Color Models

Image Processing

Outline

- Computer color representation
- Color matching, CIE experiments
- CIE XYZ color space
- CIE LAB color space
- Color space and RGB color models
- Uniform and intuitive color spaces

Chrominance and luminance

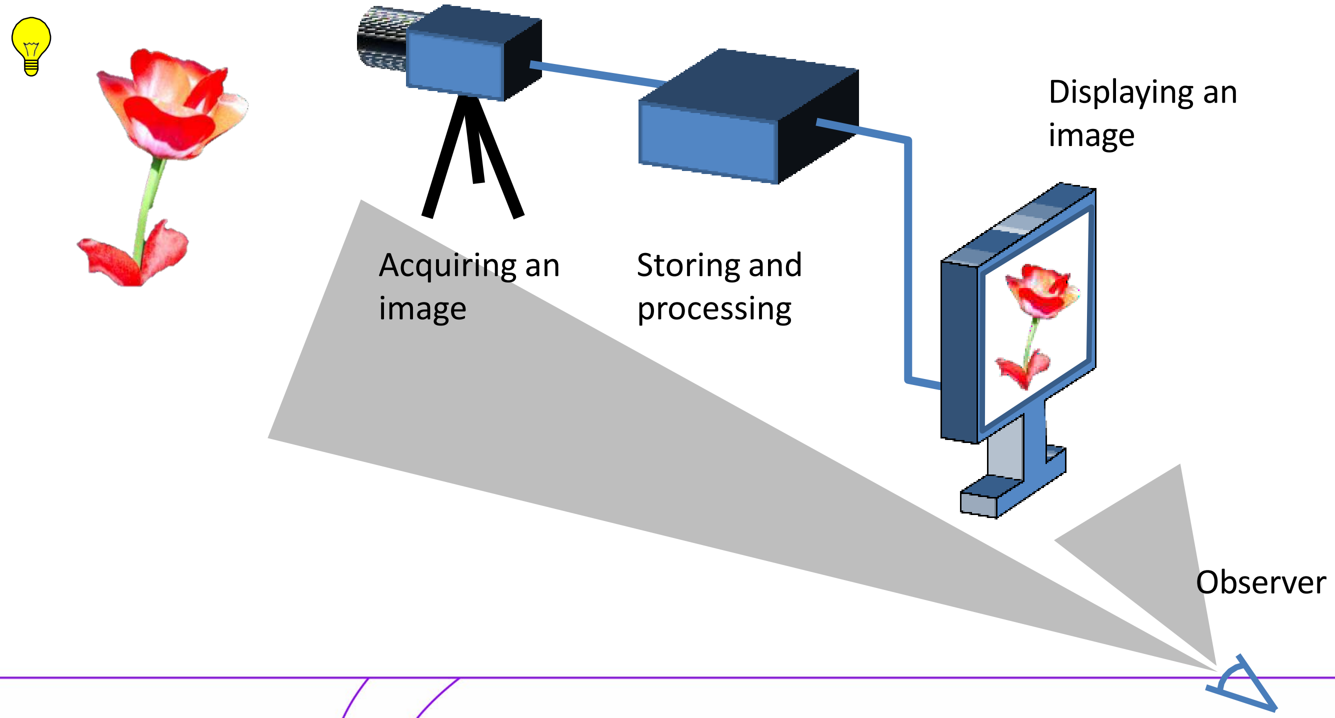
Human eye perception allows you to distinguish

- Luminance
- Hue (shade of color)
- Saturation

Chrominance is how we see the color

Luminance is the color energy

Light and color in a graphical system



Storage and display of color

How do

- Light as perceived by a human eye
- Color displayed on the screen
- Color on a printed photo
- Color in a graphics editor

correspond to each other?

Computer color representation

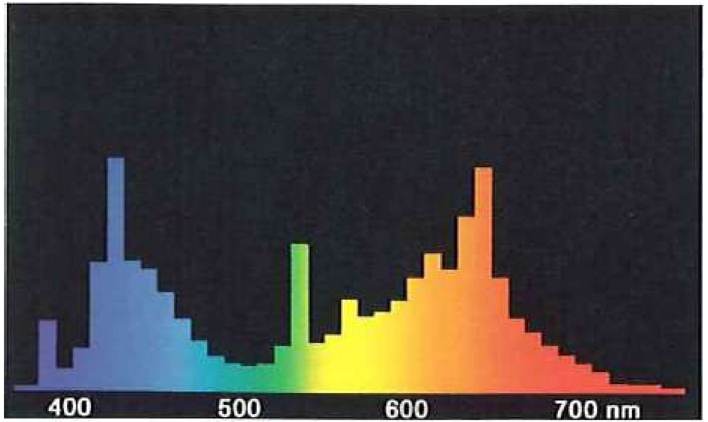
- 1st problem: How to uniquely describe a color?
  - Color is not an energy spectrum
  - A very complex perception mechanism
- 2nd problem: Digital representation of color in a computer

Computer color representation: spectrum quantization

- We can take the visible spectrum (380 - 780 nm) and quantize it in small increments (5 - 10 nm)

- 40 float per pixel = 160 bytes per pixel

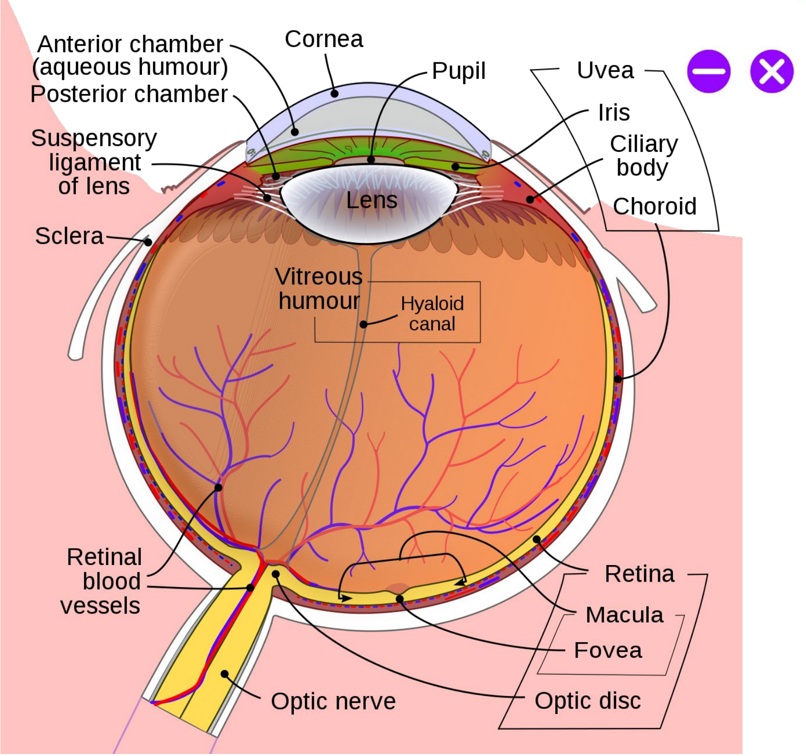
- 1Mpixel image = 160 megabytes



Human vision

We need store what human sees

So, it is necessary to understand human eye light perception

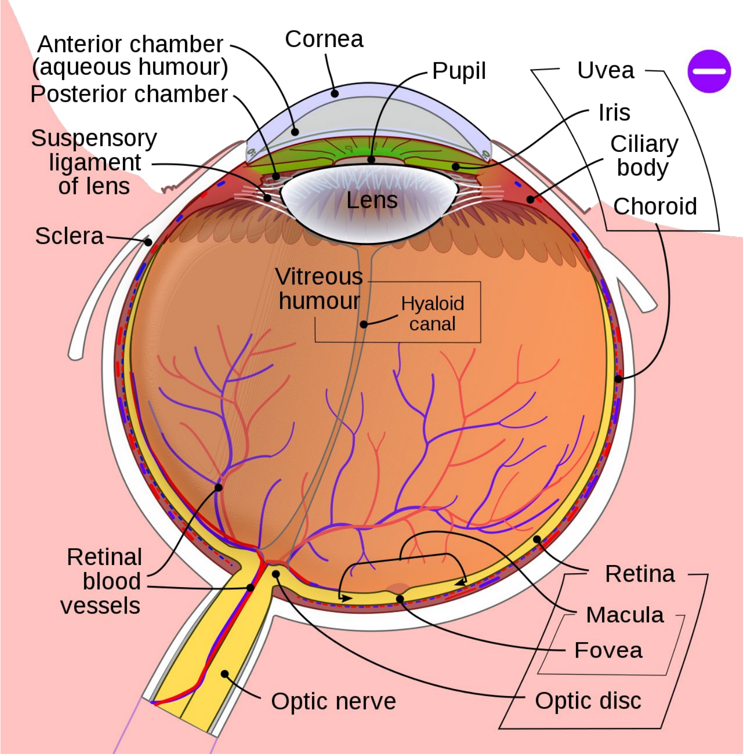


Rhcastilhos. And Jmarchn., via Wikimedia Commons

How do human eye percepts light?

How do we perceive light:

- Light rays enter the eye through the **cornea**
  - focusing
- Pass through the **pupil** surrounded by the **iris**
  - changing the amount of light
- Pass through the **lens**
  - further focusing
- Pass through the **vitreous humour**
- Reaches the retina



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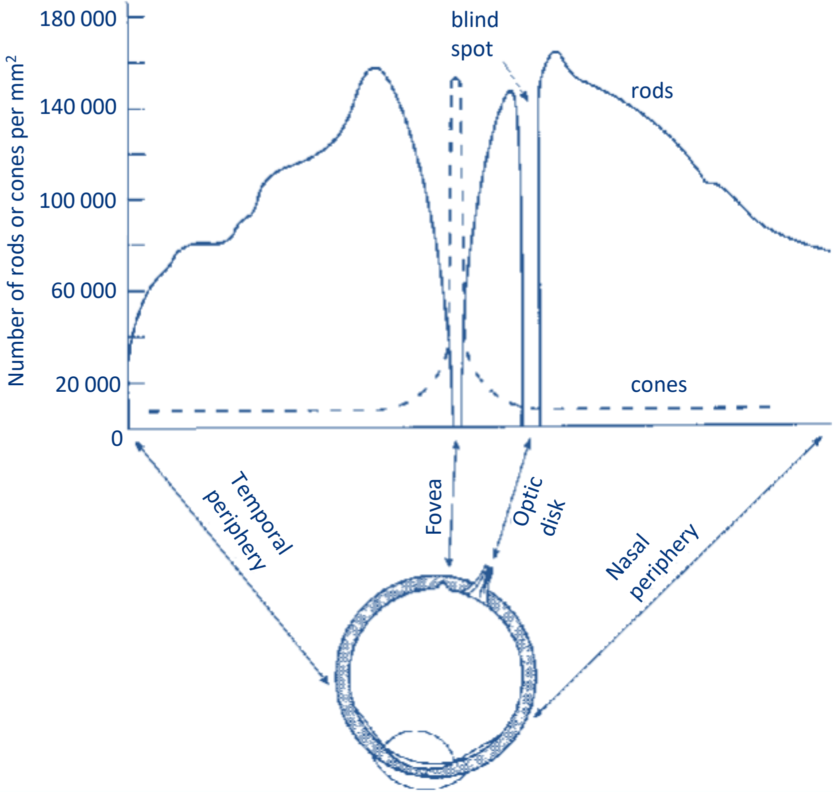
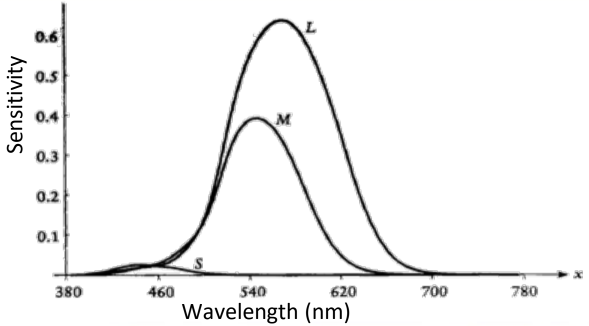
Cones and rods

