Цветовые модели

Техническое зрение

Computer Color Representation

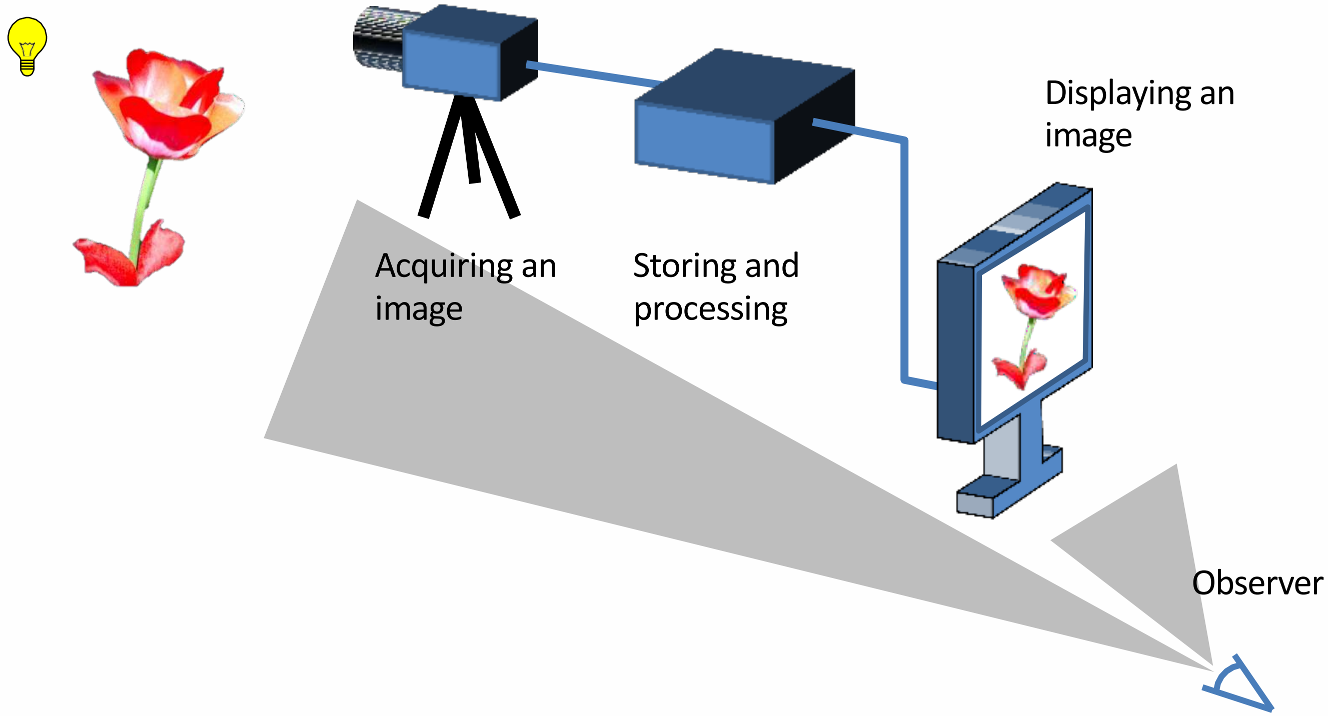
Chrominance and luminance

- 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?

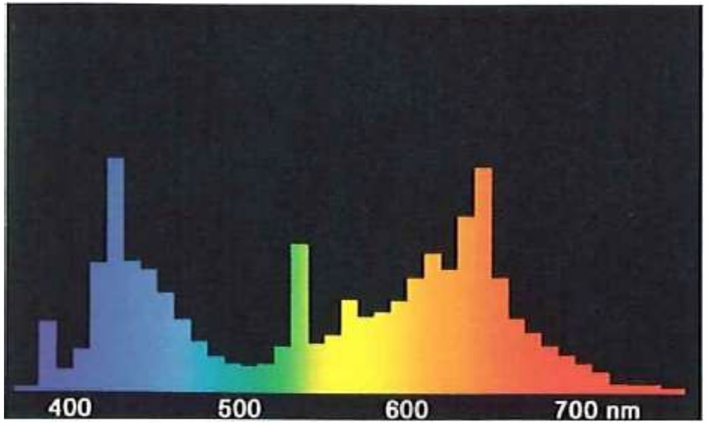
Computer color representation

- 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

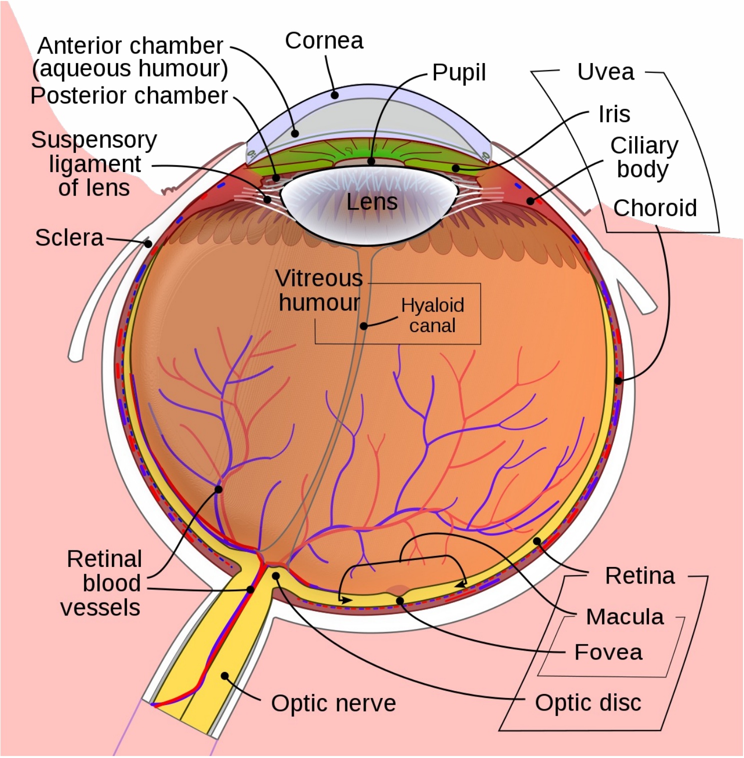
Computer color representation: spectrum quantization

- 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
- 1 Mpixel image = 160 megabytes



Human vision

- We need what the human sees
- So, it is necessary to understand the human eye light perception

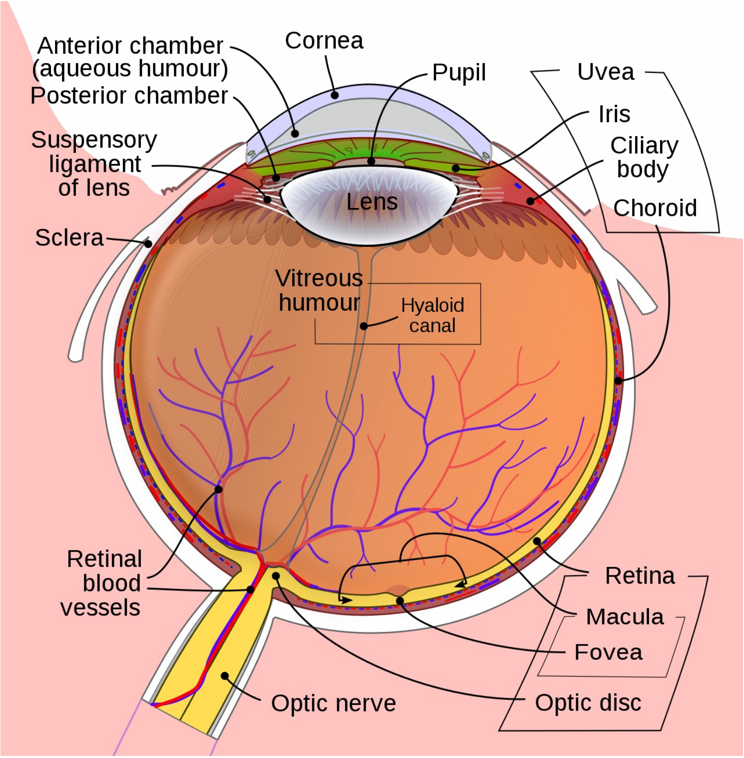


Rhcastilhos. And Jmarchn., via Wikimedia Commons

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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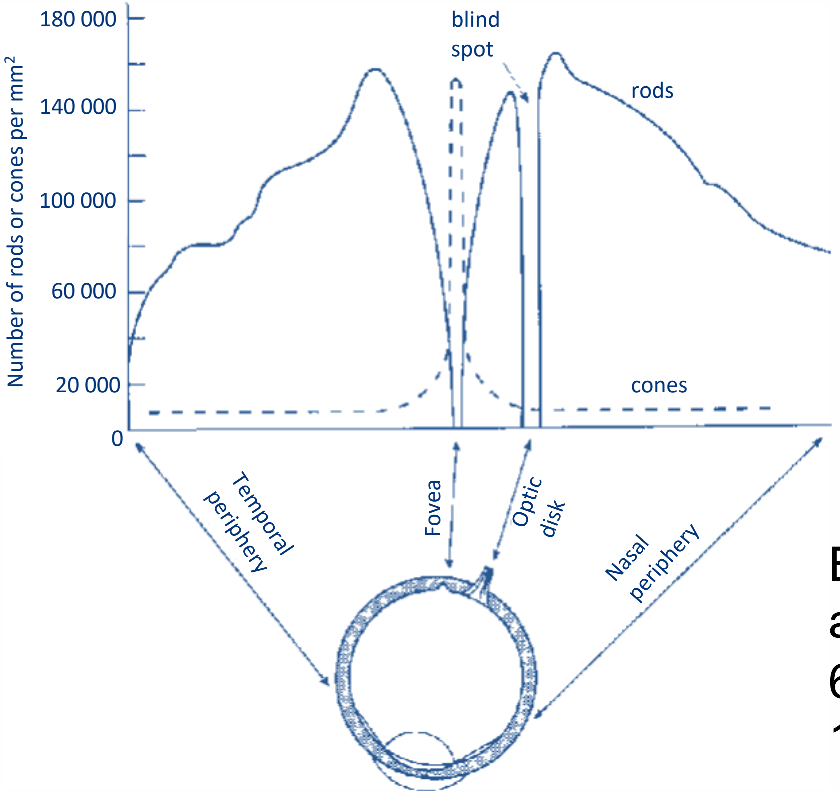
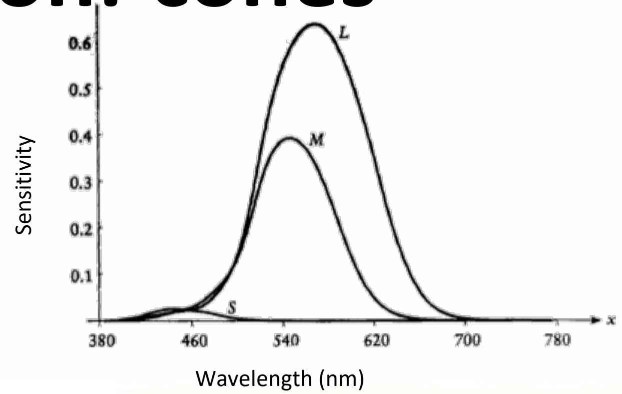
Cones and rods

