Light and Color

Graphics Systems /

Computer Graphics and Interfaces

Chromatic Light

In **perceptual terms** we evaluate Chromatic Light by the following:

1. **Hue (Hue):** distinguish between various colors like red, green, yellow, etc..

2. **Saturation:** refers to the distance to the gray color with equal intensity

   Ex: green is very saturated, but pink or sky-blue is low saturated.

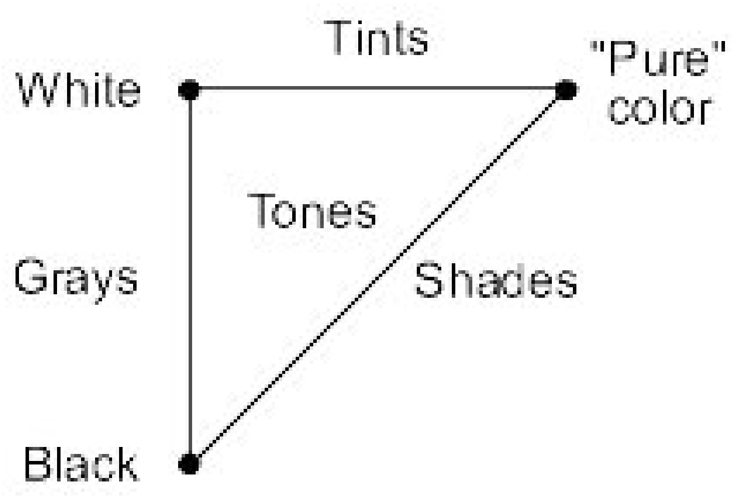
   With “more white included”, colors become less saturated

3. **Intensity (Lightness):** reflected intensity

4. **Brightness (Brightness):** emitted intensity (lamp, sun, ...)

Chromatic Light

The artists specify color as different *tints*,*shades* and *Tones* of a pure pigment



Tints (*Tintos*): result from mixing white pigment to a pure pigment (less saturated)

Shades (*Sombreados*): result of mixing black pigment to a pure pigment (decreases intensity)

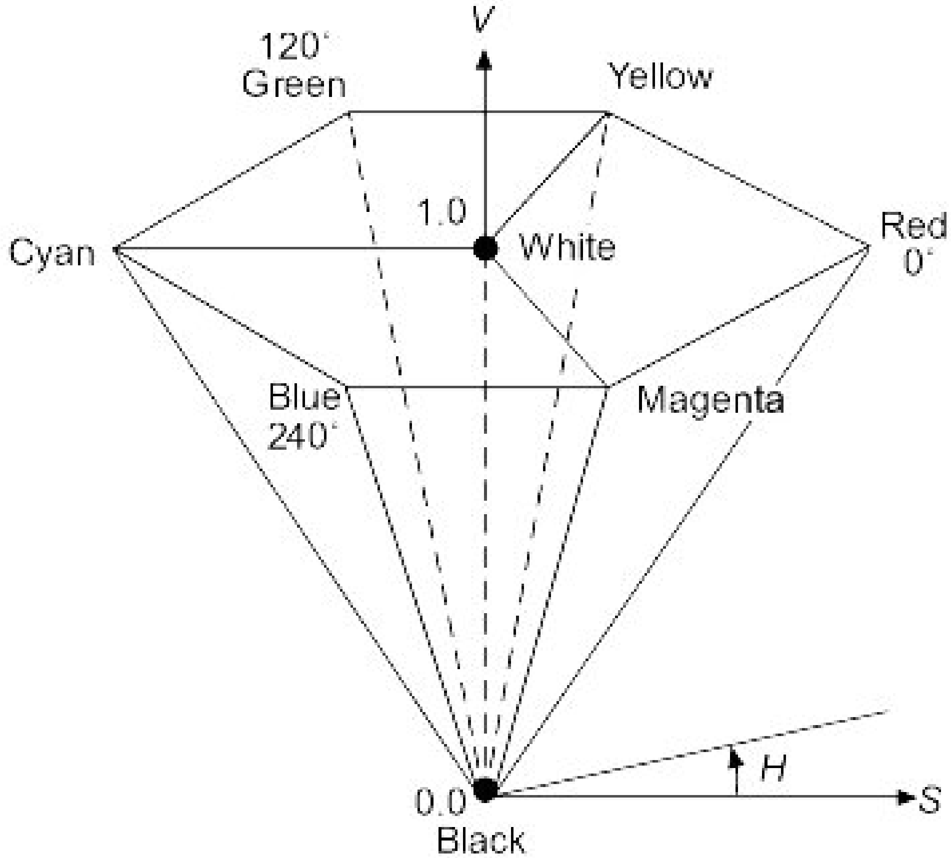
Tones (*Tons*): result from mixing white and black pigment to a pure pigment

Grays (*Cinzentos*): result of joining black and white pigment

→ The colors obtained by the referred mixture are the same color Hue (*Matiz, cor pura*) with different intensity and saturation.

Chromatic Light

HSV Model: generalization of the color definition used by the artists. Some programs allow the specification of color through this diagram.



