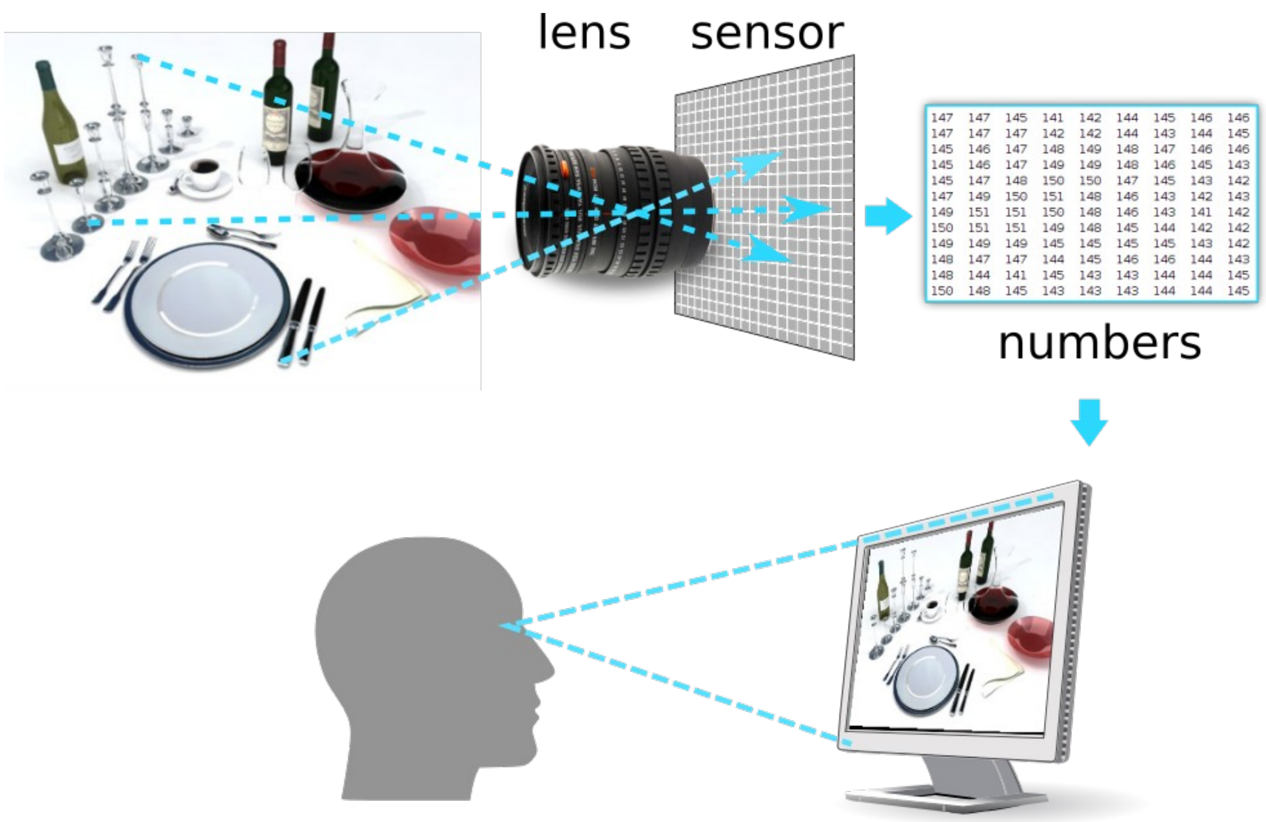
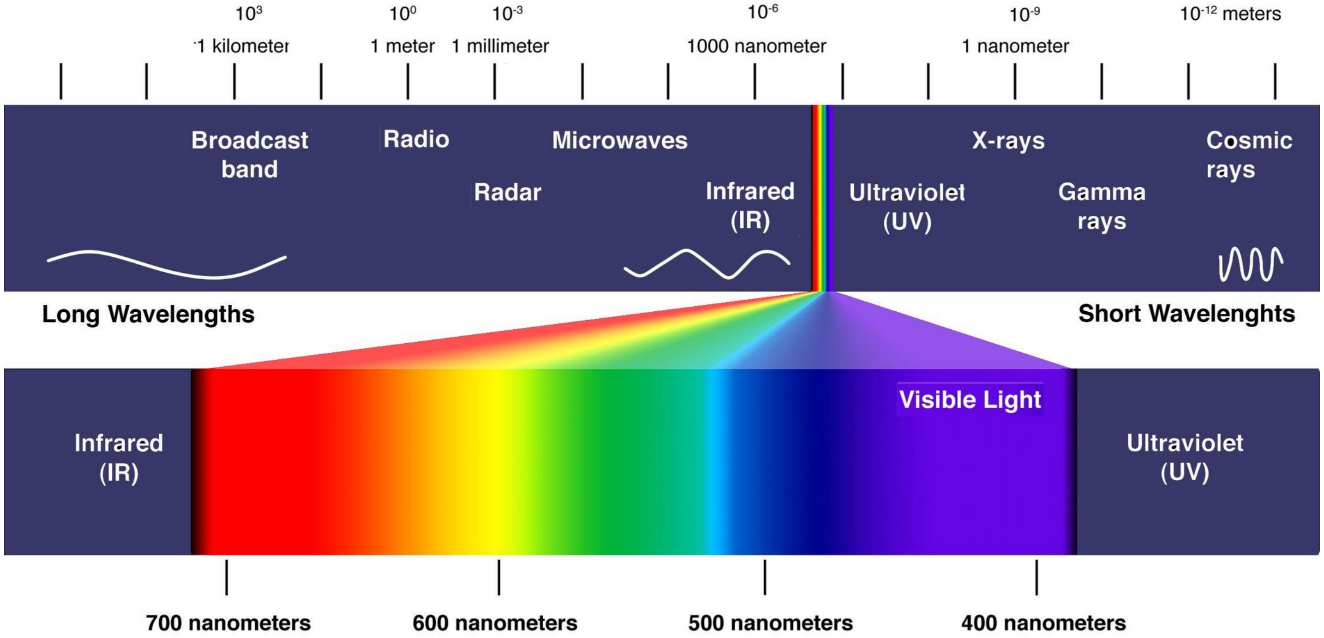
Image formation

