CS148: Introduction to Computer Graphics and Imaging

Light and Color

Painting by Cheryl Yaney

Topics

Physics of light

- Electromagnetic spectrum
- Fundamental operations: add, filter, measure

Perception of color

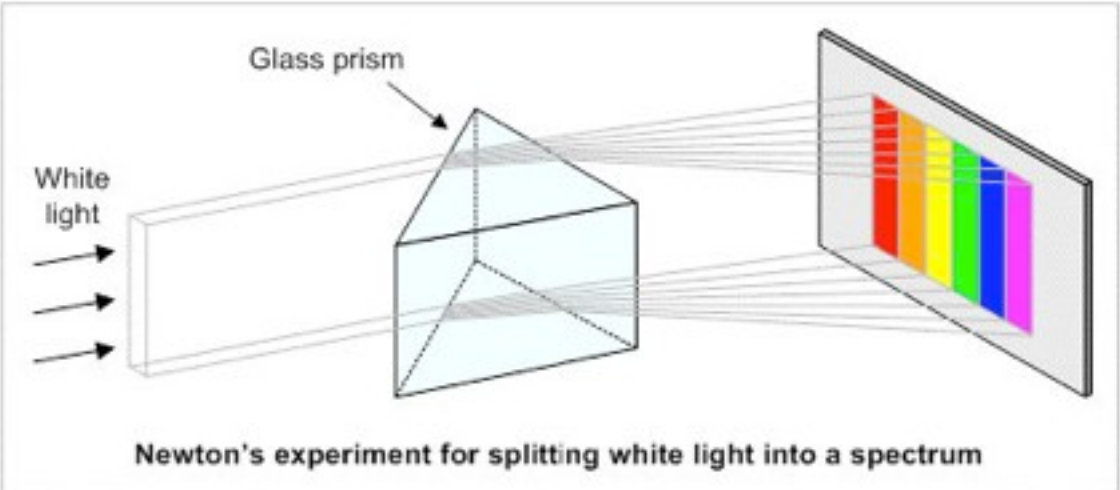
- Trichromatic theory
- Luminance
- Color spaces

Art

- Color terms
- Color wheels and intuitive color spaces

Physics of Light

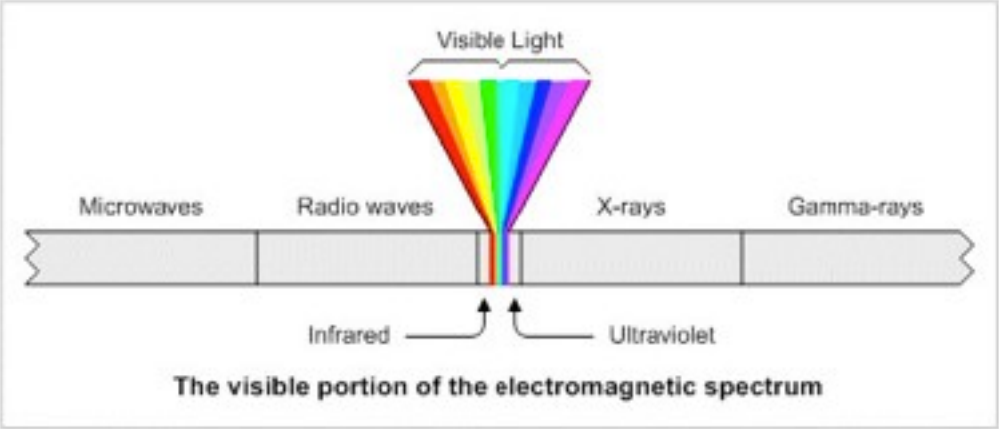
Light



Newton's experiment for splitting white light into a spectrum

Image from Clive Maxfield

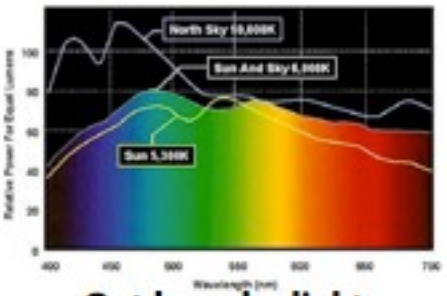
Electromagnetic Spectrum



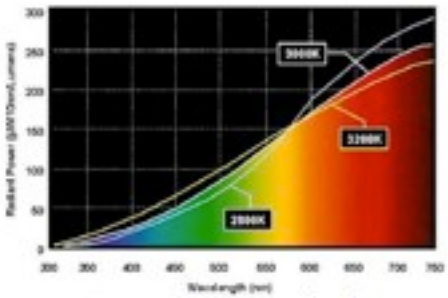
The visible portion of the electromagnetic spectrum

