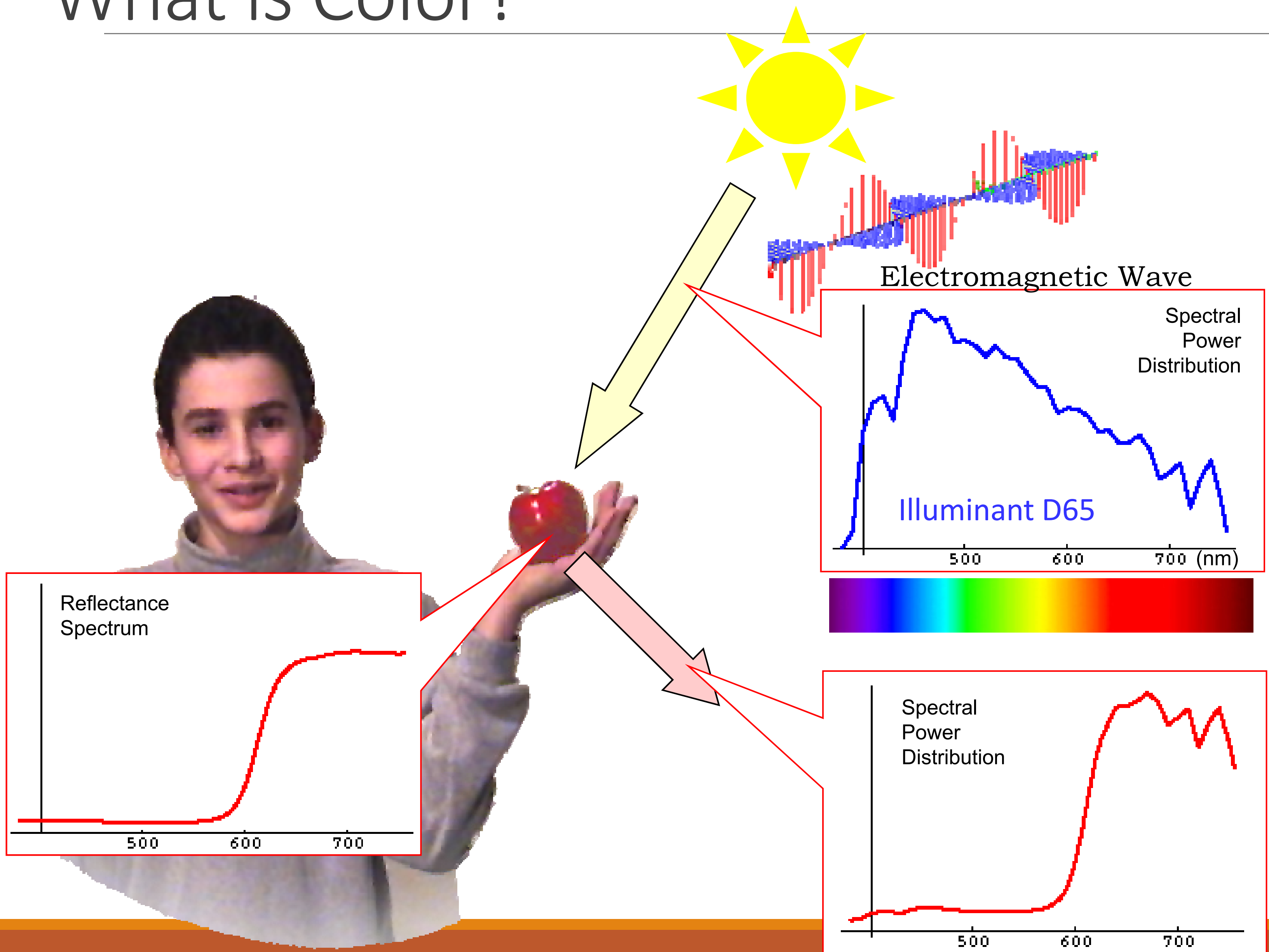
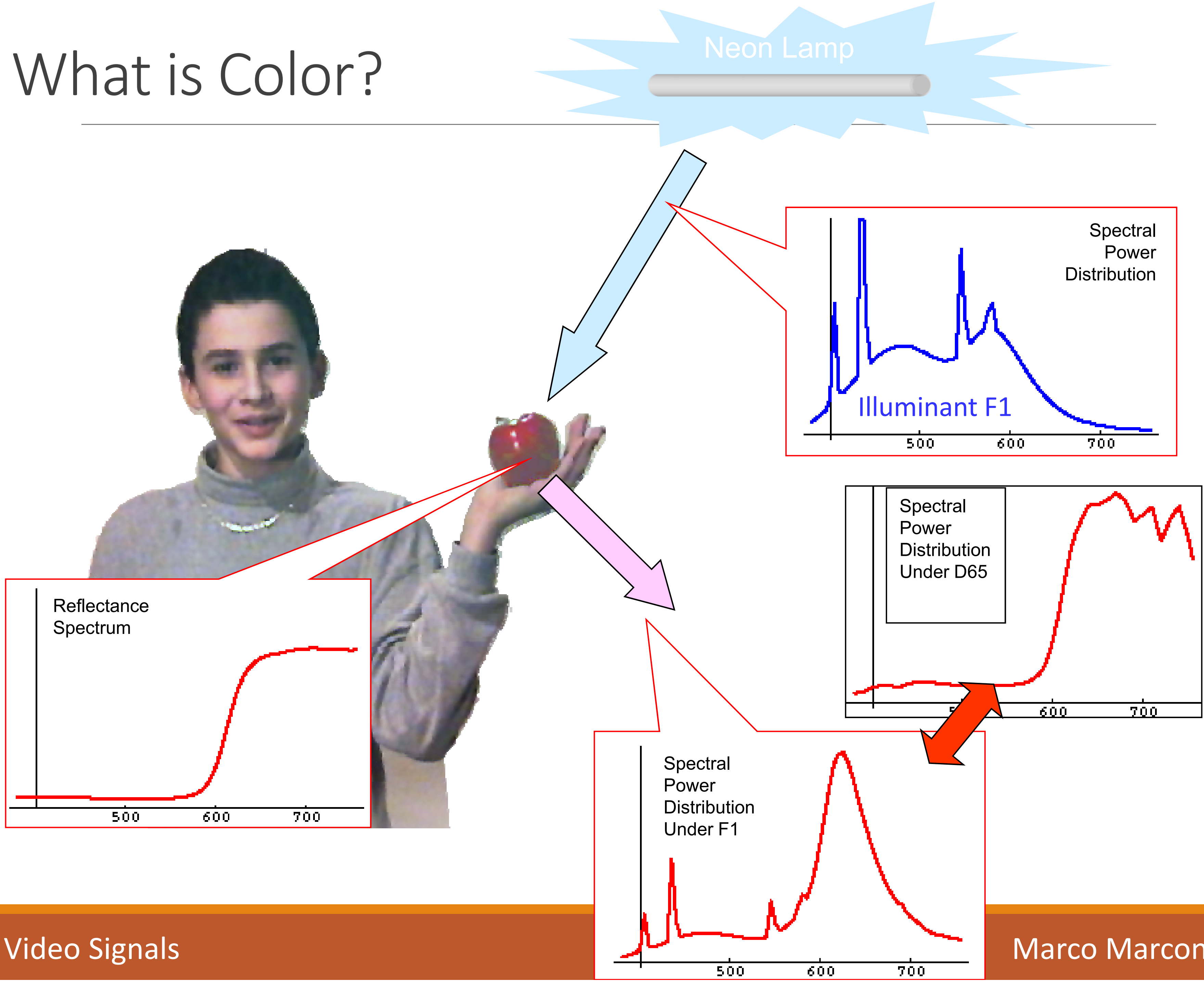
Video Signals

COLORIMETRY

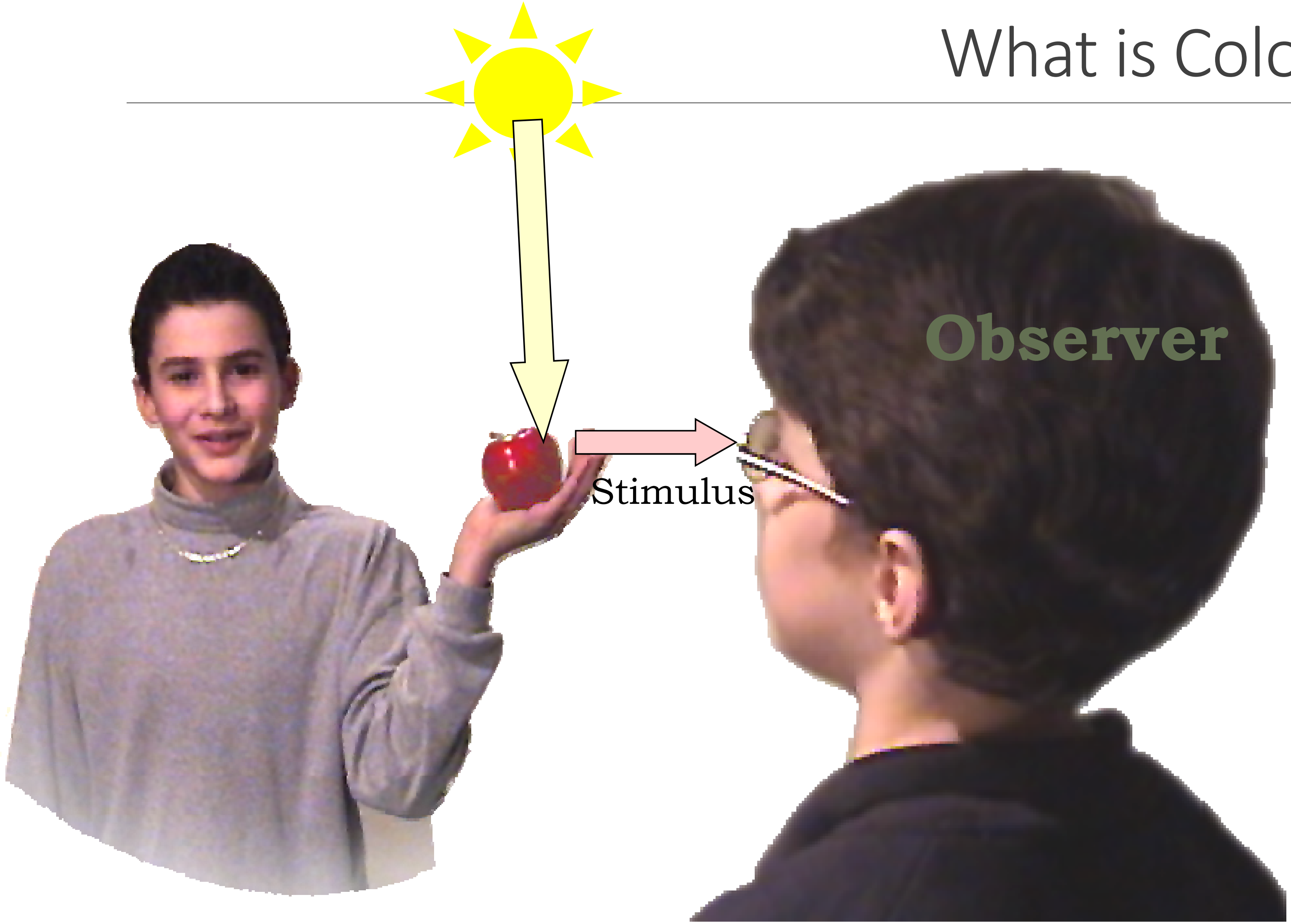
What is Color?



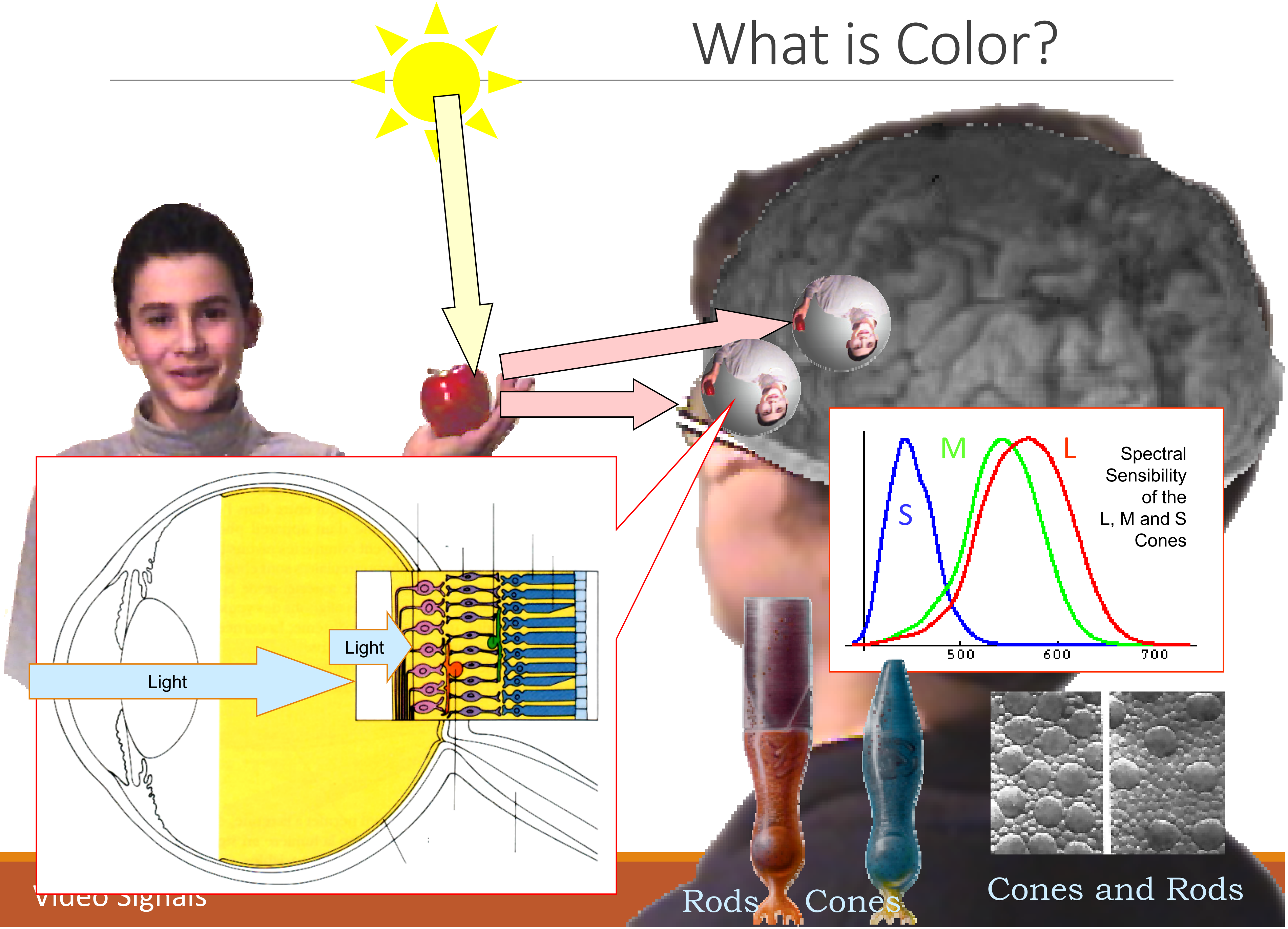
What is Color?