World, image, eye



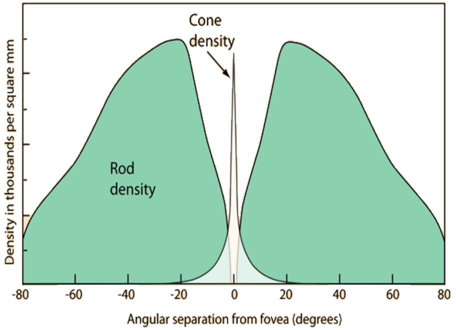
Light

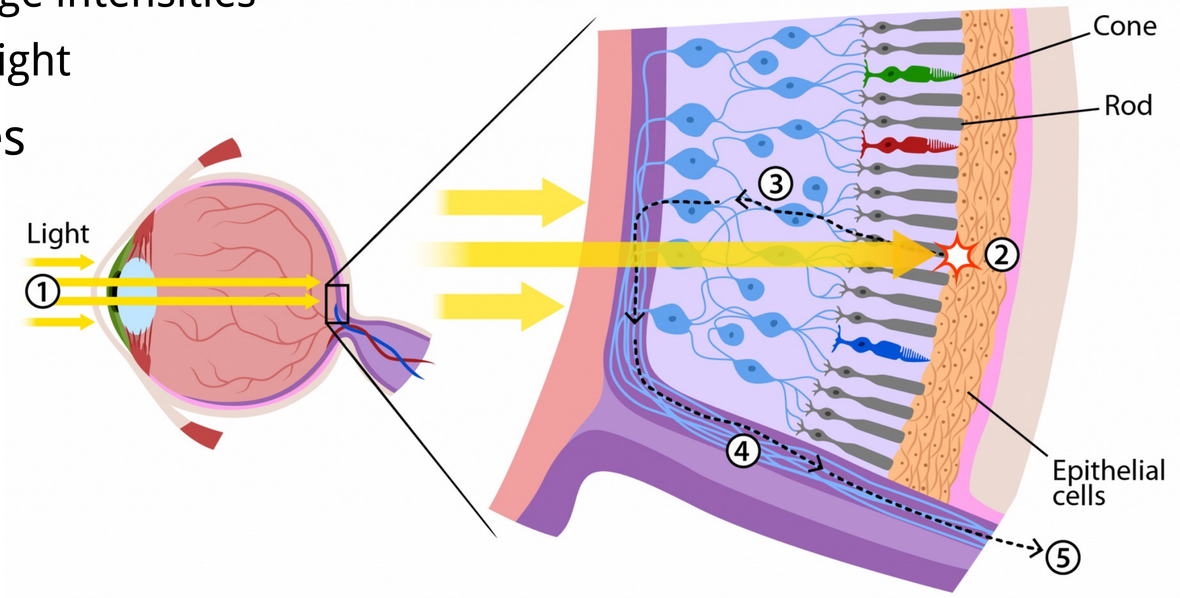


- Light is electromagnetic waves / particles (photons)
- Visible light is light with wavelength from ~400nm to ~700nm

Perceiving light

- Eye perceives light that falls on the retina
- Retina is composed of two types of cells
  - Cones - Sensitive to color and large intensities
  - Rods - Sensitive to low intensity light
- There are more rods than cones
- Not uniform distribution





Why are we trichromatic?

