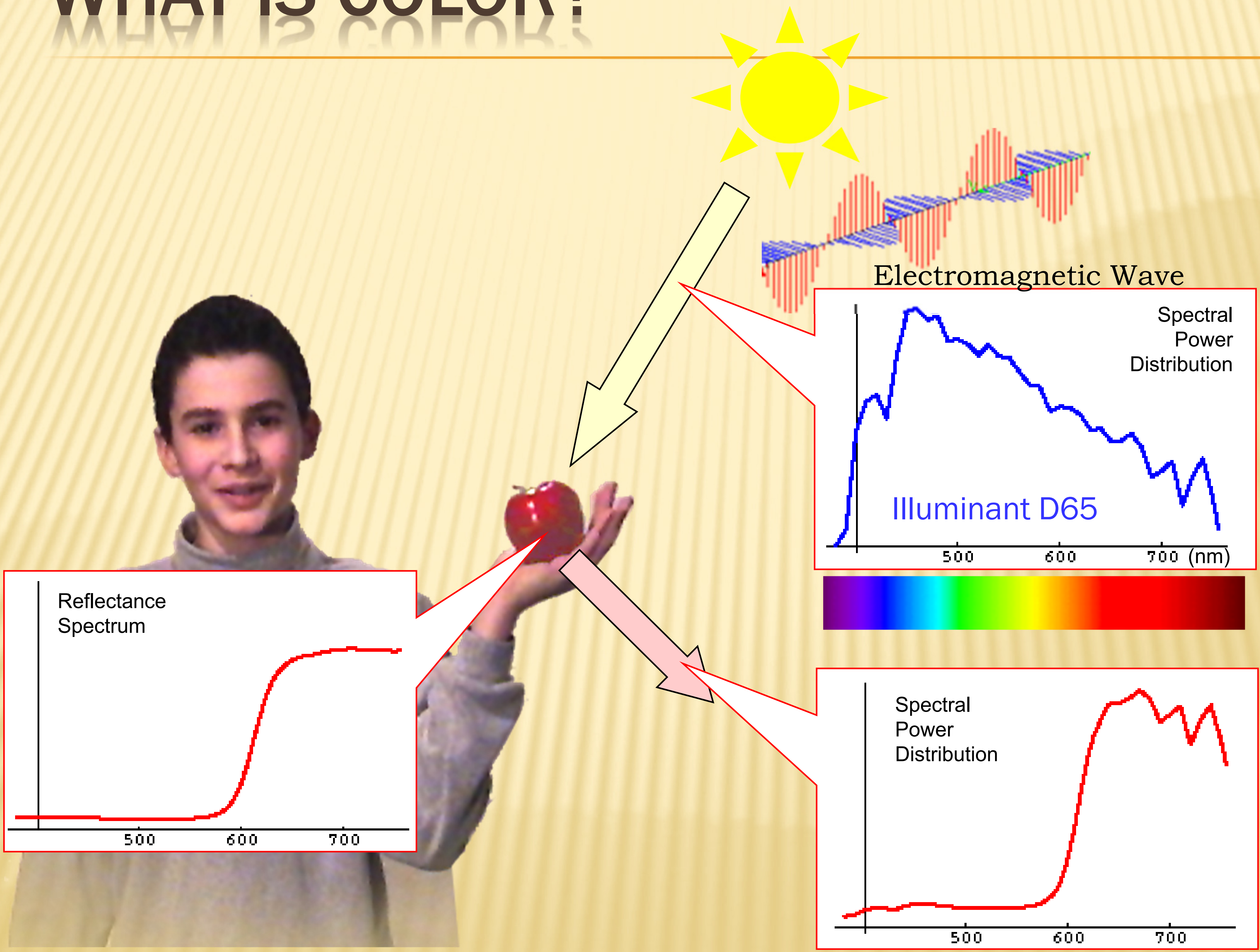
VIDEO PROCESSING

Colorimetry

WHAT IS COLOR?



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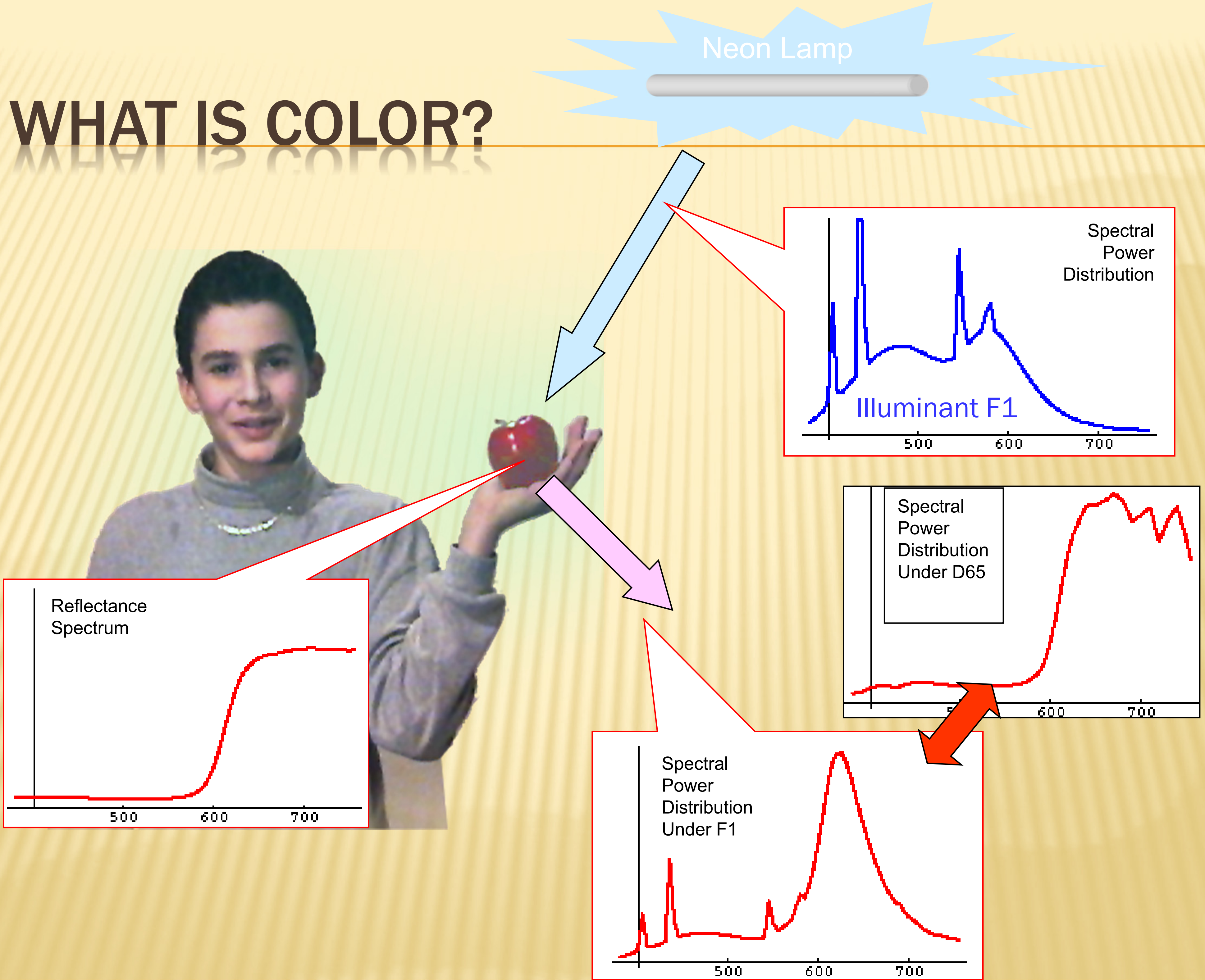

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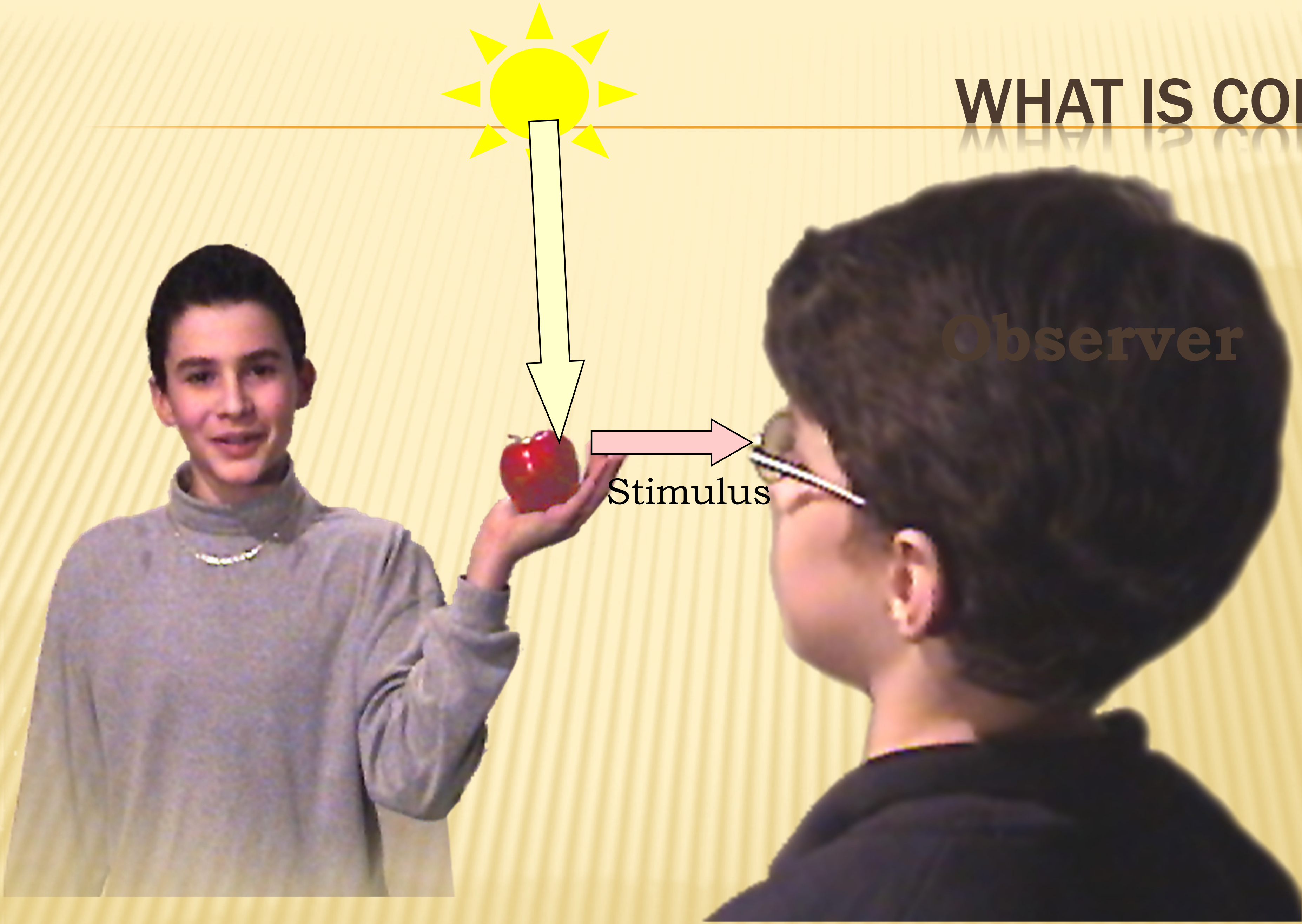