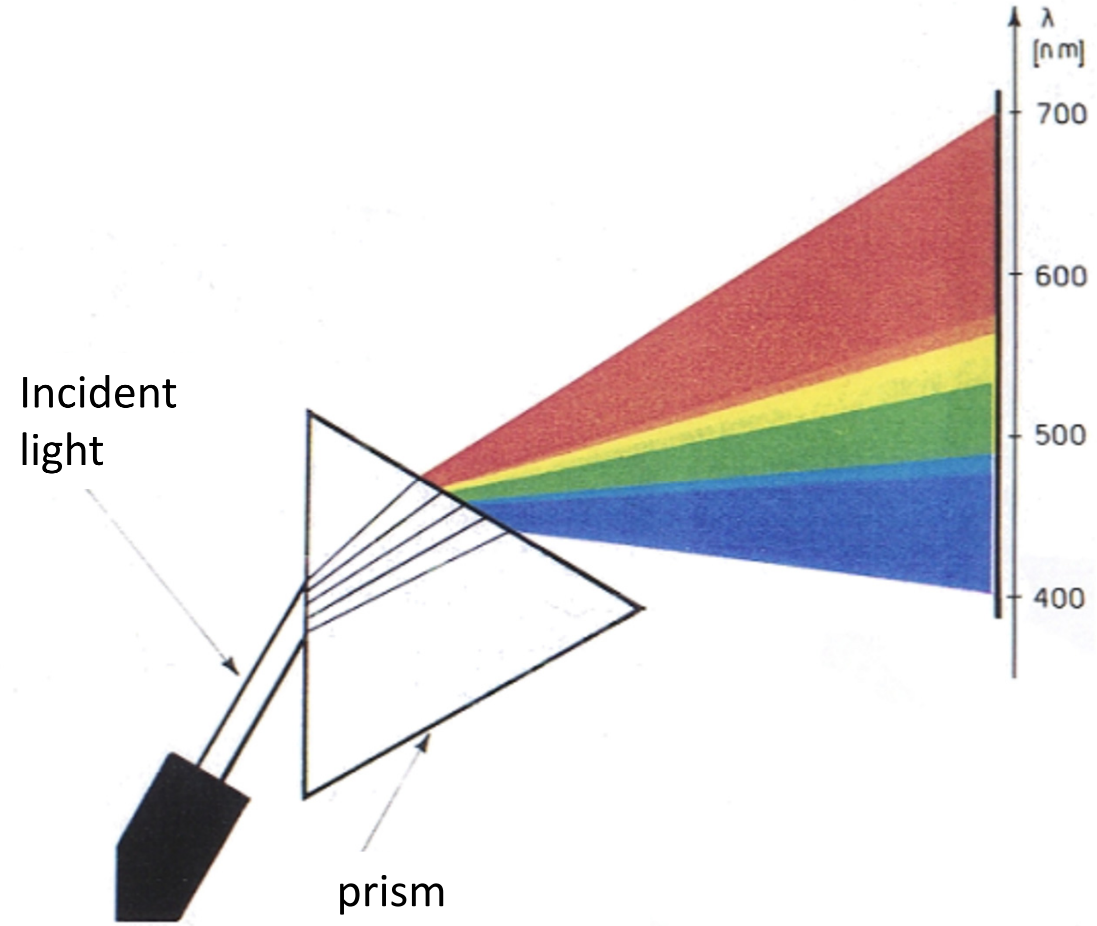
What is Color?



What is Color?

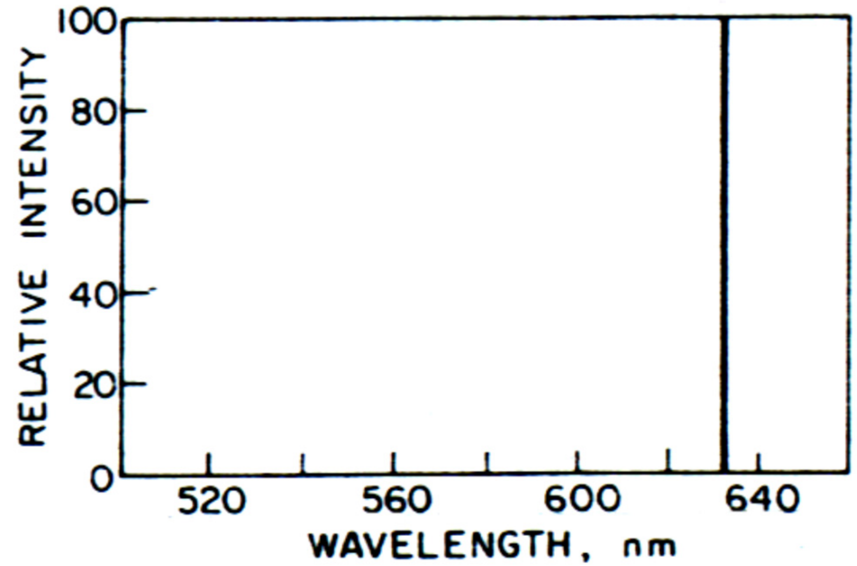


The Electromagnetic spectrum



Spectral examples

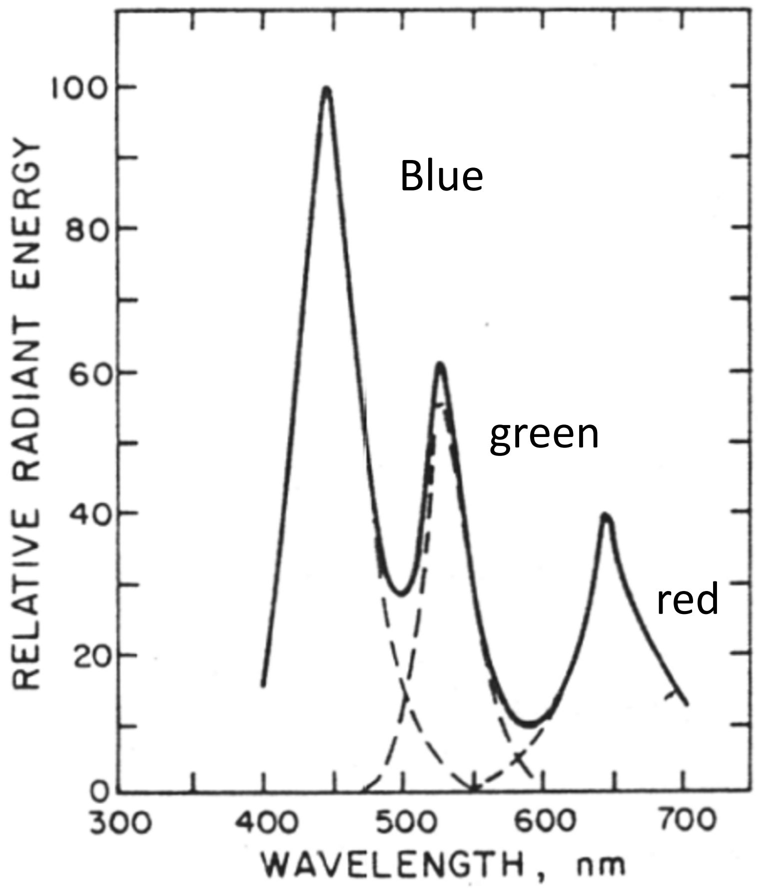
The light emitted from a Laser is strictly monochromatic and its spectrum is made from a single line where all the energy is concentrated.



Laser He - Ne

Spectral examples

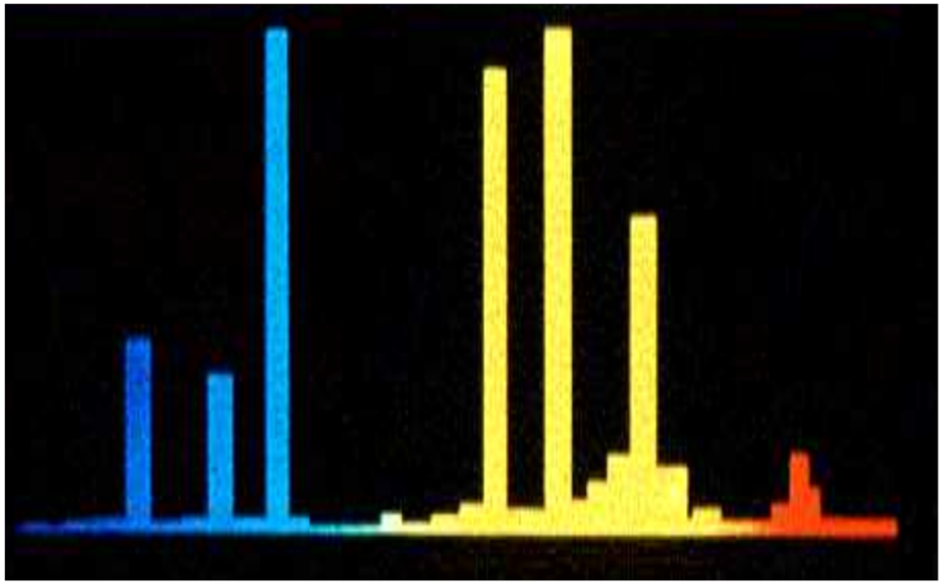
The light emitted from the 3 different phosphors of a traditional color Cathode Ray Tube (CRT)



P22 phosphor

Spectral examples

The light emitted from a gas vapour lamp is a set of diffent spectral lines. Their value is linked to the allowed energy steps performed by the excited gas electrons.

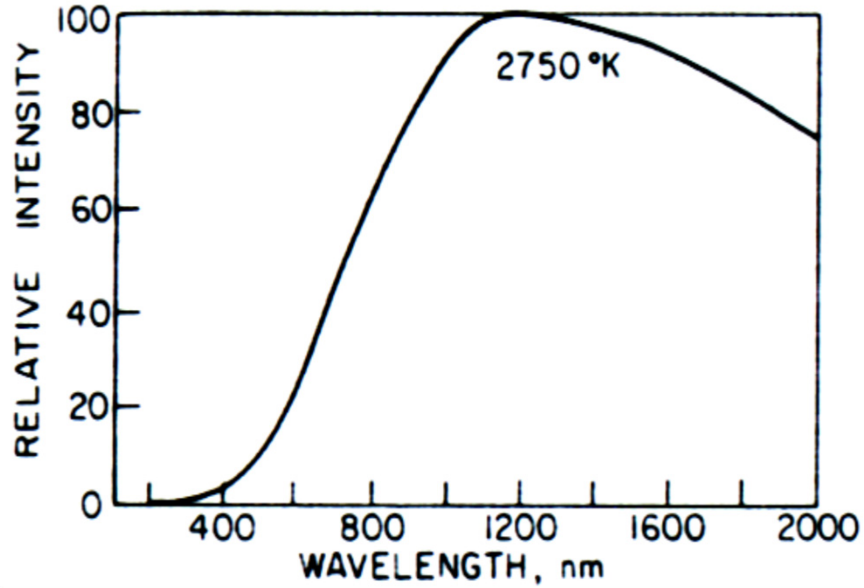


Spectral examples

Many objects, when heated, emit light with a spectral distribution close to the "Black body" radiation. It follows the Planck law and its shape depends only on the absolute object temperature.

