Color Image Processing

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Outline

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    - Visible spectrum
    - Spectral colors
    - Color perception
    - Color systems
    - Tri-stimulus colors
    - CIE primaries
    - Color mixing
  - **Color models**
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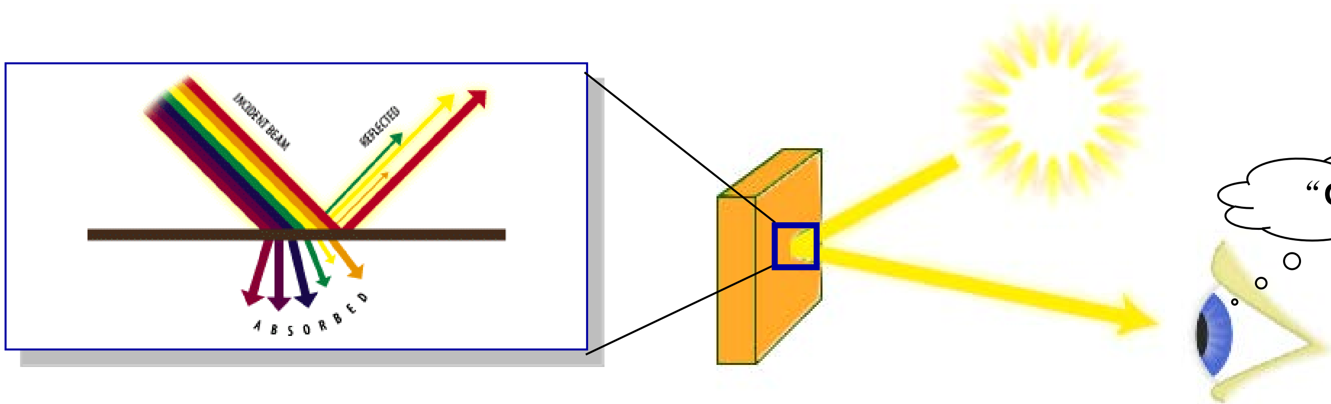
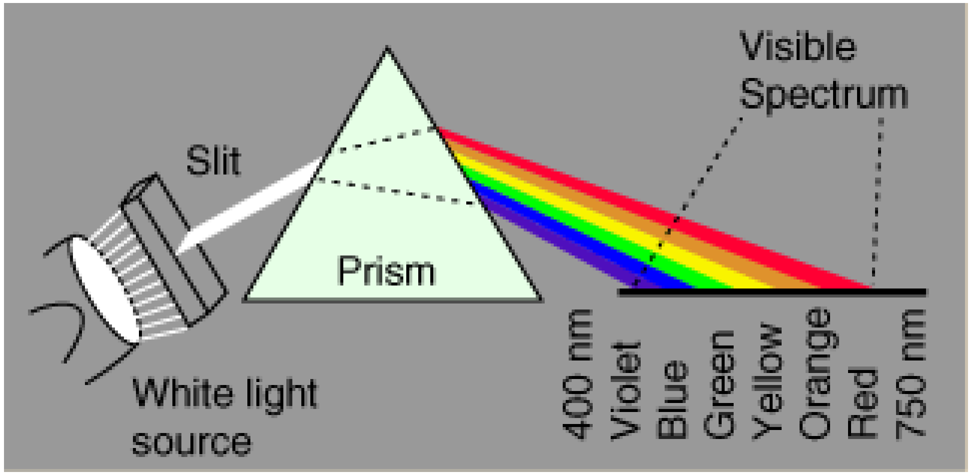
What is Color

- Human perception, not directly measurable
- Related to the light spectrum of a stimulus
- Depends on
  - Light source
  - Reflectance (Reflecting objects)
  - Image sensor (eyes or cameras)



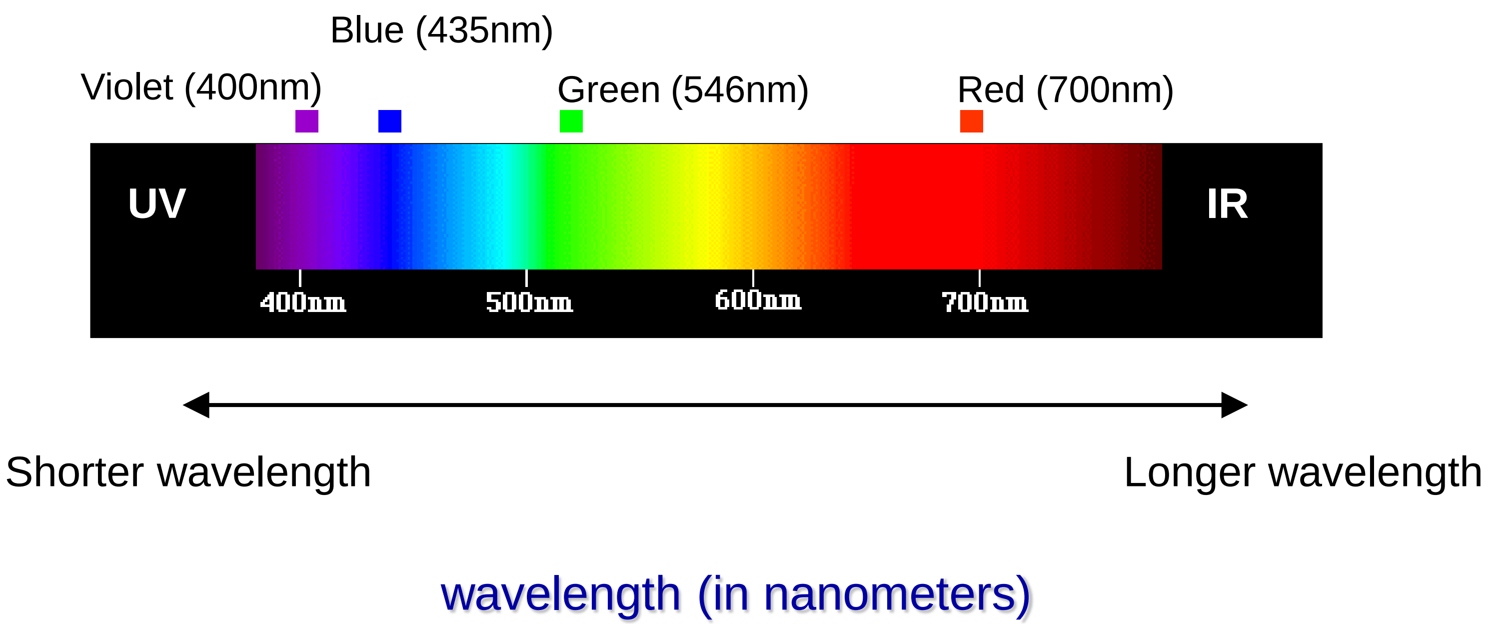
- Some or all of the light may be absorbed
- Dominant wavelength reflected by objects determines the color tone

Newton's Experiment



Visible Spectrum

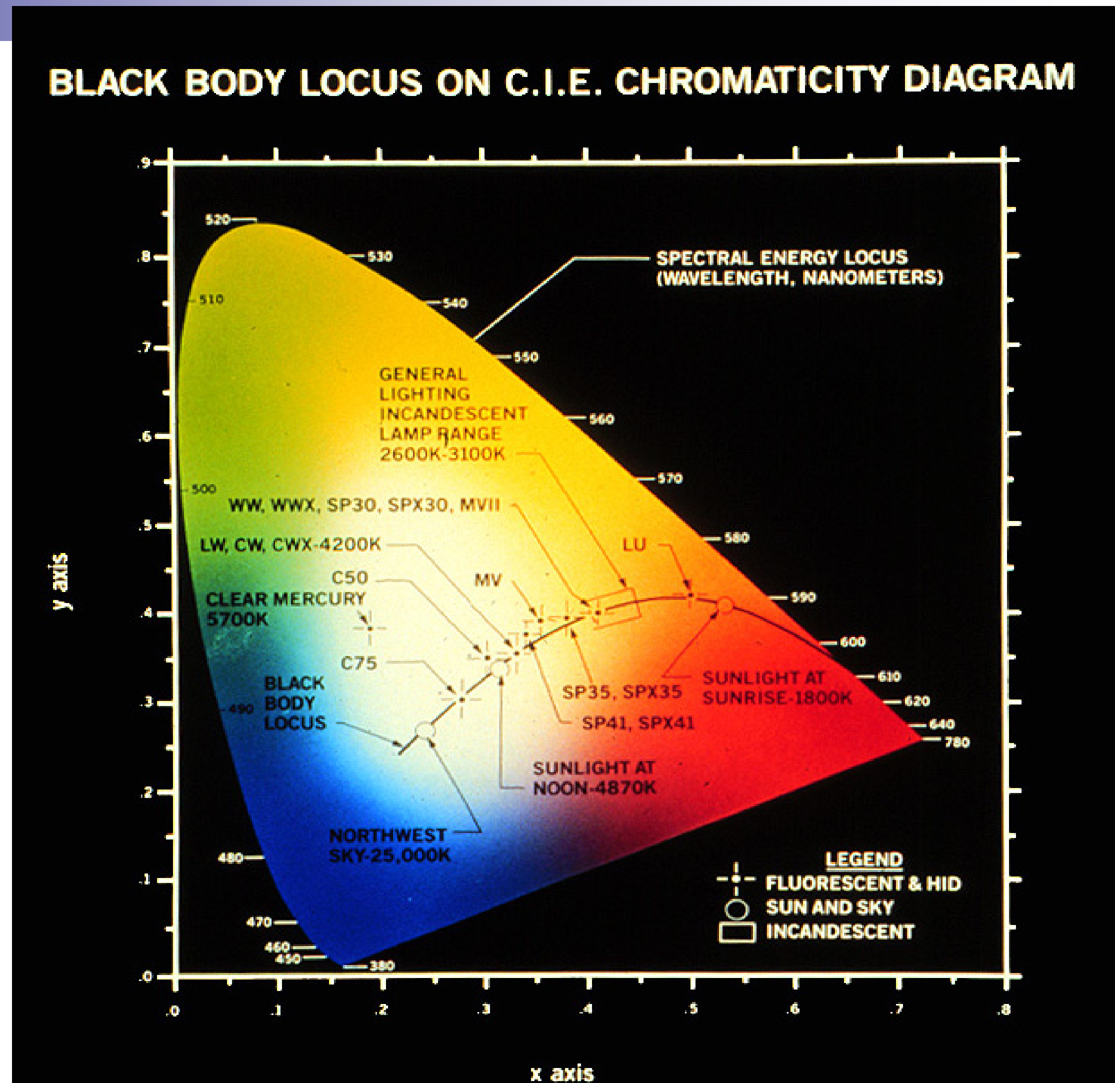
- A spectral color is composed of a single wavelength



UV: ultra violet
IR: infrared radiation

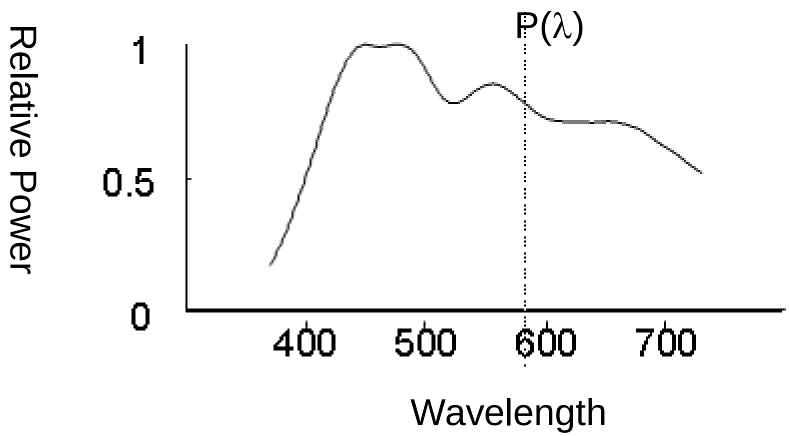
Illumination

- *Achromatic light* –"white" or uncolored light
- *Chromatic light* – colored light
- *Monochromatic light* – contained only one wavelength (laser light)

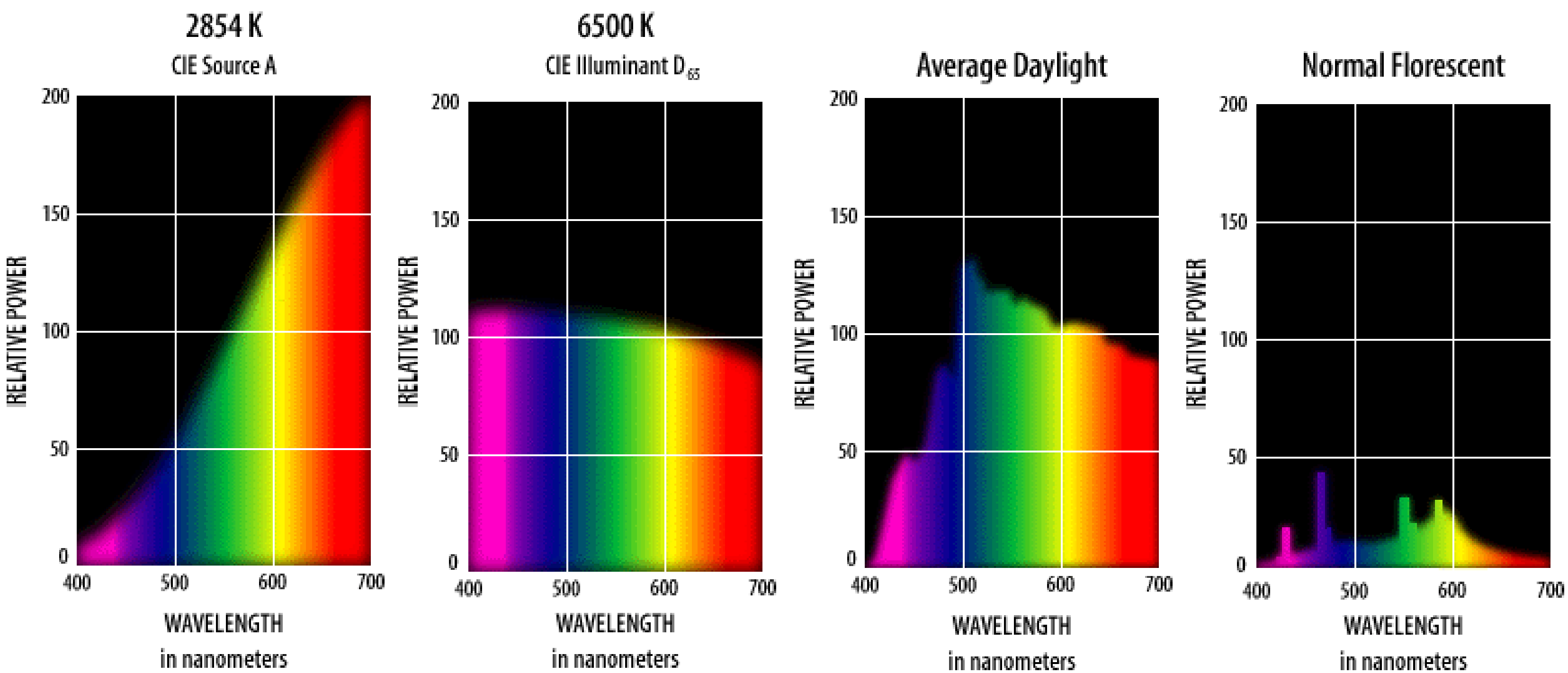


Spectral Power Distribution (SPD)

- Light may be precisely characterized by giving the power of the light at each wavelength in the visible spectrum
- SPD is a function P(λ) that defines the power of the light at each wavelength



Example of SPD



2800 K: tungsten lamp (ordinary household bulb)

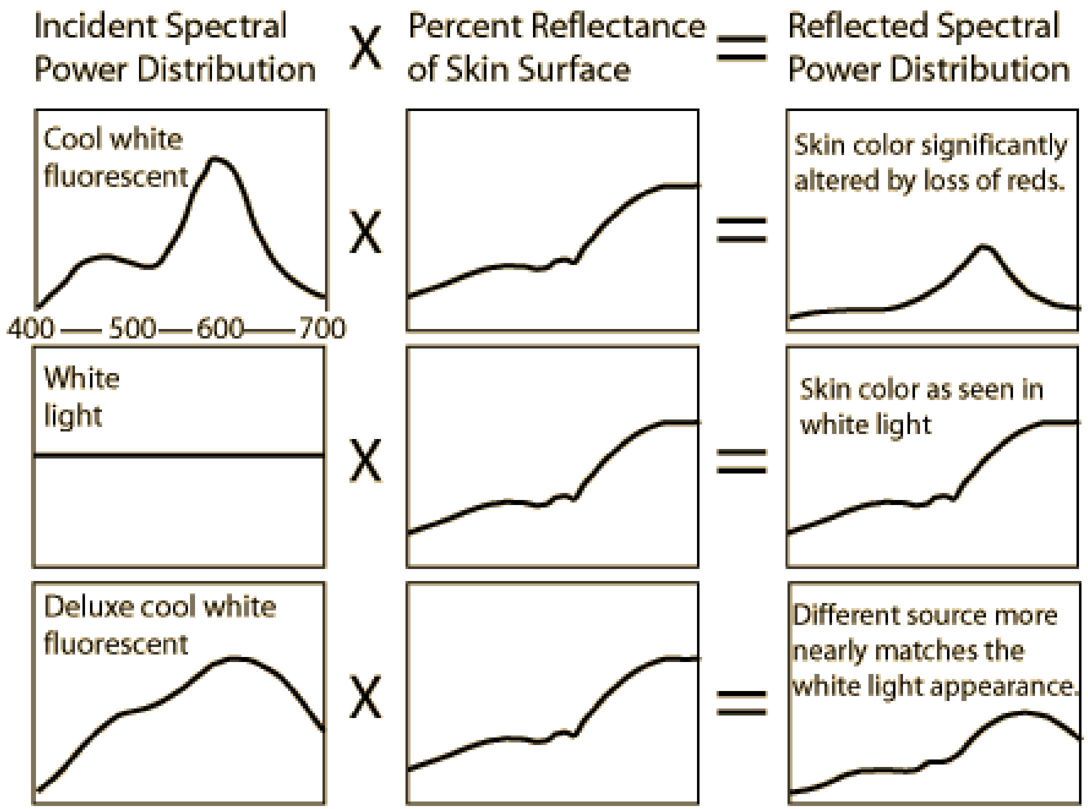
6500 K: heavily overcast sky

[Example]

Example of SPD Applications

- The color appearance change due to different illuminance may be quantified in terms of the spectral power distribution of the light

*Image source: *HyperPhysics**



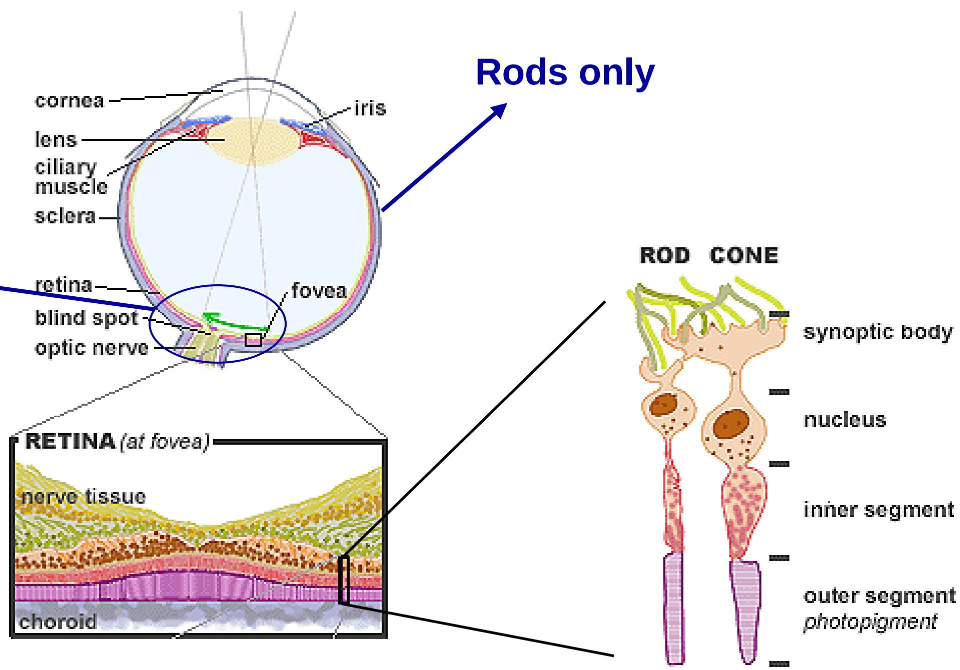
After Williamson and Cummins

Color Sensitive Cons

- Retina - a light-sensitive layer at the back of the eye
- Photosensitive cells – rods and cons
  - Rods (scotopic vision – low light): highly sensitive, sense luminance, but not color
  - Cons (photopic vision – medium and high light)

