COMP 371 -- Winter 2012

Computer Graphics

- Color

Why study Color ?

- *Synthesis of realistic* images has been the primary goal of computer graphics
- In this quest for *realism* it is necessary to relate the perceptual processing of visual information to the image display technology
- Understanding *color perception* and its relationship to both *color computation* and *color reproduction* becomes important

What is color ?

- ***Color*** is the brain’s reaction to a specific visual stimulus
- Subjective sensation experienced by the observer. There is no such thing called color without an observer
- Depends upon
  - Physics of light
  - Interaction of light with physical materials
  - Interpretation of the resulting phenomenon by the human visual system and the human brain

Physics of Light

- *Light* is a dynamic phenomenon which is difficult to observe
- Research is still on in trying to model the behavior of light
- Currently there are two models proposed by physicists to explain the behavior of light
  - *Wave Model*, which treats light as water waves
  - *Particle Model*, which assumes that light is made of tiny, invisible, vibrating particles called ***photons***
- From *color* point of view the ***particle model*** is used

Properties of Light

- The *photons* as they move along a straight line vibrate with a particular *frequency*
- Photons are assumed to carry certain amount of energy proportional to their frequency of vibration (frequency increases energy increases), given by

  $$E = h \cdot f$$

  where, h is the Planck's constant and f is the frequency of vibration
- Photon behavior is cyclic and has a repeated pattern

Properties of Light

- Distance traveled by the photon from the beginning of one cycle to the beginning of next is known as the wavelength, given by

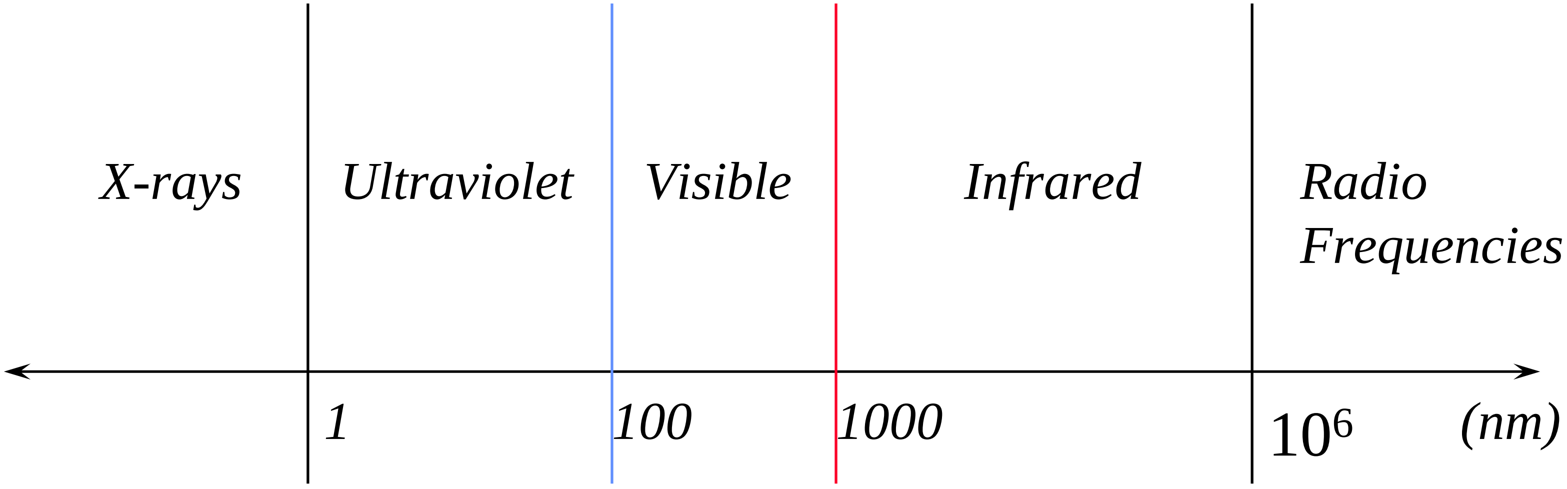
$$\lambda = \frac{c}{f}$$

where, c is the speed of light and f is the frequency

- Each photon has a wavelength associated with it and the perceived color of light depends on this wavelength
- The intensity of light depends on the number of photons present

Spectrum of Electromagnetic Radiation

- Light is a continuous electromagnetic spectrum, which can be geometrically represented by a 2D graph between wavelength v/s number of particles for each wavelength

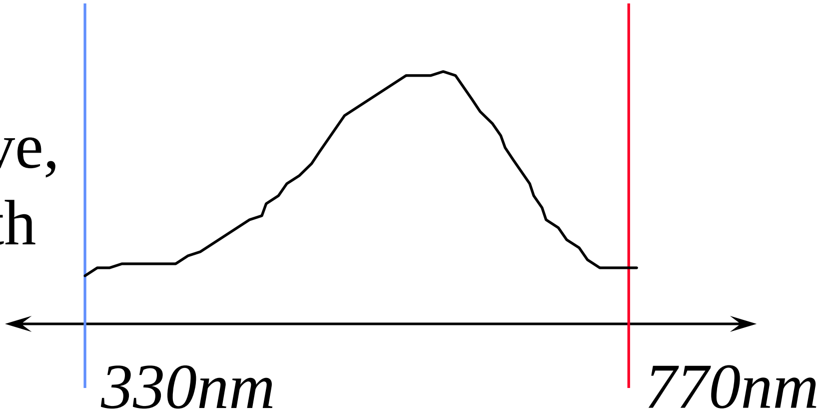


X-rays *Ultraviolet* *Visible* *Infrared* *Radio Frequencies*

1 *100* *1000* 10^6 *(nm)*

Spectral Energy Distribution Curve

- This is called the spectral energy distribution curve, and each photon set with a single wavelength is referred to as spectral component of light