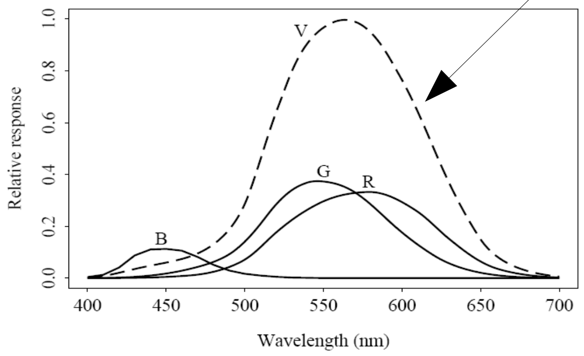
- Young-Helmholtz theory (19th century)
- Three types/lengths of cones
  - Different wavelengths (R=L, G=M, B=H)
- It is not yet entirely clear how brain combines color information
  - Ganglion trigger to differences R-G, G-B, B-R (opponent theory)
- All three channels are combined into achromatic information

Spectral sensitivity of the eye

- Eye is most sensitive to the middle of visible spectrum
- Cone distribution approximately R:G:B == 40:20:1 (varies from human to human)
- Rods are more sensitive to wavelengths closer to the red part of the spectrum.

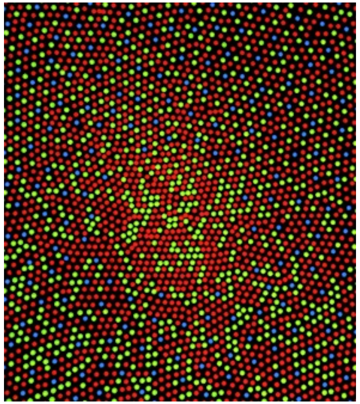
Cones sensitivity

The curve for blue is not plotted on the correct scale, it is much lower than the curve for red or green.



Rods sensitivity

Sensitivity of rods is similar to the overall sensitivity curve V for cones, it is only shifted towards the red spectrum.

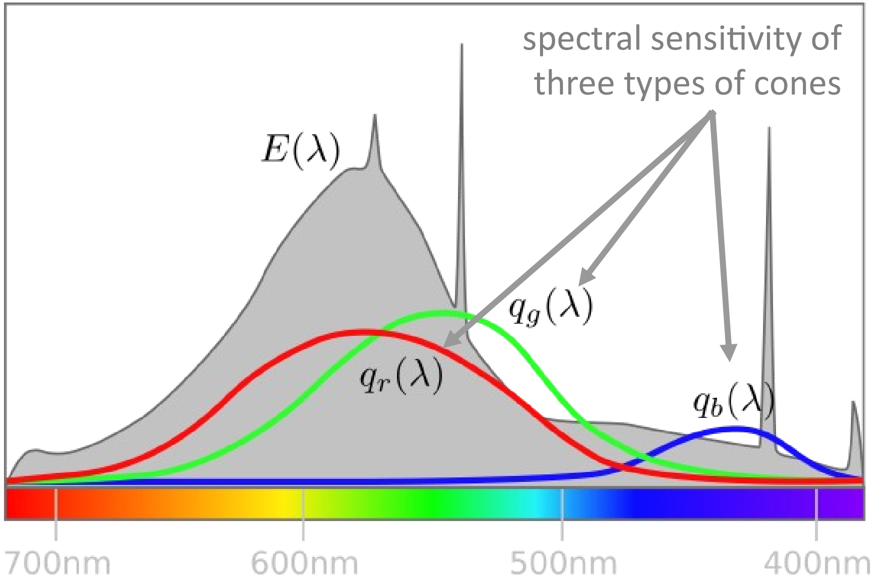


Cone distribution

Cones sensitivity

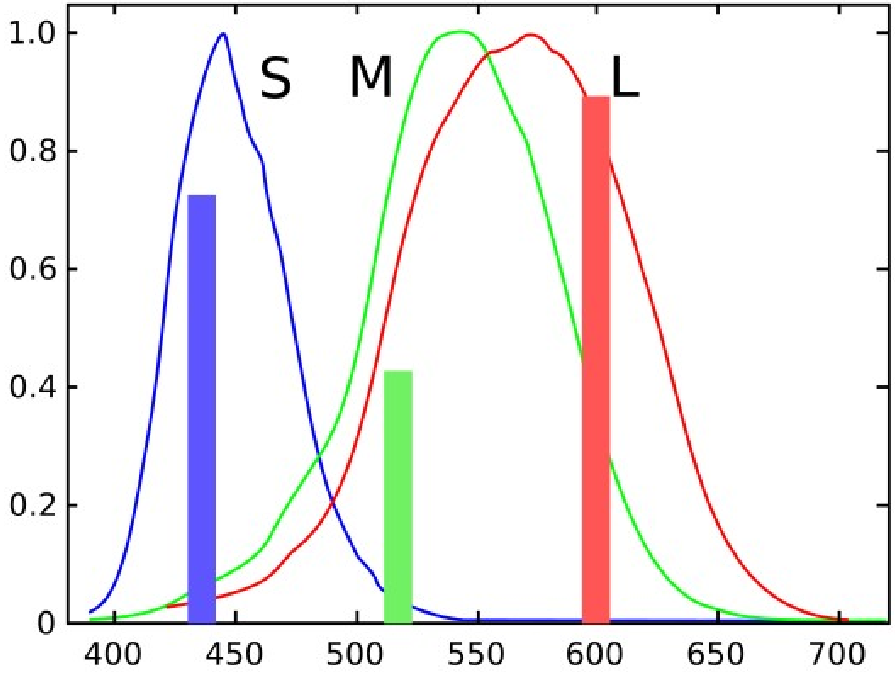
- Cones are triggered with different intensity with respect to the light's wavelength
- Filtering color spectrum $E(\lambda)$

$$R = \int E(\lambda) q_r(\lambda) d\lambda$$
$$G = \int E(\lambda) q_g(\lambda) d\lambda$$
$$B = \int E(\lambda) q_b(\lambda) d\lambda$$



