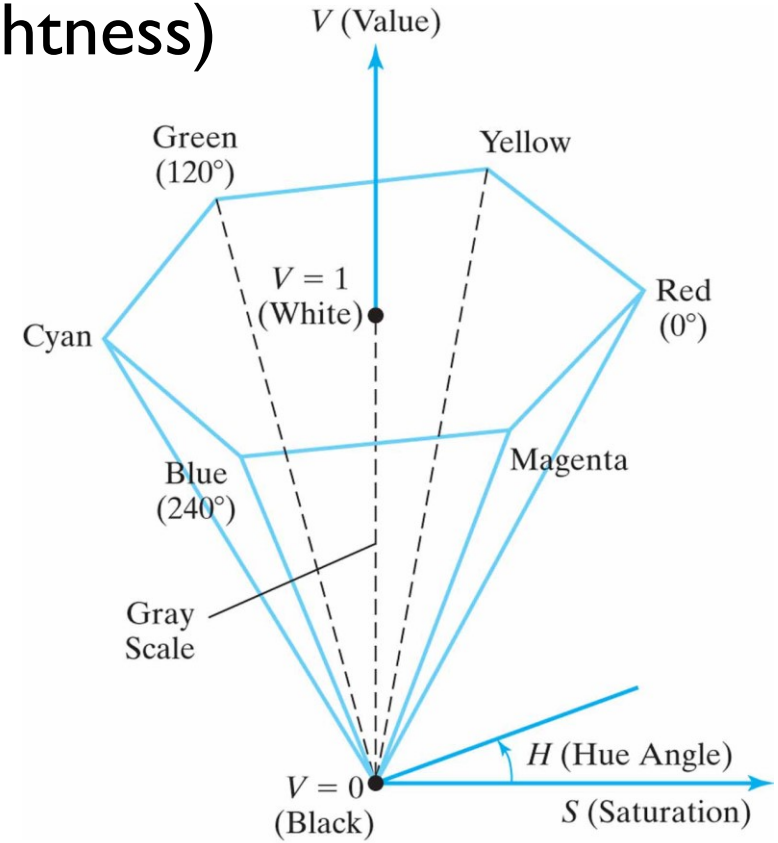
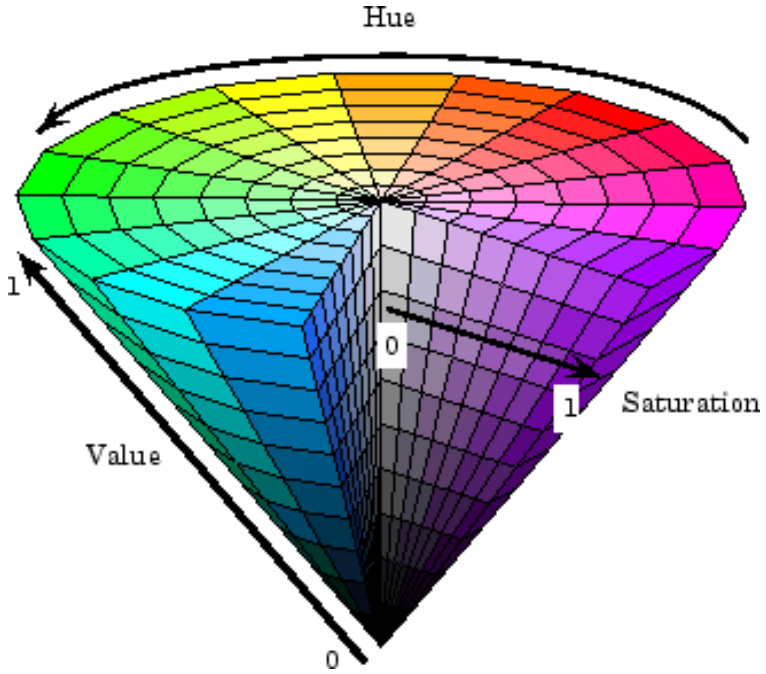