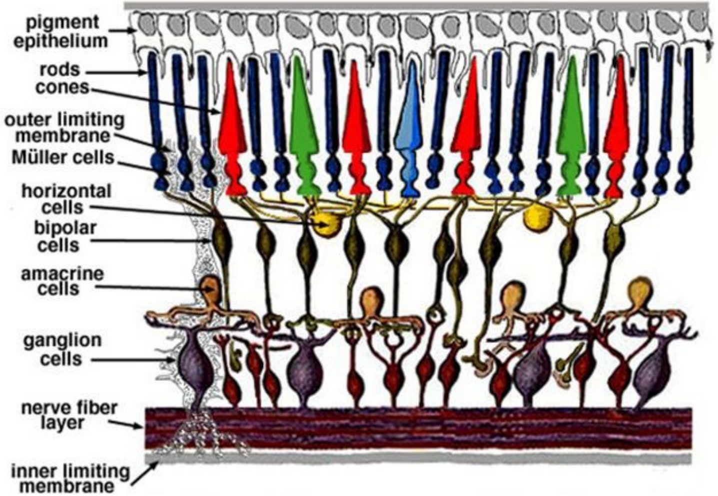


Each eye has approximately 6 mil cones and 120 mil rods

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



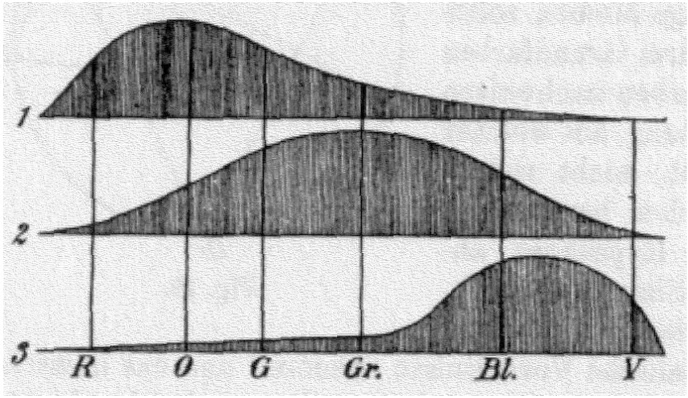


Three-component color theory (RGB)

- First described by **M.V. Lomonosov** in 1756 in the work «On the Origin of the Light»
- It was developed by the German scientist **G. Helmholtz** one hundred years later.
- **Color model** is an abstract description of colors using three numbers – *color coordinates.*
- **Color space** is the set of possible color shades and the interpretation method.

Trichromatic theory

- Thomas Young – 1802
- Hermann von Helmholtz – 1850



What is a color?

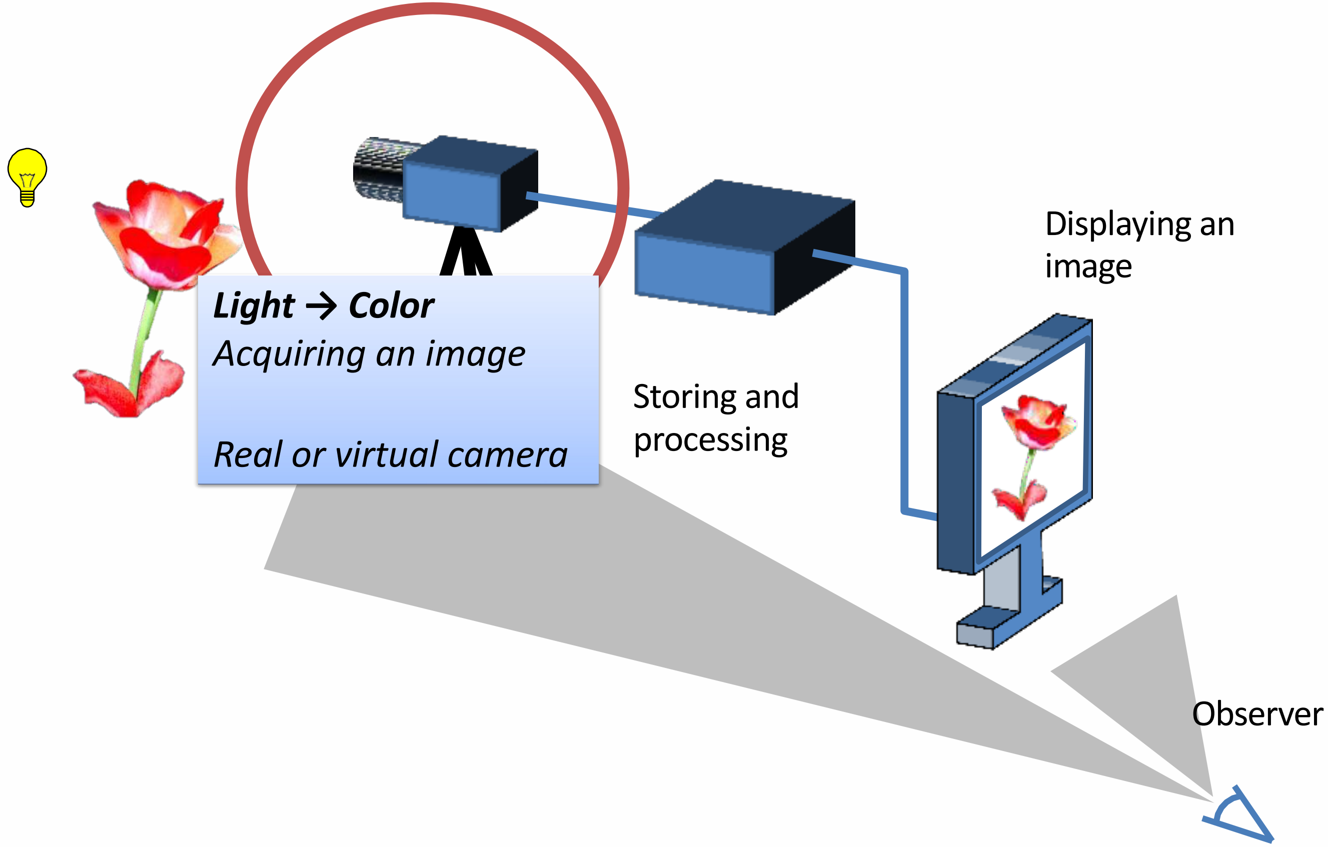
- Color: perceived effect of visible light
- **No** observer – then **no** perception and **no** color
- Each spectrum has a corresponding color
- Several spectra can be found for a single color (metamerism)

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

Color Matching Experiments

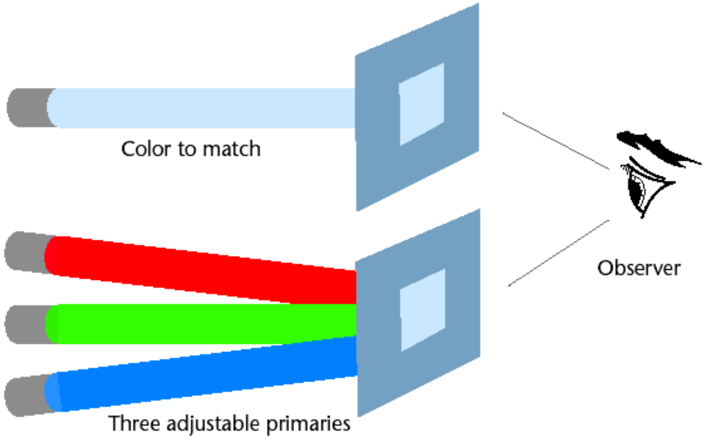
Light and color in a graphical system

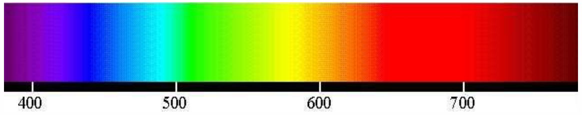


Color matching experiments

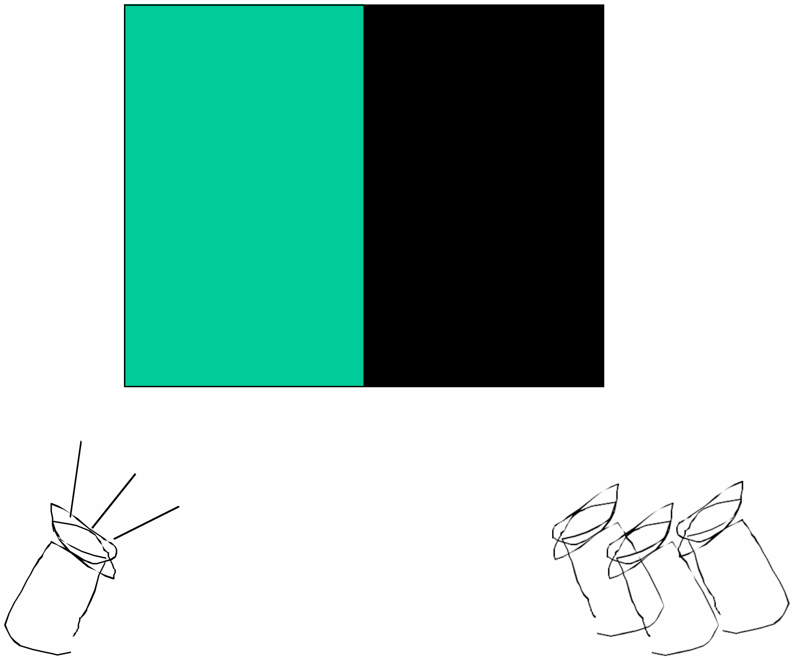
- 1920 – 1930
- Angular size of the screen is 2°
- Monochromatic original color
- Three monochromatic light sources of primary R, G, B recreate the target color
- The observer can change the intensity of each light source independently