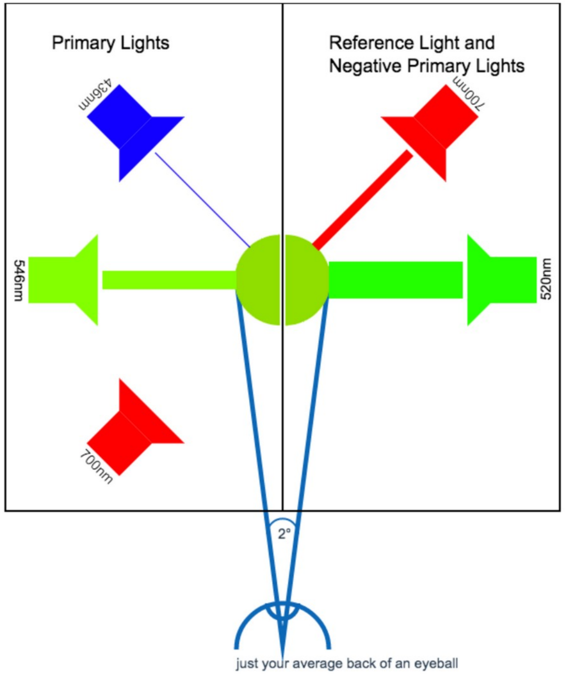
Simulating color

- Stimulating cone cells
- Metamerism
- Color primaries
  - Trichromatic (3+)
  - Different standards



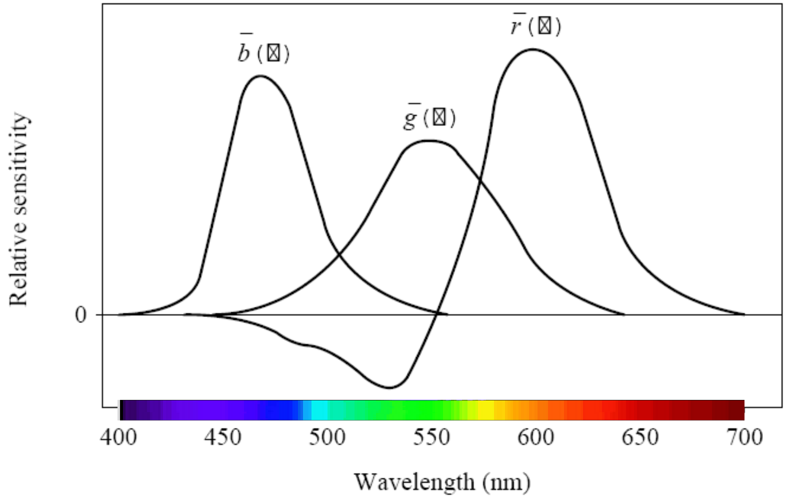
Measuring color perception

- Color reproduction evaluation
- Quantitative evaluation it in terms of human perception
- The tristimulus colorimeter experiment
  - Matching reference color
  - A person is controlling the intensity of three color channels
  - Standard observer (field-of-view)
  - Negative light

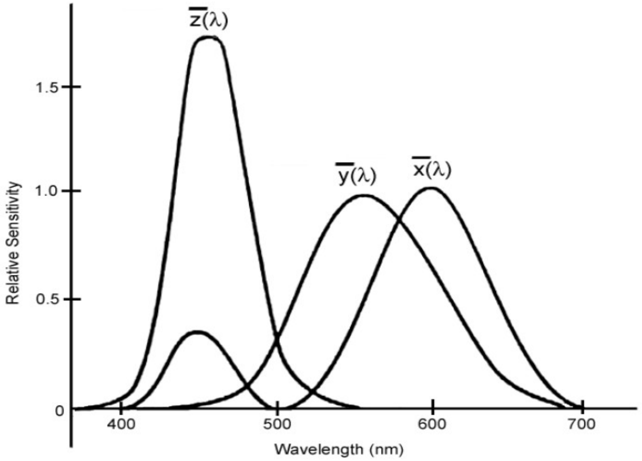


CIE 1931 curves

- Established by Commission Internationale de l'Eclairage (CIE)
- Results of the experiment are three color matching functions
- Non-negative artificial curves determined experimentally (linear transformation)



Negative values denote that the person had to adjust the light of the reference color



The y(λ) curve matches the overall sensitivity curve V(λ)