Rods only

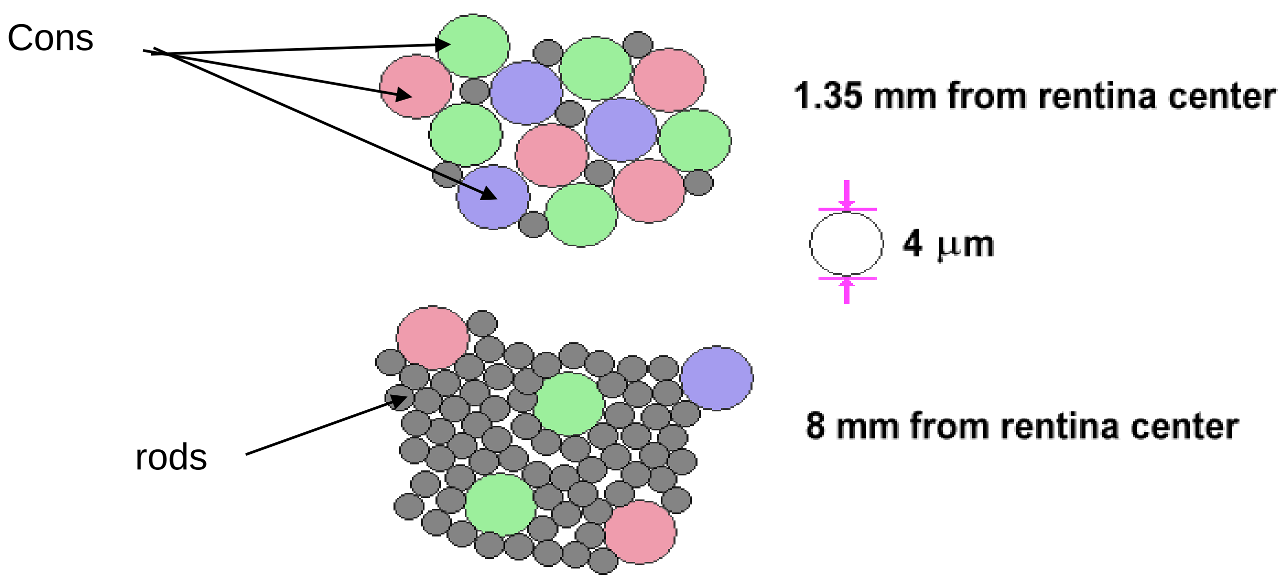
Mostly cons



Rods:120 millions
Cons:6-7 millions

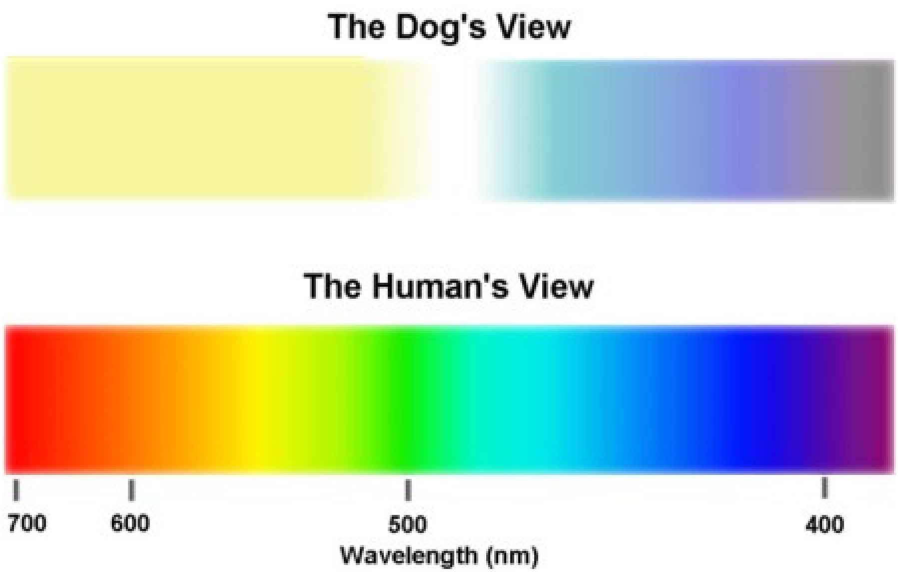
Cons

- High illumination levels (Photopic vision)
- Less sensitive than rods
- Not evenly distributed - density decreases with distance from fovea
- "red" cones (64%), "green" cones (32%), and "blue" cones (2%)



Rods and Cons

- Example: Dog's eyes have only 2 *cone* types, and it is red-green color blind. But they have more rods.



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Luminance Efficiency Function

- Brightness varies with wavelength
- Peak efficiency
  - Low light level (rods) – scotopic
  - Medium & high level (cons) - photopic

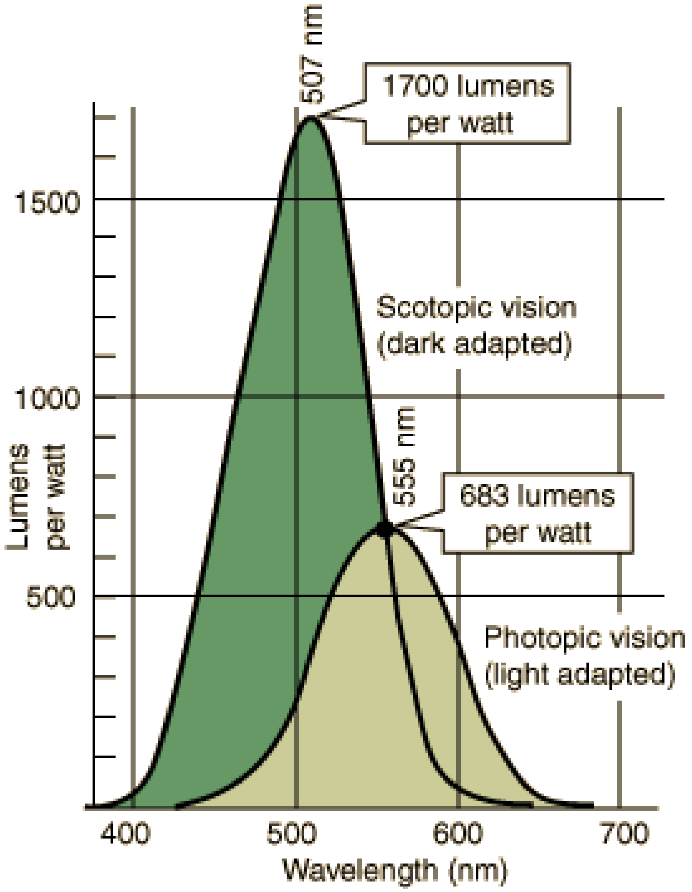


*Image source: *HyperPhysics*

Luminance Efficiency Function (Cont.)

- Is candle flame yellow?

It's red!

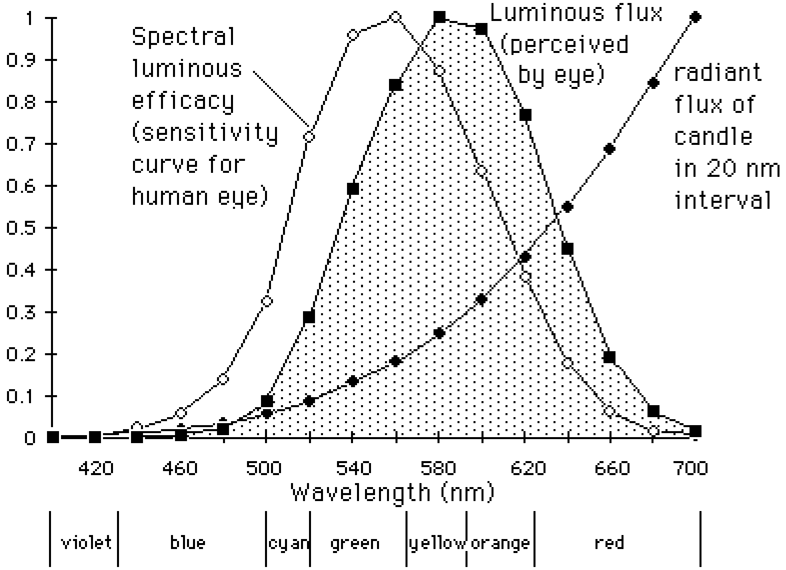
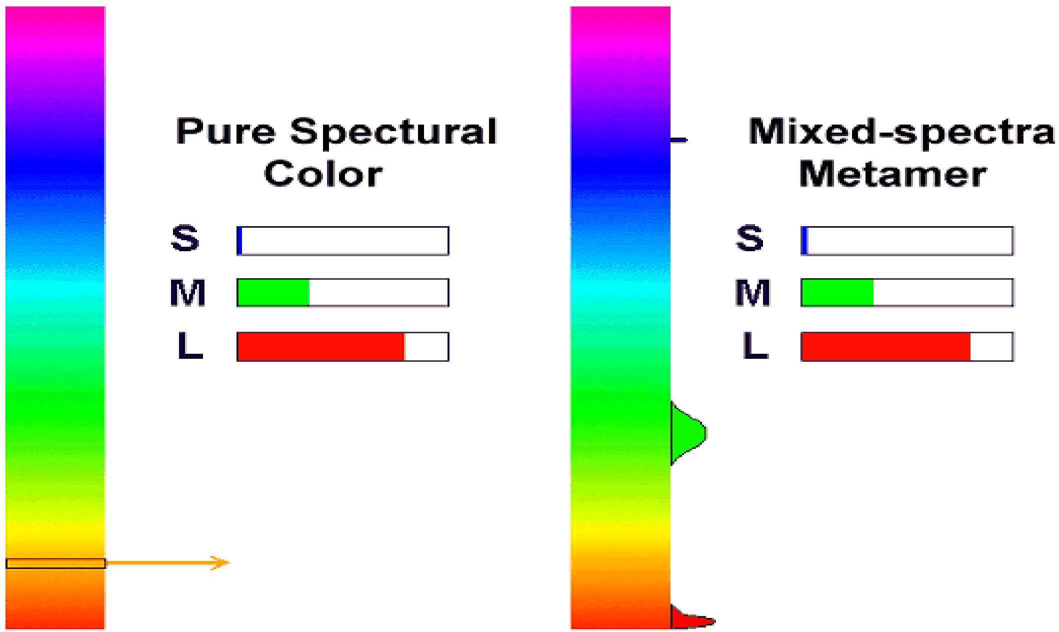


*Image source: *HyperPhysics*

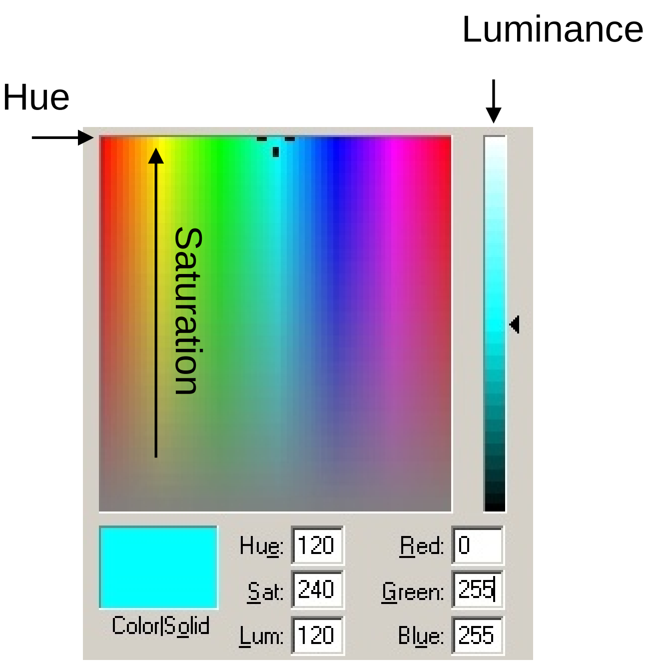
Spectral Colors vs. Metamer

- Metamer - Two colors that appear the same visually (same “tristimulus values”). They might have different SPDs (different spectral composition).



Characteristics of Colors

- Attributes of color - Hue, Saturation, Brightness
  - Hue
    - “tone” of a color (e.g.“Red” and “Green” are primarily describing hue)
    - dominant wavelength of a color (*i.e.* spectral colors)
  - Saturation
    - purity of a color (*i.e.* , how vivid a color appears)
    - fully saturated color – no mixture of white.
  - Brightness
    - luminance of a color



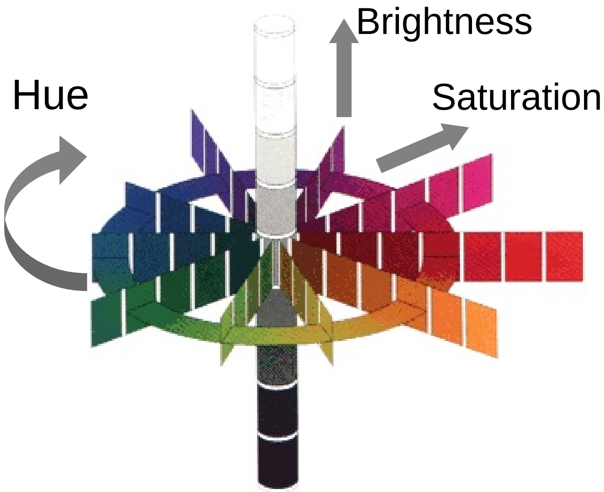
Windows color picker

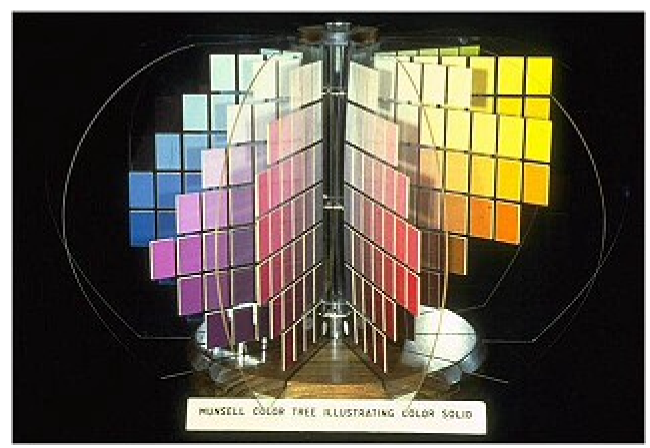
Color Systems

- How to precisely describe colors
- Subjective color systems
  - Munsell color system
  - Ostwald color system
- Quantitative C.I.E. (Commission Internationale d’Eclairage) color system (1931)
  - Based on quantitative colorimetry
  - The most widely used standard today

Munsell Color System

- Characterizes colors by
  - Hue: 100 equally spaced hues around the circle (10 hues, each subdivided into 10 subdivisions)
  - Saturation: 0 (gray) to 10-18 (full color), depending on the hue
  - Brightness: values from 0 for black and 10 for white





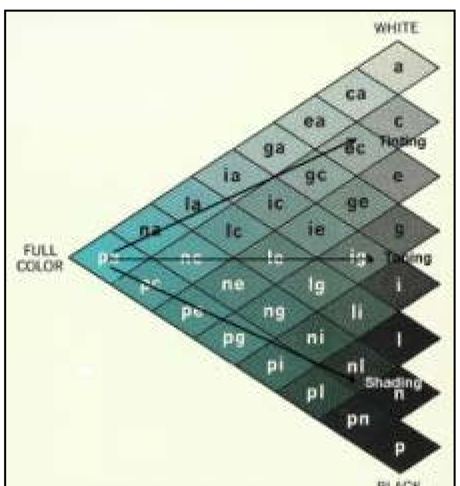
Munsell color tree

Ostwald Color System

- In Ostwald System (Natural Color System) , a color is defined by its
  Dominant Wavelength (*Hue*)
  Purity (*Saturation*)
  Luminance (*Brightness*)
- The Ostwald color space is represented by values C,W, and B to represent the percentages of the circle.
  - e.g., (C,W,B)=(35,15,50) represents 35% full color, 15% white, and 50% black.

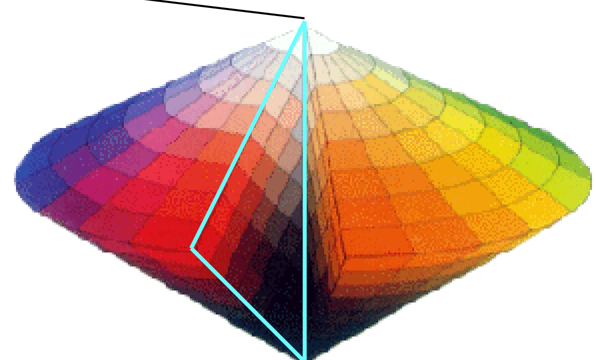
High C

Purity
(Saturation)



High W,
Low B

Luminance
(Brightness)



Ostwald color-space

Tristimulus Values

- The perception of color depends on three types of cons
- The visible color can be mapped in terms of three numbers in a color space called tristimulus values
- Primary colors – any set of three colors that yield white when added in appropriate combination

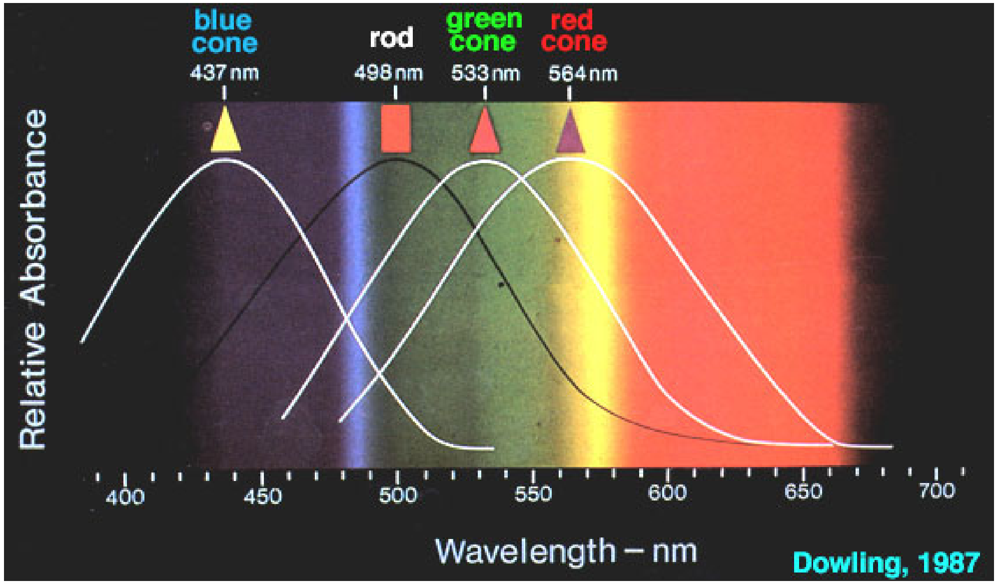
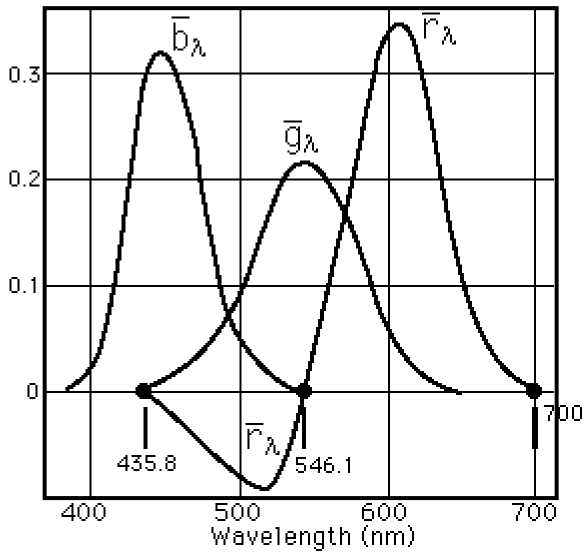


Fig. 14. The peak spectral sensitivities of the the 3 cone types and the the rods in the primate retina (Brown and Wald, 1963). From Dowling's book (1987).