Monochromatic color
380-780nm in 5nm steps



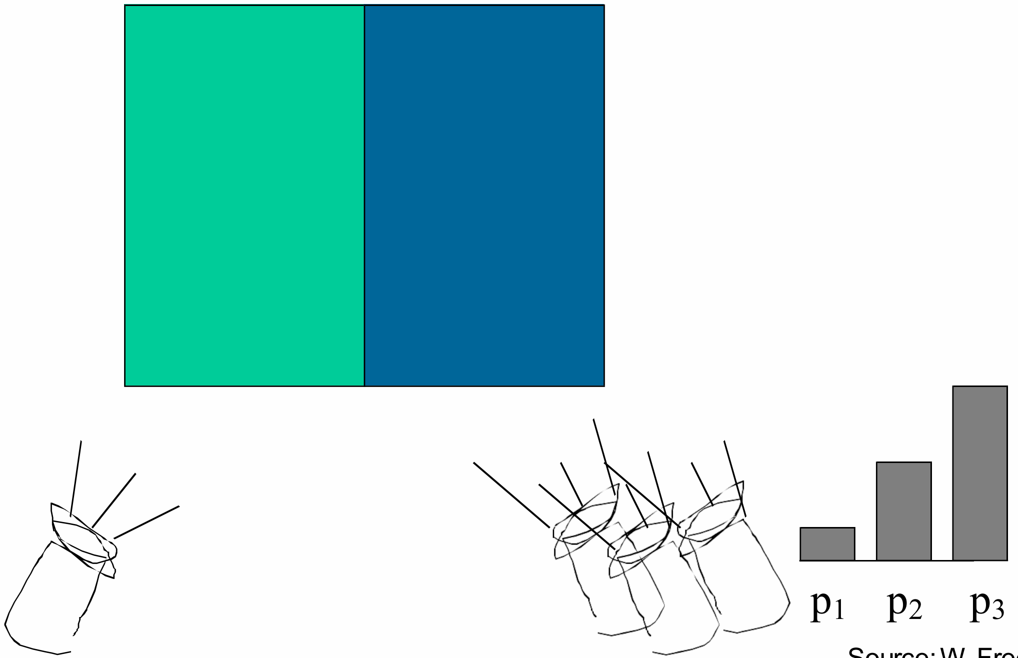


Color matching experiment: example 1



Source: W. Freeman

Color matching experiment: example 1



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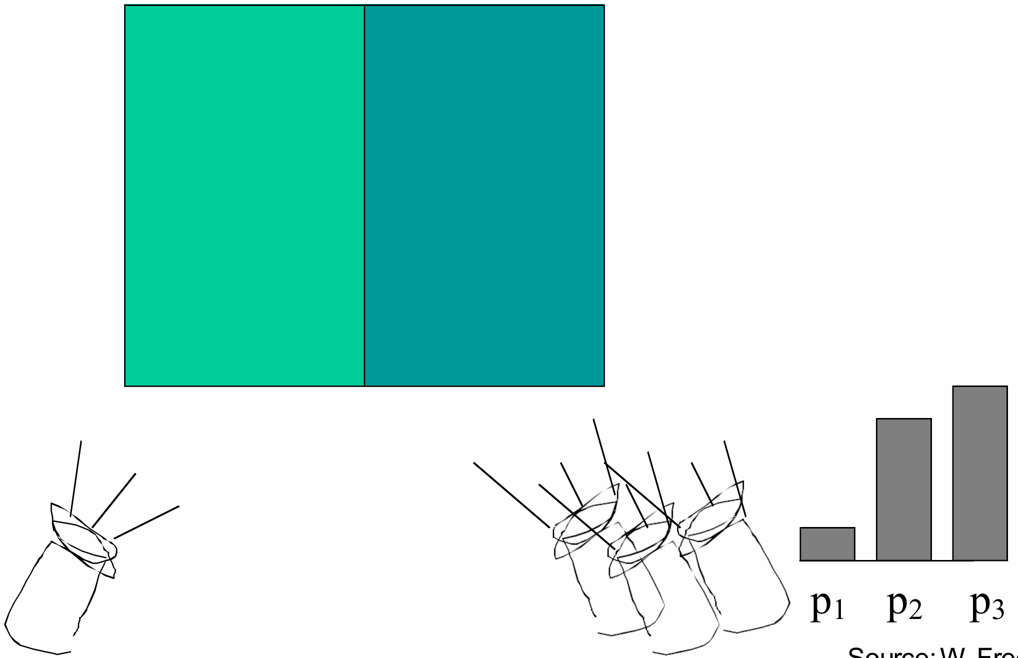
Color matching experiment: example 1



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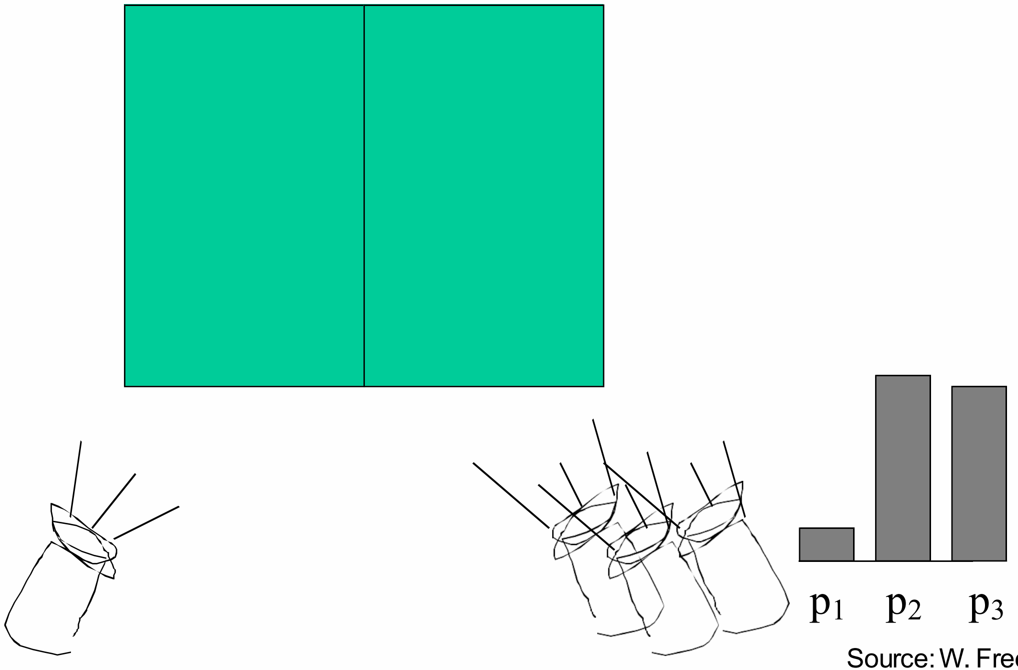
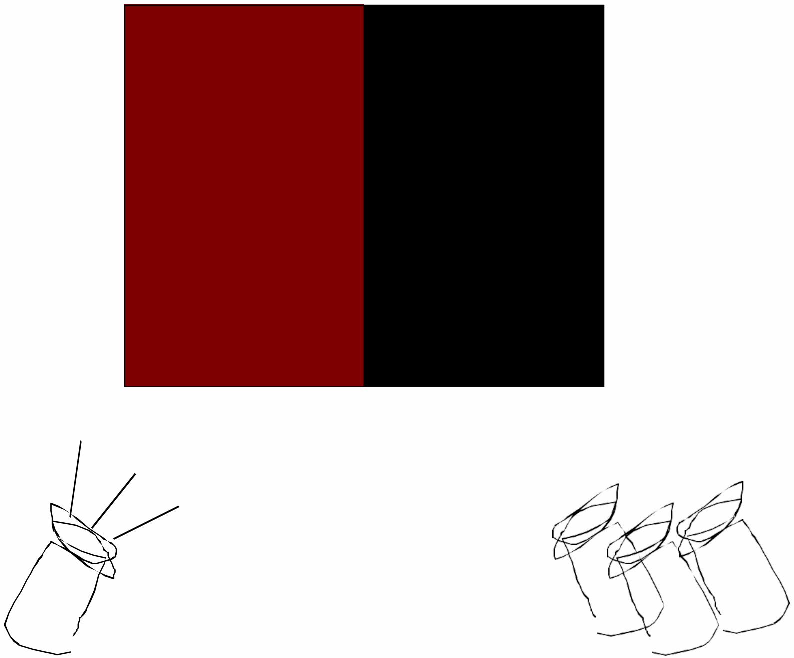
Color matching experiment: example 1