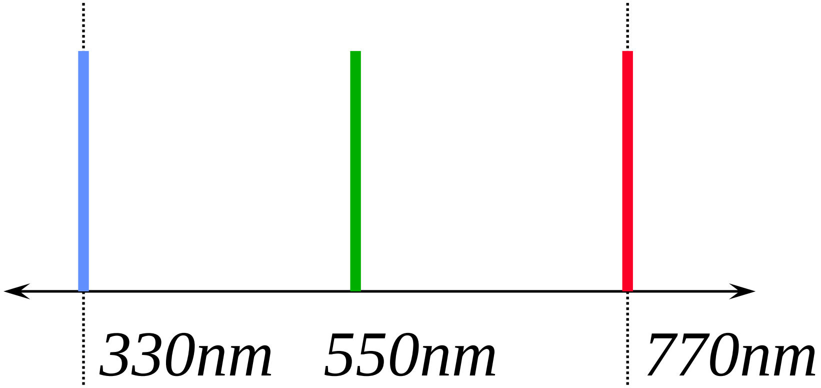
- Human eye is sensitive to a small subset of wavelengths within the range 330-770nm
- Relationship between spectral energy distribution curve and perceived color is many-to-one

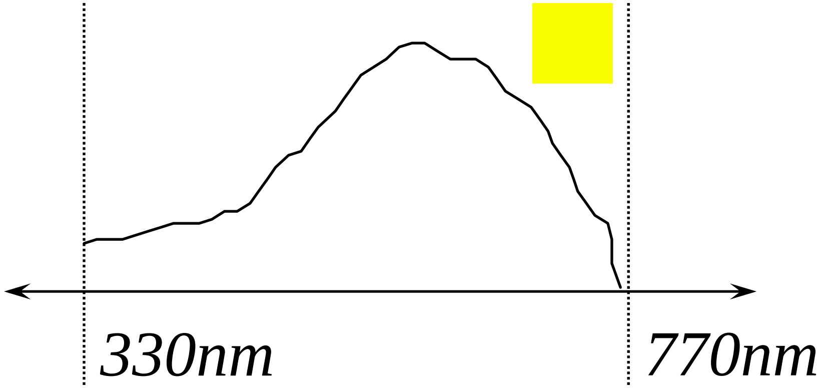
Spectral Energy Distribution Curve

- Spectral energy distribution curve of a light which resulted by adding two light sources is the sum of the spectral energy distribution curves of individual lights that are being added
- Light consisting of equal number of photons for each wavelength in the visible range is known as ***Achromatic*** light. Appears gray

Spectral Energy Distribution Curve

- Light with photons of only one wavelength is called ***monochromatic*** light. In reality monochromatic light seldom exists
- Light with different number of photons for different wavelengths is known as ***chromatic*** light





Describing Color

- *Perceived* color can be characterized by the physical properties of light
  - Dominant wavelength, which selects a particular color from the spectrum
  - Purity, measure of wavelength range within which the photons are distributed. Purer lights have its photons distributed in a narrow bandwidth of wavelengths
  - Luminance/Intensity, is the number of photons present
- Perceptual counterparts are *Hue*, *Saturation* and *Lightness*/*Brightness*

Describing Color

- *Hue*, is the perceptual property which distinguishes between color and relates to the dominant wavelength
- *Saturation*, specifies how far is a color from gray and corresponds to the purity of light.

  e.g. Pure red is highly saturated and pink is less saturated
- *Lightness* is the measure of perceived intensity. It does not specify any color information and quantifies the achromatic notion of intensity
- Only hue and saturation quantify the color information

Human Visual System

The human retina has three types of color sensors (nerve endings) called ***cones***

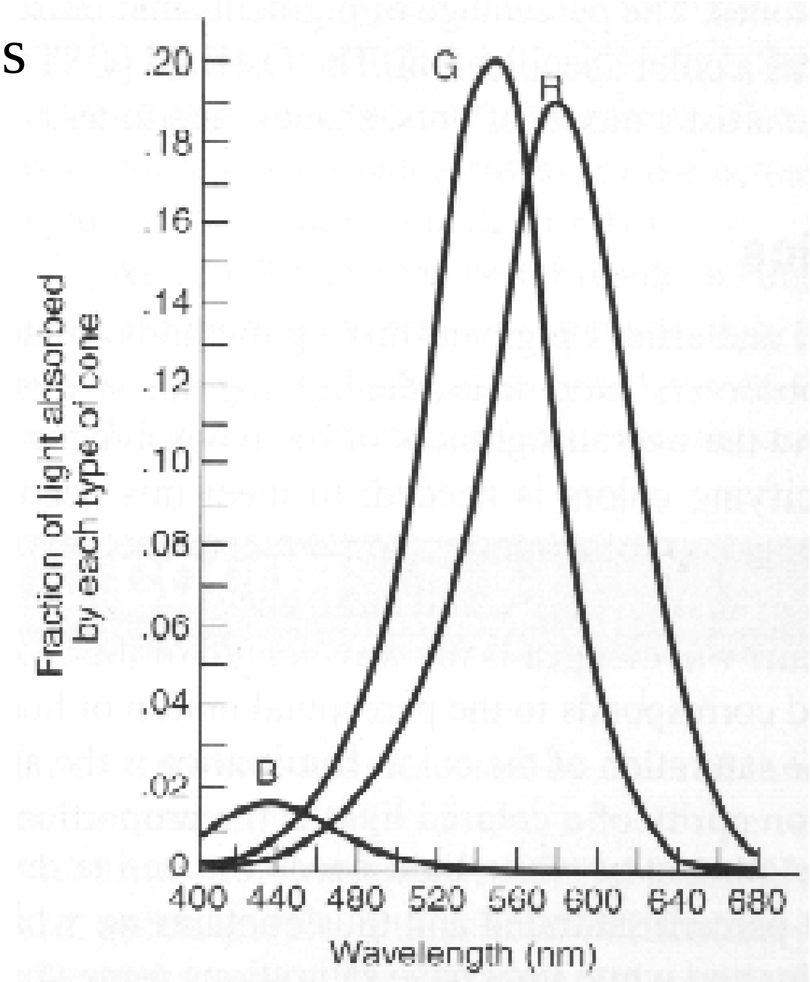
Three types, depending on their sensitivity to the wavelength of incoming light