RGB Primaries

- Colors can be matched by combinations of monochromatic primary colors Red (700 nm), Green (546.1 nm) and Blue (435.8 nm)



RGB color matching function

$$C = B\vec{B} + G\vec{G} + R\vec{R}, \text{ where}$$

$(\vec{B}, \vec{G}, \vec{R})$: "*unit values*" for blue, green, and red

(B, G, R) : *tristimulus values*

Normalized 3D (R,G,B) to 2D (r,g,b)

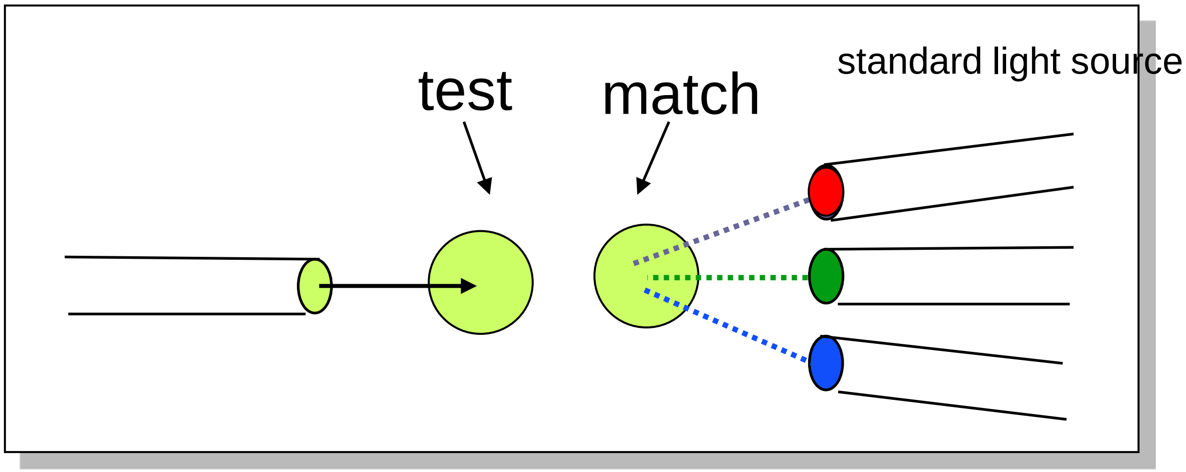
$$r = \frac{R}{R+G+B}$$

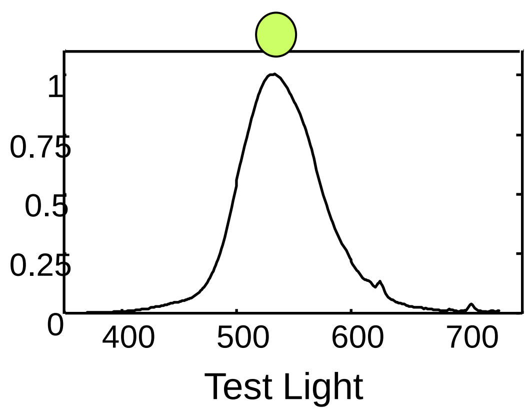
$$g = \frac{G}{R+G+B}$$

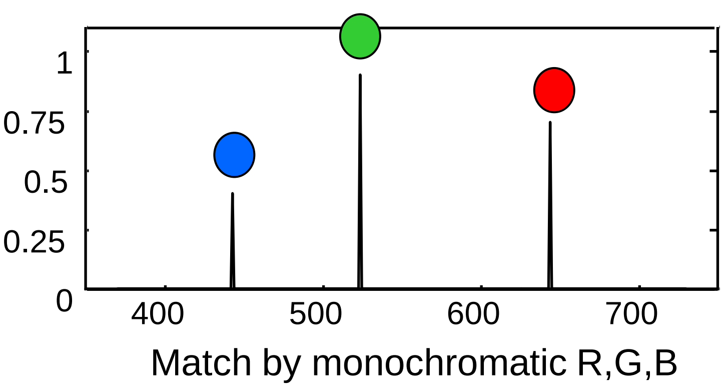
$$b = \frac{B}{R+G+B}$$

(r, g, b) maps to a triangle gamut on chromacity diagram

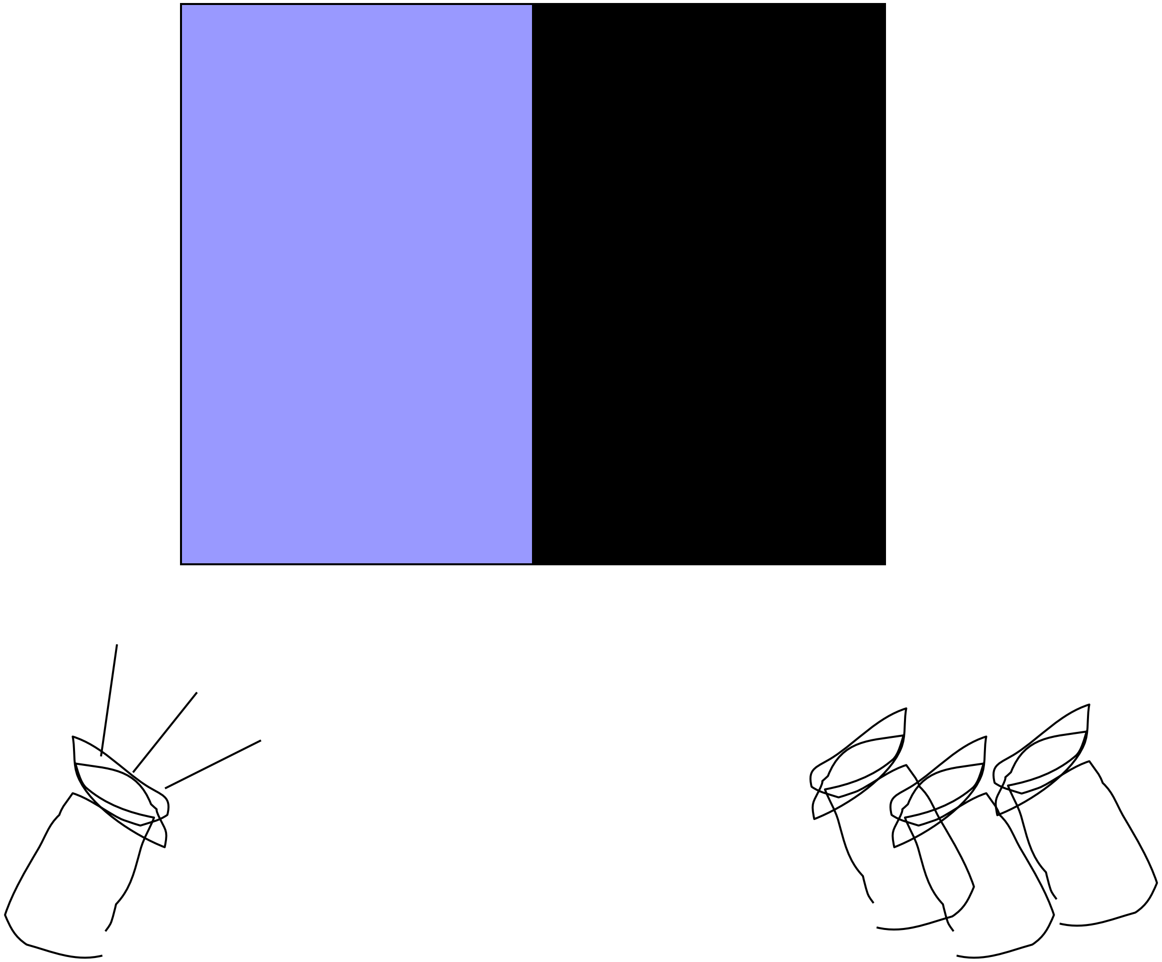
RGB Primaries--Color Matching Experiment



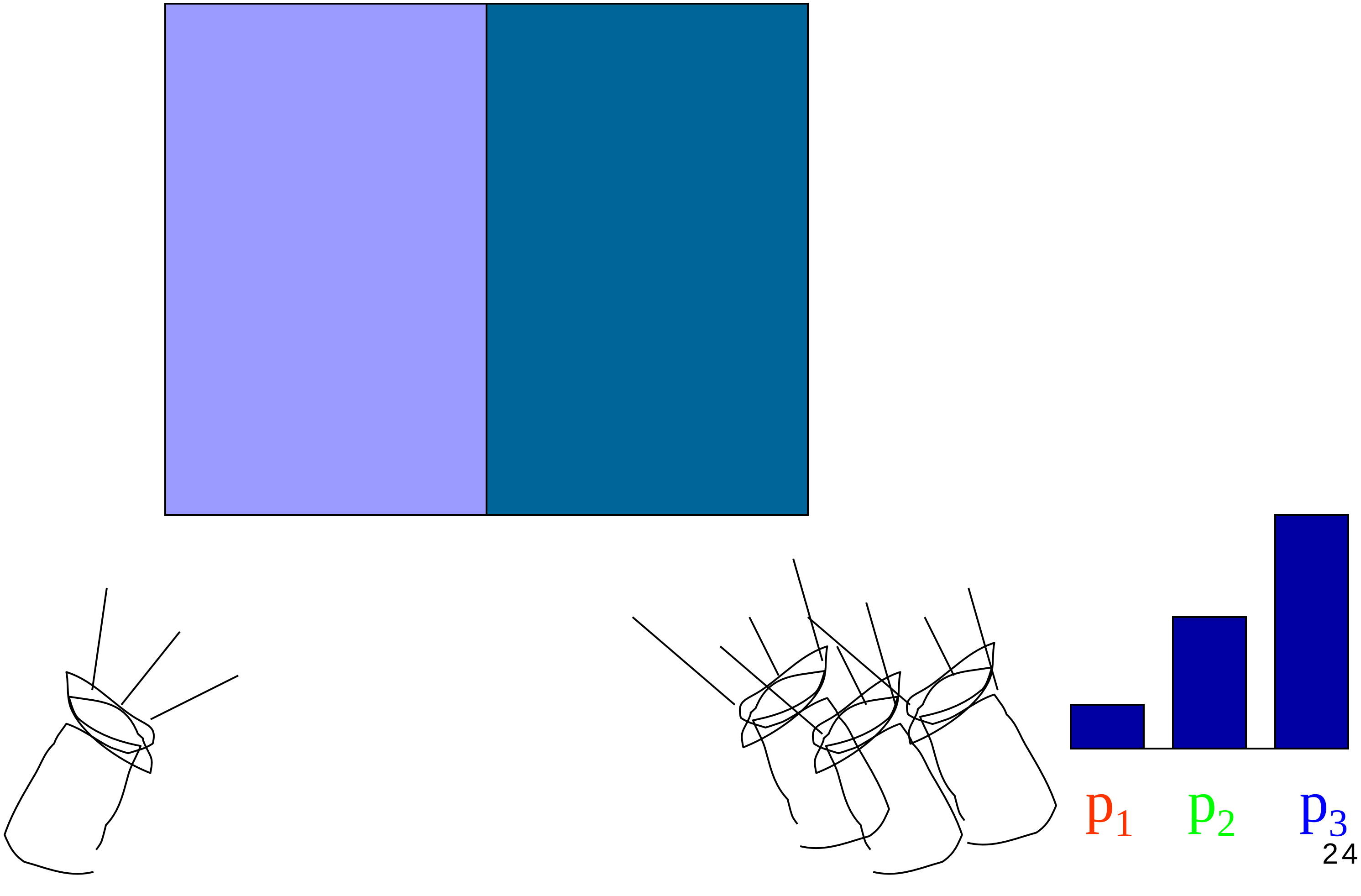




Color matching experiment 1



Color matching experiment 1



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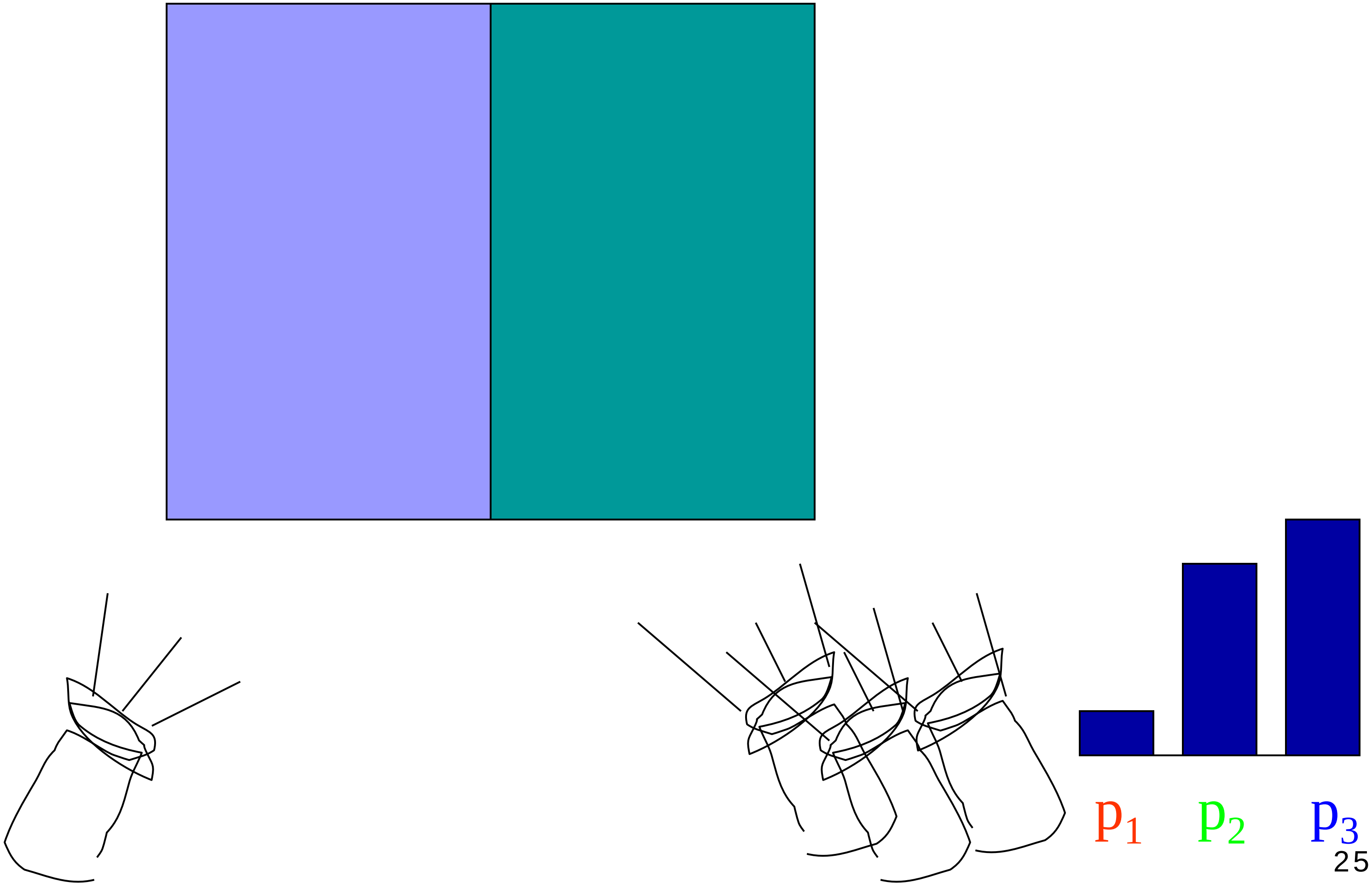