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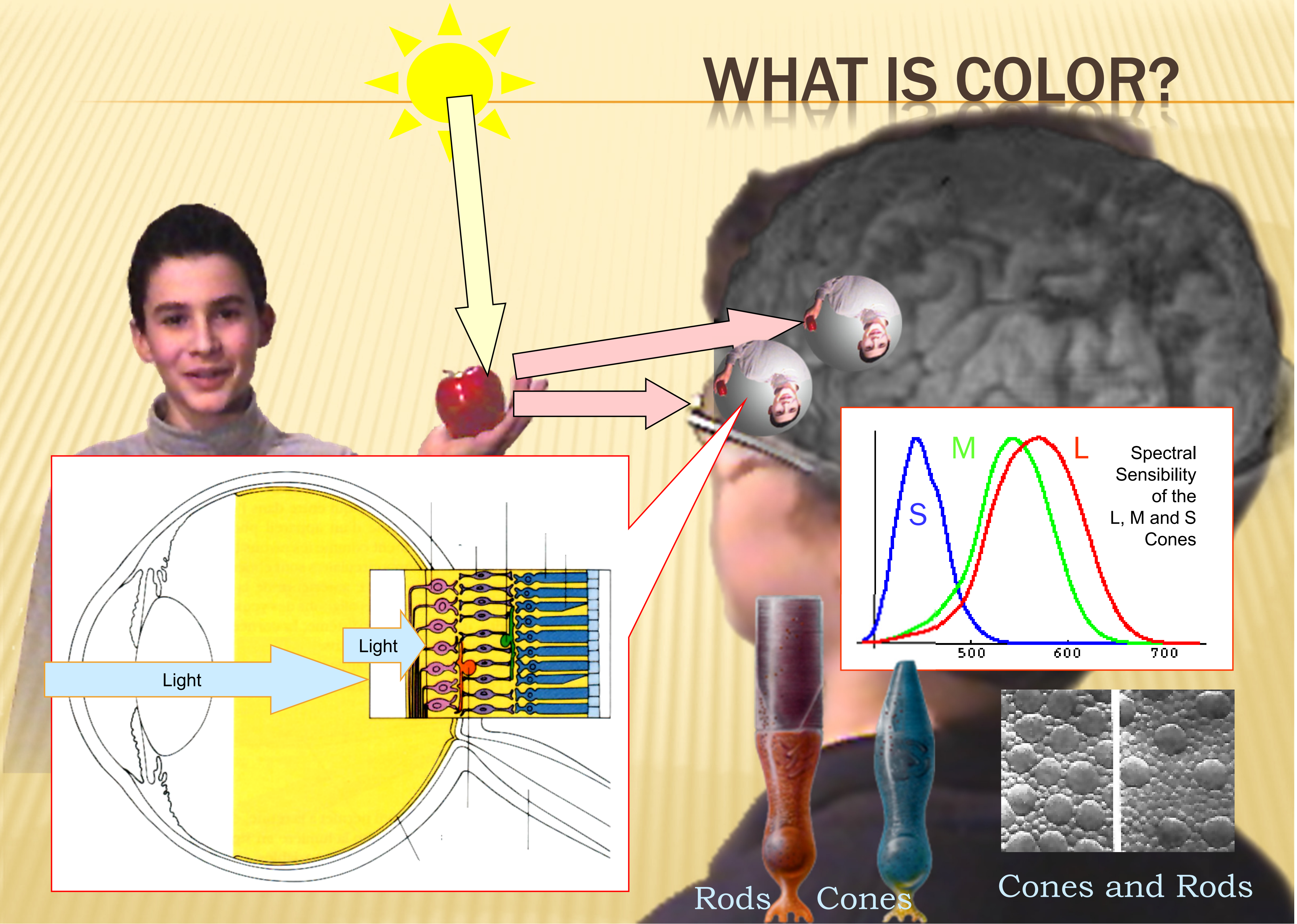
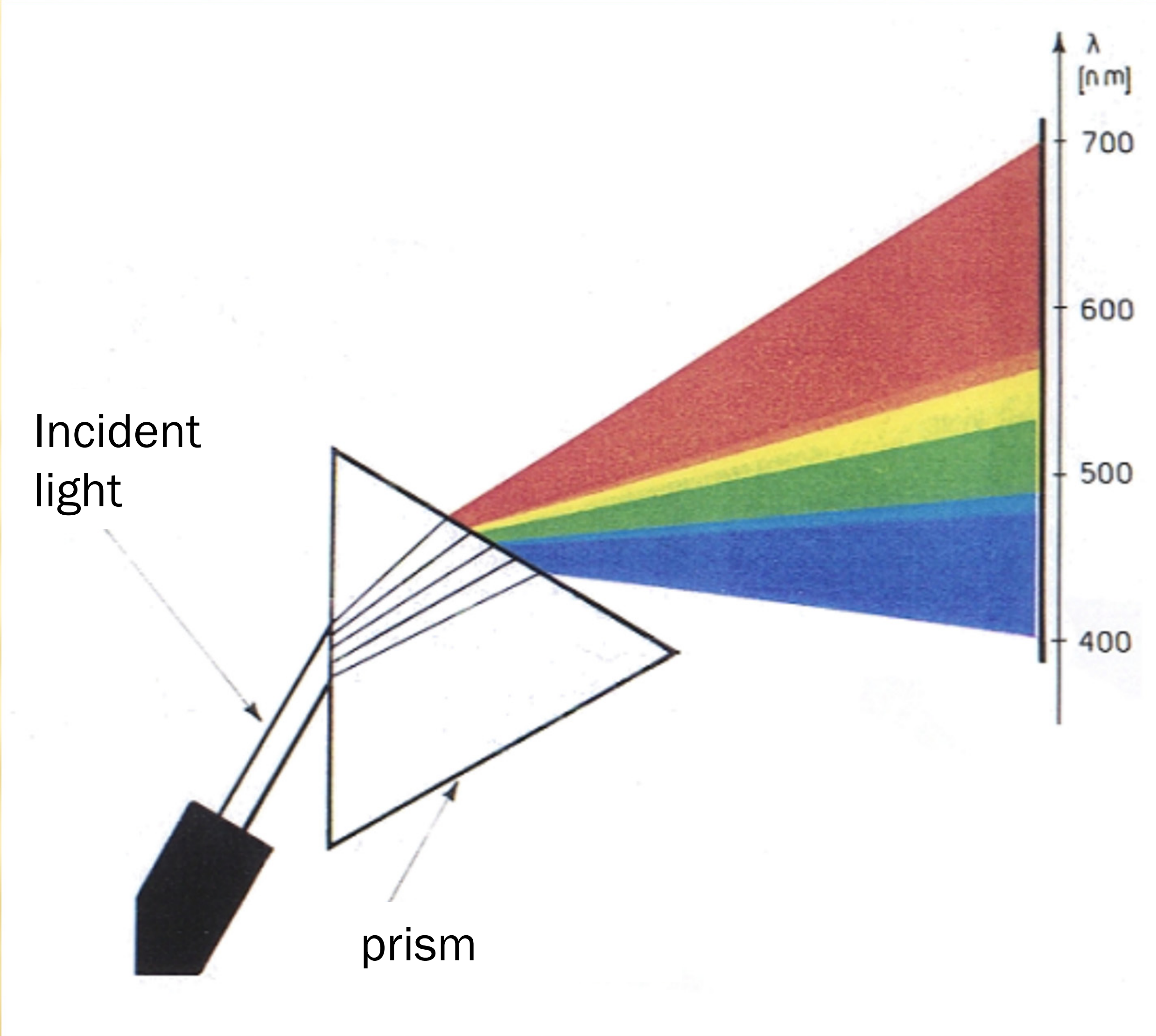
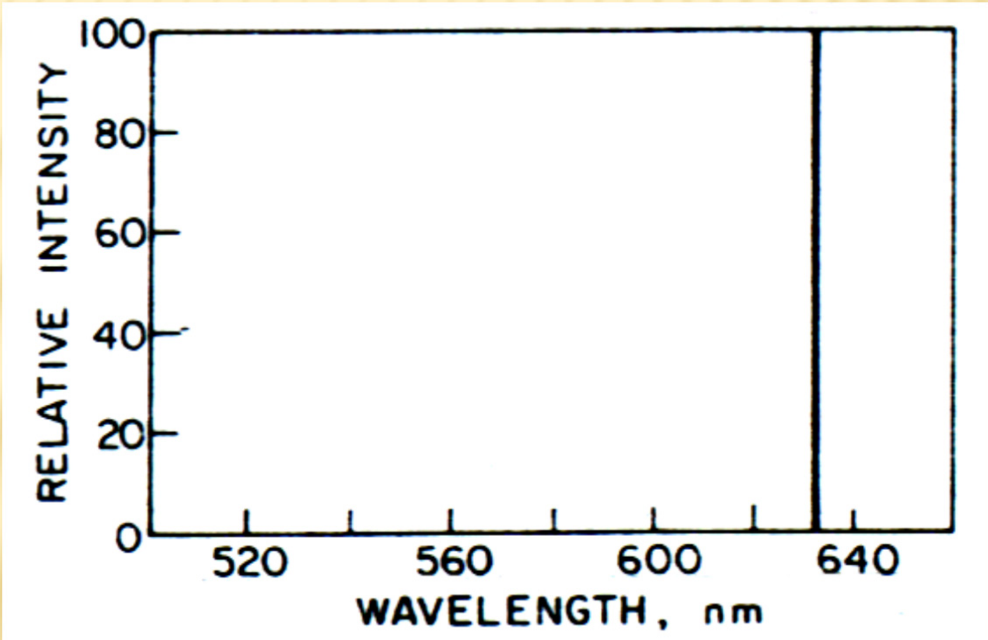


THE ELECTROMAGNETIC SPECTRUM



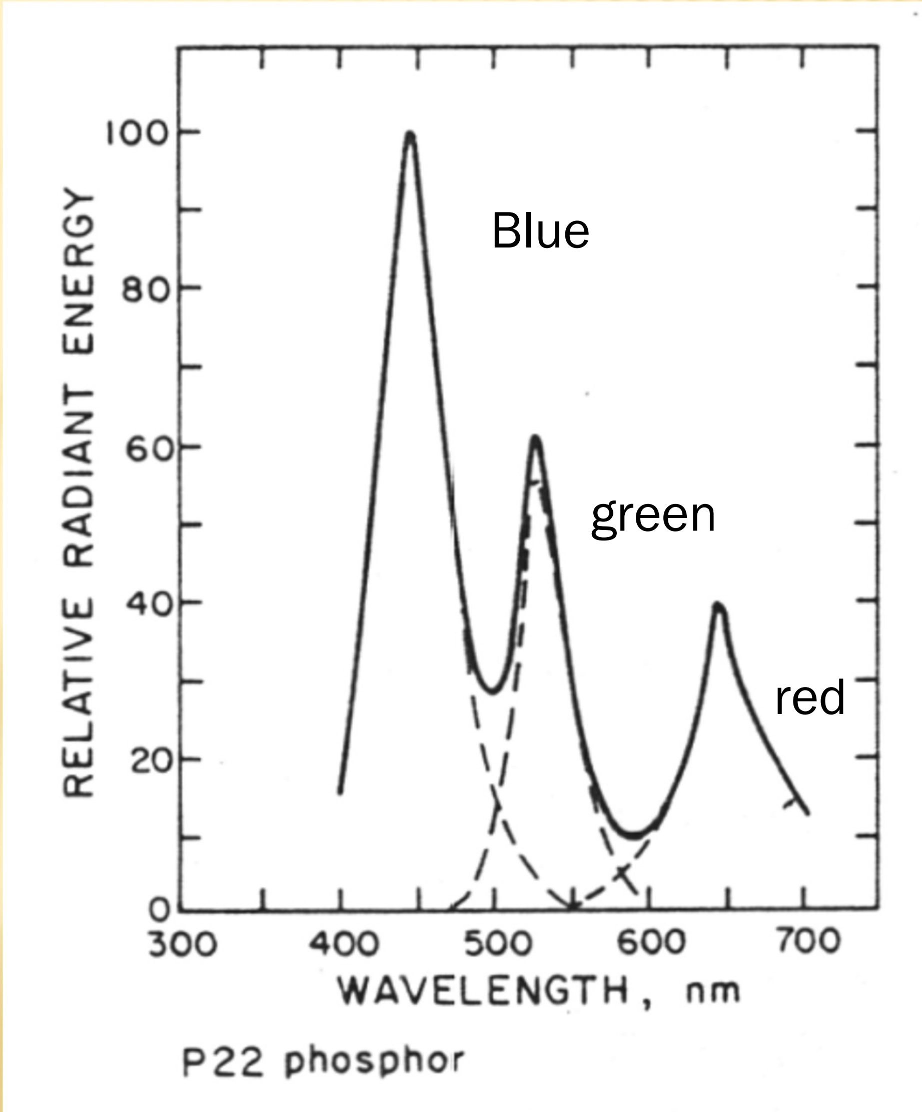
SPECTRAL EXAMPLES

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



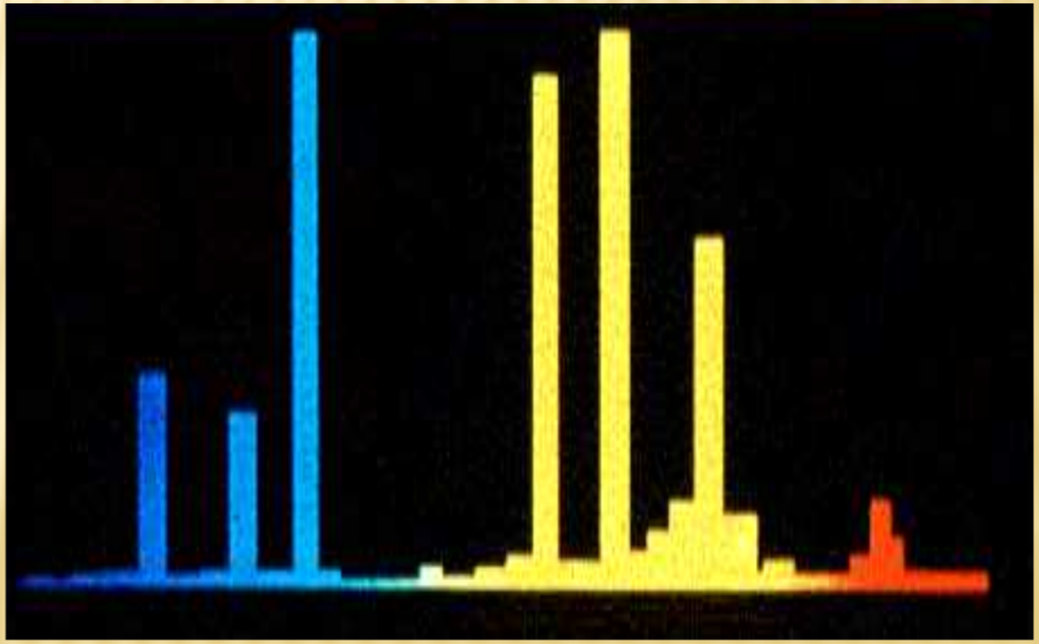
SPECTRAL EXAMPLES

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



SPECTRAL EXAMPLES

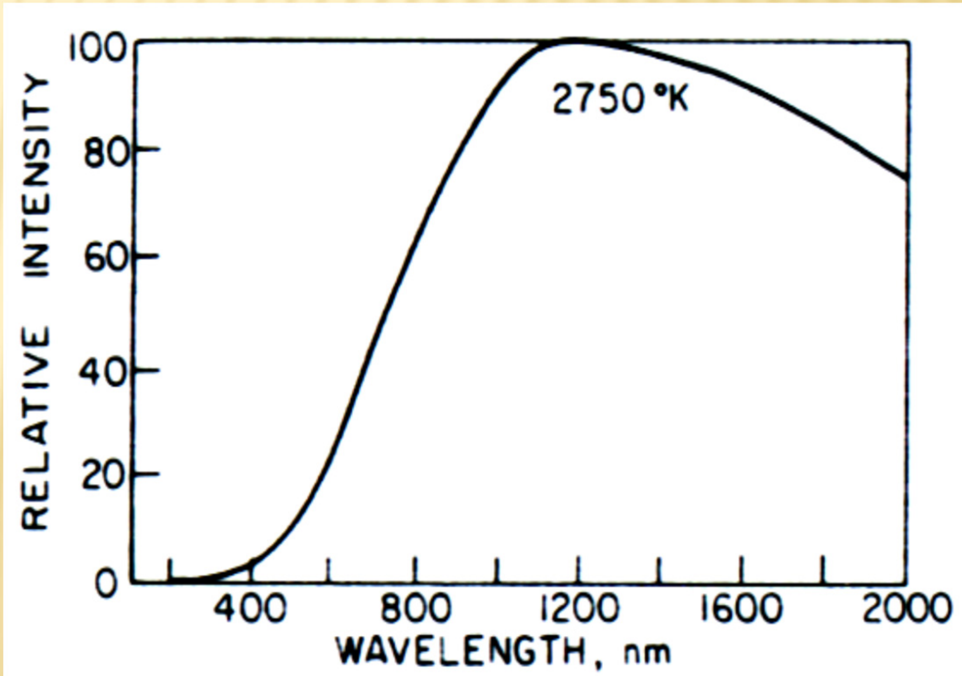
- The light emitted from a gas vapour lamp is a set of diffent spectral lines. Their value is linked to the allowed energy steps performed by the excited gas electrons.



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.
  - incandenscent
- lamps



THE "BLACK BODY" LAW

- Planck's law states that:

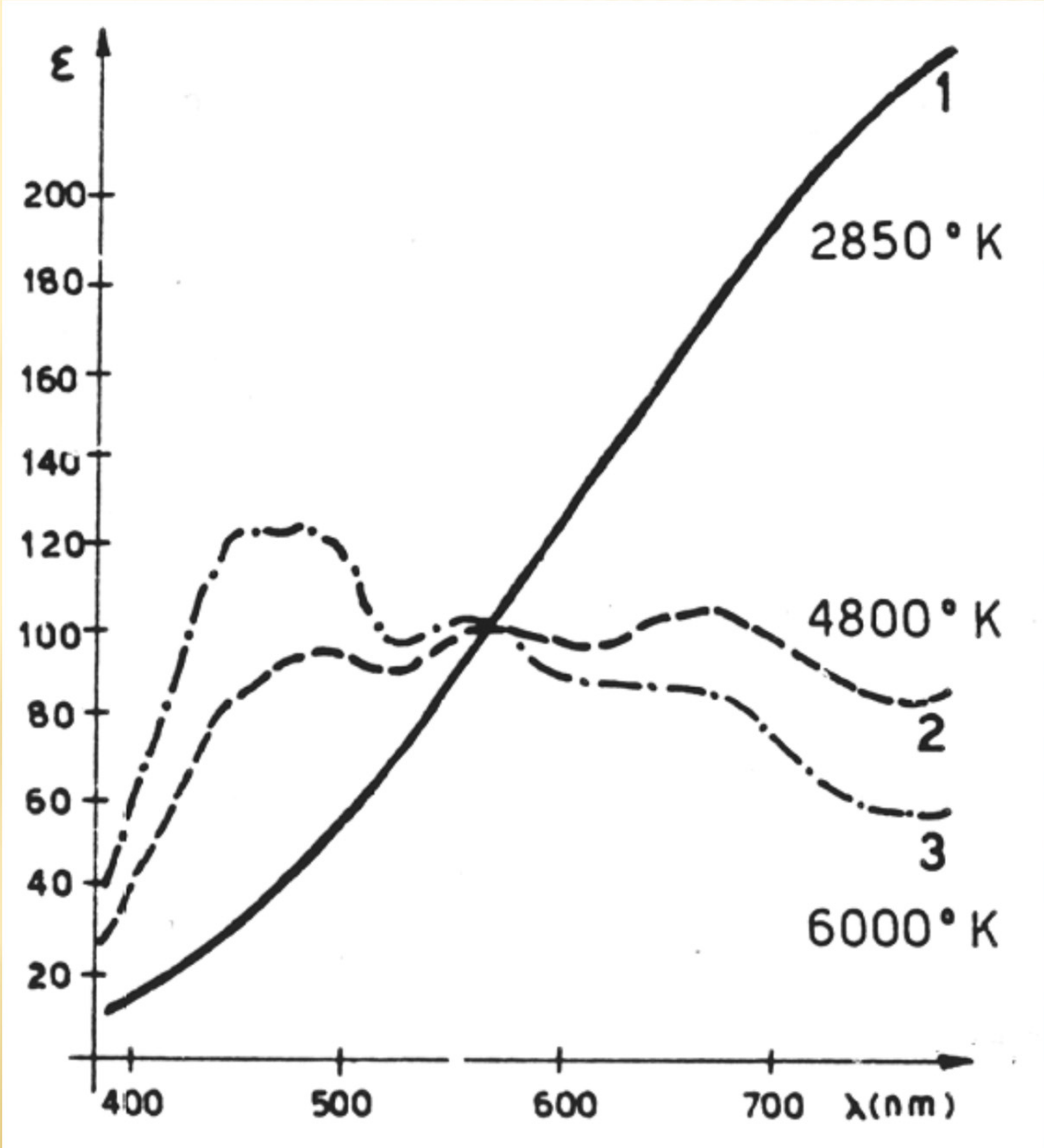
$$I(\nu, T)d\nu = \left(\frac{2h\nu^3}{c^2}\right)\frac{1}{e^{\frac{h\nu}{kT}} - 1}d\nu$$

where:

- *I*(*v*,*T*) *dv* is the amount of energy per unit surface area per unit time per unit solid angle emitted in the frequency range between *v* and *v* + *dv* 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;
- *v* is frequency of electromagnetic radiation;
- *T* is the temperature in Kelvin.