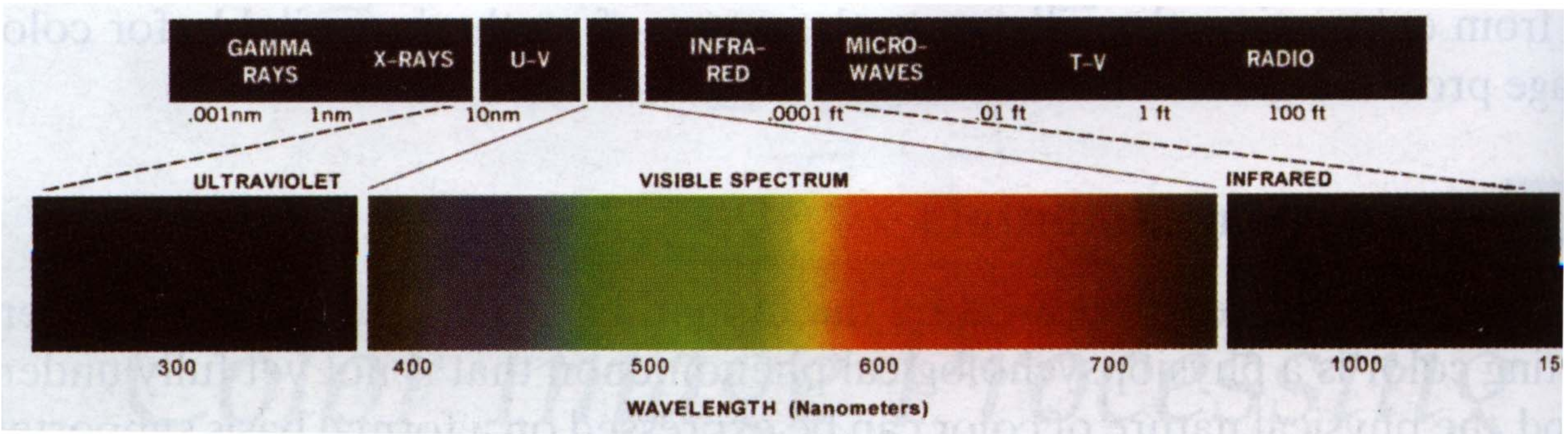
Chromatic Light

The above specifications are subjective → it is necessary to use physics to objectively quantify the color.

Light = Electromagnetic spectrum: the colors (visible light) represent a narrow band of the spectrum

- Lowest Frequency visible: Red with **λ** = 700 nm
- Highest Frequency visible: Violet with **λ** = 400 nm
- Frequency and wavelength: $\mathbf{c = \lambda . f}$

where **c** is the speed of light ($3 * 10^{10}$ cm / s)



Chromatic Light

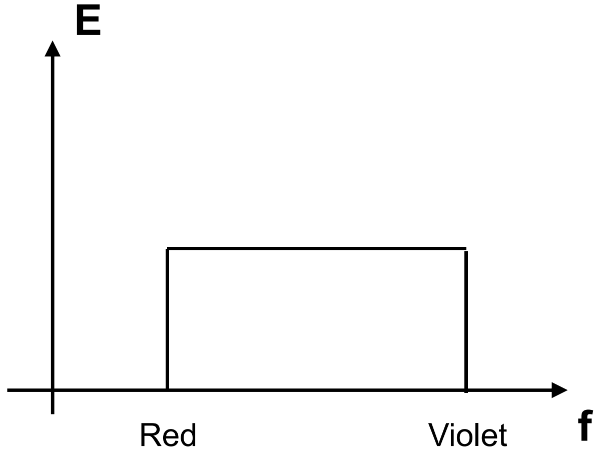
Colorimetry: Branch of physics that studies the color

- Dominant Wavelength: Dominant color (Hue)
- Luminance: Light intensity (Brightness)
- Excitation purity: Saturation

Color + Saturation = *Chromaticity (Cromatância)*, color definition regardless of the intensity of light

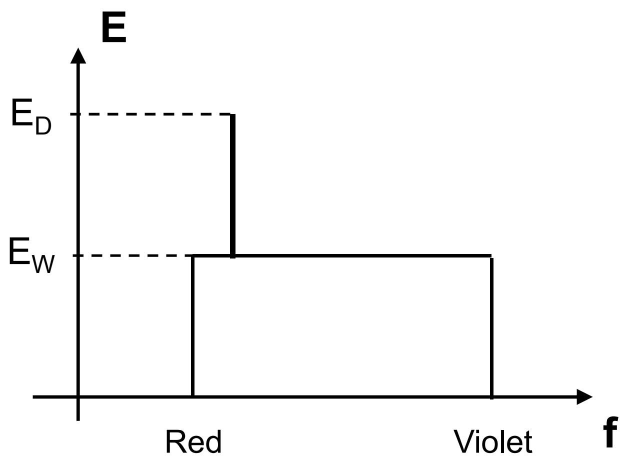
Energy Distribution of a white light source:

All frequencies are present with equal energy.



Chromatic Light

Energy Distribution of a light source with dominant wavelength near red:



E_D - Dominant Energy

E_W - Energy for white

The higher E_D- E_W, the purer the color will be issued.