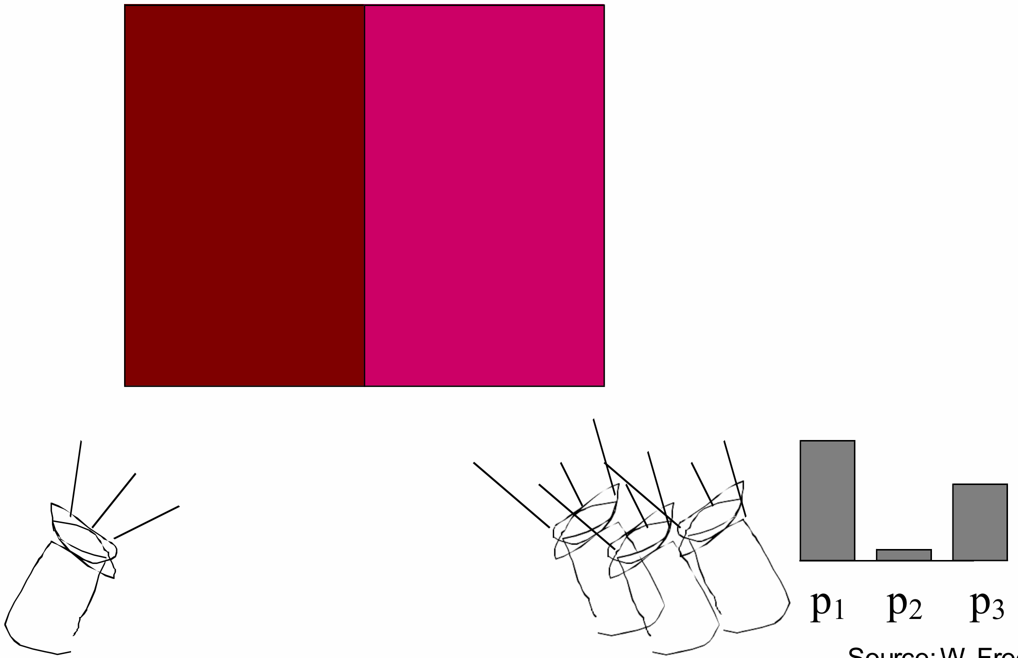
Source: W. Freeman

Color matching experiment: example 2



Source: W. Freeman

Color matching experiment: example 2



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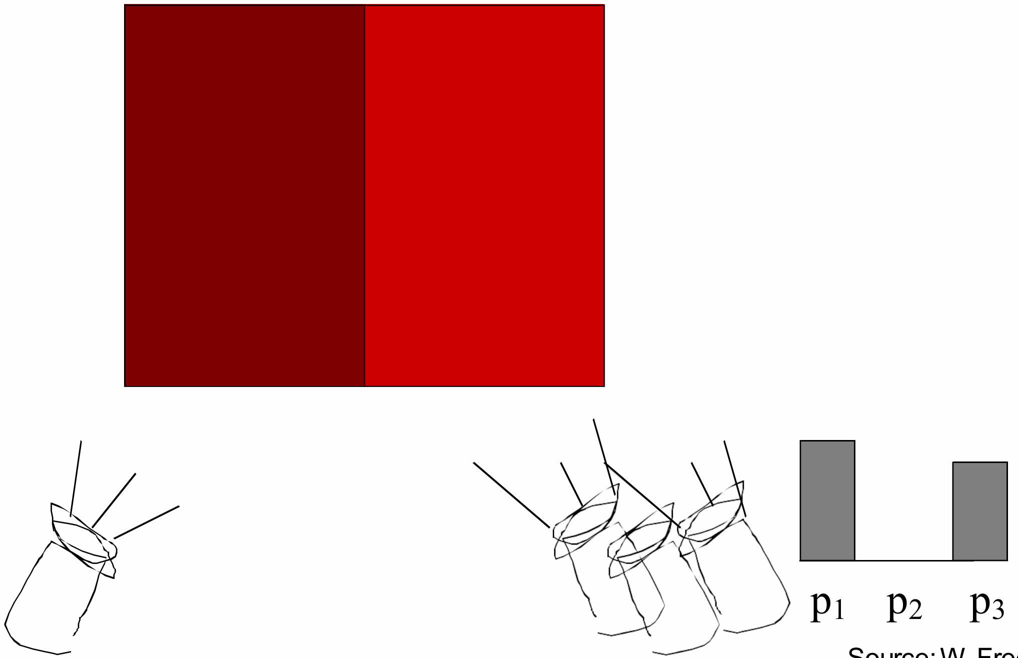
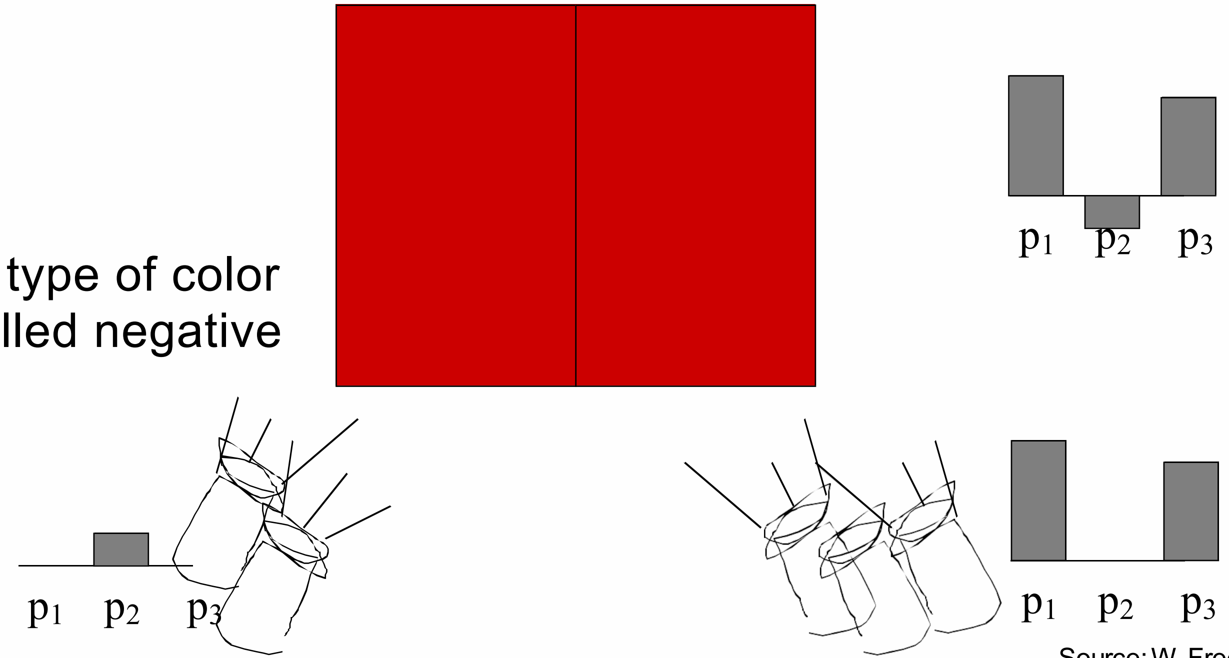
Color matching experiment: example 2



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:

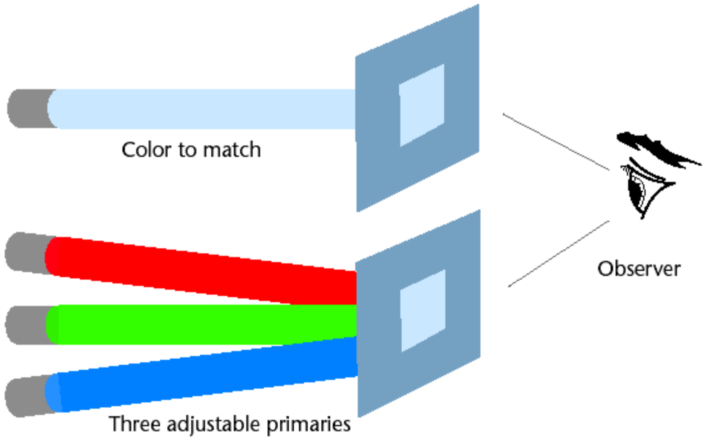
  $C = rR + gG + bB$

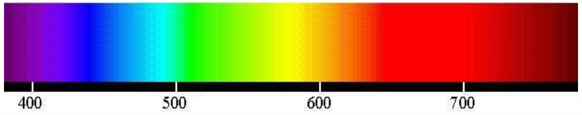
  - Additive matching
- Some colors cannot be specified this way, instead it should be:

  $C + rR = gG + bB$

  - 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

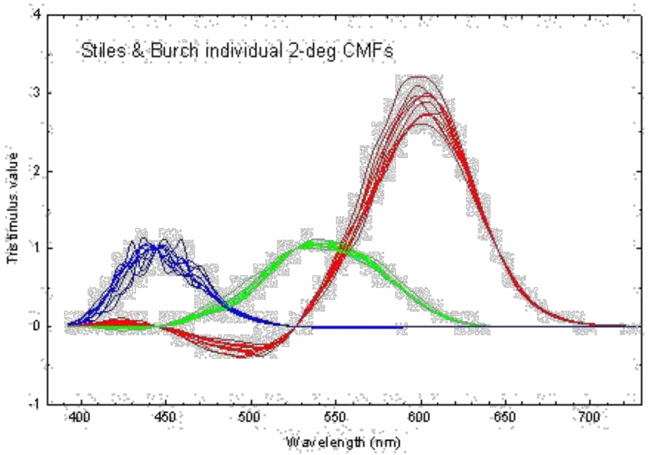
- Results are valid only
  - for a specific observer
  - for three given base colors
  - for monochromatic target colors