The peak sensitivity for

blue cones is at *440nm*,

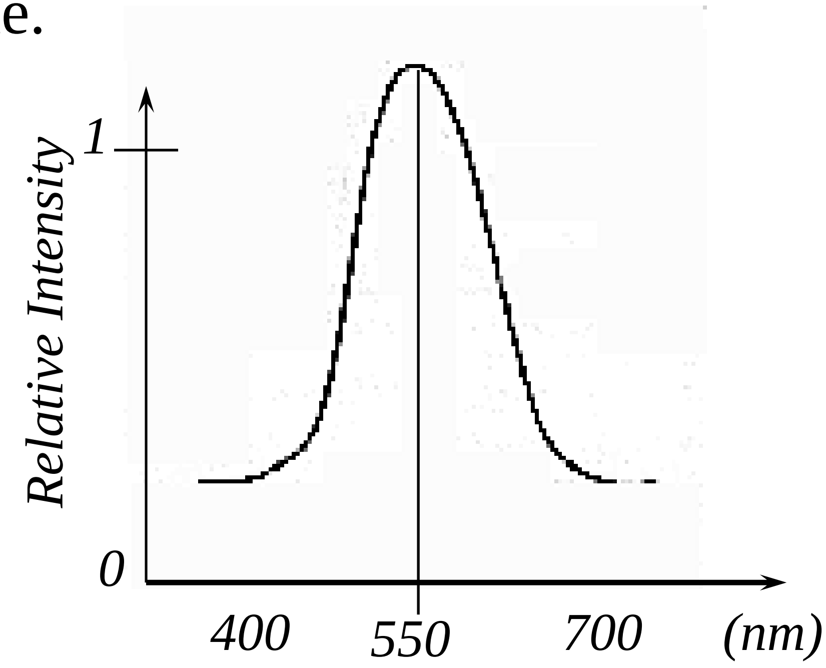
green cones is at *545nm*

red cones is at *580nm*



Human Visual System

- The response of the eye to various wavelengths with equal intensity peaks at *550nm.* So at equal intensities green looks brighter than red or blue.
- Cones require high levels of illumination to activate. So, as intensity increases distinguishable color shades also increase
- Similarly, with increase in purity, distinguishable colours increase.

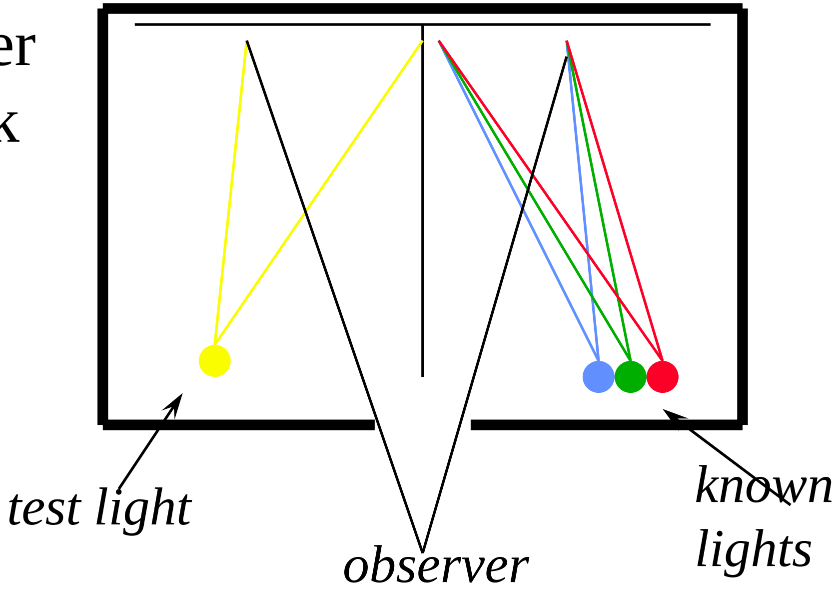


Human Visual System

- There are cylindrical nerve endings known as ***rods*** spread over the retina which are sensitive to the brightness of light and insensitive to the color information
- Rods are sensitive to small amounts of light and hence sensitive to shape and texture
- The ***trichromatic theory*** - which is also referred to as the ***tristimulus theory*** - is based on the hypothesis that the retina has three kinds of color sensors
- The theory is formulated by the results of a Color Matching Experiment

Color Matching Experiment

- Carried out by Grassman in 1835 for finding the simplest way of specifying color
- The experiment proves that a color can be specified as a combination of three different colors
- Field of view of the observer is split into two with a black partition
- The observer should match the test light by suitably mixing the three known light sources