$E_W = 0$, 100% purity

$E_W = E_D$, 0% purity (white)

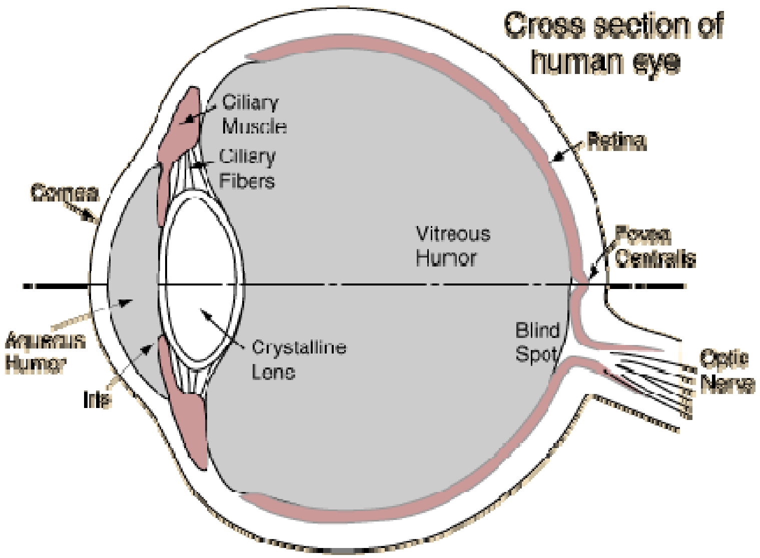
$$Sat = \frac{E_D - E_W}{E_D}$$

Luminance = Area under the curve of the total energy emitted

Chromatic Light - human eye response

Rods (*bastonetes*): Are sensitive to low light levels and do not distinguish color

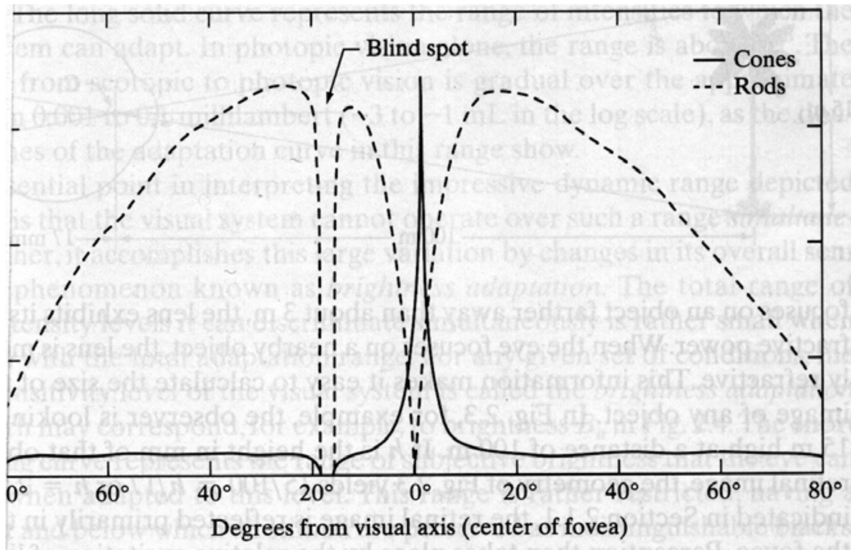
Cones: Located mainly in *fóvea*, they interpret color; low sensitive in low light conditions..



135000

90000

45000



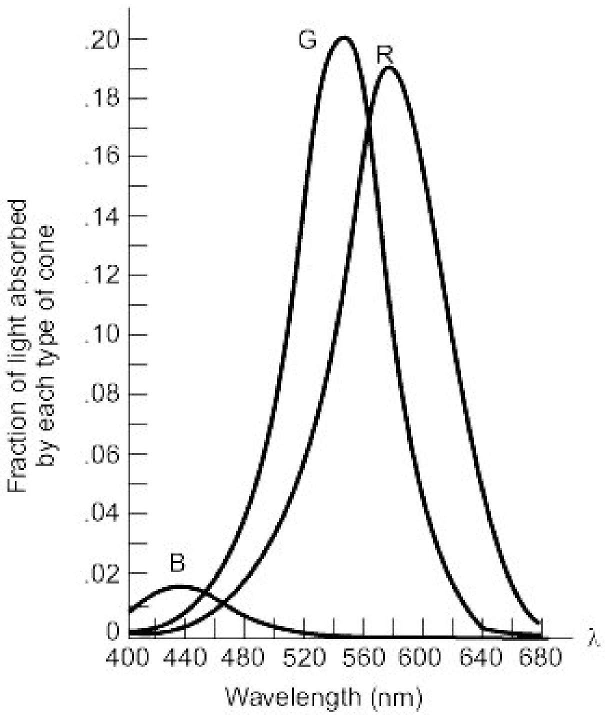
Distribution of rods and cones in the retina

Number of rods and cones per mm^2

Chromatic Light - human eye response

Theory of tri-stimulus:

There are 3 types of cones, whose response to light is maximum in Blue, Red and Green, respectively.



Response obtained for each type of cone

Due to the light absorption characteristics of the human eye, the colors are represented as a combination of so-called primary colors of R (red), G (green) and B (blue).

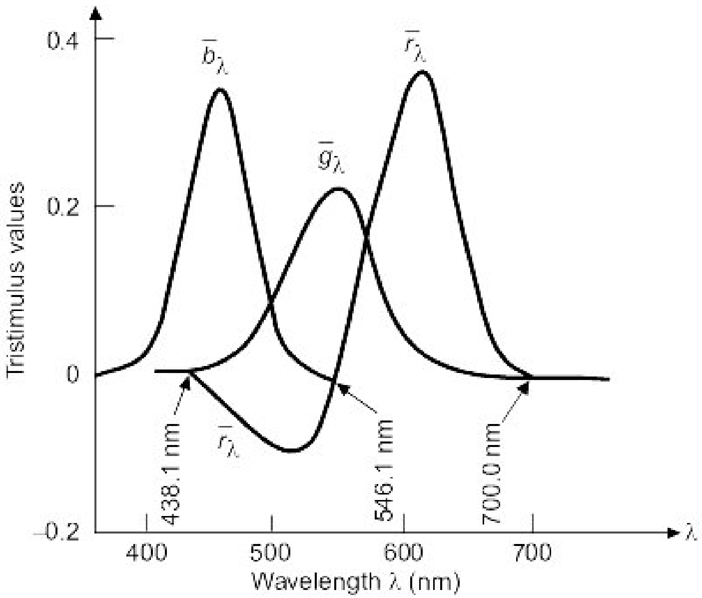
In the graph, there is a lower response of the eye to the blue light.