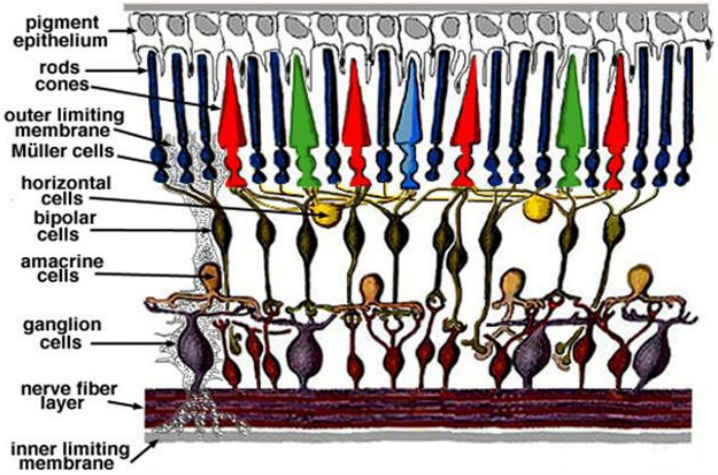


Each eye has approximately 6 mil cones and 120 mil rods

Spectral color perception: cones

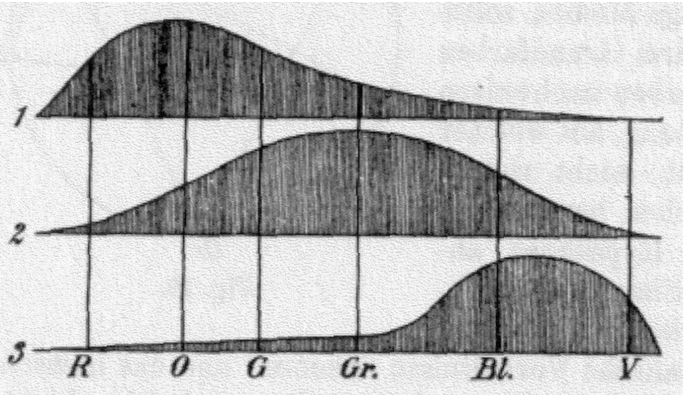
- Three types of cones
- Each type of cone contains its own special pigment
- Three types of cones are called S, M и L
- Sensitivity peaks of each type are at approximately 440 nm, 545 nm and 580 nm





Trichromatic theory

- Thomas Young – 1802
- Hermann von Helmholtz – 1850



What is a color?

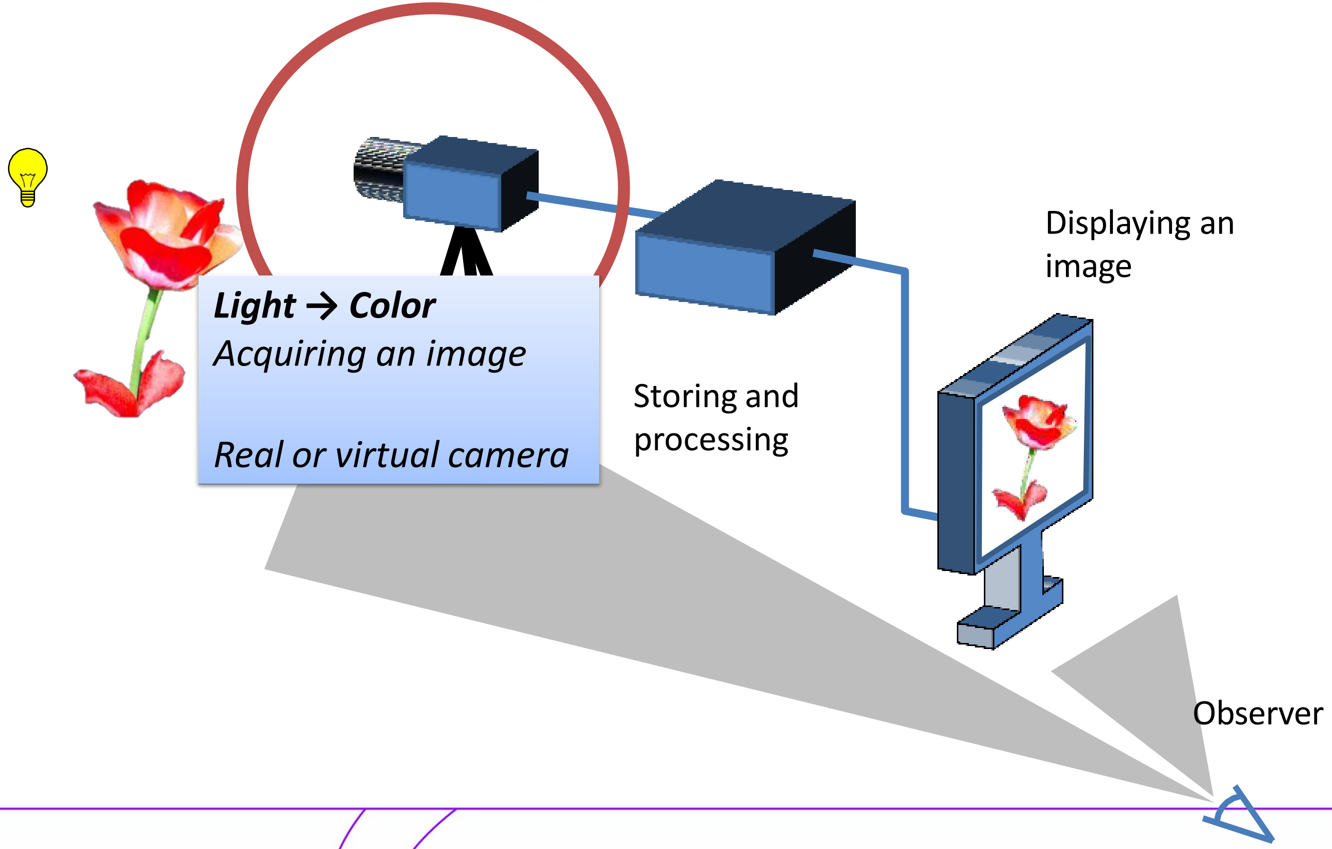
- Color: perceived effect of visible light

- **No** observer – then **no** perception and **no** color
- Each spectrum has a corresponding color
- Several spectra can be found for a single color (metamerism)

Color matching

- No need for an arbitrary spectrum
- Three numbers are enough to describe a color
- It is necessary to develop a principle for the numerical (quantitative) representation of color

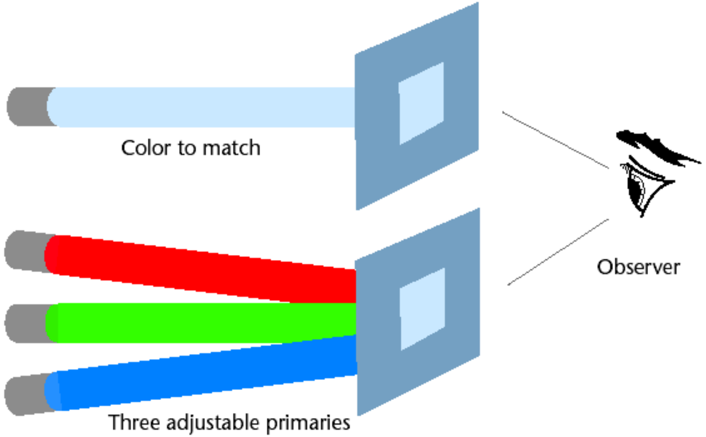
Light and color in a graphical system

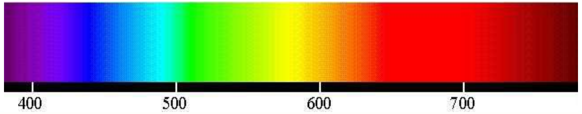


Color matching experiments

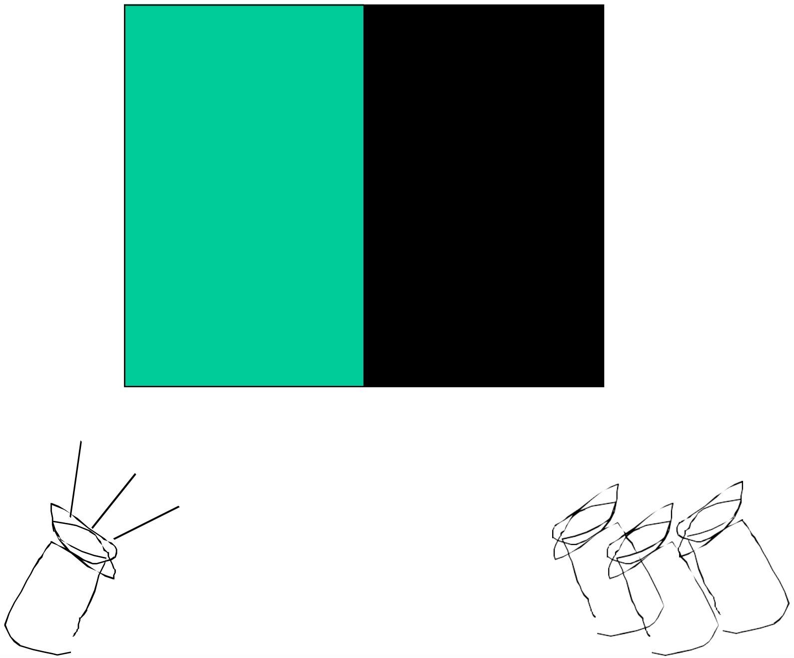
- 1920 – 1930
- Angular size of the screen is 2°
- Monochromatic original color
- Three monochromatic light sources of prir
- The observer can change the intensity of