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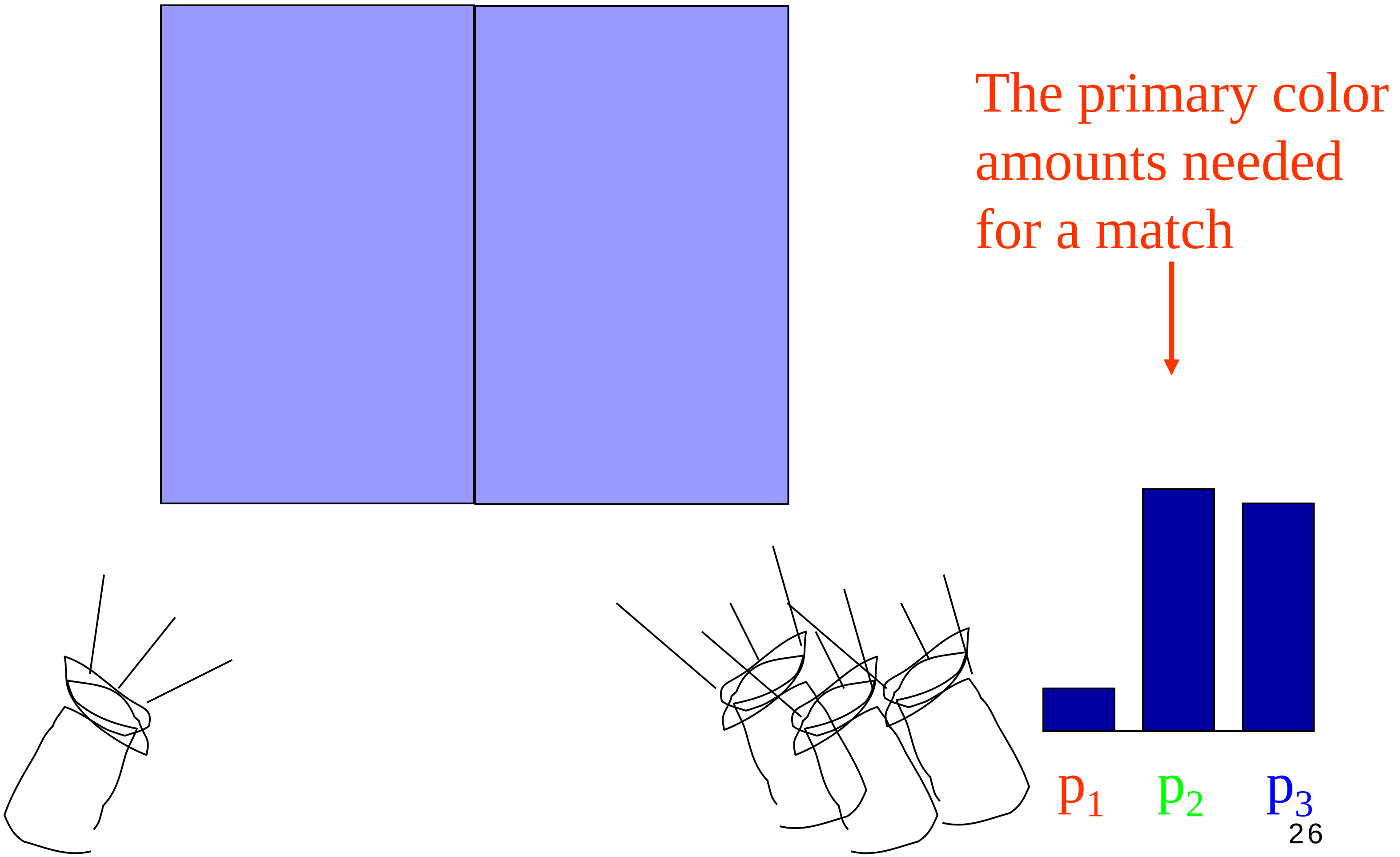
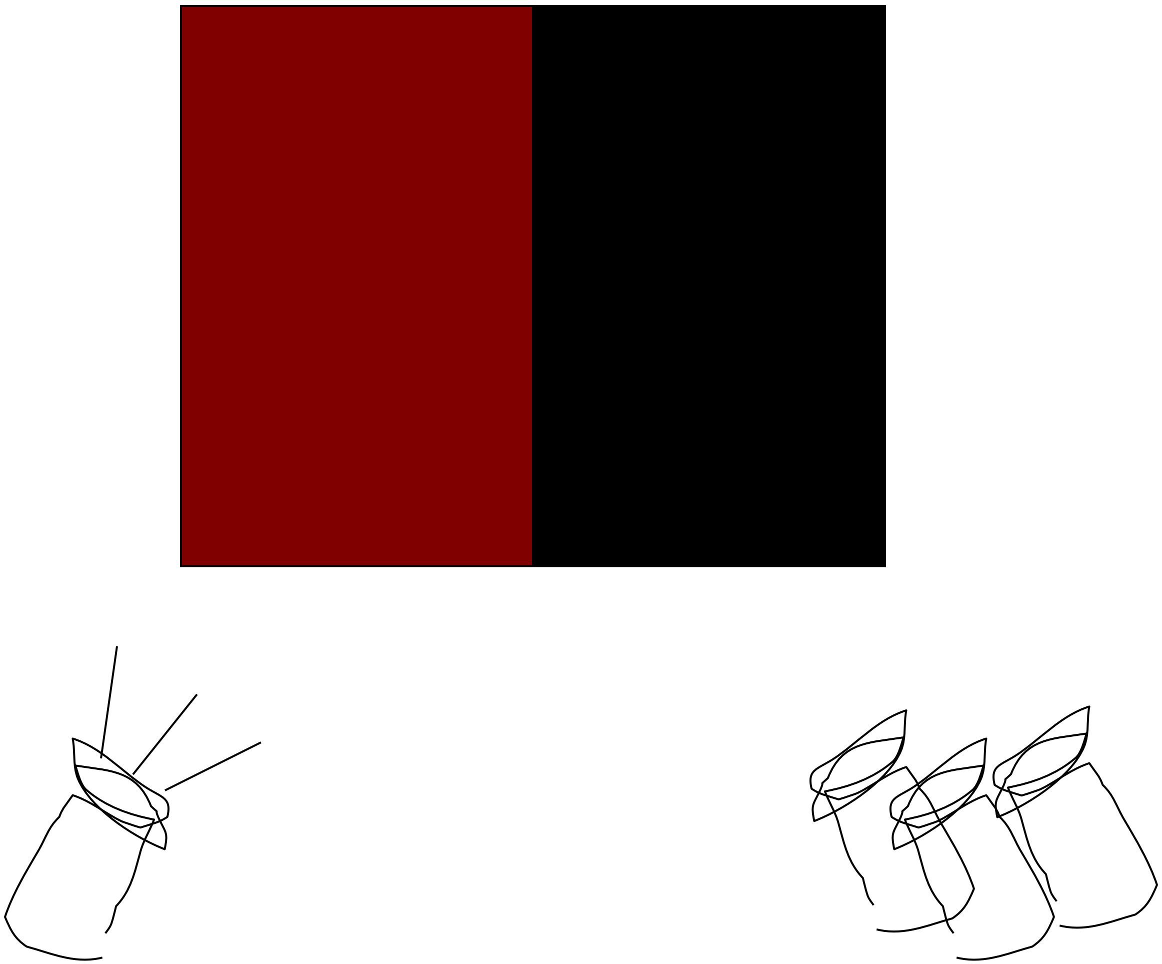
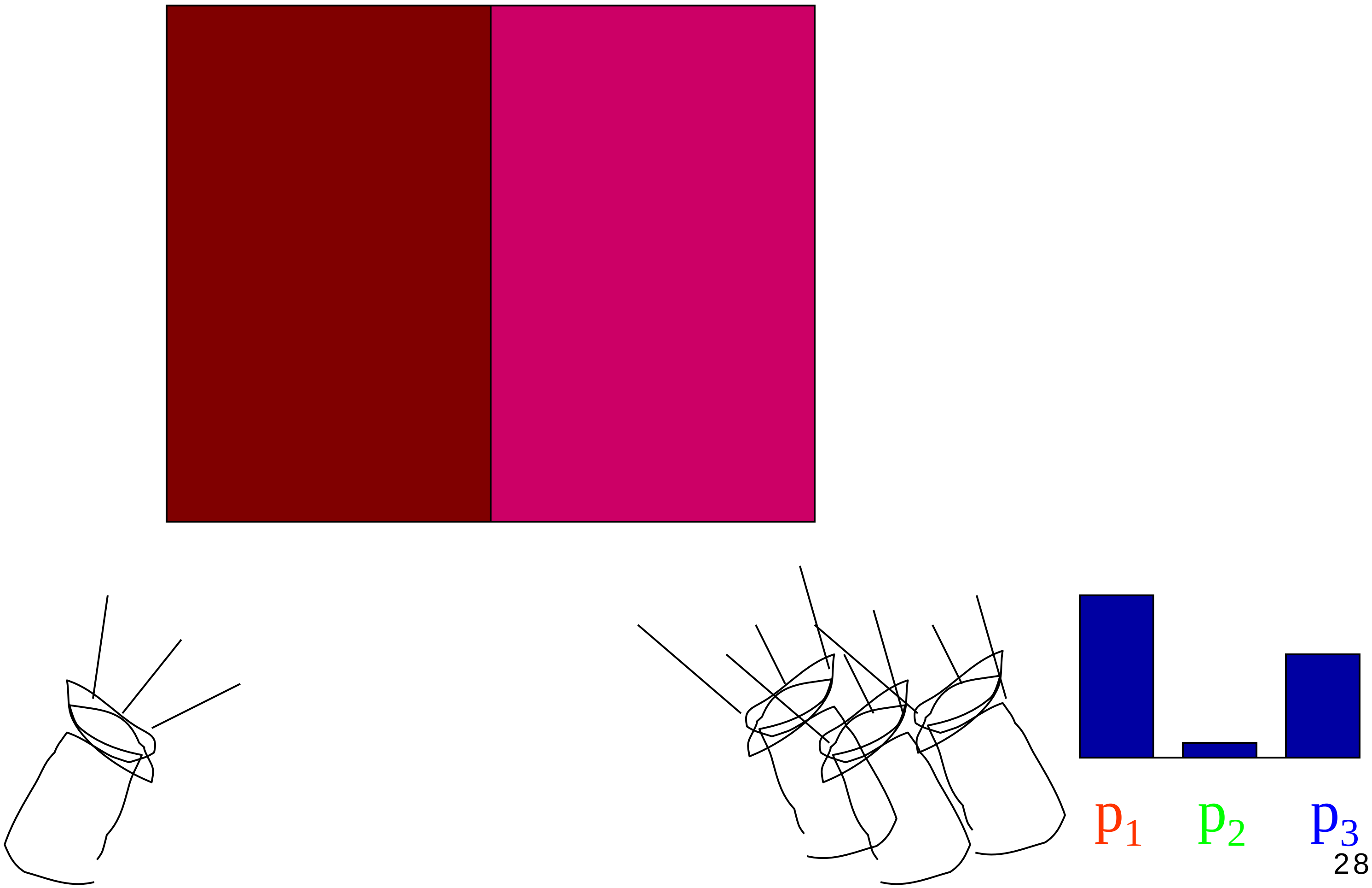


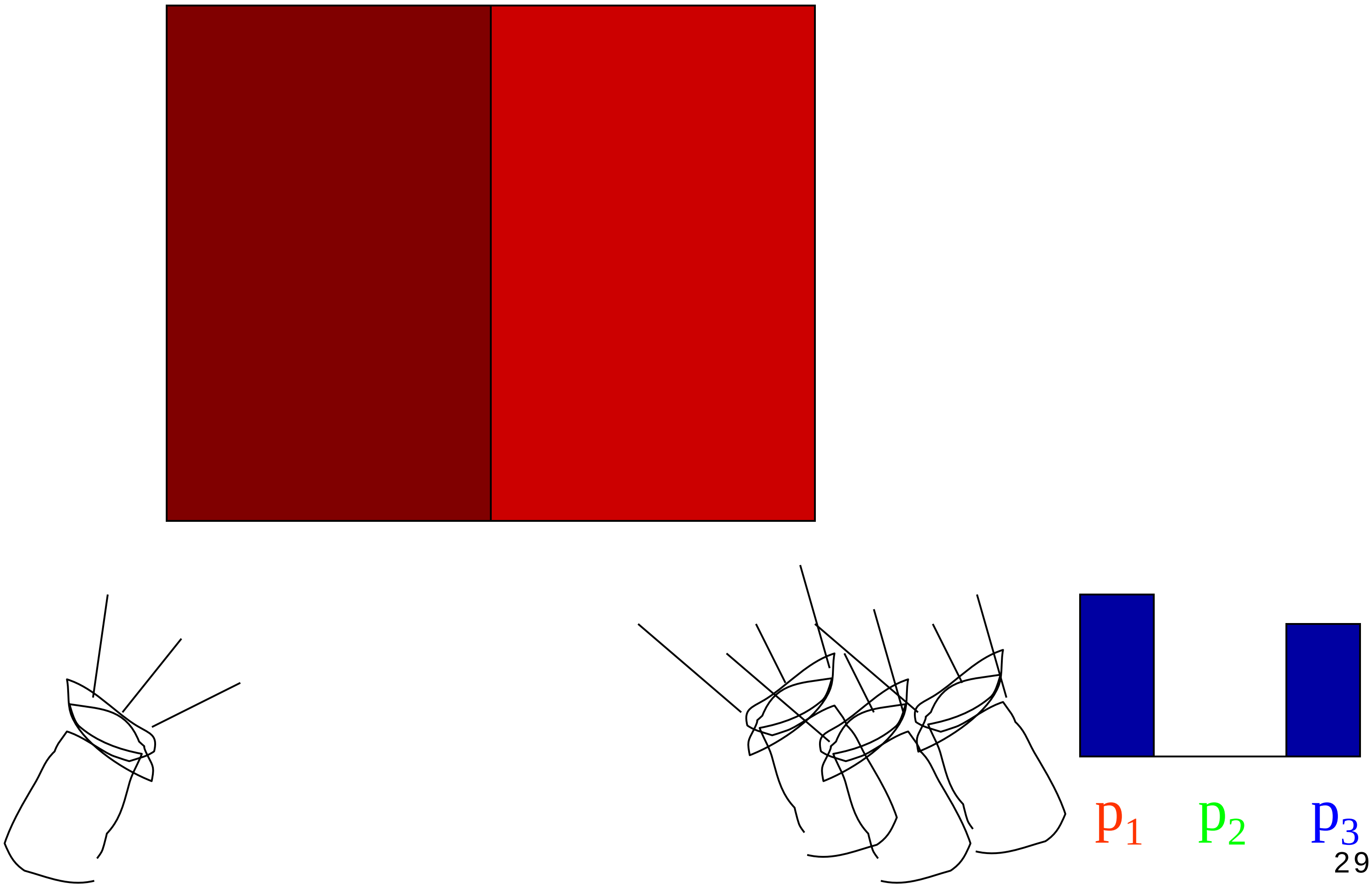
Color matching experiment 2



Color matching experiment 2

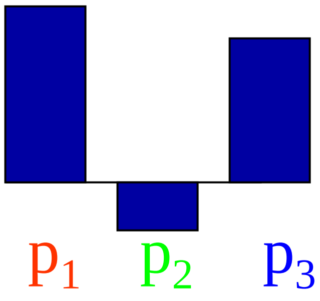


Color matching experiment 2

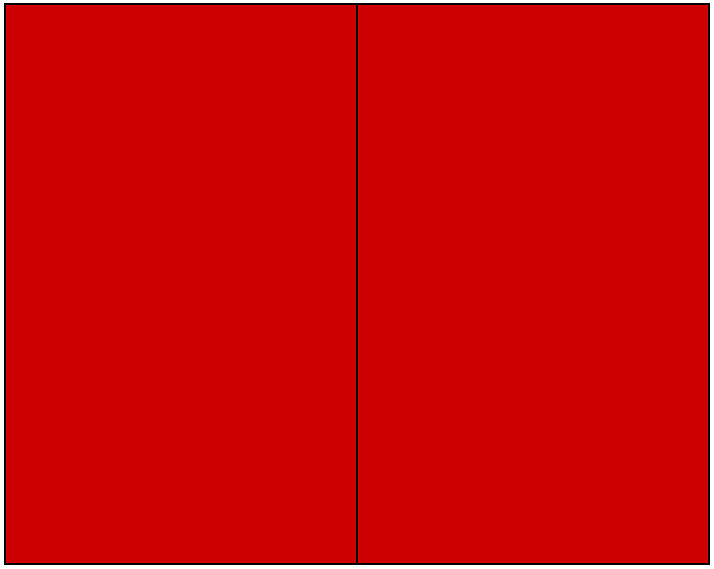


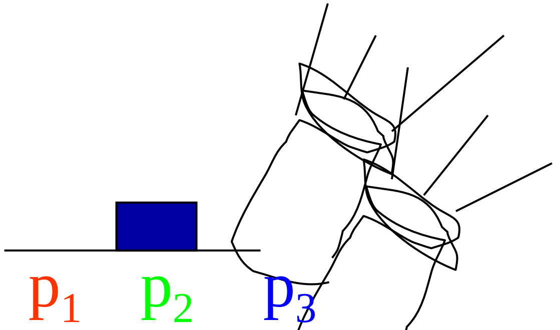
Color matching experiment 2

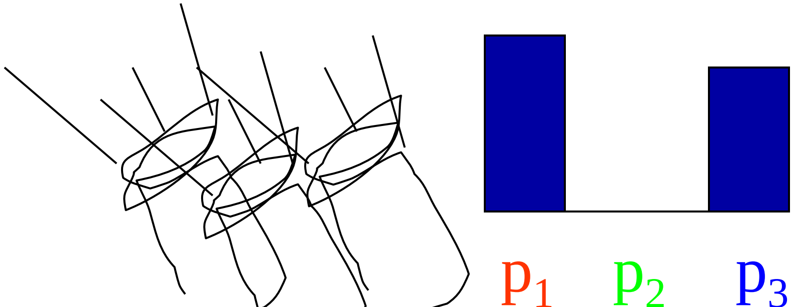
The primary color amounts needed for a match:



We say a “negative” amount of p_2 was needed to make the match, because we added it to the test color’s side.

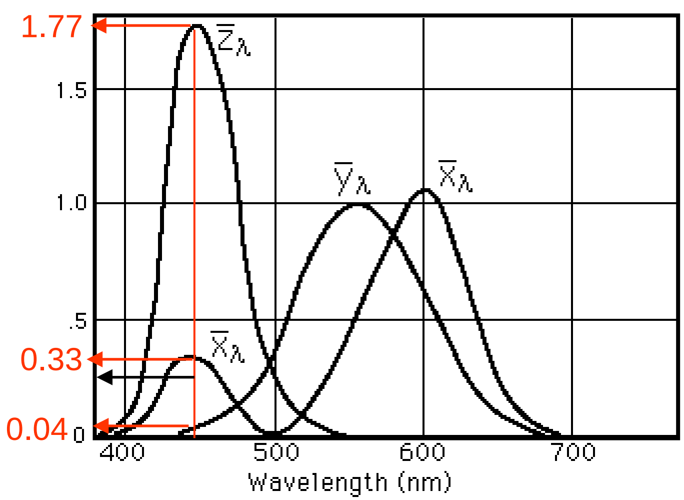






CIE Primaries

- The 3 CIE primaries called X, Y, and Z, have the following properties:
  - Y – match the luminance-efficiency function (the CIE standard photopic)
  - X, Z – selected relative to Y in order to describe the chromaticity
- Any perceivable color can be represented by X, Y, and Z



CIE color matching function

e.g. blue-violet 450nm
X: 0.33 units
Y: 0.04 units
Z: 1.77 units
(0.33,0.04,1.77) is the *CIE tristimulus values* of Blue-violet 450nm

CIE Tristimulus Values

A color C can be represented as :

$$C = X\vec{\mathbf{X}} + Y\vec{\mathbf{Y}} + Z\vec{\mathbf{Z}}$$

CIE primary colors

vector coordinates of a color

The normalized 2D (xy) diagram

$\Rightarrow$ CIE 1931 chromaticity diagram (CIE XYZ)

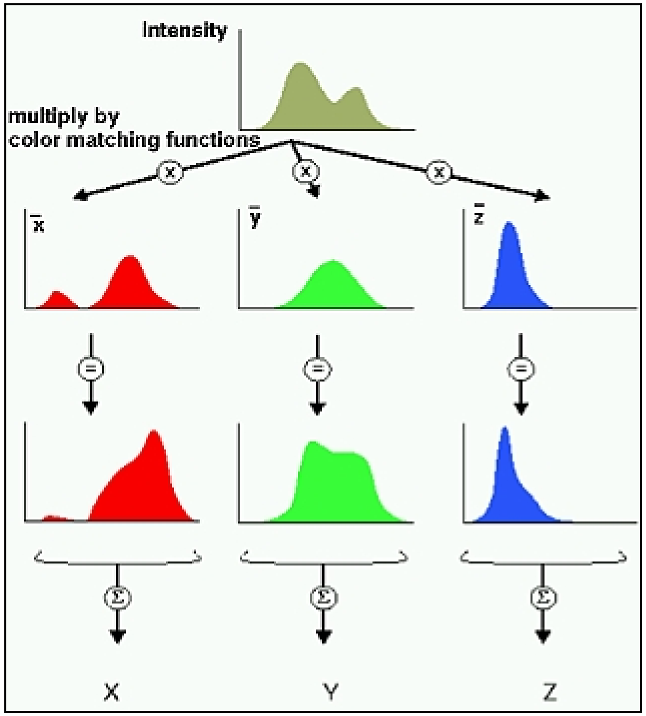
$$x = \frac{X}{X+Y+Z}$$

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

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

(x,y,z) : chromaticity values, $z = 1 - x - y$

(x,y): chromacity coordinate
Y: brightness parameters
Note: Chromaticity (*x,y*) along with a Y can convert (*x,y*) back to XYZ



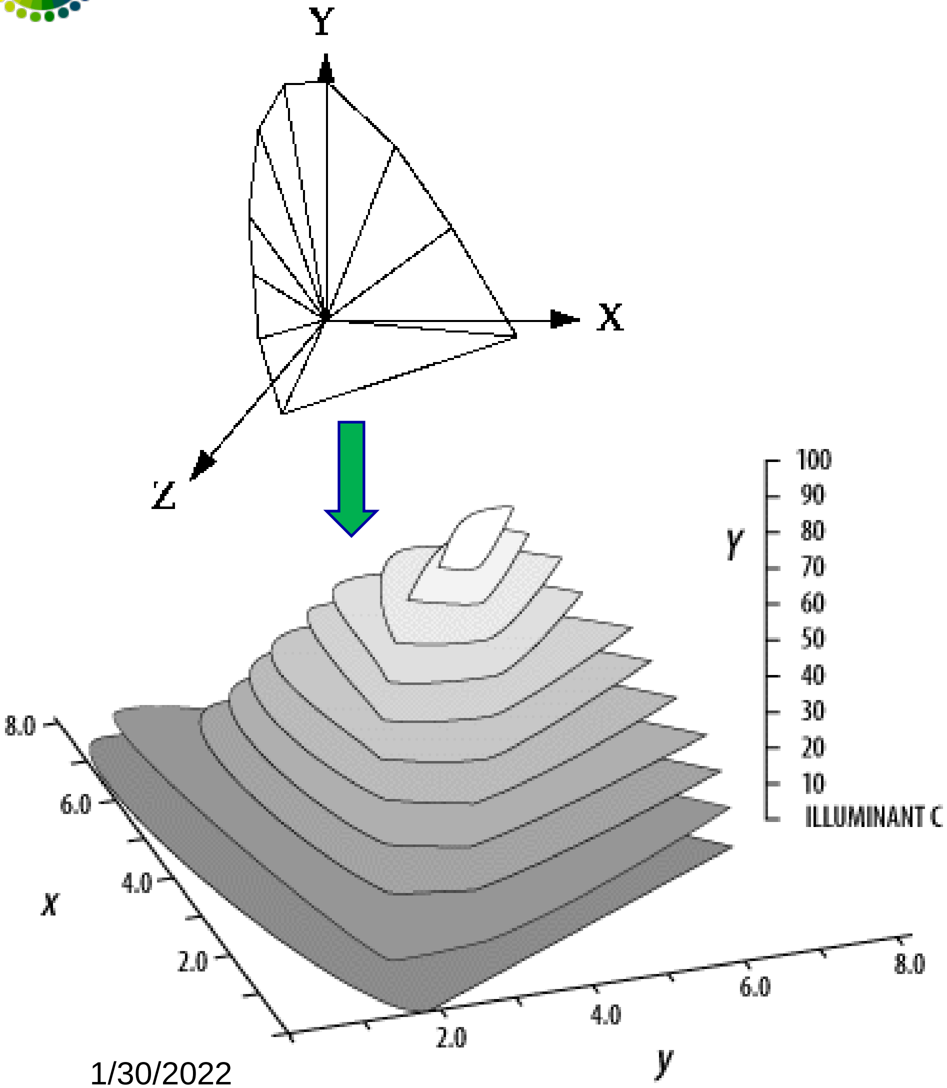
$$X = k\int P(\lambda)\bar{x}_\lambda d\lambda$$