Image courtesy of Hearn

HSV Color Model



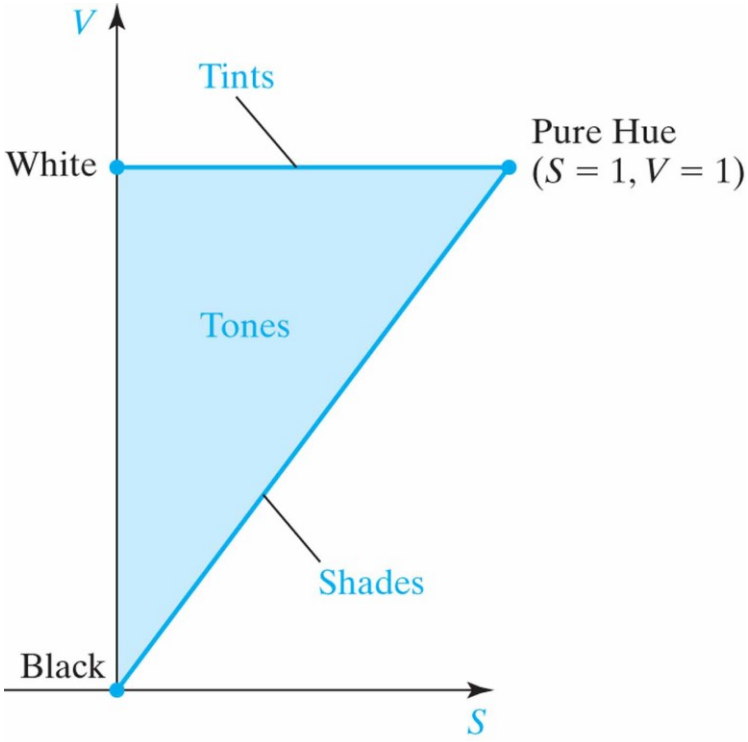
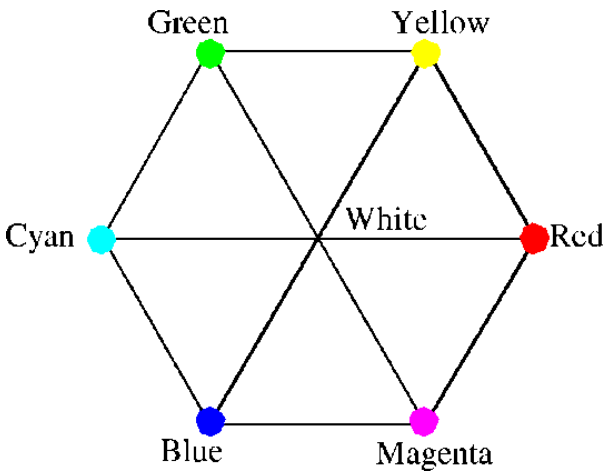