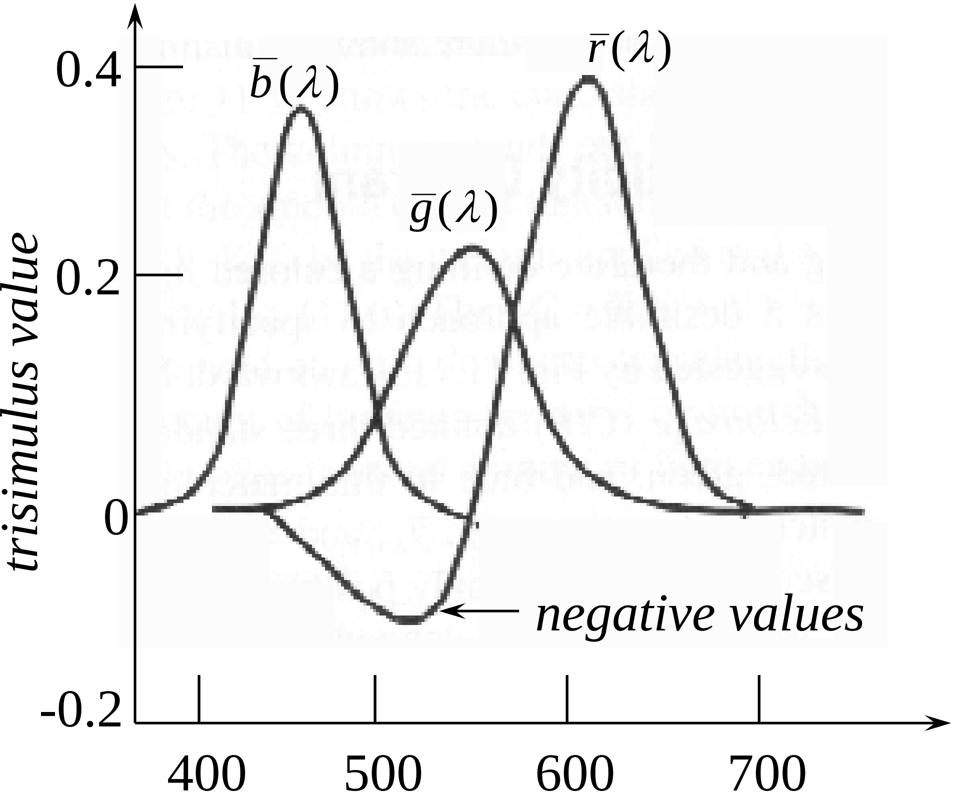


Inferences - Color Matching Experiment

- Any color can be exactly specified by a combination of any three independent *primary colors*
- *Independent* i.e. none of the primaries can be reproduced by the combination of the other two
- The amount of the color primaries that need to match the test light are called the *tristimulus values*
- *Red*, *green* and *blue* satisfy this and are the commonly used color primaries, especially in the CRT’s

Inferences - Color Matching Experiment

- Three functions called as *color matching functions* each for red, green and blue are shown to match all dominant wavelengths in the visible spectrum
- The negative values for the red matching function around *500nm* indicate that these colors cannot be produced by adding the primaries.



This means that certain colors cannot be shown on the CRT.

Inferences - Color Matching Experiment

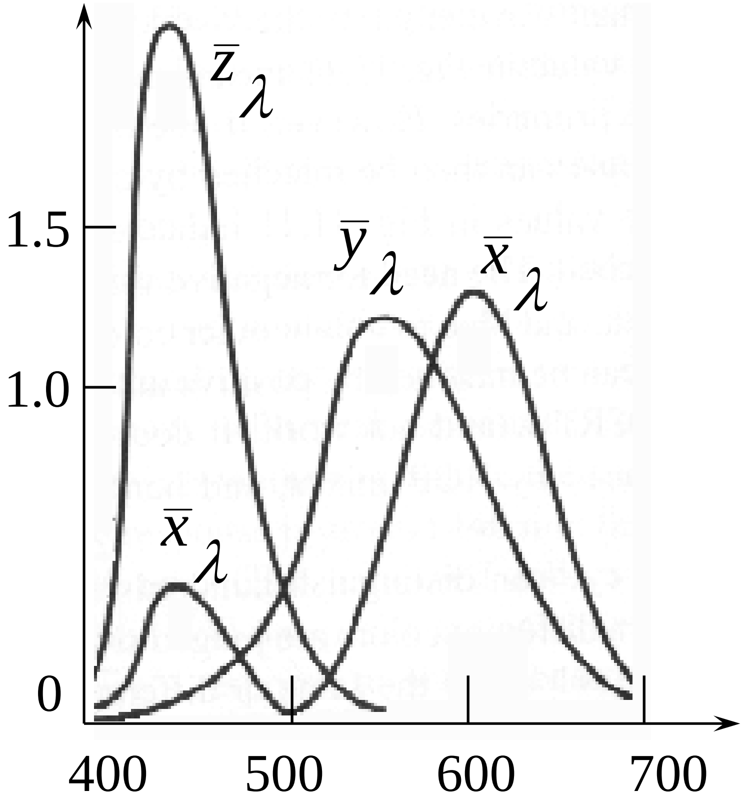
- Tristimulus vales are given by

$$r = \int_{\lambda} C(\lambda) \cdot \bar{r}(\lambda) d\lambda \qquad g = \int_{\lambda} C(\lambda) \cdot \bar{g}(\lambda) d\lambda \qquad b = \int_{\lambda} C(\lambda) \cdot \bar{b}(\lambda) d\lambda$$

- The color matching in the experiment is perceptual matching.
- The spectrum resulting from adding the three primaries need not match with the spectrum of the test light.
- Lights which are perceptually same but have different spectral distribution curves are called *metamers*

CIE Standard Specification

- It is a standard defined by the International Committee on Illumination.
- Defines three standard primaries, called **X**, **Y** and **Z** to specify a color
- Motivation was to avoid the negative weights
- The color matching functions $\bar{x}_\lambda, \ \bar{y}_\lambda, \ and \ \bar{z}_\lambda$ are positive for all wavelengths



CIE Standard Specification

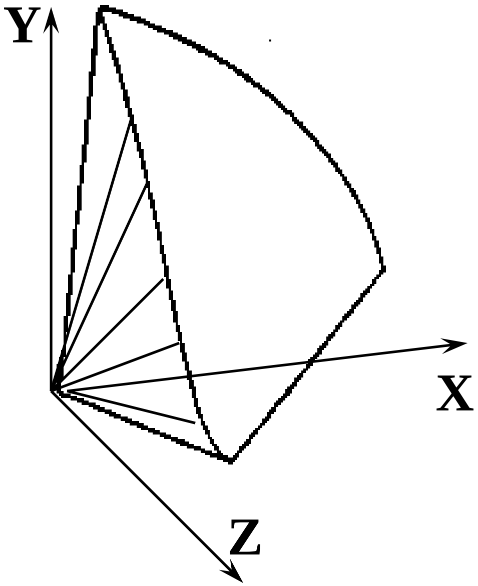
- The **Y** primary was intentionally defined to have a color matching function $\bar{y}_{\lambda}$ that matches the luminous efficiency function. **Y** primary describes the luminance component
- Amount of primaries to match a color $C(\lambda)$ is (x, y, z), given by

$$x = k\int_{\lambda} C(\lambda)\cdot\bar{x}(\lambda)d\lambda \qquad y = k\int_{\lambda} C(\lambda)\cdot\bar{y}(\lambda)d\lambda \qquad z = k\int_{\lambda} C(\lambda)\cdot\bar{z}(\lambda)d\lambda$$

- For a CRT *k* is 680 lumens per watt.
- For reflecting objects, *k* is chosen so that bright white surface has y = 100.