Examples:
- the stars,
- the sun.
- incandendenscent

lamps



The “Black body” law

Planck's law states that:

$$I(\nu, T)d\nu = \left(\frac{2h\nu^3}{c^2}\right)\frac{1}{e^{\frac{h\nu}{kT}} - 1}d\nu$$

where:

I(*ν*,*T*) *dν* is the amount of energy per unit surface area per unit time per unit solid angle emitted in the frequency range between *ν* and *ν* + *dν* by a black body at temperature *T*;

h is the Planck constant;

c is the speed of light in a vacuum;

k is the Boltzmann constant;

ν is frequency of electromagnetic radiation;

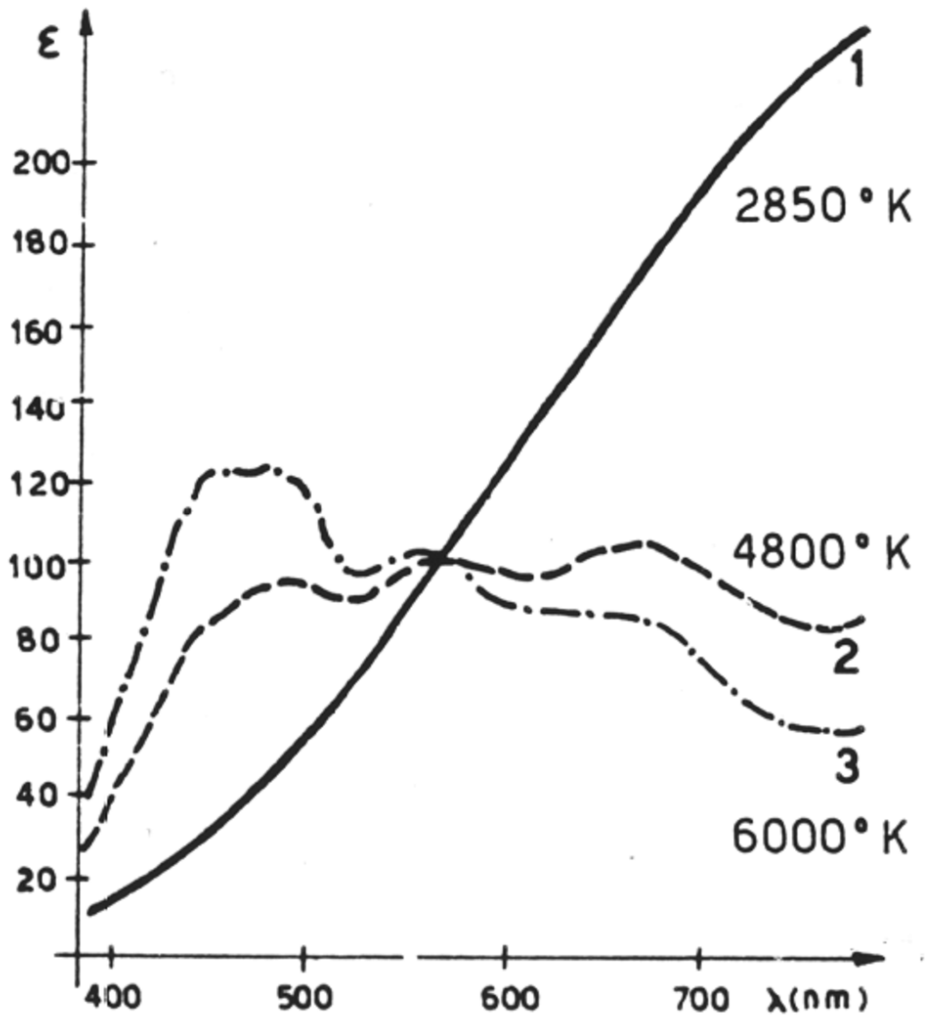
T is the temperature in Kelvin.

The "white" light

An ideal illuminant with flat spectrum is not realizable.

The sun can be assumed as a Planck source a 6000K

Incandescent lamps can be assumed as planck sources ranging from 2000K to 5000K



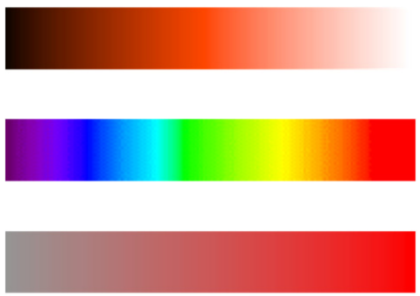
Possible color representations

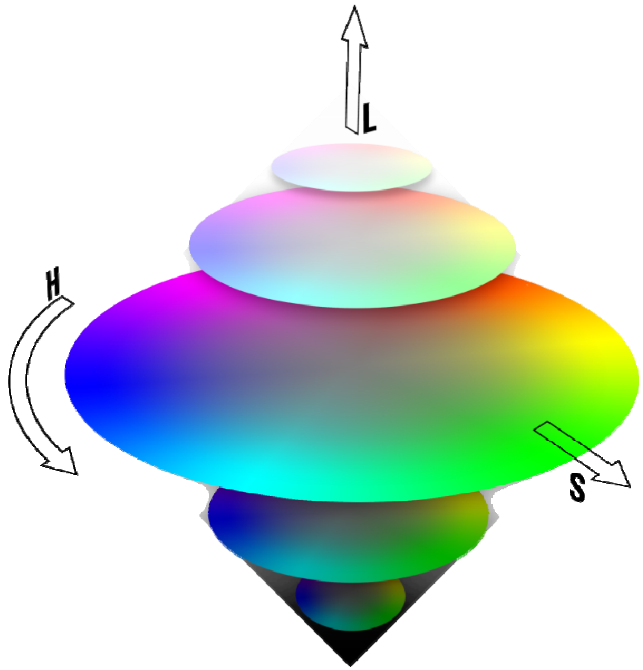
A detailed description of the power spectrum where providing power density at each frequency.

30 values to specify energy in every sub-band (of 10 nm) in the visible range (from 400 to 700 nm)

Following the trichromatic description

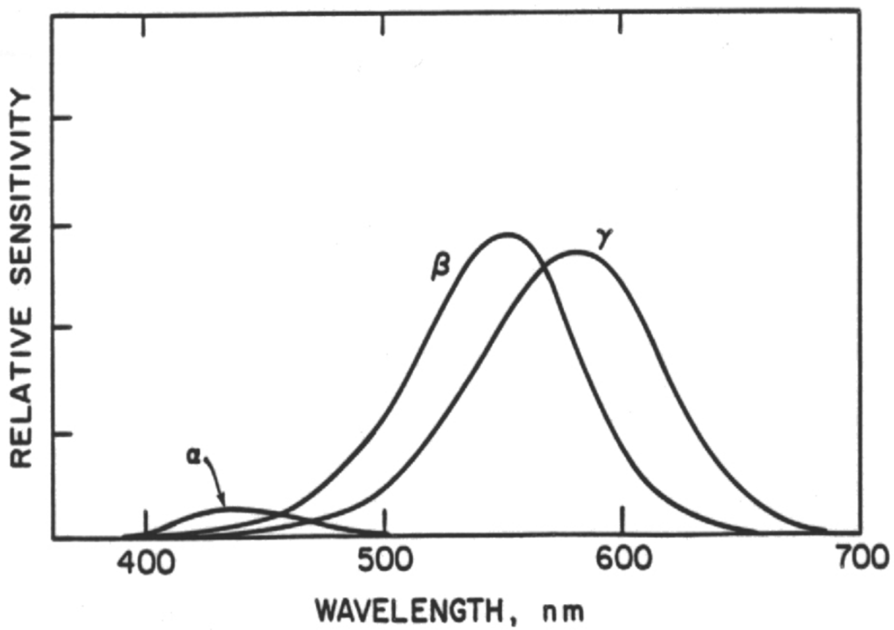
- Lightness
- Hue
- Saturation

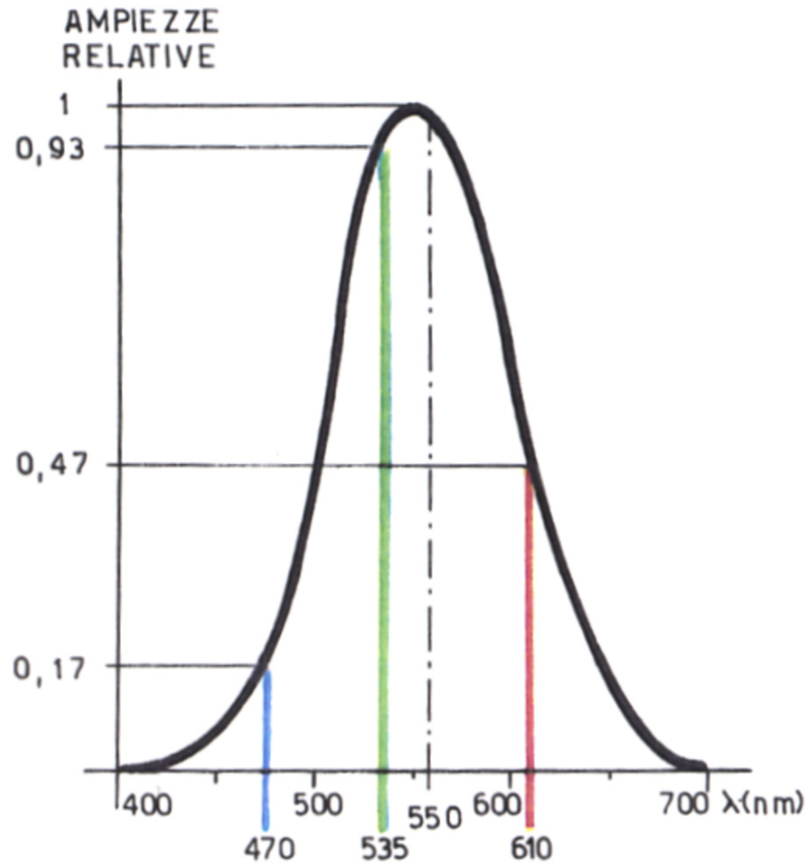




The human eye sensibility

Concerning the daylight visual system, the la retina can be assumed as composed of 3 different cones(α, β, γ), with different, but partially overlapped, spectral sensitivity.

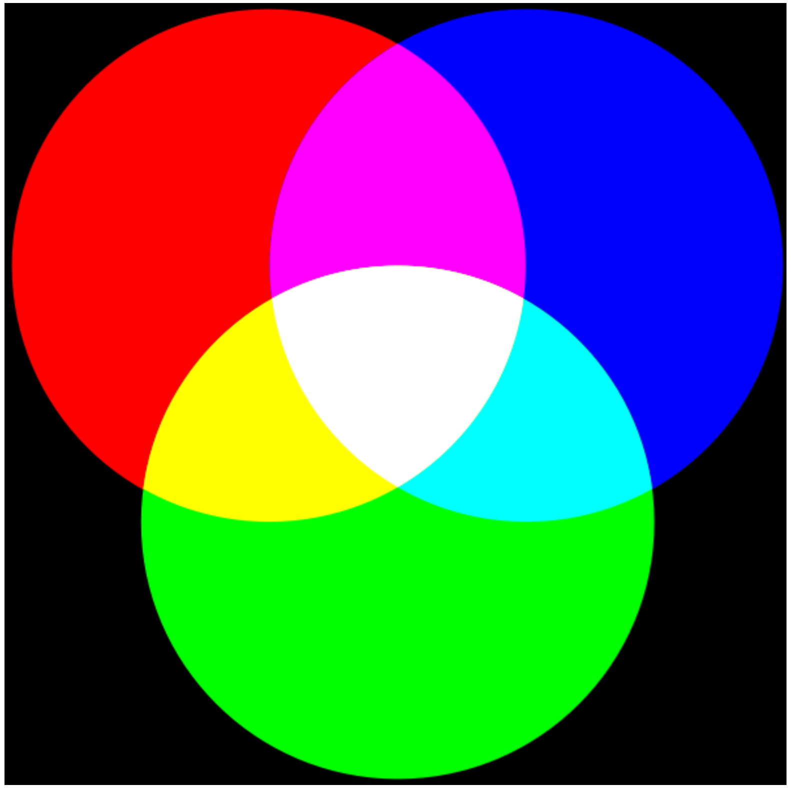




Additive synthesis

A certain color can be though as a weighted sum of 3 primary colors
Red ->**R**;
Green ->**G**;
Blu ->**B**

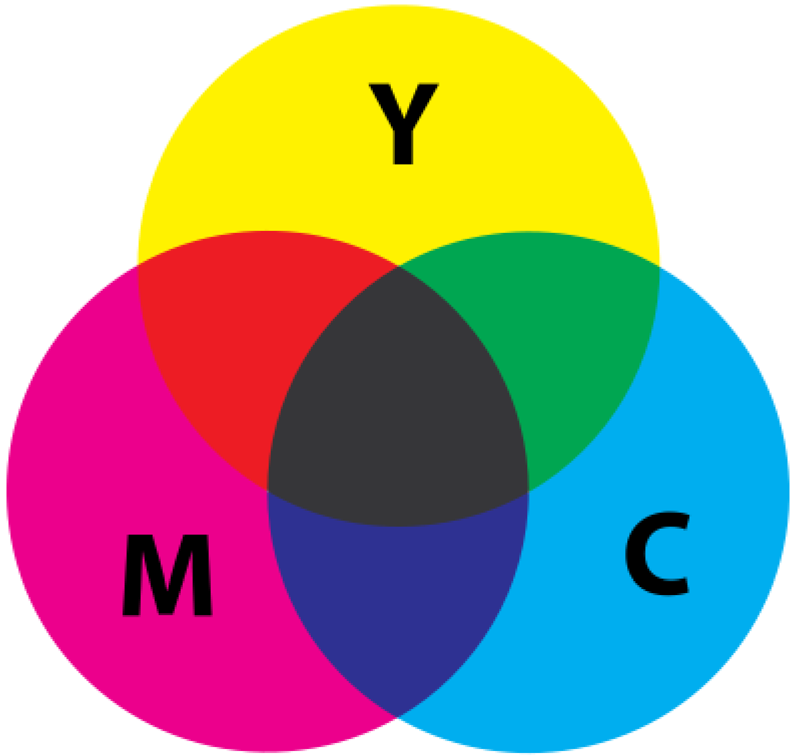
A "normalized" white can be described as:
White=1·R+1·G+1·B



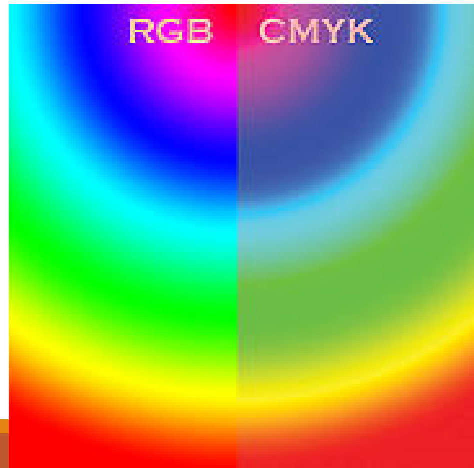
Subtractive synthesis

In order to obtain a specific color three filters with different weights are applied to white light. They will absorb different spectral parts of the white color.