Image courtesy of Hearn

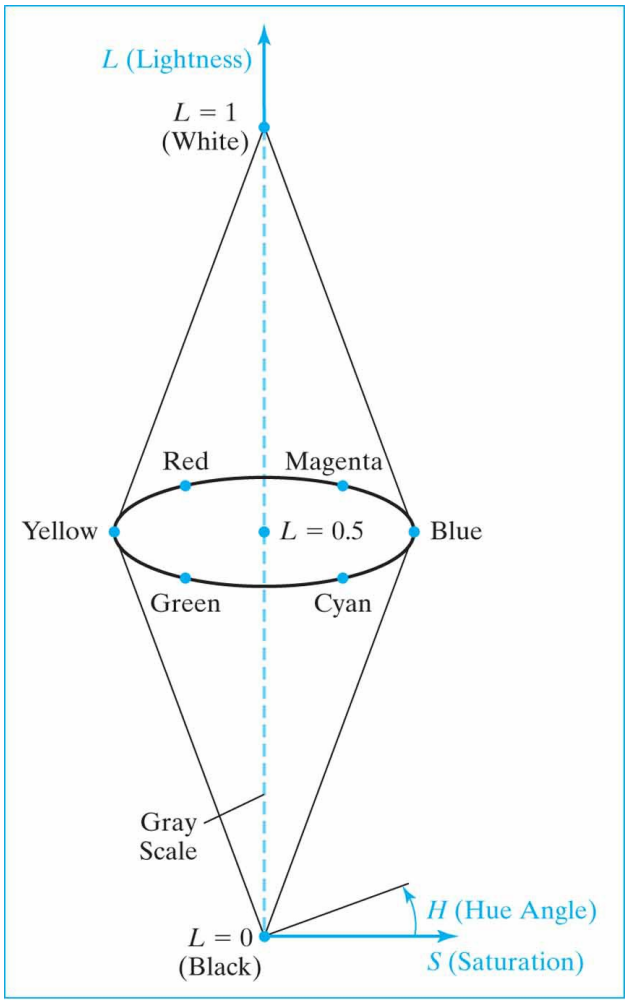
HSV Color Models

- Colors on V=1 plane are not perceptually uniform (not equally bright)
- Complementary colors are 180° opposite
- S=1 is not pure spectral color
  - HSV color space is a subset of CIE space