CIE Chromaticity Diagram

- A cone shaped volume that contains all the visible colors could be built in the **XYZ** space
- If *(x, y, z)* are the weights to match a color **C,** then $\mathbf{C} = x\mathbf{X} + y\mathbf{Y} + z\mathbf{Z}$
- *(x + y + z)* could be thought as the total light energy
- ***Chromaticity values*** are defined by normalizing against *(x + y + z)*



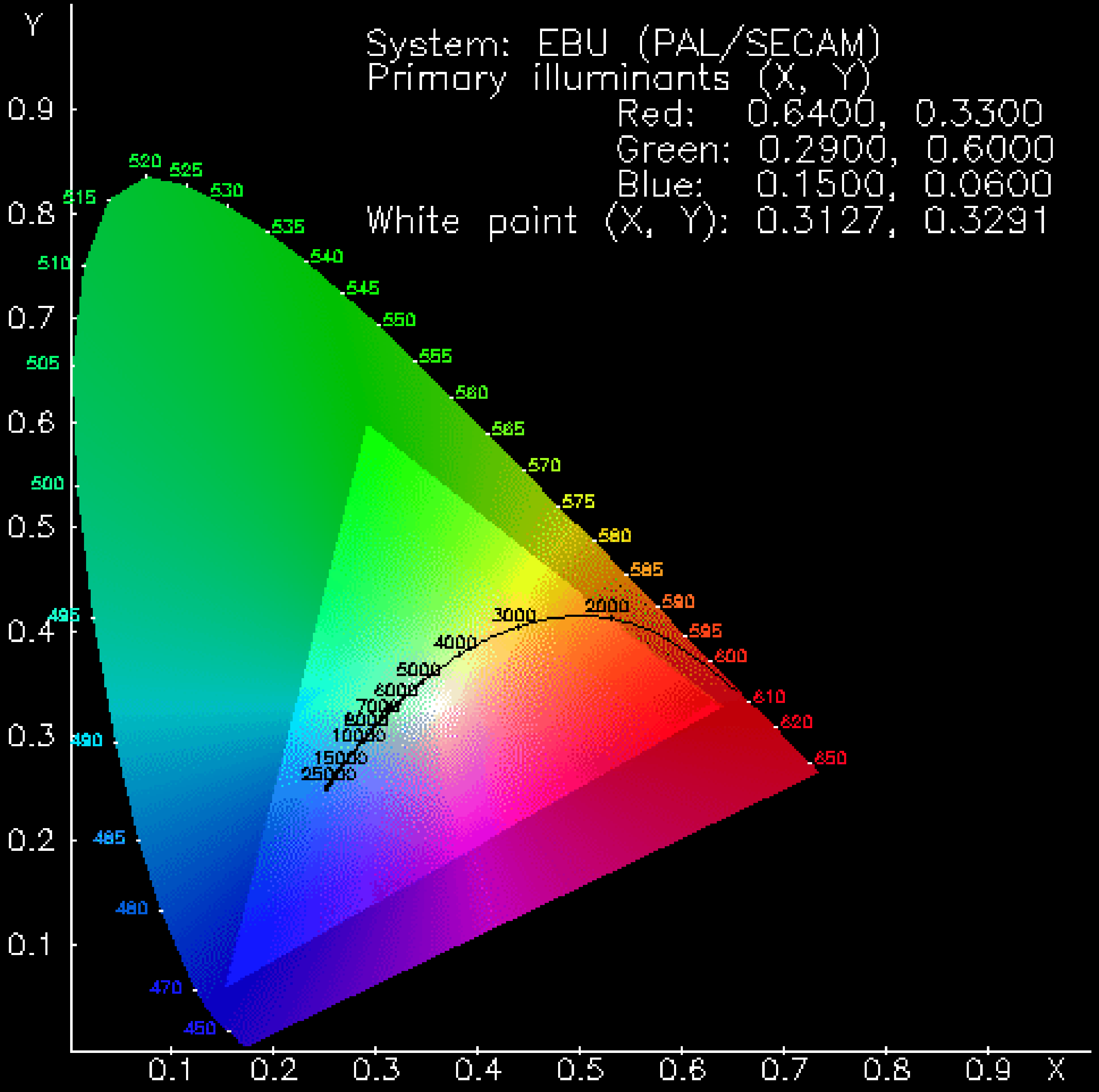
$$x_C = \frac{x}{(x+y+z)}, \qquad y_C = \frac{y}{(x+y+z)}, \qquad z_C = \frac{z}{(x+y+z)}$$

CIE Chromaticity Diagram

- If we specify x_c and y_c, then z_c can be calculated as $(1 - x_c - y_c)$. *I*n addition if y (*luminance*) is specified than x and z could be calculated. So given (x_c, y_c, y) the transformation corresponding to (x, y, z) is given as

$$x = \frac{x_c}{y_c} \cdot y, \qquad y = y, \qquad z = \frac{1 - x_c - y_c}{y_c} \cdot y$$