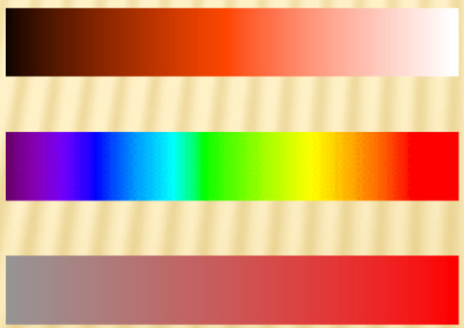
THE "WHITE" LIGHT

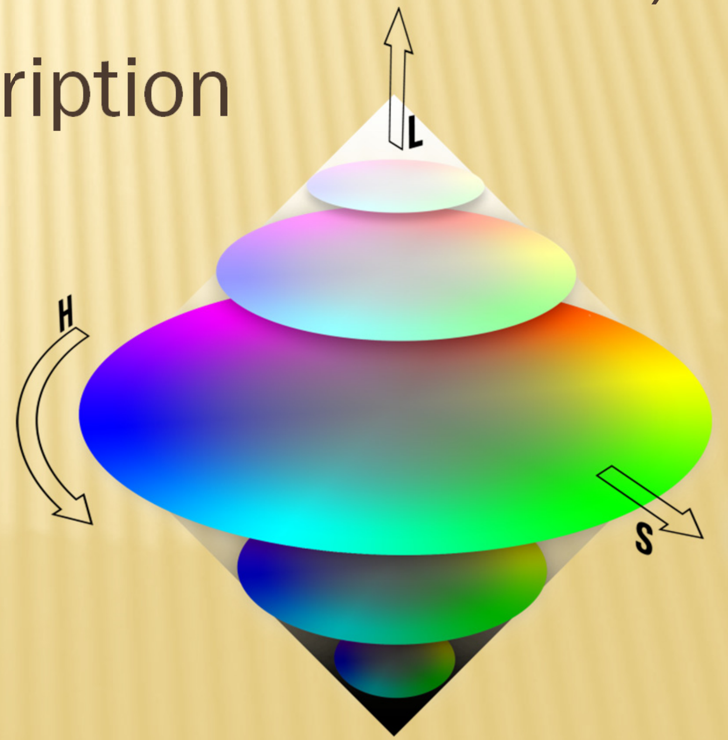
- An ideal illuminant with flat spectrum is not realizable.
- The sun can be assumed as a Planck source a 6000K
- Incandescent lamps can be assumed as planck sources ranging from 2000K to 5000K



POSSIBLE COLOR REPRESENTATIONS

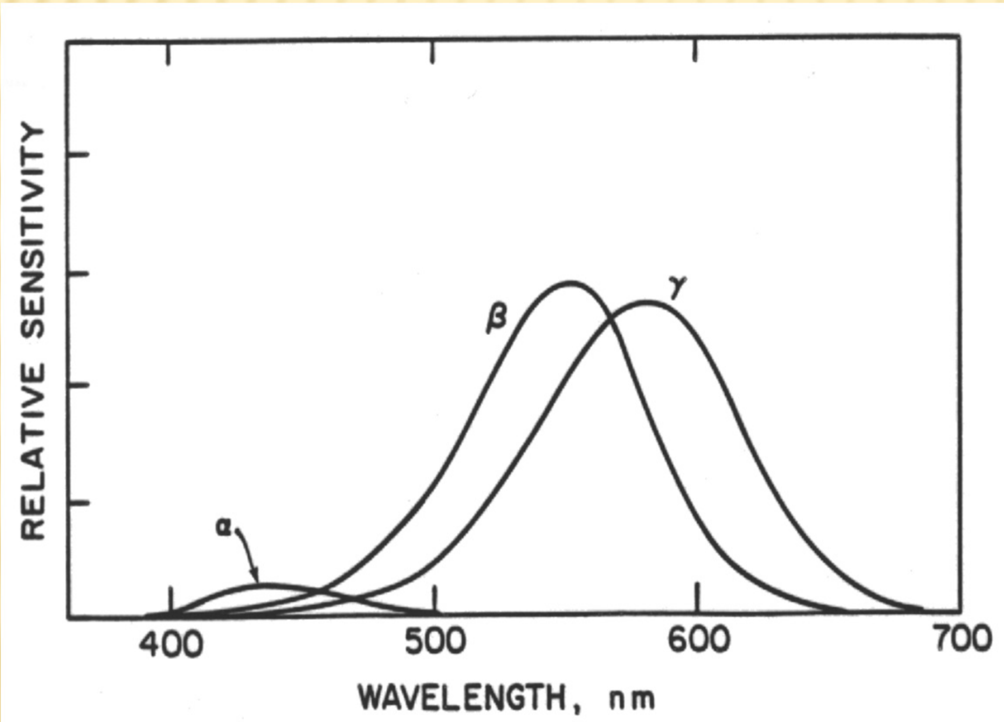
- A detailed description of the power spectrum where providing power density at each frequency.
- 30 values to specify energy in every sub-band (of 10 nm) in the visible range (from 400 to 700 nm)
- Following the trichromatic description
  - Lightness
  - Hue
  - Saturation

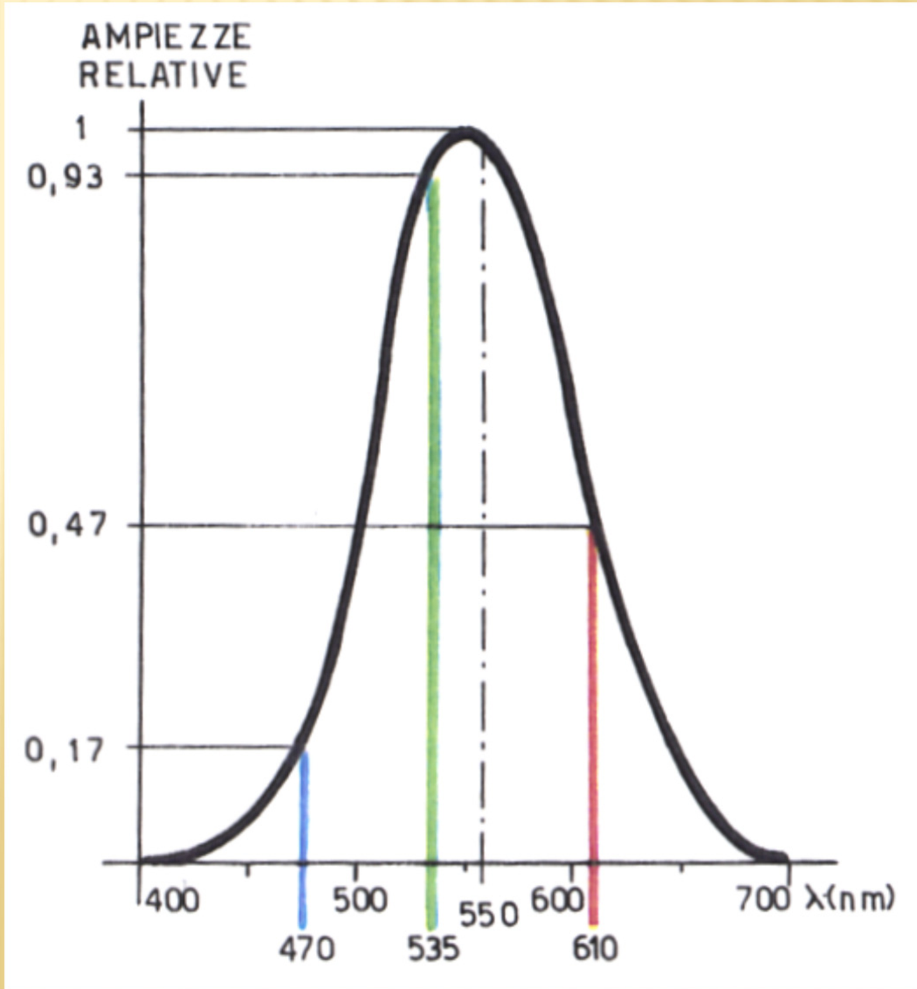




THE HUMAN EYE SENSIBILITY

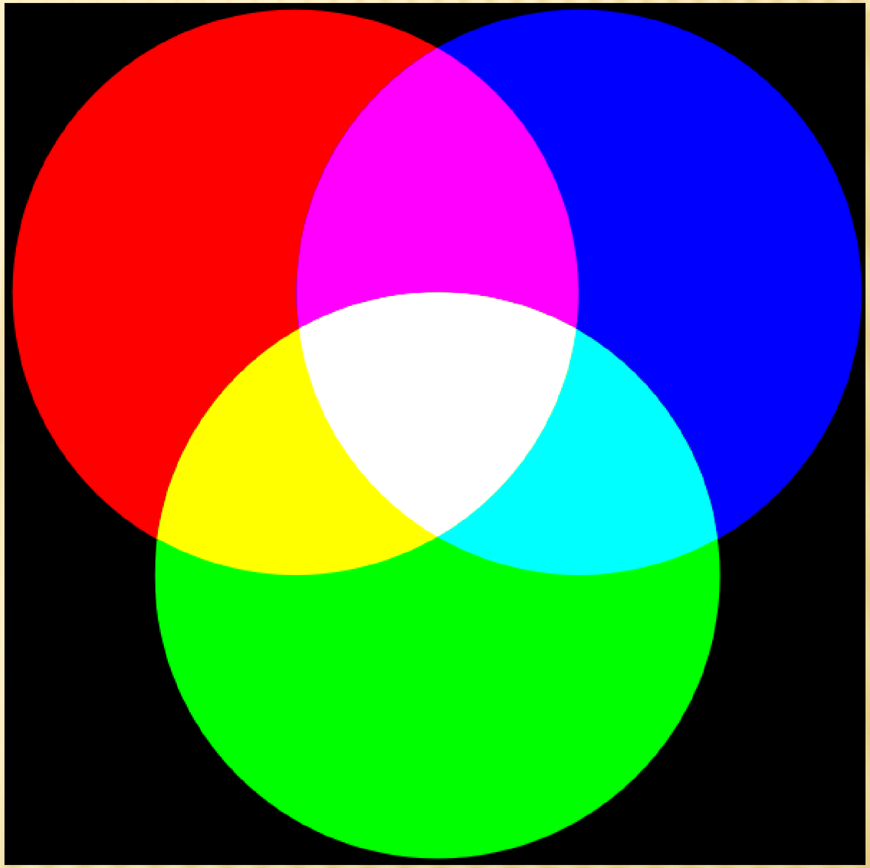
- Concerning the daylight visual system, the la retina can be assumed as composed of 3 different cones(α, β, γ), with different, but partially overlapped, spectral sensitivity.





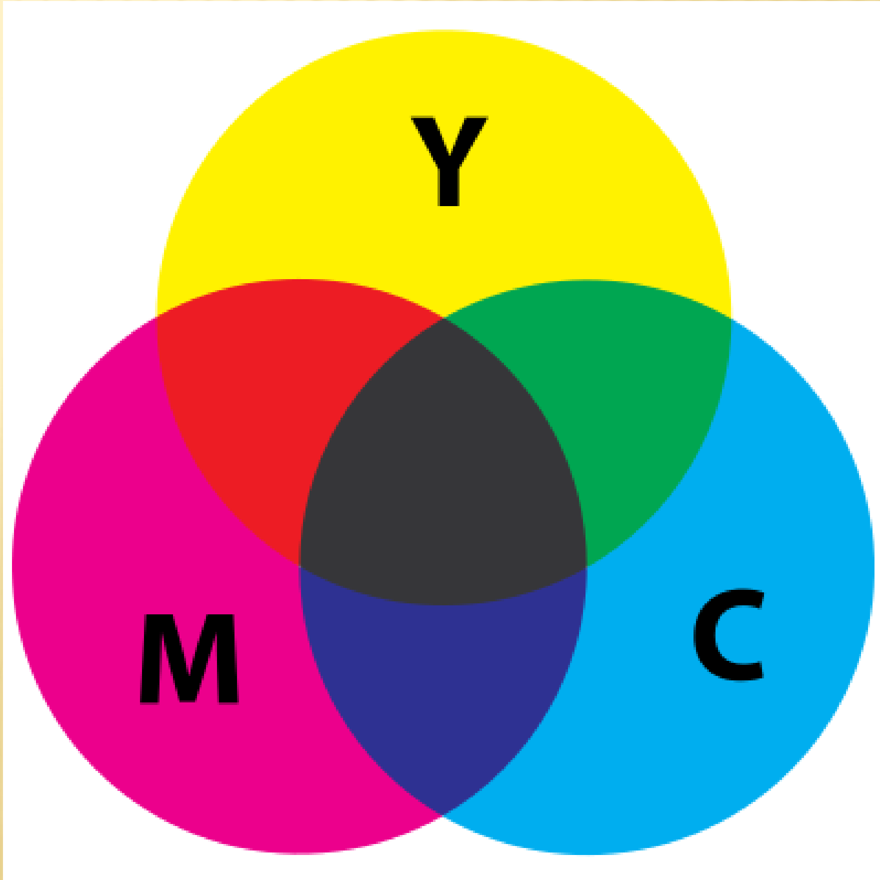
ADDITIVE SYNTHESIS

- 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 order to obtain the reference white color.