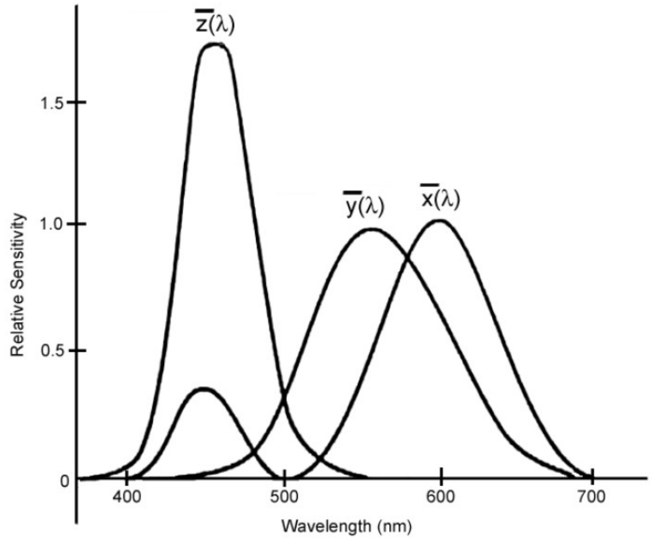
The CIE XYZ model

- Arbitrary color determined by spectrum E(λ), can be formulated with values of the three stimuli X, Y, Z
- The CIE XYZ standard:

$$X = \int E(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int E(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int E(\lambda)\bar{z}(\lambda)d\lambda$$



Chromatic diagram

- 3D space visualization is difficult $x = \frac{X}{X+Y+Z},\ y = \frac{Y}{X+Y+Z},\ z = \frac{Z}{X+Y+Z}$