Monochromatic color
380-780nm in 5nm steps



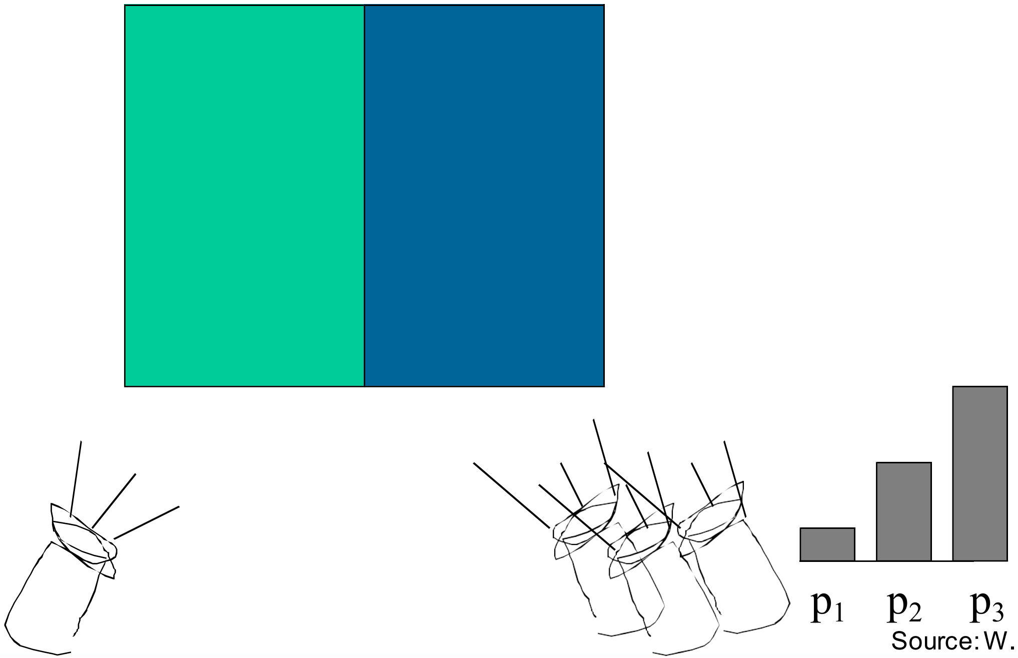


Color matching experiment: example 1



Source: W. Freeman

Color matching experiment: example 1



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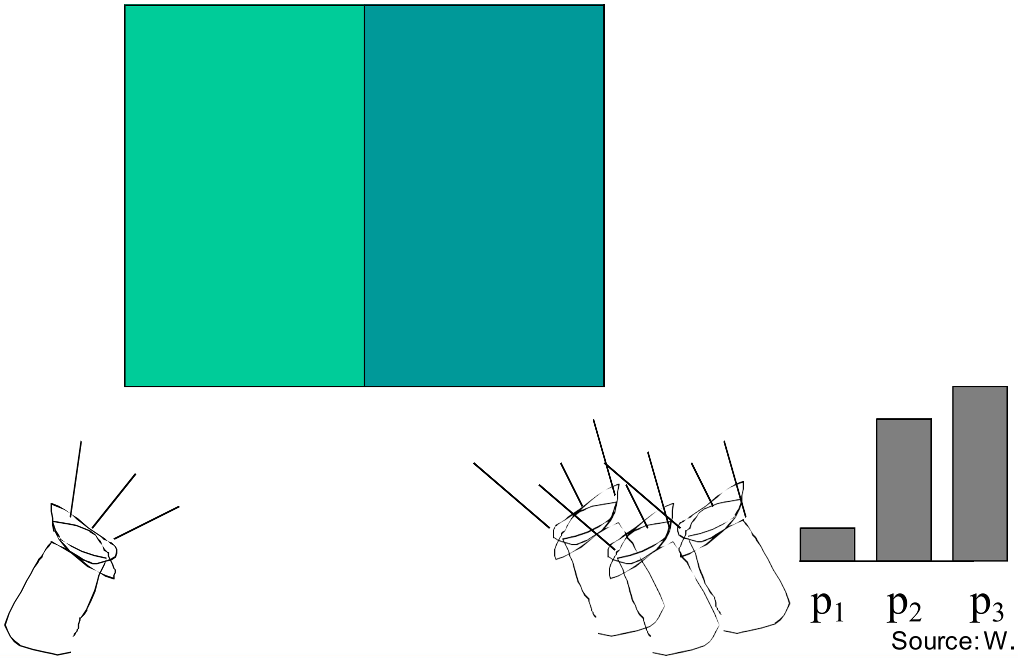
Color matching experiment: example 1



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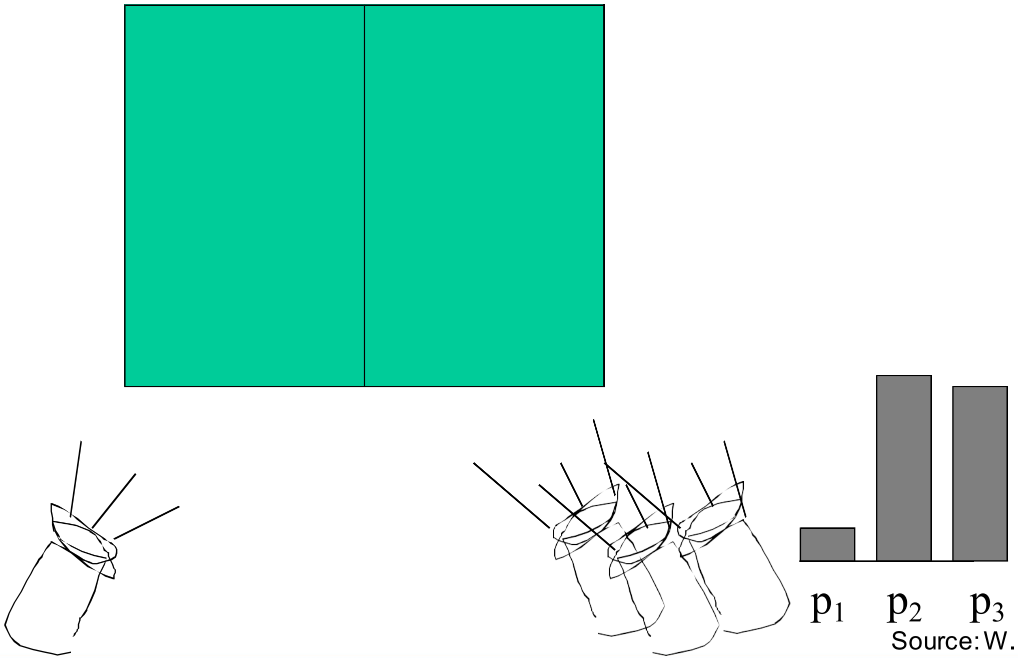
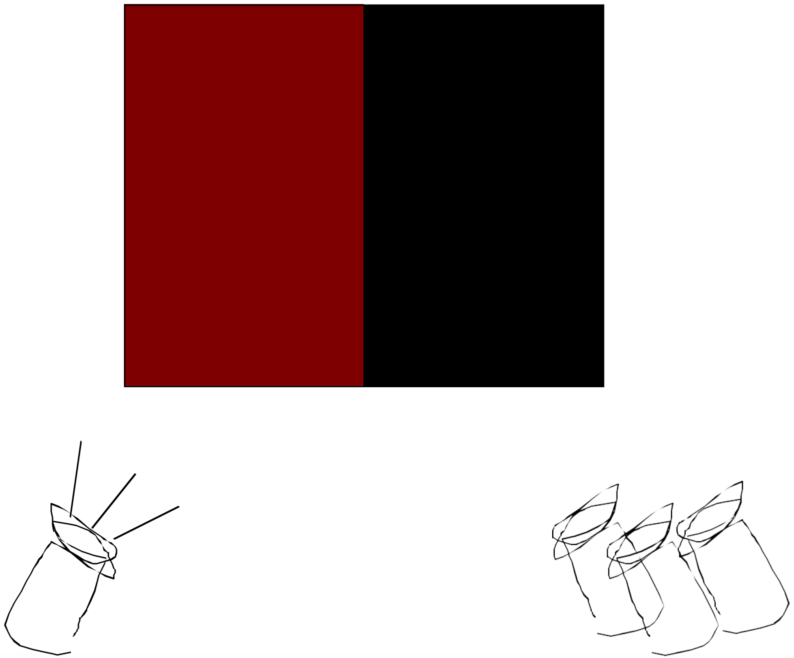
Color matching experiment: example 1