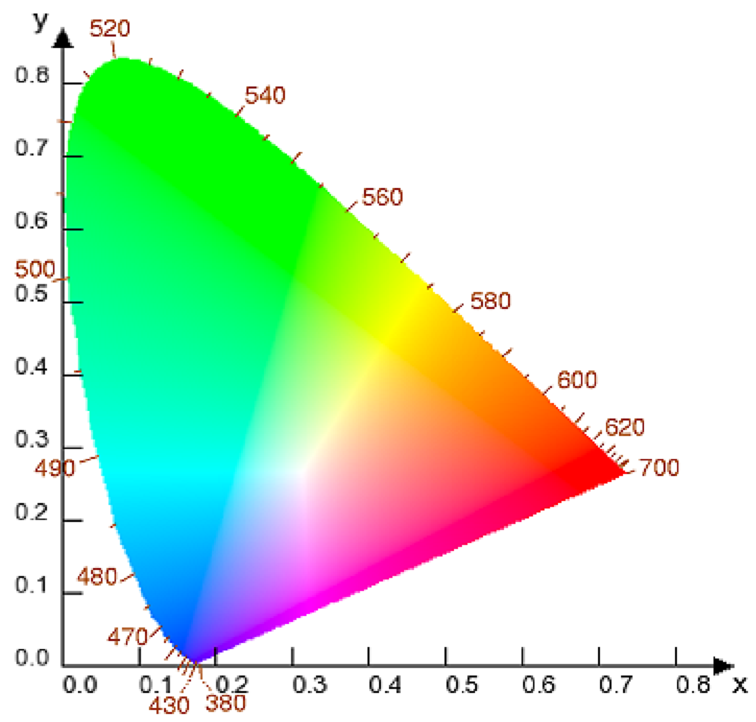
$$Y = k\int P(\lambda)\bar{y}_\lambda d\lambda$$

$$Z = k\int P(\lambda)\bar{z}_\lambda d\lambda$$

where $P(\lambda)$: a spectral energy distribution

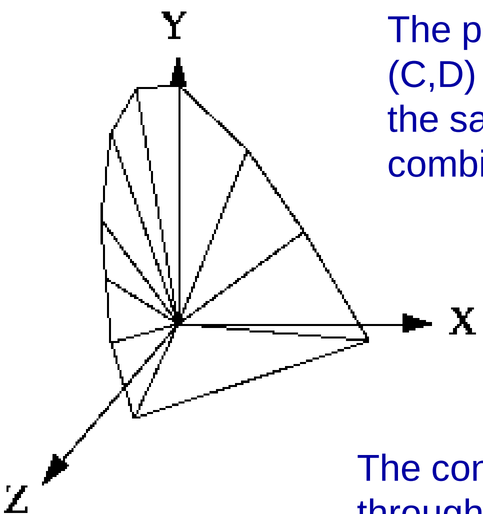
C.I.E. Chromaticity Diagram





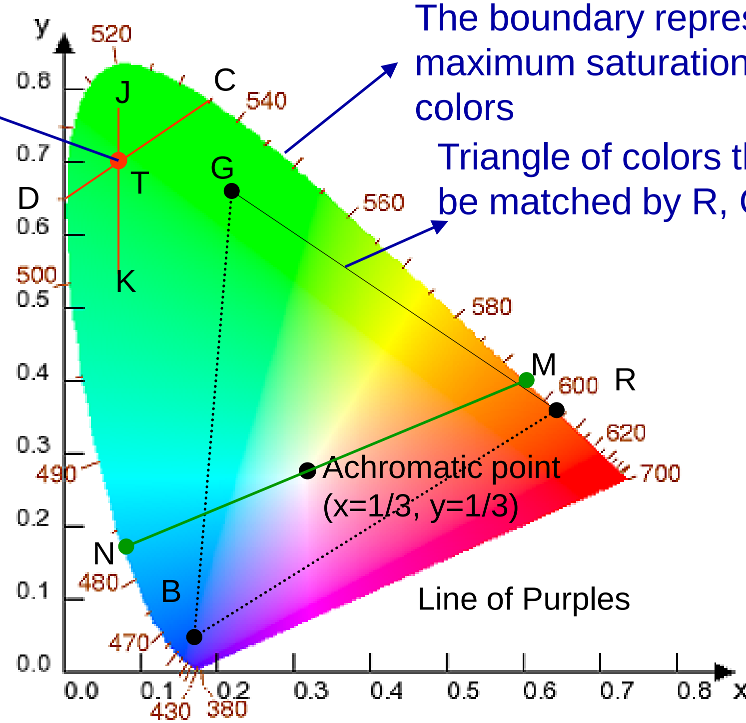
C.I.E. Chromaticity Diagram

- The C.I.E. system uses
  - The plane X+Y+Z=1's projection onto the x-y plane
  - Luminance (Brightness) – parameter Y
  - Chromaticity (Hue & Saturation) as a combination of 2 coordinates (x,y)



The pairs (J,K) and (C,D) can produce the same color T if combined properly

The connecting line pass through achromatic point form a complementary color pair, e.g. (M,N)

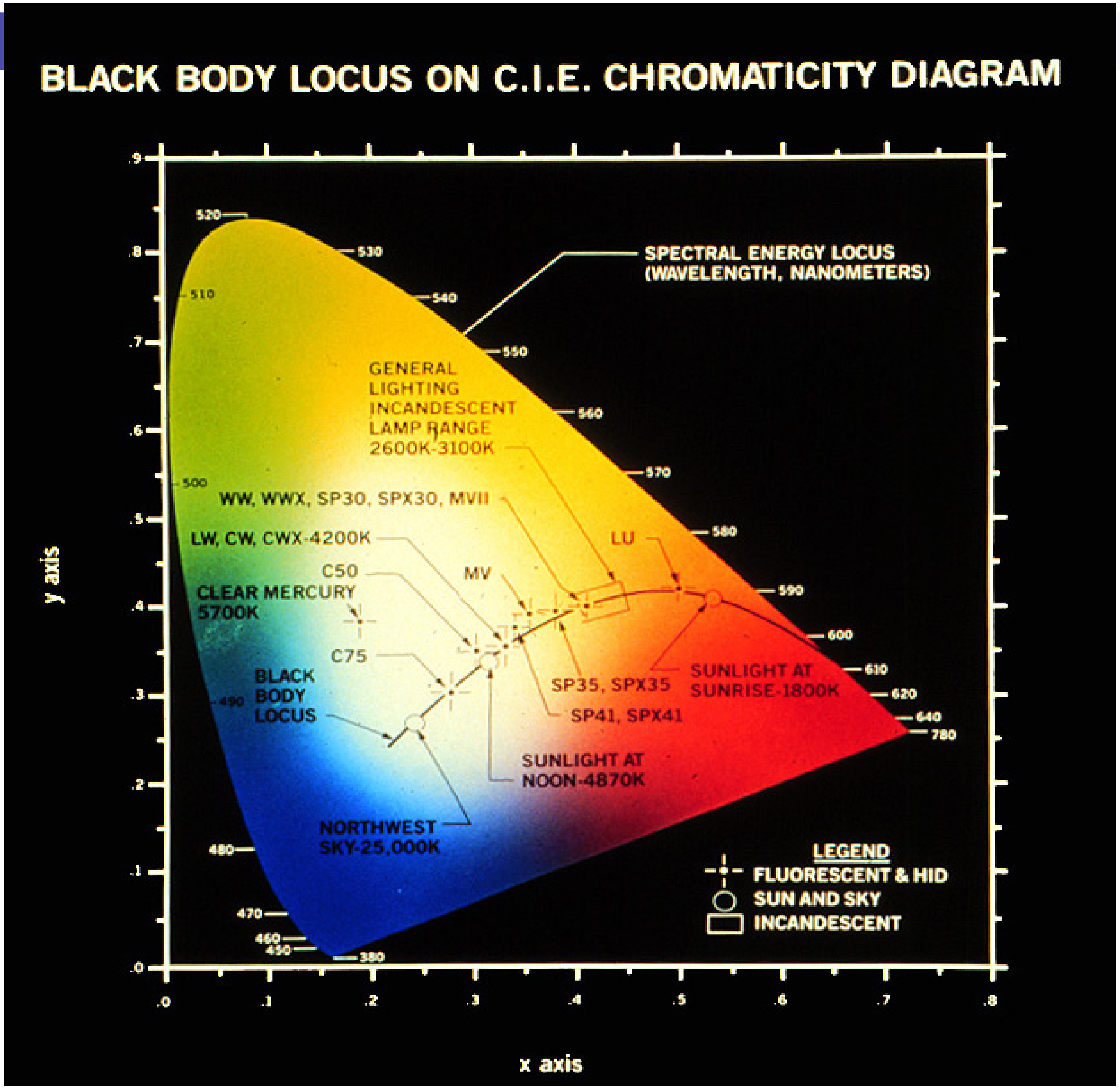


The boundary represents maximum saturation for the spectral colors

Triangle of colors that can be matched by R, G, B

CIE 1931 *xy* Chromaticity Diagram

CIE 1931 Chromaticity Diagram



Color Reproduction

- CIE chromaticity diagram is used to show color reproduction of various color imaging methods
- “Gamut”- the range of colors accessible to a given process
- Color Coverage Examples

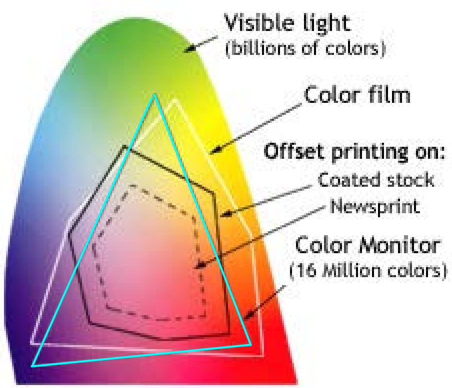
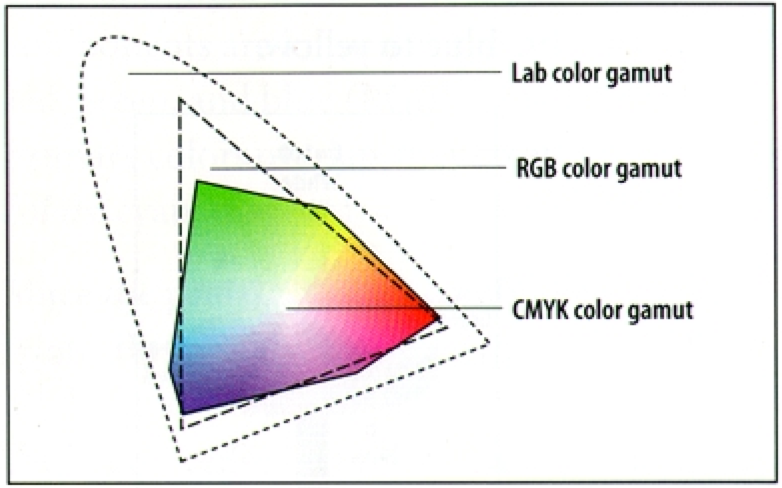


Image source: www.worgx.com



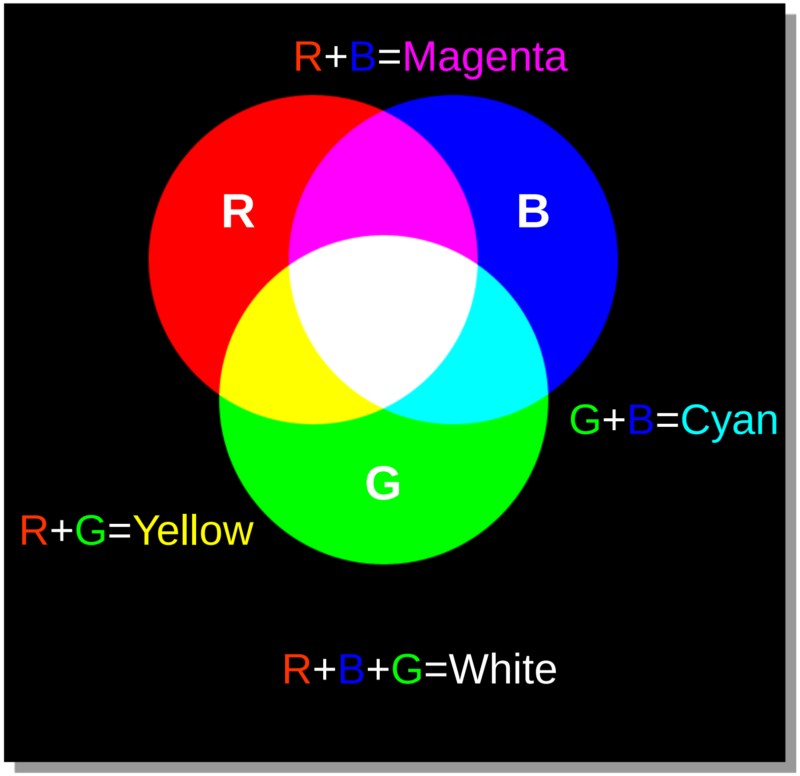
http://www.cs.sfu.ca/

Color Mixing

- Get more colors based on the primary colors
  - Additive color mixing
    - RGB
  - Subtractive color mixing
    - CMY

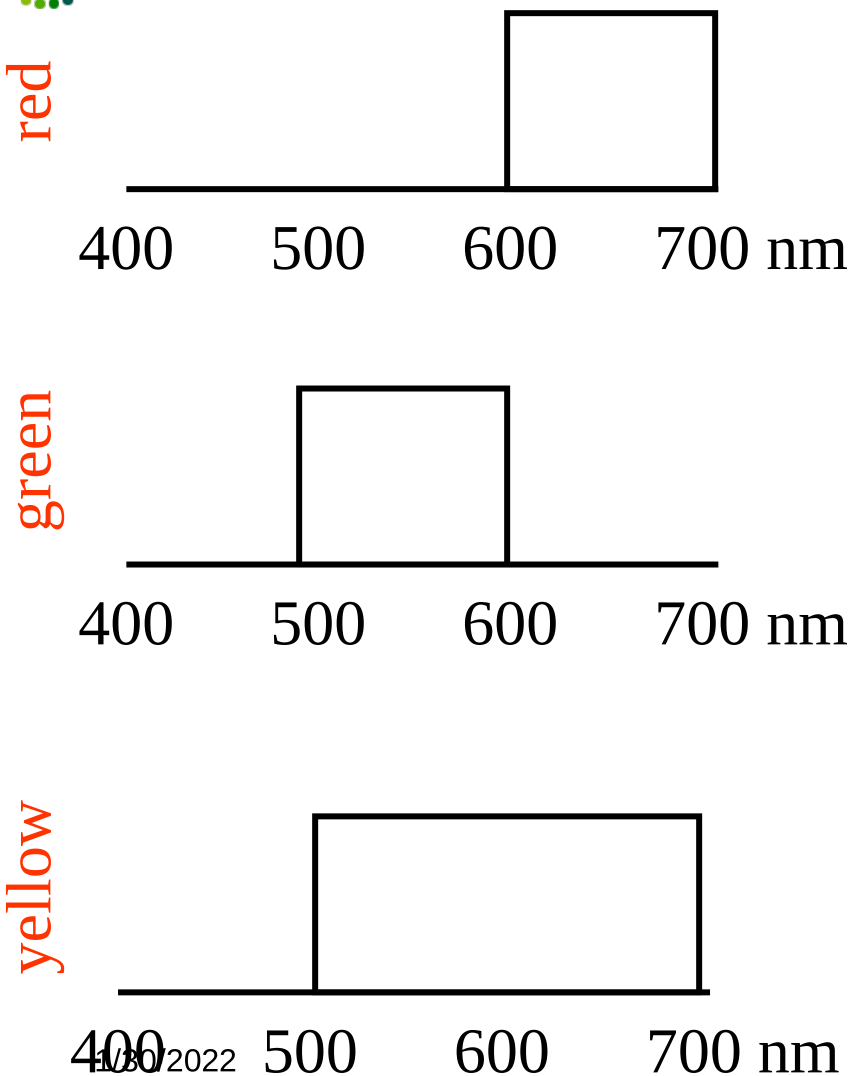
Additive Color Mixing

- Additive mixture
  - Overlap Spotlights in dark rooms
  - Primary colors
    - Red – long wavelengths
    - Green – middle wavelengths
    - Blue – short wavelengths
  - Secondary colors
    - Magenta
    - Cyan
    - Yellow
  - Applications
    - CRT phosphors
    - multiple projectors aimed at a screen
    - Polachrome slide film



Additive color mixing with red, green, blue primary colors

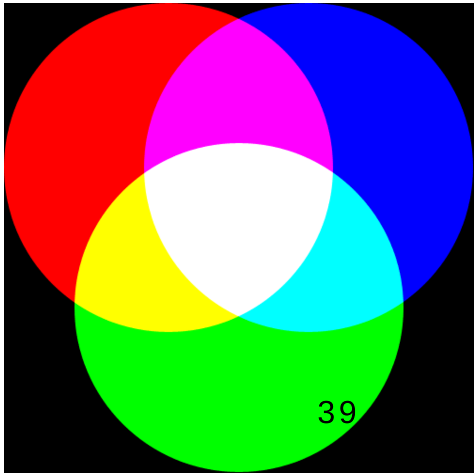
Additive color mixing



When colors combine by **adding** the color spectra. Example color displays that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

Red and green make…

Yellow!