Image from Clive Maxfield

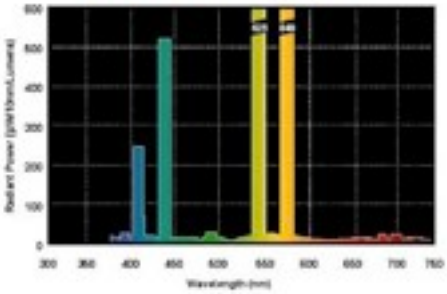
Spectral Power Distribution of Lights



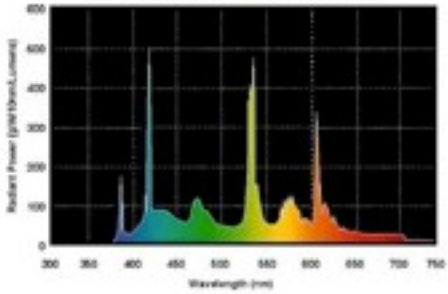
Outdoor daylight



Incandescent bulb

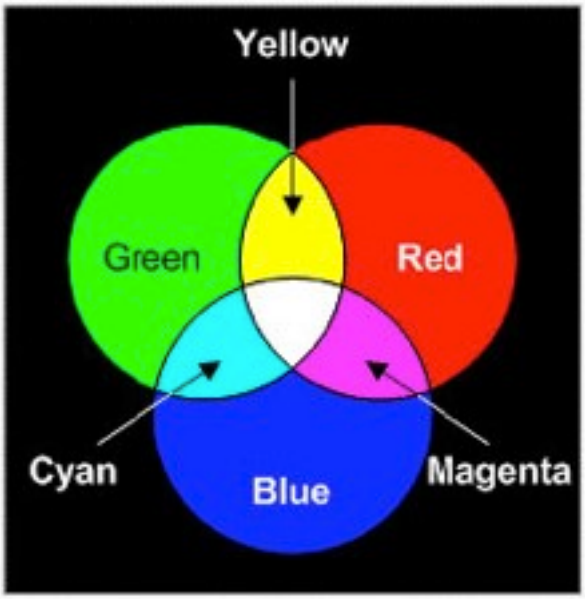


Mercury lamp

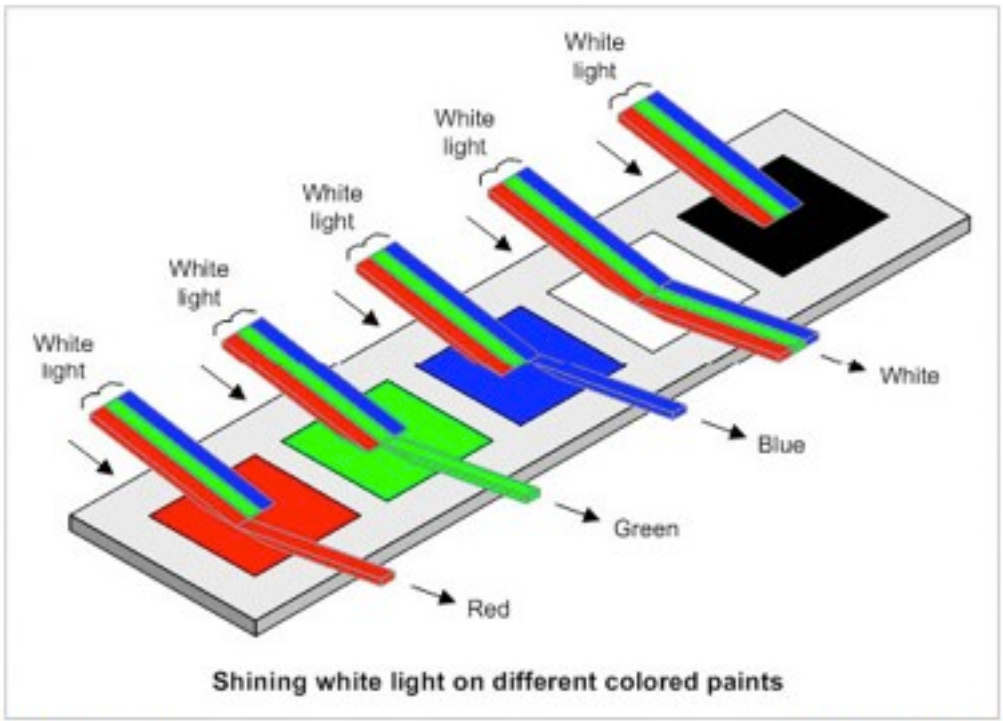


SP65 triphosphor fluorescent

Adding Light Energy



Reflecting Light



Shining white light on different colored paints

Light Operations

Add spectra $L(\lambda) = S_1(\lambda) + S_2(\lambda)$

