COLOR

and the human response to light

Contents

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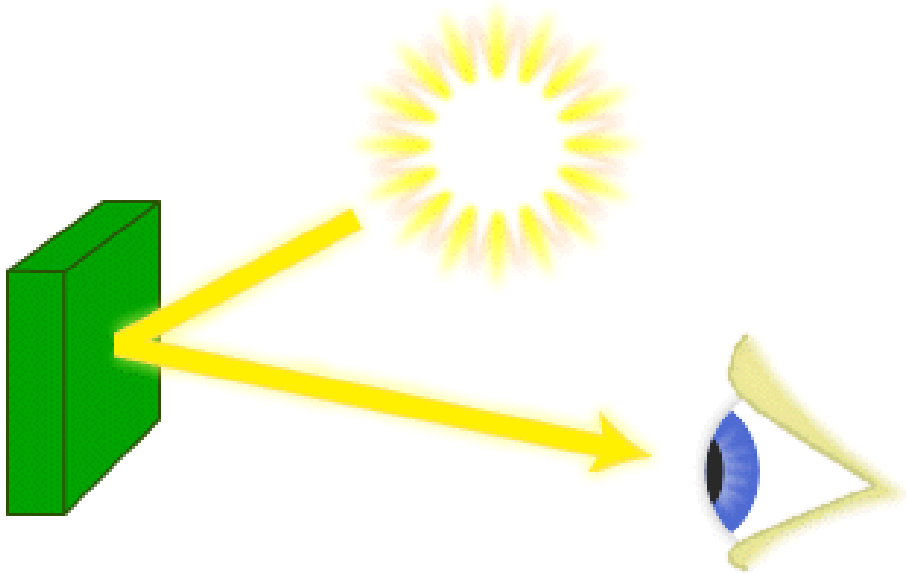
  - The nature of light
  - The physiology of human vision
- Color Spaces:
  - Linear
  - Artistic View
- Standard
- Distances between colors
- Color in the TV

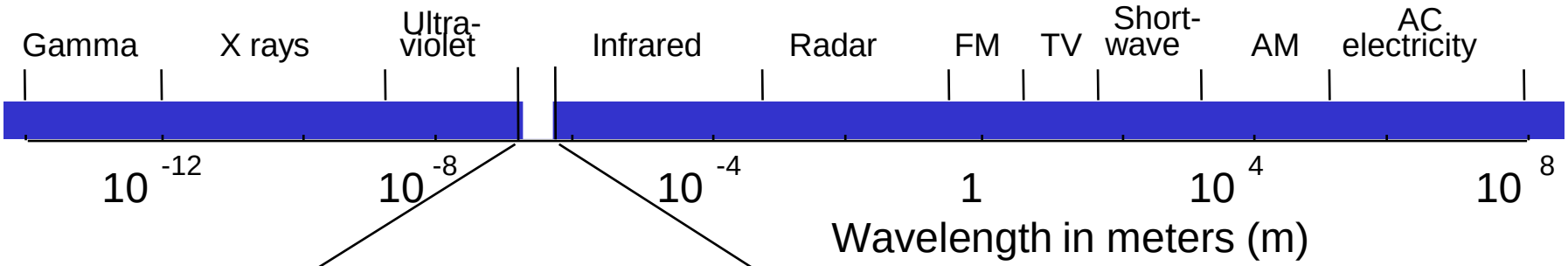
How many dimension ?

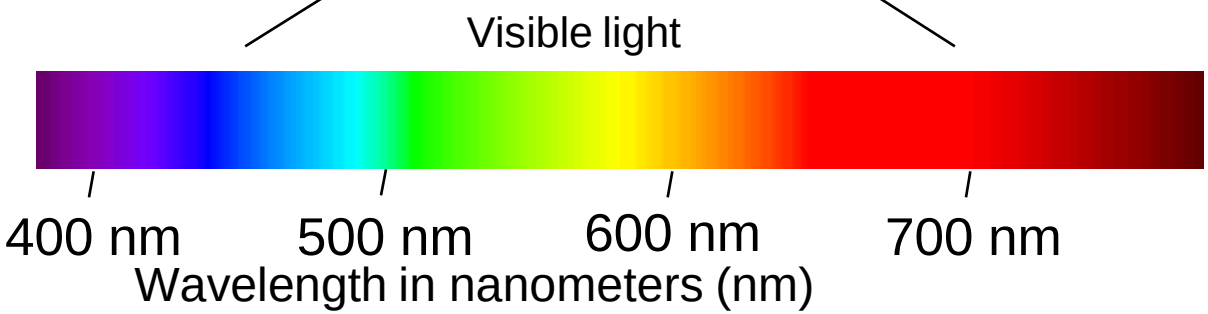
- RBG
- Lab
- CMY
- …

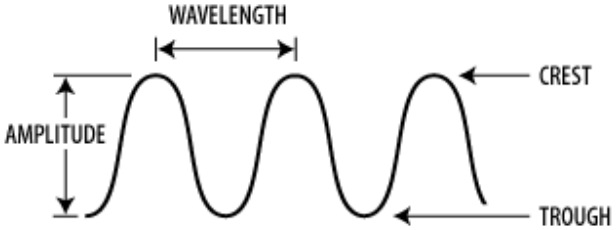
Introduction



Electromagnetic Radiation - Spectrum

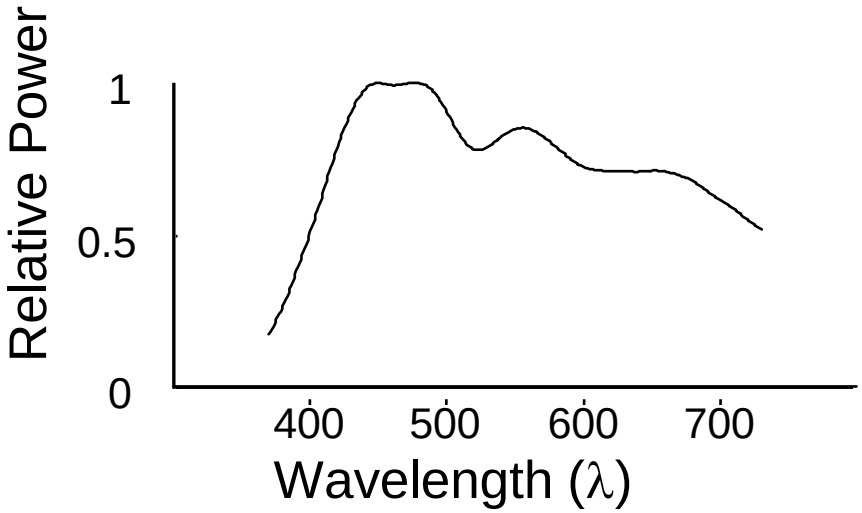




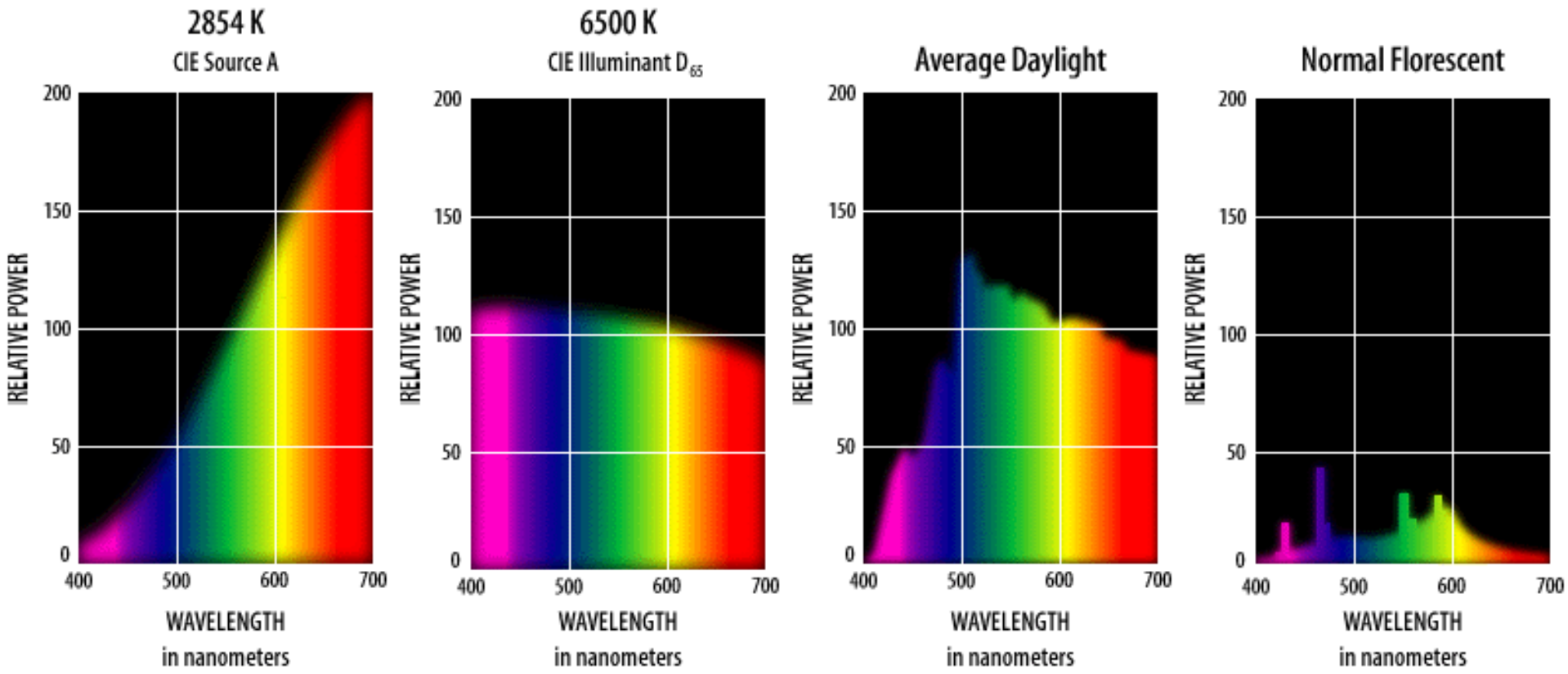


Spectral Power Distribution

- The **Spectral Power Distribution** (SPD) of a light is a function P(λ) which defines the power in the light at each wavelength



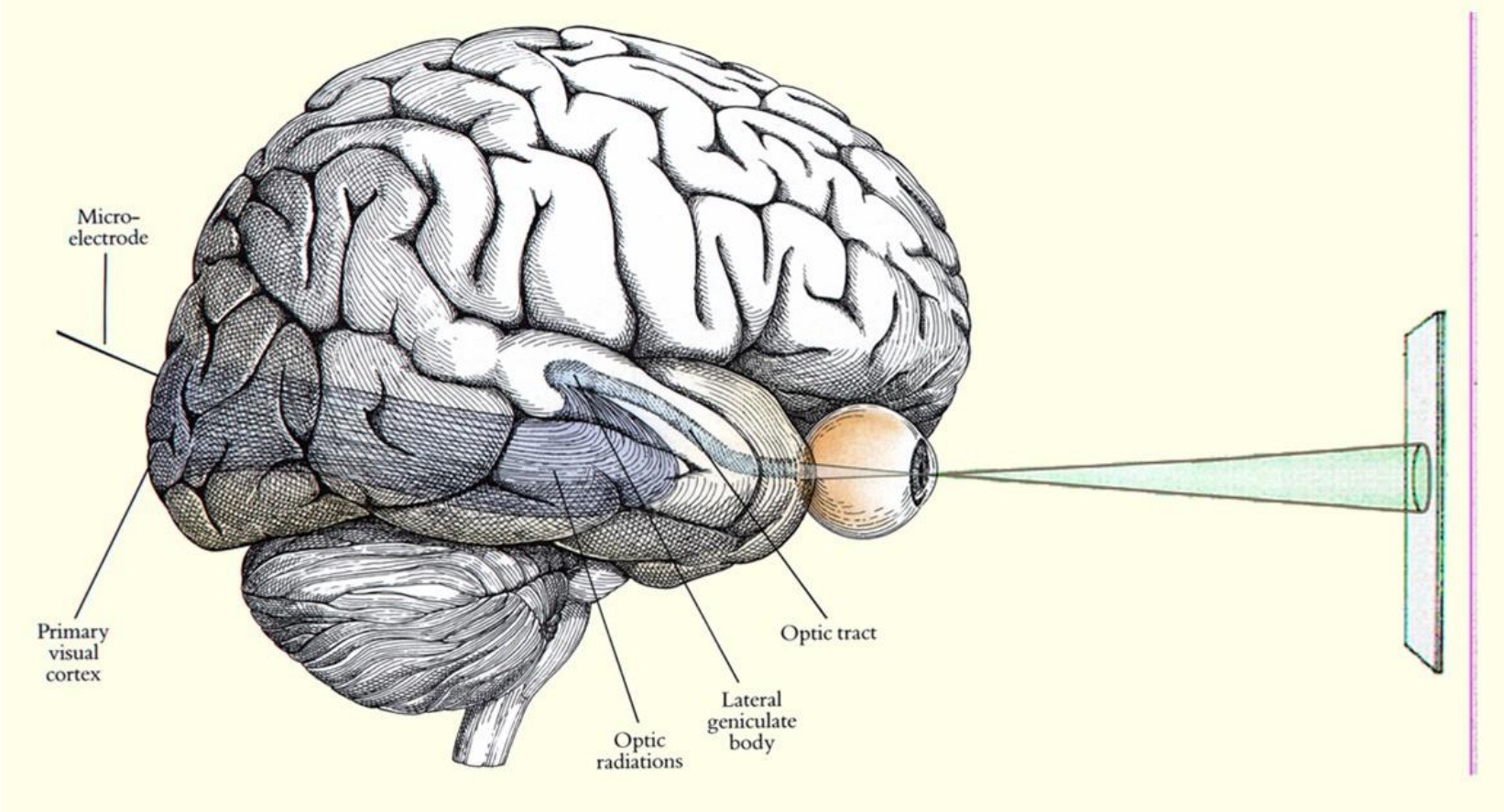
Examples


2854 K
CIE Source A
6500 K
CIE Illuminant D65
Average Daylight
Normal Florescent
RELATIVE POWER
200
150
100
50
0
400
500
600
700
WAVELENGTH
in nanometers

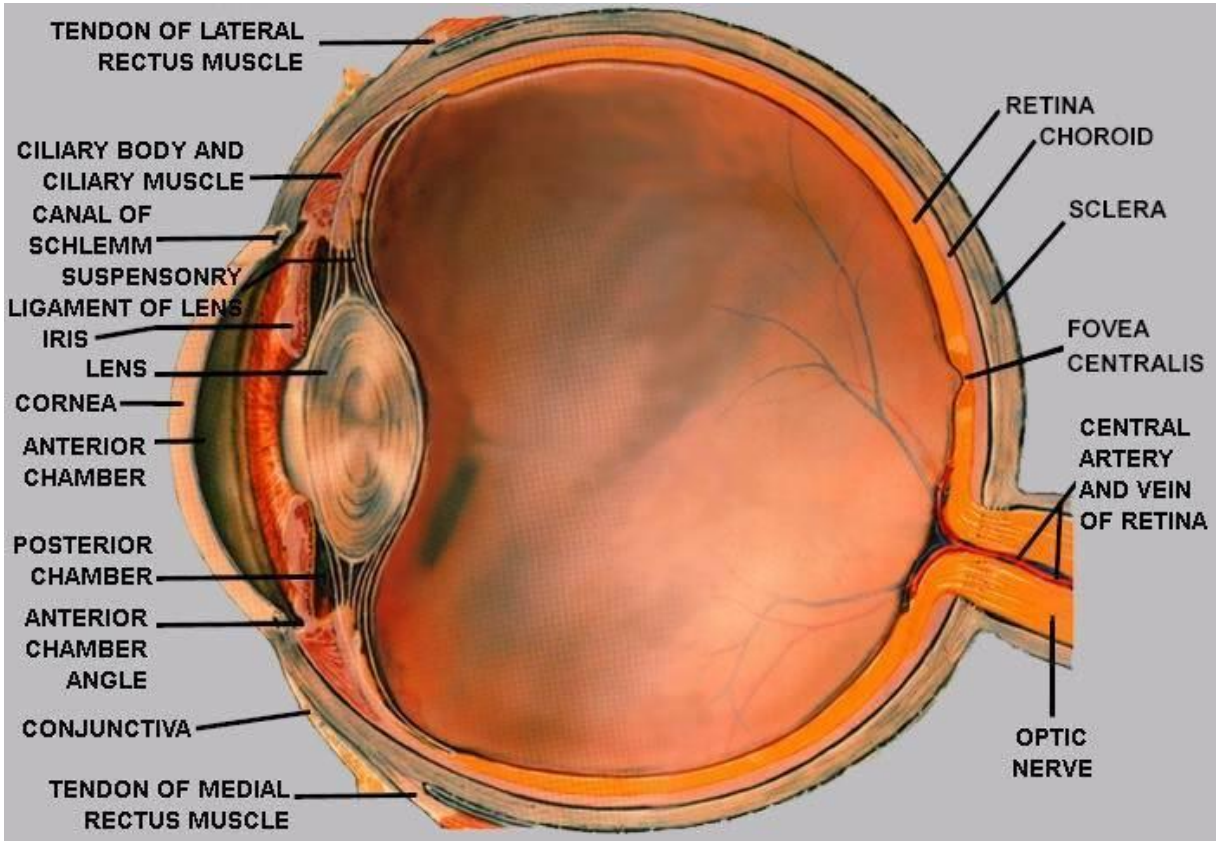
The Interaction of Light and Matter

- Some or all of the light may be absorbed depending on the pigmentation of the object.