- 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

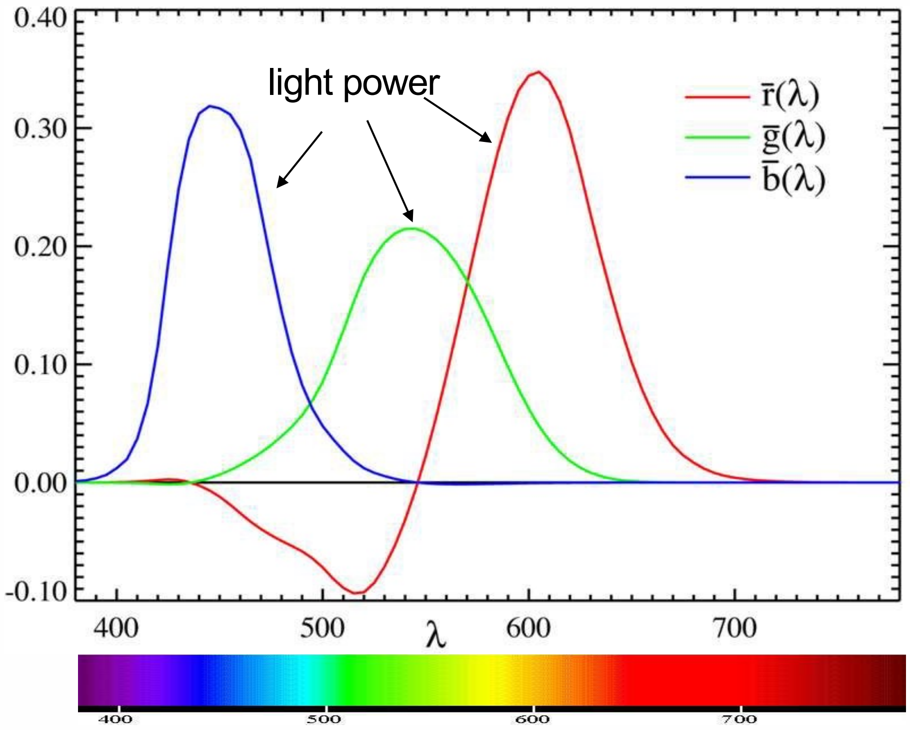
CIE Experiments

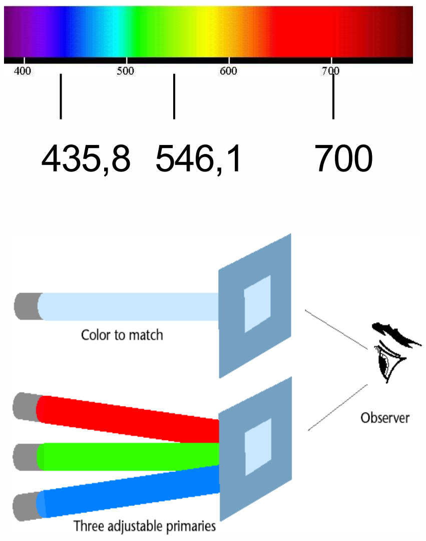
CIE experiments, 1931

- 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

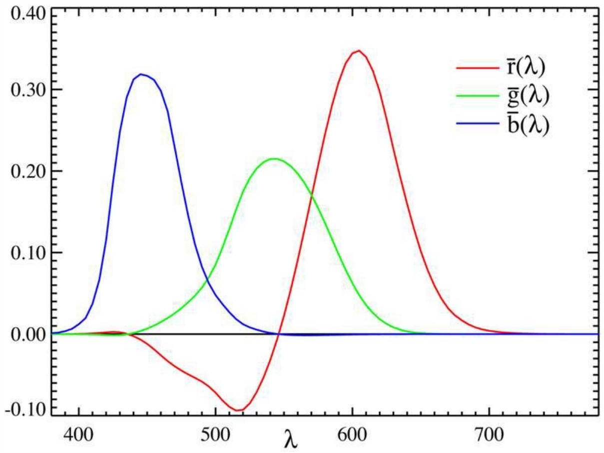
$$R = \int_{380}^{780} C(\lambda) r(\lambda) d\lambda$$

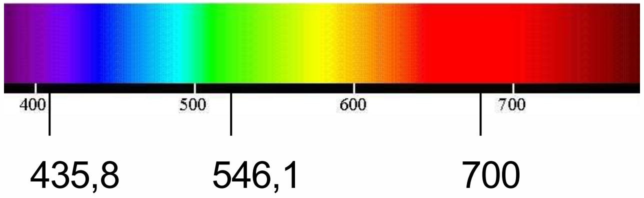
$$G = \int_{380}^{780} C(\lambda) g(\lambda) d\lambda$$

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

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(λ), Y(λ), Z(λ)

- 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

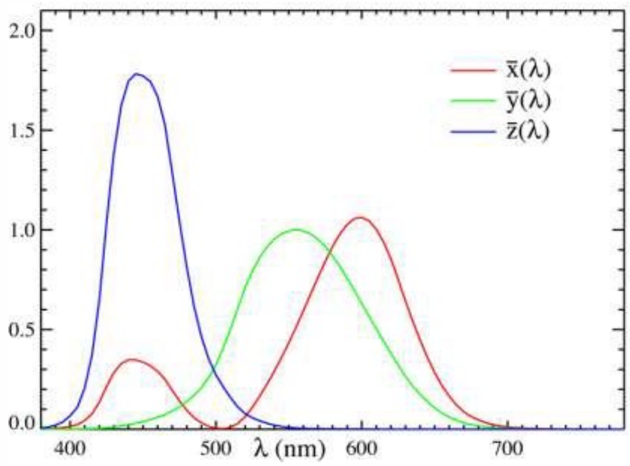
$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = \begin{bmatrix} r_1 & r_2 & r_3 \\ g_1 & g_2 & g_3 \\ b_1 & b_2 & b_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

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

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



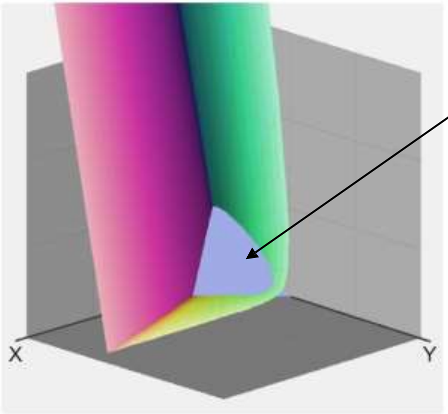
CIE XYZ 1931

CIE xy color model

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

- CIE xy

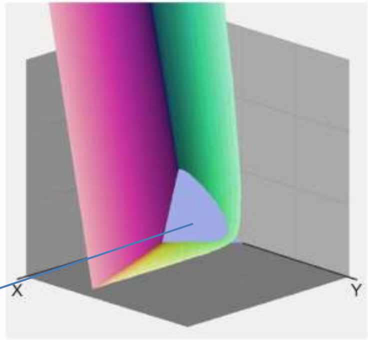
$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$

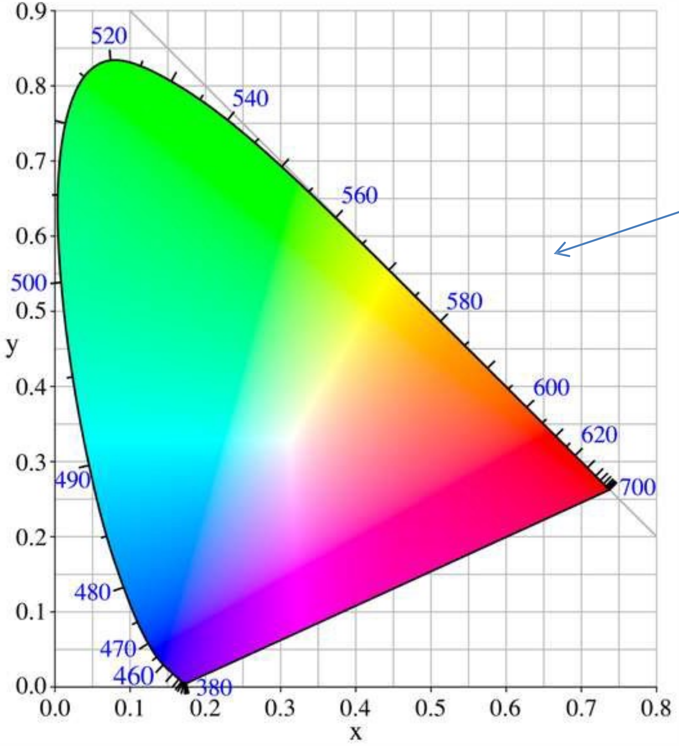


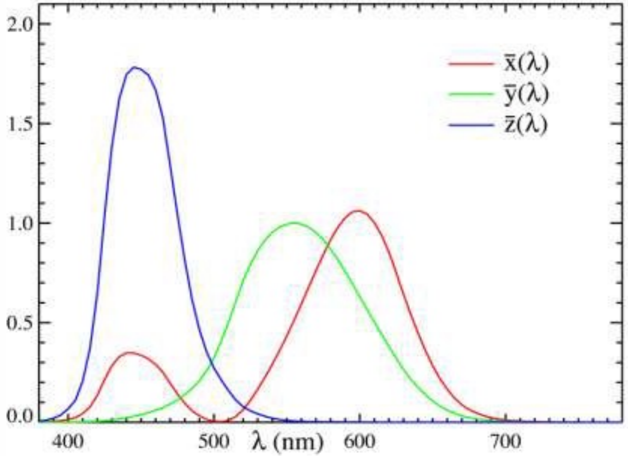
Projection to

X + Y + Z = 1

Chromaticity diagram





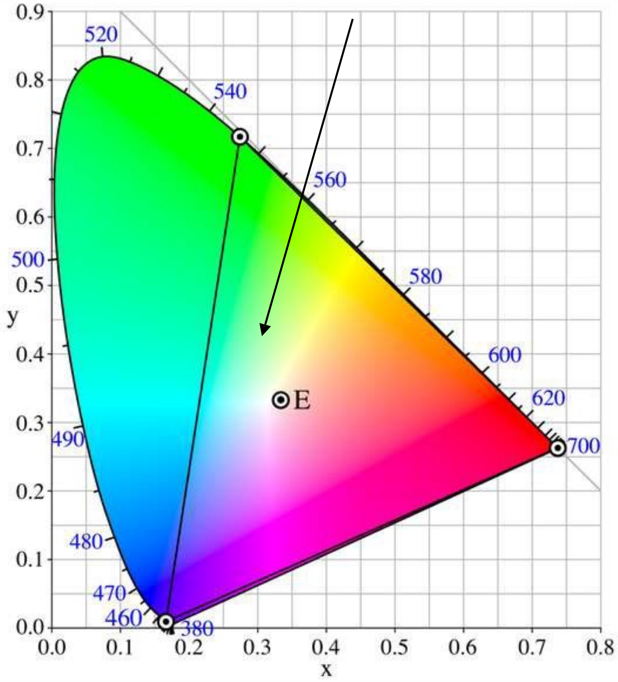


Chromaticity diagram: properties

iTMO

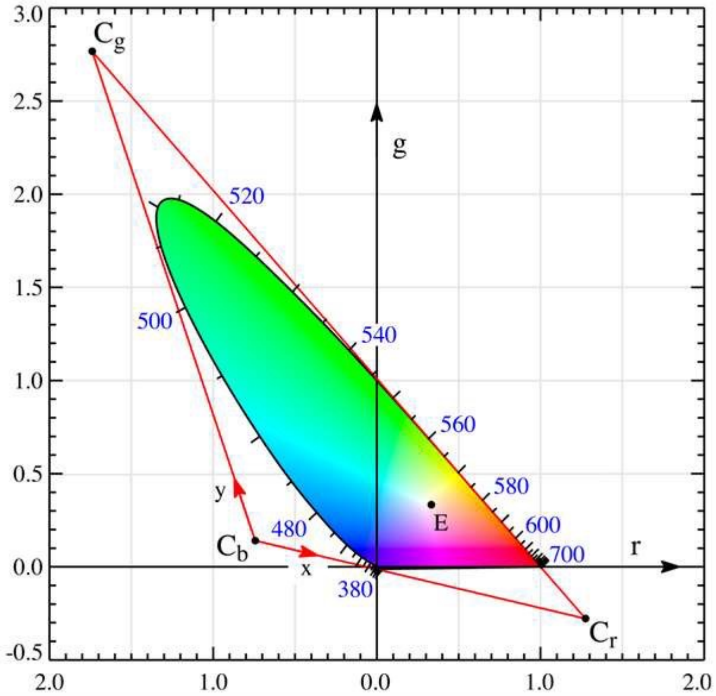
- The diagram shows all the colors visible to humans
  - Located inside the spectral curve
- All colors that can be obtained by mixing any two colors lie on a straight line connecting these colors
- All colors that can be obtained by mixing three colors lie inside the triangle
  - It is not possible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