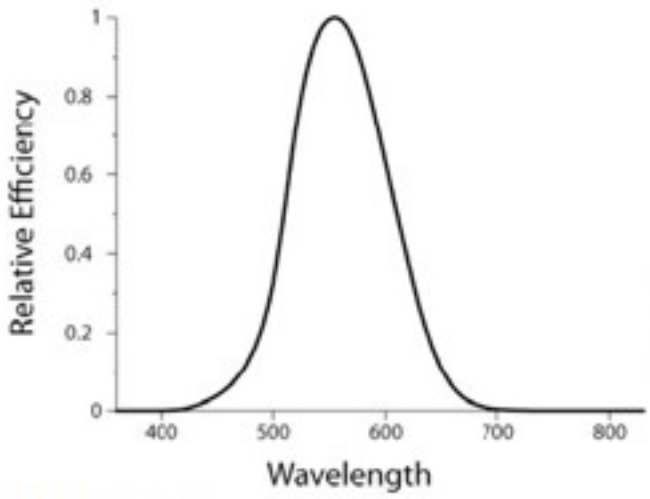
$$R = R_1 + R_2$$
$$G = G_1 + G_2$$
$$B = B_1 + B_2$$

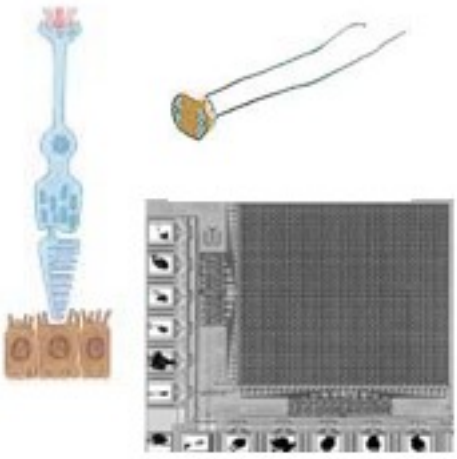
Multiply spectra $L(\lambda) = T(\lambda)S(\lambda)$

$$R = R_1 R_2$$
$$G = G_1 G_2$$
$$B = B_1 B_2$$

Measuring Light

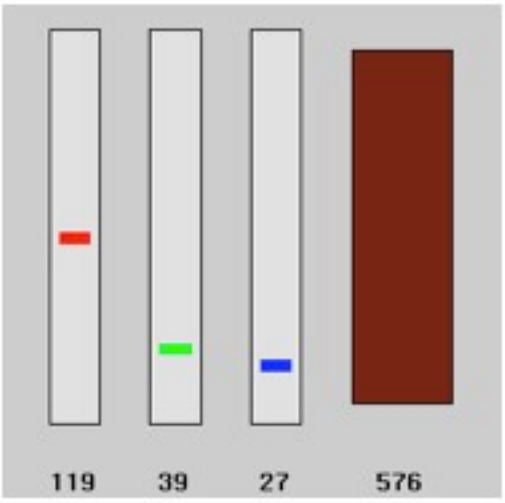
Photon detector $R = \int R(\lambda)L(\lambda)\,d\lambda$





Trichromatic Theory

RGB Color



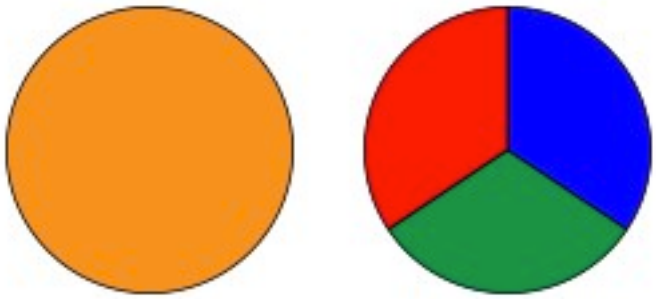
Result: colors can be matched with three colors