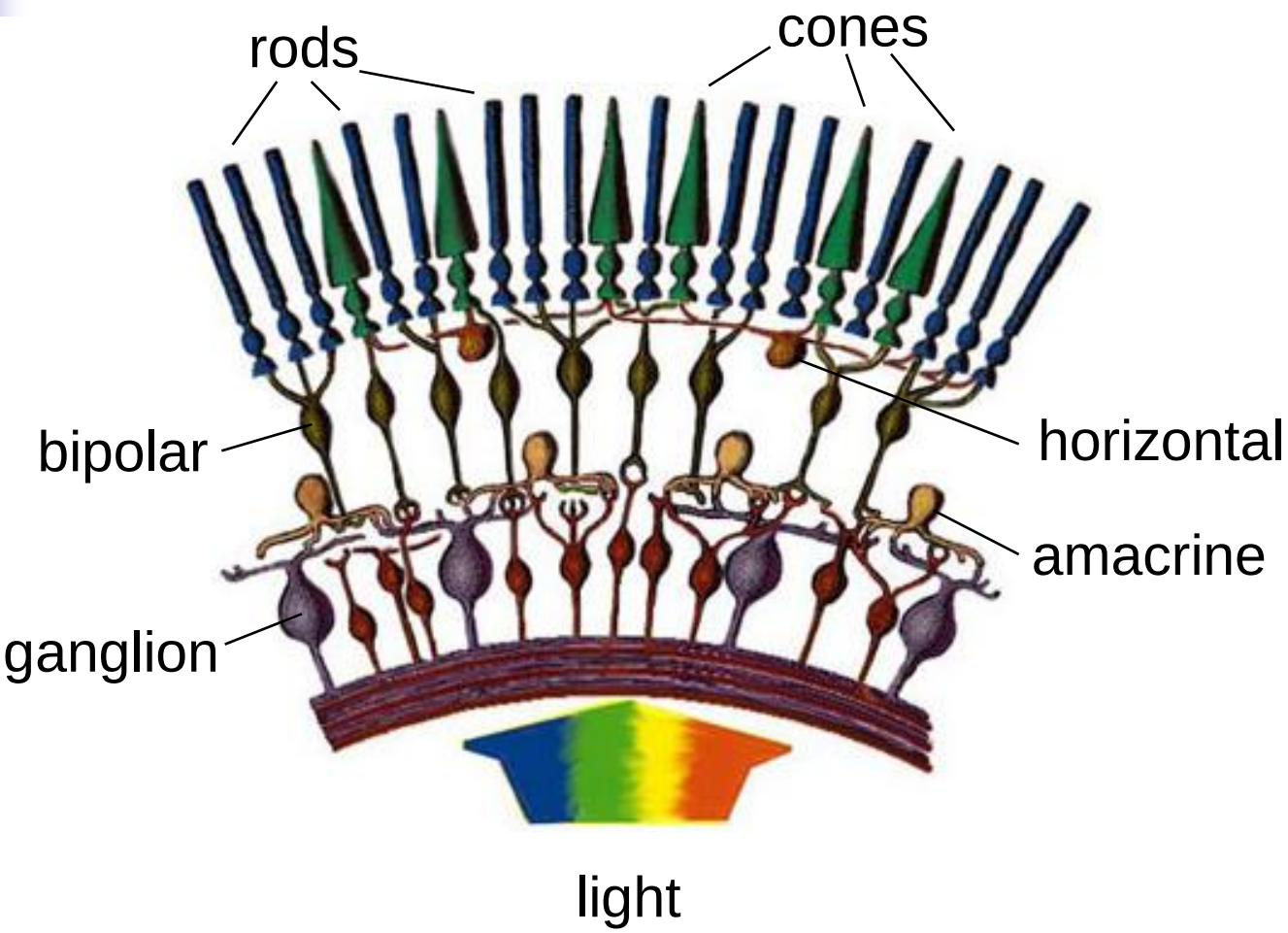
The Physiology of Human Vision



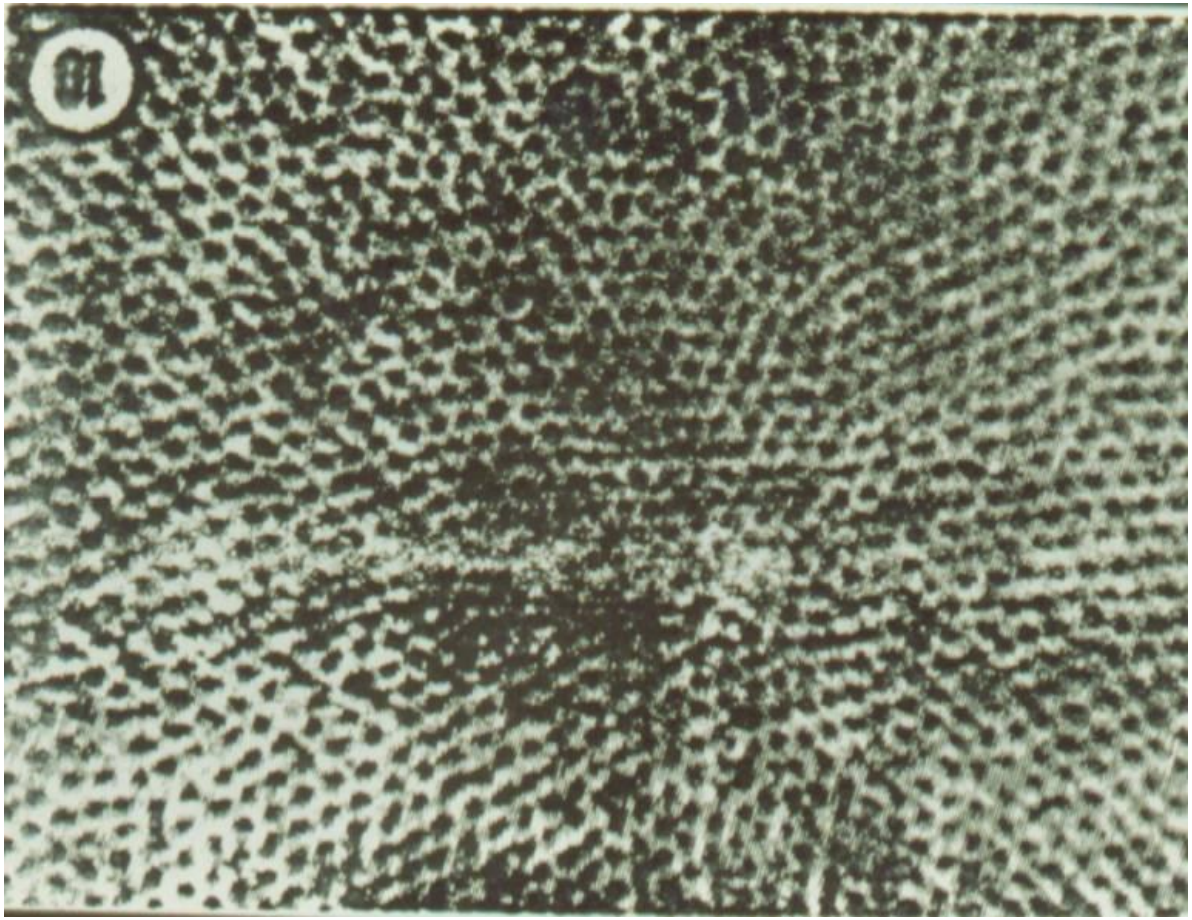
The Human Eye



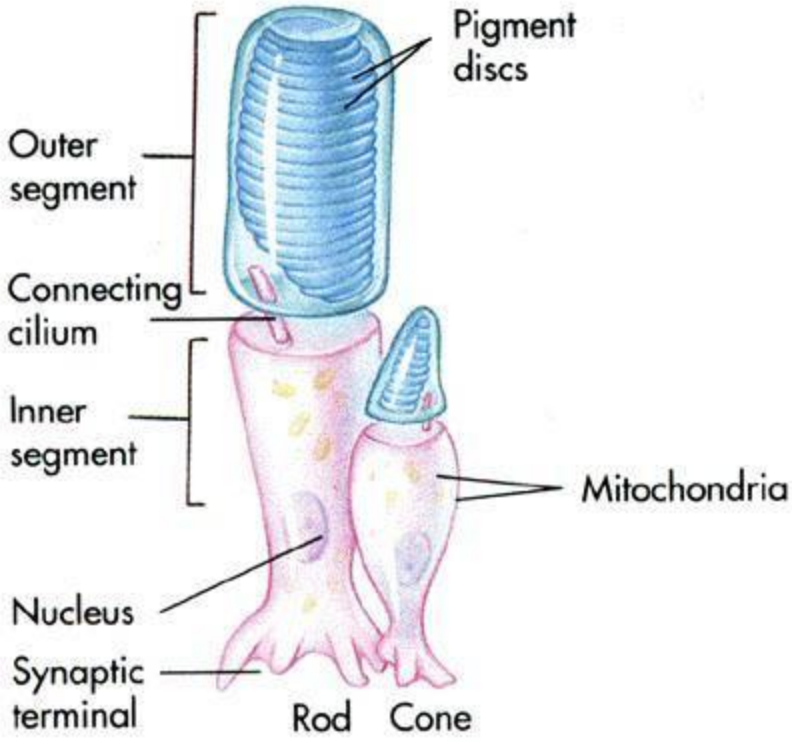
The Human Retina

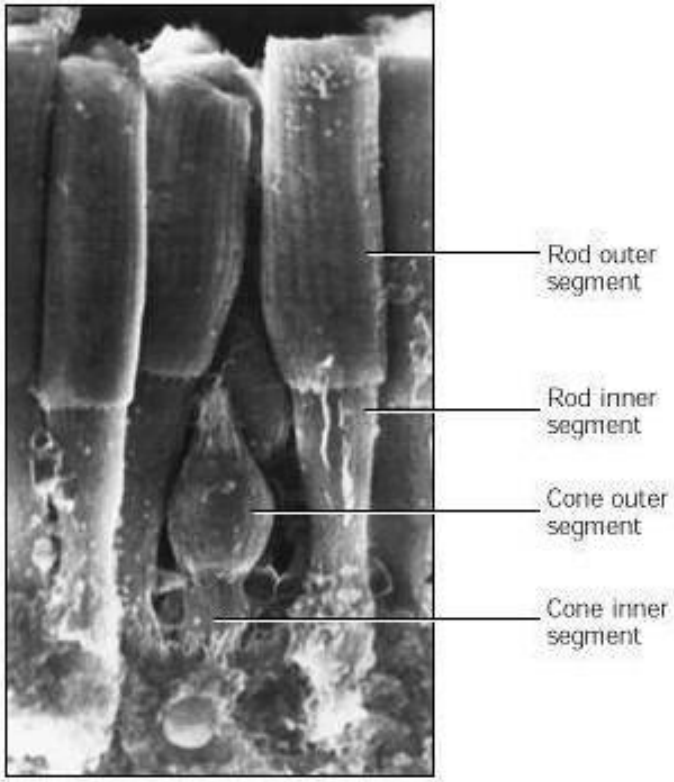


The Human Retina



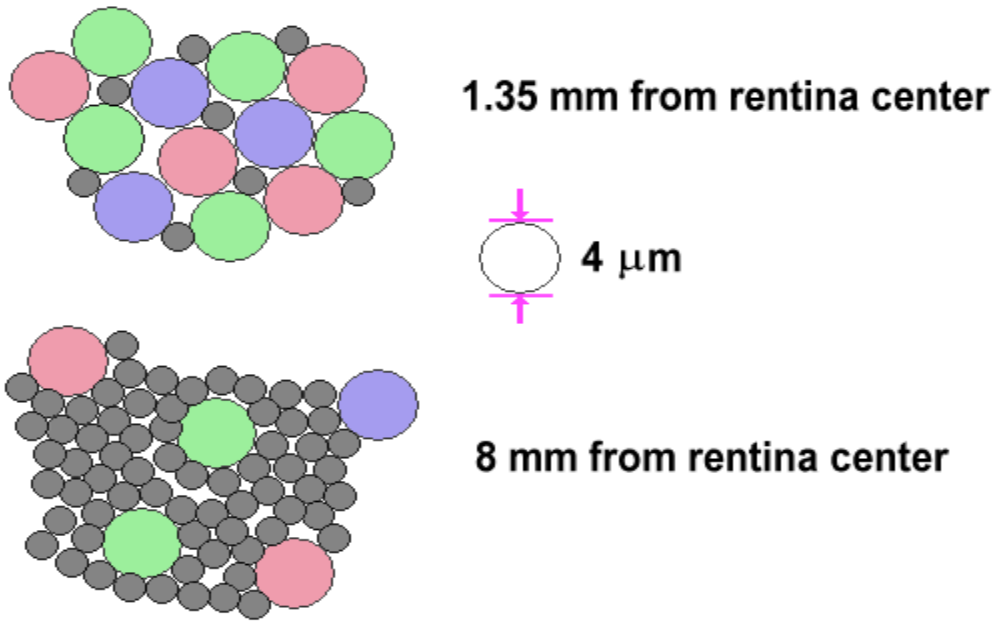
Retinal Photoreceptors





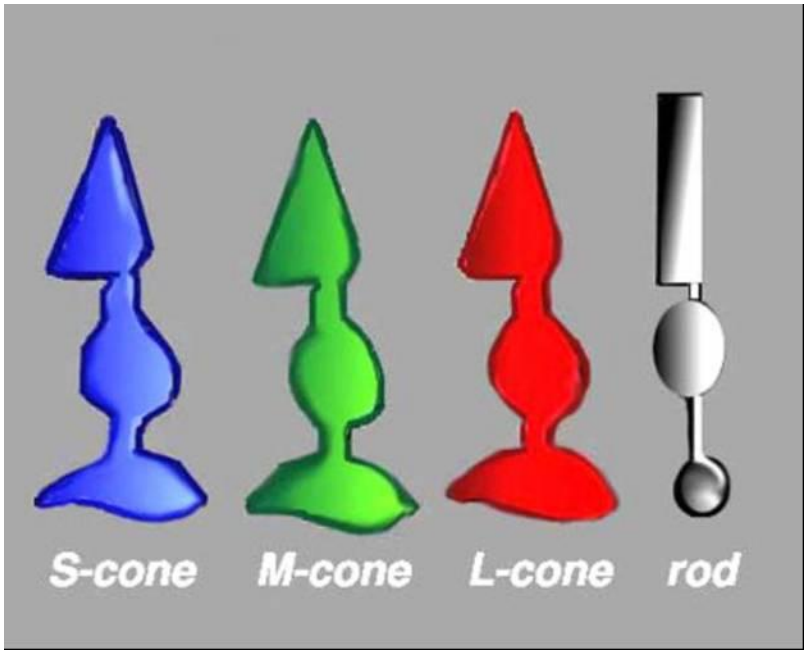
Cones

- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Density decreases with distance from fovea.



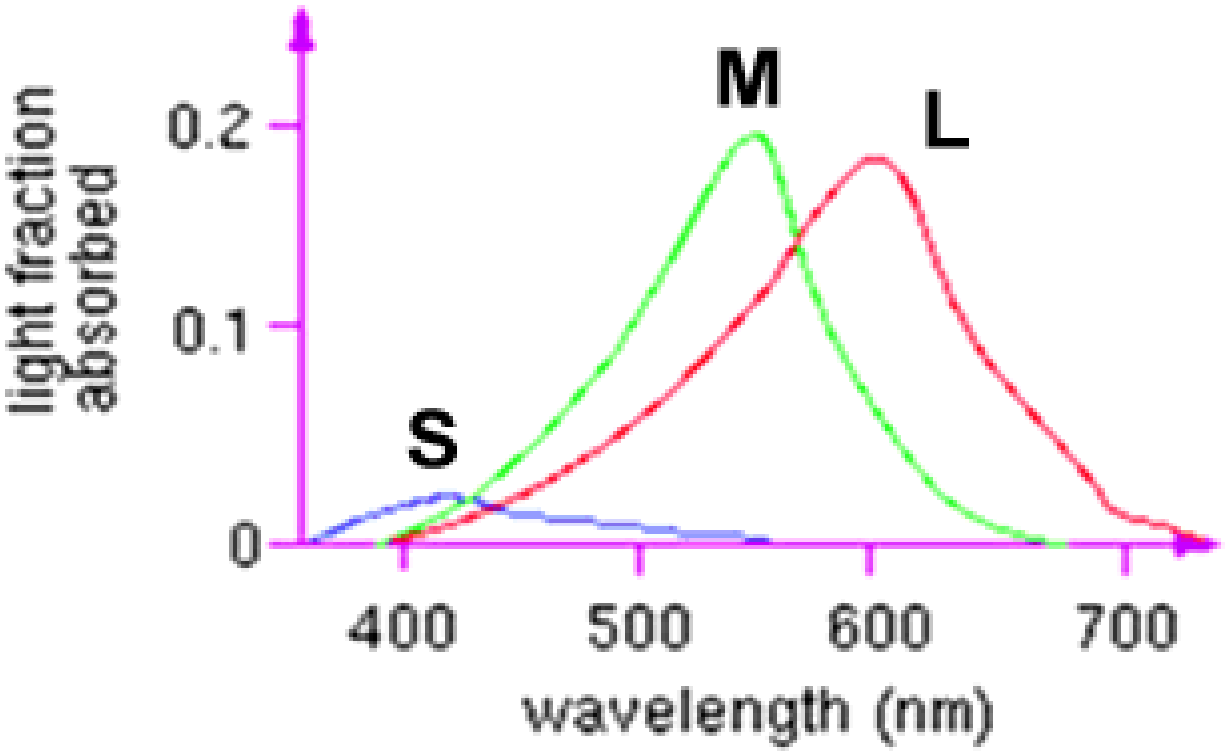
3 Types of Cones

- **L**-cones, most sensitive to red light (610 nm)
- **M**-cones, most sensitive to green light (560 nm)
- **S**-cones, most sensitive to blue light (430 nm)



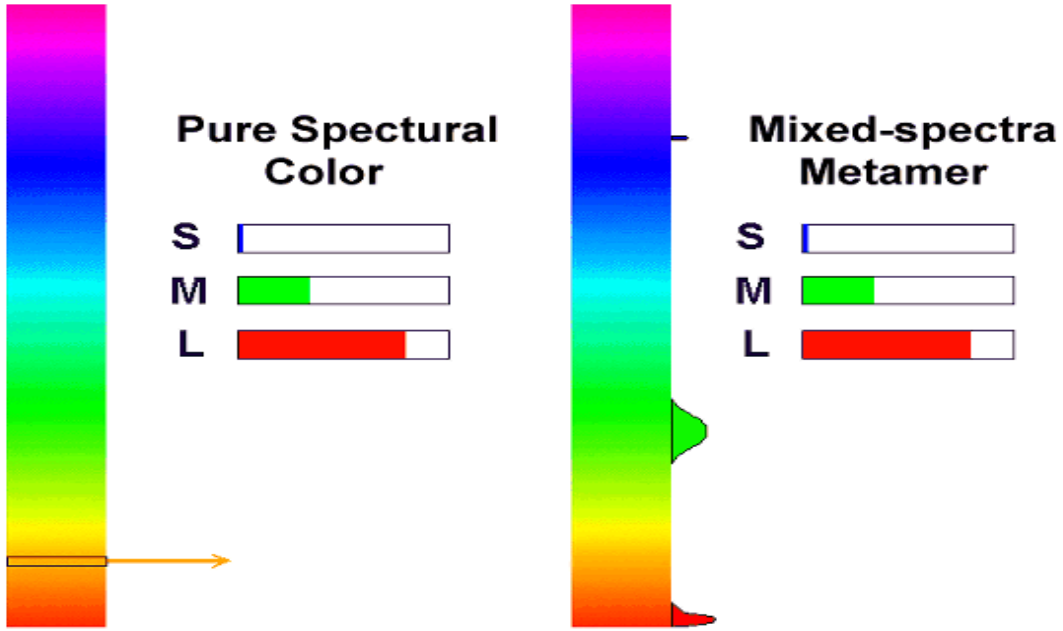
Cones Spectral Sensitivity

$$\boxed{(L, M, S)} \Leftarrow \quad L = \int_{\lambda} P(\lambda) L(\lambda) d\lambda$$



Metamers

- Two lights that appear the same visually. They might have different SPDs (spectral power distributions)



History

- Tomas Young (1773-1829)

  "A few different retinal receptors operating with different wavelength sensitivities will allow humans to perceive the number of colors that they do. "

- James Clerk Maxwell (1872)

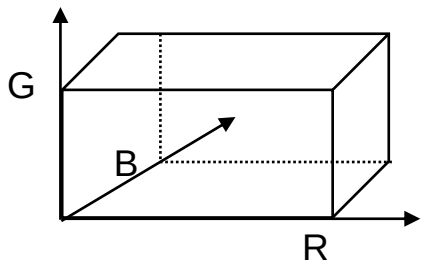
  "We are capable of feeling three different color sensations. Light of different kinds excites three sensations in different proportions, and it is by the different combinations of these three primary sensations that all the varieties of visible color are produced. "

- Trichromatic: "Tri"=three "chroma"=color

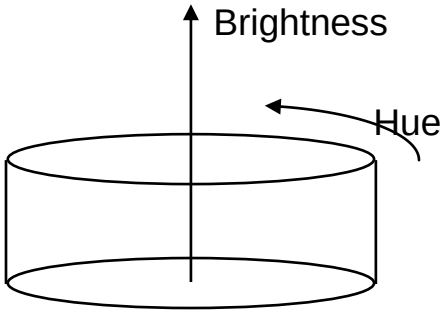
3D Color Spaces

- Three types of cones suggests color is a 3D quantity. How to define 3D color space?