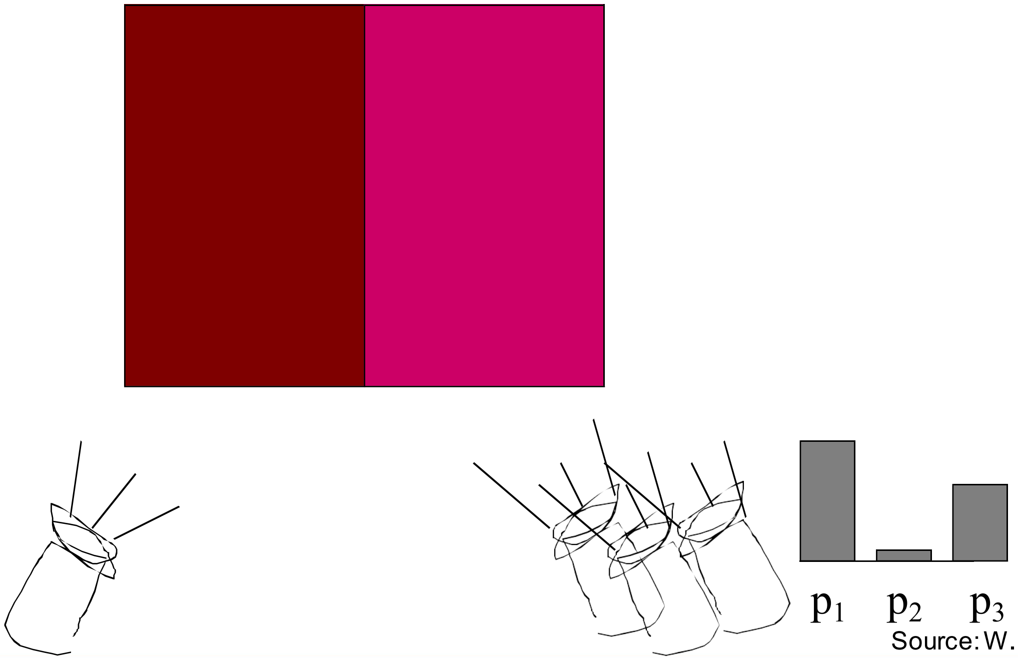
Source: W. Freeman

Color matching experiment: example 2



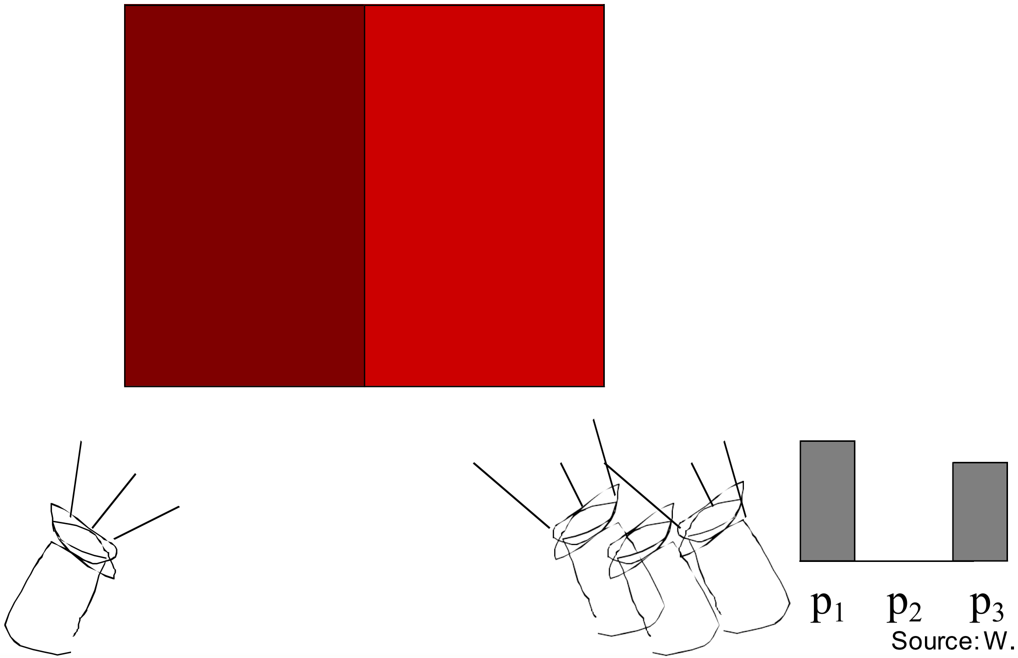
Source: W. Freeman

Color matching experiment: example 2



Source: W. Freeman

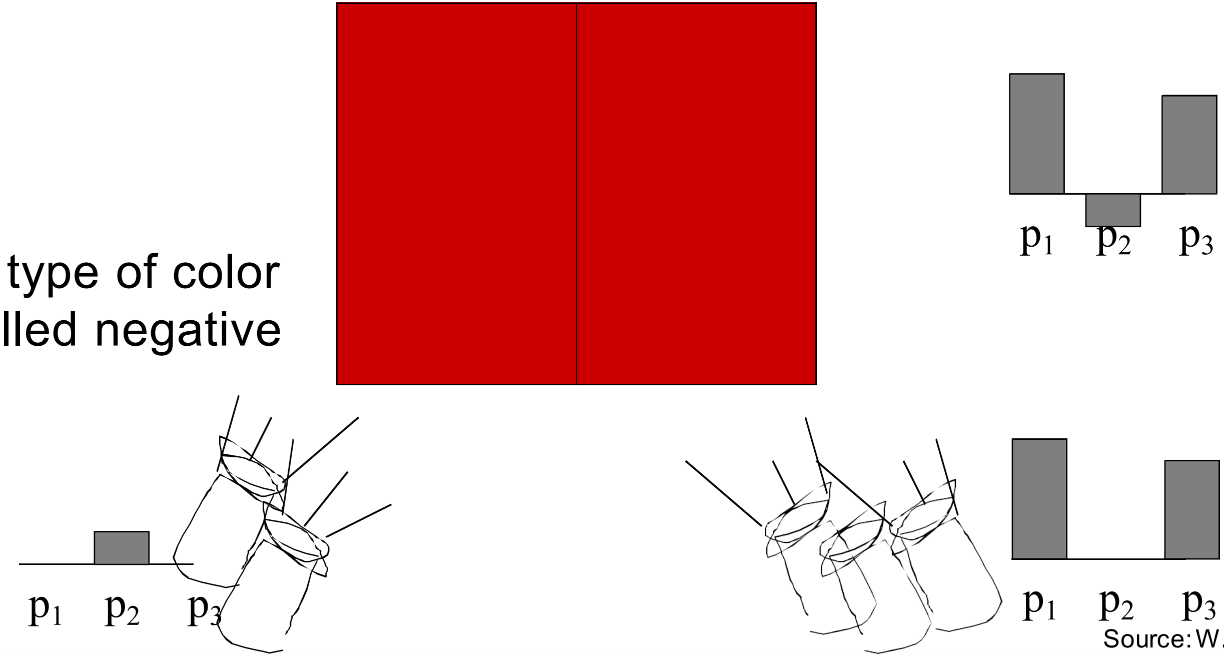
Color matching experiment: example 2



Source: W. Freeman

Color matching experiment: example 2

This type of color is called negative



Source: W. Freeman

Color matching experiments

- Most of the colors can be defined as the sum :

  $C = rR + gG + bB$

  – Additive matching
- Some colors cannot be specified this way, instead it should be:

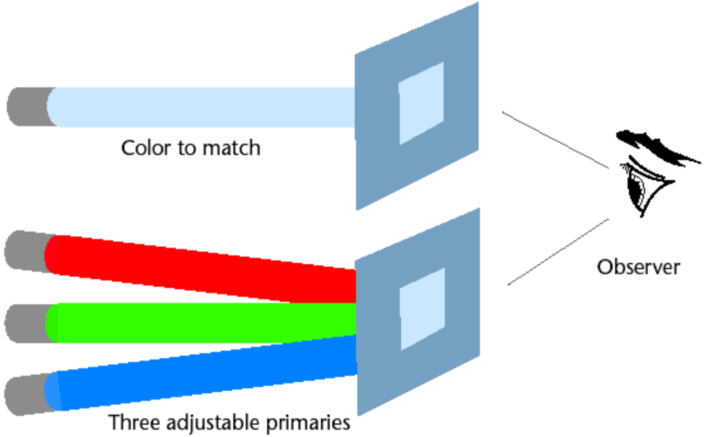
  $C + rR = gG + bB$

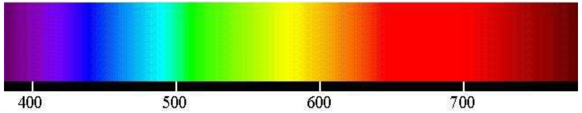
  – Subtractive matching

  – Creates problems for output devices - you cannot create a lamp that subtracts energy

  – Allows using various base colors

Monochromatic color
380-780nm in 5nm steps





Color matching experiments: problems

Results are valid only

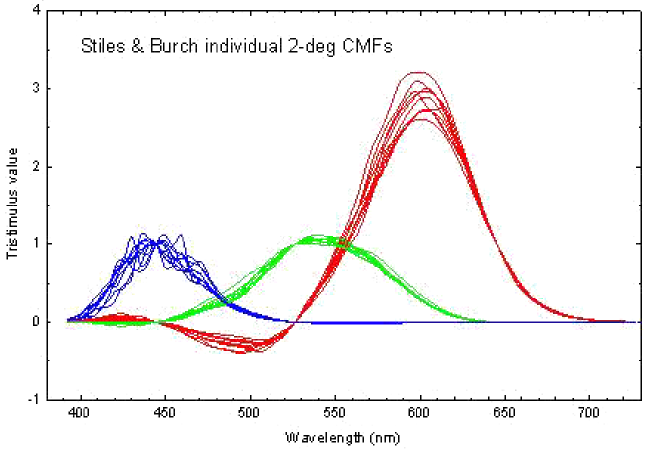
- for a specific observer
- for three given base colors
- for monochromatic target colors

For practical use, it is necessary to expand it

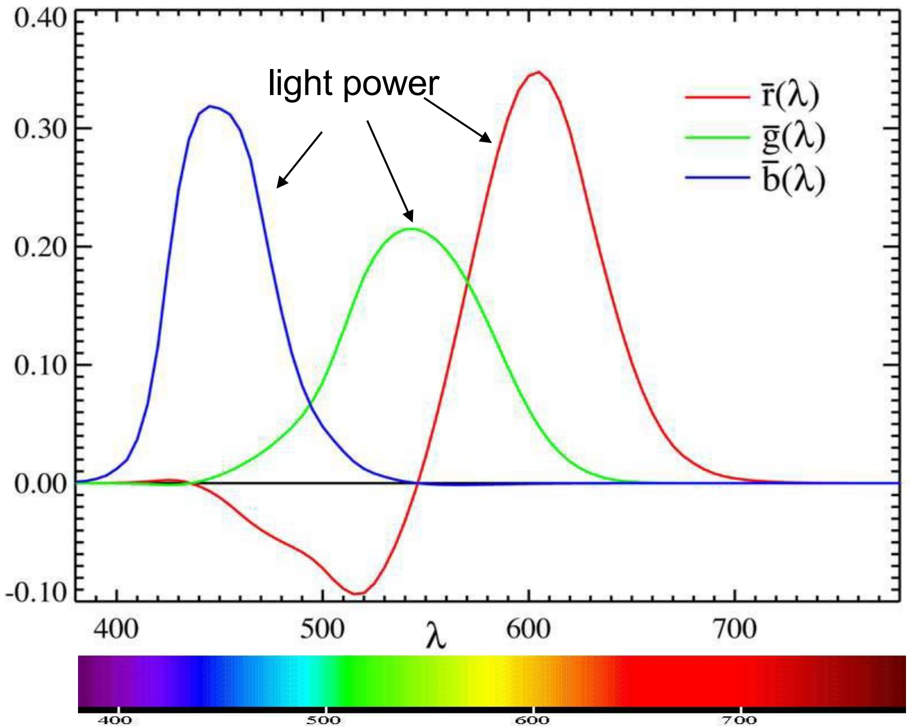
- to a wider class of observers
- to a wider class of base colors
- to a wider class of target colors

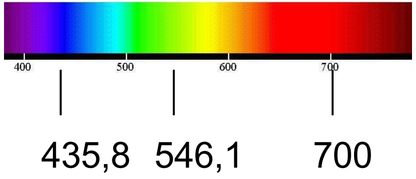
CIE experiments, 1931

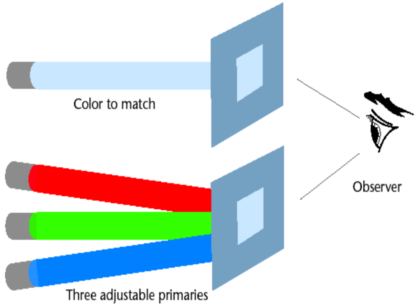
- Perceptual color matching experiments have been conducted on a large number of people
- For people with normal color perception, the results were quite close to each other
  - can be averaged
- In 1931, basing on the experiments, CIE created the concept of a standard observer
- The results of color matching experiments for a standard observer can be applied to anyone with normal vision.



CIE color matching experiments: results







Is it possible to find a triplet for any arbitrary spectrum?

We know:

- Any radiation is the sum of monochromatic radiation of different intensity (wave amplitude)
- Any color can be defined by three numbers
- How to represent monochromatic colors using a triplet of numbers for base color data (from CIE experiments)

So, is it possible, based on this information, to find triplets of numbers for any color?