Cyan -> **C**;
Yellow -> **Y**;
Magenta -> **M**;



Comparison between CMY, CMYK, RGB



Additive synthesis: linearity

$$A_1 = d_1\mathbf{R} + e_1\mathbf{G} + f_1\mathbf{B}$$

$$A_2 = d_2\mathbf{R} + e_2\mathbf{G} + f_2\mathbf{B}$$

$$A_1 + A_2 = [d_1 + d_2]\mathbf{R} + [e_1 + e_2]\mathbf{G} + [f_1 + f_2]\mathbf{B}$$

We can define $P_j(\lambda)$ ($j=1,2,3$) the spectra of the primary sources. In case of primary sources we will have $P_j(\lambda)=\delta(\lambda-\psi_j)$; we also assume unitary power for each primary source.

$$\int P_j(\lambda)\, d\lambda = 1$$

Additive synthesis

A color can be defined as:

$$C(\lambda) = \sum_{j=1}^{3} A_j(C) P_j(\lambda)$$

If we define V(λ) as the sensibility of the human eye, the perceived **luminance** for a color is:

$$Y(C) = \int C(\lambda) V(\lambda)\, d\lambda$$

The luminance can also be described in terms of primary sources:

$$Y(C) = \sum_{j=1}^{3} A_j(C) \int P_j(\lambda) V(\lambda)\, d\lambda$$

The *color Matching* experiment

In order to define the coefficient of the 3 primary sources for a specific color C (for a set of people)

The first step consists in primary sources calibration in

$$White = \sum_{j=1}^{3} A_j(W)P_j(\lambda)$$

order to obtain the reference white color.
The $A_j(W)$ coefficients indicate the weights for each primary source in order to obtain the *reference white* [which is different from the *absolute white* for that set of sources obtained when all the $A_j(W)$ coefficients are 1]

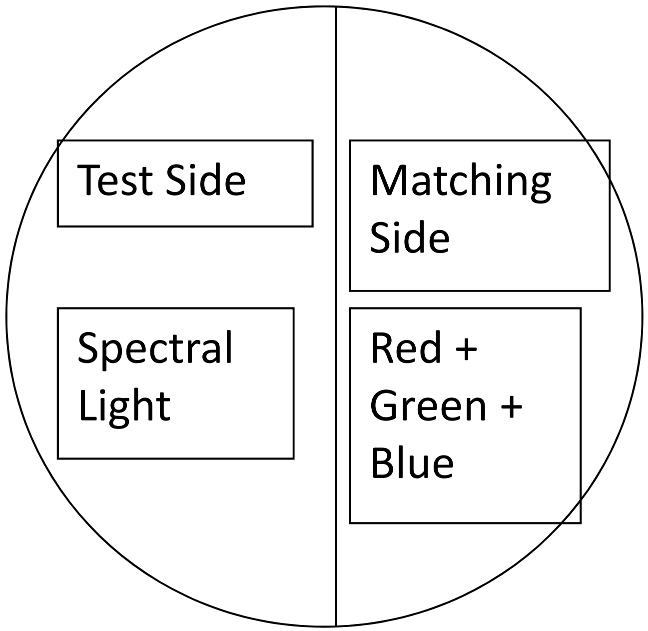
The CIE Standard Observers

CIE: International Commission on Illumination:
Established in 1931 and based in Vienna, Austria, the **International Commission on Illumination** (usually known as the **CIE** for its French name ***Commission internationale de l'éclairage***, but the English abbreviation is sometimes seen in older papers) is the international authority on light, illumination, color, and color spaces.

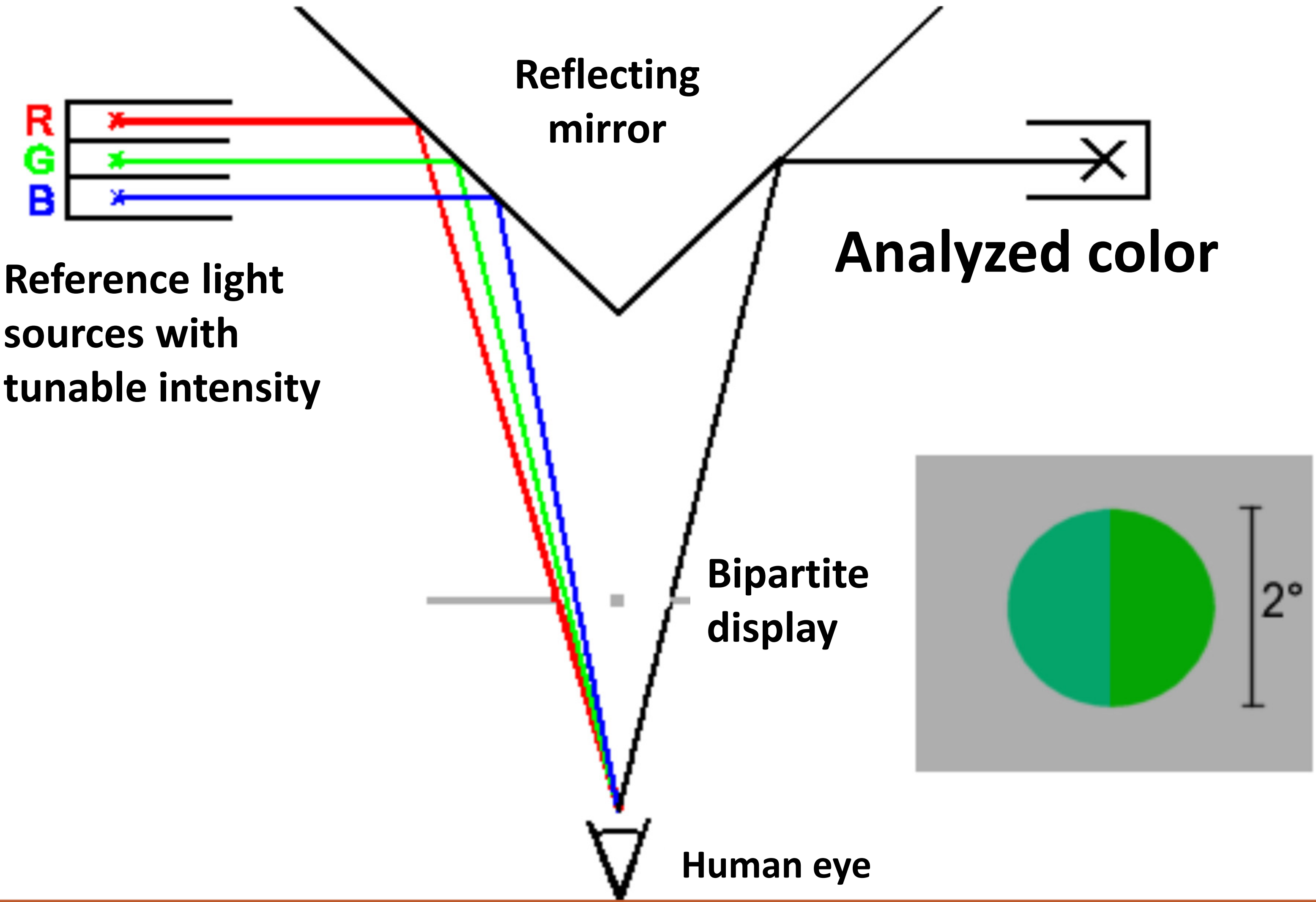
In the CIE experiment one half of a circular field is illuminated with spectrum color and the other with a mixture of red, green and blue

The observer adjusts the red, green and blue until it matches the spectrum color

The result is a set of color matching functions used to calculate the tristimulus values



The CIE standard device



Tristimulus components

The tristimulus values of a color are the amounts of three primary colors in a three-component additive color model needed to match that test color.

$$T_j(C) = \frac{A_j(C)}{A_j(W)} \quad j = 1,2,3$$

When the generated color meets the analyzed color, we can store the 3 values $A_j(C)$ that are the tristimulus values.

$$Y(C) = \int C(\lambda) V(\lambda)\, d\lambda = \sum_{y=1}^{3} T_j(C)\, A_j(W) \int P_j(\lambda) V(\lambda) d\lambda$$

Tristimulus components

Aj(C) can be calculated from Tj(C) since:

$$e_1(C) = \int C(\lambda) s_1(\lambda) d\lambda = \int \sum_{y=1}^{3} T_j(C) A_j(W) P_j(\lambda) s_1(\lambda) d\lambda$$

$$e_2(C) = \int C(\lambda) s_2(\lambda) d\lambda = \int \sum_{y=1}^{3} T_j(C) A_j(W) P_j(\lambda) s_2(\lambda) d\lambda$$

$$e_3(C) = \int C(\lambda) s_3(\lambda) d\lambda = \int \sum_{y=1}^{3} T_j(C) A_j(W) P_j(\lambda) s_3(\lambda) d\lambda$$

where e_j(C) are the relative excitations for the observed color while $s_j(\lambda)$ is the i-th cone sensitivity.

Tristimulus components

Then we can write:

$$e_1(C) = \int C(\lambda) s_1(\lambda) d\lambda = \sum_{y=1}^{3} T_j(C) A_j(W) \int P_j(\lambda) s_1(\lambda) d\lambda$$

$$e_2(C) = \int C(\lambda) s_2(\lambda) d\lambda = \sum_{y=1}^{3} T_j(C) A_j(W) \int P_j(\lambda) s_2(\lambda) d\lambda$$

$$e_3(C) = \int C(\lambda) s_3(\lambda) d\lambda = \sum_{y=1}^{3} T_j(C) A_j(W) \int P_j(\lambda) s_3(\lambda) d\lambda$$

Tristimulus components

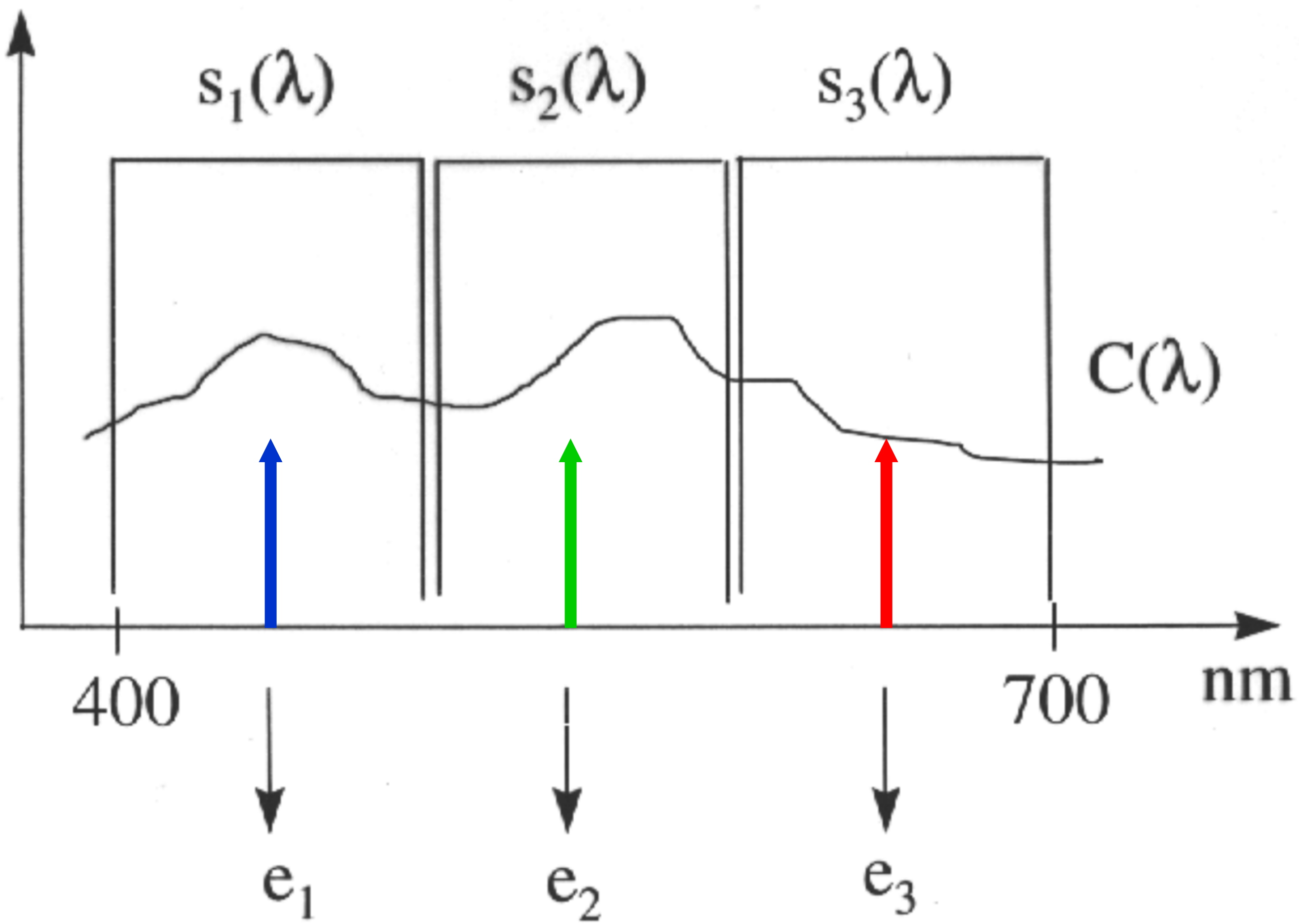
If the primary sources are monochromatic with unitary power ($P_j(\lambda)=\delta(\lambda-\psi_j)$) we can write:

$$e_1(C) = \int C(\lambda)s_1(\lambda)d\lambda = \sum_{y=1}^{3} T_j(C)\, A_j(W)\, s_1(\psi_i)$$