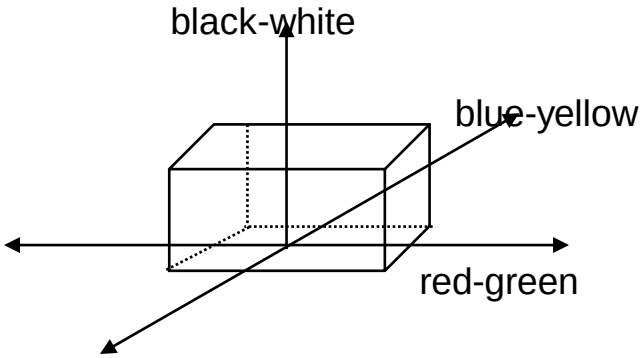
Cubic Color Spaces



Polar Color Spaces

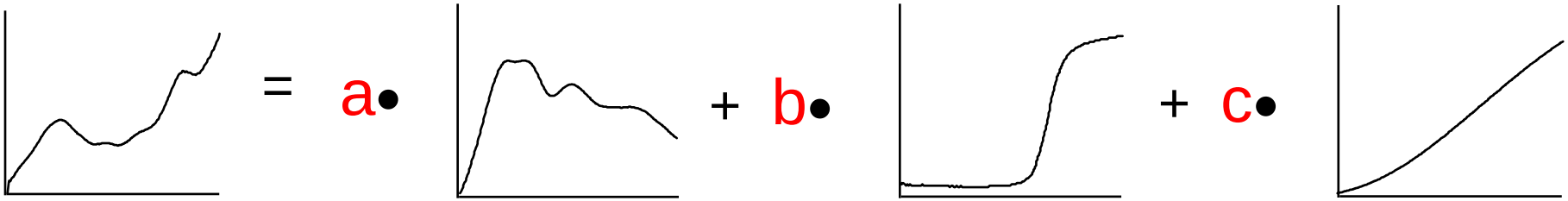


Opponent Color Spaces

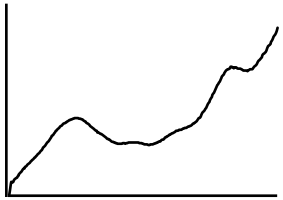


Linear Color Spaces

Colors in 3D color space can be described as linear combinations of 3 basis colors, called primaries



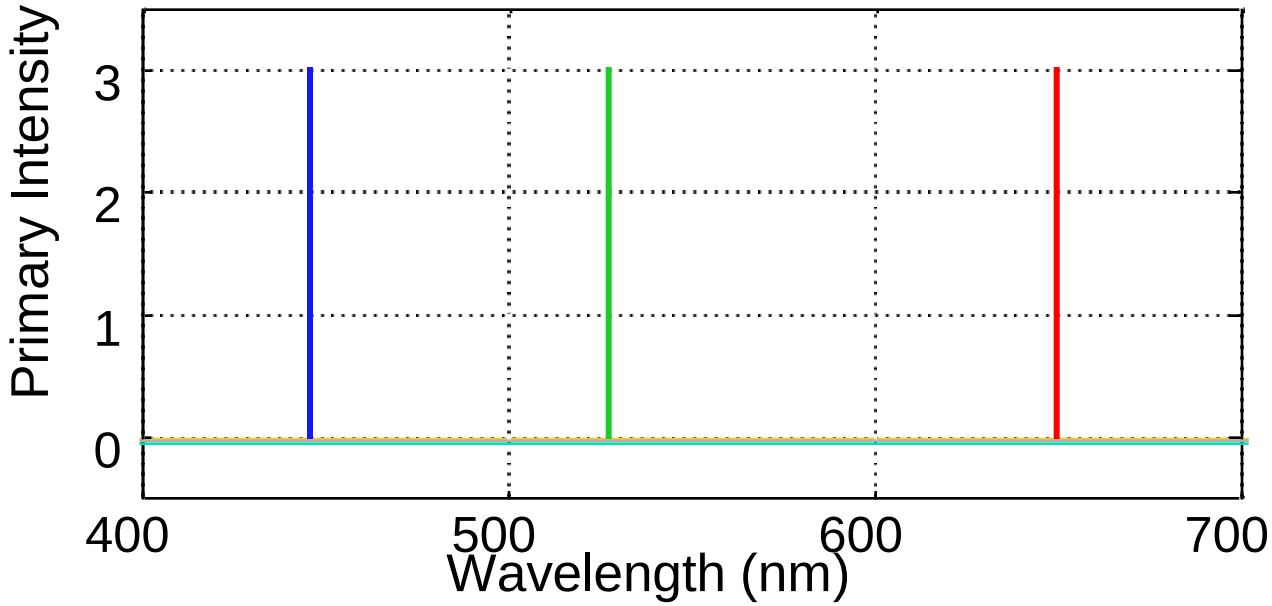
The representation of :



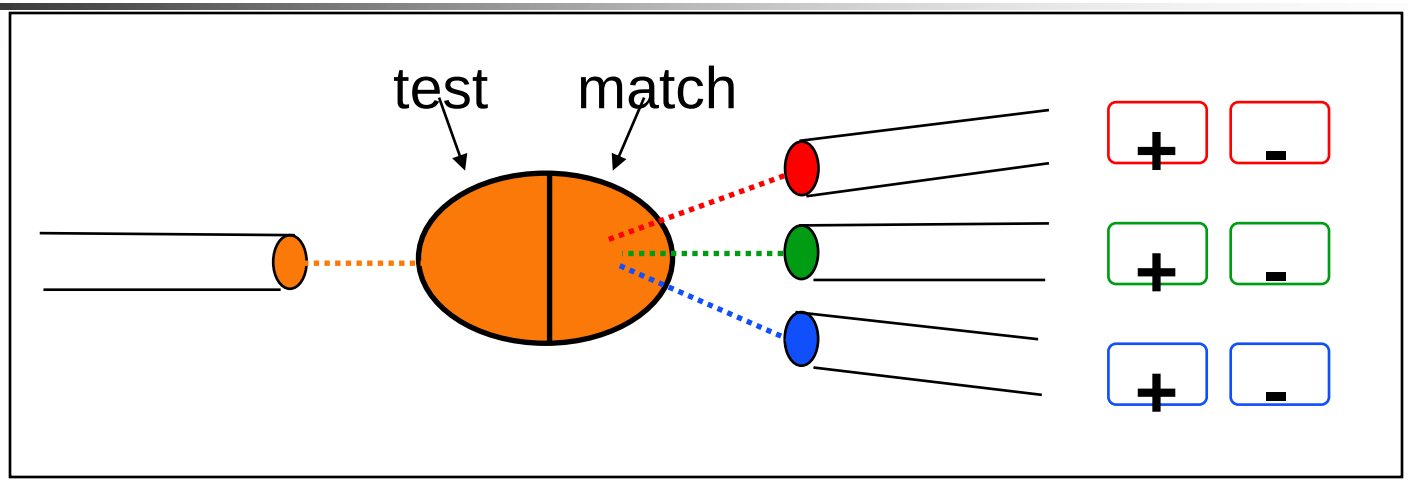
is then given by: (a, b, c)

RGB Color Model

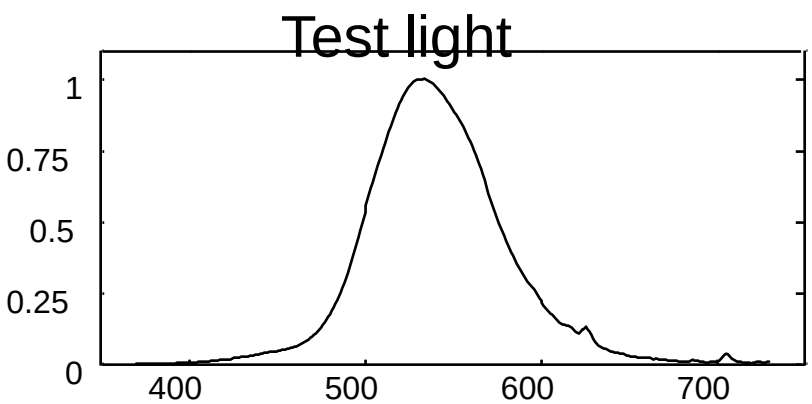
- RGB = Red, Green, Blue
- Choose 3 primaries as the basis SPDs (Spectral Power Distribution.)



Color Matching Experiment



- Three primary lights are set to match a test light



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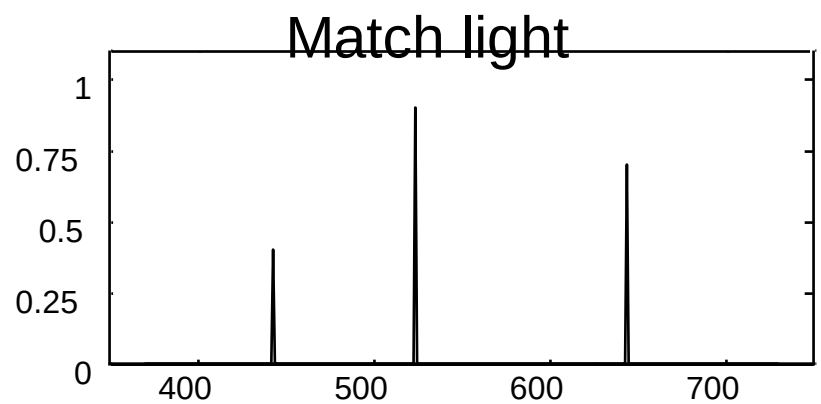
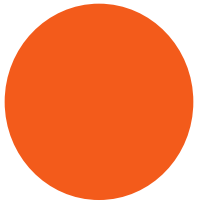
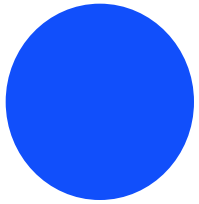


CIE-RGB

- Stiles & Burch (1959) Color matching Experiment.
- Primaries are: 444.4 525.3 645.2
- Given the 3 primaries, we can describe any light with 3 values (CIE-RGB):



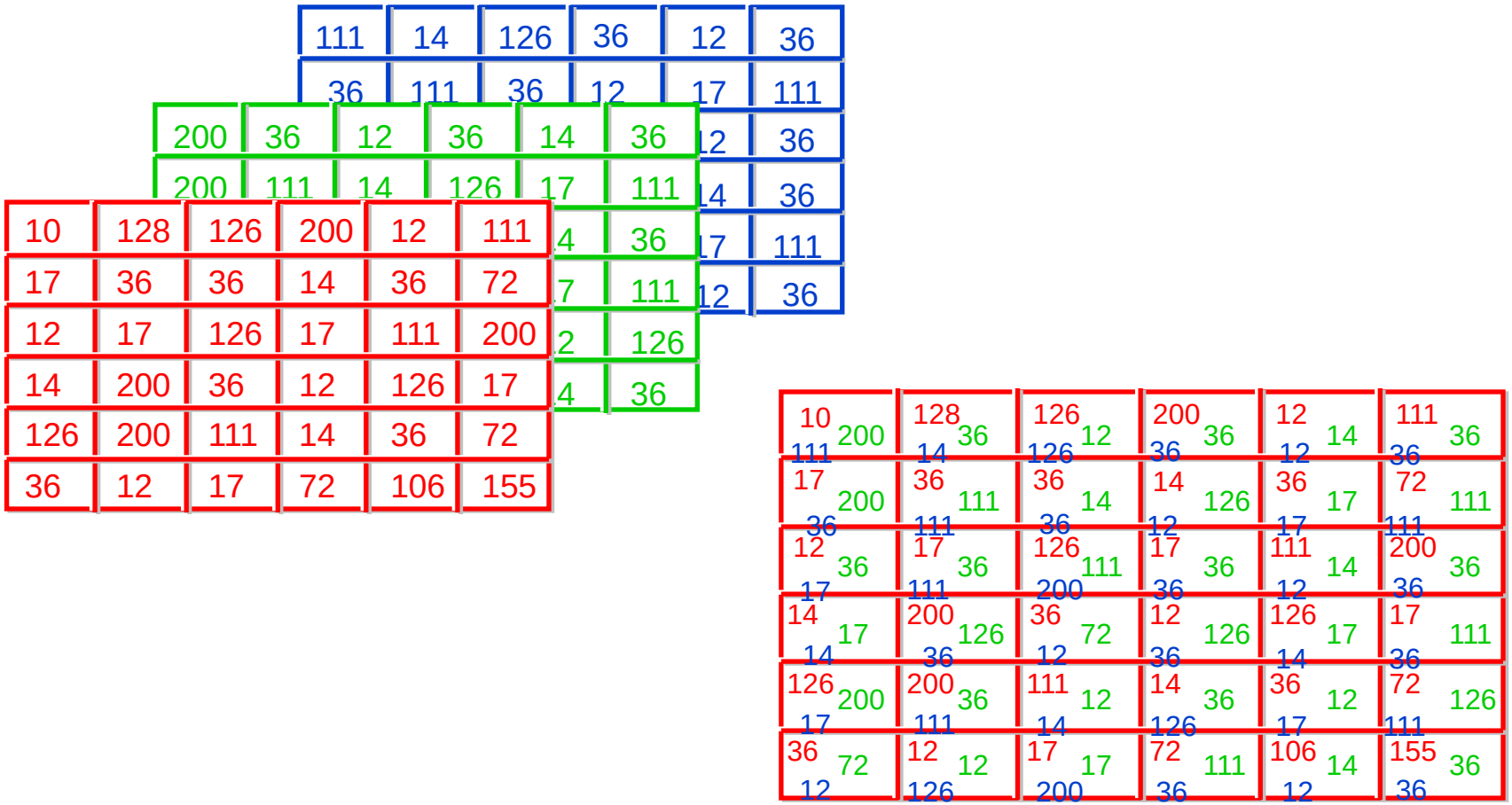
(85, 38, 10)



(21, 45, 72)

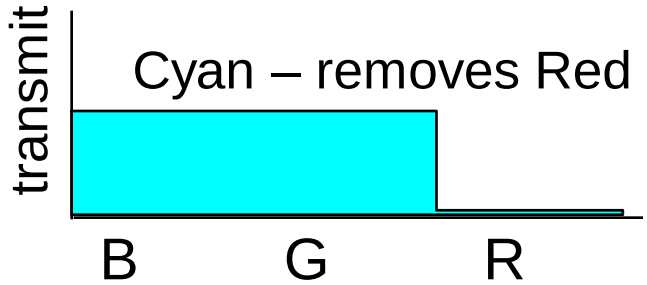
(65, 54, 73)

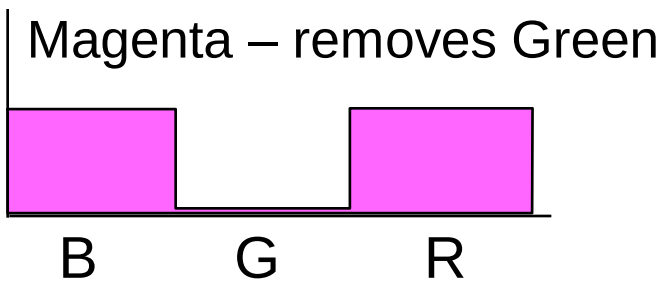
RGB Image

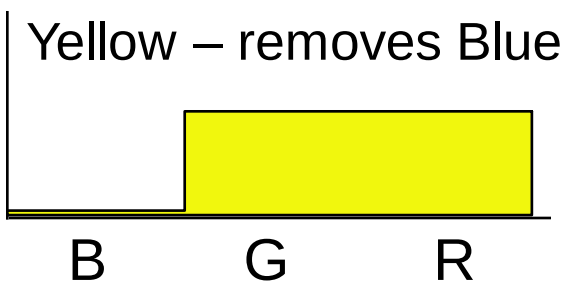

111 14 126 36 12 36
36 111 36 12 17 111
200 36 12 36 14 36
200 111 14 126 17 111
10 128 126 200 12 111
17 36 36 14 36 72
12 17 126 17 111 200
14 200 36 12 126 17
126 200 111 14 36 72
36 12 17 72 106 155