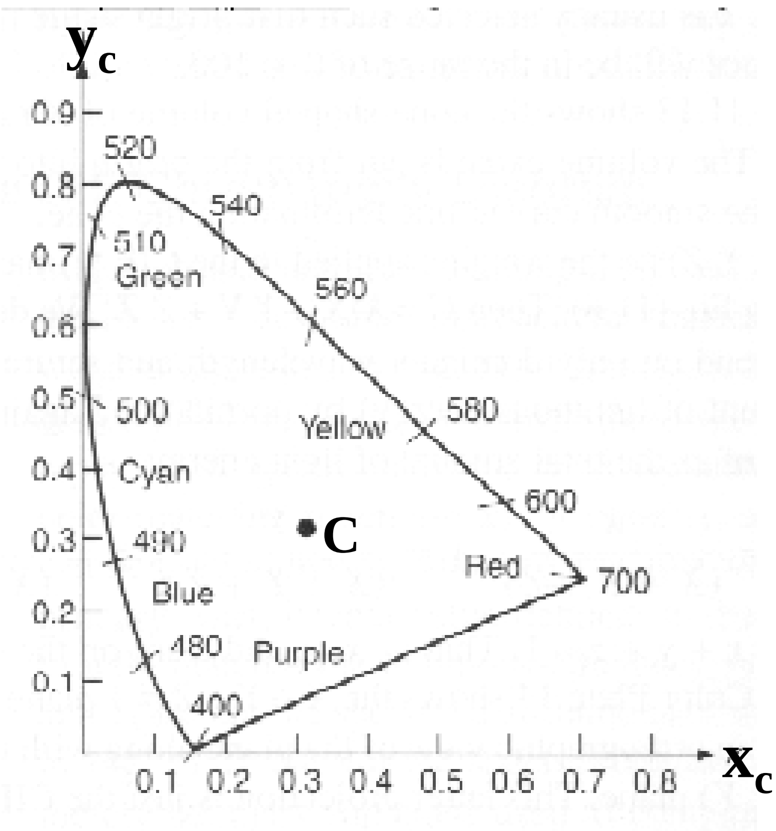
- The *chromaticity values* depend only on the dominant wavelength and saturation and are independent of luminance
- Plotting x_c and y_c for all visible colors gives the ***CIE Chromaticity diagram***, which is extensively used in color science



System: EBU (PAL/SECAM)
Primary illuminants (X, Y)
Red: 0.6400, 0.3300
Green: 0.2900, 0.6000
Blue: 0.1500, 0.0600
White point (X, Y): 0.3127, 0.3291

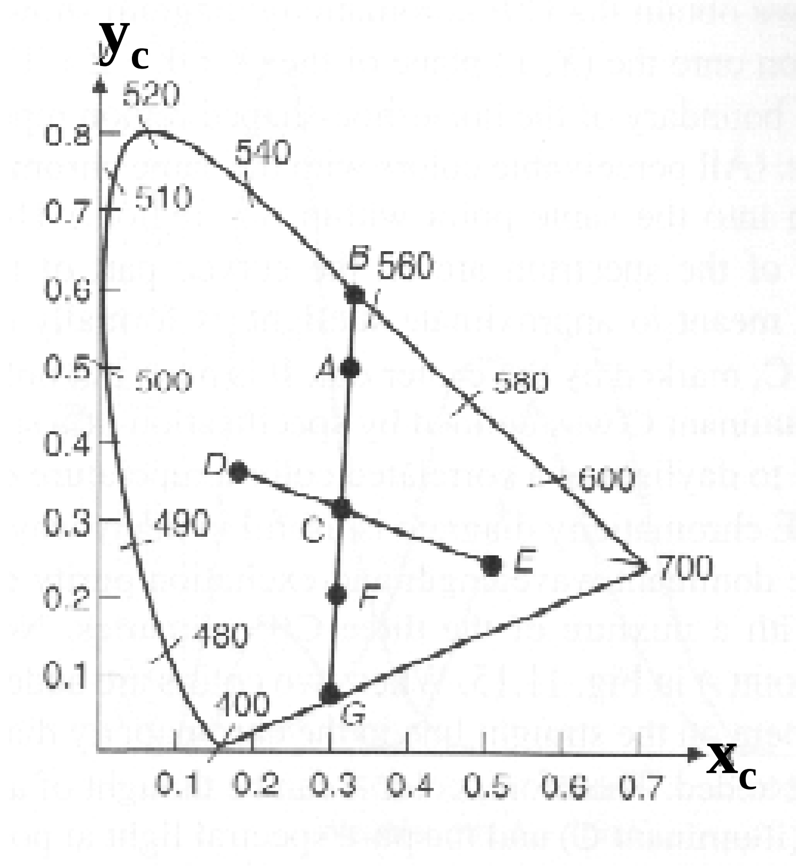
Uses of CIE Chromaticity Diagram

- Represents all the visible chromaticity values
- Pure colors map to the curved part of the boundary
- Same color with different intensities map to the same point
- A standard white light to approximate sunlight is defined by a light source illuminant **C**