Application: Colorimetric conversion to grayscale

GRAY = 21% R + 72% G + 7% B

Chromatic Light - human eye response

Amount needed of the 3 primary colors to achieve all wavelengths of the visible spectrum colors with constant luminance:



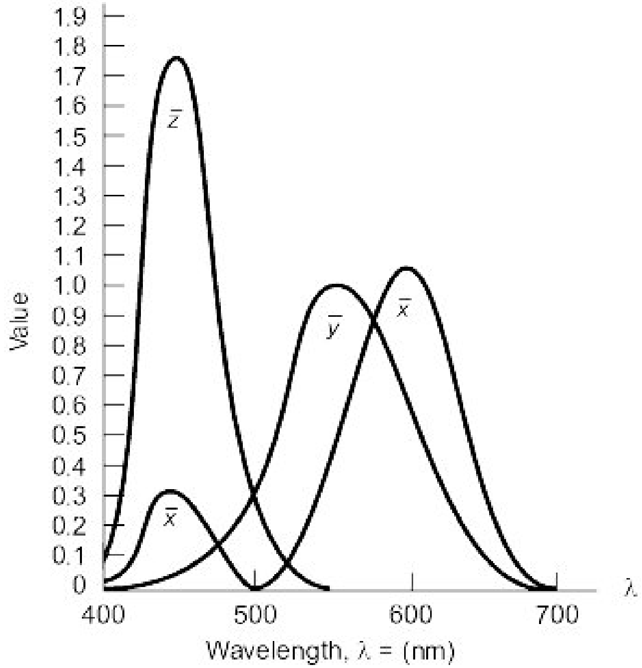
- Negative values in the figure mean that we can not get all the colors of the sum of the primary colors R, G, B.

- Thus, in CRT monitors, based on the sum of the 3 primary colors, we can not represent all the visible colors.

Chromatic Light - Model CIE

- The representation of color by mixing three primary colors is desirable, but the need for negative weights is not convenient.

- To overcome this difficulty, in 1931, the *Commission Internationale de l'Eclairage* *(**CIE**)* defined 3 imaginary primary colors **X, Y** and **Z** to replace **red, green** and **blue**.



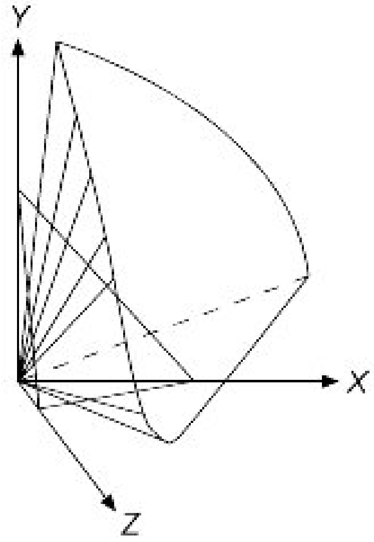
Primary colors:

- Imaginary, **X, Y** and **Z**
- **Y** coincides with the luminous-efficiency function

$$C = x\,\mathbf{X} + y\,\mathbf{Y} + z\,\mathbf{Z}$$

The color is obtained with the x, y and z weights of primaries **X, Y** and **Z**

Chromatic Light - Model CIE



- The figure shows the conical volume that contains the visible colors.

The **values of Chromaticity** are defined by normalizing against $X + Y + Z$, ie luminance

$x = X / (X+Y+Z)$ $y = Y / (X+Y+Z)$ $z = Z / (X+Y+Z)$

The **Chromaticity values** x, y, z:

- Depend on the dominant wavelength and saturation
- Do not depend on the luminance

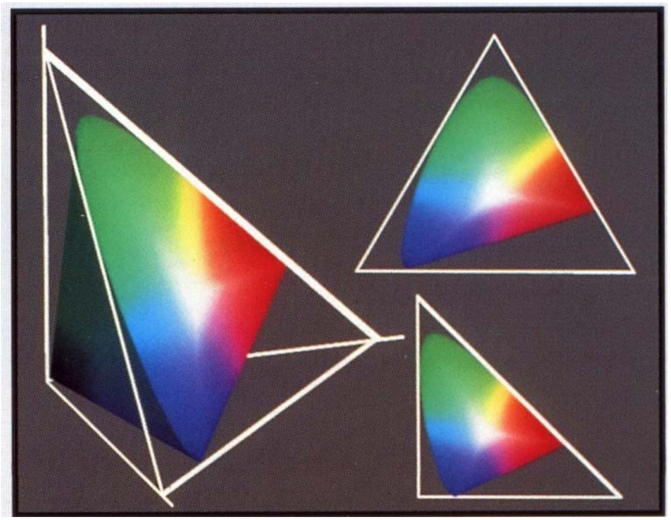
Note that:

$x + y + z = 1$, or: x, y, z are in the plane $X + Y + Z = 1$ as shown in the figure

Chromatic Light - CIE Diagram

- x, y and Y define a color:

$X = (x / y) * Y$ $Y = Y$ $Z = (1 - x - y) / y * Y$



The projection of the X + Y + Z = 1 plane (X, Y) corresponds to the **CIE Chromaticity diagram**

Chromatic Light - CIE Diagram

- **x, y define a color (not considering) the luminance.**

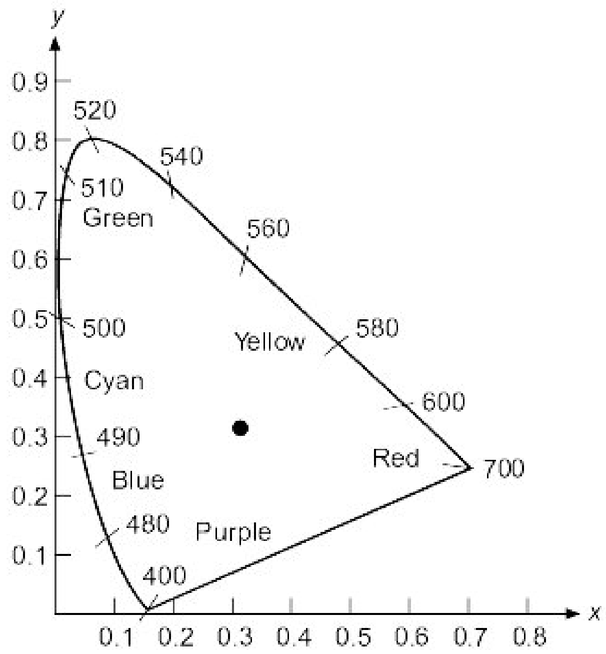
- Drawing x and y for all visible colors, gives the CIE diagram of Chromaticity

- For each point of that region there are several colors with the same Chromaticity but with different luminances.

- The colors are 100% pure on the boundary curve

- The central point corresponds to the color **white**

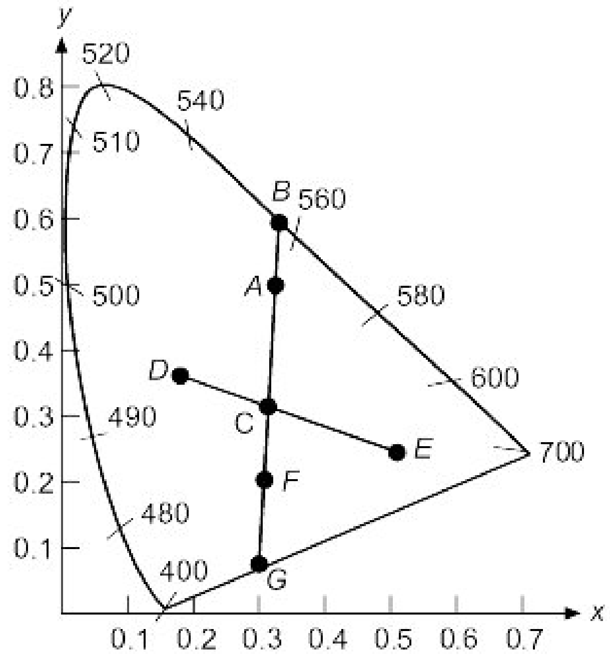
CIE Chromaticity diagram



Chromatic Light - CIE Diagram

Determining the dominant wavelength:

- Adding two colors, the resulting color is on the line joining the two colors added.
- Color **A** can be seen as **B + C,** so **B** is the dominant wavelength of **A**.



Determination of the purity of a color:

- **AC / BC** expresses the purity / saturation (in percentage) of the color **A**.
- The closer **A** is from **C**, the more white will be included in **A** so this color becomes less pure (less saturated).

- **NOTE: "C" is the white color**

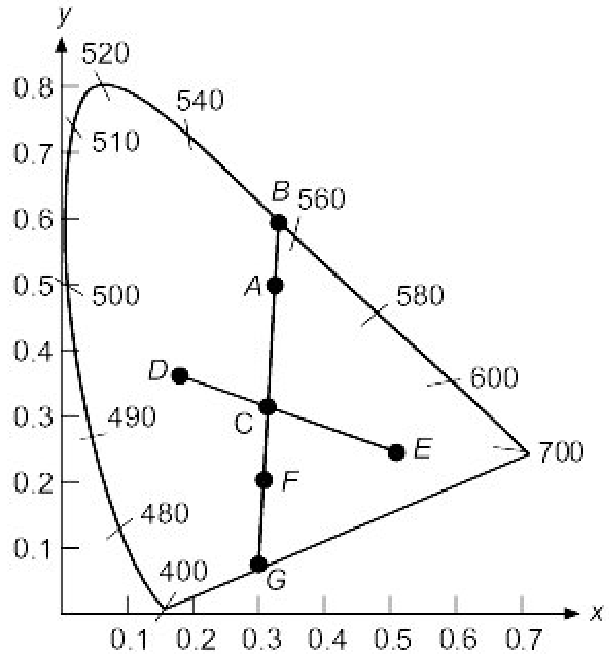
Chromatic Light - CIE Diagram

Complementary colors:

- Two colors that, once added, become white
- Ex: Colors **D** and **E**.