CMYK Color Model

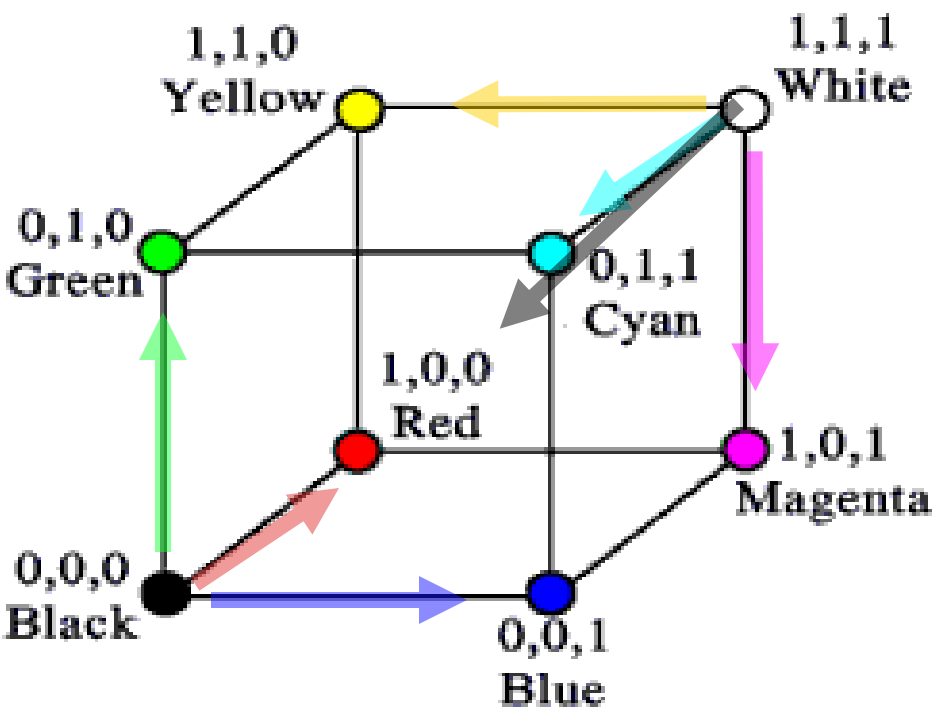
CMYK = Cyan, Magenta, Yellow, blacK





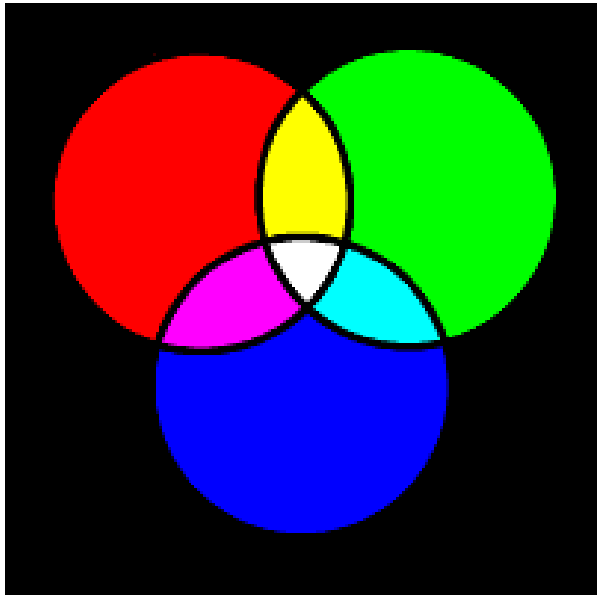


Black – removes all

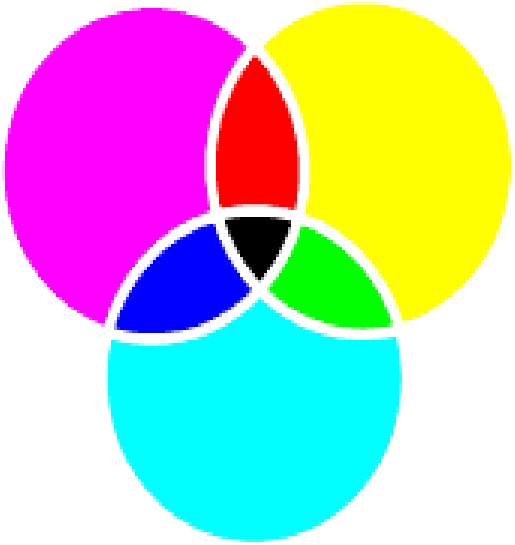


Combining Colors

Additive (RGB)

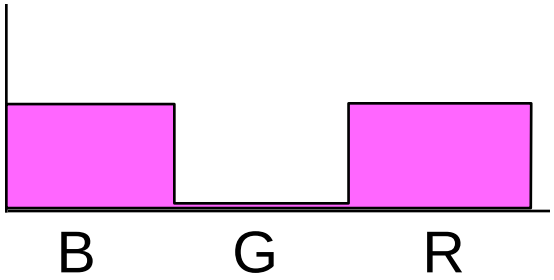


Subtractive (CMYK)



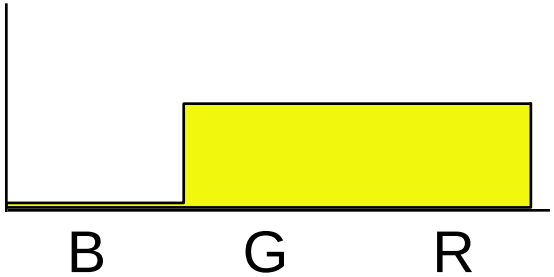
Example: red = magenta + yellow

magenta



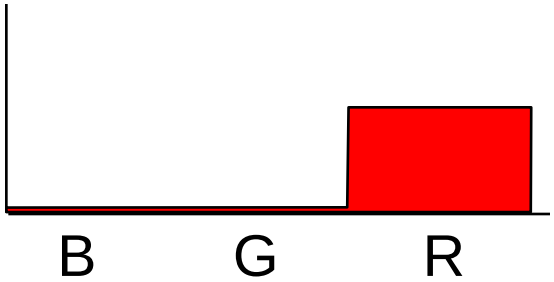
+

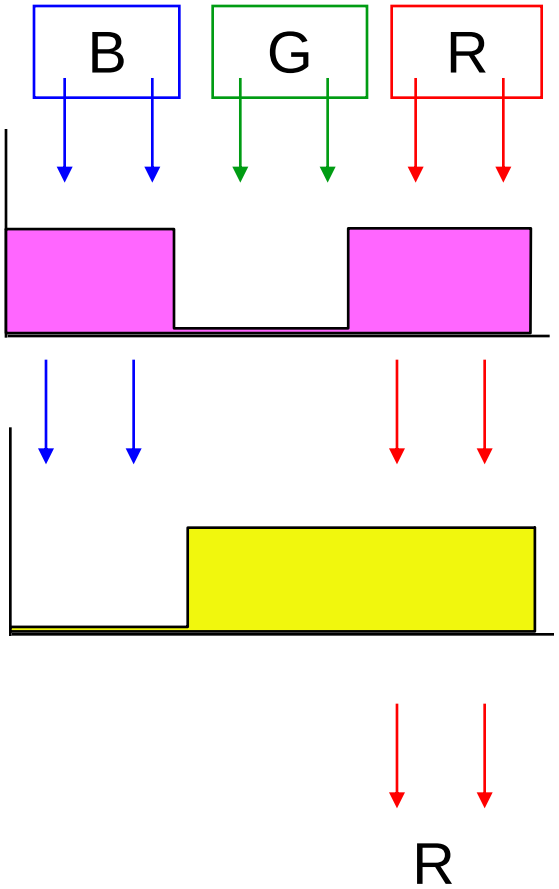
yellow



=

red

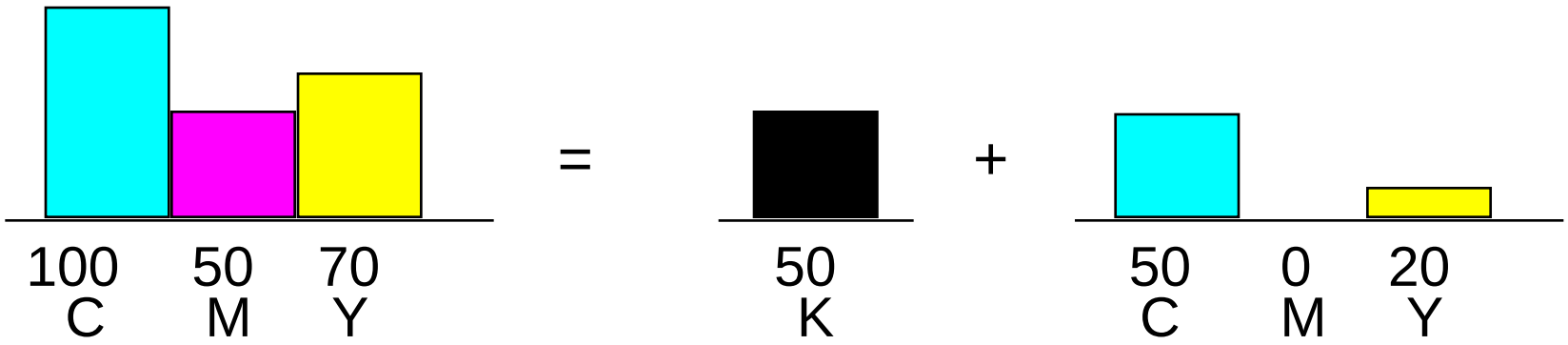




CMY + Black

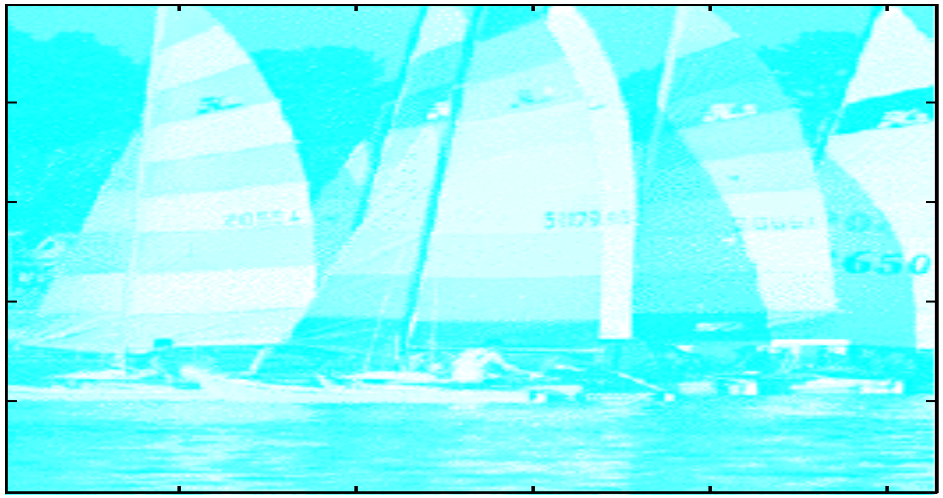
C + M + Y = K (black)

- Using three inks for black is expensive
- C+M+Y = dark brown not black
- Black instead of C+M+Y is crisper with more contrast

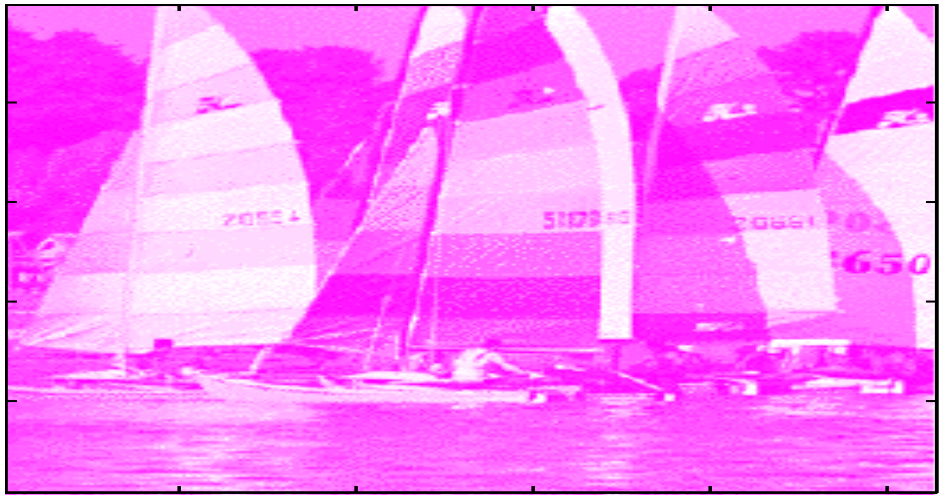


Example

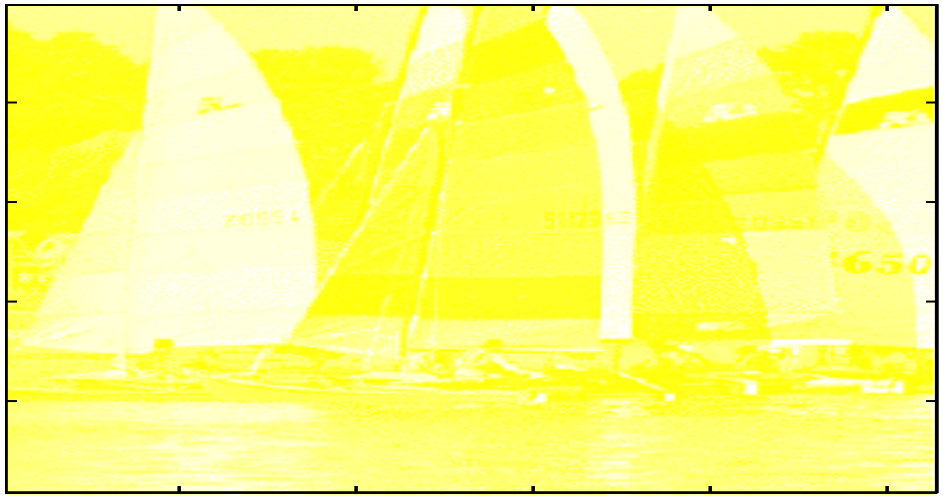
Example



Example



Example



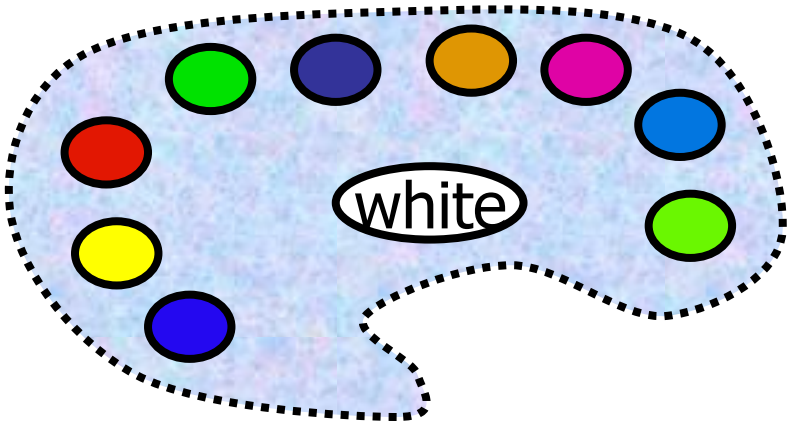
Example

From RGB to CMY

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

The Artist Point of View

- **Hue** - The color we see (red, green, purple)
- **Saturation** - How far is the color from gray (pink is less saturated than red, sky blue is less saturated than royal blue)
- **Brightness/Lightness (Luminance)** - How bright is the color



Munsell Color System

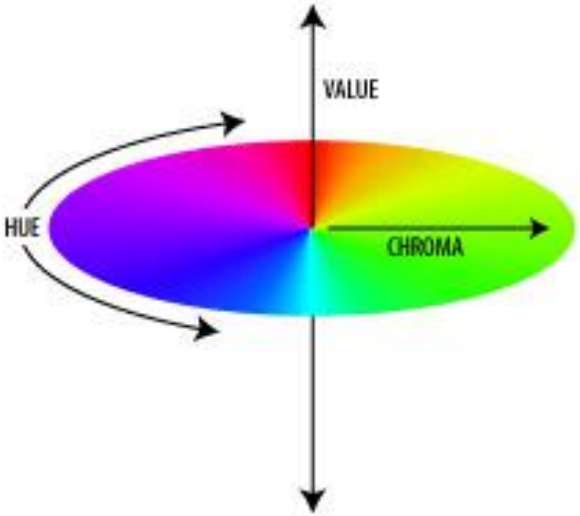
Equal perceptual steps in Hue Saturation Value.

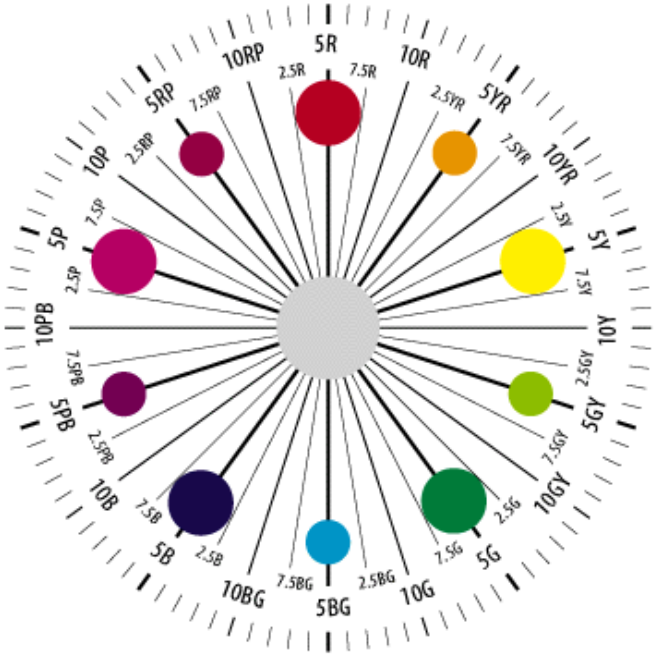
Hue: R, YR, Y, GY, G, BG, B, PB, P, RP
(each subdivided into 10)

Value: 0 ... 10 (dark ... pure white)

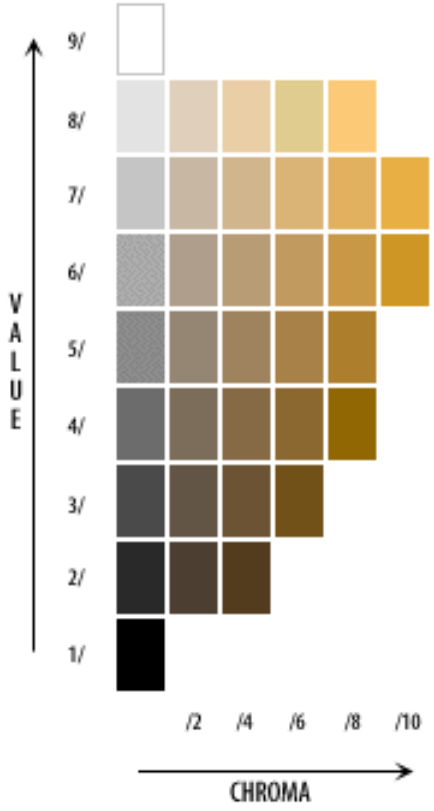
Chroma: 0 ... 20 (neutral ... saturated)