Color Matching Experiment

Adjust brightness of three primaries

Lasers: R = 700 nm, G = 546 nm, B = 435 nm

until it "matches" another color C



C = R + G + B

Result: all colors can be matched with three colors

Therefore: humans have trichromatic color vision

Color Matching is Linear

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 that match each color

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

Human Retina: Three Types of Cones

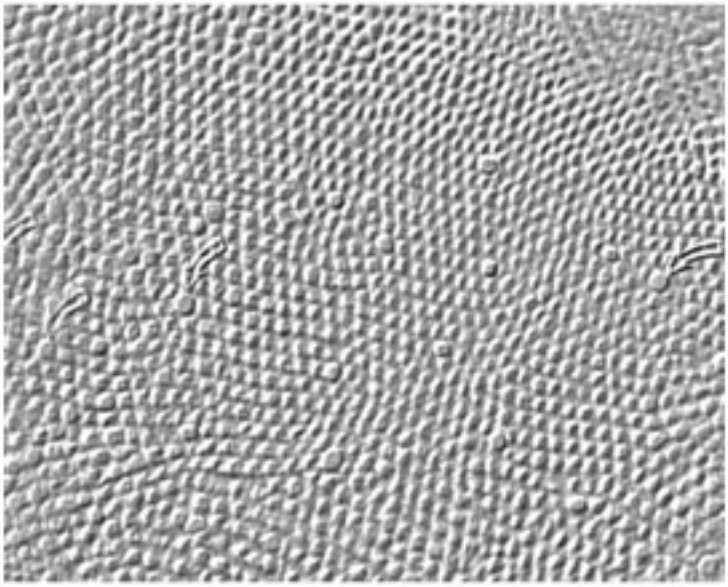
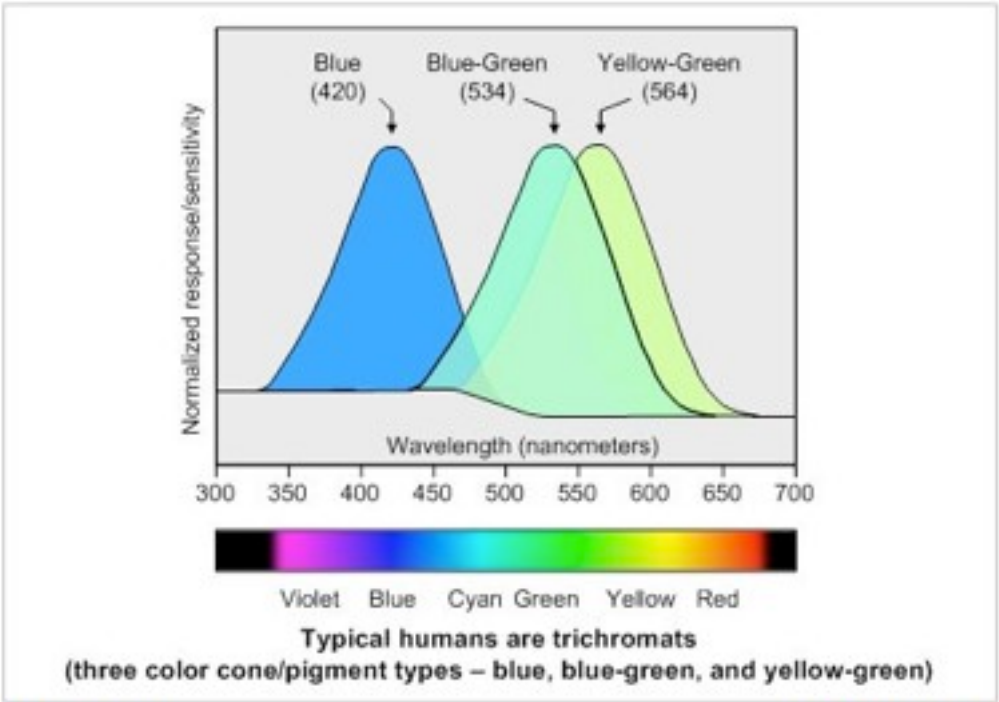


Fig. 13. Tangential section through the human fovea. Larger cones (arrows) are blue cones.