Yes. Grassmann's law of additivity

Grassmann's law of additivity

- The empirical law of linearity of the human vision (Hermann Grassman)

- Additivity:
  - If the observer sets the color of rays 1 and 2 as $R_1B_1G_1$ and $R_2B_2G_2$ relative to the given primary colors
  - Then the color of their combination will be
    $R = R_1 + R_2$
    $G = G_1 + G_2$
    $B = B_1 + B_2$

- Is true for any intensity level
  - $kC_1=kC_2$, if $C_1=C_2$

Grassmann's law of additivity

- Allows **use a finite** set of colors to **describe an infinite** set of colors
- Any spectral distribution can be specified as a weighted sum of monochromatic sources
- So, if you set RGB matches for these colors, then RGB for any spectral color will be the weighted sum of RGB triplets of monochromatic colors

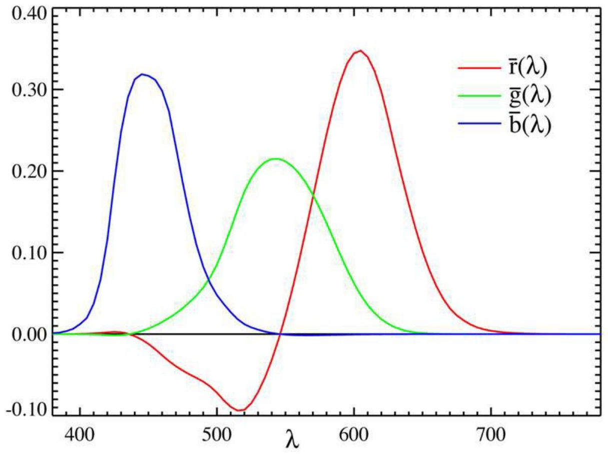
$$R = \int_{380}^{780} C(\lambda) r(\lambda) d\lambda$$

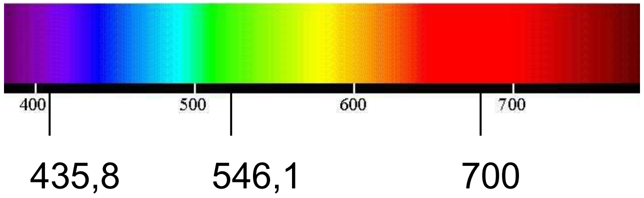
$$G = \int_{380}^{780} C(\lambda) g(\lambda) d\lambda$$

$$B = \int_{380}^{780} C(\lambda) b(\lambda) d\lambda$$

CIE RGB 1931 color space

- Curves for r(λ), g(λ), b(λ) and the specification of the basic light sources define a three-dimensional additive color space called
  CIE RGB 1931
- For any spectrum, you can find a point in this color space
- **Not all** of the color space points correspond to some visible color
  - Invisible
  - Negative spectrum





Transition between color spaces

- Let's assume that we want to create a new color space with color sources

  $X(\lambda), Y(\lambda), Z(\lambda)$

- Let us know the coordinates of these color sources:
  $X = (r_1, g_1, b_1), Y = (r_2, g_2, b_2), Z = (r_3, g_3, b_3)$
  in RGB color space

- Then:

Combination of new color sources with unknown coefficients

$$C = xX + yY + zZ =$$

$$= x(r_1R + g_1G + b_1B) + y(r_2R + g_2G + b_2B) + z(r_3R + g_3G + b_3B) =$$

$$= \underbrace{(xr_1 + yr_2 + zr_3)}_{r}R + \underbrace{(xg_1 + yg_2 + zg_3)}_{g}G + \underbrace{(xb_1 + yb_2 + zb_3)}_{b}B$$

Transition between color spaces

Transition between color spaces is a linear conversion

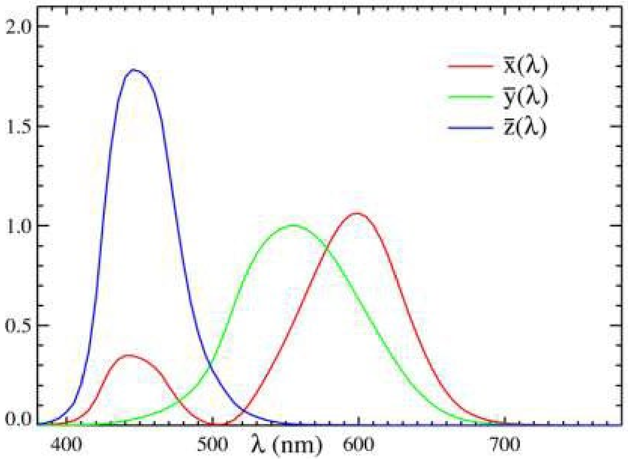
$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = \begin{bmatrix} r_1 & r_2 & r_3 \\ g_1 & g_2 & g_3 \\ b_1 & b_2 & b_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

CIE XYZ 1931 color space

Challenge: Create a new XYZ color space that is more “user-friendly” than CIE RGB

- Base colors x (λ), y (λ), z (λ) are always non-negative
- y (λ) corresponds to the CIE standard spectral efficiency function
- The white point of "equal energy" must correspond to
  x = y = z = 1/3
  - ”flat" spectral distribution

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



CIE XYZ 1931

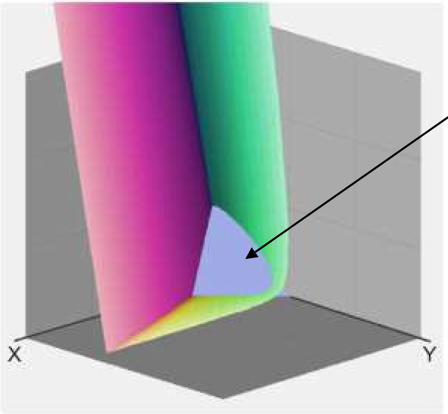
CIE xy color model

- Challenge: separate intensity and color
  - Vectors of different lengths are projected to one point
  - Straight lines are persistent

- CIE xy

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

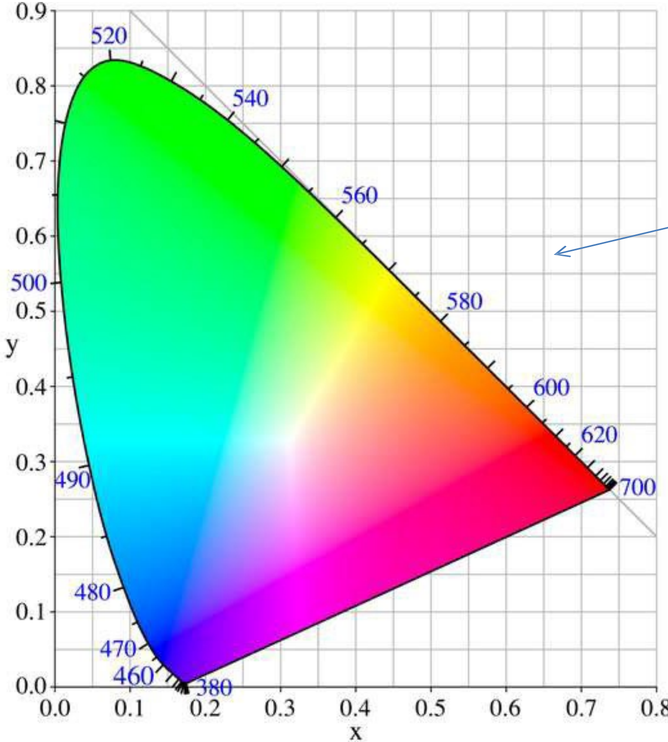
$$y = \frac{Y}{X+Y+Z}$$

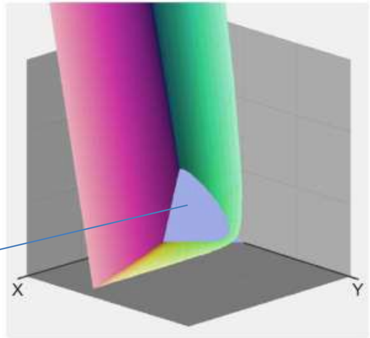


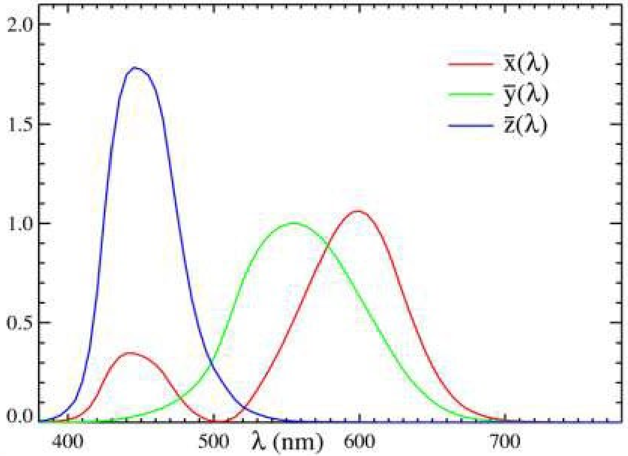
Projection to

X + Y + Z = 1

Chromaticity diagram

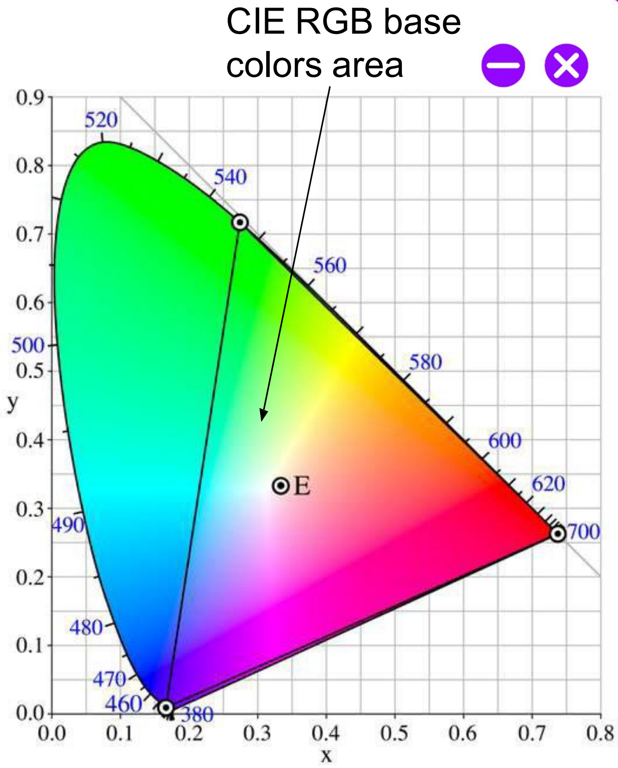






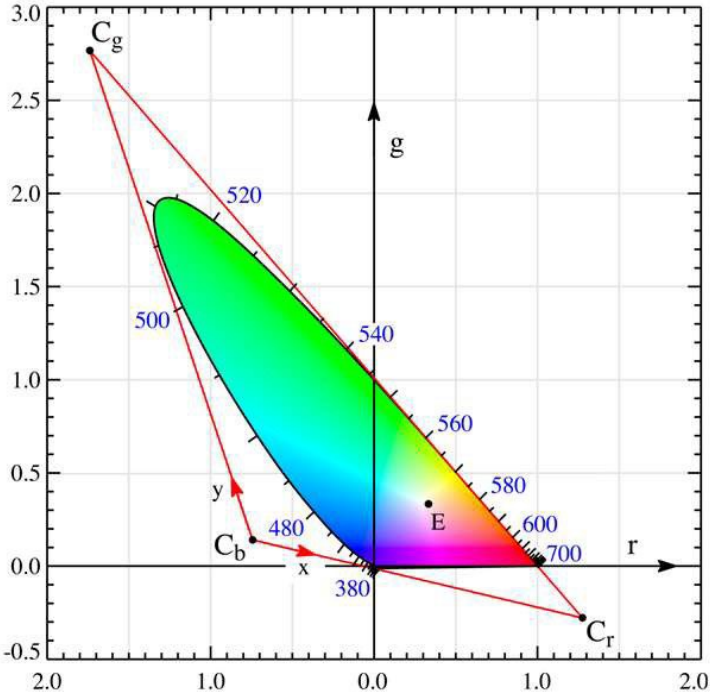
Chromaticity diagram: properties

- The diagram shows all the colors visible to humans
  – Located inside the spectral curve
- All colors that can be obtained by mixing any two colors lie on a straight line connecting these colors
- All colors that can be obtained by mixing three colors lie inside the triangle
  – It is not possible to get all the colors visible to humans by mixing three real light sources



CIE XYZ on the chromaticity diagram

- All visible colors lie inside CIE XYZ
- However, basic light sources cannot be physically reproduced (do not have a color)
  - oversaturated