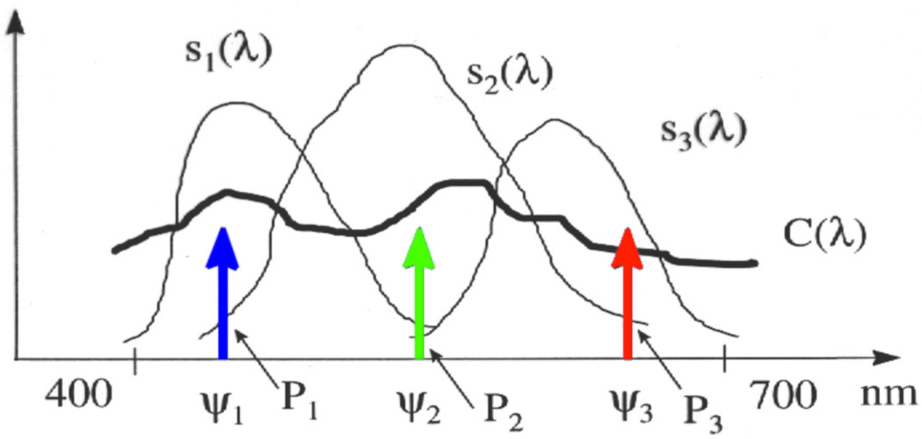
$$e_2(C) = \int C(\lambda)s_2(\lambda)d\lambda = \sum_{y=1}^{3} T_j(C)\, A_j(W)\, s_2(\psi_i)$$

$$e_3(C) = \int C(\lambda)s_3(\lambda)d\lambda = \sum_{y=1}^{3} T_j(C)\, A_j(W)\, s_3(\psi_i)$$

Tristimulus components



Tristimulus components

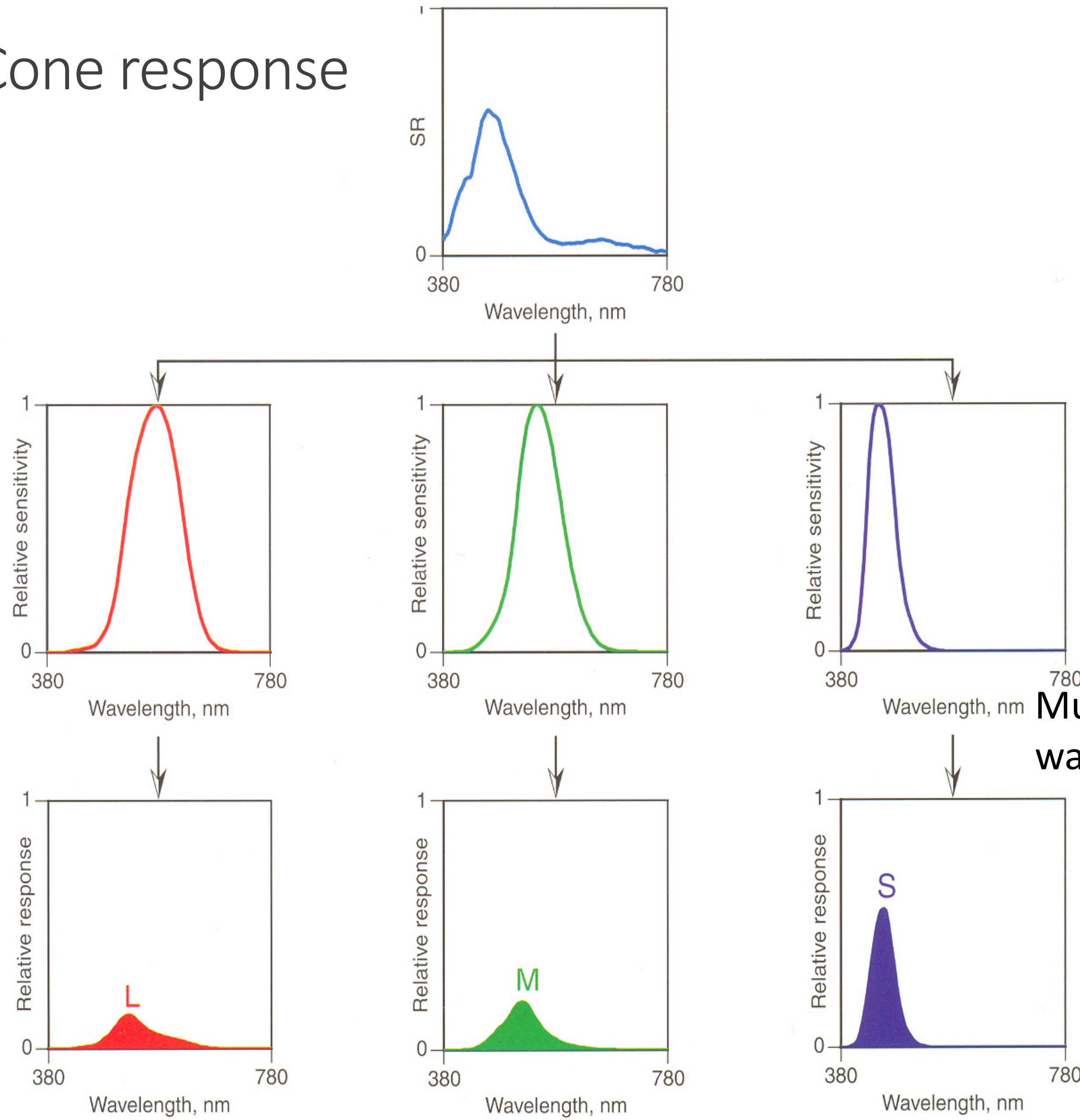


$$e_1(C) = \int C(\lambda)s_1(\lambda)d\lambda = \sum_{j=1}^{3} A_j(C)s_1(\psi_j)$$

$$e_2(C) = \int C(\lambda)s_2(\lambda)d\lambda = \sum_{j=1}^{3} A_j(C)s_2(\psi_j) \qquad A_1, A_2, A_3 \geq 0$$

$$e_3(C) = \int C(\lambda)s_3(\lambda)d\lambda = \sum_{j=1}^{3} A_j(C)s_3(\psi_j)$$