From http://webvision.med.utah.edu/imageswv/fovmoswv.jpeg

Response of Three Cones



Typical humans are trichromats
(three color cone/pigment types – blue, blue-green, and yellow-green)

Cone Response

Three cones

L (long) $$L = \int L(\lambda)E(\lambda)\,d\lambda$$

M (medium) $$M = \int M(\lambda)E(\lambda)\,d\lambda$$

S (short) $$S = \int S(\lambda)E(\lambda)\,d\lambda$$

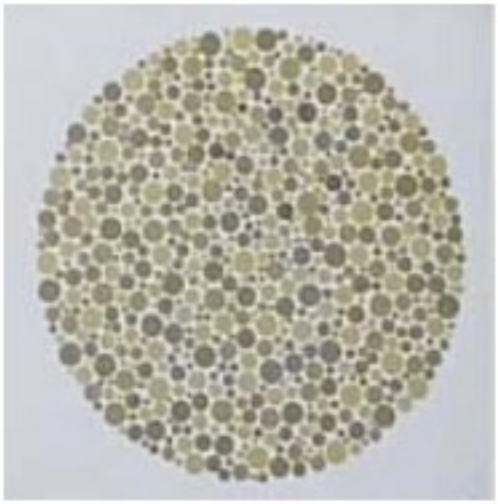
Metamerism: Different spectra, same color response

Color Blindness: Ishihara Test

Normal

http://www.toledo-bend.com/colorblind/Ishihara.html

Color Blindness: Ishihara Test



Normal Deuteranopia

http://www.toledo-bend.com/colorblind/Ishihara.html

Types of Color Blindness

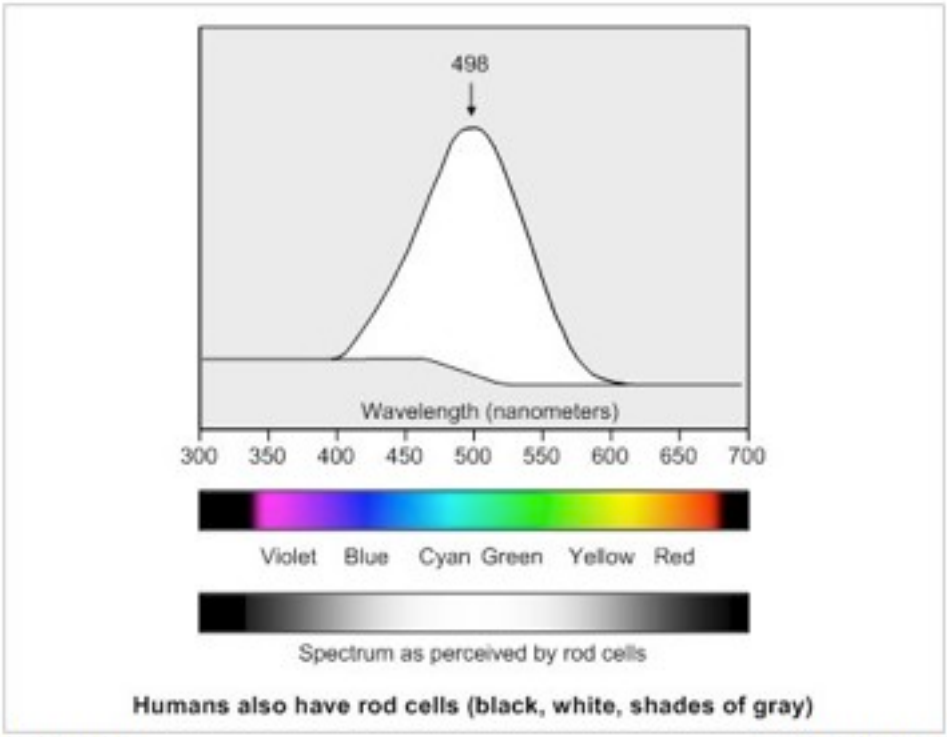
Dichromacy: missing pigment (10% M, 1% F)

- Protanopia – missing L
- Deuteranopia – missing M (red-green)
- Tritanopia – missing S