CIE RGB base colors area



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



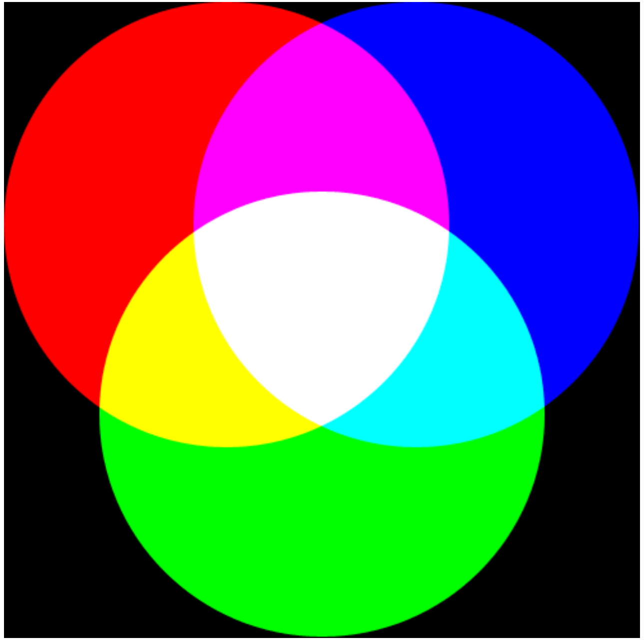
Color Spaces and Models

Color spaces and color models

- Color models 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

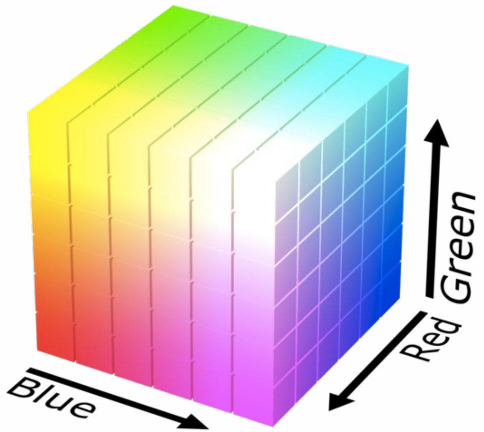
- Based on an additive combination of three primary colors – **Red**, **Green**, and **Blue**
- Describes the systems based on the emission of light to produce the desired color (TVs, monitors)
- The r, g, and b values do not have physical meaning
  – Snapping to original color space is required
- It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



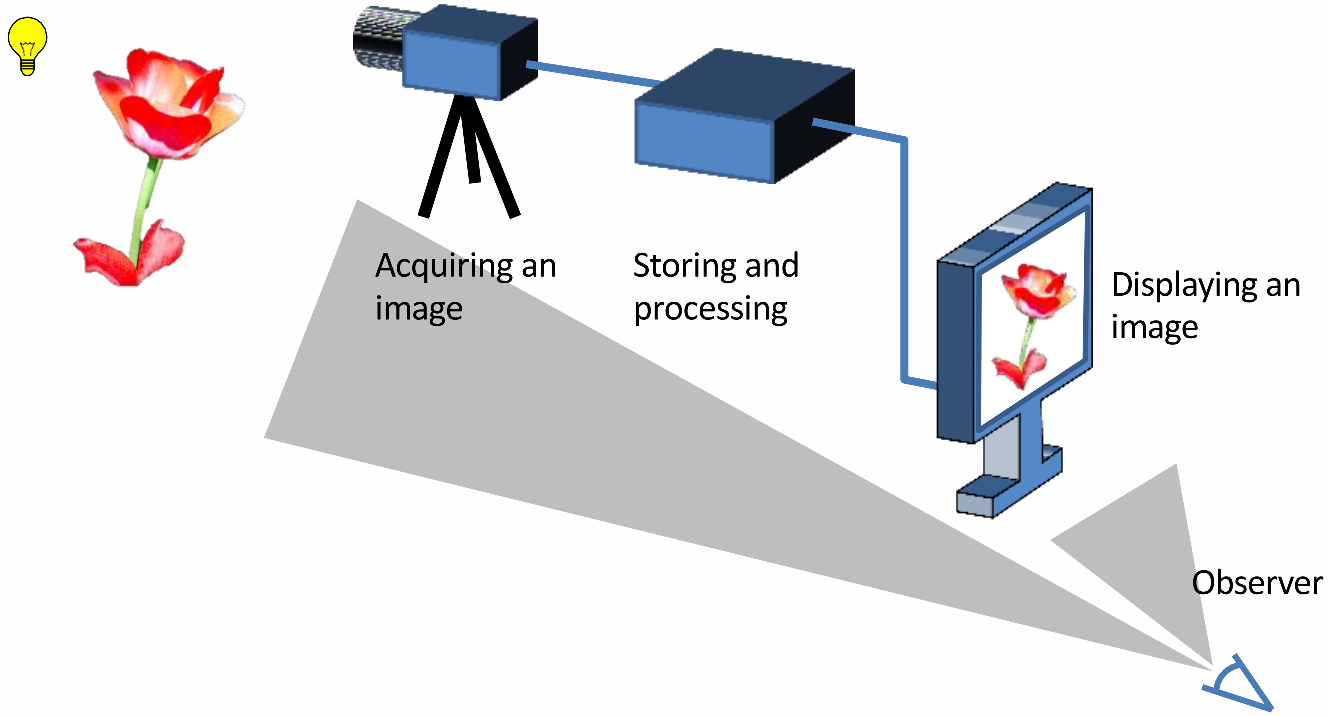
RGB color model

- **RGB** – consists of three equal and independent colors:
  - red, green, blue,
  - 0 – black color,
  - max – white color.

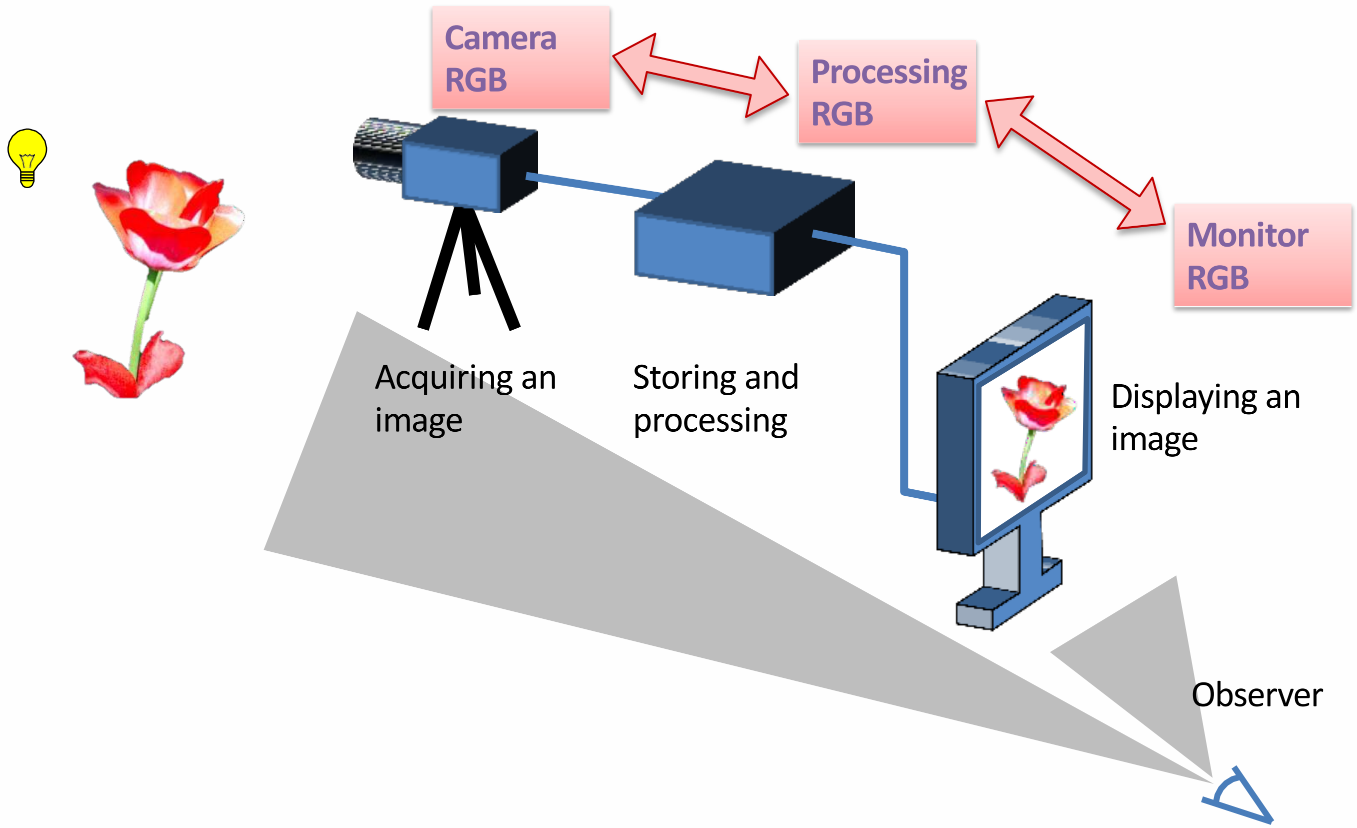
  Additive model, used on devices with a black background (monitors).