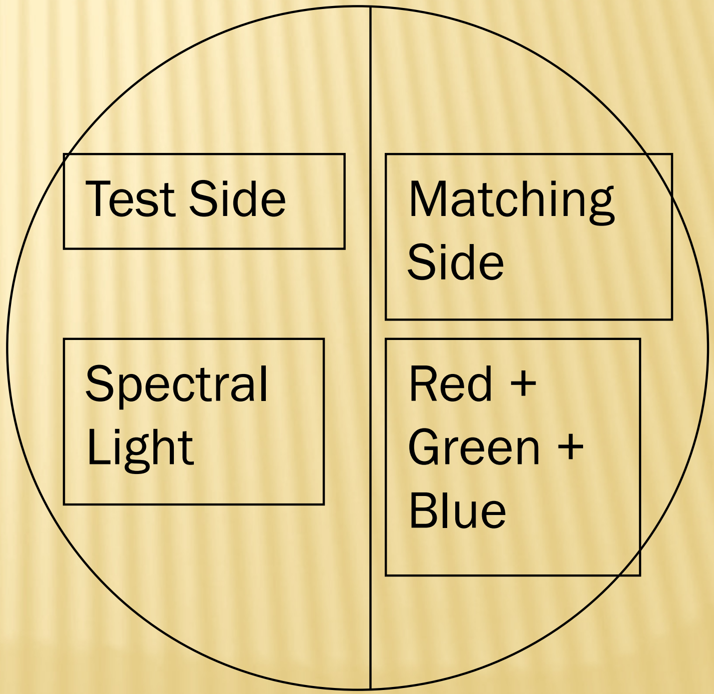
$$White = \sum_{j=1}^{3} A_j(W) P_j(\lambda)$$

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]

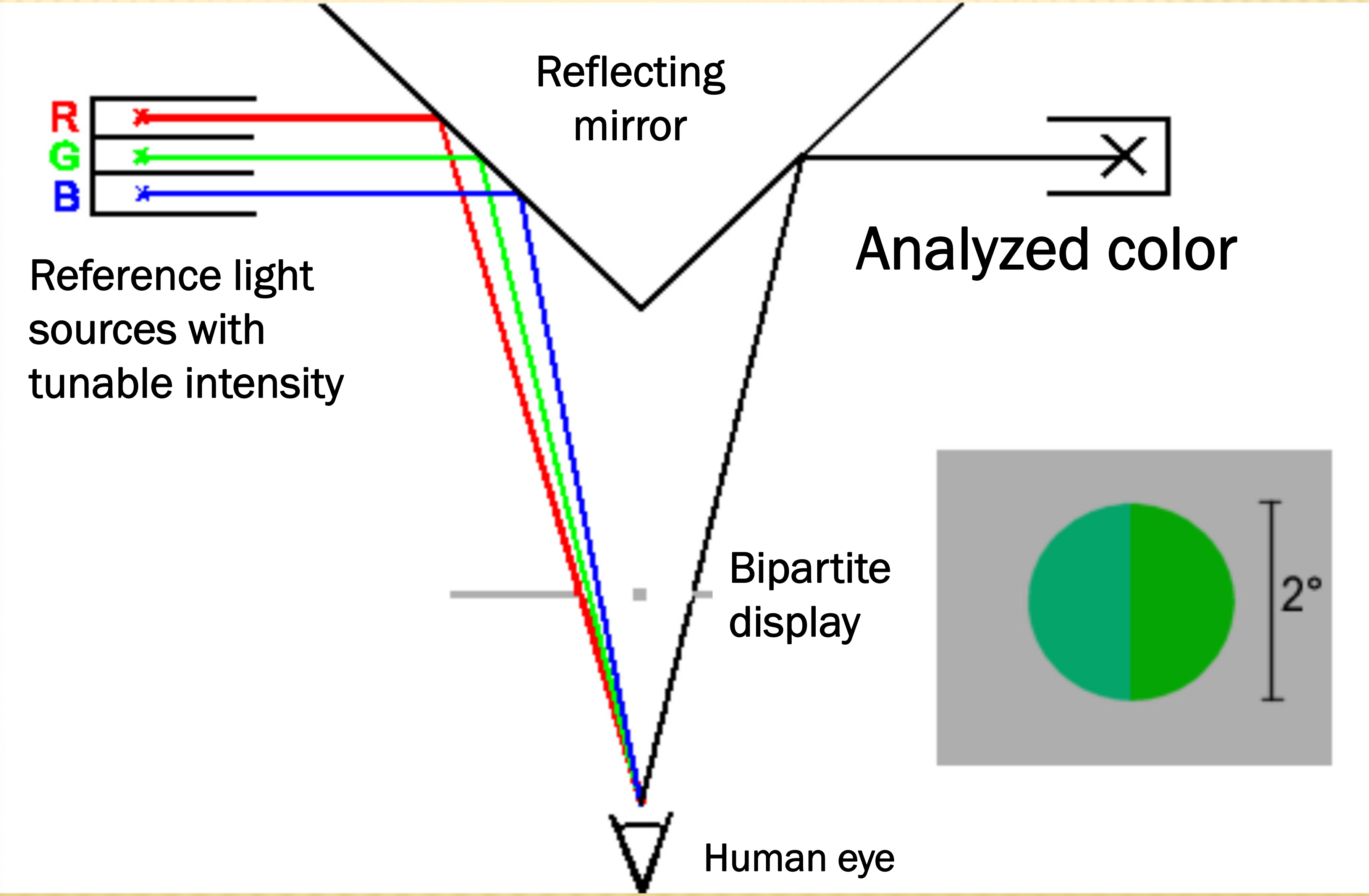
THE CIE STANDARD OBSERVERS

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.

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

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

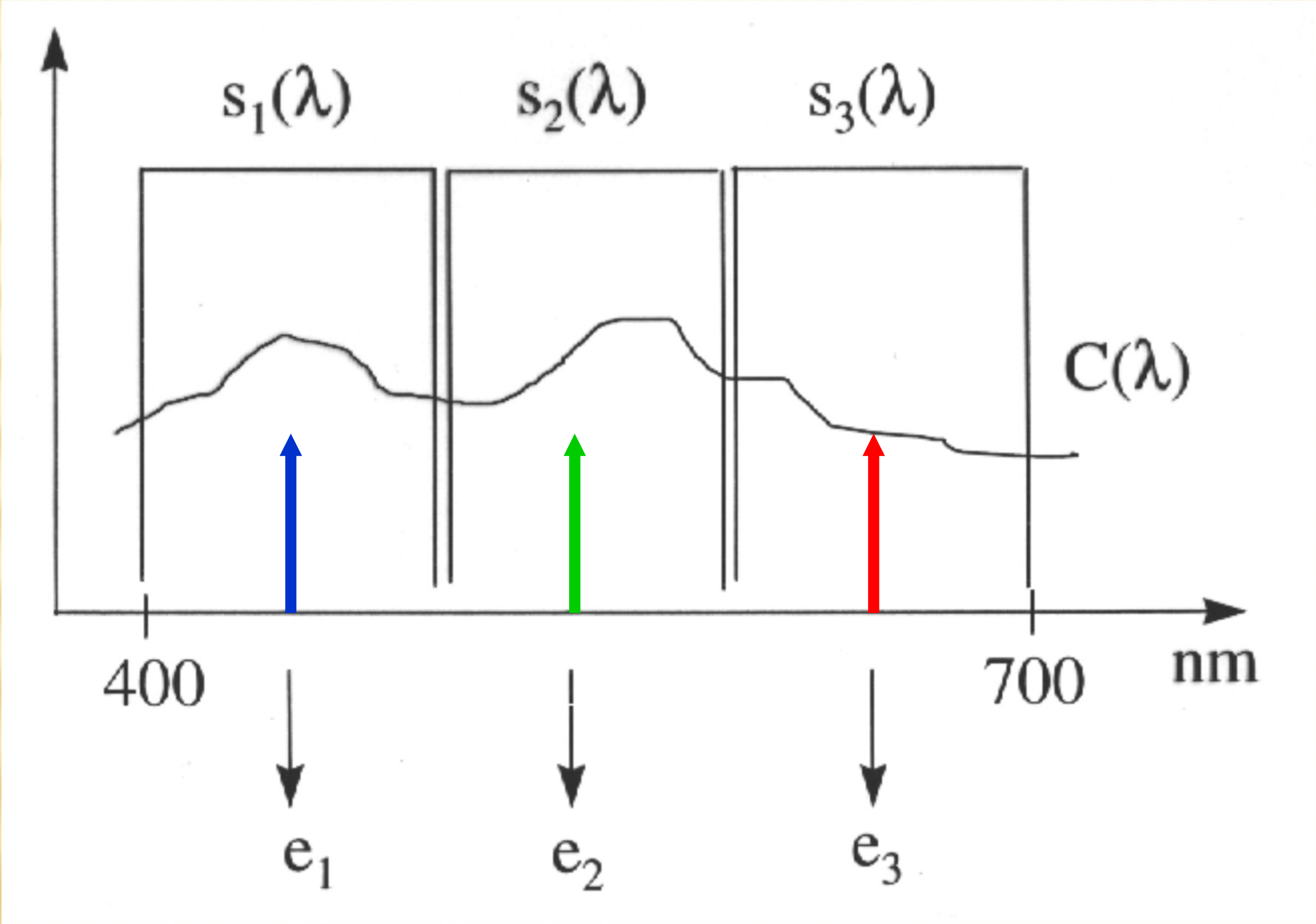
If the primary sources are monochromatic with unitary power ($P_j(\lambda)=\delta(\lambda-\psi_j)$) we can write:

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

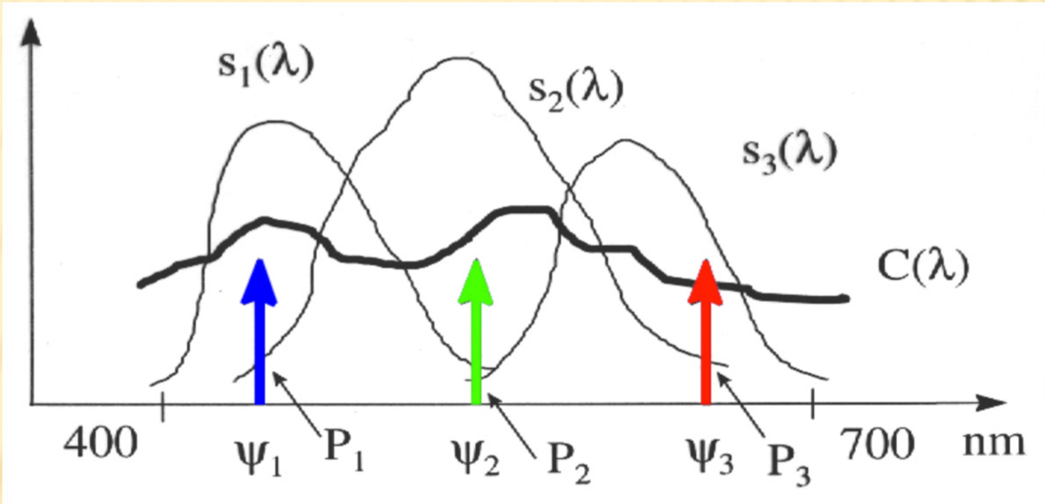
$$e_2(C)=\int C(\lambda)s_2(\lambda)d\lambda=\sum_{y=1}^{3}T_j(C)\,A_j(W)\,s_2\left(\psi_i\right)$$

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

TRISTIMULUS COMPONENTS



TRISTIMULUS COMPONENTS

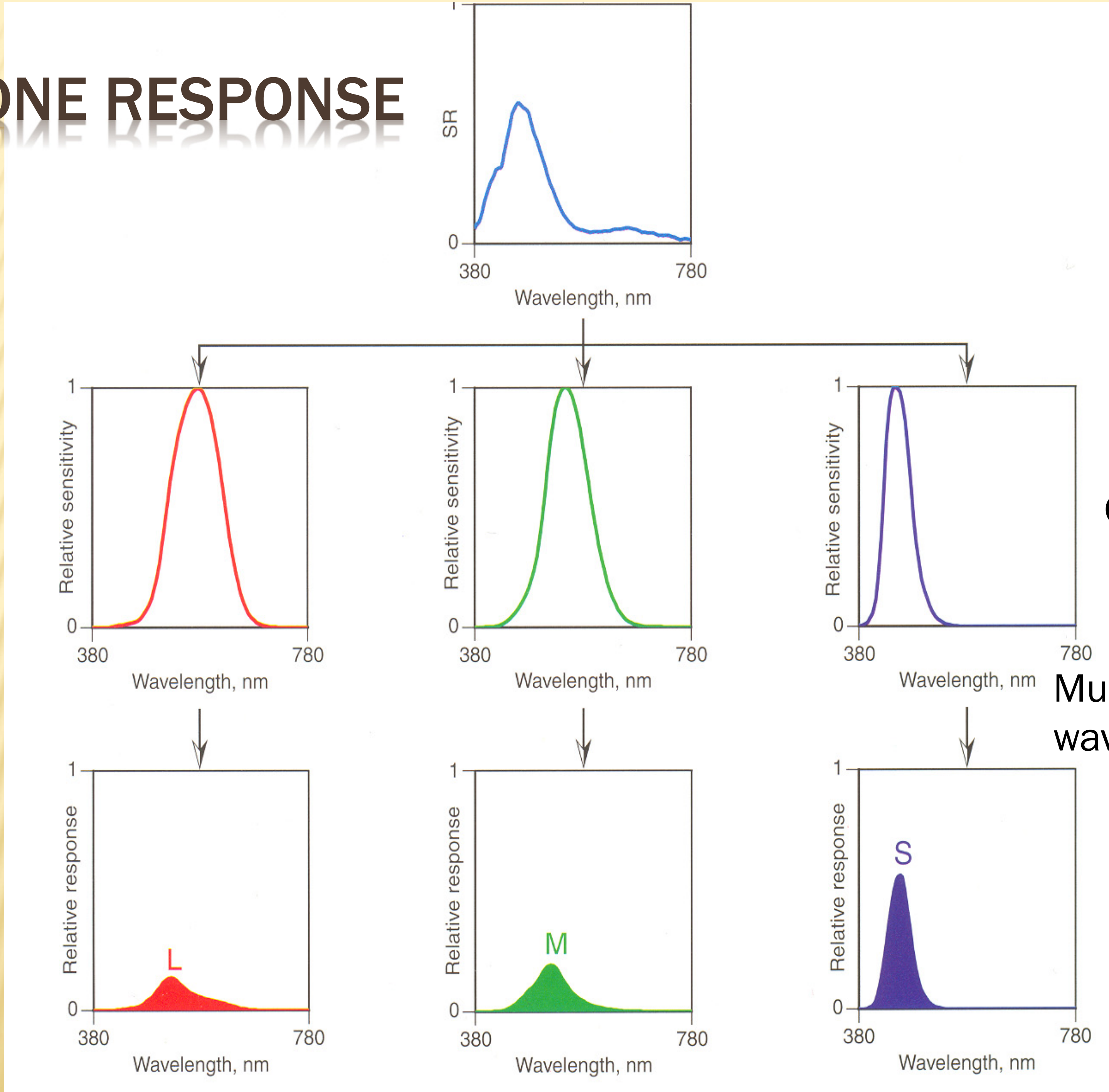


$$e_1(C) = \int C(\lambda) s_1(\lambda) d\lambda = \sum_{j=1}^{3} A_j(C) s_1(\psi_j)$$