Additive Color Mixing with CIE

- Given (x,y) coordinate of 2 sources

x_1, y_1 with brightness Y_1 and x_2, y_2 with brightness Y_2

the additive mixture color coordinates are

$$\left.\begin{cases} (x_1, y_1, \mathrm{Y}_1) \Rightarrow (\mathrm{X}_1, \mathrm{Y}_1, \mathrm{Z}_1) \\ (x_2, y_2, \mathrm{Y}_2) \Rightarrow (\mathrm{X}_2, \mathrm{Y}_2, \mathrm{Z}_2) \end{cases}\right\} \Rightarrow (\mathrm{X}_3, \mathrm{Y}_3, \mathrm{Z}_3) \Rightarrow (x_3, y_3, \mathrm{Y}_3)$$

$$x_3 = \frac{\mathrm{Y}_1}{\mathrm{Y}_1 + \mathrm{Y}_2} x_1 + \frac{\mathrm{Y}_2}{\mathrm{Y}_1 + \mathrm{Y}_2} x_2$$

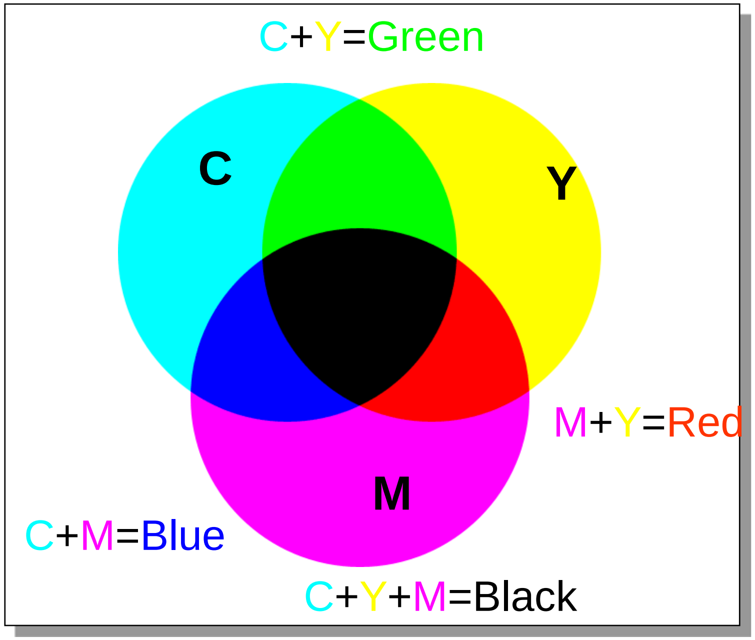
$$y_3 = \frac{\mathrm{Y}_1}{\mathrm{Y}_1 + \mathrm{Y}_2} y_1 + \frac{\mathrm{Y}_2}{\mathrm{Y}_1 + \mathrm{Y}_2} y_2$$

Subtractive Color Mixing

- Subtractive color mixing
  - Employed with paints and pigments
  - Primary colors
    - Yellow – white light subtracts blue (short wavelengths)
    - Magenta – white light subtracts green (middle wavelengths)
    - Cyan – white light subtracts red (long wavelengths)
  - All lights are subtracted - black

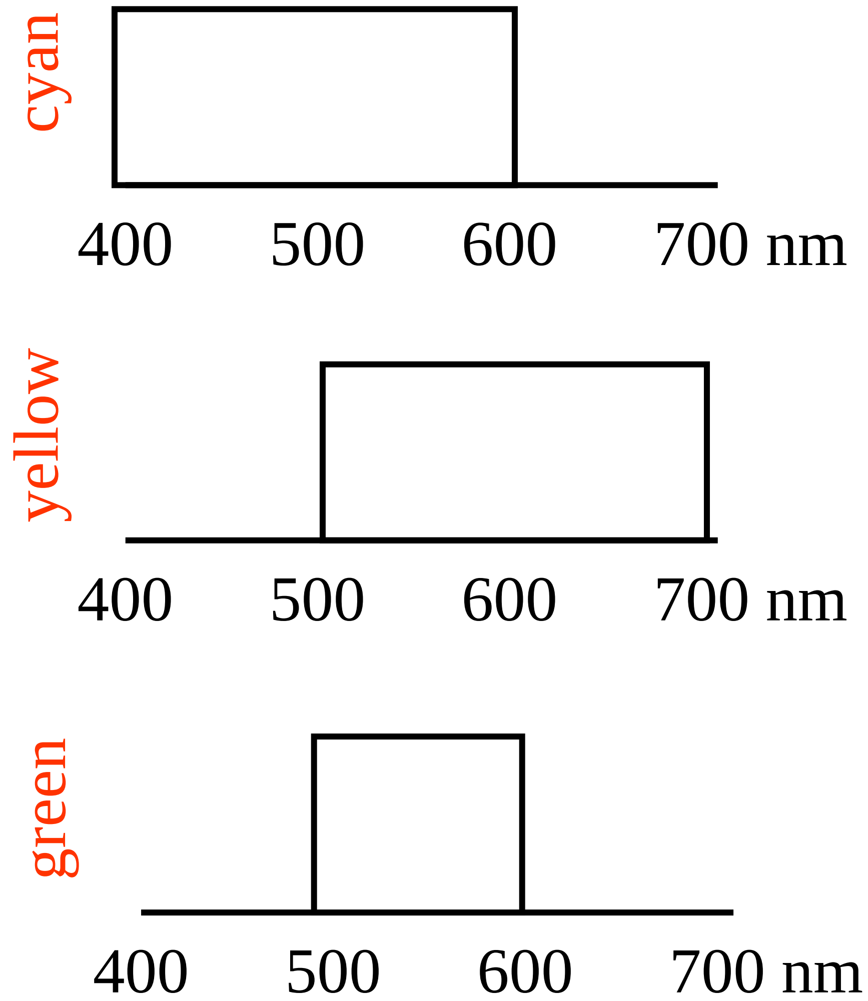
Demo

Ink Color	Absorbs	Reflects	Appears
C	Red light	Green and Blue light	Cyan
M	Green light	Red and Blue light	Magenta
Y	Blue light	Red and Green light	Yellow
M + Y	Green & Blue light	Red light	Red
C + Y	Red and Blue light	Green light	Green
C + M	Red and Green light	Blue light	Blue



Color subtraction with primary filters

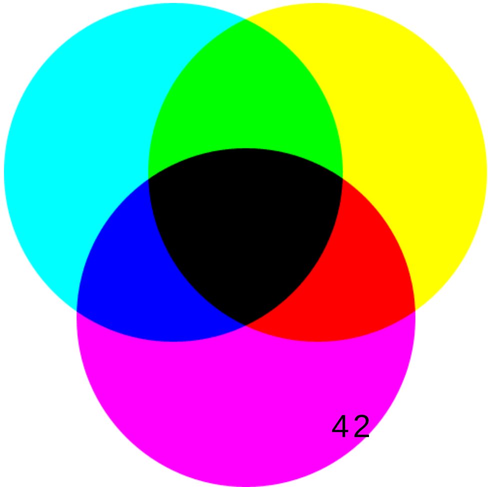
Subtractive color mixing



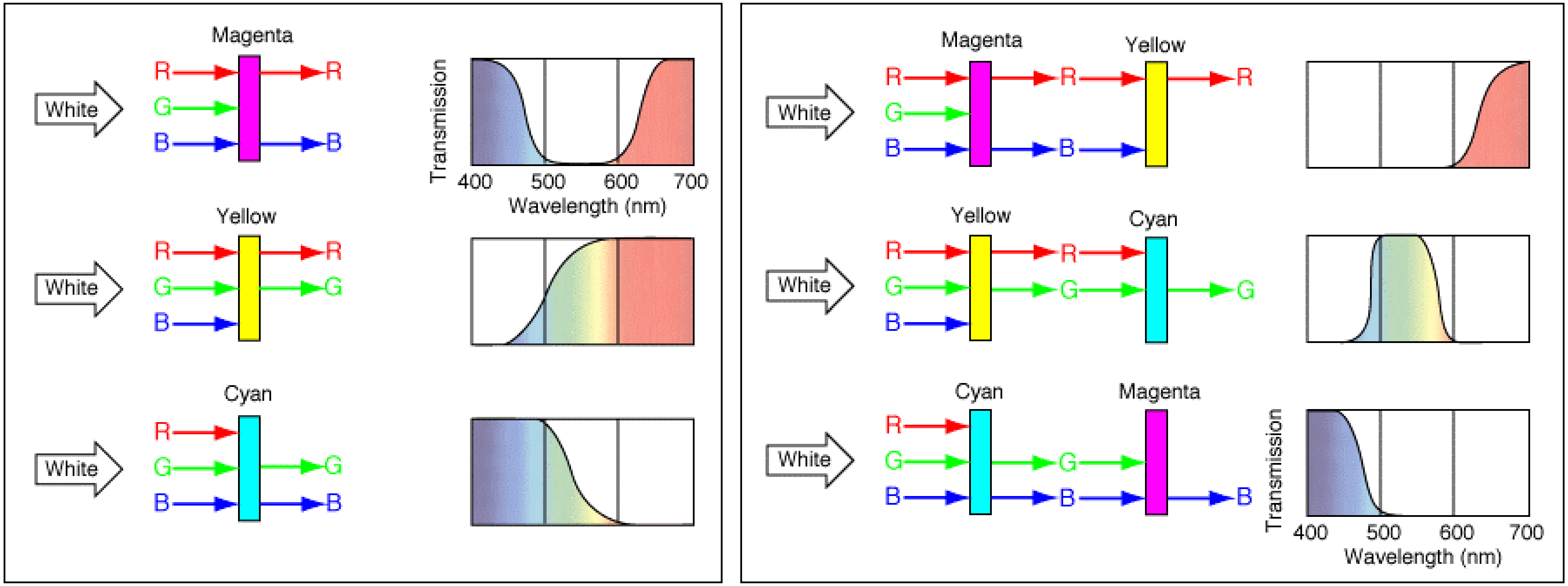
When colors combine by *multiplying* the color spectra. Examples that follow this mixing rule: most photographic films, paint, cascaded optical filters, crayons.

Cyan and yellow (in crayons, called "blue" and yellow) make…

Green!



Subtractive Color Mixing - Example



Illuminate colored filters with white light from behind*

*Image source: *HyperPhysics*

Demo

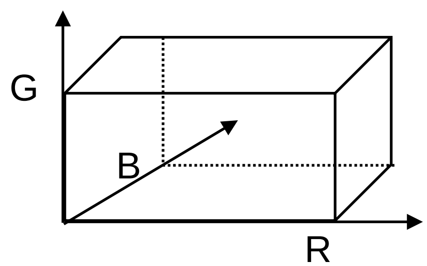
Color Models (or Spaces)

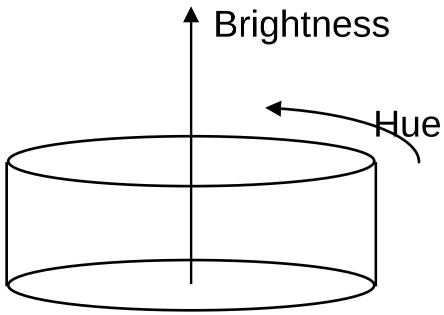
- Three types of cones suggests color is a 3D quantity
- A color model is a 3D (or N-D) unique representation of a color
- What to use is application oriented
- Example
  - RGB – TV monitors, cameras, computer graphics, etc.
  - CMY (or CMYK) – color printing
  - YIQ / YUV – TV broadcasting

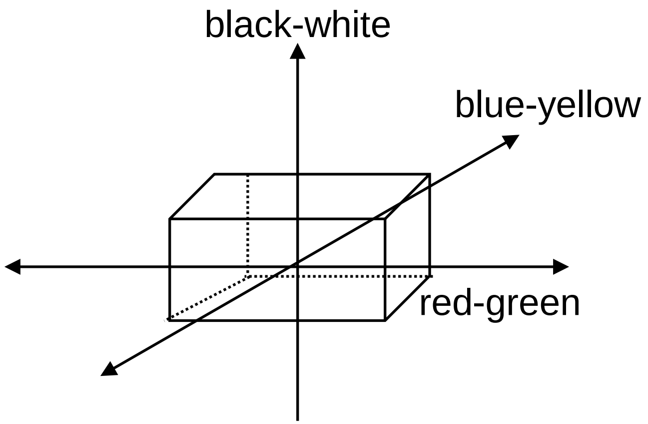
  hardware-oriented

  - HSI / HSV – color image manipulation → user-oriented
  - CIE L*u*v* / CIE L*a*b* – Image retrieval → equal visual variance

3D Color Models







Cubic Color Models

RGB
CMYK

Polar Color Models

HSI
HSV

Opponent Color Spaces

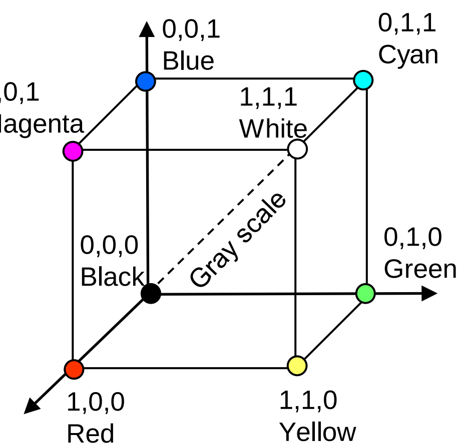
YUV
L*a*b*

RGB

- The simplest and most common lighting model
- The RGB model is additive
- Pros. - convenient for programming

  Cons.- not all perceptually uniform, not intuitive in color mixing

  - highly device dependent, different CRTs have different RGB gamuts
- RGB is used when portability or reproducibility is not a major concern
  - e.g. computer graphics, TV monitors , and cameras



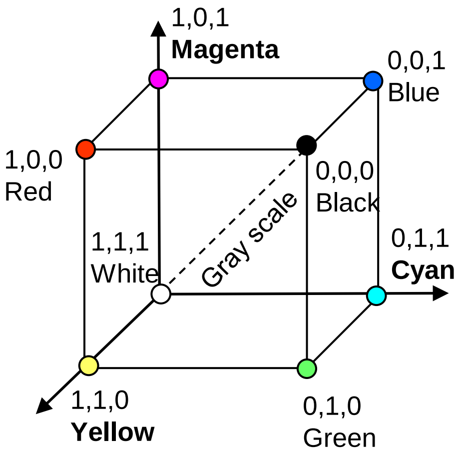
RGB color cube

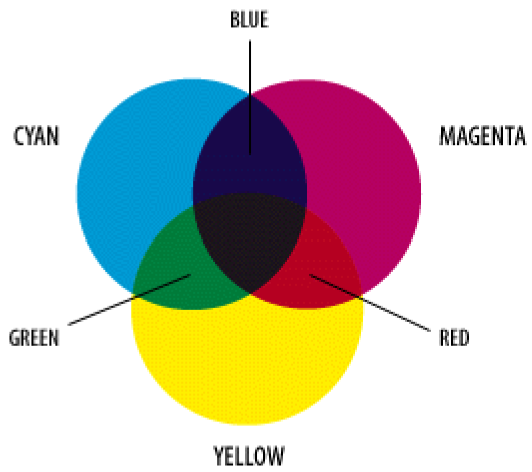
CMY (or CMYK)

- CMY is used for printing (subtractive color mixing)
- CMYK models adds pure black (K) to the mix – a richer black and less ink consumption
- Directly specifying colors in CMY is complicated, but conversion from RGB model is simple
  - Some corrections are required when converting CRT-colors RGB to ink-colors CMY
  - To produce more colors, tricks like halftoning and dithering must be used

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

Ideally, CMY model is simply transposition of RGB Model





Demo

YIQ / YUV

- Recoding of the RGB model for TV transmission
  YIQ: the US and Japanese standard for NTSC system of color TV
  YUV: the European standard for PAL system of color TV
- Y component – intensity
  I (Inphase) and Q (Quadrature) components – hue
- Pros.
  - Easy to get achromatic images
  - No correlation between chromaticity and intensity
  - Good for compression
    - Human vision is more sensitive to luminance change
    - Chromatic part may be subsampled for transmission/storage efficiencies
- Cons.
  - Not intuitive, not perceptually uniform

RGB to YIQ/YUV

- RGB* to YIQ

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.532 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Here, R, G and B are assumed to range from 0 to 1

$$Y = 0.299R + 0.587G + 0.114B$$

This part is used for B/W TV

- RGB to YUV

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.199 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{aligned} U &= 0.493(B-Y) \\ &= -0.147R - 0.289G + 0.436B \\ V &= 0.877(R-Y) \\ &= 0.615R - 0.515G - 0.100B \end{aligned}$$

*NTSC receiver primary system R_N, G_N, B_N

YIQ/YUV to RGB

- YIQ to RGB

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0.956 & 0.621 \\ 1 & -0.272 & -0.647 \\ 1 & -1.106 & 1.703 \end{bmatrix} \begin{bmatrix} Y \\ I \\ Q \end{bmatrix}$$

- YUV to RGB

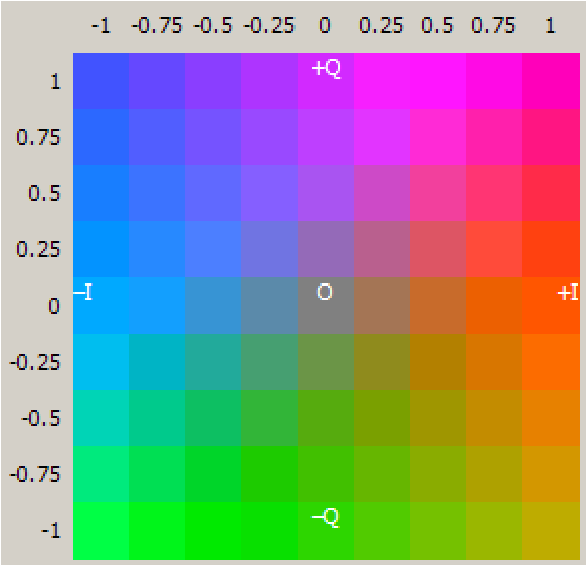
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.140 \\ 1 & -0.395 & -0.581 \\ 1 & 2.032 & 0 \end{bmatrix} \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

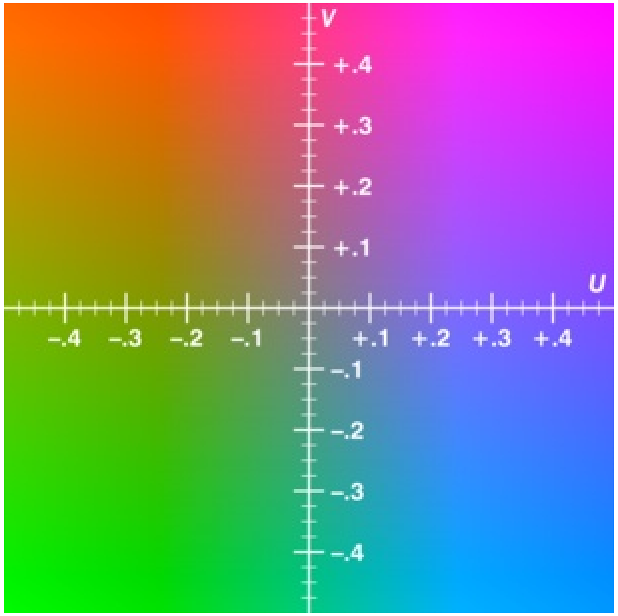
YIQ v.s. YUV

The relation between (I,Q) and (U,V) is

$$I = V\cos 33^\circ - U\sin 33^\circ$$

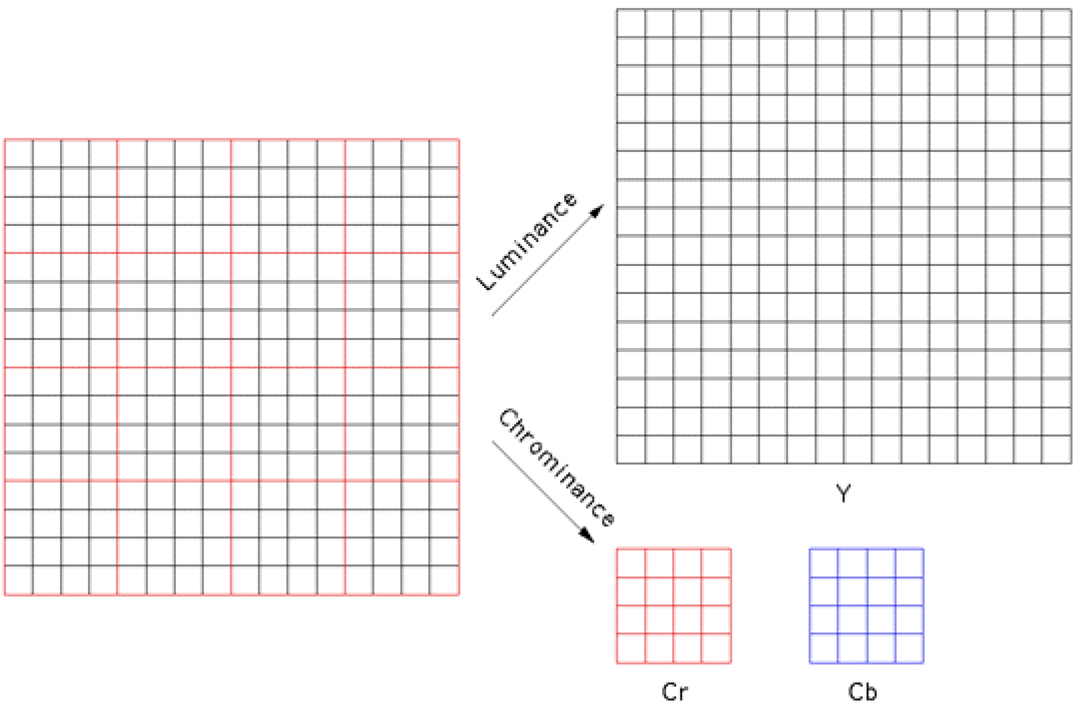
$$Q = V\sin 33^\circ + U\cos 33^\circ$$





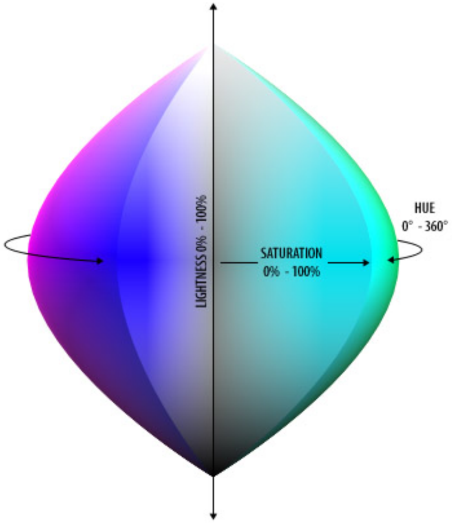
Color Models in Compression Standards

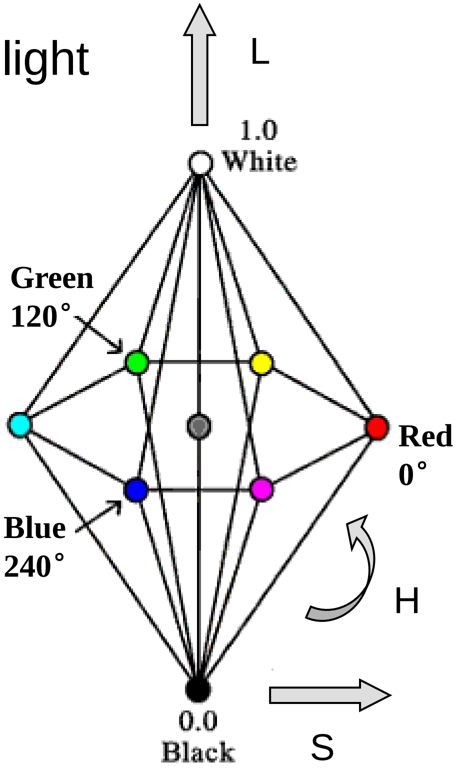
- In JPEG, Cb,Cr are used for the chromaticity coordinates and they are proportional to U,V