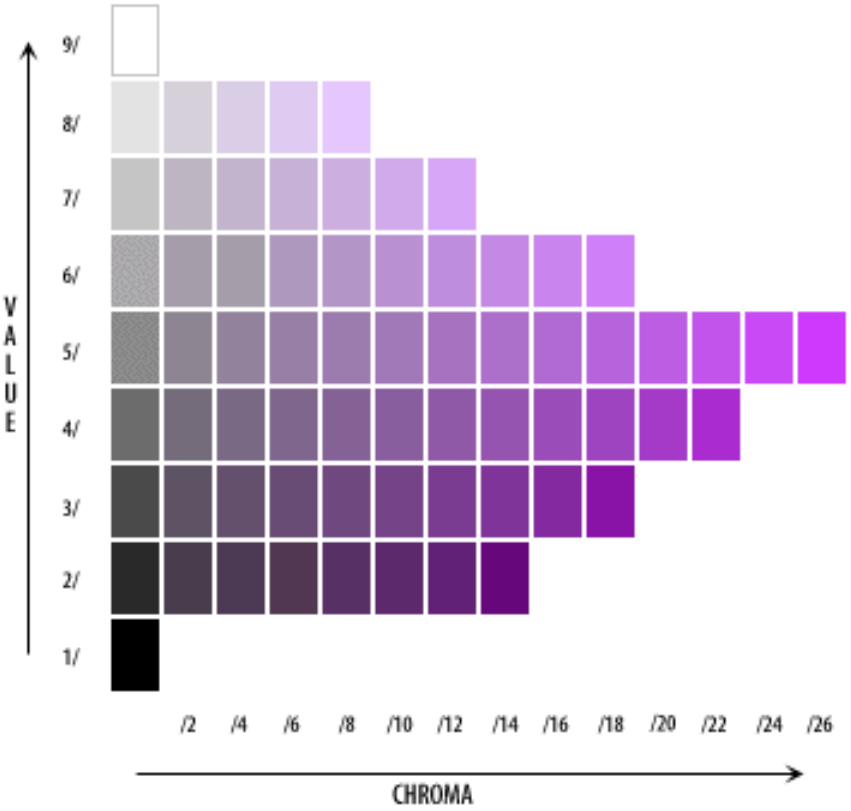
Example:
5YR 8/4



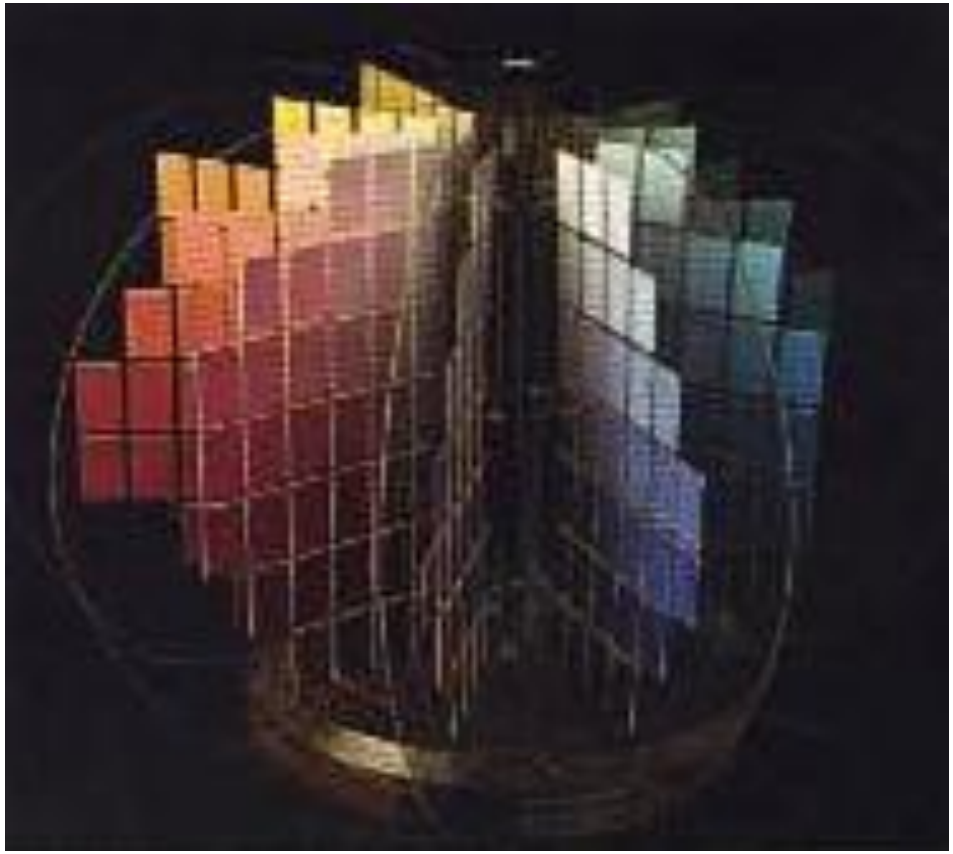


Munsell Book of Colors



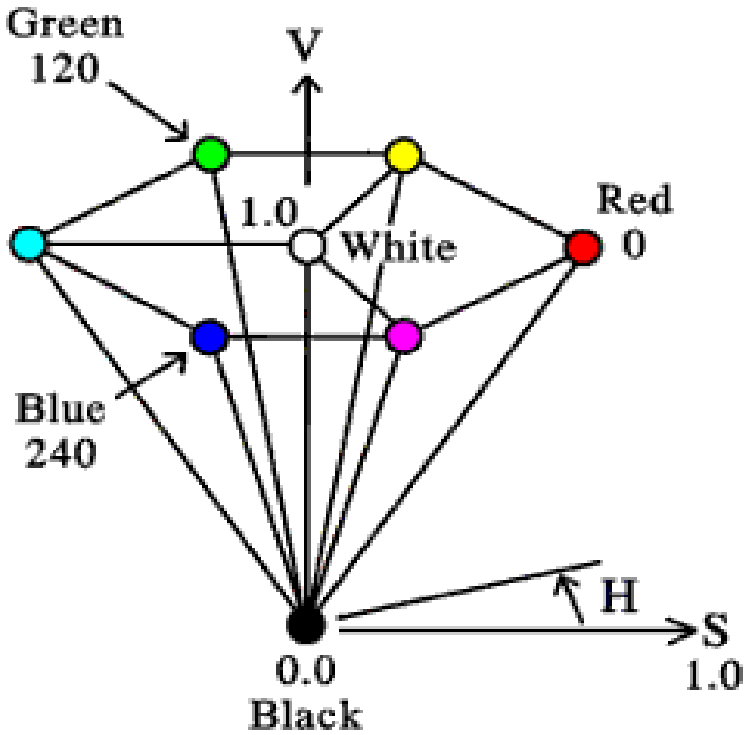


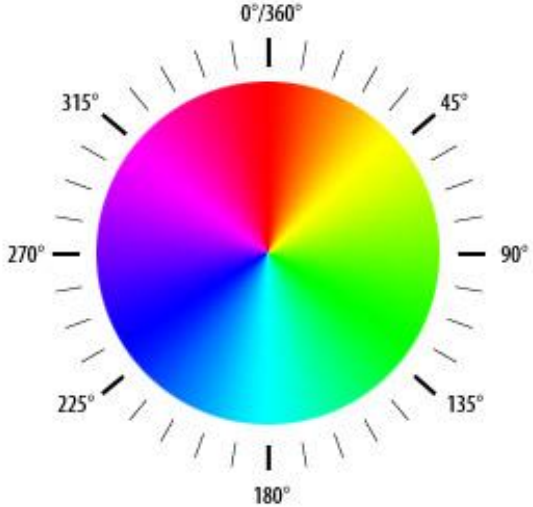
Munsell Book of Colors



HSV/HSB Color Space

HSV = Hue Saturation Value
HSB = Hue Saturation Brightness

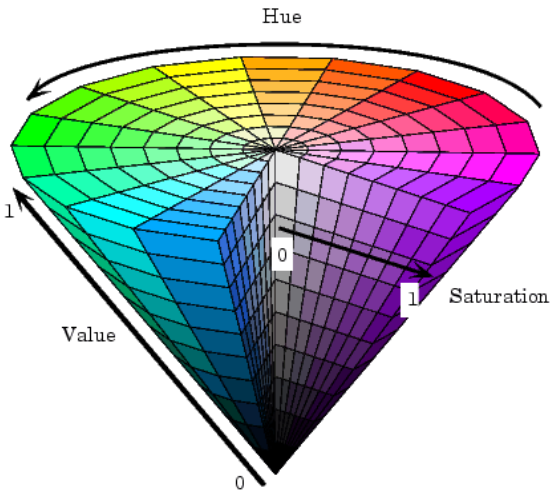


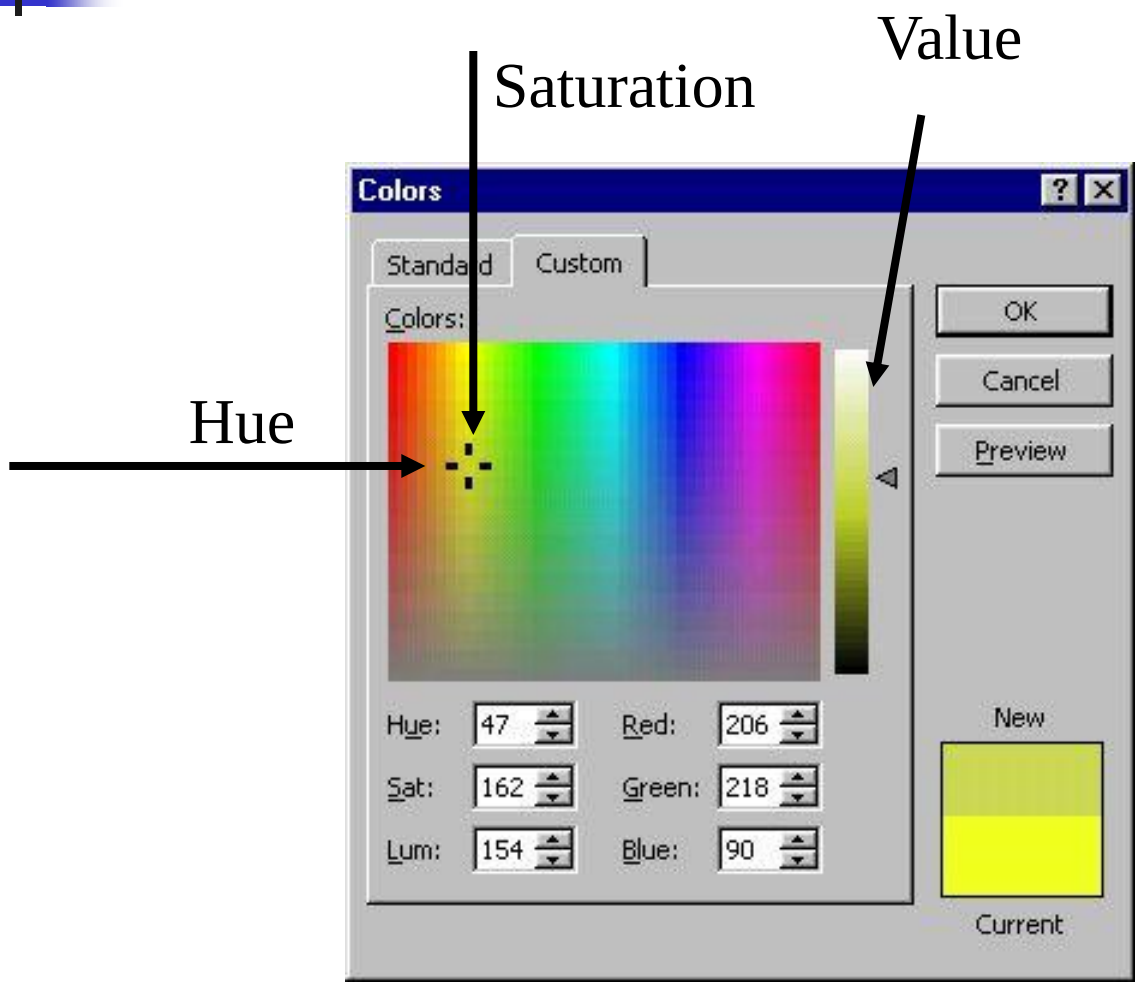


Saturation Scale

Brightness Scale

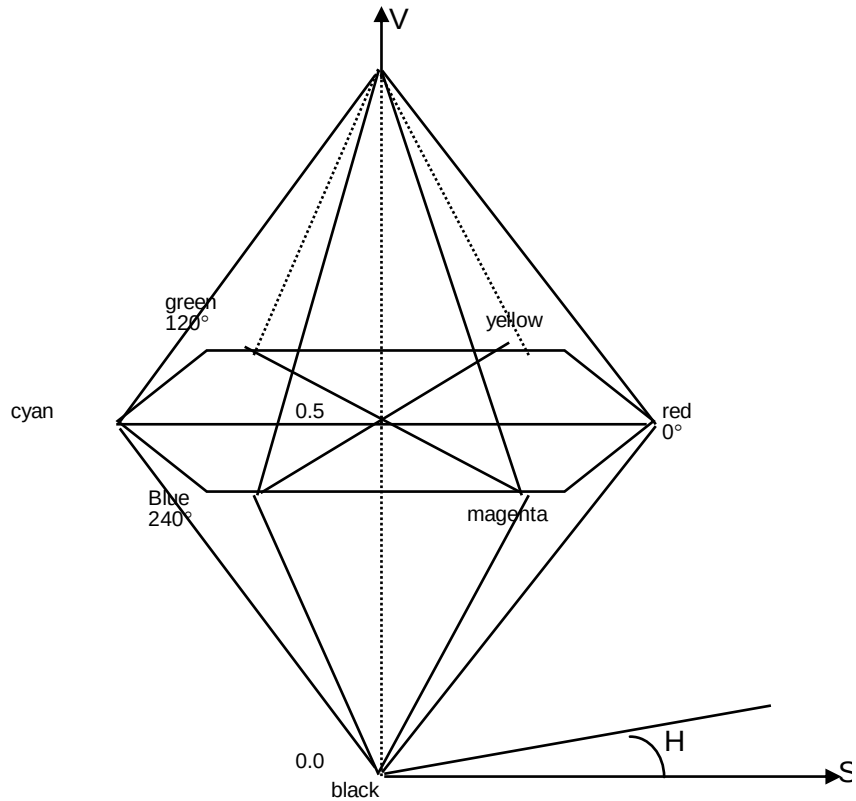
HSV

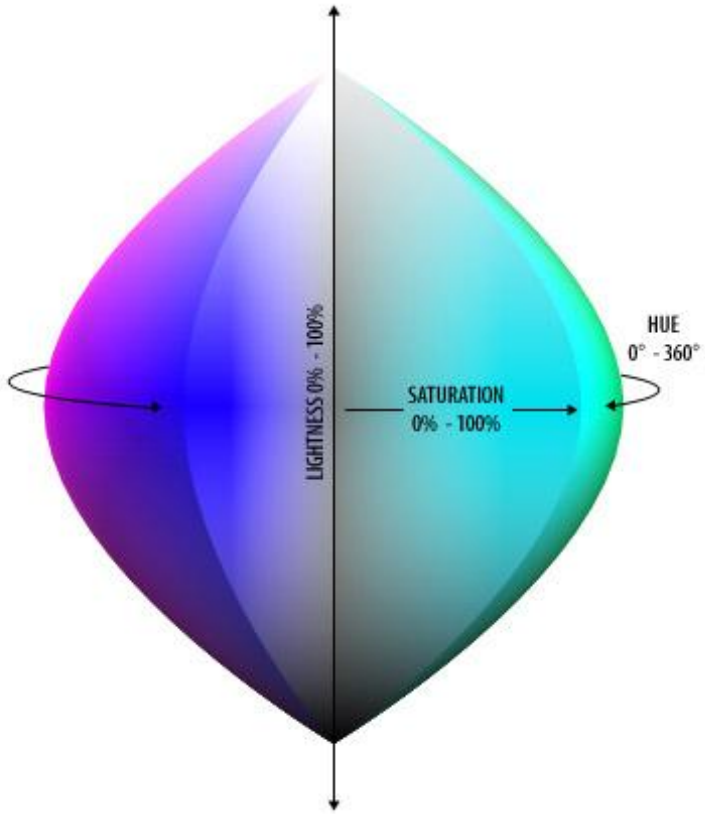

Hue
1
0
1
Saturation
Value
0


Saturation
Value
Hue
Colors
Standard
Custom
Colors:
OK
Cancel
Preview
Hue: 47
Red: 206
Sat: 162
Green: 218
Lum: 154
Blue: 90
New
Current