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

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

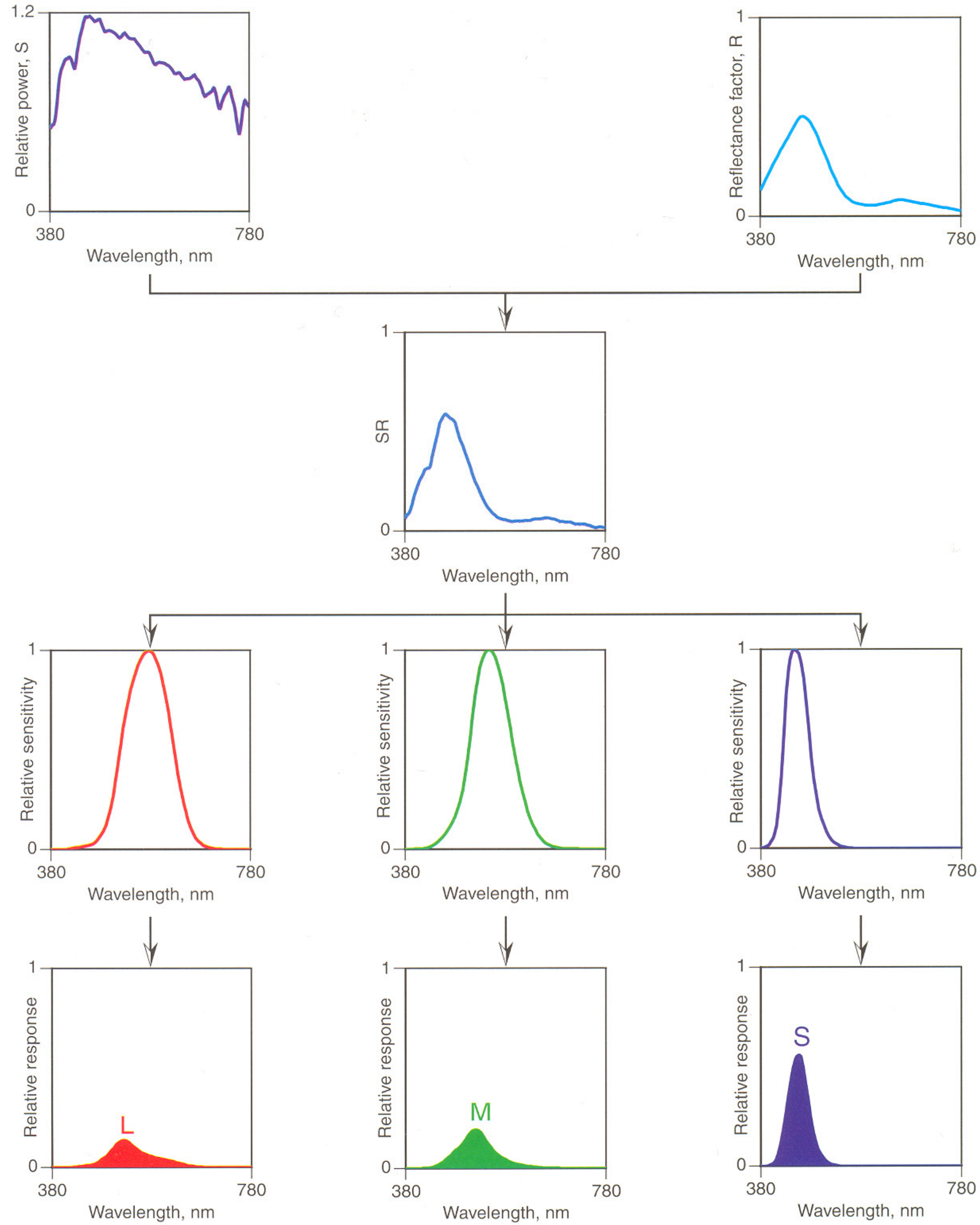
CONE RESPONSE



Cone responses

Multiply wavelength by wavelength

Integrate



Stimulus

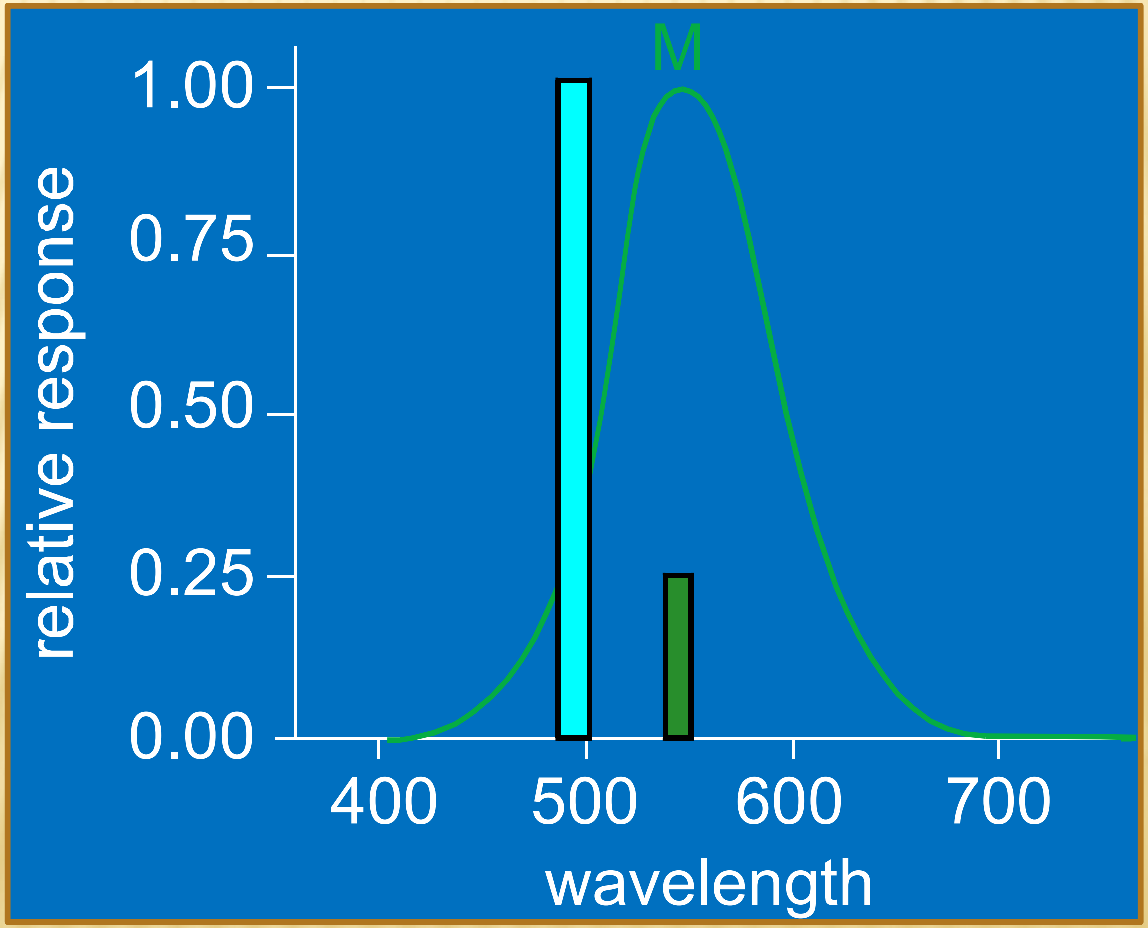
Cone responses

Multiply wavelength by wavelength

Integrate

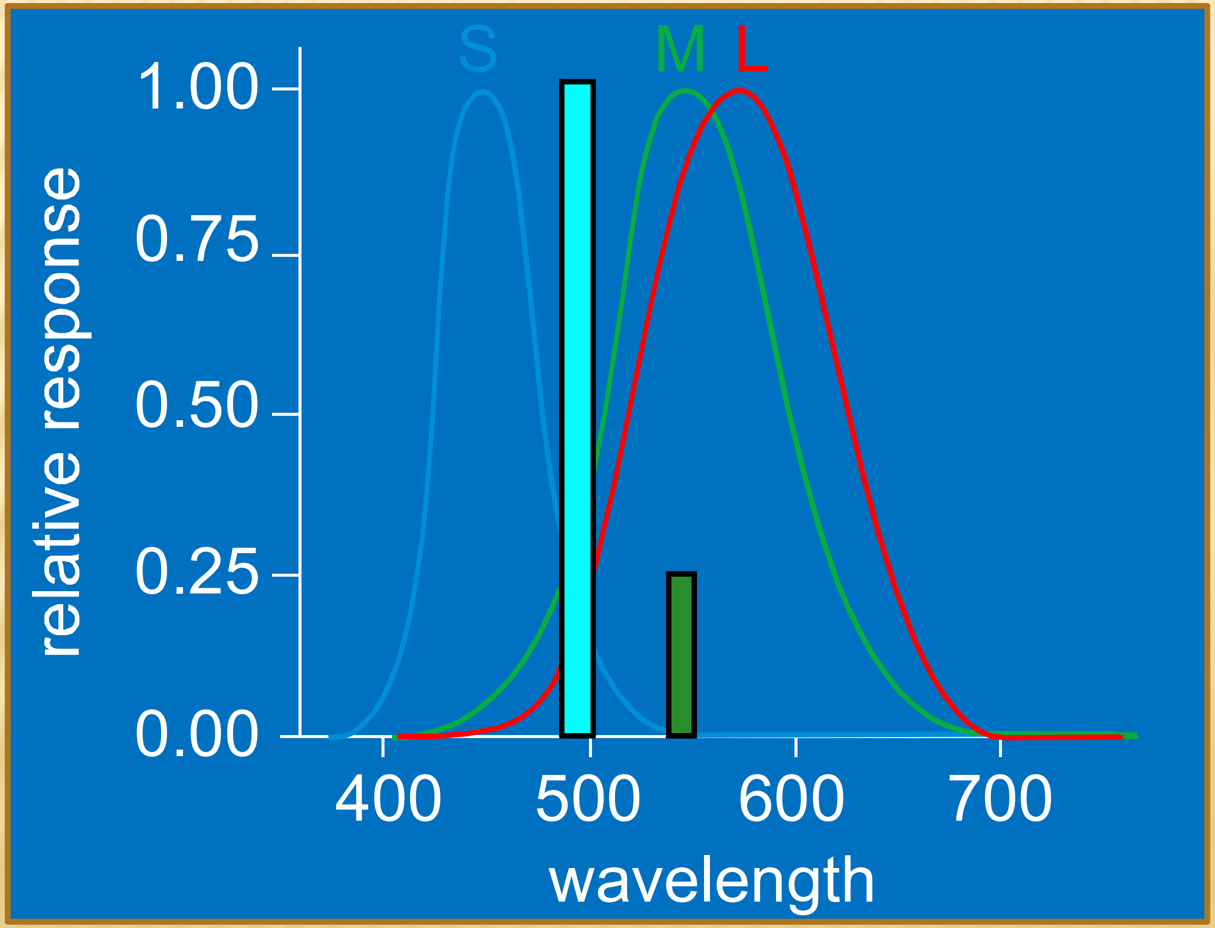
CONES DO NOT "SEE" COLORS

- Different wavelength, different intensity
- Same response

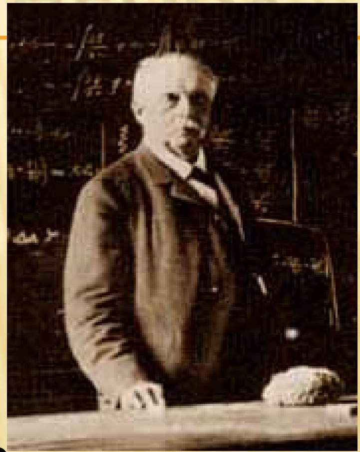


RESPONSE COMPARISON

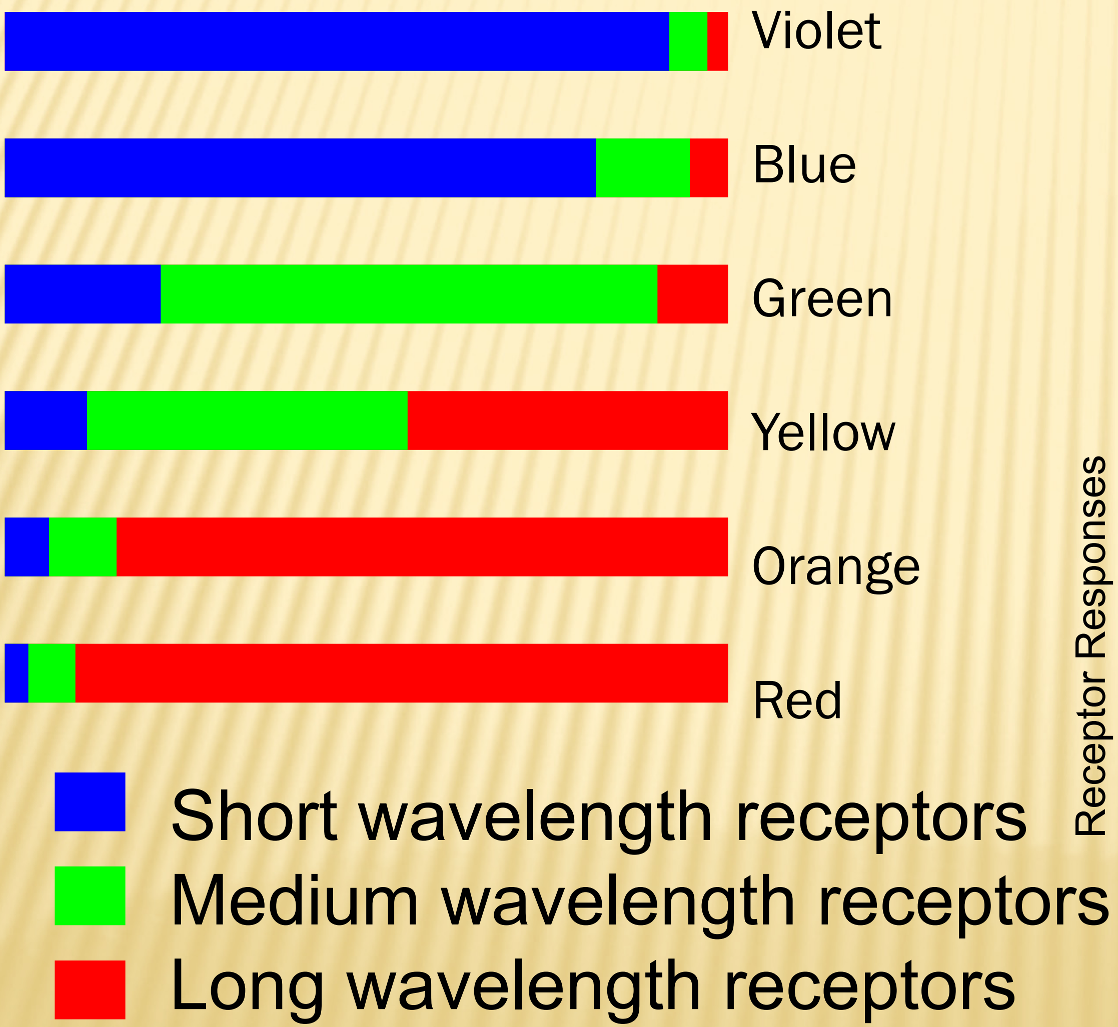
- Different wavelength, different intensity
- But different response for different cones

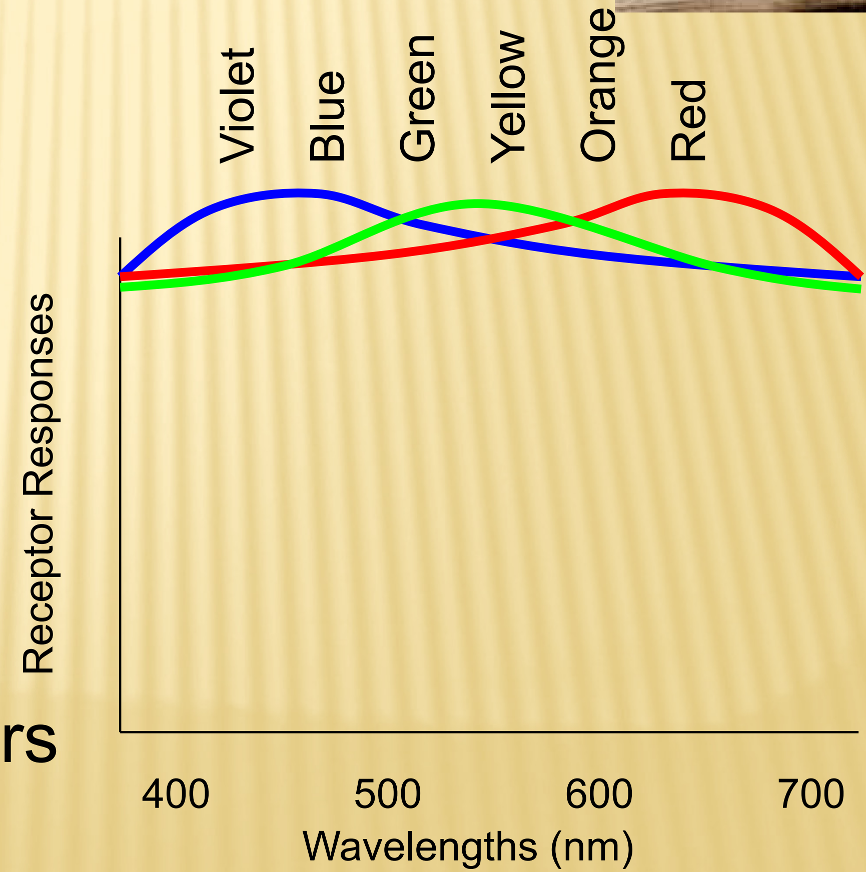


VON HELMHOLTZ 1859: TRICHROMATIC THEORY



- 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:

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

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

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:

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

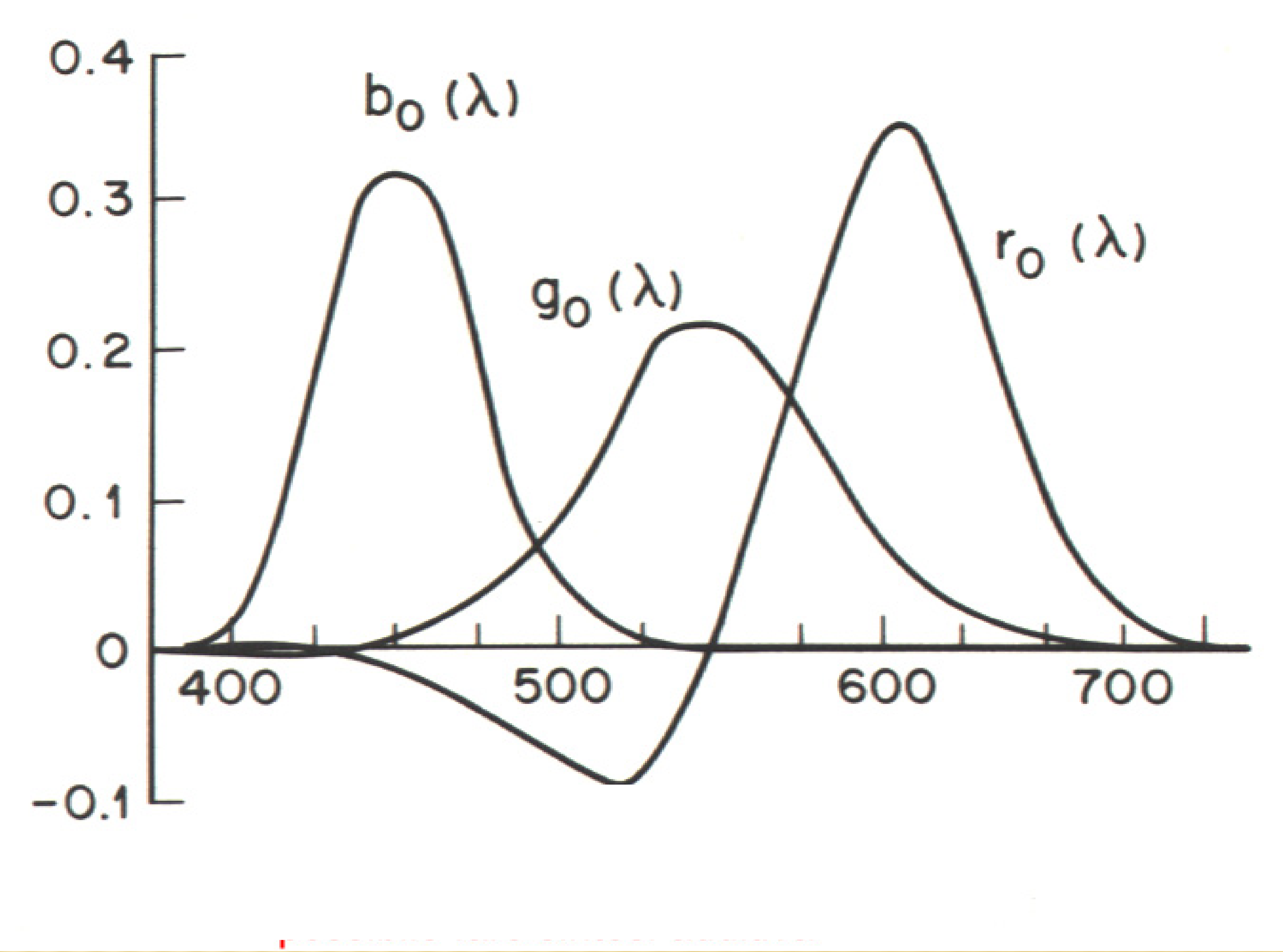
COLOR MATCHING FUNCTIONS R_0 G_0 B_0

Primary sources

R_0=700 nm

G_0=546 nm

B_0=436 nm

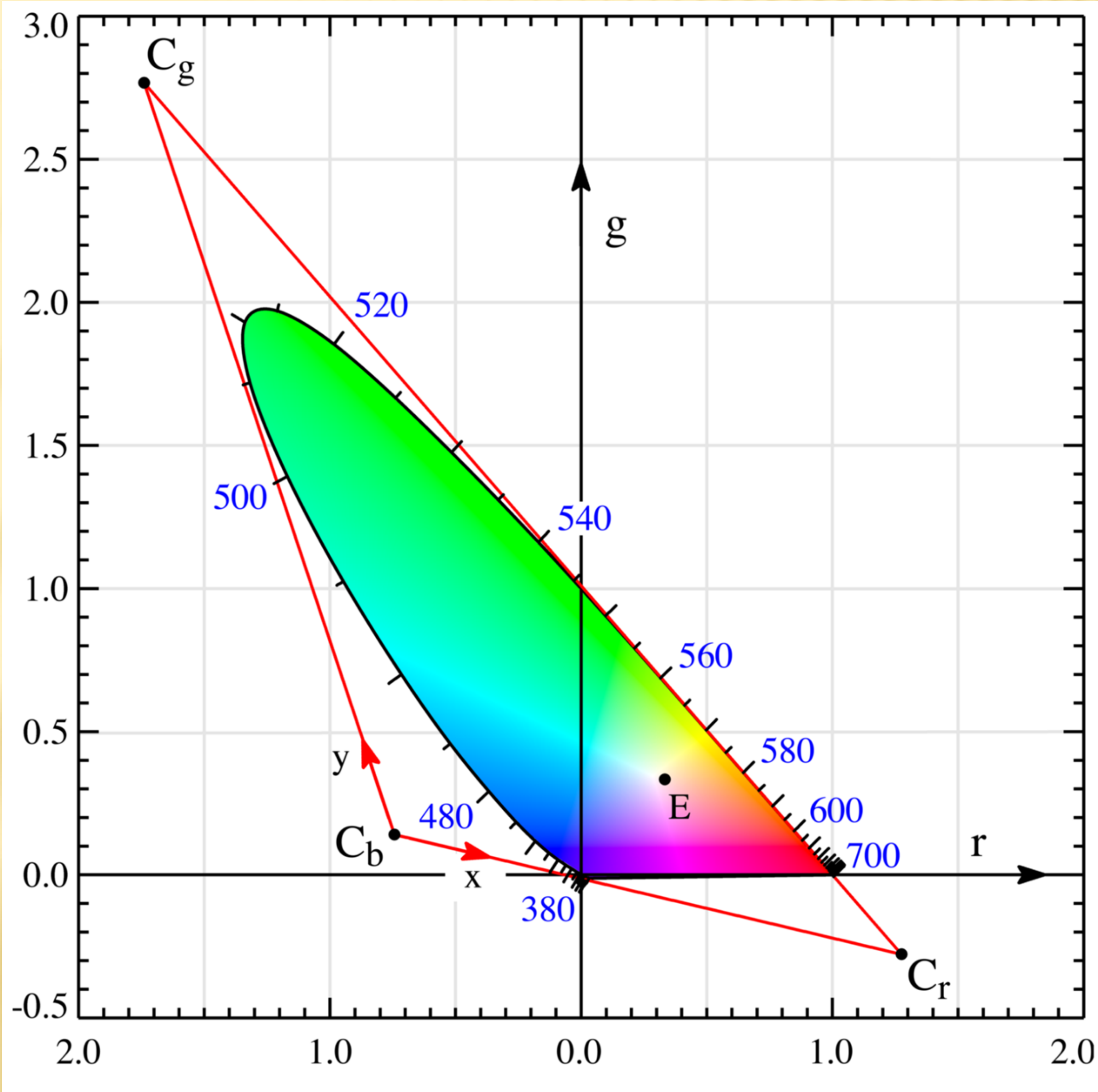


COLOR SPACE

- 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.

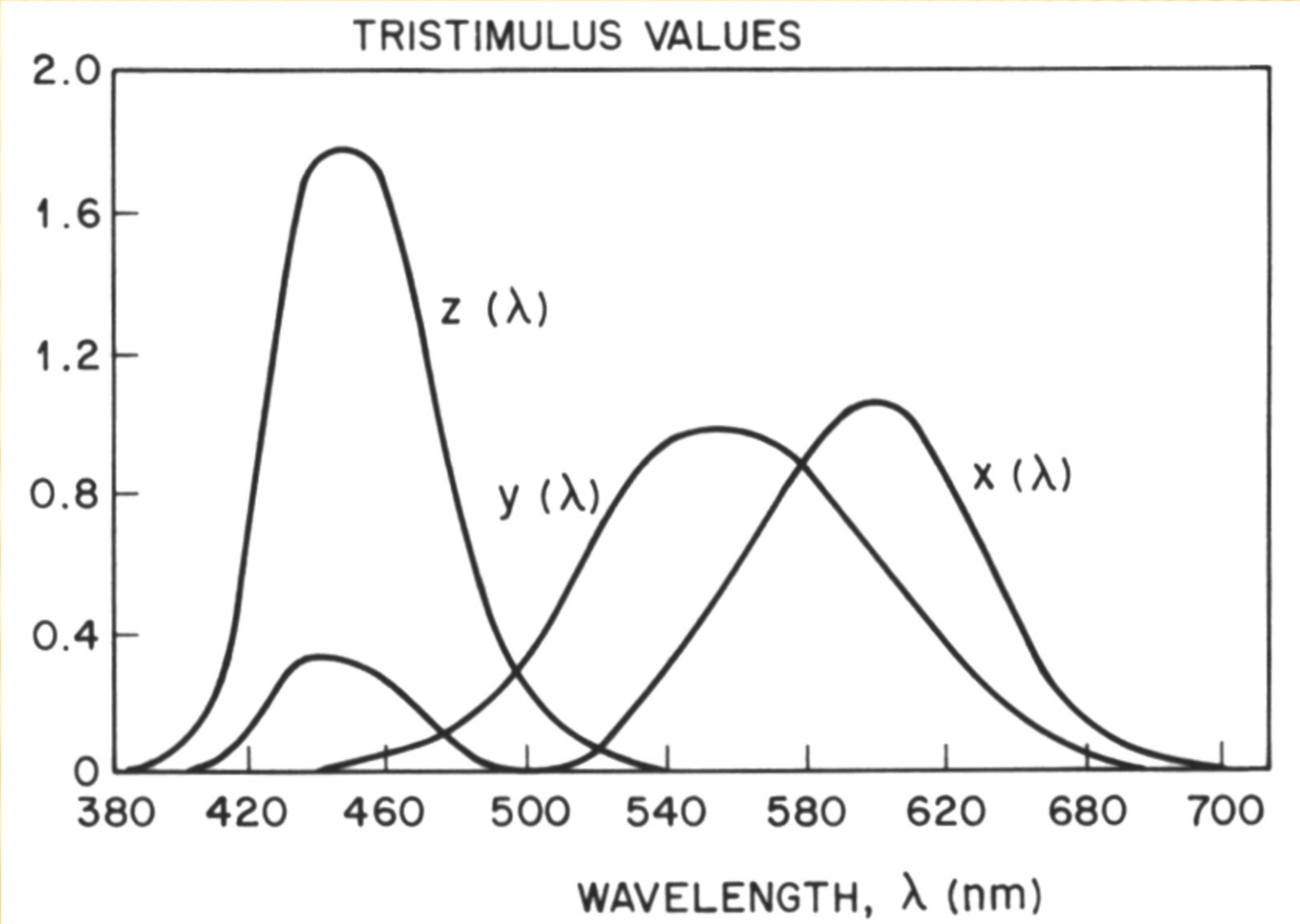


NEW CHROMATIC SPACE

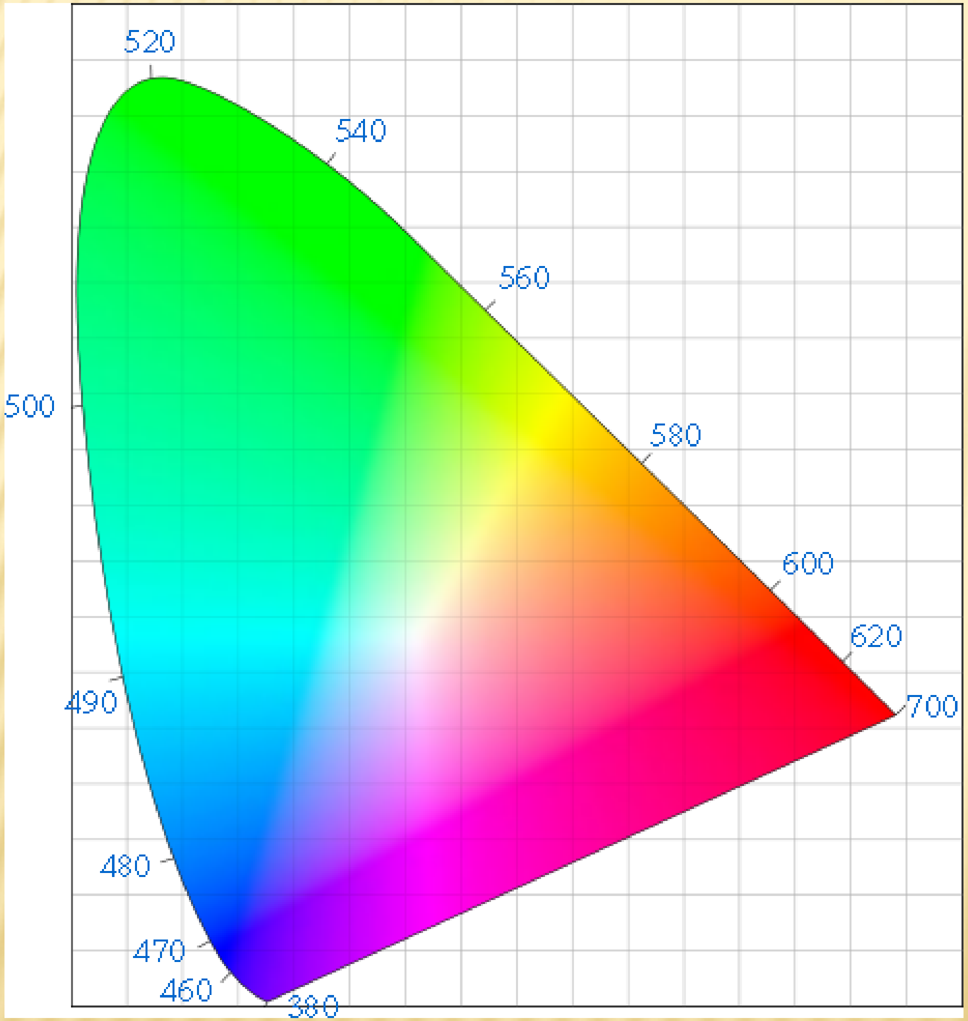
With a proper primary choice it is possible to obtain positive chomaticity space (for each λ).