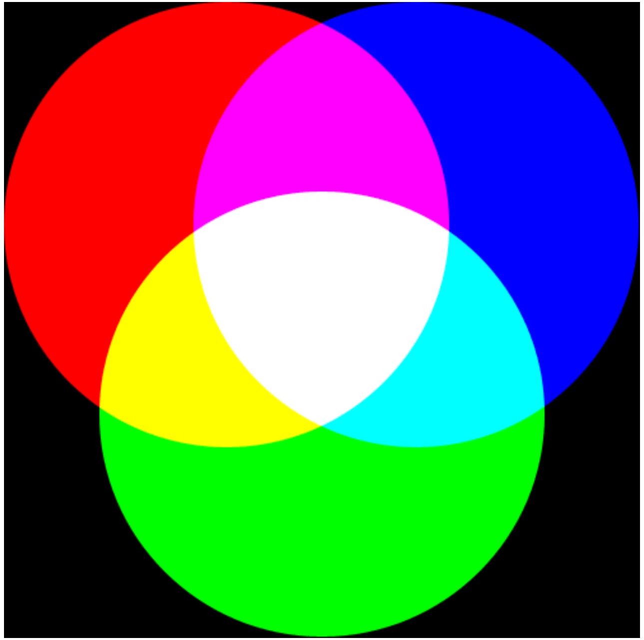


Color spaces and color models

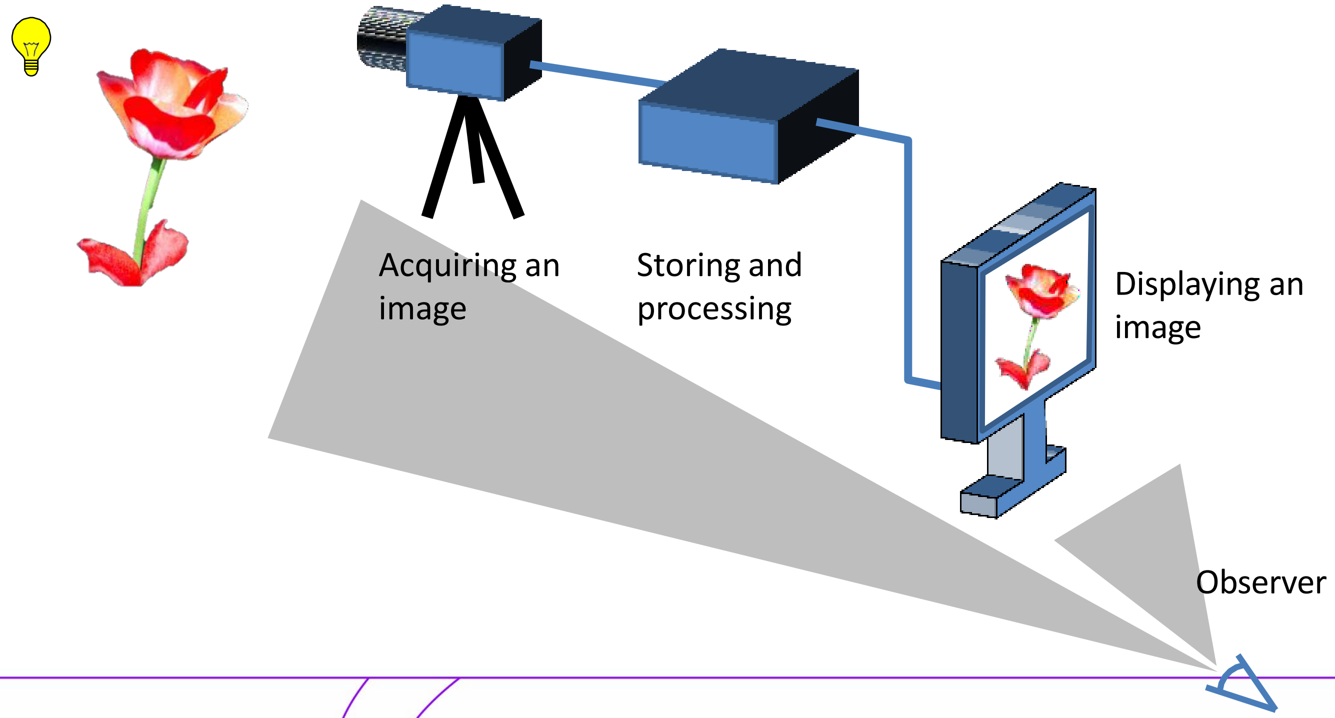
- Color modes is an abstract mathematical description of a color by a set of numbers (usually three)
  - Does not have an absolute color space mapping function
  - Cannot be used in applied tasks without mapping to an absolute color space
- Color space = color model + mapping function to some reference color space
  - Colors are independent of external factors

RGB color model

- Based on an additive combination of three primary colors - **Red**, **Green**, and **Blue**
- Describes the systems based on the emission of light to produce the desired color (TVs, monitors)
- The r, g, and b values do not have physical meaning
  - Snapping to original color space is required
- It is most commonly used in the computer graphics, because computer graphics works with images on the monitor



Light and color in a graphical system



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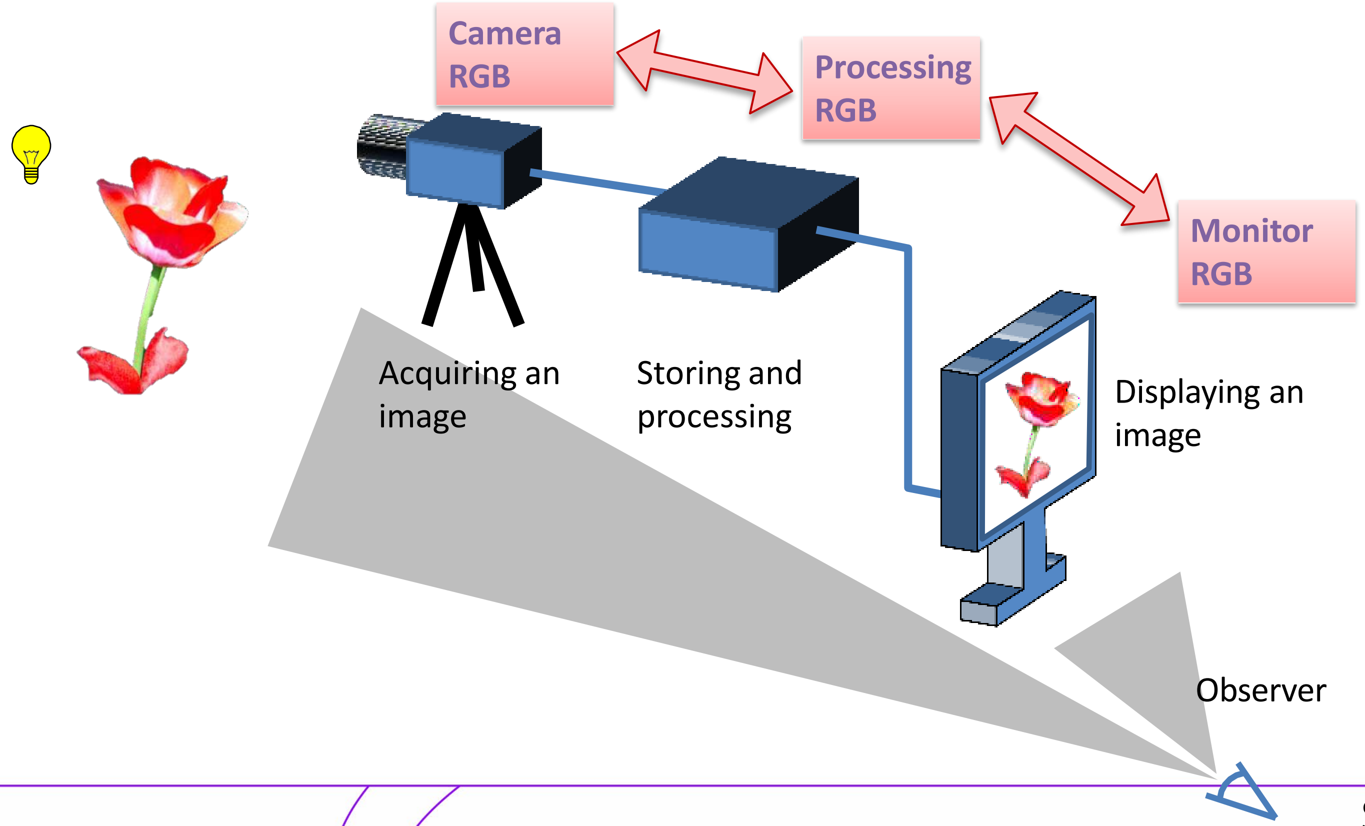
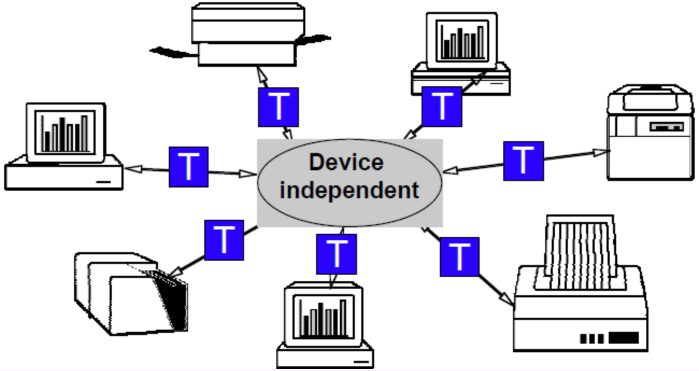