HLS Color Space

HLS = Hue Lightness Saturation

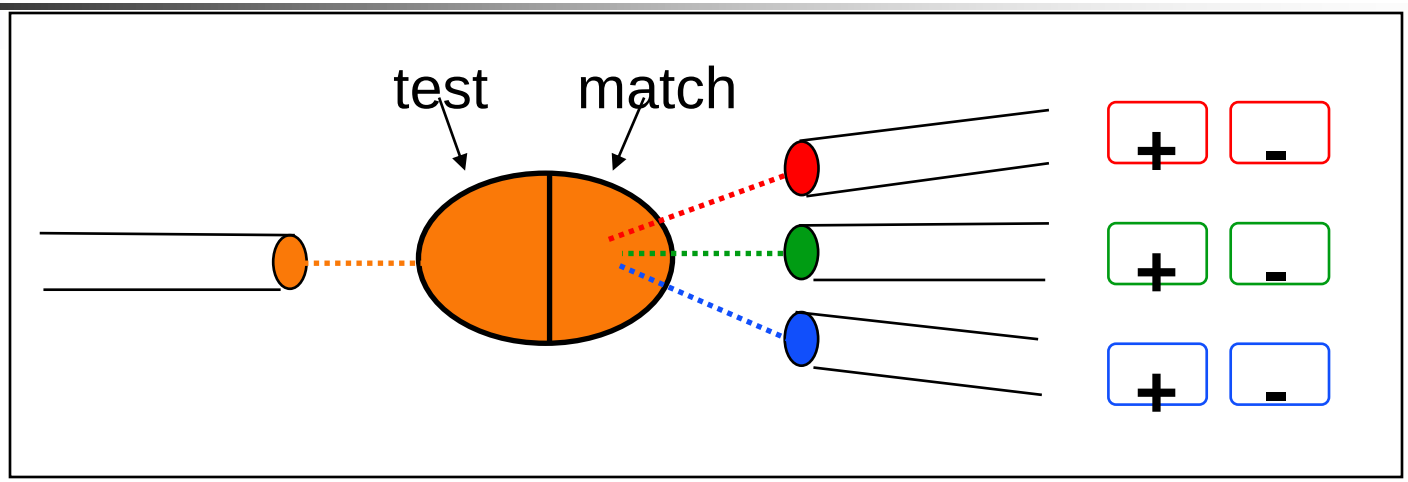




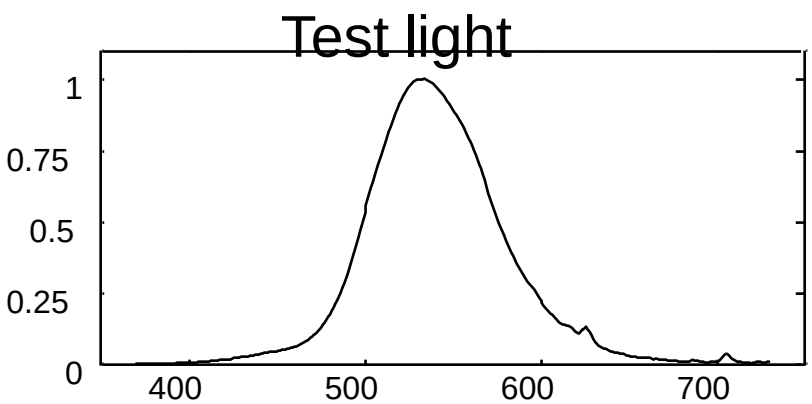
Back to RGB

- Problem 1: RGB differ from one device to another

Color Matching Experiment



- Three primary lights are set to match a test light



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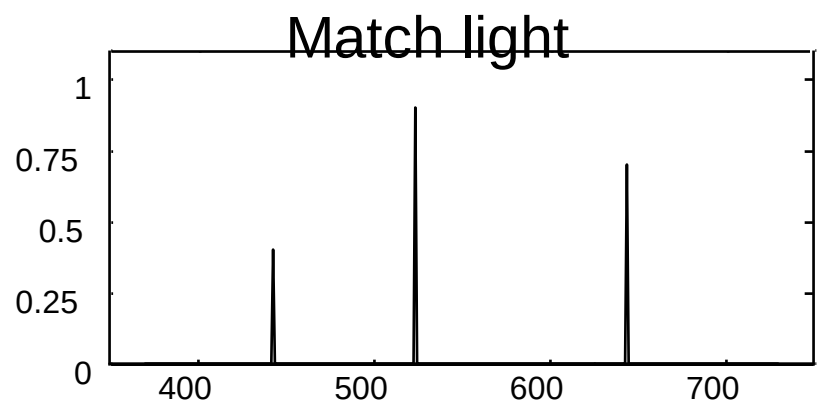
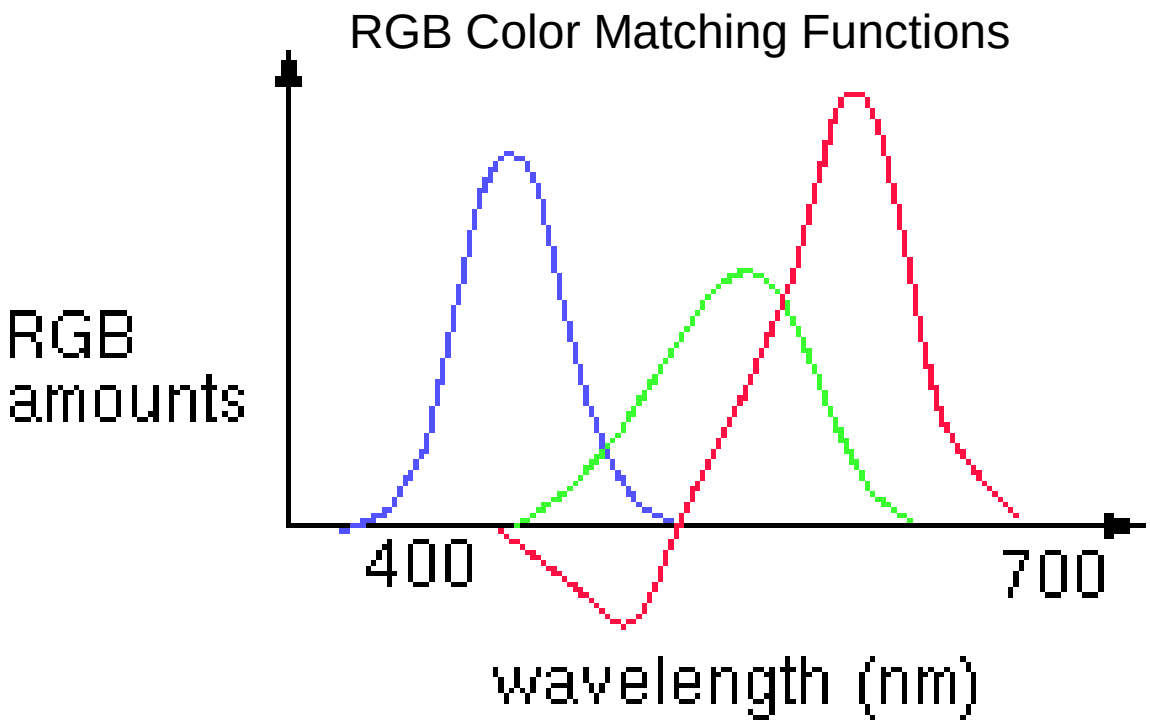


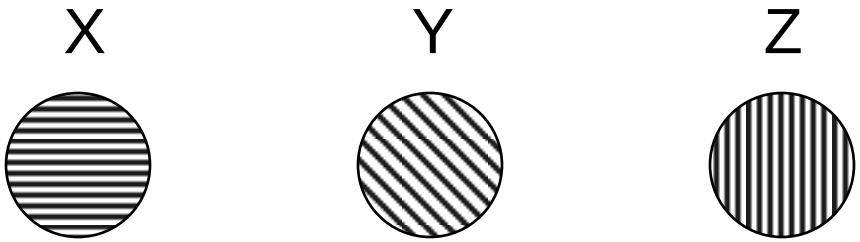
Back to RGB

- Problem 2: RGB cannot represent all colors



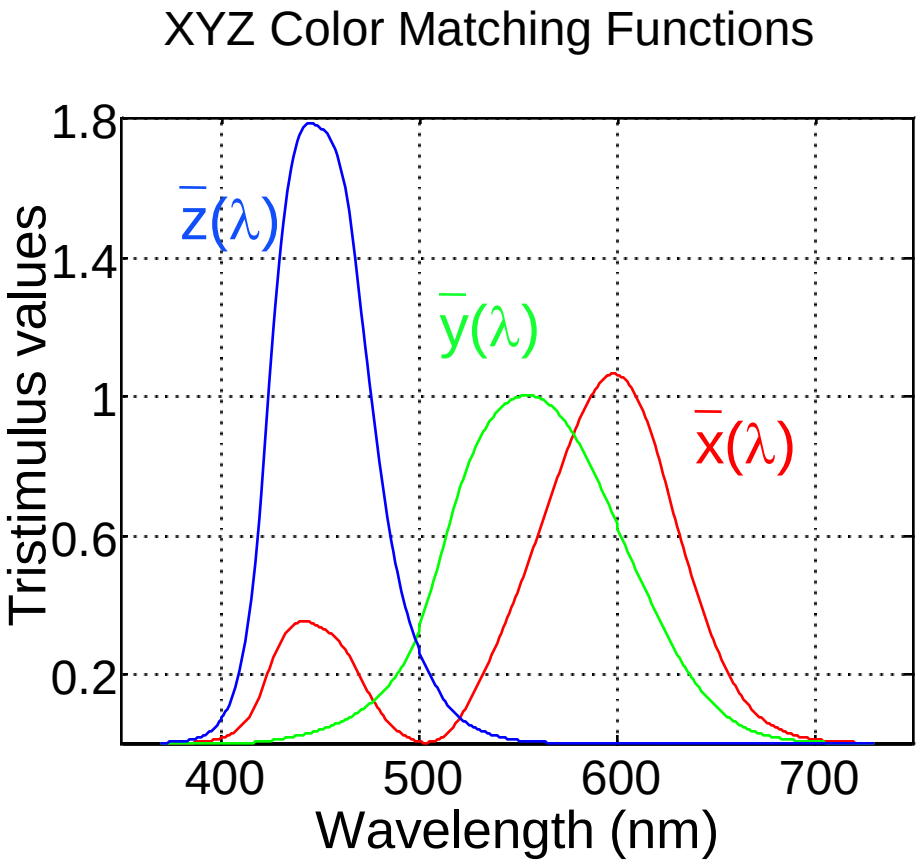
CIE Color Standard - 1931

- CIE - Commision Internationale d'Eclairage
- 1931 - defined a standard system for color representation.
- XYZ tristimulus coordinate system.



XYZ Spectral Power Distribution

- Non negative over the visible wavelengths.
- The 3 primaries associated with x y z spectral power distribution are unrealizable (negative power in some of the wavelengths).
- The color matching of Y is equal to the spectral luminous efficiency curve.

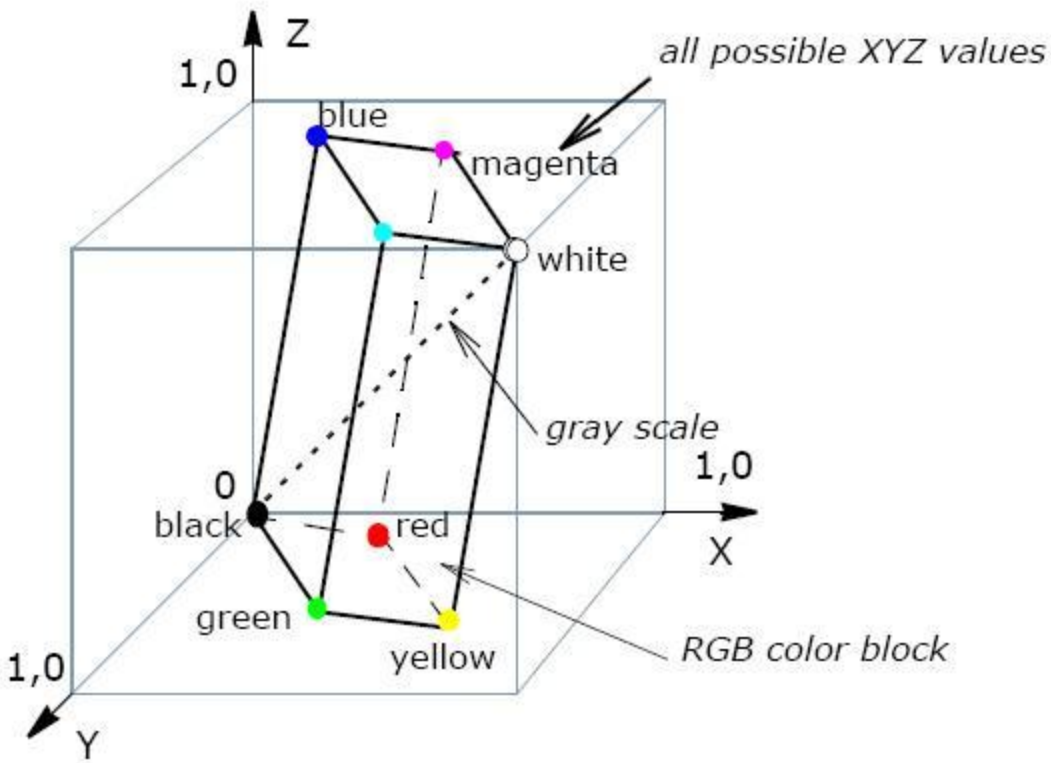


RGB to XYZ

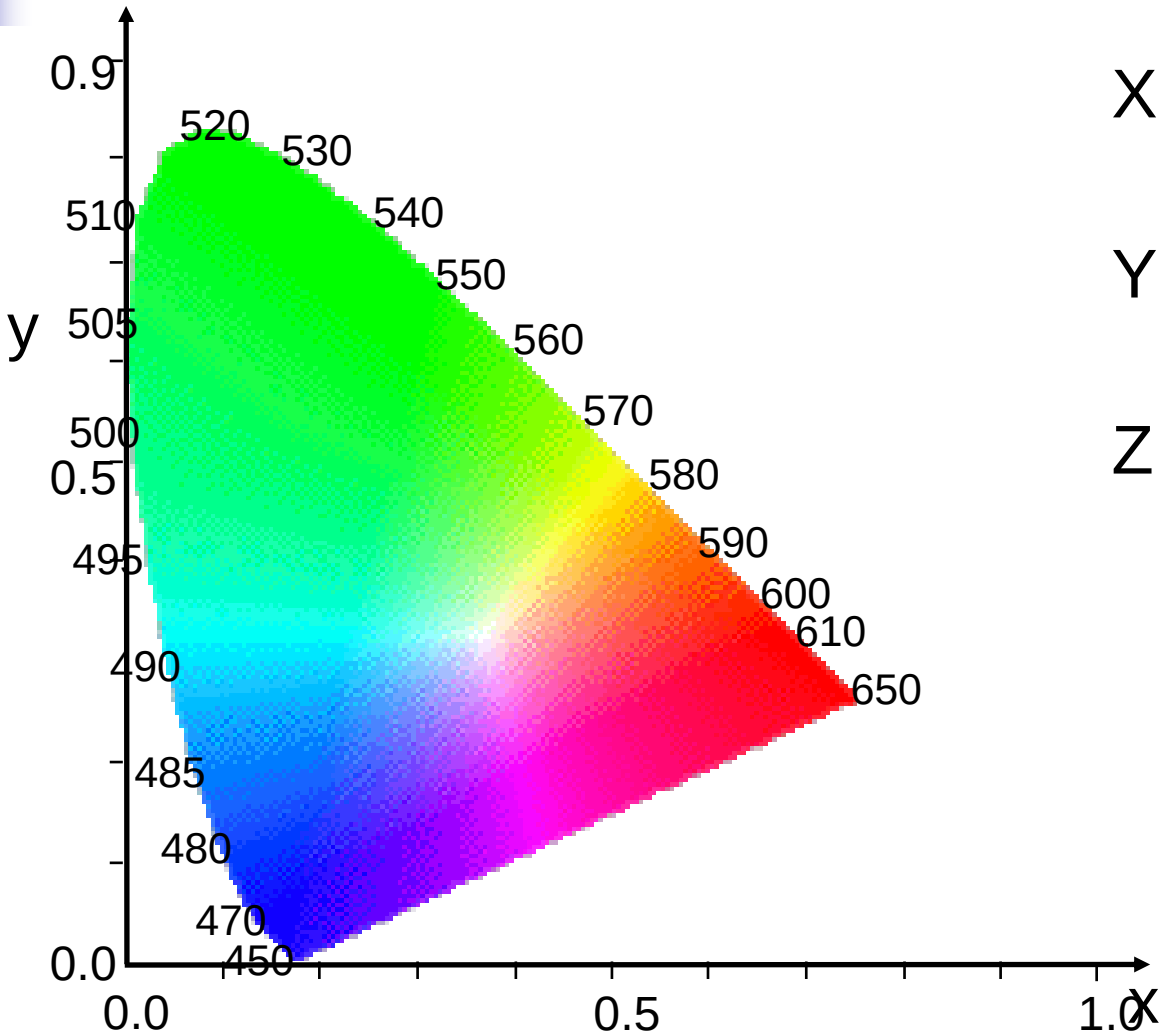
- RGB to XYZ is a linear transformation

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.490 & 0.310 & 0.200 \\ 0.177 & 0.813 & 0.011 \\ 0.000 & 0.010 & 0.990 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

A linear transformation



CIE Chromaticity Diagram



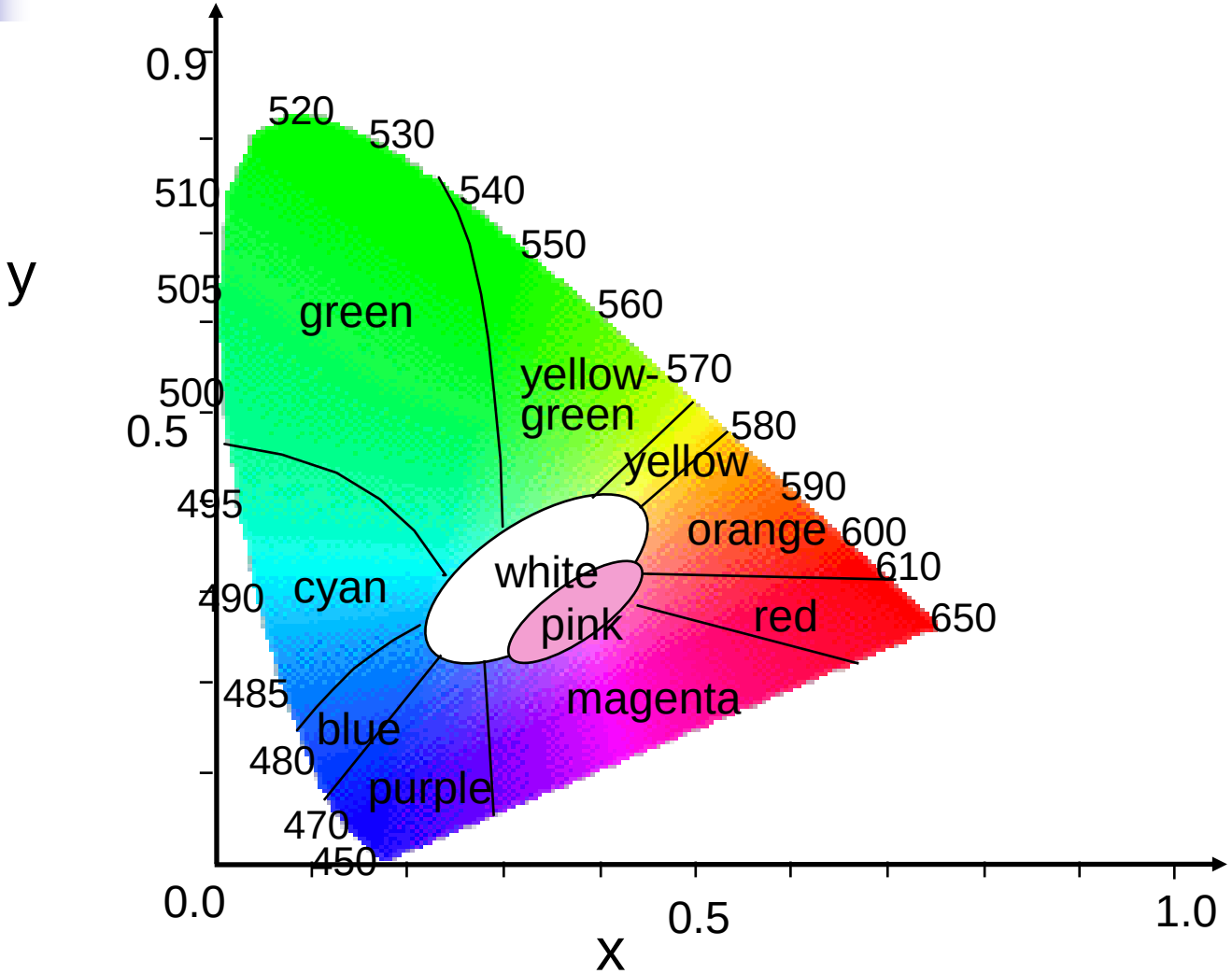
$$X \longrightarrow \frac{X}{X+Y+Z} = x$$

$$Y \longrightarrow \frac{Y}{X+Y+Z} = y$$

$$Z \longrightarrow \frac{Z}{X+Y+Z} = z$$

$$x+y+z = 1$$

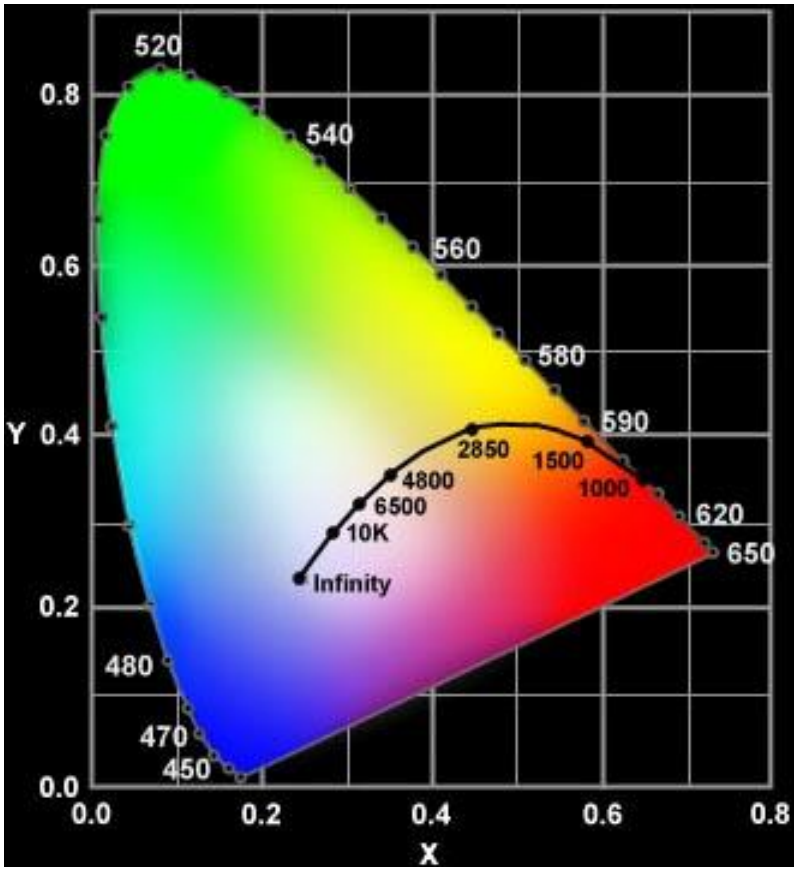
Color Naming



Blackbody Radiators and CIE Standard Illuminants

CIE Standard Illuminants:

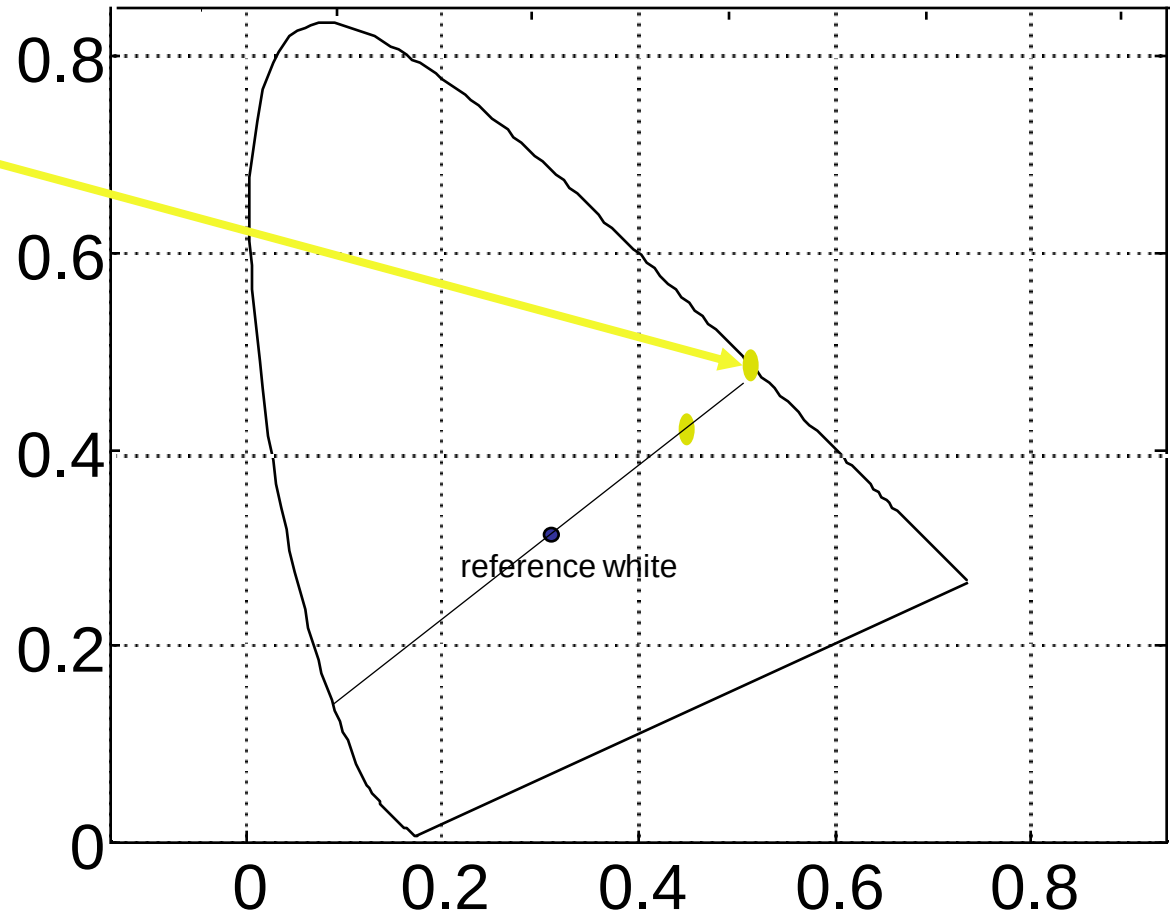
2500 - tungsten light (A)
4800 - Sunset
10K - blue sky
6500 - Average daylight (D65)



Chromaticity Defined in Polar Coordinates

Given a reference white.

Dominant Wavelength – wavelength of the spectral color which added to the reference white, produces the given color.

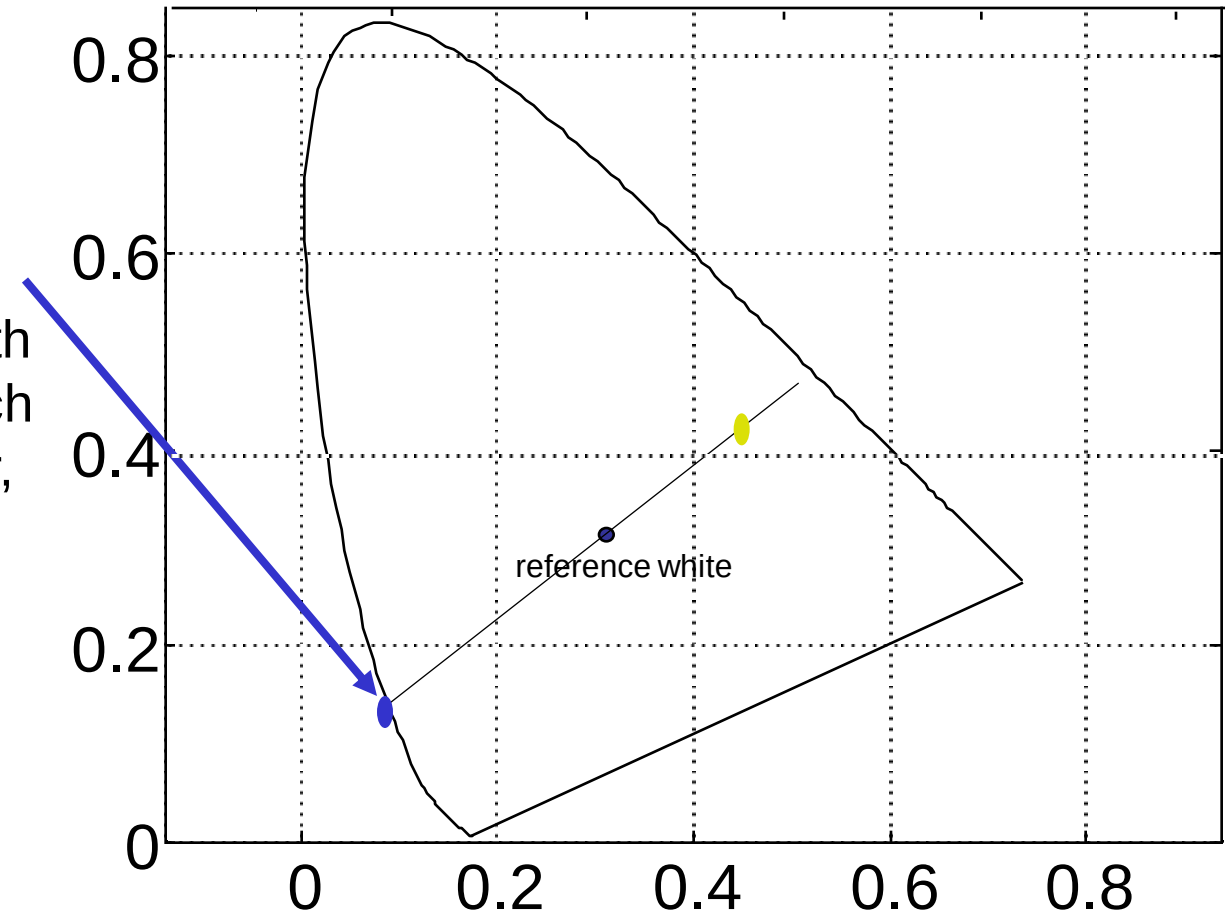


Chromaticity Defined in Polar Coordinates

Given a reference white.

Dominant Wavelength

Complementary Wavelength - wavelength of the spectral color which added to the given color, produces the reference white.



Chromaticity Defined in Polar Coordinates

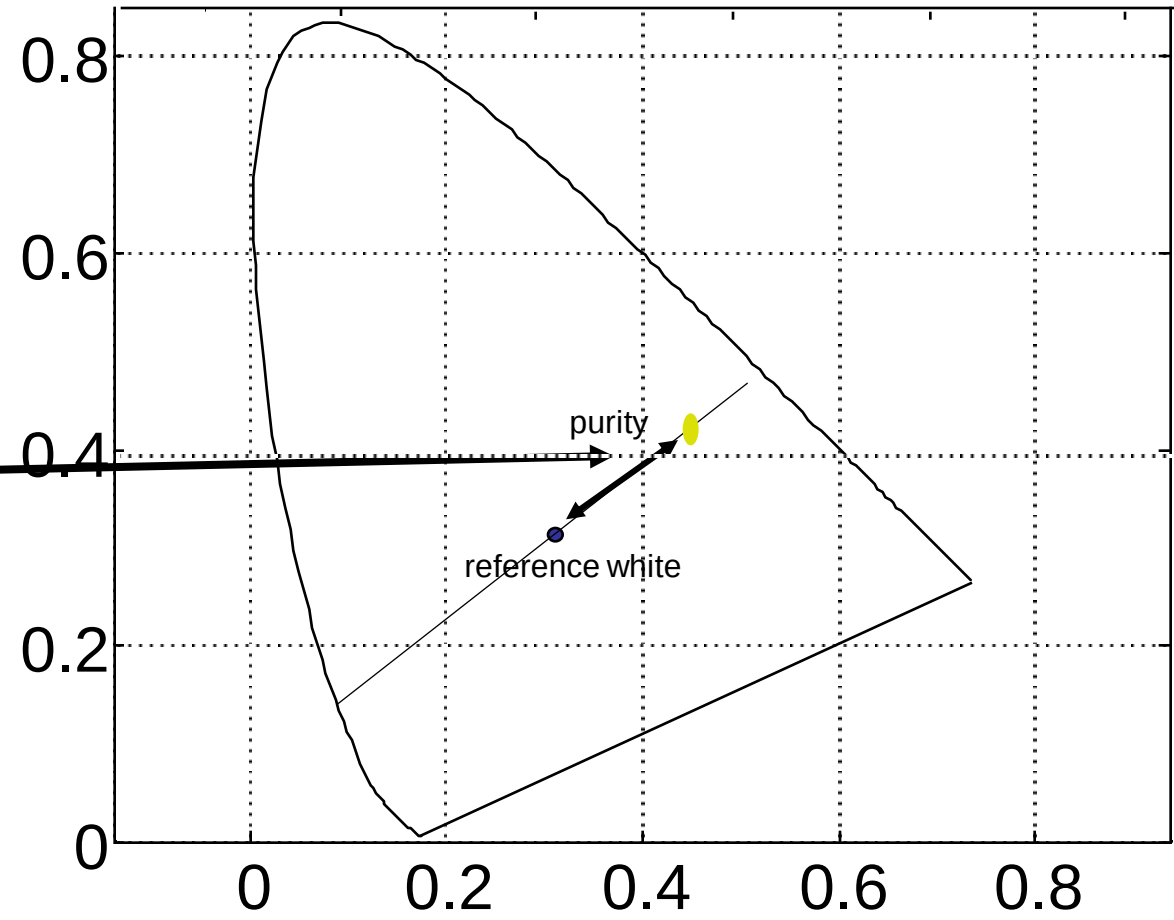
Given a reference white.

Dominant Wavelength

Complementary Wavelength

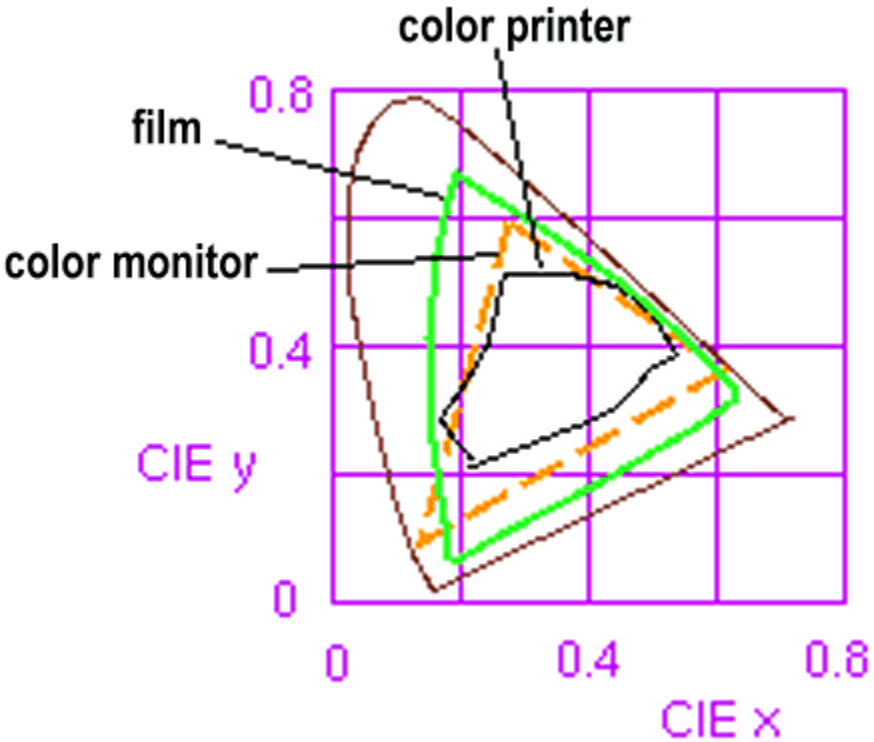
Excitation Purity – the ratio of the lengths between the given color and reference white and between the dominant wavelength light and reference white.

Ranges between 0 .. 1.



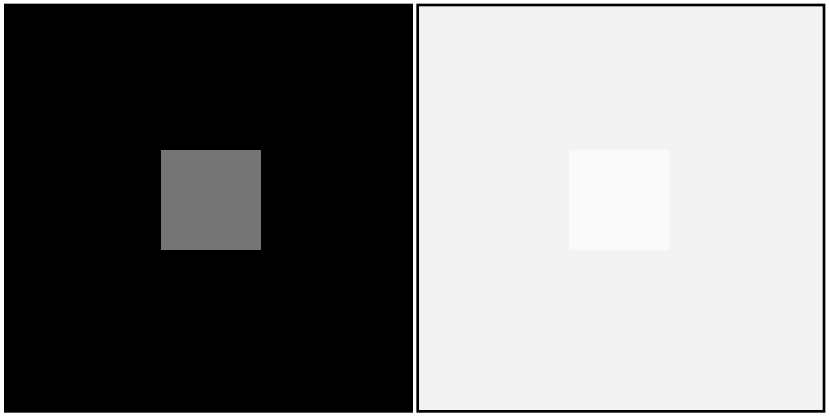
Device Color Gamut

- We can use the CIE chromaticity diagram to compare the gamut of various devices:
- Note, for example, that a color printer cannot reproduce all shades available on a color monitor

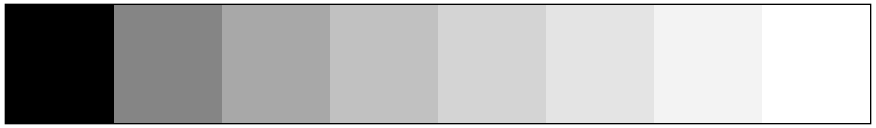


Luminance v.s. Brightness

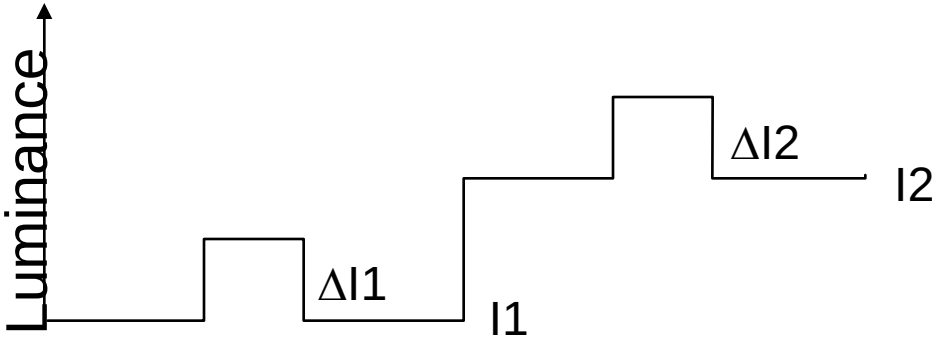
Luminance (intensity) Y in XYZ vs **Brightness (Lightness) V in HSV**



Equal intensity steps:



Equal brightness steps:



$I1 < I2, \ \Delta I1 = \Delta I2$

Weber's Law

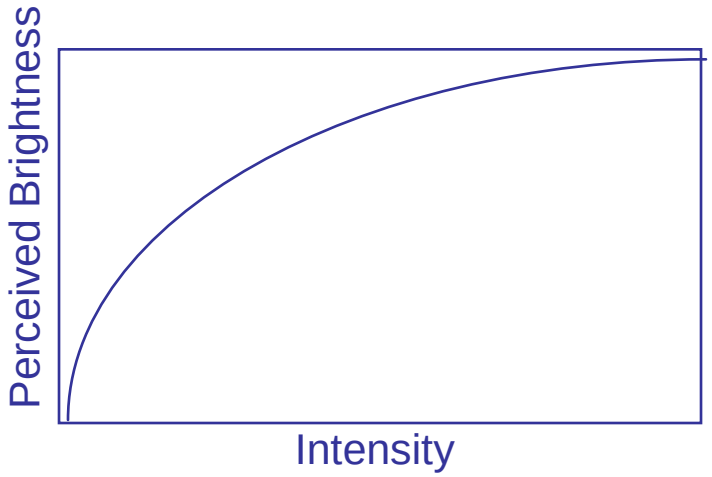
In general, ΔI needed for just noticeable difference (JND) over background I was found to satisfy:

$$\frac{\Delta I}{I} = \text{constant}$$

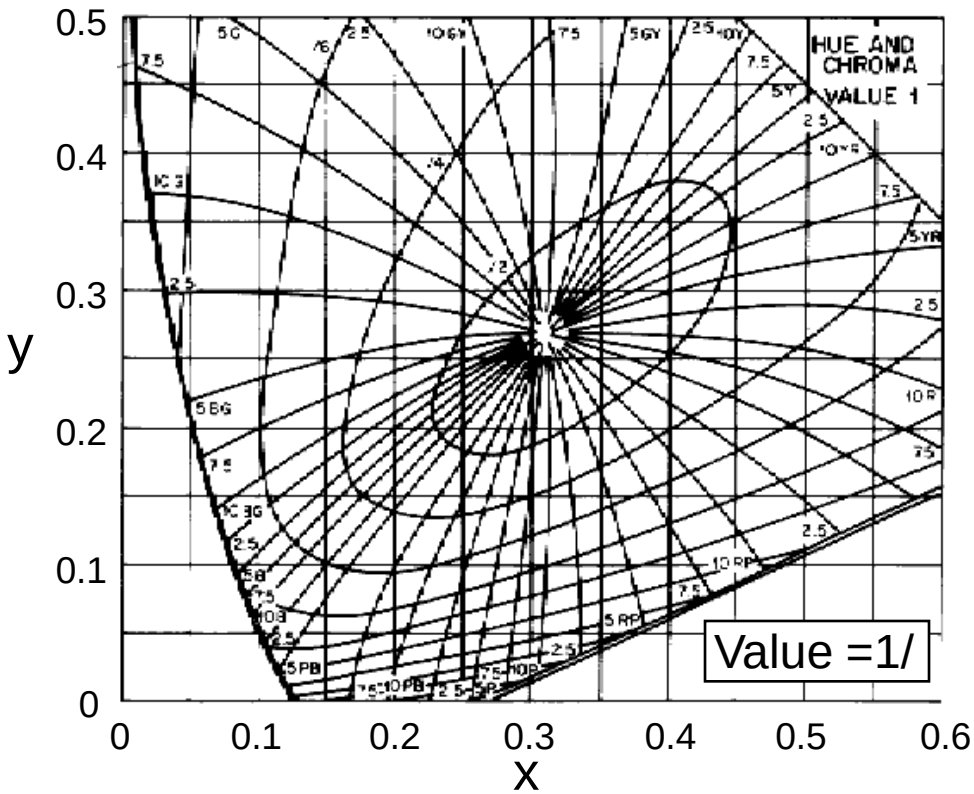
(I is intensity, ΔI is change in intensity)

Weber's Law:

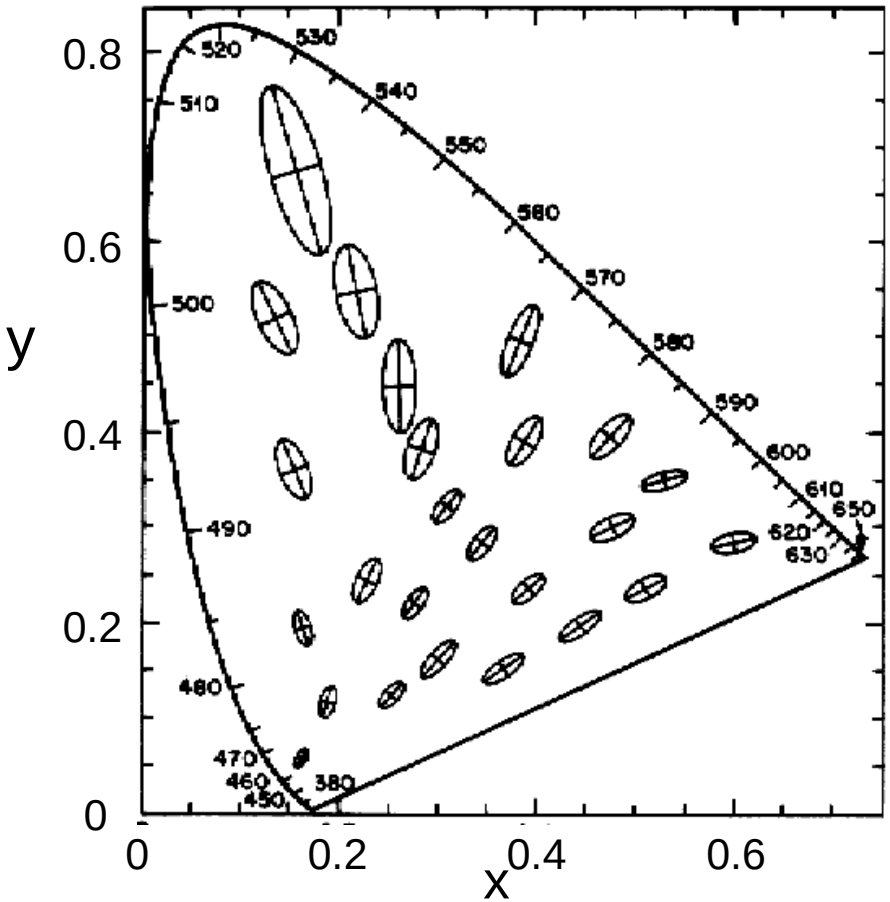
$$\text{Perceived Brightness} = \log(I)$$



Munsell lines of constant Hue and Chroma



MacAdam Ellipses of JND (Just Noticeable Difference)

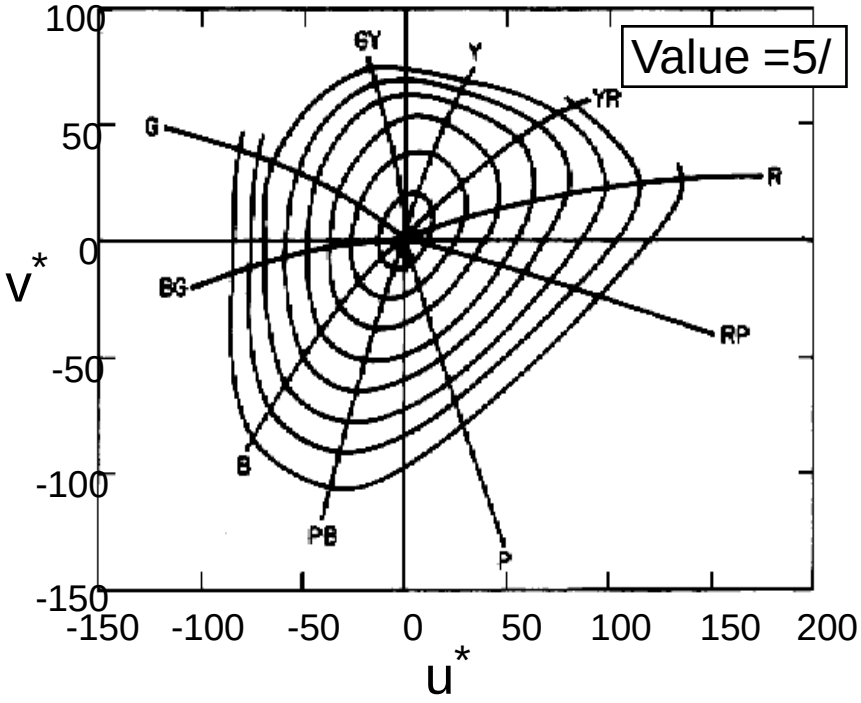


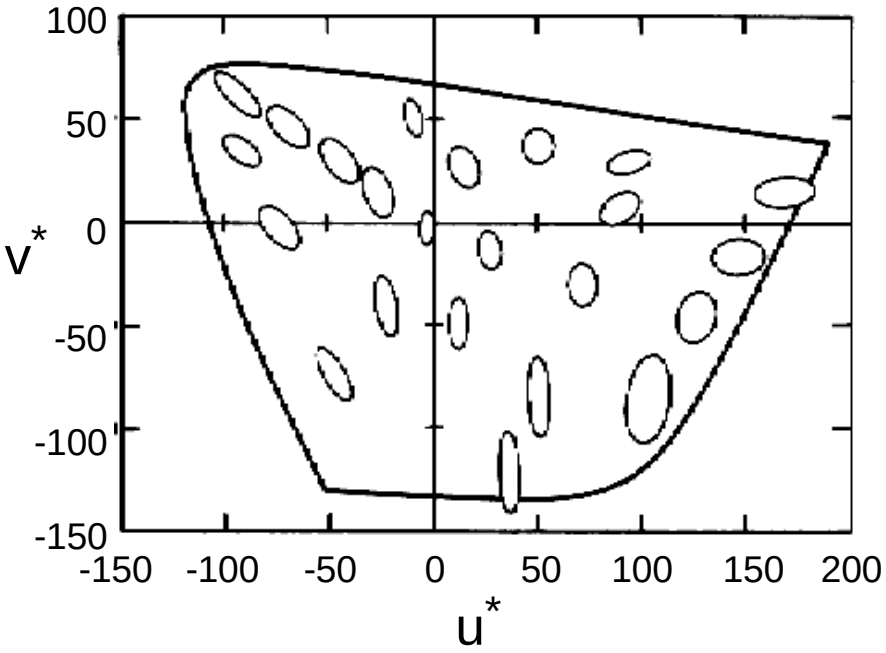
(Ellipses scaled by 10)

Perceptual Color Spaces

- An improvement over CIE-XYZ that represents better uniform color spaces
- The transformation from XYZ space to perceptual space is **Non Linear**.
- Two standard adopted by CIE are **L*u'v'** and **L*a*b***
- The L* line in both spaces is a replacement of the Y lightness scale in the XYZ model, but it is more indicative of the actual visual differences.

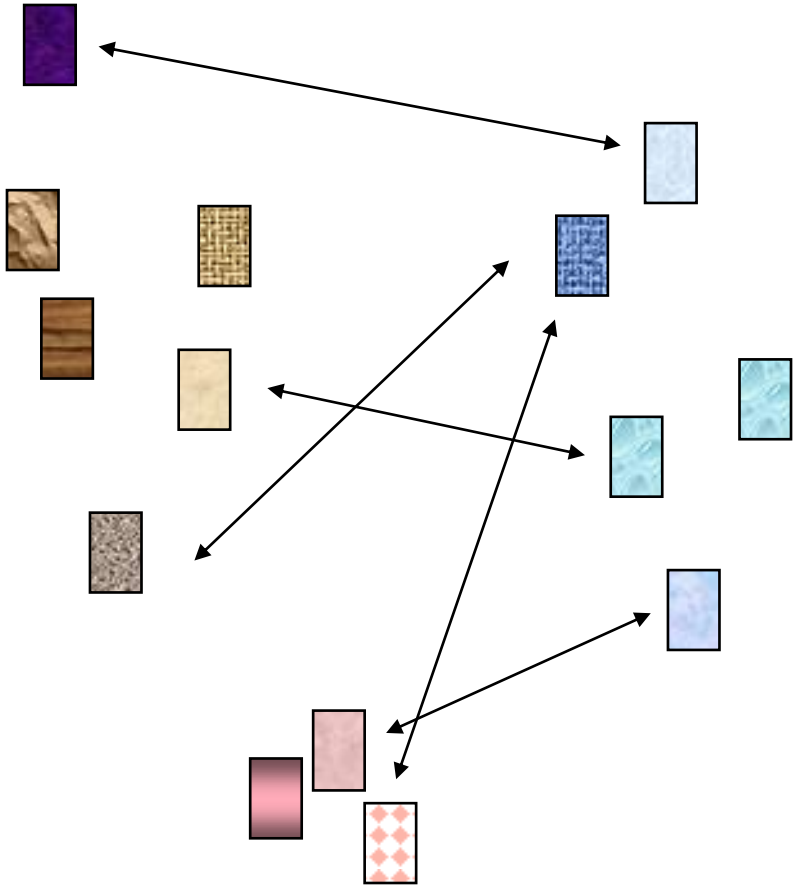
Munsell Lines and MacAdam Ellipses plotted in CIE-L*u'v' coordinates



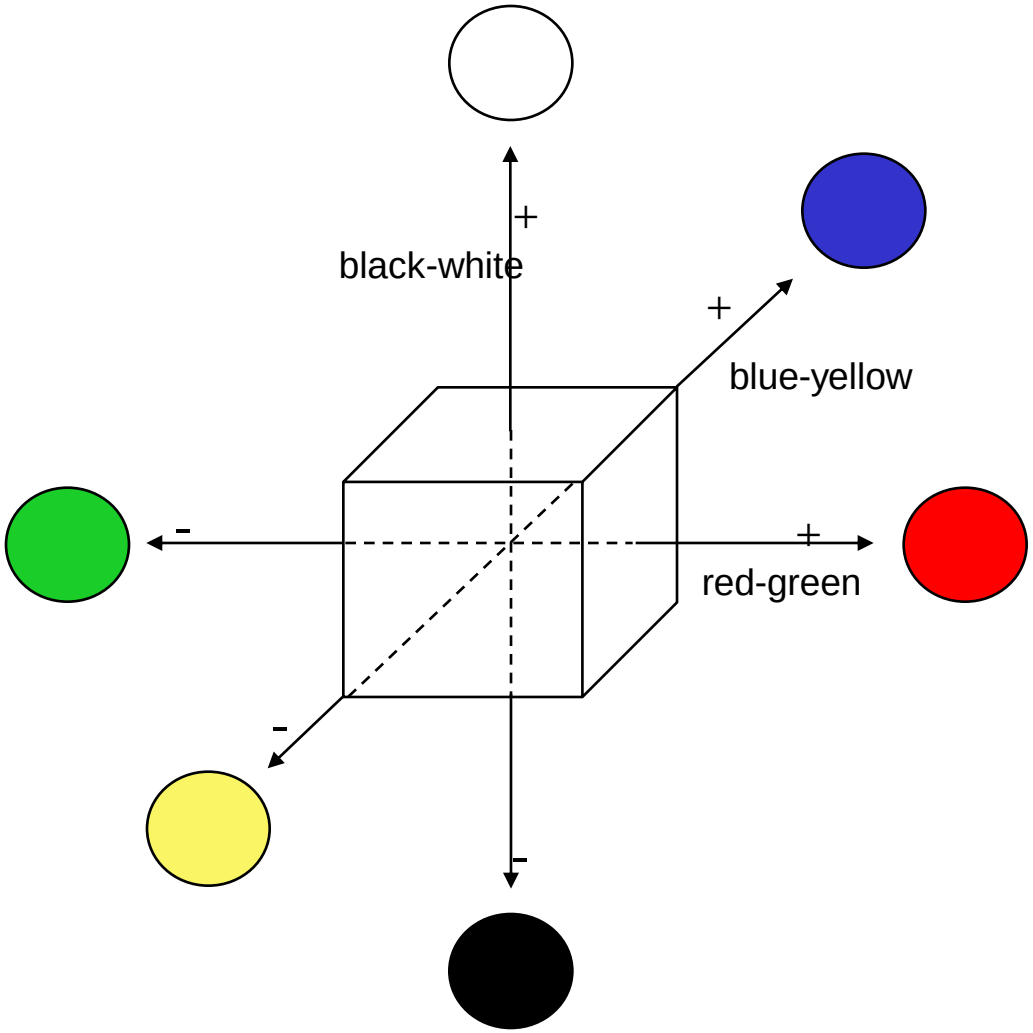


Distances between colors

- Distances are not linear in any color space.
- In perceptual color space distances are more suitable for our conception.
- Measuring color differences between pixels is more useful in perceptual color spaces.



Opponent Color Spaces



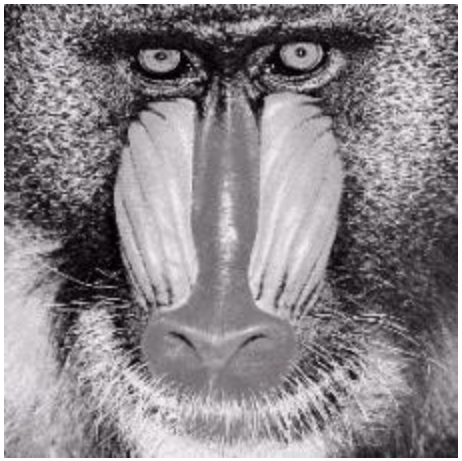
YIQ Color Model

- **YIQ** is the color model used for color TV in America (NTSC= National Television Systems Committee)
- **Y** is luminance, **I** & **Q** are color (I=red/green,Q=blue/yellow)
  - Note: **Y** is the same as CIE's **Y**
  - Result: backwards compatibility with B/W TV!
- Convert from RGB to YIQ: $$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$
- The YIQ model exploits properties of our visual system, which allows to assign different bandwidth for each of the primaries (4 MHz to Y, 1.5 to I and 0.6 to Q)

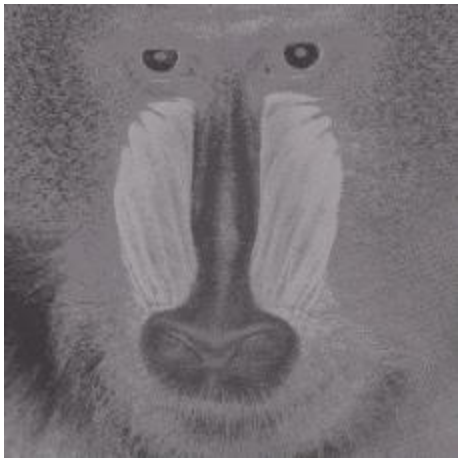
YUV Color Model

- **YUV** is the color model used for color TV in Israel (PAL), and in video. Also called YCbCr.
- **Y** is luminance as in YIQ.
- U and V are blue and red (Cb and Cr).
- The YUV uses the same benefits as YIQ, (5.5 MHz for Y, 1.3 for U and V).
- Converting from RGB to YUV:
  - $Y = 0.299R + 0.587G + 0.114B$
  - $U = 0.492(B - Y)$
  - $V = 0.877(R - Y)$

YUV - Example



Y



U

V

Summary

- Light → Eye (Cones,Rods) → [l,m,s] → Color
- Color standards (Munsell, CIE)
- Many **3D** color models:
  - RGB, CMY, Munsell(HSV/HLS), XYZ, Perceptual(Luv,Lab), Opponent(YIQ,YUV).
- Reproducing **Metamers** to Colors
- Different reproduction **Gamut**
- Non-linear distances between colors