HSI (or HLS)

- HSI (Hue-Saturation-Intensity) or HLS (Hue-Lightness-Saturation)
- Two-ended hexagonal pyramid
- Intensity decouple from color
- Closely related to how human perceive color
- Very intuitive model for color artists working with light





RGB to HSI

$$I = \frac{1}{3}(R+G+B)$$

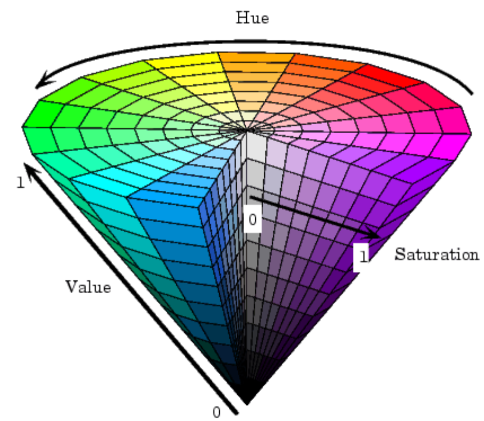
$$H = \cos^{-1}\left\{\frac{\frac{1}{2}[(R-G)+(R-B)]}{[(R-G)^2+(R-B)(G-B)]^{1/2}}\right\}$$

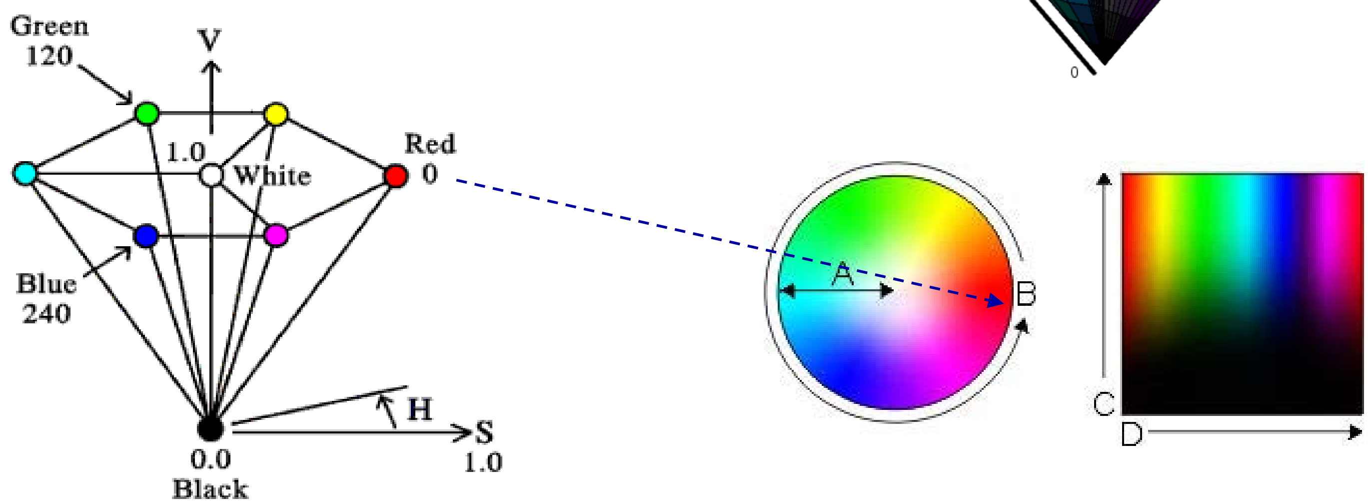
$$S = 1-\frac{3}{(R+G+B)}[\min(R,G,B)]$$

Note:
- H = (360º - H) if (B/I) > (G/I) and H is normalized by H = H/360º
- H is undefined if S = 0
- S is undefined if I = 0

HSV

- The Hue-Saturation-Value (HSV) model is similar to the HSI model
- Sometimes also referred to as HSB model





RGB to HSV

- Non-linear, no transform matrix
- Value V is the biggest value of R,G and B

  V = max (R,G,B)
- Saturation S

  S = (max (R,G,B) - min (R,G,B))/ max (R,G,B)

  min (R,G,B) = 0 S = 1(pure color)

  max (R,G,B) = min (R,G,B) S = 0 (grey)
- Hue H depends on V
  - e.g.

```
delta = max (R,G,B) - min (R,G,B) ;
max  = max (R,G,B) ;
If ( R = = max )  H = ( G - B ) / delta;          // between yellow & magenta
else if( G = = max )  H = 2 + (B - R ) / delta;  //between cyan & yellow
else H = 4 + ( R - G ) / delta;                  // between magenta & cyan
H *= 60;                                         // in degrees
if( H < 0 ) H += 360;
```

RGB to CIE XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\text{let } \mathbf{M} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}$$

M is the 3x3 matrix of color matching coefficients given by the manufacturer or by measurement.

$$\text{Monitor } 1 \Rightarrow \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M}_1 \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}$$

$$\text{Monitor } 2 \Rightarrow \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M}_2 \begin{bmatrix} R_2 \\ G_2 \\ B_2 \end{bmatrix} \Rightarrow \begin{bmatrix} R_2 \\ G_2 \\ B_2 \end{bmatrix} = \mathbf{M}_2^{-1} \mathbf{M}_1 \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}$$

Example – XYZ to sRGB

- sRGB monitor –
  - D65 white point (x = 0.3127, y= 0.3290, z= 0.3583)
  - Gamma of the monitor is 2.2

Converting sRGB to XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Converting XYZ to sRGB

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

CIE LUV

- The 1931 CIE chromaticity diagram is not perceptually uniform
- The 1976 CIE uniform chromaticity space (UCS) system provides a perceptually uniform color space.

Transform from CIE $XYZ \Rightarrow$ CIE Luv

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16\,;\ \ \frac{Y}{Y_n} \geq 0.008856$$

$$L^* = 903.3\frac{Y}{Y_n};\ \ \frac{Y}{Y_n} < 0.008856$$

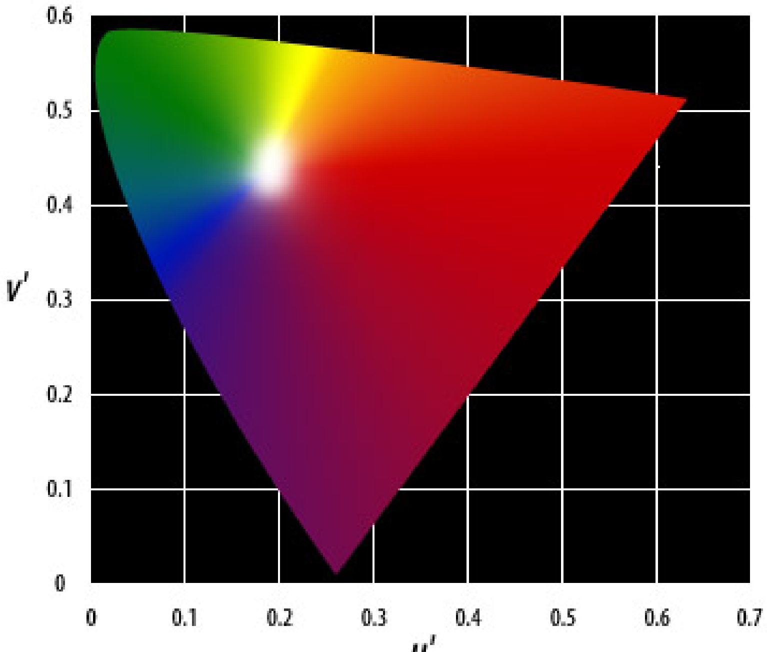
$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

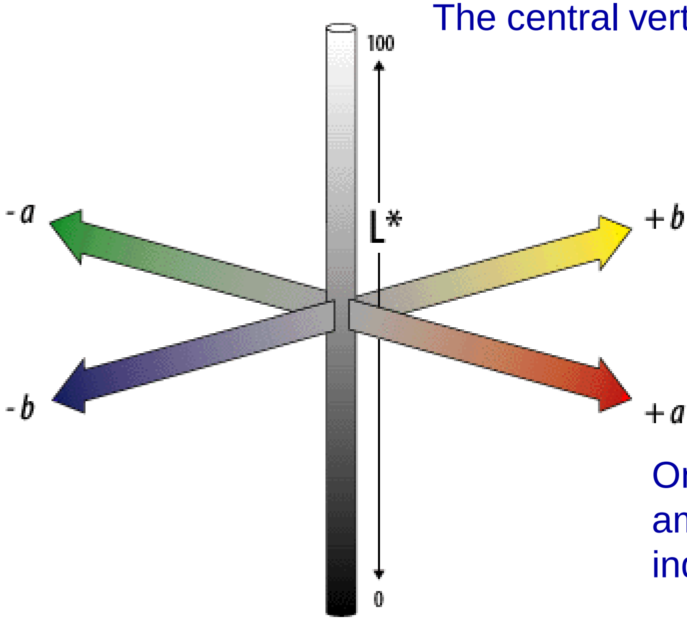
Y_n is the luminance of the white reference



CIE L*a*b*

- CIE L*a*b* is an opponent color system based on the earlier (1942) system called L, a, b.
- Color opposition correlates with discoveries in the mid-1960s
- CIE L*a*b* indicates these values with three axes: L*, a*, and b*.

The central vertical axis represents lightness (L*)



On the **b-b'** axis, yellow is positive and blue is negative. For both axes, zero is neutral gray.

On the **a-a'** axis: positive values indicate amounts of red while negative values indicate amounts of green

Color opposition: a color can't be both red and green, or both blue and yellow

CIE XYZ to CIE L*a*b*

Transform from CIE $XYZ \Rightarrow$ CIE $L^*a^*b^*$

$$L^* = \begin{cases} 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16; & \frac{Y}{Y_n} > 0.008856 \\ 903.3\frac{Y}{Y_n}; & otherwise \end{cases}$$

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

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

$$\text{where } \begin{cases} f(t) = t^{1/3} & t > 0.008856 \\ 7.787 * t + 16/116 & otherwise \end{cases}$$

index n refers to the coordinates of white

Note: All CIE models are device independent

Comparison

- Device-oriented models – linear, easy for computation
  - RGB
  - CMY/CMYK
- User-oriented models – Intuitive, for artistic applications
  - HSI/HLS
  - HSV/HSB
- Device independent models
  - All CIE models
- Perceptual uniform models – uniform chromaticity
  - CIE L*u*v
  - CIE L*a*b
- Opponent models
  - YIQ/YUV
  - CIE L*a*b

Color Image Processing

- How to apply image processing techniques to color images?
  - Individual vs. vector
  - Directly apply to each color plane of RGB
  - Intensity component of HSI

    (or luminance component of YIQ/YUV)

RGB to HSI → Apply Image Processing to I component → HSI to RGB

- What to use depends on applications

Color Image Processing

- Histogram Equalization
- Intensity & Contrast Adjustment
- Smoothing & Sharpening
- Color Correction- Automatic White Balancing
- Color Depth Reduction
- Other Image Processing
    - Color image segmentation
    - Color edge detection

Color Depth Reduction

- How to display 24-bit color images on 8-color devices
  - Color Quantization
  - Color Halftoning

Color Quantization

- Reduce color information for display or storage purpose
  - 24-bit color $\Rightarrow$ 8-bit color
- A lossy process
- Two issues
  - What color should be preserved
  - How to map discarded colors to the remaining ones
- Examples: 24-bit color $\Rightarrow$ 8-bit color
  - Uniform (or non-uniform) quantization on each axis independently
    - e.g. 3 bits to red, 3 bits to green and 2 bits to blue (3-3-2)
    - Yield poor results, some regions are empty with no color mapped to them
    - Use non-uniform quantization to each axis will produce slightly better results
  - Palette-based techniques
    - Use colormaps with 8-bit index numbers, e.g. 8-bit GIF
  - Octree-based techniques
  - Others: perceptually optimized color quantization

Colormaps (Color Palettes)

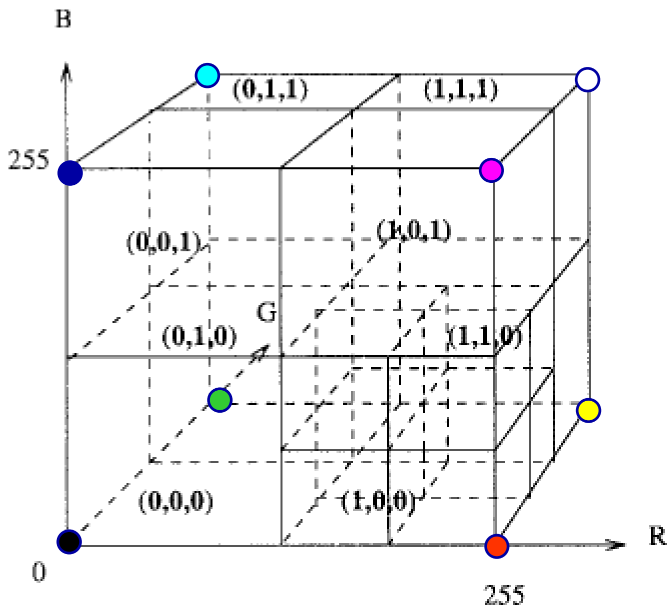
- How to build a colormap
  - *popularity algorithm* (most commonly used)
    - Create a histogram of all colors and retain the 256 most frequent ones
    - Map to the closest one if a non-empty region is not selected
  - *median-cut algorithm* (better results, more processing time)
    - Find the smallest box which contains all the colors in the image
    - Sort the enclosed colors along the longest axis of the box
    - Split the box into 2 regions at median of the sorted list
    - Repeat the above process until the original color space has been divided into 256 regions
    - Note: each box will contains approximately same number of colors
  - *Example*

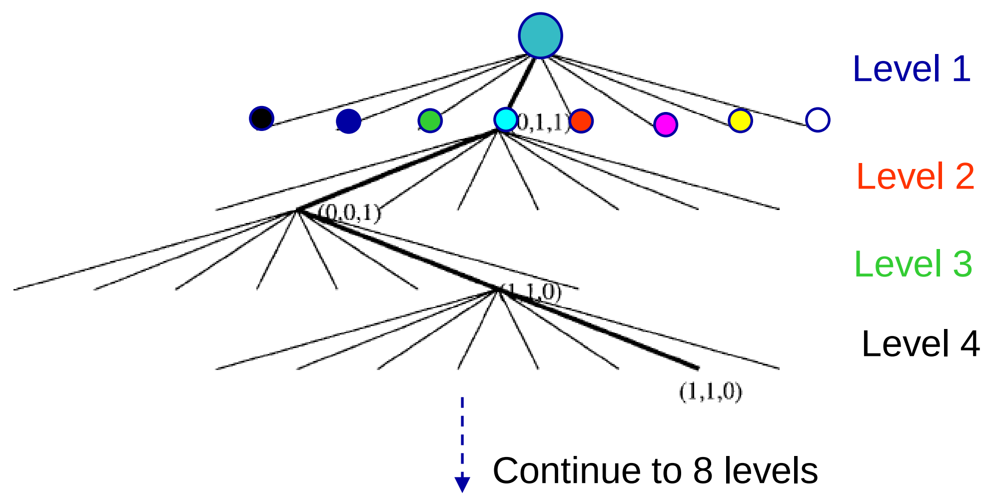
Octree Color Quantization

- The idea here is to build a tree structure containing always a maximum of K different colors.
- If a further color is to be added to the tree structure, its color value has to be merged with the most likely one that is already in the tree. The both values are substituted by their mean
- The K leaves are used as entries for the color look-up table. the representative color value for a leave is computed as the mean value of the color value and the color count. The color index is also stored in the octree.