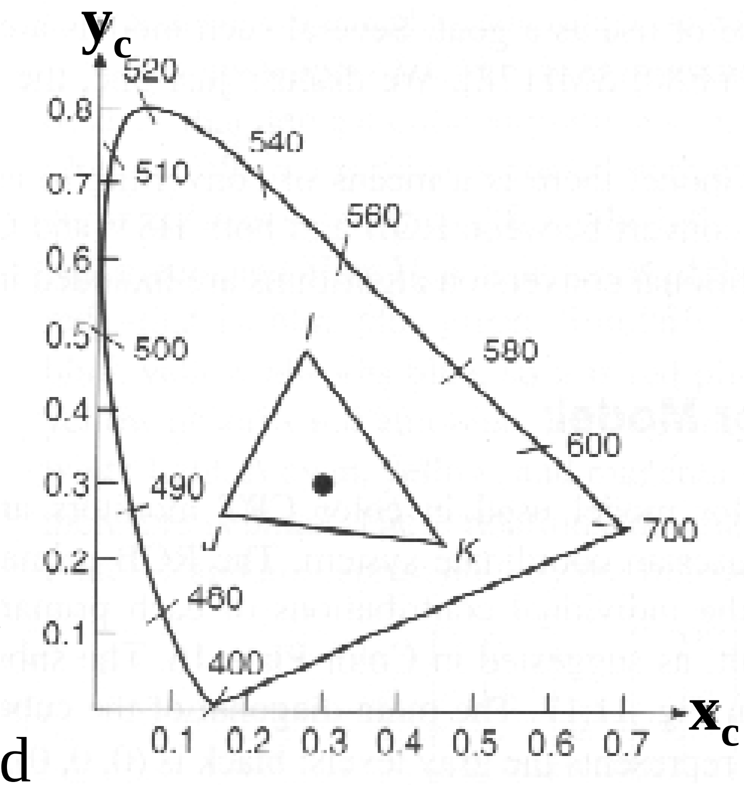
Uses of CIE Chromaticity Diagram

- Helps to determine dominant wavelength
- Helps to measure the excitation purity
- When two colors are added, new color lies on the straight line in the chromaticity diagram connecting the two colors



Uses of CIE Chromaticity Diagram

- When three primary colors are used, then all the colors in the triangle formed by the three primaries could be produced
- This helps in comparing ***color gamuts***, i.e. collection of colors
- Some colors cannot be defined by dominant wavelength are called non-spectral (purples and magentas)



Color Models

- Color model is a geometric representation of the space of all colors such that any color is a point in that space
- Traditionally color models for computer graphics were designed for specific devices
- They could be classified based on
  - Hardware color generation i.e. **RGB** for displays, **CMY** for printers, **YIQ** for television transmission
  - Color perception i.e. **HSV** for interactive color specification.

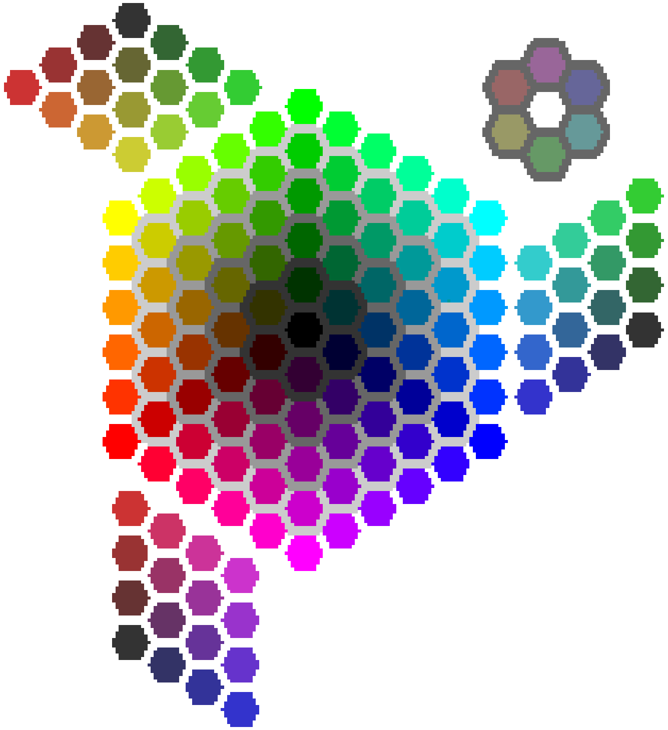
RGB Color Model

- Standard Model for color monitor
- Primaries are *Red*, *Green* and *Blue*
- Represents only a subset of perceivable colors
- Known as ***Additive Model***, because individual contributions of each primary are added
- Perceptually non-uniform color space

Colour Applet (http://mc2.cchem.berkeley.edu/Java/RGB/example1.html)

CMY Color Model

- Standard for ink-jet and xerographic printers
- Primaries are *Cyan*, *Magenta* and *Yellow*
- Known as ***Subtractive Model***, because the colors act as filter to subtract color from white light
- Printer color gamut is smaller than CRT color gamut
- $C = 1 - R$, $M = 1 - G$ and $Y = 1 - B$



YIQ Color Model

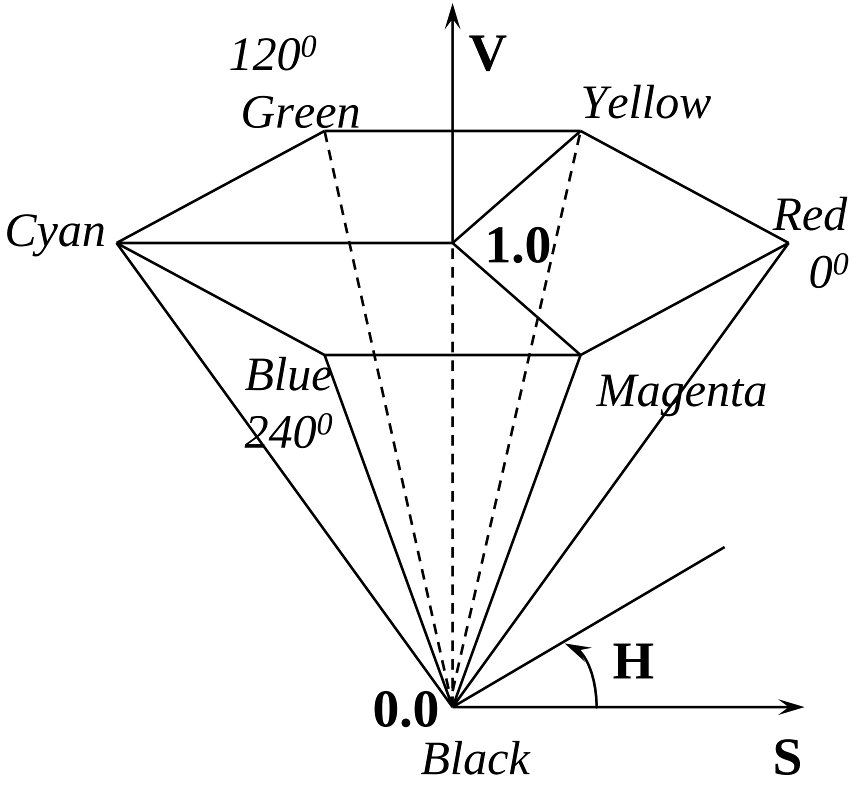
- Used in commercial TV broadcasting
- Primaries are *Y* (luminance) and *I*, *Q* which are the chrominance components
- *Y* is same as the *y* primary of **CIE standard**