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

CHROMATIC SPACE X Y Z



CHROMATIC COORDINATES X Y

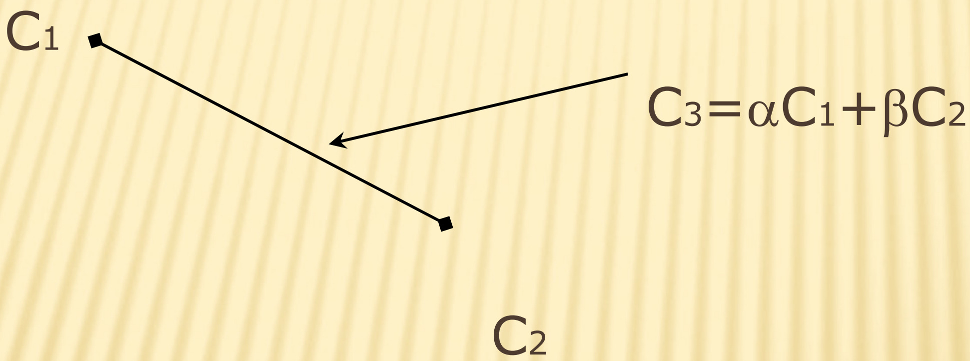


C=aX+bY+cZ,
Where a+b+c=T

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



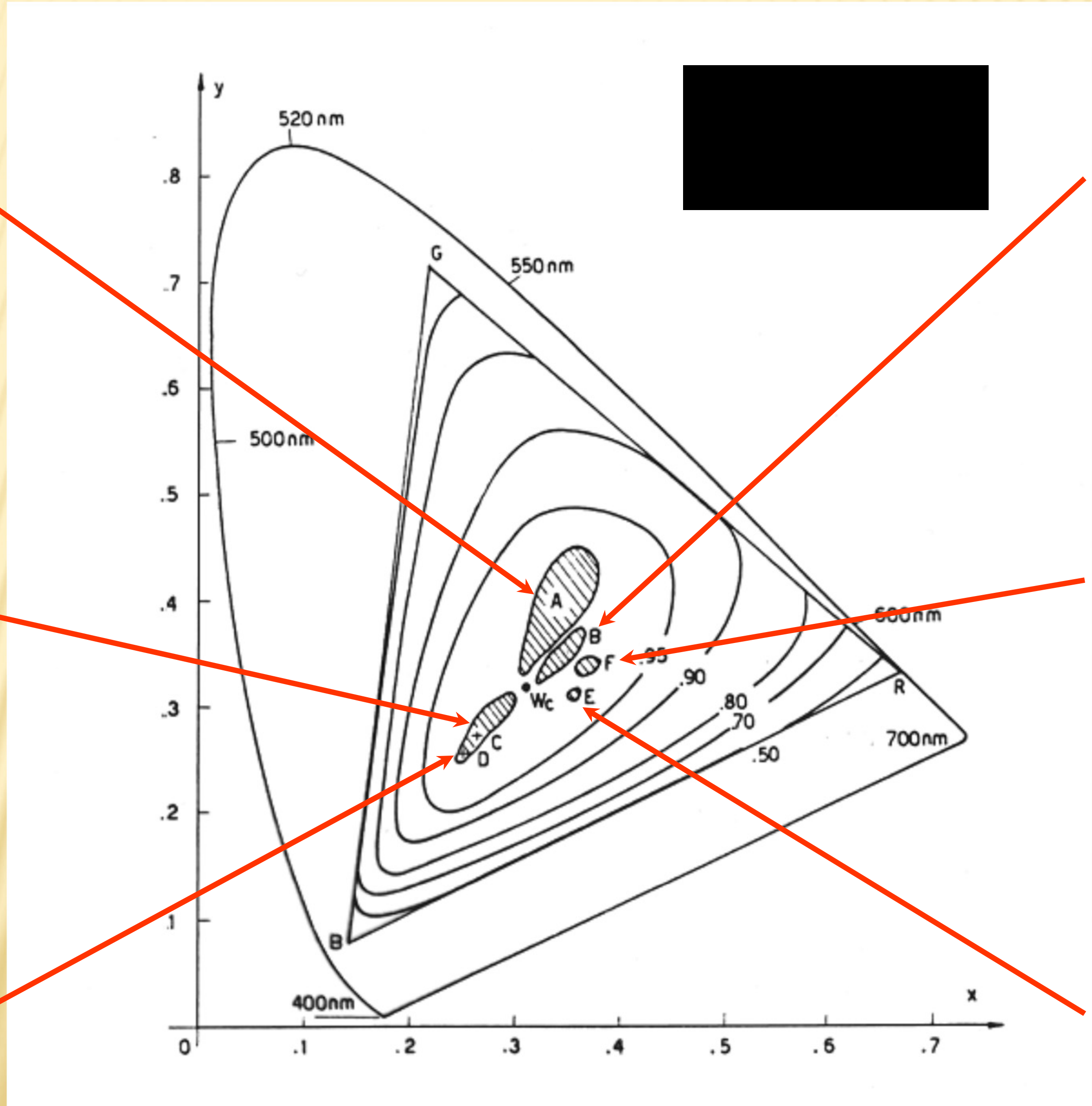
- Once three primary sources are chosen a triangle is defined in the chromatic space.