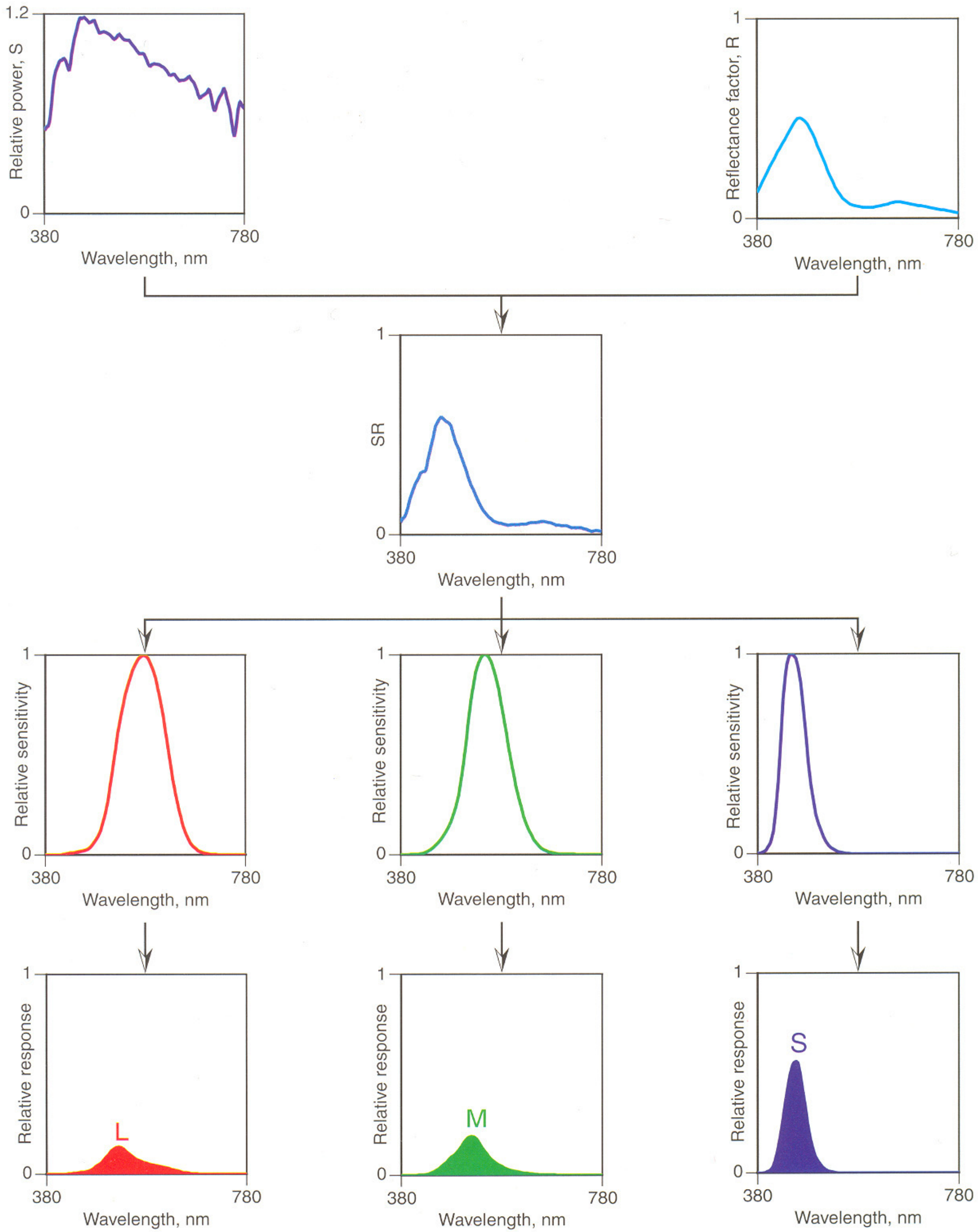
Cone response



Cone responses

Multiply wavelength by wavelength

Integrate



Stimulus

Cone responses

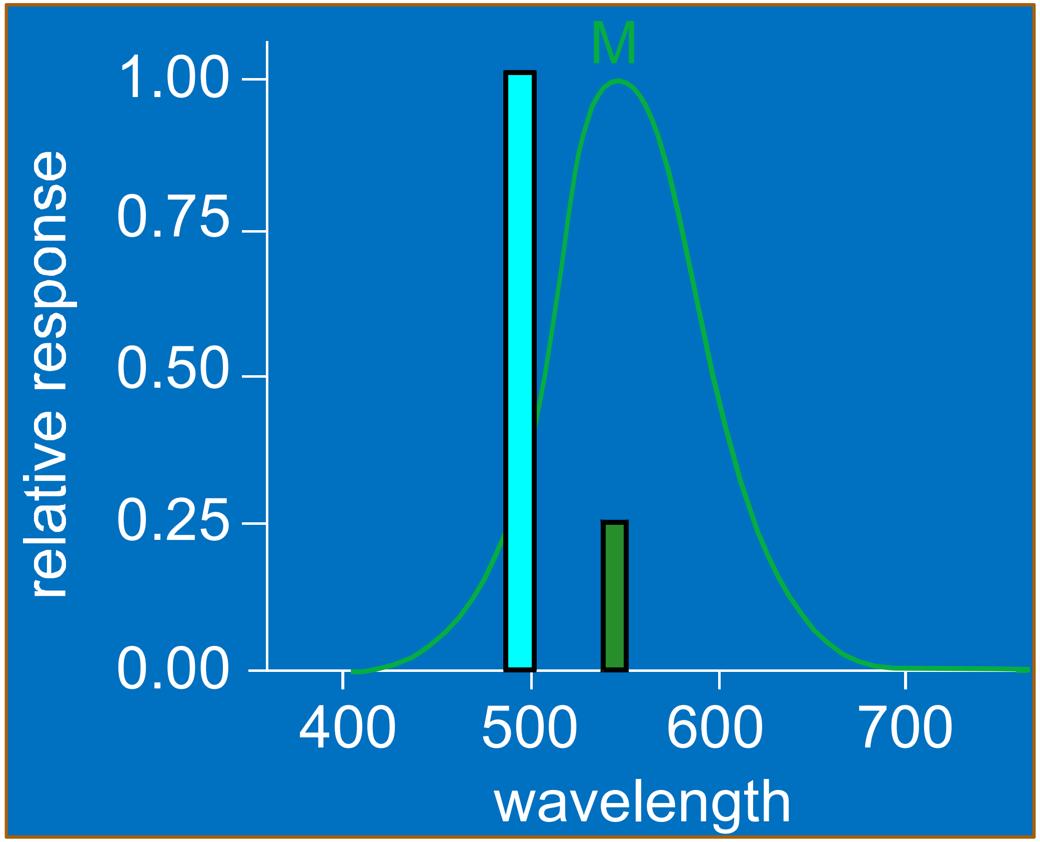
Multiply wavelength by wavelength

Integrate

Cones do not “see” colors

Different wavelength, different intensity

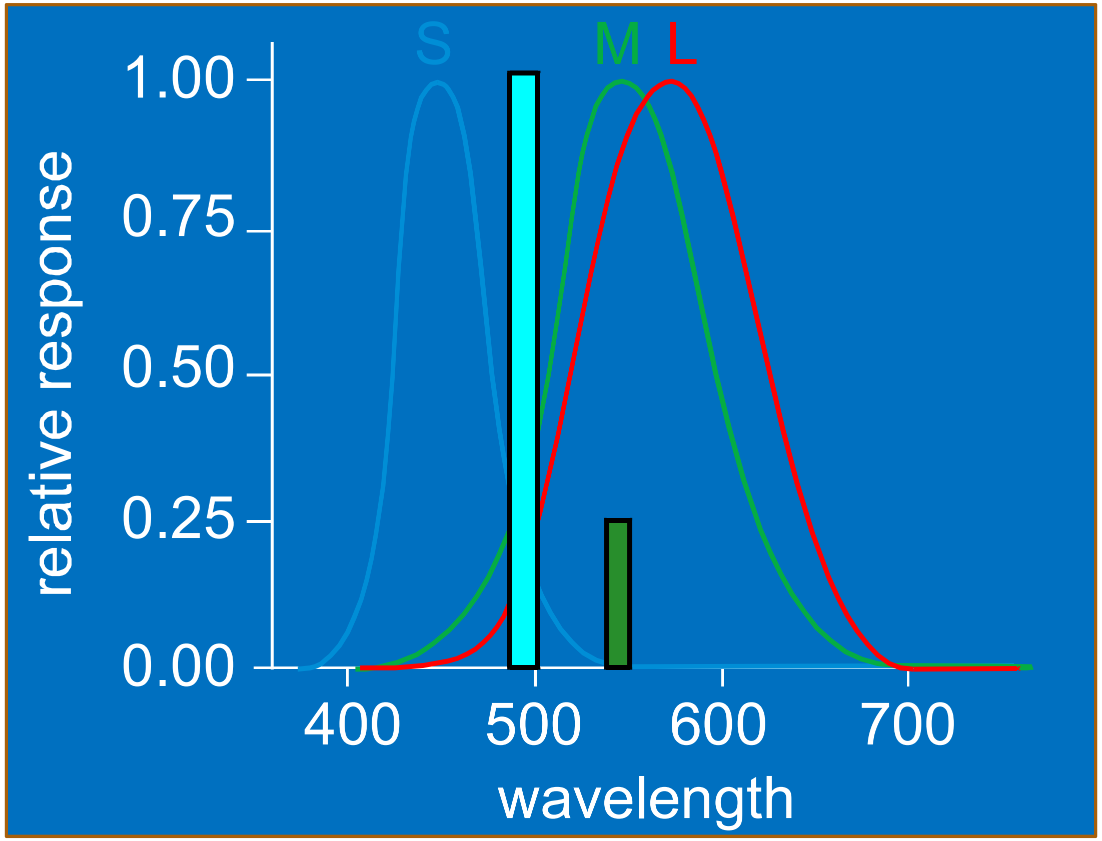
Same response



Response comparison

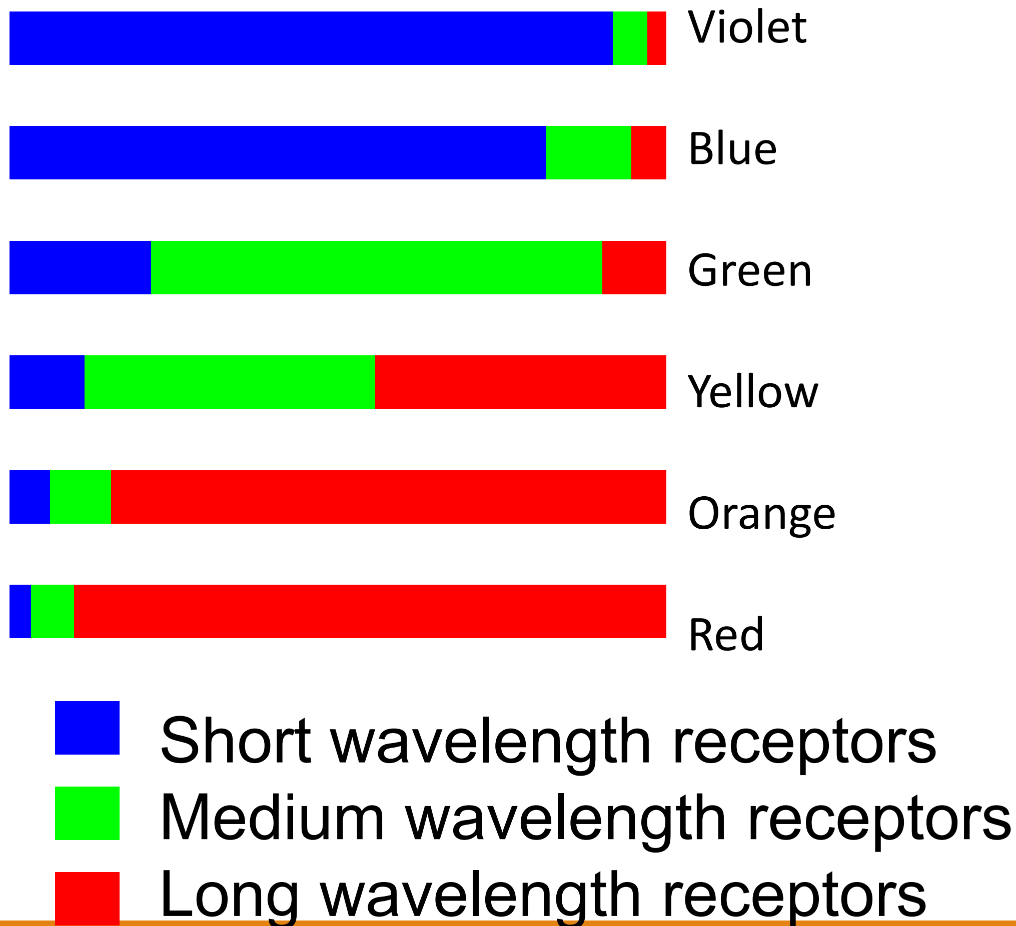
Different wavelength, different intensity

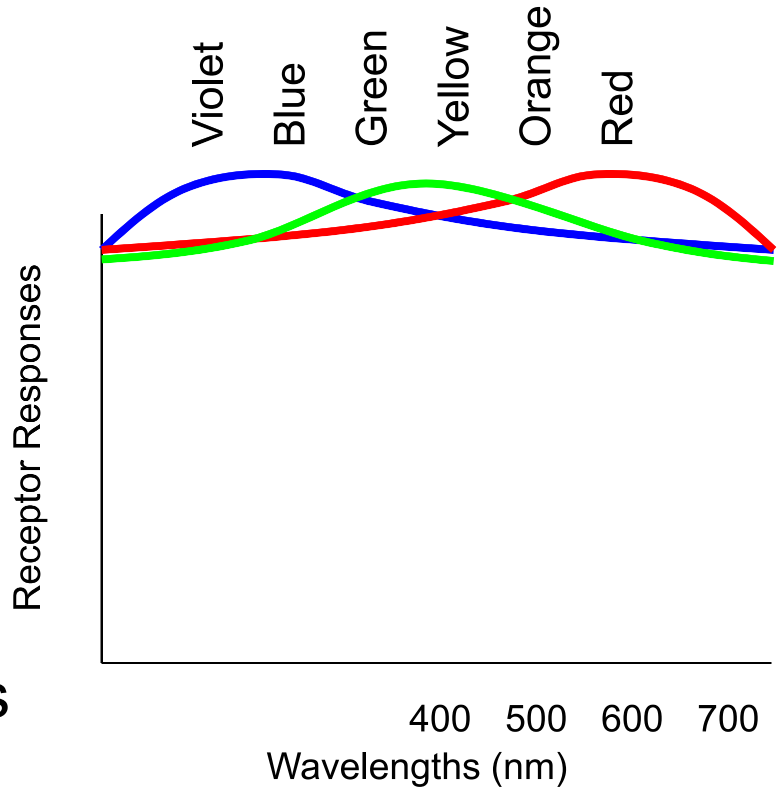
But different response for different cones



von Helmholtz 1859: Trichromatic theory

Colors as relative responses (ratios)





Tristimulus components

For some colors it is impossilbe to find A_1, A_2, A_3 all positives, i.e. it is impossible to obtain the match as the sum: $A_1(C)\mathbf{R}+A_2(C)\mathbf{G}+A_3(C)\mathbf{B}$.

The "trick" is to add to the analyzed color one or more primary colors:

this is equivalent to say that primary components can have negative values:

$$C+A_1(C)\mathbf{R}= \qquad A_2(C)\mathbf{G}+A_3(C)\mathbf{B}$$

$$C=-A_1(C)\mathbf{R}+A_2(C)\mathbf{G}+A_3(C)\mathbf{B}$$

Mixing curves

Mixing curves$T_{s1}(\lambda)$, $T_{s2}(\lambda)$, $T_{s3}(\lambda)$ represents, within a resolution of ~1 nm the tristimulus values for a unitary energy

$$C_\psi = \delta(\lambda - \psi)$$

$$e_i(C_\psi) = \int \delta(\lambda - \psi) s_i(\lambda) d\lambda =$$

$$= \sum_{j=1}^{3} A_j(W) T_{sj}(\psi) \int P_j(\lambda) s_i(\lambda) d\lambda$$

For a color with specttrum $C(\lambda)$ the tristimulus components can be obtained as:

$$T_j(C) = \int C(\psi) T_{sj}(\psi) d\psi \qquad \mathrm{j} = 1,2,3$$

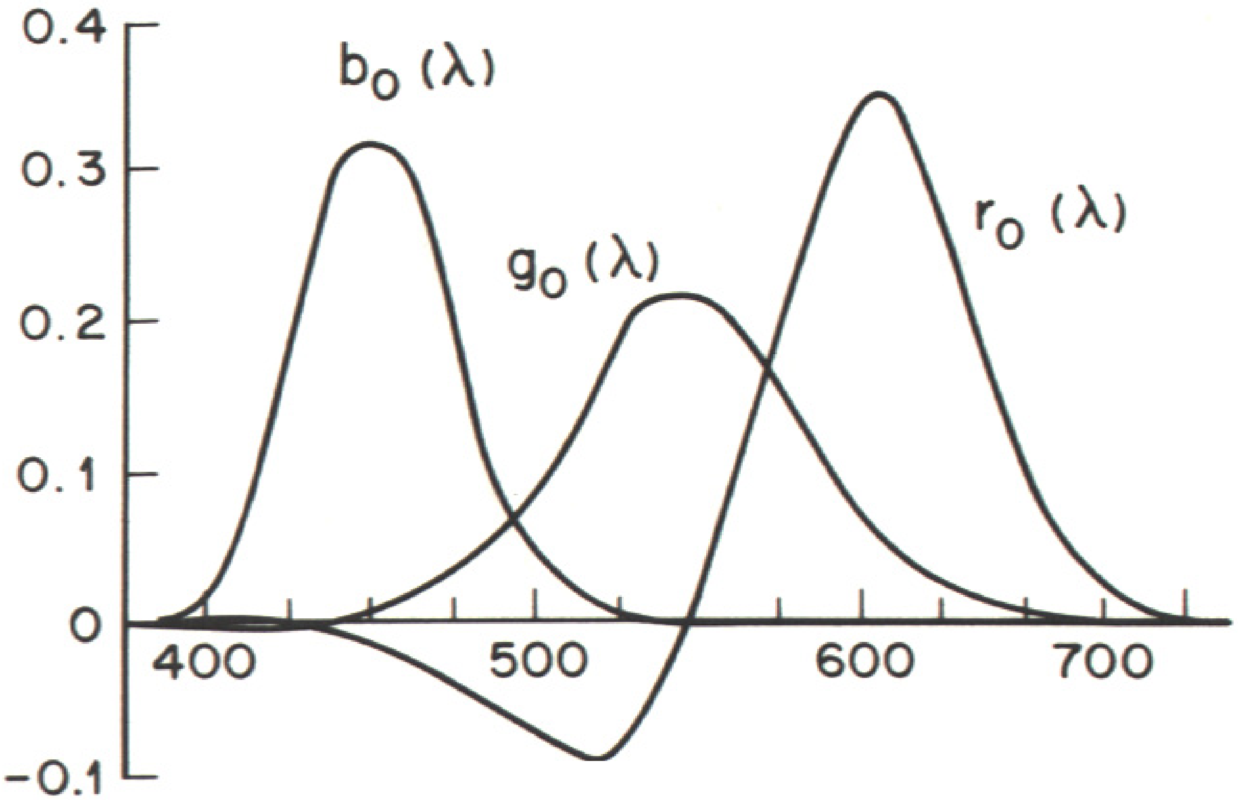
Color Matching functions R_0 G_0 B_0

Primary sources

R_0=700 nm

G_0=546 nm

B_0=436 nm



Color space

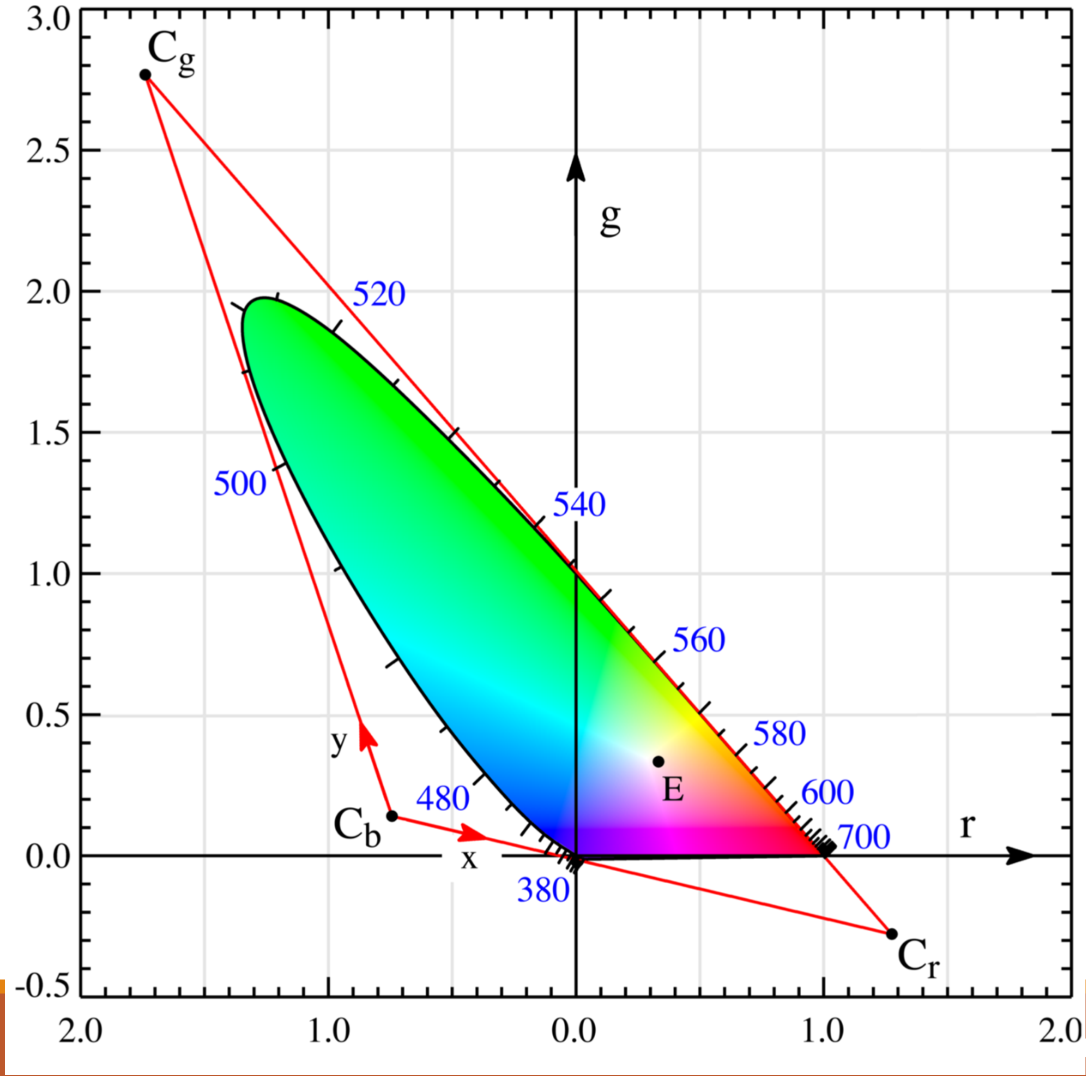
Colors can be represented in a 3D space but it is simpler to work with only two coordinates (assuming Y constant)

C=d**R**+e**G**+f**B**, if d+e+f=T
r=d/T; **g**=e/T; **b**=f/T
Since **r**+**g**+**b**=1, we can work with two coordinates (*chromatic coordinates*), the luminance is assumed constant(Y)

We then get chormaticity diagrams with only **hue** and **saturation**.

Chromaticity diagram r_0 g_0

Points locus for visible light.

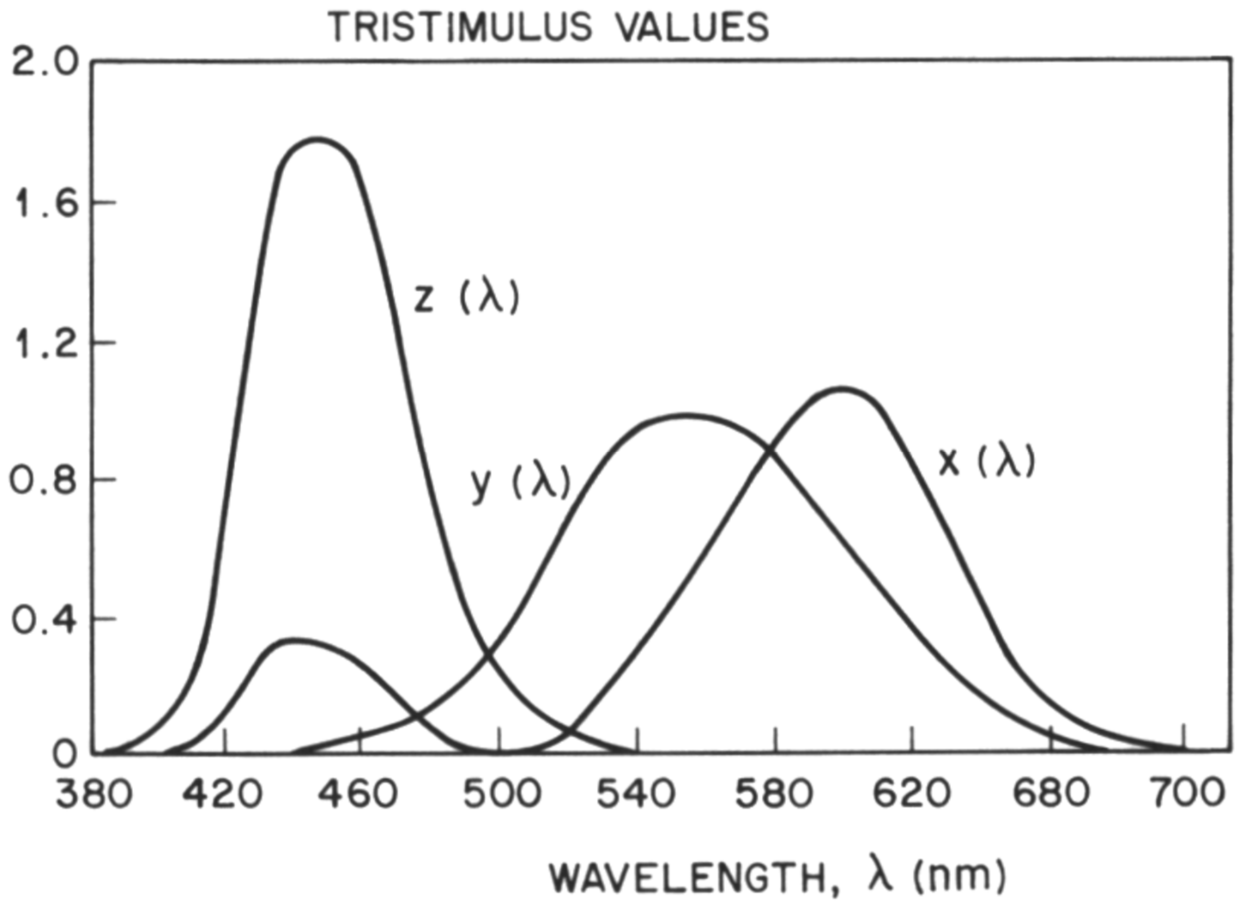


New chromatic space

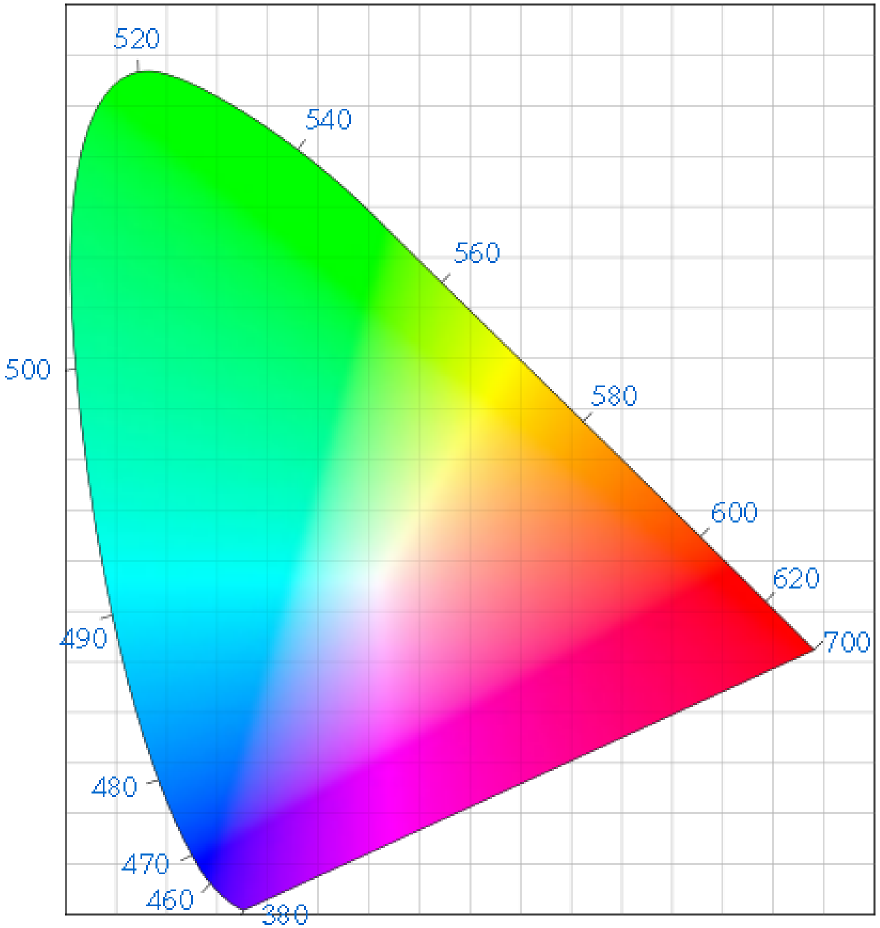
With a proper primary choice it is possible to obtain positive chomaticity space (for each λ).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{b_{21}} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Chromatic space X Y Z



Chromatic coordinates x y

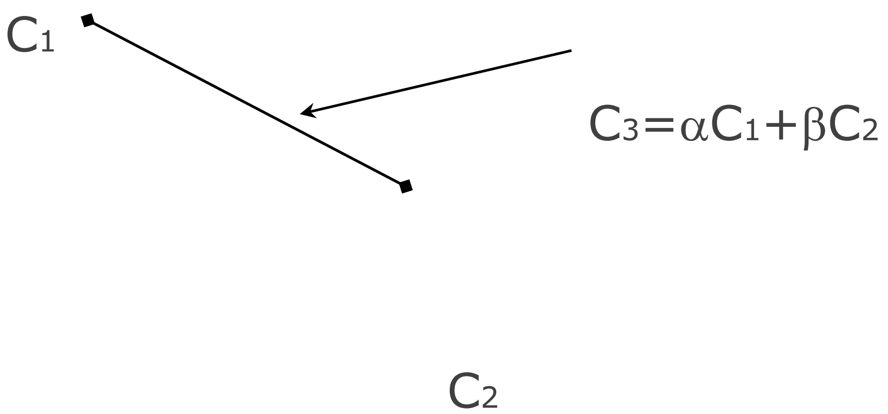


C=aX+bY+cZ,
Where a+b+c=T

x=a/T; **y**=b/T; **z**=c/T

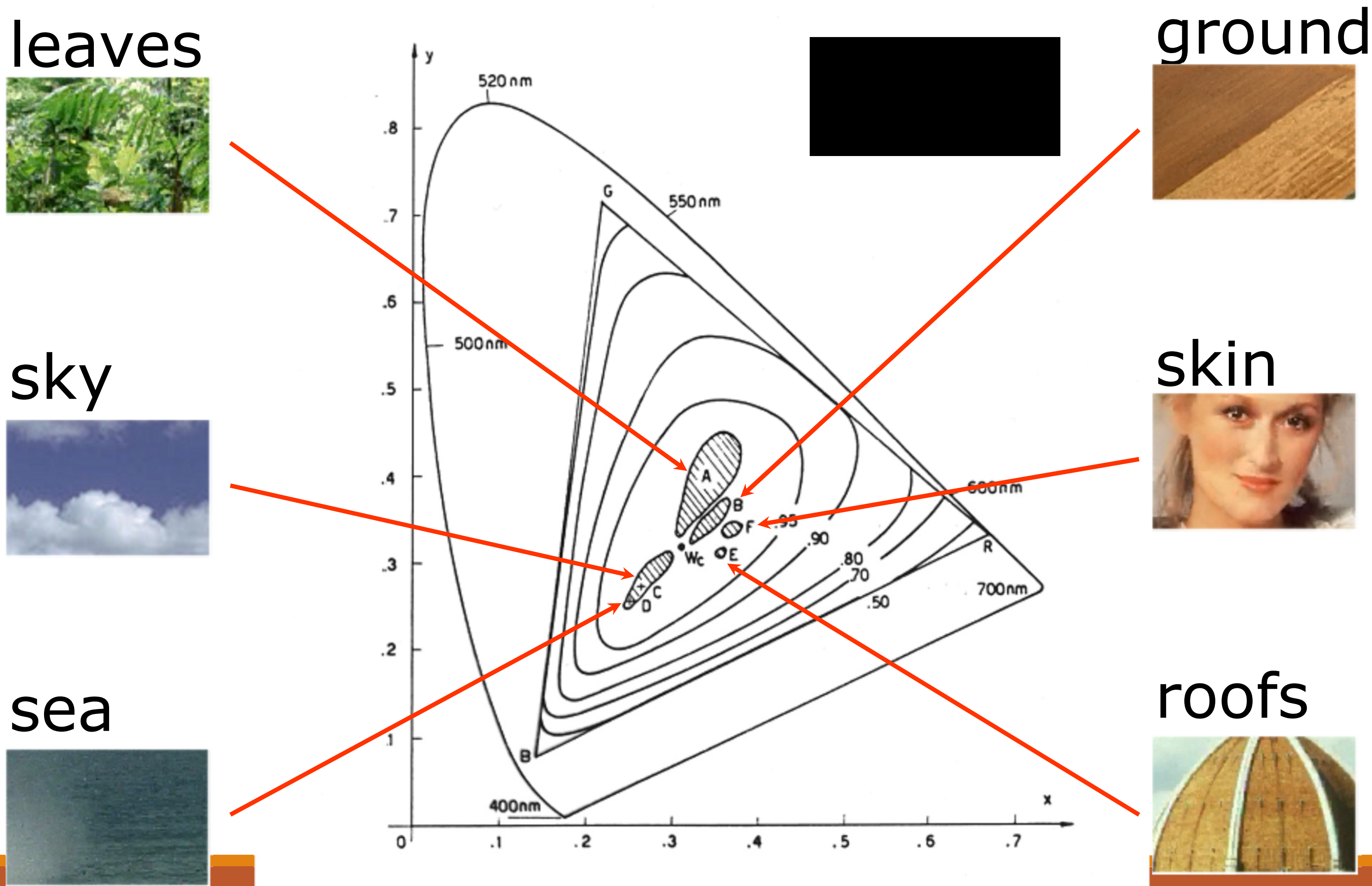
Summing colors

In the chromaticity diagram the linear combination of two colors (with positive coefficients) represents the segment joining those two colors