- Normalized redundant system $x + y + z = 1$
  - Display (x,y) when z=0
  - Chromatic components: (x, y)
  - Luminance: Y
- Saturated colors at borders
- White color in the middle
- Mixture of two light sources corresponds to color on the line between their colors in chromatic diagram

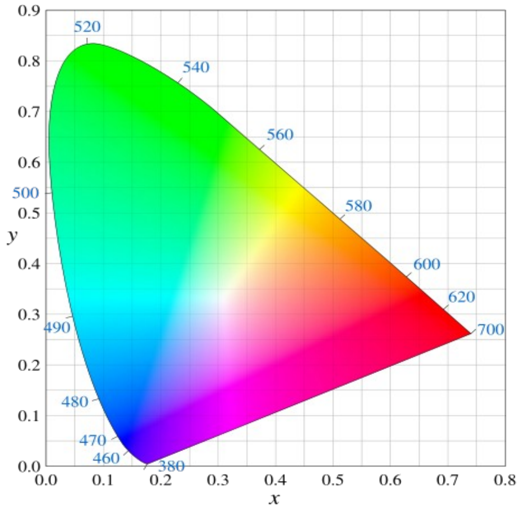
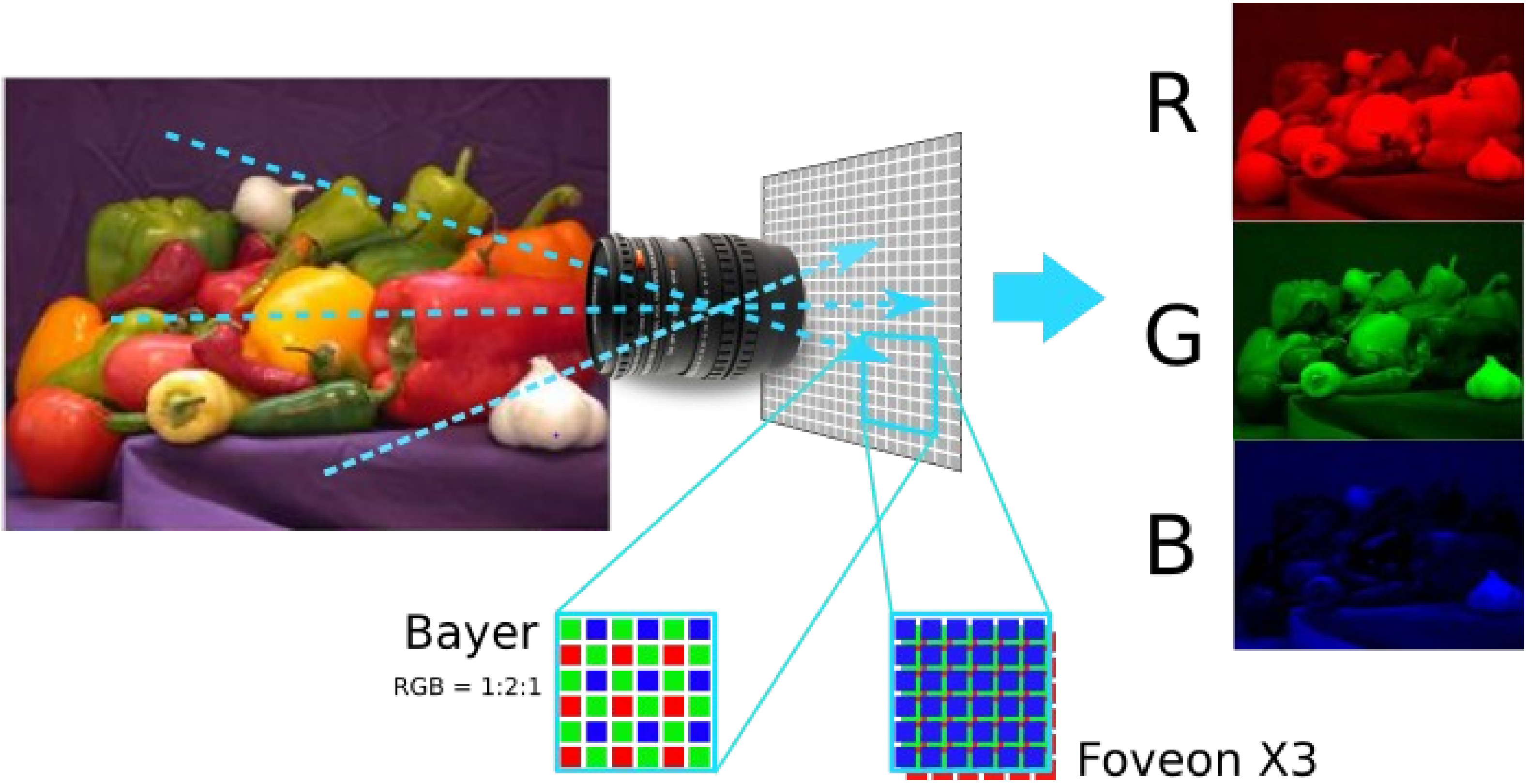
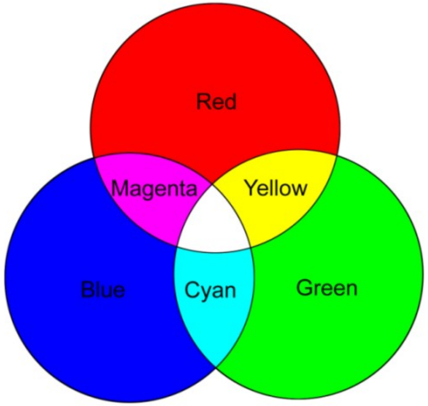
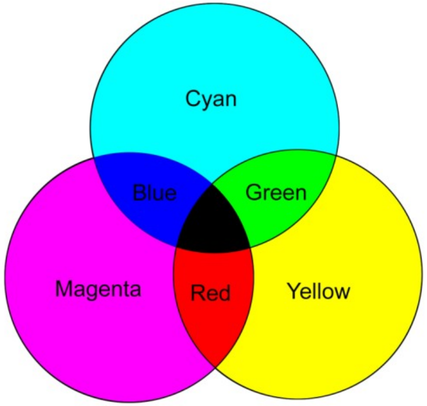