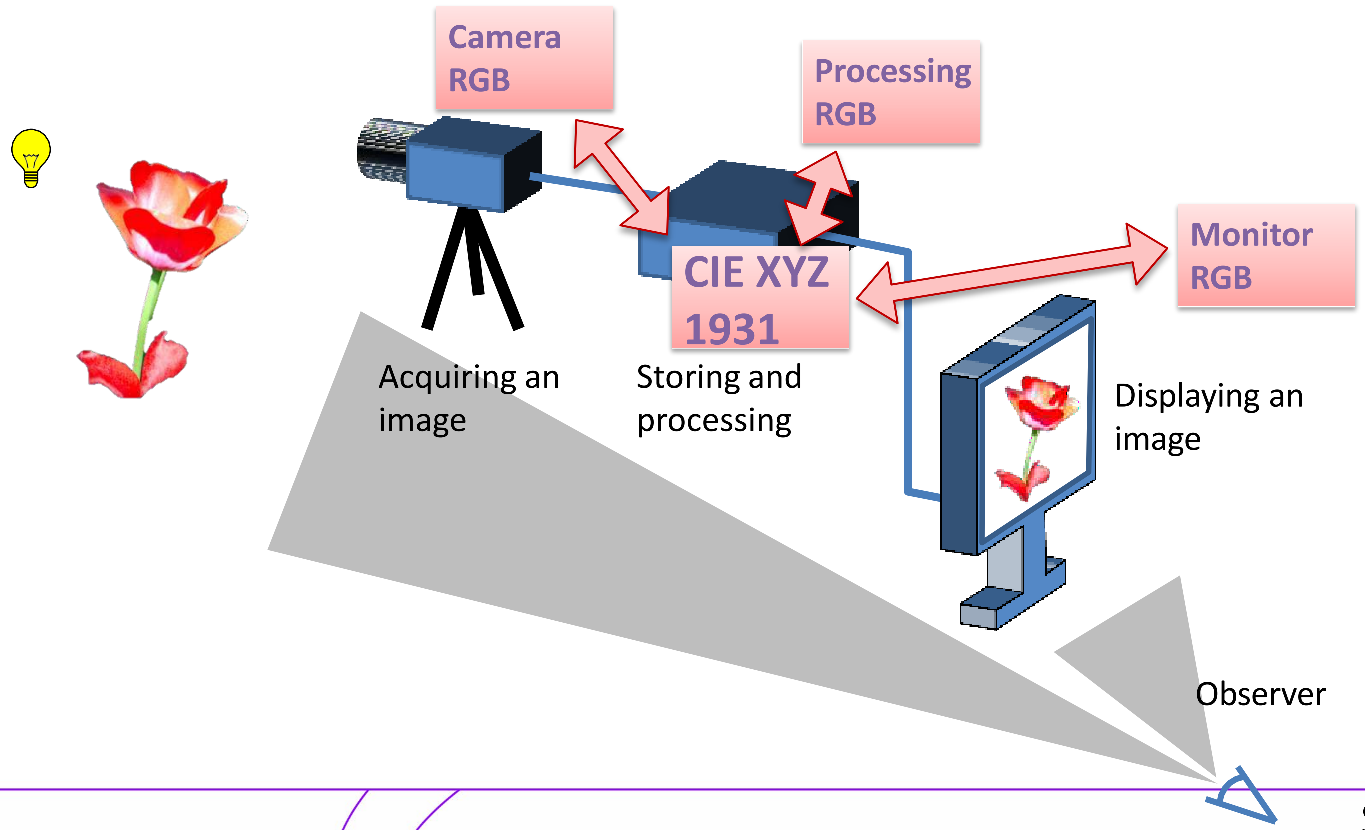
Specifying RGB color space

- In practice, there are many RGB spaces:
  - Device specific color spaces
  - Standardized “working” color spaces

- The color space can be specified by the matrix **RGB->XYZ**
- However, the *xy* colors of the base color sources and the ratio of their luminance (white point) are usually used instead

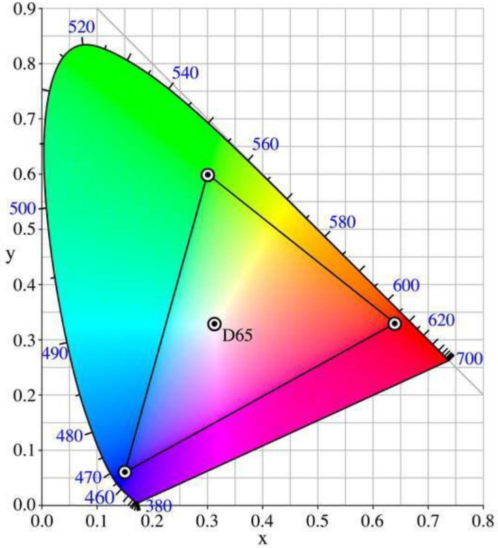


Light and color in a graphical system



Specifying RGB color space: base color sources

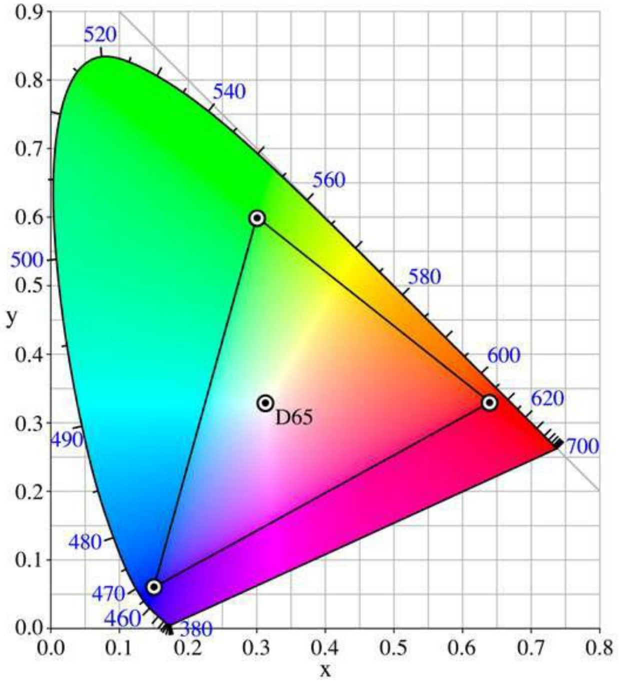
- Three base colors define an additive color space
- For a complete specification, usually define
  - *xy* coordiates for r,g,b base colors (phosphors)
  - white point (relative luminance)
- Examples:
  - NTSC RGB (TV)
  - HDTV RGB (TV)
  - sRGB (monitors)
- When transmitting a signal (for example, TV), the color is encoded with the assumption that the phosphors of the monitor (TV) comply with the standard
  - If not, then the monitor must include color correction (hardware or software)



sRGB color space
(base colors and white point)

sRGB color space

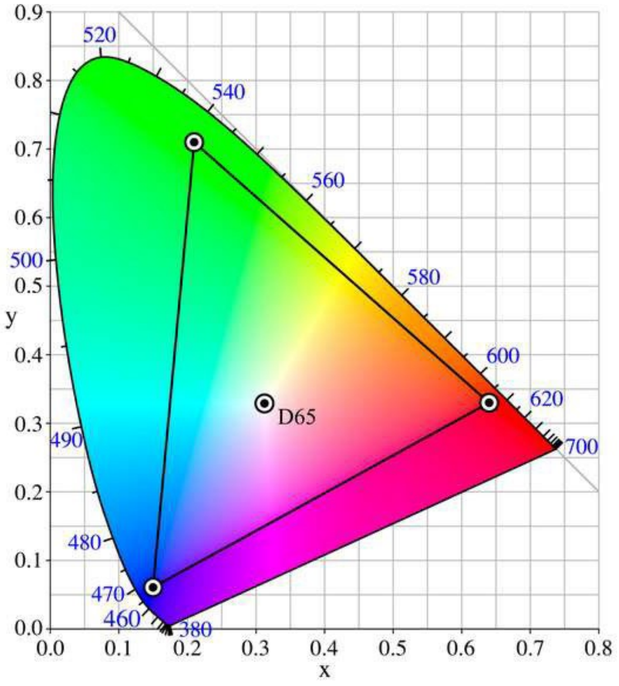
- Developed by Microsoft and Hewlett-Packard in 1996
- Currently is being widely used in:
  - Monitors
  - Photo cameras
- If no color space is specified for the image, it can be assumed to be sRGB
- Disadvantages: the original colors are deep within the human visible area



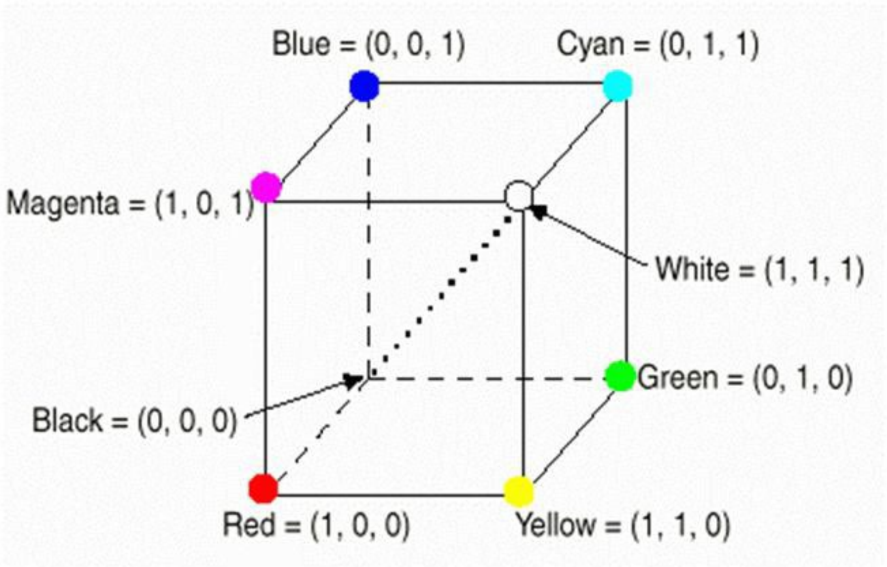
Adobe RGB color space

- Developed by Adobe in 1998
- The main goal is to be able to work on a monitor with most of the colors available in the CMYK model used by printers
- Wider range of defined colors (gamut)

- Problem: 8 bits per pixel might be not enough



CMY color space, color cube



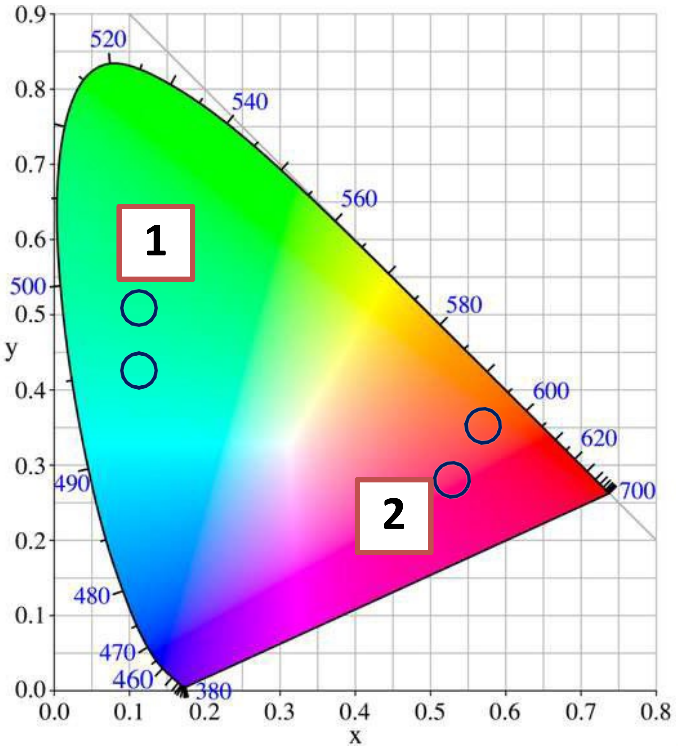
- RGB – additive color space
- CMY – subtractive color space

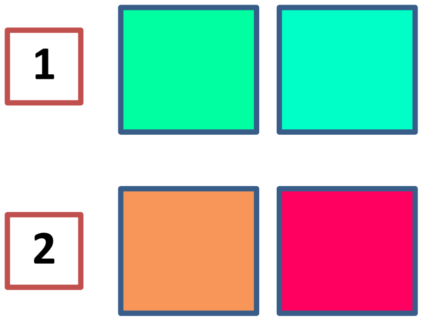
$$C = G + B = W - R$$
$$M = R + B = W - G$$
$$Y = R + G = W - B$$

Uniform and intuitive color spaces

- XYZ and RGB are not “user-friendly”
  - X and Z components have no meaningful values
    - Y stands for luminance
  - XYZ and RGB are non-linear from the human perception point of view
    - Changing xyz values does not mean the proportional change of color
- Several color spaces have been developed to satisfy human perception conditions