Normal Deuteranopia Tritanopia

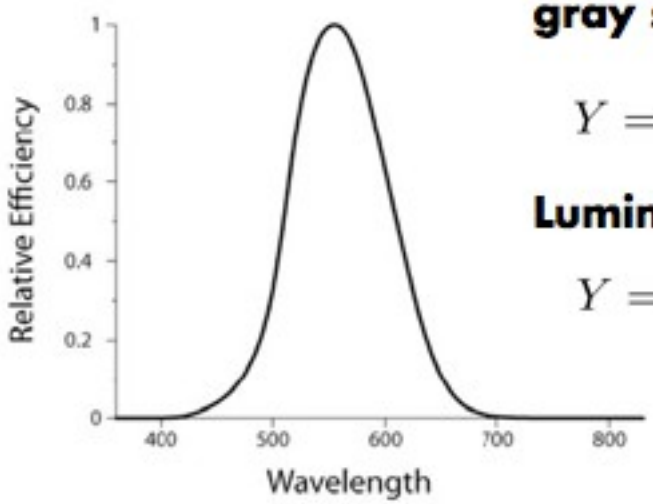
www.vischeck.com

Rod



Humans also have rod cells (black, white, shades of gray)

Luminance



Compare color to a gray source

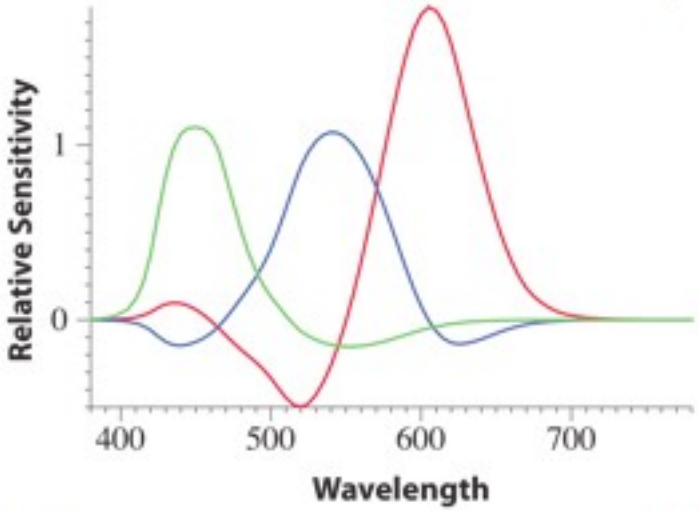
$$Y = \int V(\lambda)E(\lambda)\,d\lambda$$

Luminance (B&W TV)

$$Y = 0.30R + .59G + .11B$$

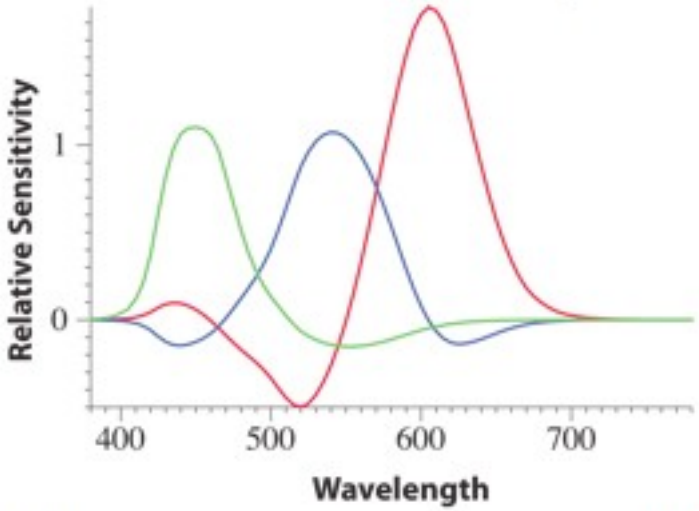
Spectral Matching Functions

Match each pure (monochromatic) color in the visible spectrum (rainbow) and record the color coordinates as a function of wavelength