Light and color in a graphical system



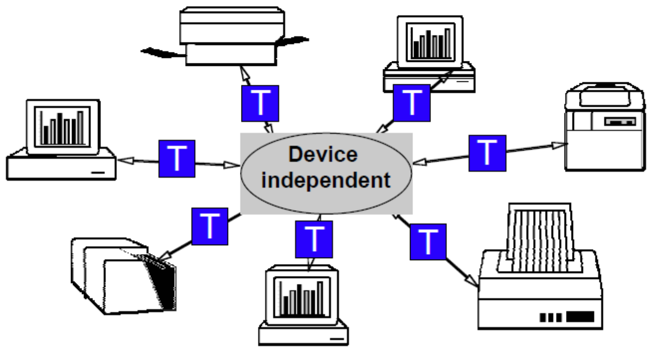
Light and color in a graphical system



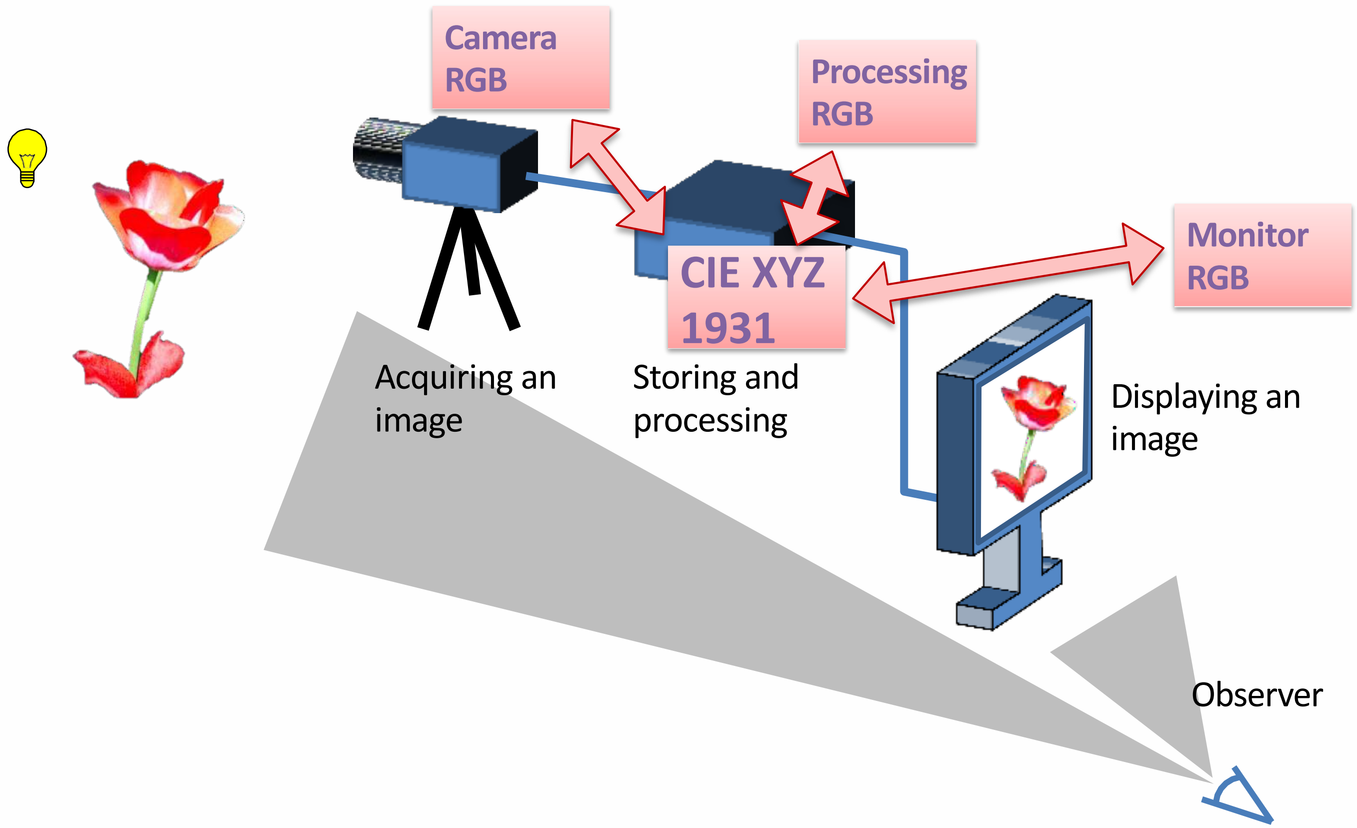
Specifying RGB color space

- 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

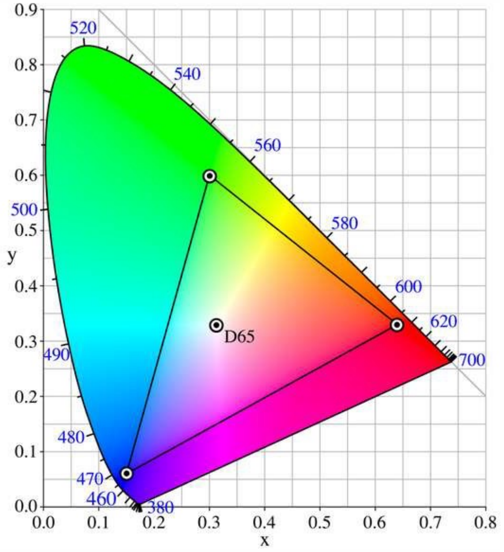


Light and color in a graphical system



Specifying RGB color space: base color sources

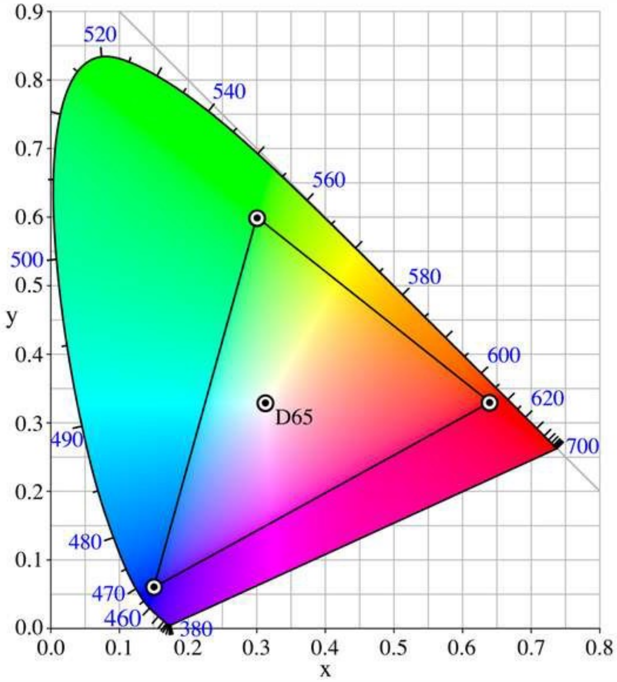
- Three base colors define an additive color space
- For a complete specification, usually define
  - *xy* coordiates for r,g,b base colors (phosphors)
  - white point (relative luminance)
- Examples:
  - NTSC RGB (TV)
  - HDTV RGB (TV)
  - sRGB (monitors)
- When transmitting a signal (for example, TV), 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)

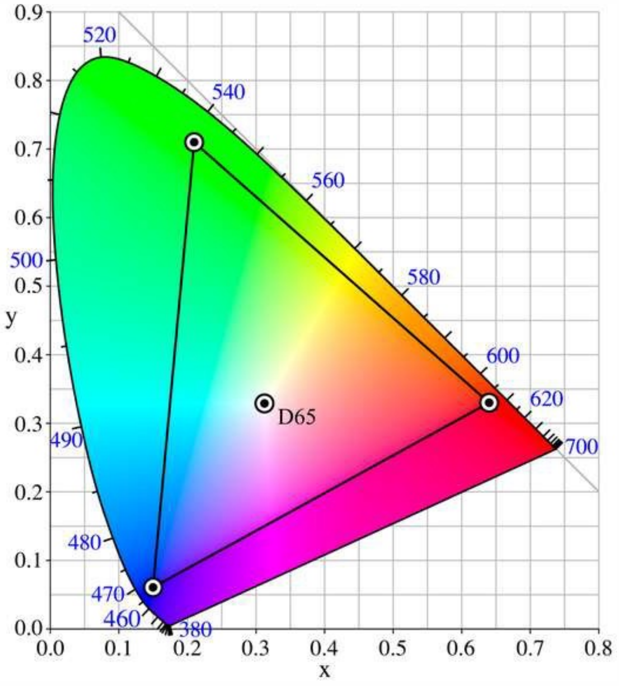
sRGB color space

- 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



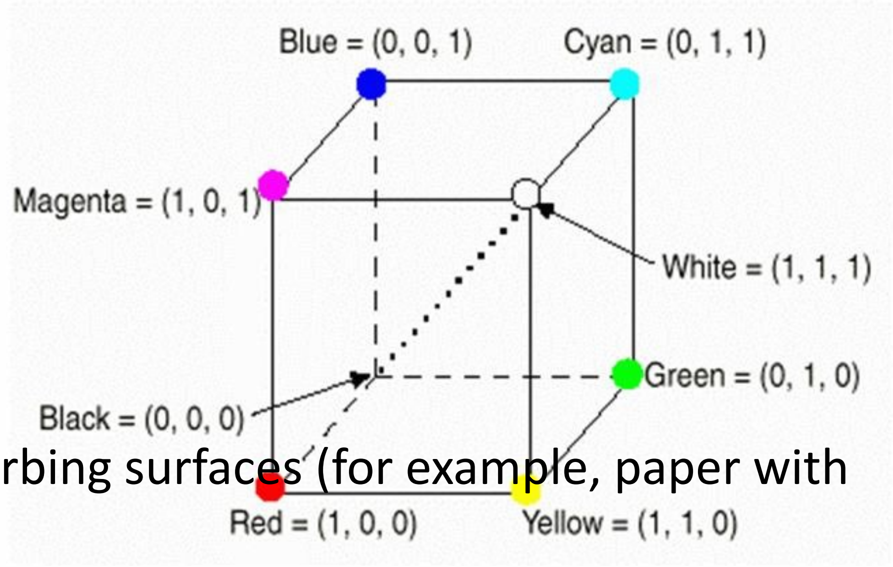
Adobe RGB color space

- 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

- **CMY** (Cyan, Magenta, Yellow)
  - C = max – R,
  - M = max – G,
  - Y = max – B,
  - Additional model to the RGB,
  - Subtractive model, used on absorbing surfaces (for example, paper with a white background),
  - Typically max = 255.