Color difference and color distance





CIE 1976 L*a*b

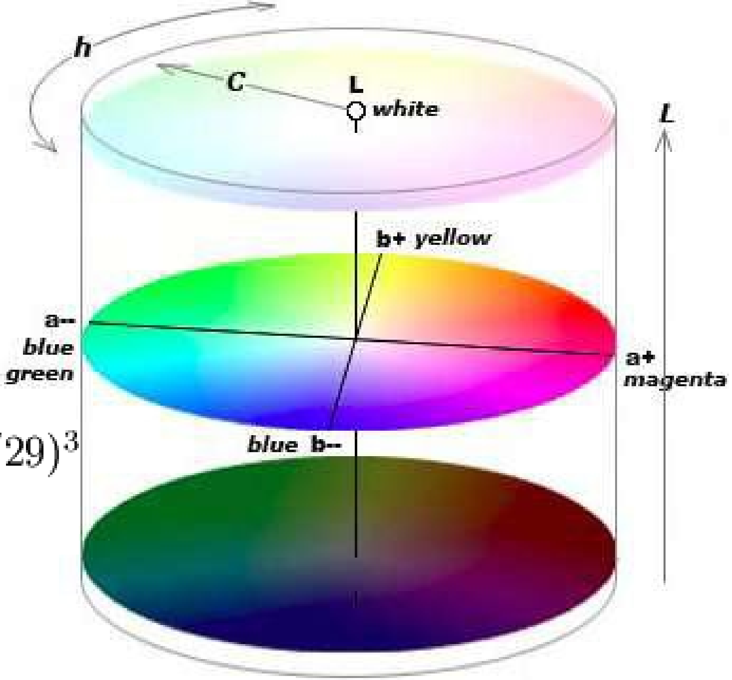
$$L^* = 116\, f(Y/Y_n) - 16$$

$$a^* = 500\,[f(X/X_n) - f(Y/Y_n)]$$

$$b^* = 200\,[f(Y/Y_n) - f(Z/Z_n)]$$

$$f(t) = \begin{cases} t^{1/3}, & t > (6/29)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} \end{cases}$$

Xn,Yn,Zn – white point



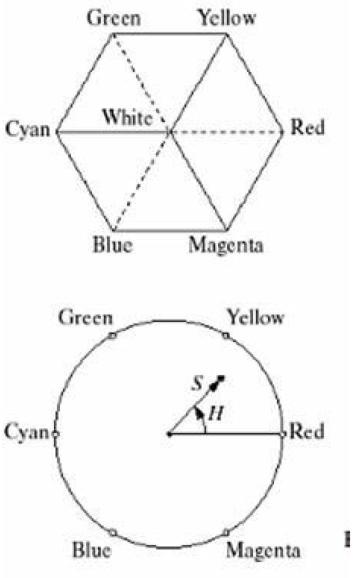
[© 2005 Bruce MacEvoy – http://www.handprint.com/HP/WCL/color6.html]

CIE 1976 L*a*b

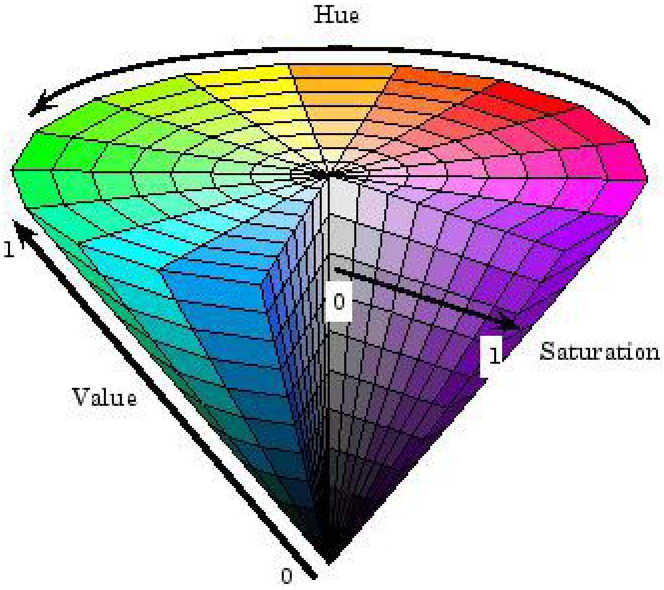
Intuitive color models: HSV

- RGB, CMY(K) color models are focused on working with equipment and are inconvenient for defining a color by human
- Human perceived color attributes :
  - Color tone
  - Saturation
  - Lightness
- Psychophysical equivalents:
  - Dominant wavelength
  - Purity
  - Brightness
- HSV model is convenient for human to define color
  - Hue Saturation Value

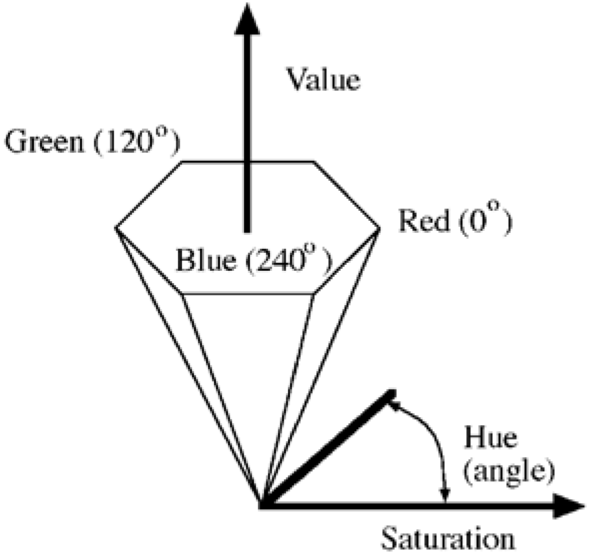
HSV



Green
Yellow
White
Cyan
Red
Blue
Magenta
Green
Yellow
S
H
Cyan
Red
Blue
Magenta



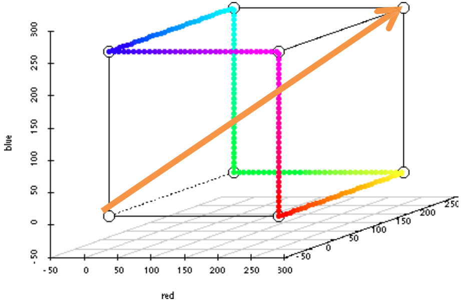
Hue
1
0
Saturation
1
Value
0



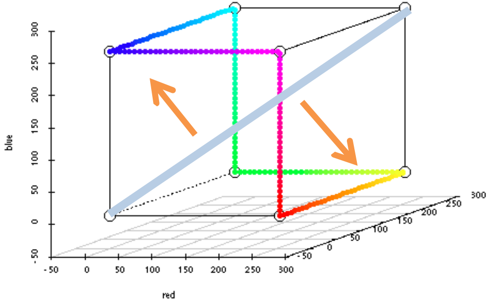
Value
Green (120°)
Red (0°)
Blue (240°)
Hue
(angle)
Saturation

HSV

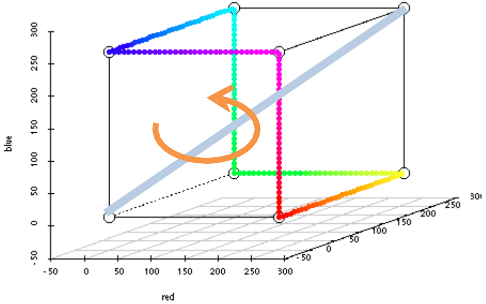
V (Value)



S (Saturation)



H (Hue)



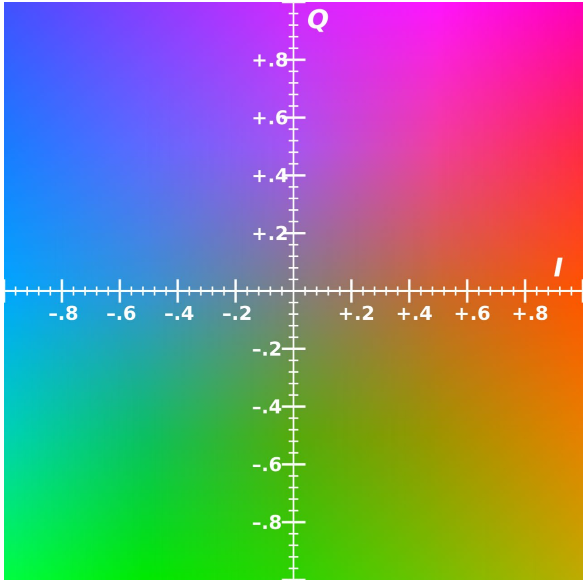
HSV: conversion from RGB

R,G,B : input values of RGB all in range [0,1] or [0,255];
I : output value of intensity in same range as input;
S : output value of saturation in range [0,1];
H : output value of hue in range $[0,2\pi)$, -1 if S is 0;
R,G,B,H,S,I are all floating point numbers;

```
procedure RGB_to_HSI( in R,G,B; out H,S,I)
{
I := max ( R, G, B );
min := min ( R, G, B );
if (I ≥ 0.0) then S := (I - min )/I else S := 0.0;
if (S ≤ 0.0) then { H := -1.0; return; }
   "compute the hue based on the relative sizes of the RGB components"
diff := I - min;
"is the point within +/- 60 degrees of the red axis?"
if (r = I) then H := (π/3)*(g - b)/diff;
"is the point within +/- 60 degrees of the green axis?"
else if (g = I) then H := (2 * π/3) + π/3 *(b - r)/diff;
"is the point within +/- 60 degrees of the blue axis?"
else if (b = I) then H := (4 * π/3) + π/3 *(r - g)/diff;
if (H ≤ 0.0) H := H + 2π;
}
```

YIQ

- Used by the NTSC color TV system
- **Y** component represents the luma information (*BW*)
- **I** (*in-phase)* and **Q** (*quadrature*) represent the chrominance information



https://commons.wikimedia.org/wiki/File:YIQ_IQ_plane.svg

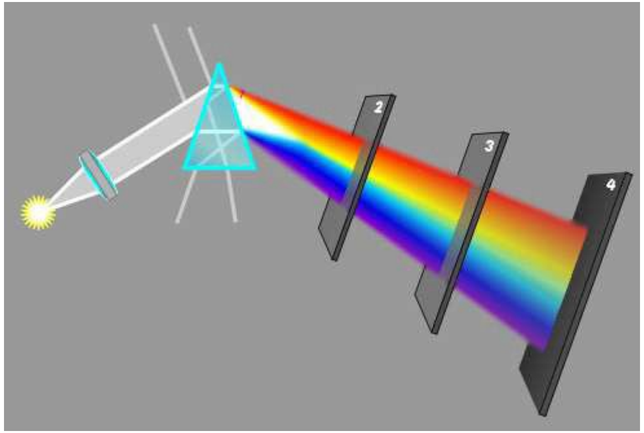
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} \approx \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.5959 & -0.2746 & -0.3213 \\ 0.2115 & -0.5227 & 0.3112 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color spaces

- Reference color spaces:
  - CIE XYZ
  - CIE L*a*b
  - CIE RGB (not used)
- Color models:
  - RGB
  - CMYK
  - YIQ
  - HSV
  - HSL
- Derived color spaces:
  - sRGB (RGB)
  - Adobe RGB (RGB)
  - Apple RGB (RGB)

Color space limitations

- Cannot be used for accounting wave light effects:
  – interference
  – diffraction
  – interference
- Additive color spaces have a fairly narrow range of color reproduction



THANK YOU
FOR YOUR TIME!

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