FUNDAMENTAL COLORS IN TELEVISION

leaves

sky

sea

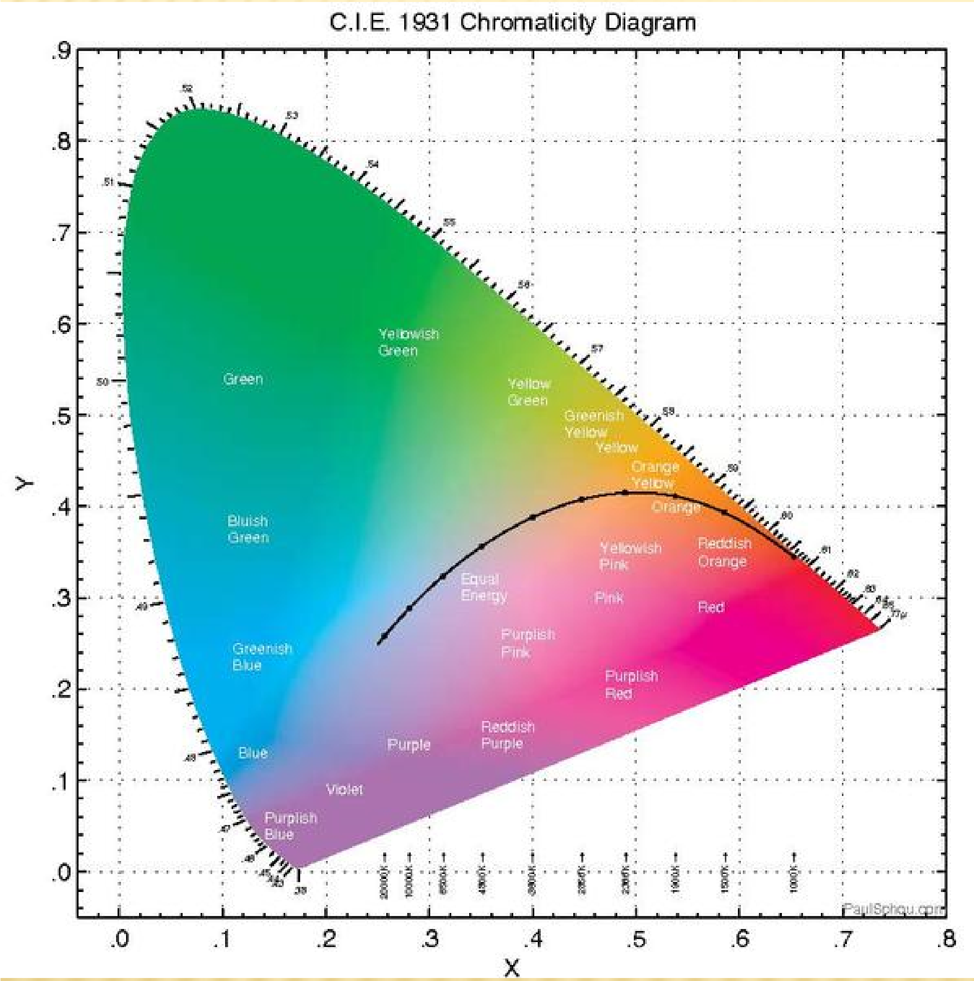


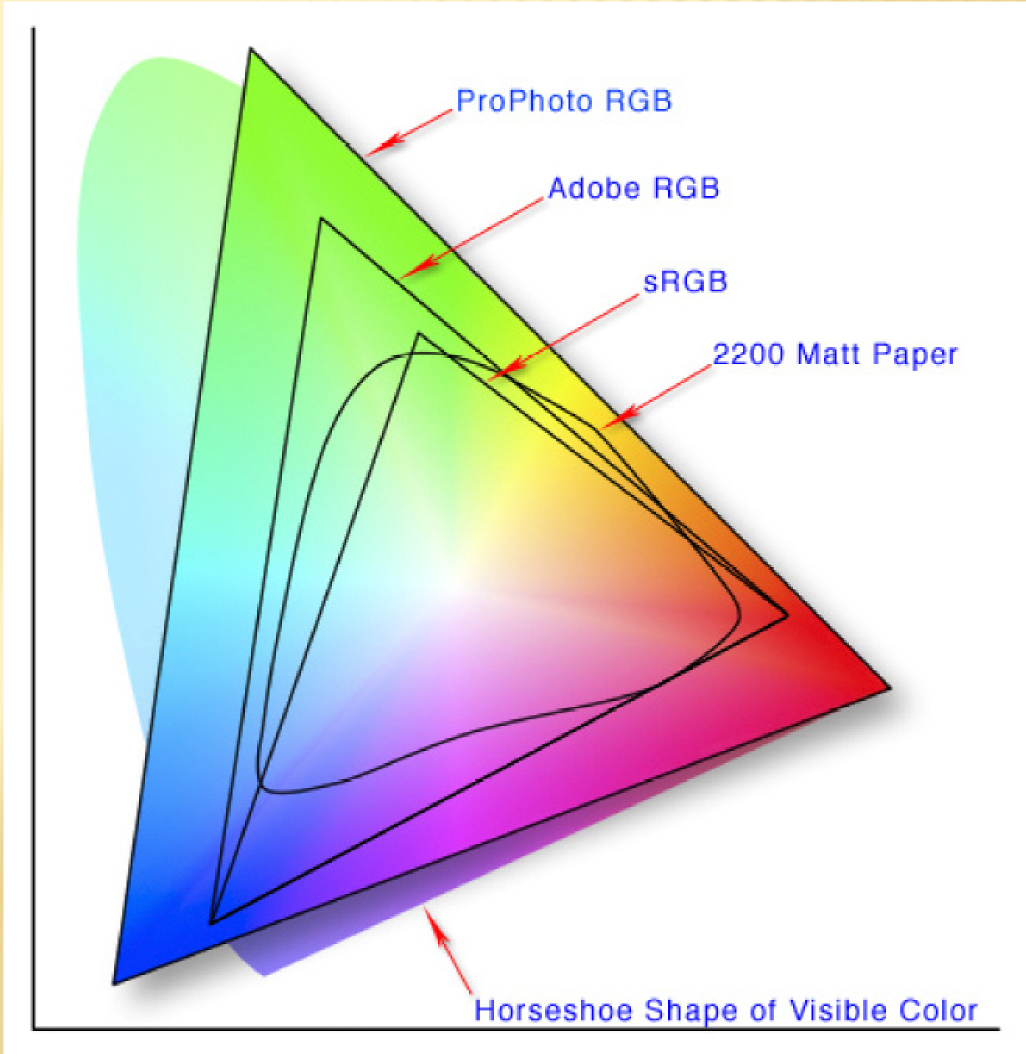
ground

skin

roofs

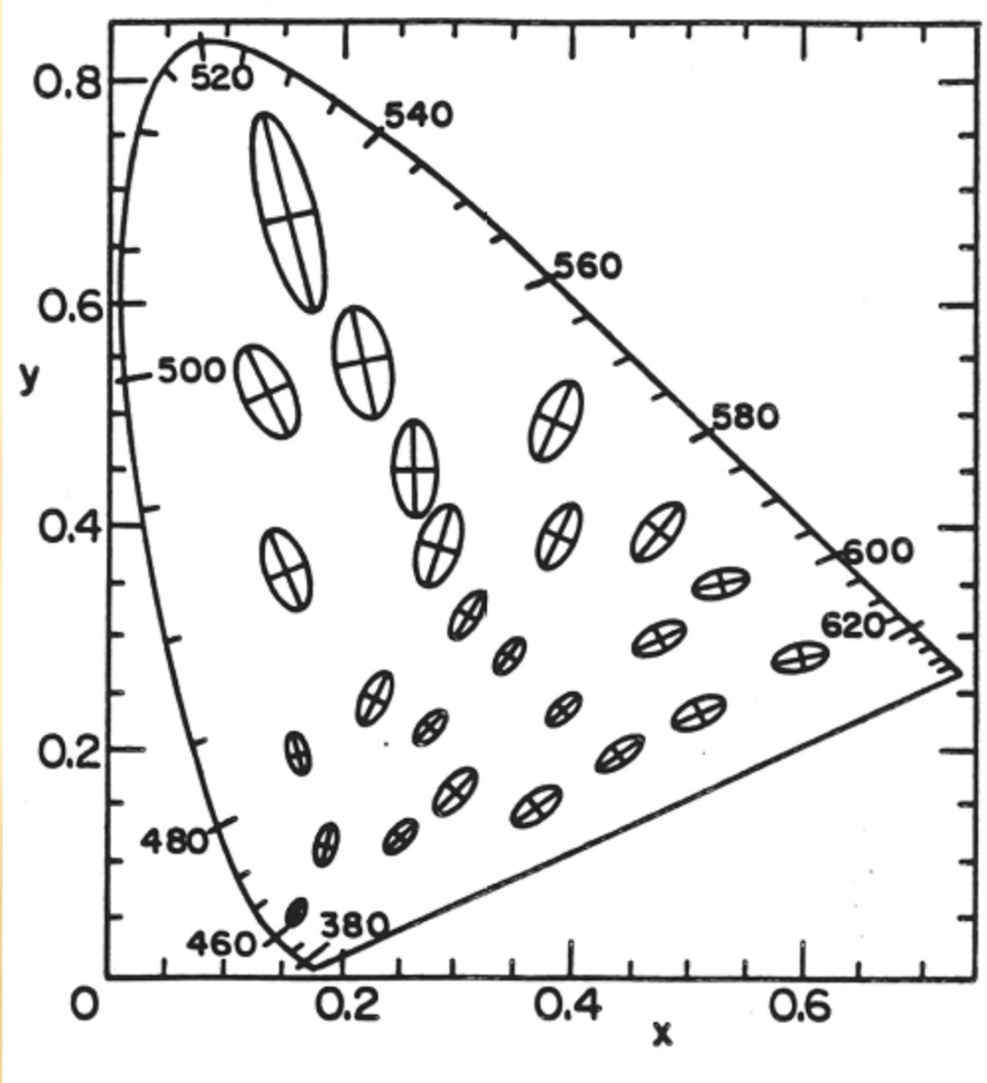
FUNDAMENTAL COLORS





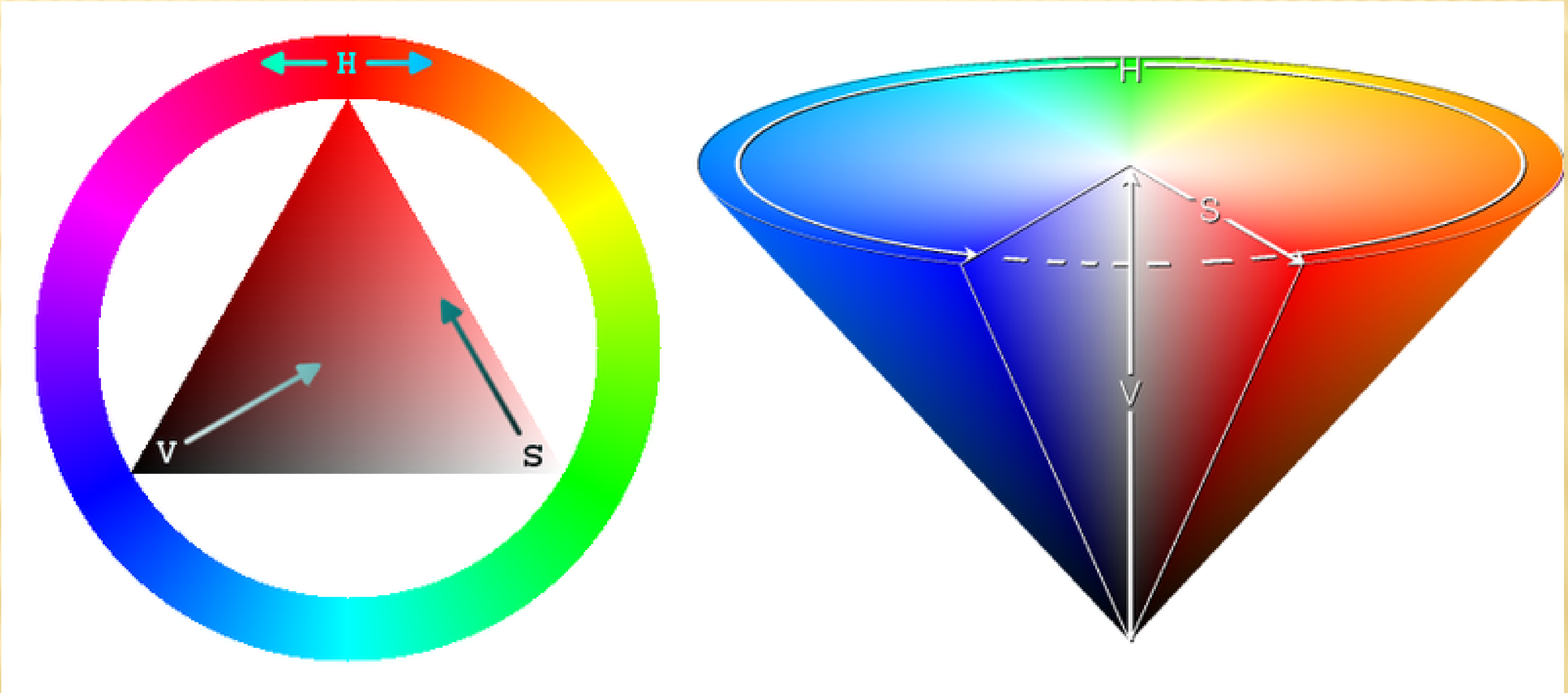
COLORS PERCEPTIVITY

- 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:

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

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

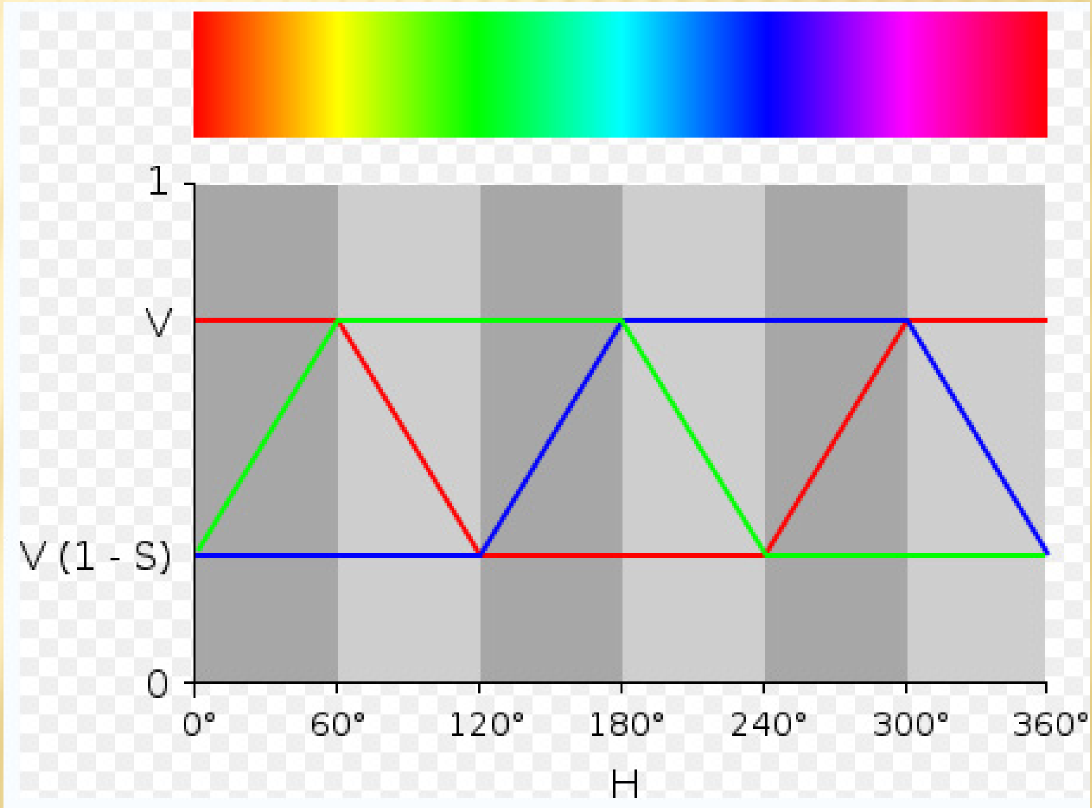
$$p = v \times (1 - s)$$

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

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

- Co

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



ADVANCED TOPICS ON VIDEO PROCESSING

Appendix I

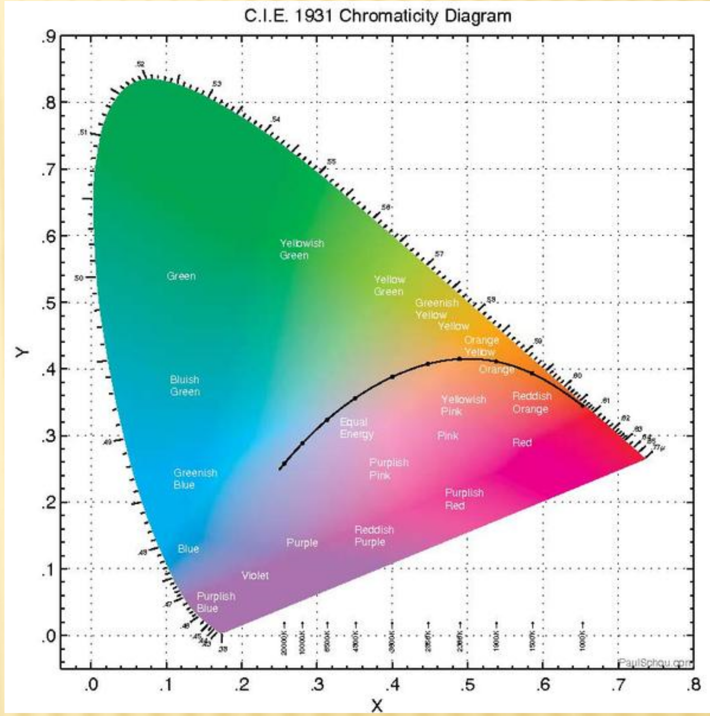
Further aspects of Colorimetry

CIE XYZ COLOR SPACE

- The CIE RGB color space is one of many RGB color spaces, distinguished by a particular set of monochromatic (single-wavelength) primary colors.
- In the 1920s, W. David Wright and John Guild independently conducted a series of experiments on human sight which laid the foundation for the specification of the CIE XYZ color space.
- Gamut of the CIE RGB primaries and location of primaries on the CIE 1931 xy chromaticity diagram.
- The experiments were conducted by using a circular split screen 2 degrees in size, which is the angular size of the human fovea. On one side of the field a test color was projected and on the other side, an observer-adjustable color was projected. The adjustable color was a mixture of three primary colors, each with fixed chromaticity, but with adjustable brightness.
- The observer would alter the brightness of each of the three primary beams until a match to the test color was observed. Not all test colors could be matched using this technique. When this was the case, a variable amount of one of the primaries could be added to the test color, and a match with the remaining two primaries was carried out with the variable color spot. For these cases, the amount of the primary added to the test color was considered to be a negative value. In this way, the entire range of human color perception could be covered. When the test colors were monochromatic, a plot could be made of the amount of each primary used as a function of the wavelength of the test color. These three functions are called the *color matching functions* for that particular experiment.

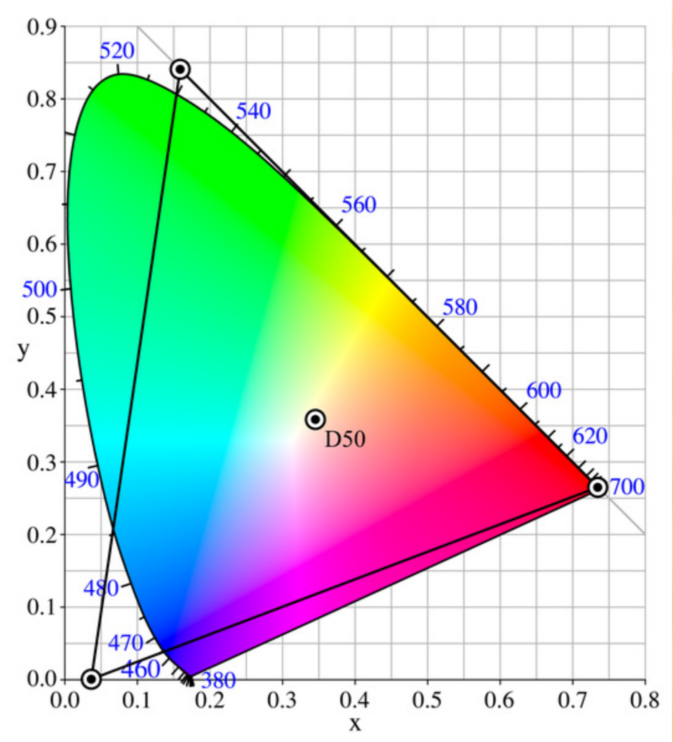
THE CIE COLOR SPACE

- The CIE 1931 RGB Color matching functions.
- The color matching functions are the amounts of primaries needed to match the monochromatic test primary at the wavelength shown on the horizontal scale.
- Although Wright and Guild's experiments were carried out using various primaries at various intensities, and a number of different observers, all of their results were summarized by the standardized CIE RGB color matching functions , , and , obtained using three monochromatic primaries at standardized wavelengths of 700 nm (red), 546.1 nm (green) and 435.8 nm (blue). The color matching functions are the amounts of primaries needed to match the monochromatic test primary. These functions are shown in the plot on the right (CIE 1931).
- The primaries with wavelengths 546.1 nm and 435.8 nm were chosen because they are easily reproducible monochromatic lines of a mercury vapor discharge. The 700 nm wavelength, which in 1931 was difficult to reproduce as a monochromatic beam, was chosen because the eye's perception of color is rather unchanging at this wavelength, and therefore small errors in wavelength of this primary would have little effect on the results.



THE PROPHOTO RGB COLOR SPACE

- The **ProPhoto RGB color space**, also known as ROMM RGB, is an output referred RGB color space, developed by Kodak, that offers an especially large gamut designed for use with photographic output in mind. The ProPhoto RGB color space encompasses over 90% of possible surface colors in the CIE color space, and 100% of likely occurring real world surface colors making ProPhoto even larger than the Adobe Wide Gamut RGB color space.
- The ProPhoto RGB primaries were also chosen in order minimize hue rotations associated with non-linear tone scale operations. **One of the downsides to this color space is that approximately 13% of the representable colors are imaginary colors that do not exist and are not visible colors.** This means that potential color accuracy is wasted for reserving these unnecessary colors.
- When working in color spaces with such a large gamut, it is recommended to work in 16-bit color depth to avoid posterization effects. This will occur more frequently in 8-bit modes as the gradient steps are much larger.
- There are two corresponding scene space color encodings known as RIMM RGB intended to encode standard dynamic range scene space images, and ERIMM RGB intended to encode extended dynamic range scene space images.

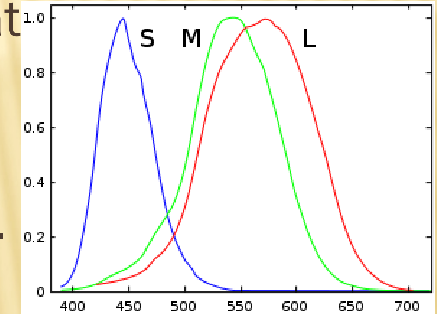


ProPhoto RGB (ROMM RGB) Encoding Primaries

Color	CIE x	CIE y
red	0.7347	0.2653
green	0.1596	0.8404
blue	0.0366	0.0001
white	0.3457	0.3585

WHAT ARE IMAGINARY COLORS

- **Non-physical, unrealizable**, or **imaginary colors** are points in a color space that correspond to combinations of cone cell responses that cannot be produced by any physical (non-negative) light spectrum. Thus, no object can have an imaginary color, and imaginary colors cannot be seen under normal circumstances. Nevertheless, they are useful as mathematical abstractions for defining color spaces.



- The spectral sensitivity curve of medium-wavelength ("M") cone cells overlaps those of both short-wavelength ("S") and long-wavelength ("L") cone cells. Light of any wavelength that interacts with M cones also interacts with S or L cones, or both, to some extent. Therefore, there is no wavelength, and no non-negative spectral power distribution, that excites only M cones without exciting S or L cones at all. The hypothetical excitation of the M cone alone would correspond to an imaginary color greener than any physical green, corresponding to a spectral power distribution with positive power in the green (medium) wavelengths and (non-physical) negative power in the red and blue (long and short) wavelengths.

REAL COLORS AND IMAGINARY COLORS

- Real colors are colors that can be produced by a physical light source. Any additive mixture of two real colors is also a real color. When colors are displayed in the CIE 1931 XYZ color space, additive mixture results in a color along the line between the colors being mixed. By mixing any three colors, one can therefore create colors in the triangle between the three colors—this is called the gamut formed by those three colors, which are called primary colors. Any colors outside of this triangle can not be obtained.
- When defining primaries, the goal is often to leave as many real colors in gamut as possible. Since the region of real colors is not a triangle (see illustration), it is not possible to pick three real colors that span the whole region. It is possible to increase the gamut by selecting more than three real primary colors, but since the region of real colors is not a polygon, there will always be some colors at the edge left out. Therefore, one selects colors outside of the region of real colors as primary colors; in other words, imaginary primary colors. Mathematically, the gamut created in this way contains so-called “imaginary colors”

PERCEPTION OF IMAGINARY COLORS

- If a saturated green is viewed until the green receptors are fatigued and then a saturated red is viewed, a perception of red more intense than pure spectral red can be experienced. This is due to the fatigue of the green receptors and the resulting lack of their ability to desaturate the perceptual response to the output of the red receptors.