HSL Color Model

- Similar to HSV except double-cone model

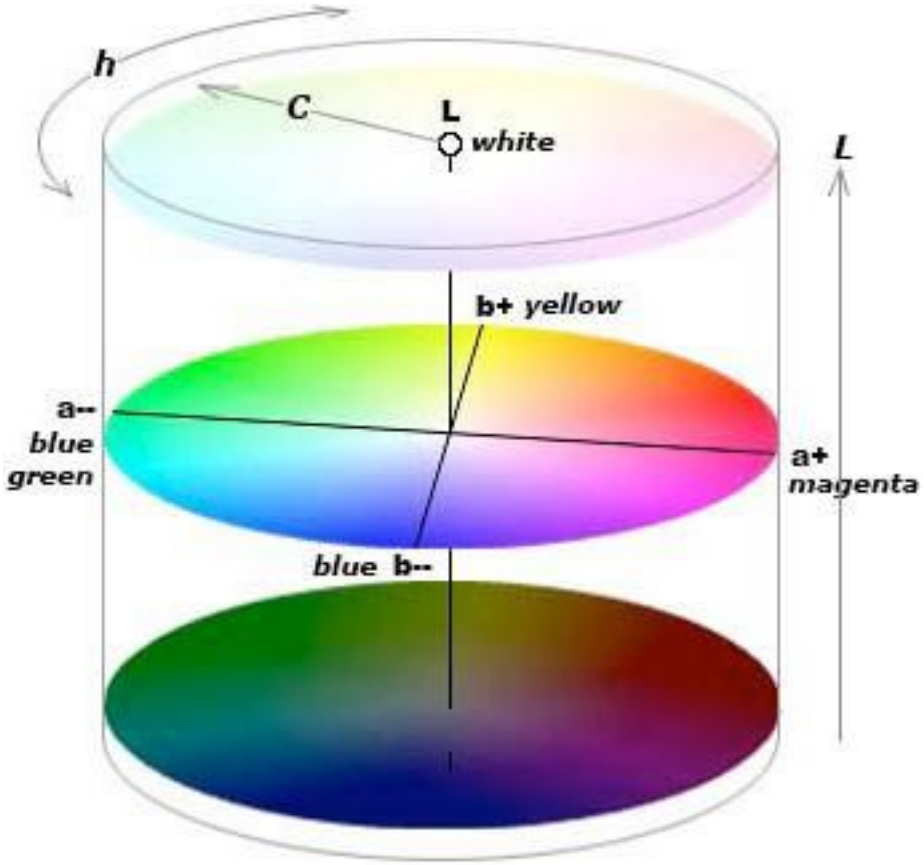


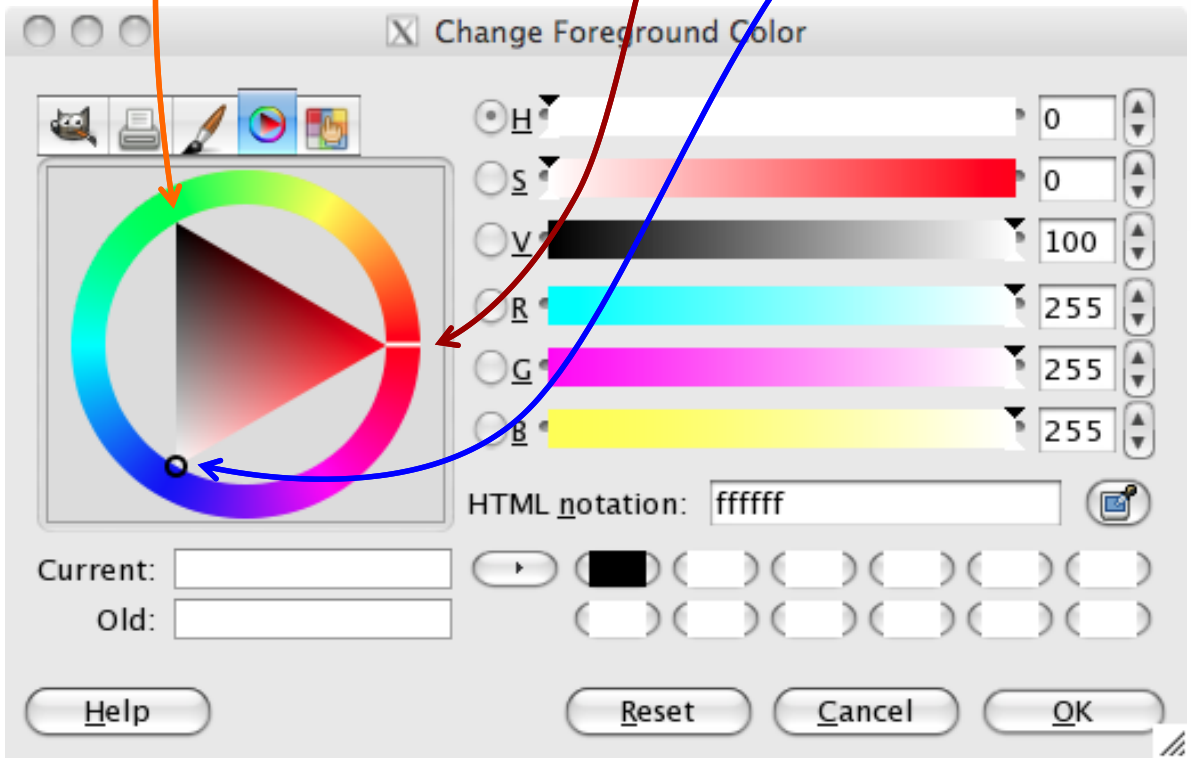
White: L=1
Black: L=0
Pure color: L=0.5, S=1

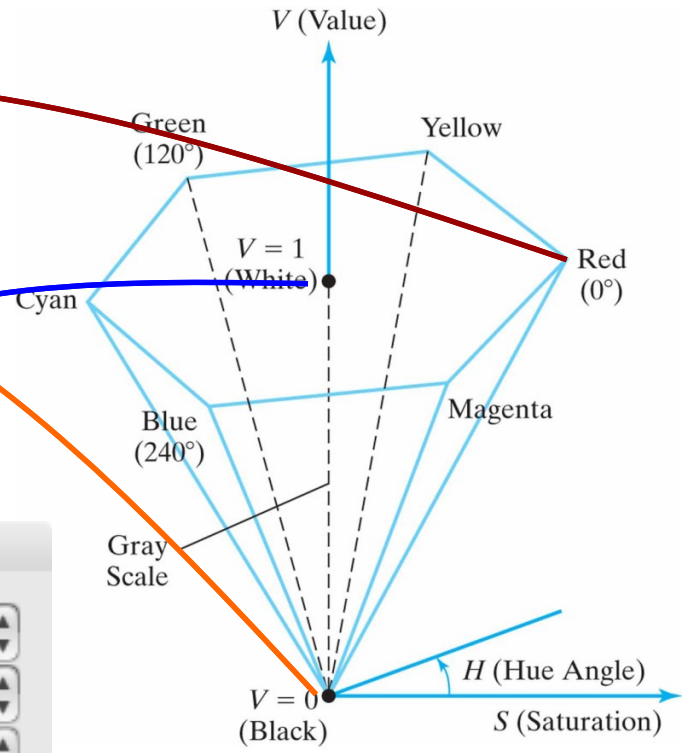
Image courtesy of Hearn

LAB / HCL Color Model

- Perceptually uniform
  - L : luminance
  - a : green to red
  - b : blue to yellow
- HCL is a cylindrical transformation of LAB







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Questions?