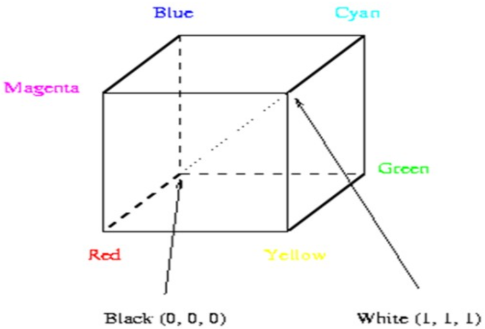
Image formation in camera



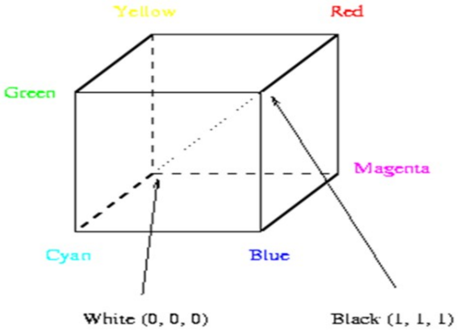
Additive vs subtractive







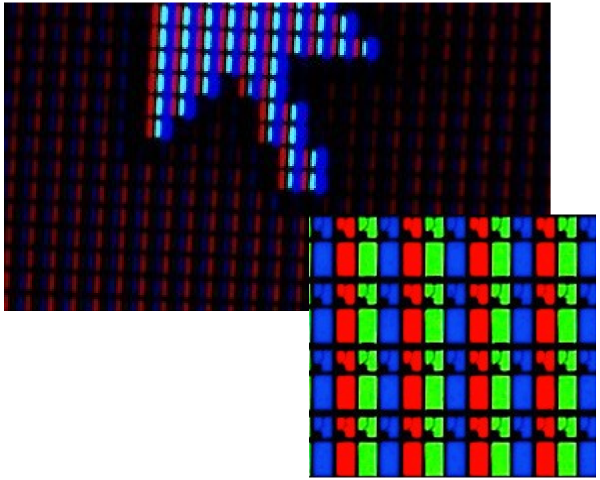
The RGB Cube



The CMY Cube

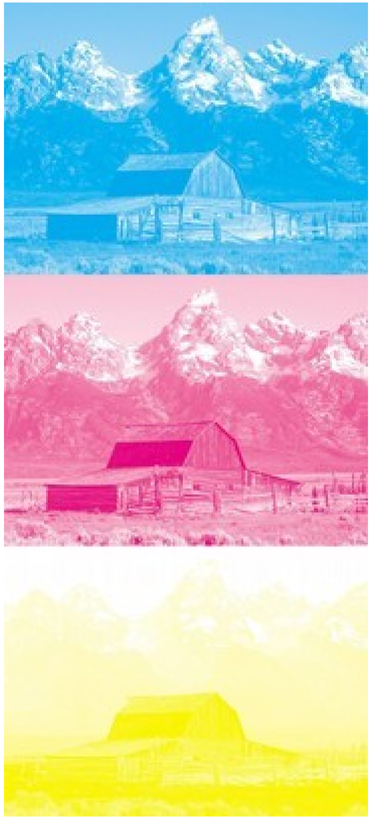
Additive models

- Starting point is black color, we then add colors
- Devices
  - Monitors
  - TVs
  - Projectors



Subtractive models

- Starting point is white color
- We then add pigments that remove wavelengths by absorption
  - Yellow pigment absorbs blue and still reflects red and green
  - Green pigment only reflects green
- Usage
  - Crayons
  - Printers (CMYK)
  - Analogue photographic paper

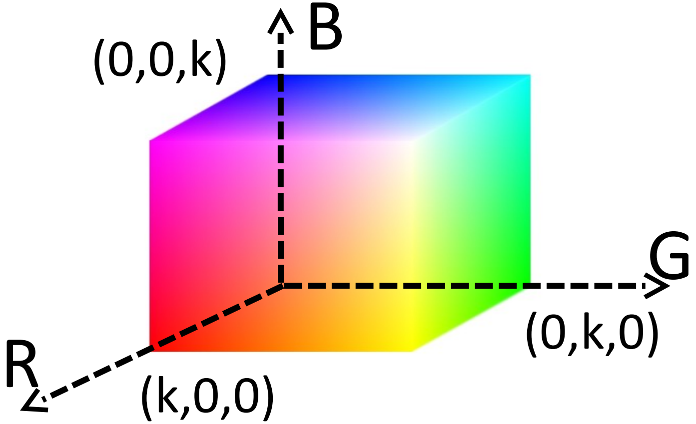


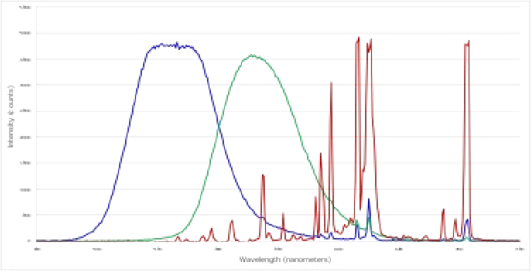
The RGB color space

- Three primaries: red, green, blue
- Foundations in color cathode television
- k ... maximum value of primary color

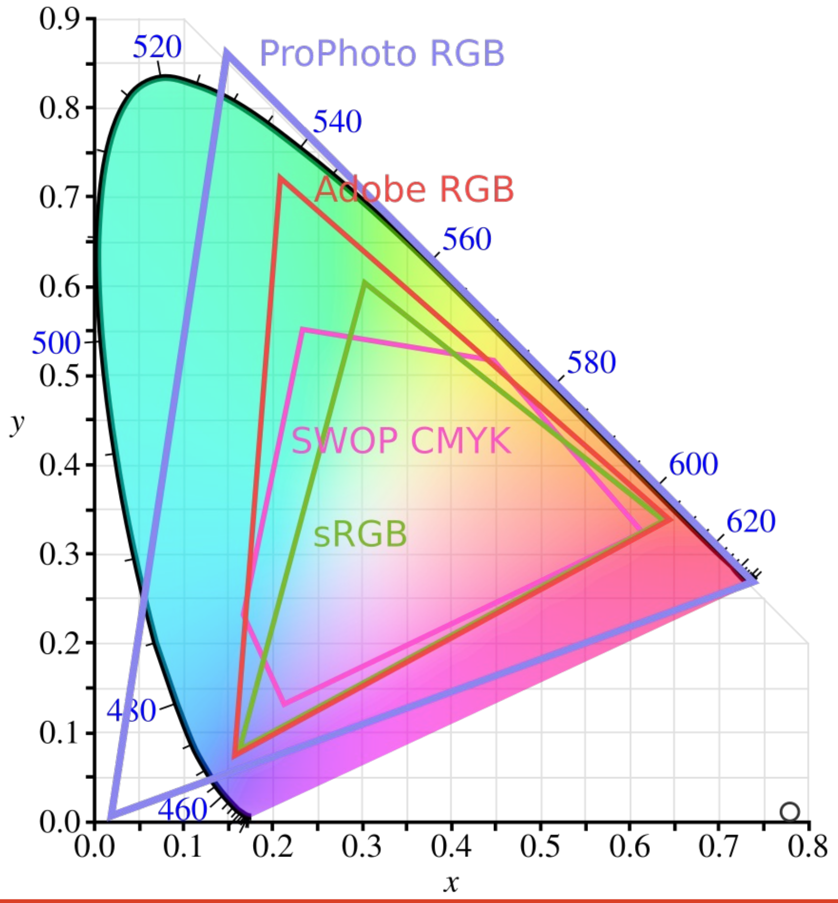
$$\begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Different standards define the matrix differently
(sRGB, Adobe RGB, Adobe wide gamut RGB)