Non spectral colors:

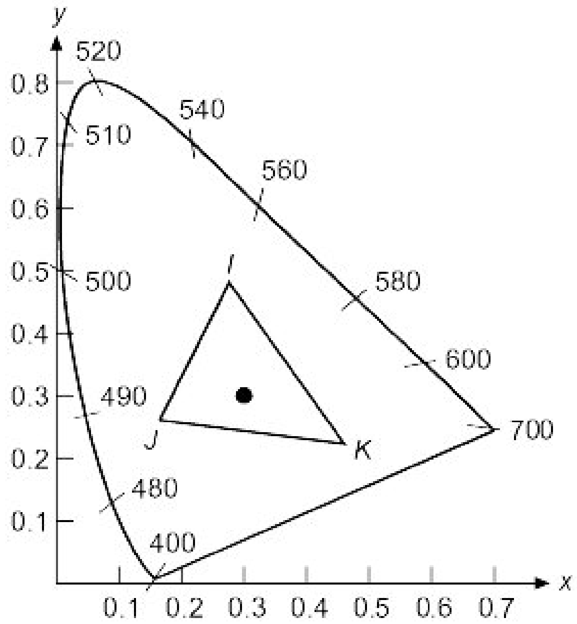
- Colors which can not be defined by a dominant wavelength. Ex: color **F**.
- In this case, the dominant wavelength is defined as the complement of the wavelength where the line joining **F** and **C** intersects in **B** (In this example 555 nm).
- The purity /saturation of a color is defined by **FC / GC**.
- Non-spectral colors are purple and magenta



Chromatic Light - CIE Diagram

Range of colors:

- The colors of the segment **IJ** are obtained by the mixture of colors **I** and **J**.
- Joining the color **K**, one may obtain any color situated inside the triangle.

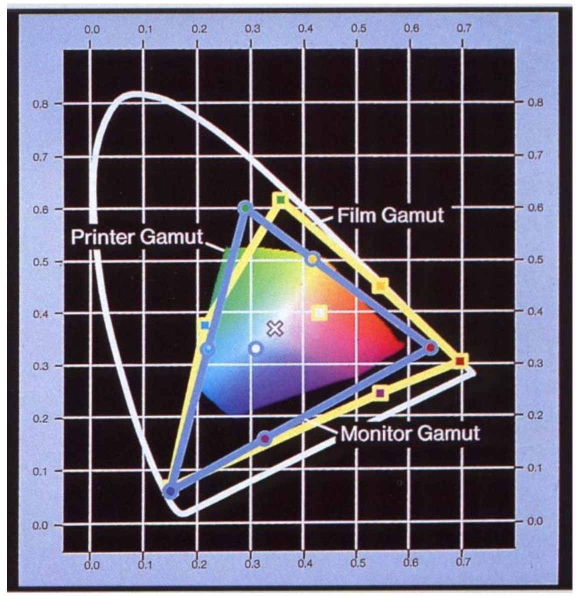


Coverage of colors in the CIE model:

- No triangle covers all colors of the CIE Diagram
- **Conclusion**:
- No set of 3 colors is sufficient to produce all the colors of the CIE Diagram.

→ **Some colors are not obtainable by the addition of R, G, and B.**

The diagram is also used to compare the range of colors available in devices such as monitors and printers.



Chromatic Light
Color models in Raster Systems

The aim of a color model is to provide a format in which colors can be coded clearly. There are models oriented to the User Interface and to the Hardware.

Color Model for monitors

- RGB additive model

Color Model for printers

- Subtractive CMY model

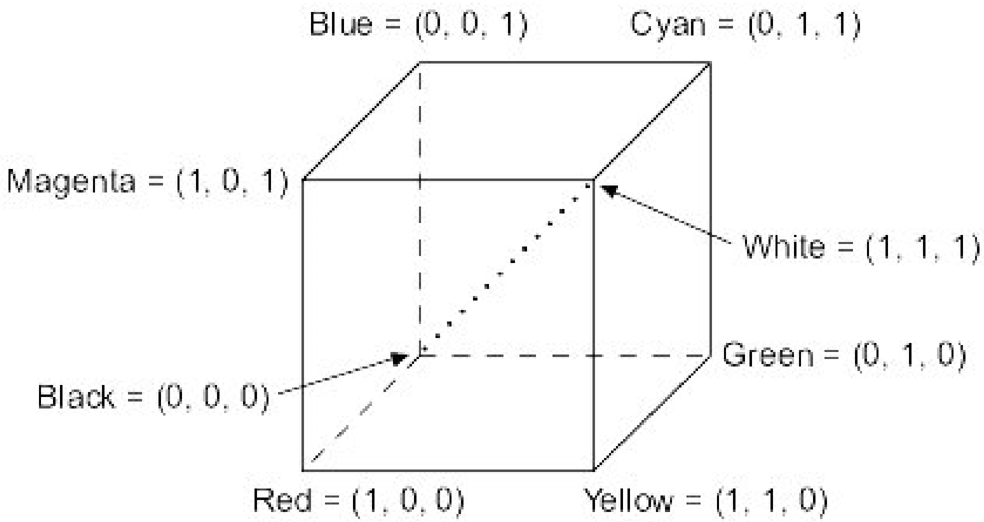
Color Model for user interfaces

- Intuitive model HSV

Chromatic Light
RGB color model

Model used in Monitors

- Additive model
- Primary colors: R, G, B
- Black = (0, 0, 0)
- White = (1, 1, 1)



RGB Cube

- The diagonal (0, 0, 0) to (1, 1, 1) represents the gray levels, with an equal contribution of the three primary colors.

Chromatic Light
CMY color model

Model used in printers

- Primary colors: **Cyan**, **Magenta** and **Yellow**

  These are the complementary colors of R, G and B respectively.
- The colors are specified by what is removed or subtracted from the **white light,** Instead of what is **added to black** (such as RGB).
- The cube is identical to the RGB model; white is on the origin of coordinates.