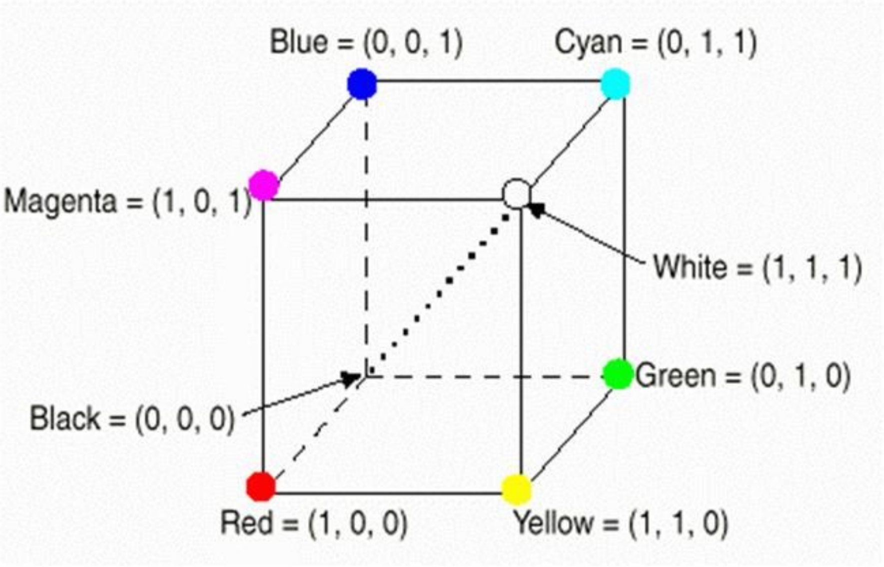


- RGB – additive color space
- CMY – subtractive color space

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

CMYK color space

- **CMYK** (Cyan, Magenta, Yellow, Black)
  - $K := min(C, M, Y);$
  - $C := C - K;$
  - $M := M - K;$
  - $Y := Y - K.$
  - Additional model to the CMY.
- Example:
  - CMYK = (30, 45, 80, 5) or C30M45Y80K5

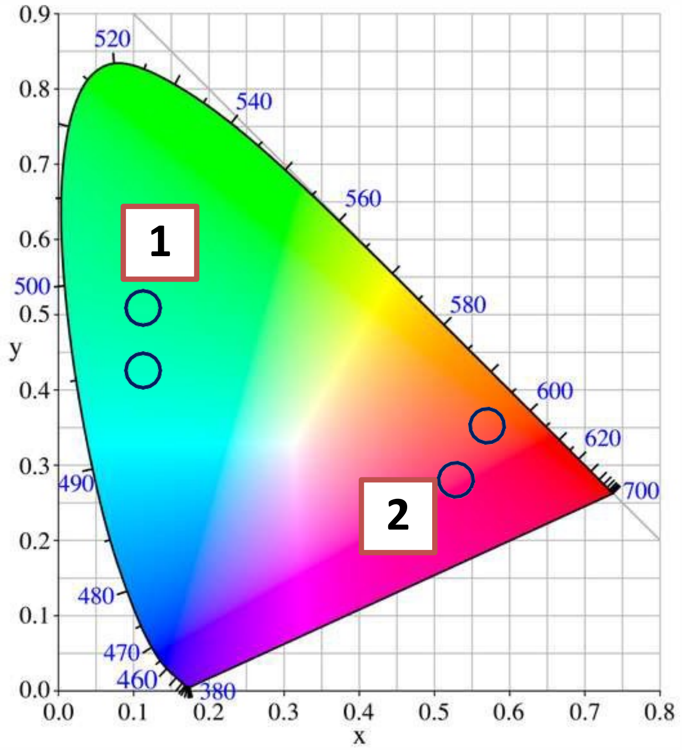


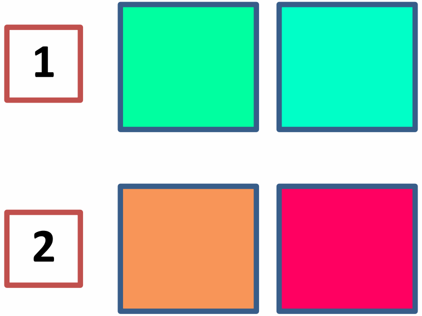
Khaki

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

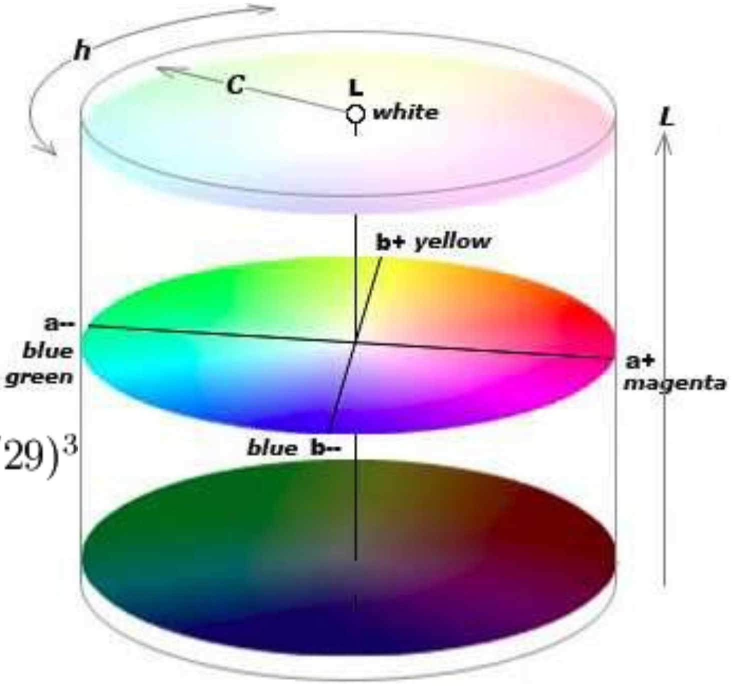
$$L^* = 116\, f(Y/Y_n) - 16$$

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

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

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

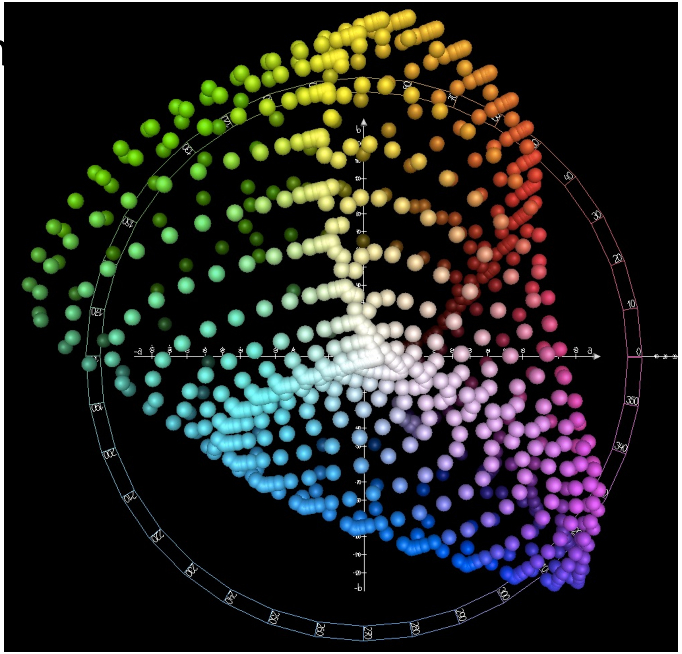
Xn, Yn, Zn – white point



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

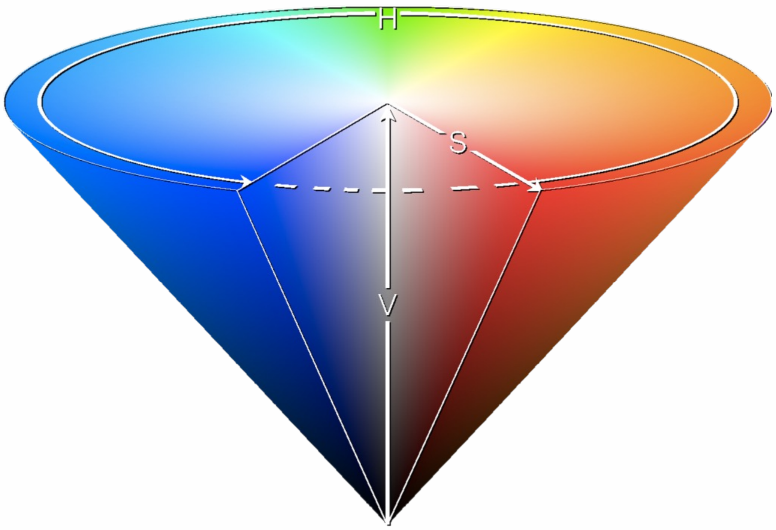
CIE 1976 L*a*b

- **CIE Lab** – the *lightness* value is separated from the color (*hue* and *saturation*).
  - L – lightness (luminance from the darkest
  - a – from red to green;
  - b – from yellow to blue.



HSV model

- **HSV** (Hue, Saturation, Value) – doesn’t consider the connection with the devices.
  - **Hue** – 0-360°,
    - 0° – red,
    - 120° – green,
    - 240° – blue;
  - **Saturation** – 0-100 (0-1);
  - **Value** – 0-100 (0-1).



THANK YOU FOR YOUR TIME!

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