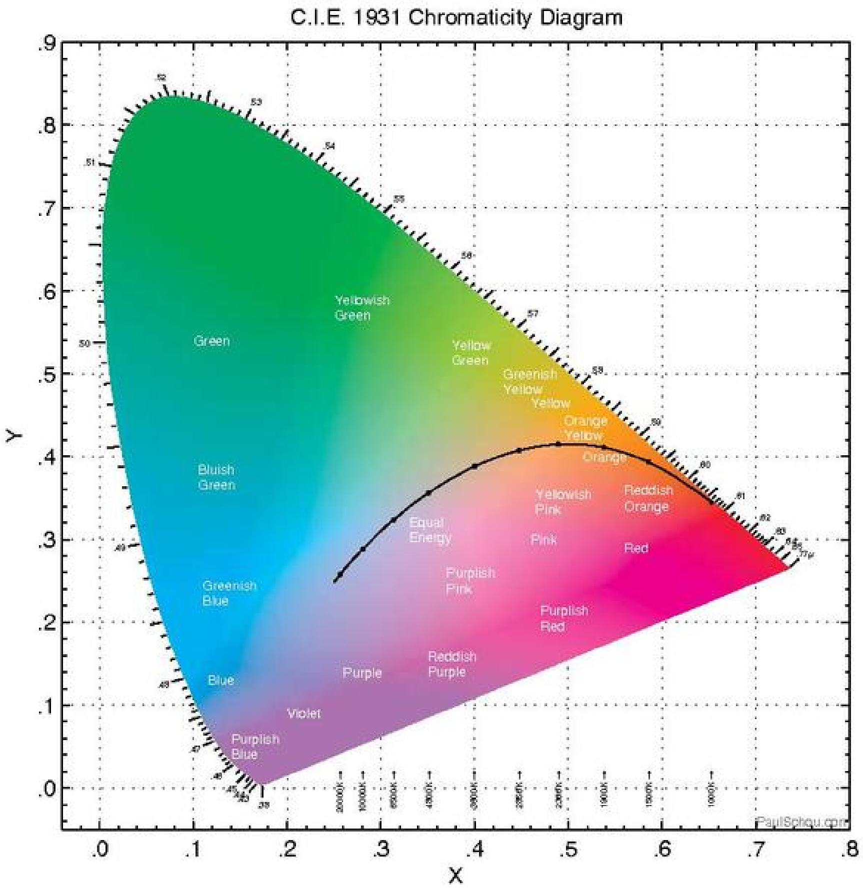


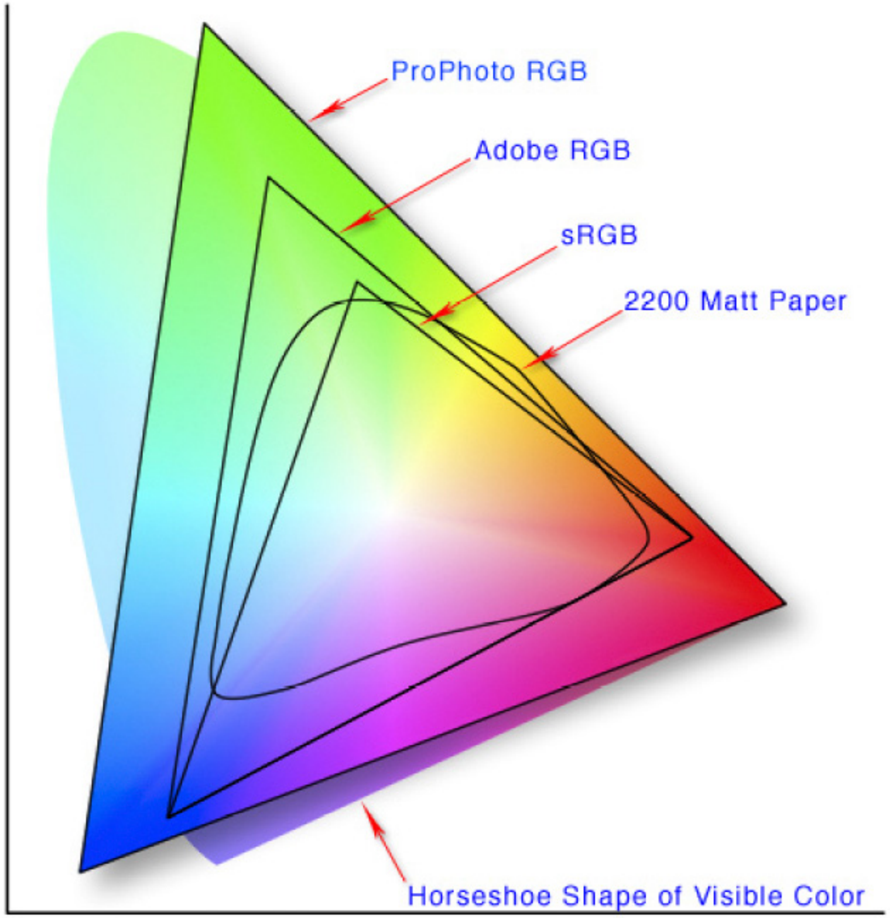
Once three primary sources are chosen a triangle is defined in the chromatic space.

Fundamental colors in Television



Fundamental colors

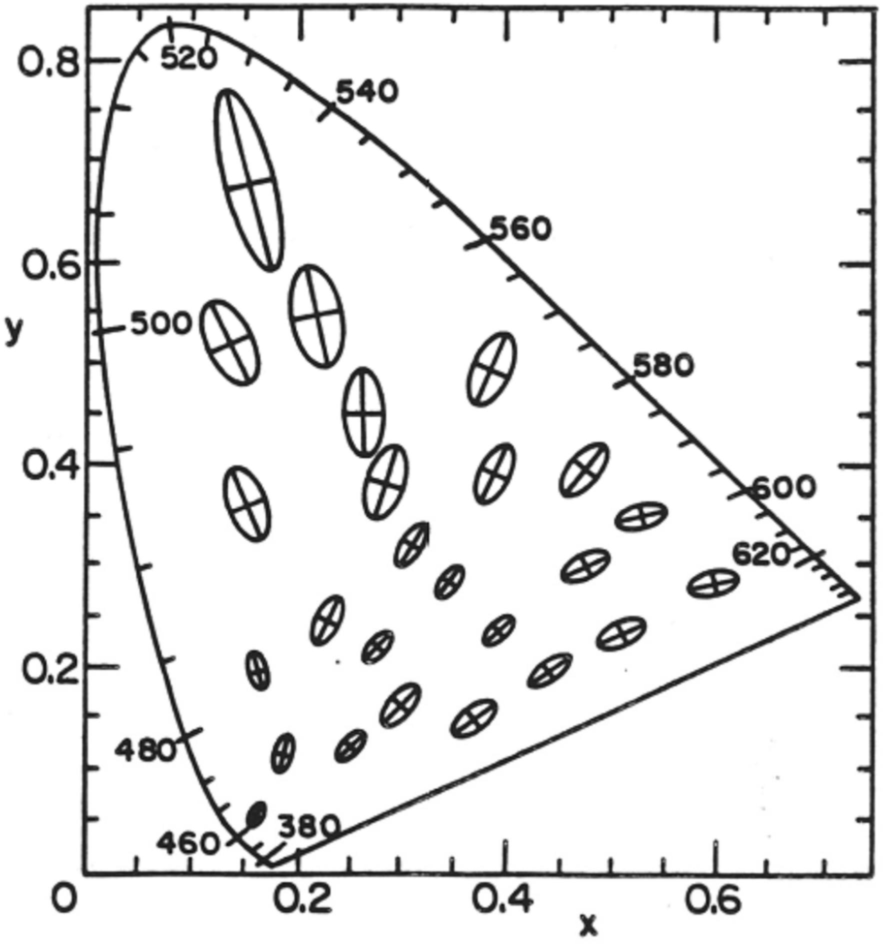




Colors perceptivity

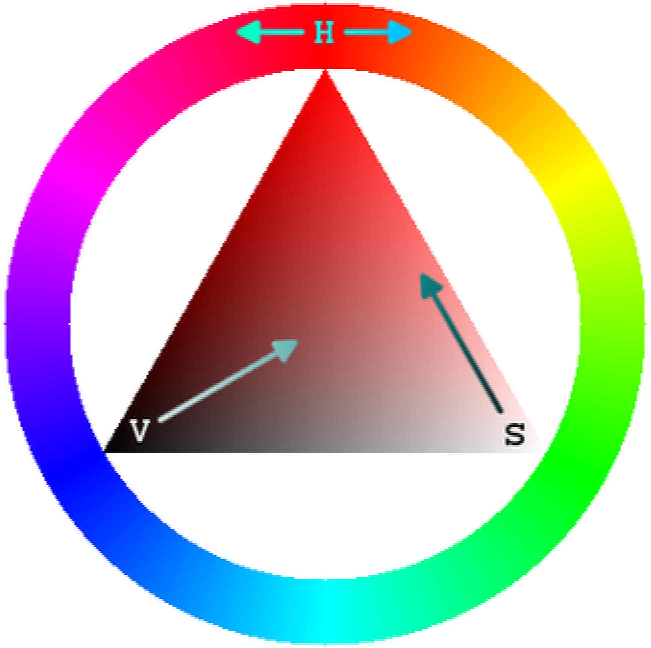
Ellipses represent the locus of colors hardly distinguishable with respect to the central point color.

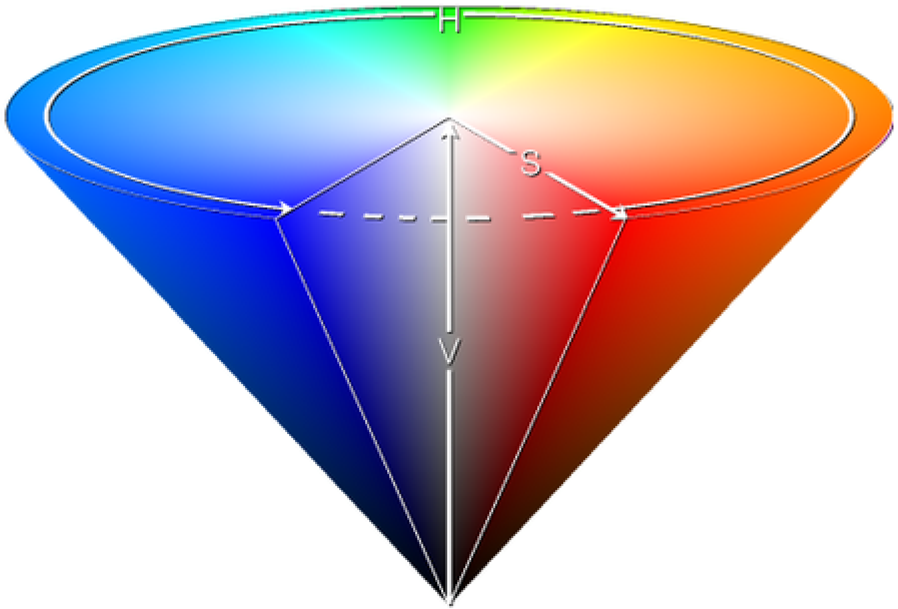
The X,Y space is not perceptively uniform.



(a) x–y chromaticity diagram

The Hue, saturation, value space





Conversion from RGB to HSV

Let *r*, *g*, *b* ∈ [0,1] be the red, green, and blue coordinates, respectively, of a color in RGB space.

Let *max* be the greatest of *r*, *g*, and *b*, and *min* the least.

To find the hue angle *h* ∈ [0, 360] for HSV space, compute:

$$h = \begin{cases} 0, & \text{if } \max = \min \\ (60^\circ \times \frac{g-b}{\max - \min} + 360^\circ) \bmod 360^\circ, & \text{if } \max = r \\ 60^\circ \times \frac{b-r}{\max - \min} + 120^\circ, & \text{if } \max = g \\ 60^\circ \times \frac{r-g}{\max - \min} + 240^\circ, & \text{if } \max = b \end{cases}$$

To find saturation and lightness *s*, *l* ∈ [0,1] for HSV space, compute:

$$s = \begin{cases} 0, & \text{if } \max = 0 \\ \frac{\max - \min}{\max} = 1 - \frac{\min}{\max}, & \text{otherwise} \end{cases}$$

Conversion from HSV to RGB

Similarly, given a color defined by (*h*, *s*, *v*) values in HSV space, with *h* as above, and with *s* and *v* varying between 0 and 1, representing the saturation and value, respectively, a corresponding (*r*, *g*, *b*) triplet in RGB space can be computed:

$$h_i = \left\lfloor \frac{h}{60} \right\rfloor \mod 6$$

$$f = \frac{h}{60} - \left\lfloor \frac{h}{60} \right\rfloor$$

$$p = v \times (1 - s)$$

$$q = v \times (1 - f \times s)$$

$$t = v \times (1 - (1 - f) \times s)$$

$$(r, g, b) = \begin{cases} (v, t, p), & \text{if } h_i = 0 \\ (q, v, p), & \text{if } h_i = 1 \\ (p, v, t), & \text{if } h_i = 2 \\ (p, q, v), & \text{if } h_i = 3 \\ (t, p, v), & \text{if } h_i = 4 \\ (v, p, q), & \text{if } h_i = 5 \end{cases}$$