  White = (0, 0, 0), and Black = (1, 1, 1)

The white paper reflects white light (***red*** + ***green*** + ***blue)***

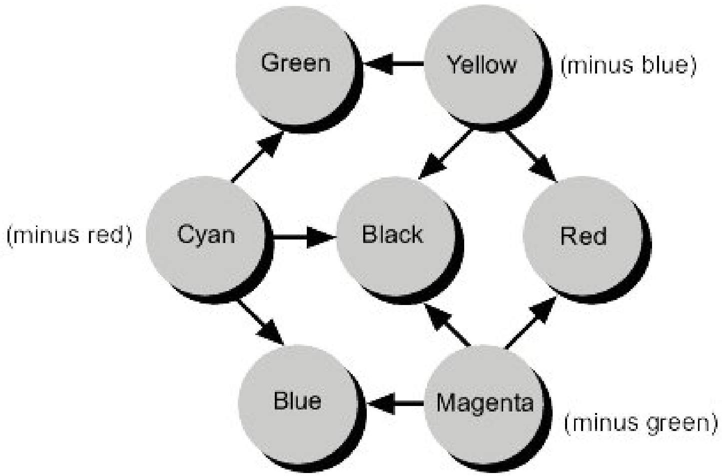
Example:

If the surface is covered with ink ***cyan:***

→ ***cyan*** absorbes color ***red***;

→ Reflected light is only **green + blue**

Chromatic Light
CMY color model



Transformation RGB to CMY:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

In RGB, Cyan = (0,1,1)

In CMY, cyan = (1,0,0)

Transforming CMY to RGB:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix}$$

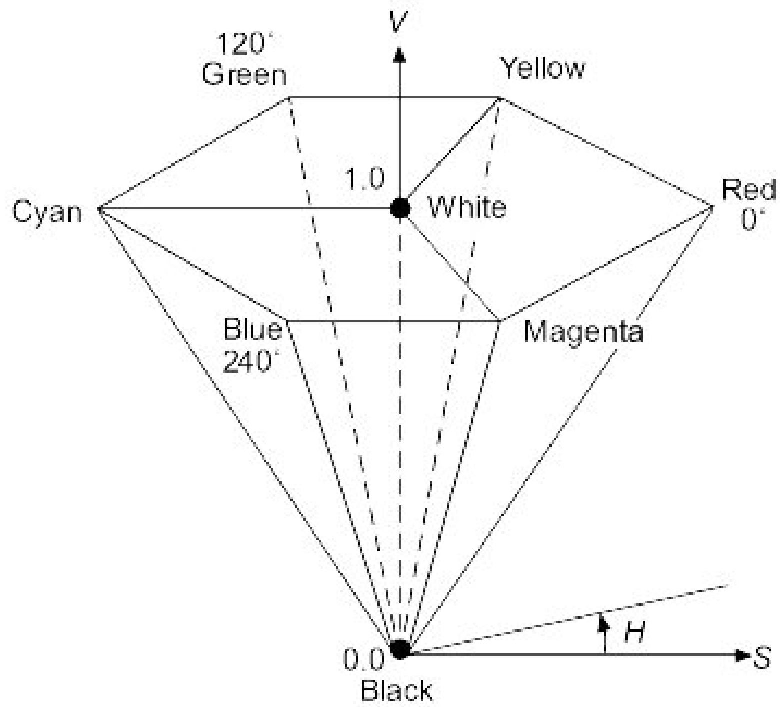
Chromatic Light
HSV model

Model oriented for the user interface

- HSV (Hue, Saturation, Value)
- Top: V = 1, where the brighter colors are situated
- Angle around the vertical axis:

  H = 0 ° corresponds to red

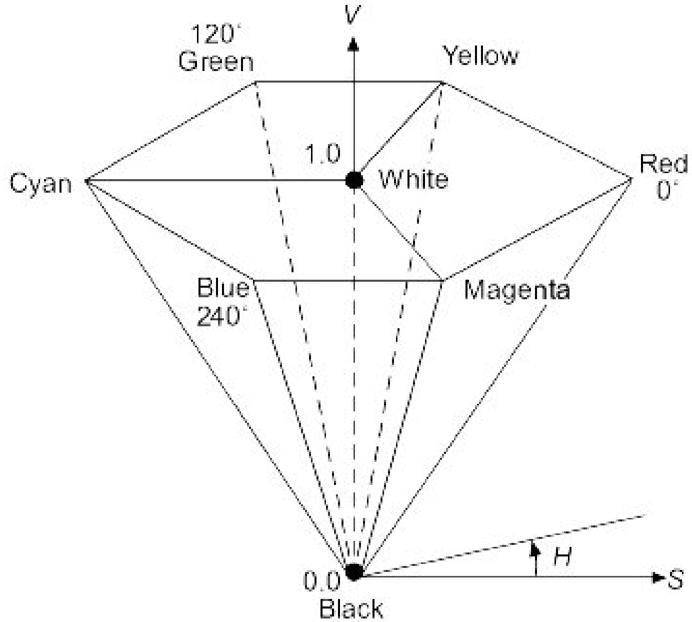
  H = 120º, corresponds to the green
- Complementary colors: differ from 180º
- Saturation: ranges from 0 (center) to 1 (in the cone periphery)