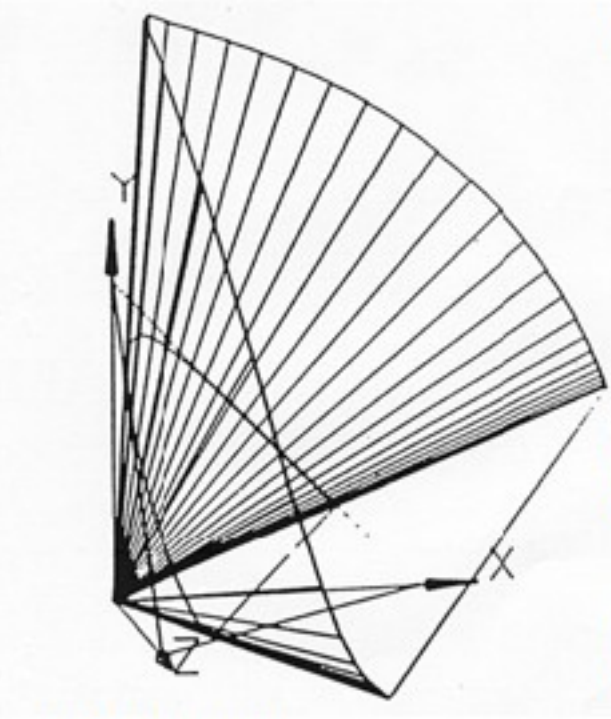


Spectral Matching Functions

Gotcha! Sometime you have to add R to the color and then match it to a combination of B and G. This situation means that R is negative



CIE XYZ Space



From RGB to XYZ

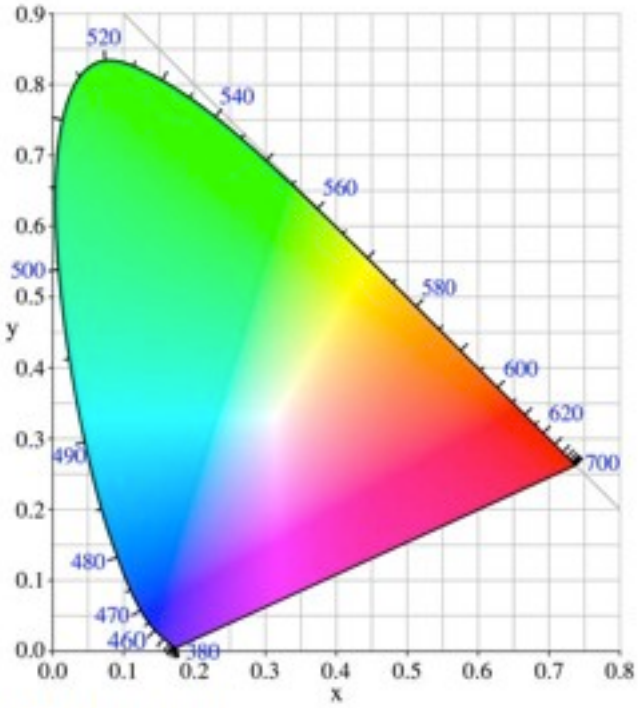
- **Y is luminance**
- **Force X, Y and Z to be positive**

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.77 & 1.75 & 1.13 \\ 1.00 & 4.59 & 0.06 \\ 0.00 & 0.57 & 5.59 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Colors of the rainbow are on the outer horseshoe curve

All perceivable colors are inside the curve

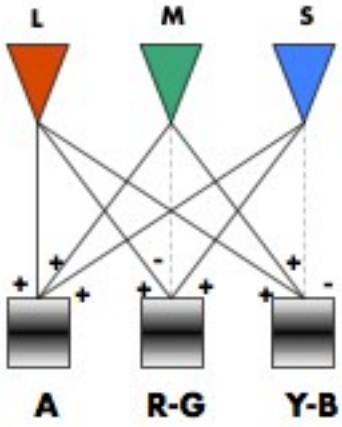
CIE XYZ Chromaticity Coordinates



$$\begin{aligned} x &= X/(X+Y+Z) \\ y &= Y/(X+Y+Z) \\ z &= Z/(X+Y+Z) \end{aligned}$$