Color model comparision



- Different coverage
- Conversion loss
  - Rounding
  - Truncation

The CIE L*a*b* color space

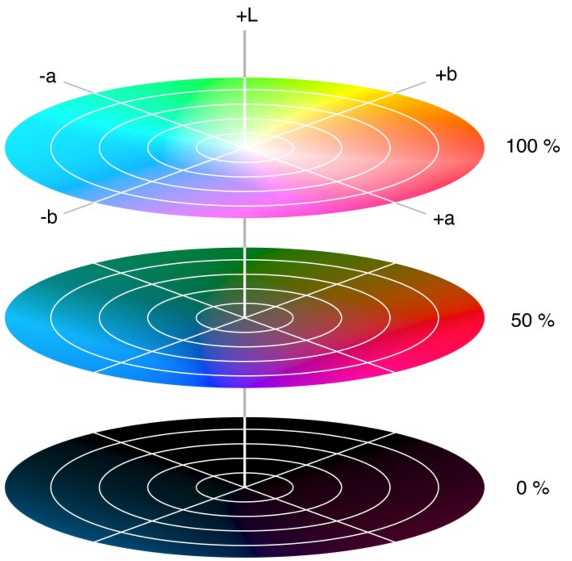
- Different projection of the same colors
- Mimics human color perception - similar colors are near in color space

$$L^\star = 116\, f\left(\frac{Y}{Y_\mathrm{n}}\right) - 16$$

$$a^\star = 500\left(f\left(\frac{X}{X_\mathrm{n}}\right) - f\left(\frac{Y}{Y_\mathrm{n}}\right)\right)$$

$$b^\star = 200\left(f\left(\frac{Y}{Y_\mathrm{n}}\right) - f\left(\frac{Z}{Z_\mathrm{n}}\right)\right)$$

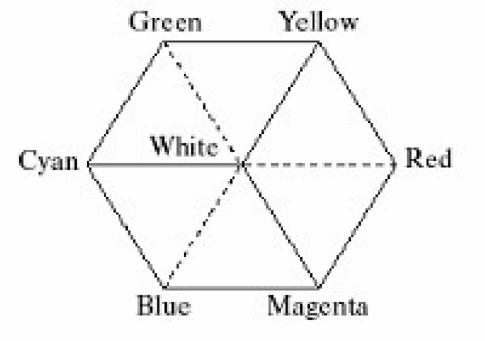
$$\Delta E = \sqrt{(L\ast)^2 + (a\ast)^2 + (b\ast)^2}$$

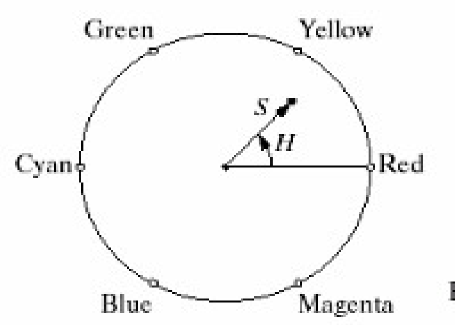


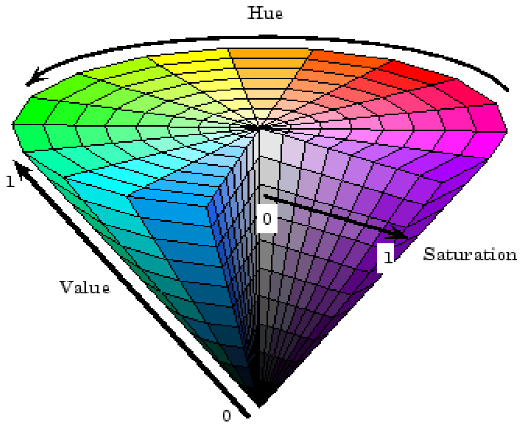
(X_n, Y_n, Z_n) value of white color according to CIE XYZ

The HSV color space

- Hue, Saturation, Value
- Psychological motivation
- Non-linear: hue is an angle







Color spaces usage

- Image presentation
  - RGB, CMYK
- Manipulation
  - RGB, HSV
- Video and image encoding
  - Analog devices in North America and Japan: YIQ
  - Analog devices in Europe: YUV
  - Digital television, JPEG: YCbCr