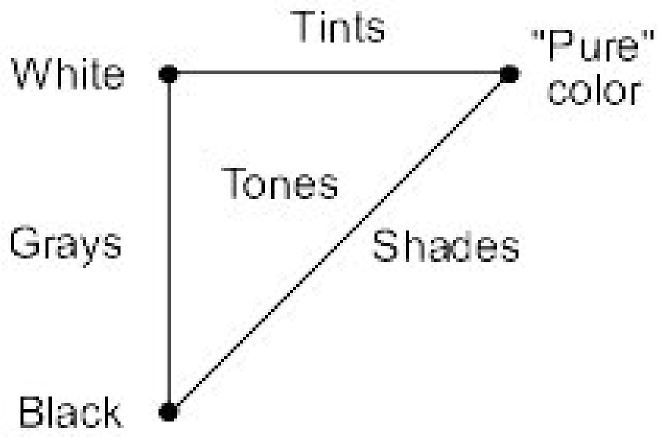
Chromatic Light
HSV model

Examples:

- S = 0 and V = 1 → white
- S = 0 and V = 0 .. 1 → gray
- H = 0 and S = 1 and V = 1 → pure red
- V = 1 and S = 1 → pure colors (border at the top)
- V = 1 and mixing white → tints (decrement of S)
- S = 1 and joining black → shades (decrement of V)
- varying S and V → tones

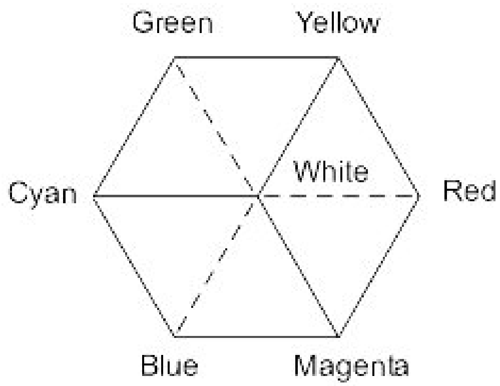


Corresponds to the model of the artists referred to in the beginning.



Chromatic Light
HSV model

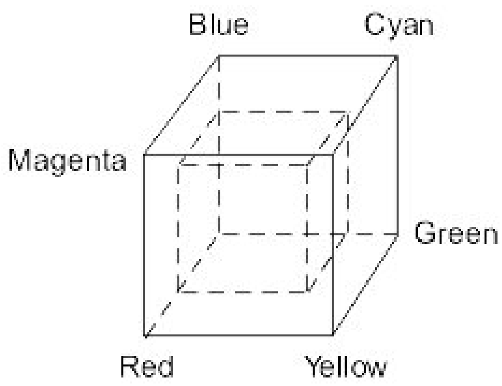
- The top of the pyramid of the HSV model corresponds to the projection of the RGB cube seen along its diagonal from white to black.



- Varying V from1 to 0

  The RGB cube becomes smaller

  The diagonal of the RGB cube corersponds to the V axis

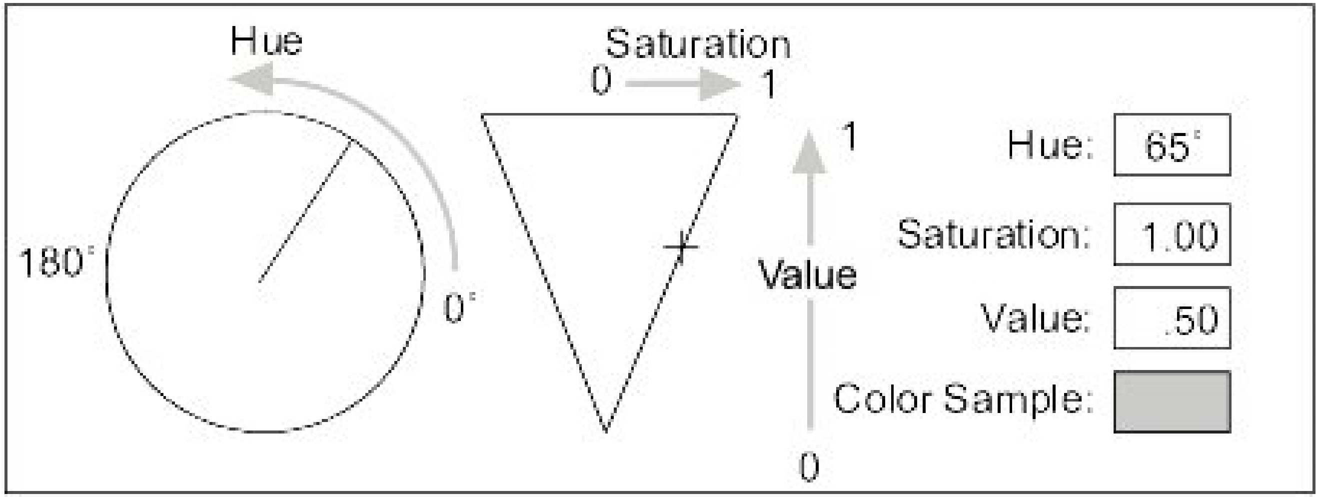


- It is this correspondence that the conversion algorithms between the two RGB systems are based:

  HSV → RGB and HSV → RGB

Chromatic Light
HSV model

Example of interface for interactive color specification:



Chromatic Light
Exercise

3. Sejam duas cores representadas, no modelo HSV, por $C_1=(h_1, 0.5, 0.8)$ e $C_2=(h_2, 0.8, 0.5)$, com h_1 e h_2 desconhecidos. Comente a possibilidade de cada uma delas corresponder aproximadamente a cada um dos três pontos P_1, P_2 e P_3 marcados no diagrama CIE junto.