Perceptual Models of Color

Early Visual Processing

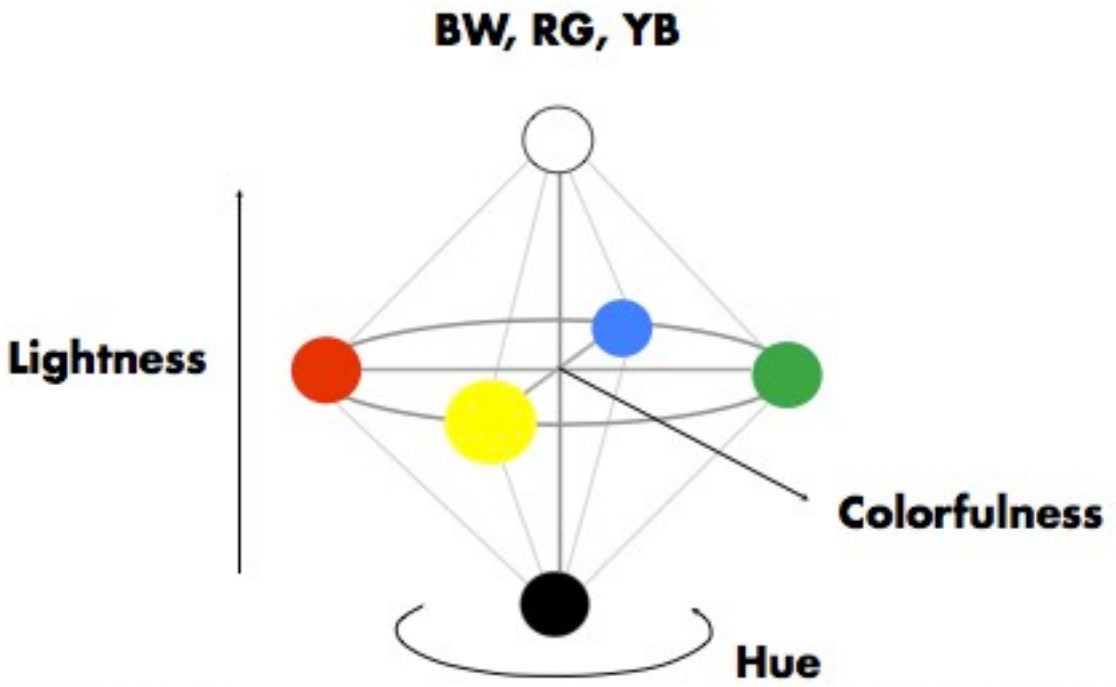


$$A = R + G + B$$

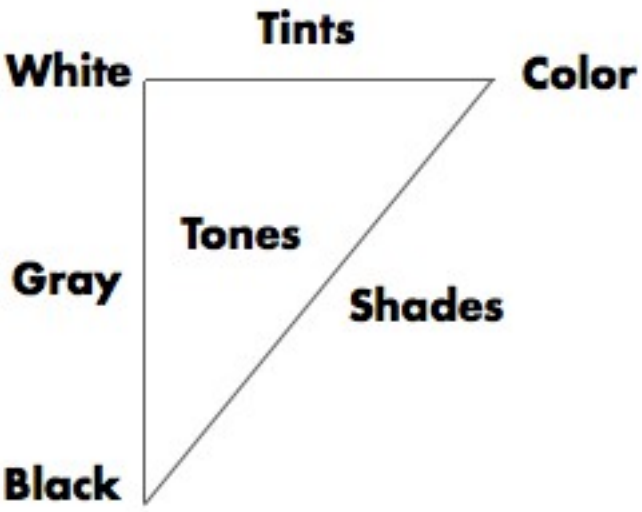
$$(Y - B) = R + G - B$$

$$(R - G) = R - G$$

Perceptual Organization

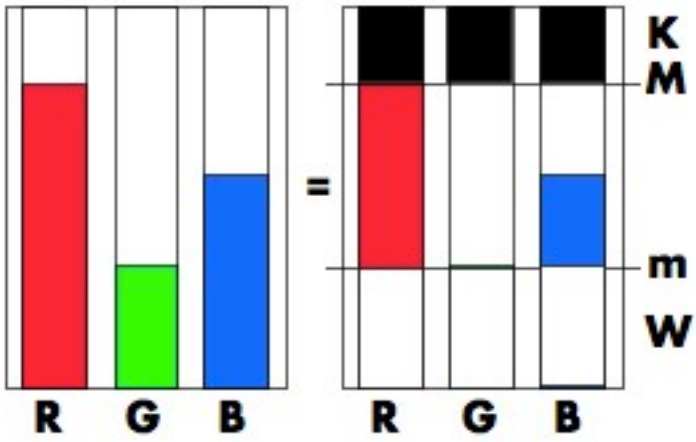


Intuitive Color Space



MetaDesign Color Picker

HSV



M=max(R,G,B)

m=min(R,G,B)

r=(M-R)/(M-m)

g=(M-G)/(M-m)

b=(M-B)/(M-m)

if(M==R)

H=(6+b-g)/6

....

V=M

S=(M-m)/M

Things to Remember

Physics of color

- Addition, transmission/reflection, measurement

Perception of color

- Three colors will match another color
- Trichromatic because we have 3 cones
- Explains metamerism, color blindness
- Color matching is linear
- Perceptual organization in terms of BW, YB, RG
- Hue-Saturation-Value