Octree Algorithm

Insert a color into octree





(R,G,B) = (53,187,197)

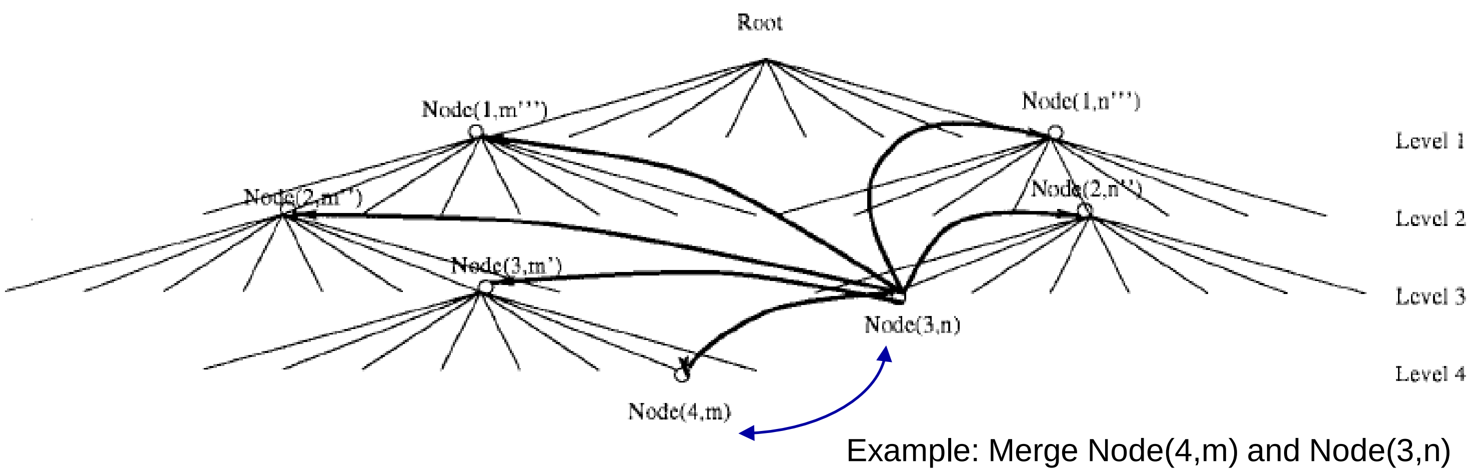
Level 2

R = 0 0 1 1 0 1 0 1
G = 1 0 1 1 1 0 1 1
B = 1 1 0 0 0 1 0 1

Level 1 Level 3

Octree Pruning & Nodes Merging

- Full octree is too big to store
- Octree pruning
  - Limit number of levels
  - Remove parent nodes with smaller pass numbers
- Nodes merging

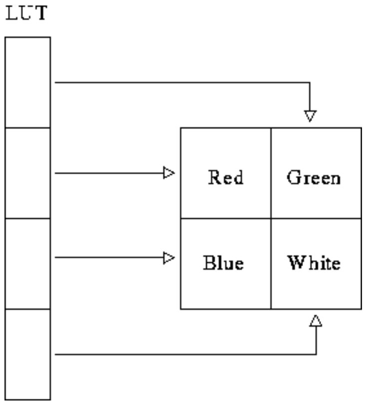


Color Quantization Summary

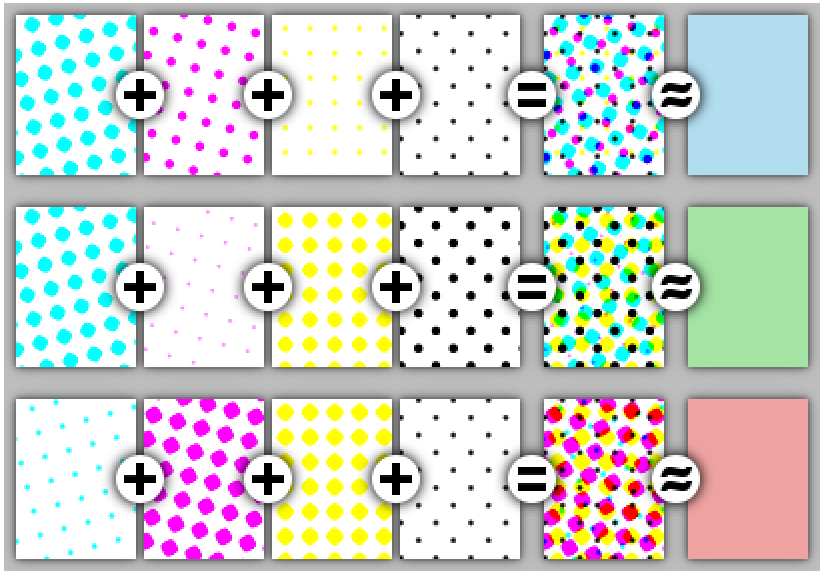
- Color palette generation
  - Fixed partition (fast) vs. Content dependent (slow, smaller errors)
- Mapping color
  - By space partition (fast) vs. nearest neighbor (slow, smaller errors)

Color Halftoning

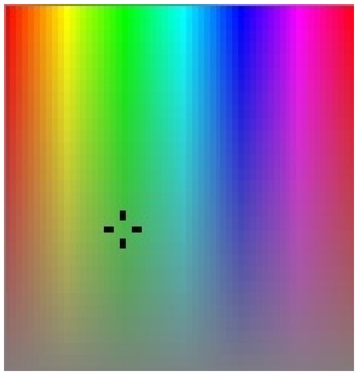
- How to display 24-bit color images on 8-color devices
  - Color halftoning – increase color resolution at the cost of spatial resolution
  - Example:
    - The 256 values of the colormap are divided into four sections containing 64 different values of red, green, blue and white.
    - Increase color resolution from 256 (8-bit color) to 65536 (16-bit color)



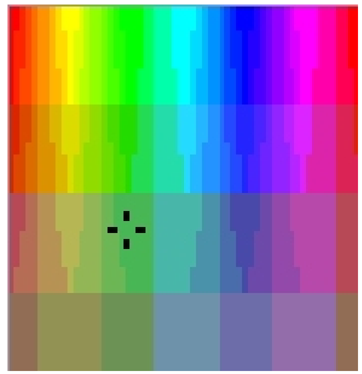
A 2×2 pixel area displaying one composite color



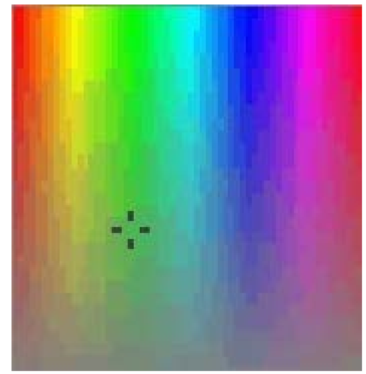
Color Quantization - Example



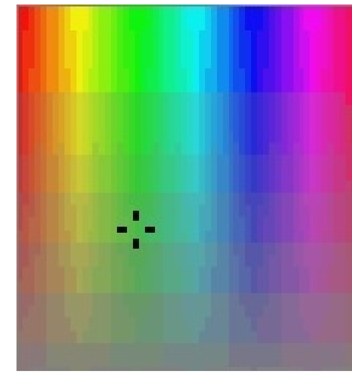
Original, 24-bit color



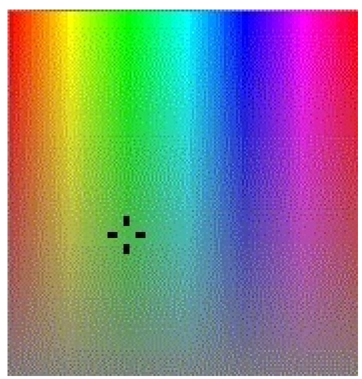
3-3-2, Nearest Color



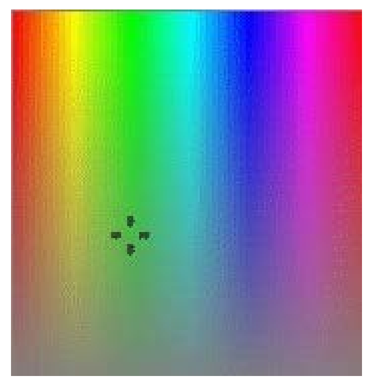
Median cut, Nearest Color



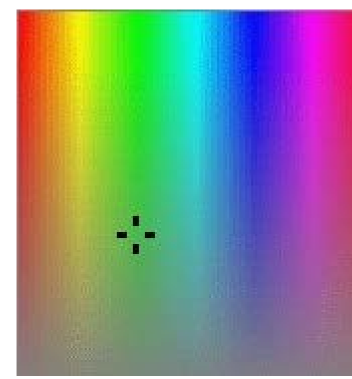
Octree, Nearest Color



3-3-2, Error Diffusion



Median cut, Error Diffusion



Octree, Error Diffusion

Quantized to 8-bit Color

Other Image Processing

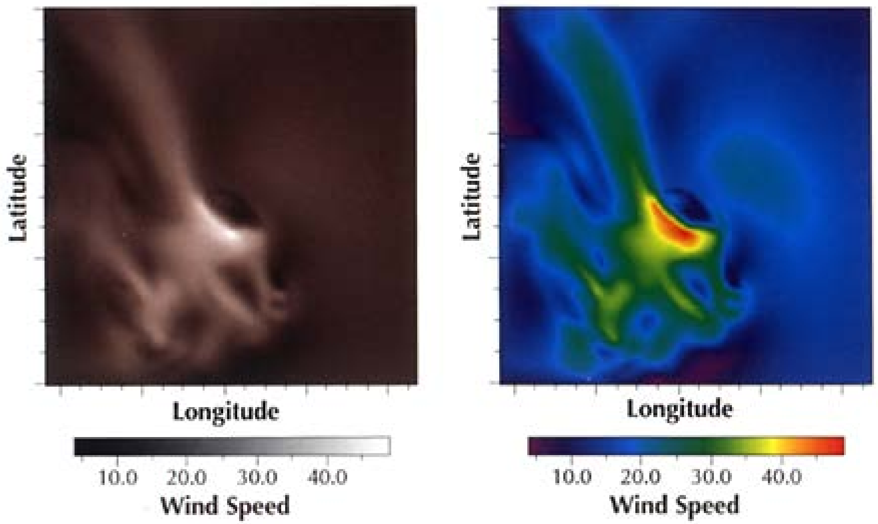
- Color image segmentation
  - Histogram thresholding-based techniques
  - Thresholding on various property value histograms
  - KLT yields better results in general
  - Other approaches: clustering-based methods
- Color edge detection
  - Use vector instead of individual
  - Edge extracted by thresholding the vector sum gradient defined as

$$G(j,k) = \{[G_1(j,k)]^2 + [G_2(j,k)]^2 + [G_3(j,k)]^2\}^{1/2}$$

  - YIQ gradient vector sum yields the best result (page. 553, Pratt's book)

Pseudo-Coloring

- Human visual system can distinguish 350000 colors, but only around 30 shades of gray
- To replace grayscale images with color ones for better visualization of information
- A technique that artificially assigns colors to the gray scale.
- How to choose colors?
- Example:



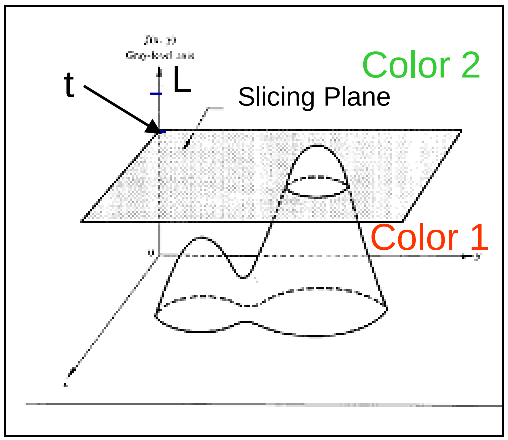
We can define:
Hue – the value of temperature
Intensity – pressure
Saturation – moisture

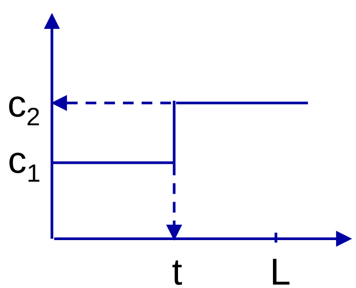
Pseudo-Coloring Methods

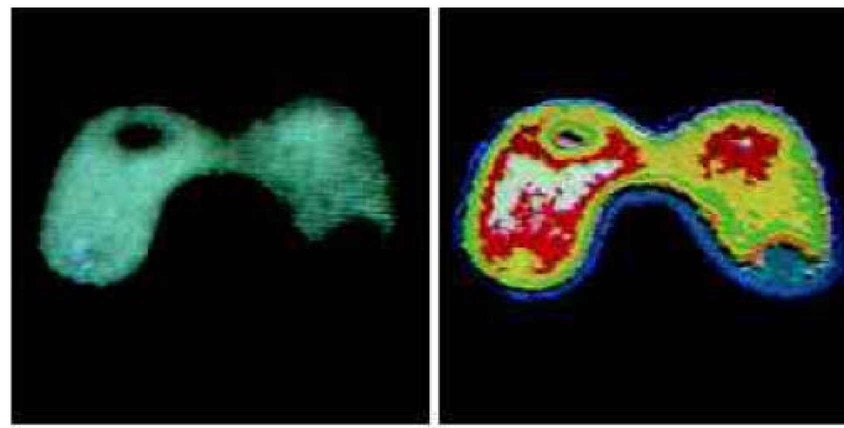
- Intensity slicing
- Gray-level to color transform
- Others: color map

Intensity Slicing

- Grey levels smaller than t – color 1
  Grey levels larger than t – color 2



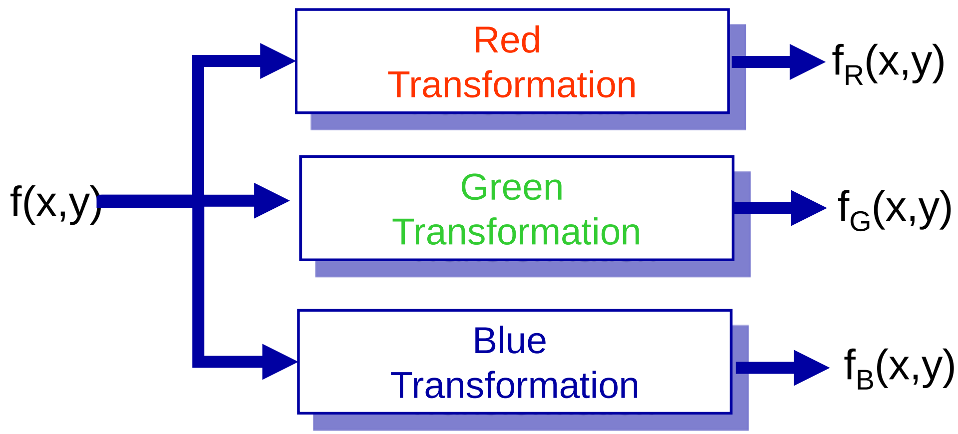


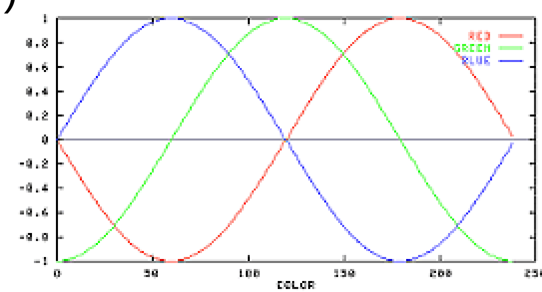


Example: intensity slicing into 8 colors

Gray-level to Color Transformation

- One transformation function apply to R,G,B independently



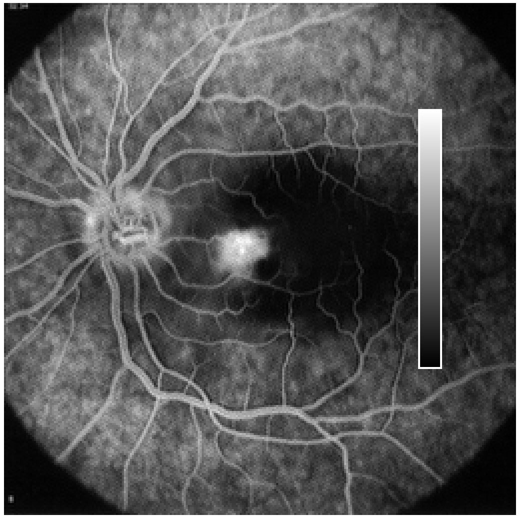


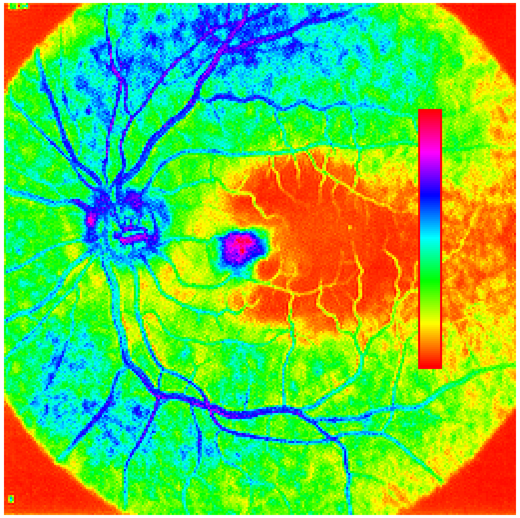
- How to design the transformation?

Example:

- Using *sin* functions with same frequency and different phases
- Adjust frequency to get the best visual quality

Example





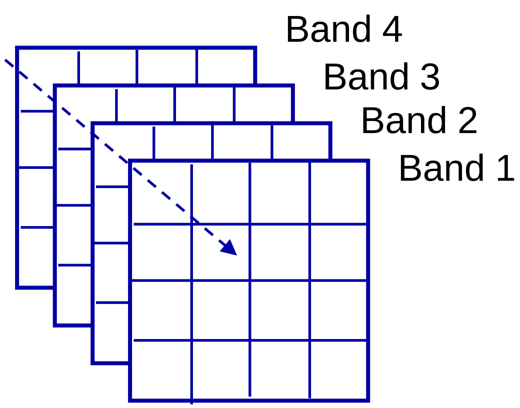
Note: It is important to include scale to the final result

Image source: http://www.mcs.csuhayward.edu/~grewe/CS6825/Mat/Color/color3.htm

Multi-spectral Images

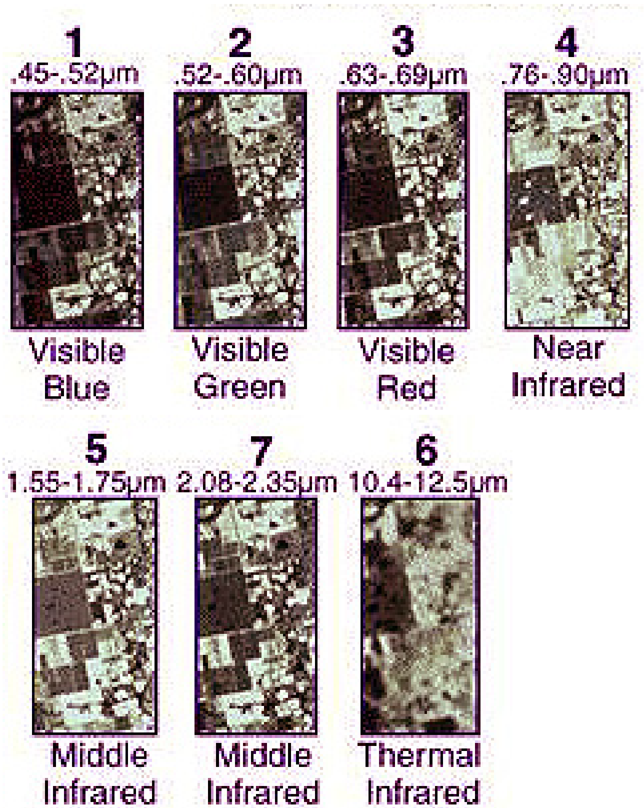
- A collection of several monochrome images of the same scene
- Each image is referred to as a *band*
- Example:
  - RGB images: 3 images with R, G, B
  - Satellite images (from visual to non-visual bands)

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$



NASA Landsat

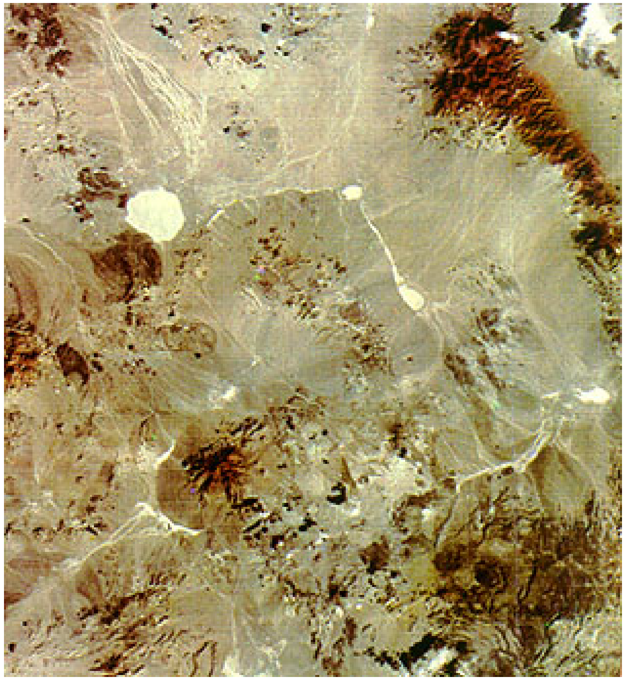
- *NASA Landsat 5* has 7 band images with the wavelength of bands between *450* and *1250 nm*



Band No.	Wavelength Interval (µm)	Spectral Resp onse	Resolution (m)
1	0.45 - 0.52	Blue-Green	30
2	0.52 - 0.60	Green	30
3	0.63 - 0.69	Red	30
4	0.76 - 0.90	Near IR	30
5	1.55 - 1.75	Mid-IR	30
6	10.40 - 12.50	Thermal IR	120
7	2.08 - 2.35	Mid-IR	30

Image source: NASA Landsat

Pseudo-coloring Satellite Images



quasi-natural color

MSS Bands 4/5 appear in blue
5/6 in yellow
and 6/7 in magenta

Image source: NASA Landsat, The Goldfield, Nevada Study