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Designed for transmission efficiency and compatibility with black and white television
- Exploits two properties of human visual system
  - high sensitivity to change in luminance than to color variations
  - Objects small in the field of view produce limited color sensation

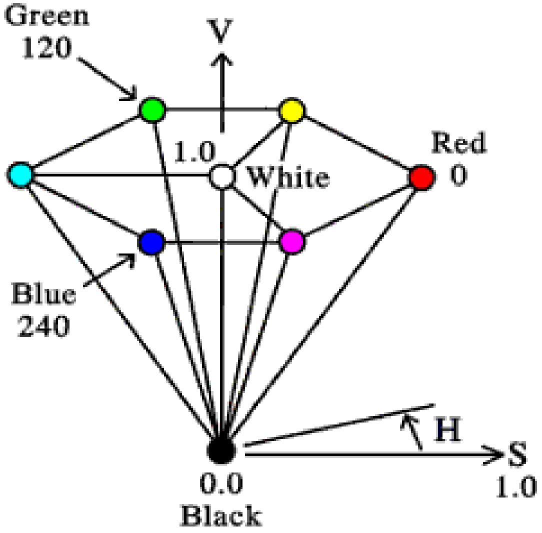
HSV Color Model

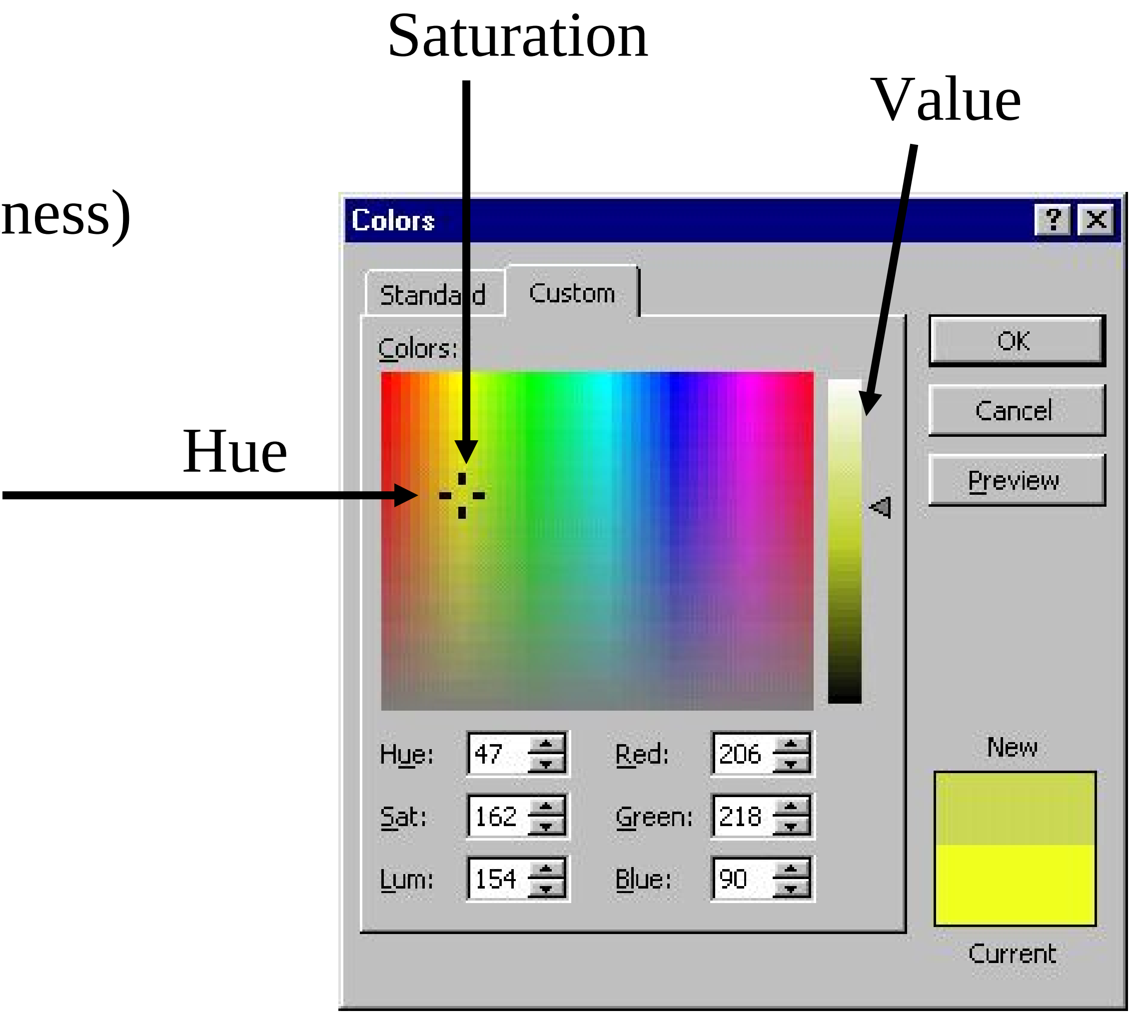
- Useful in user interface design for color specification
- Primaries are *Hue*, *Saturation* and *Value* (luminance)
- Considered as direct geometric representation of perception of color
- Based on cylindrical coordinate system



HSV Color Space

- A more intuitive color space
  - H = Hue
  - S = Saturation
  - V = Value (or brightness)




Saturation

Value

Hue

Hue: 47
Sat: 162
Lum: 154
Red: 206
Green: 218
Blue: 90

Color in OpenGL

- **`glColor3f(1.0,0.0,0.0)`**
  - this present a red color

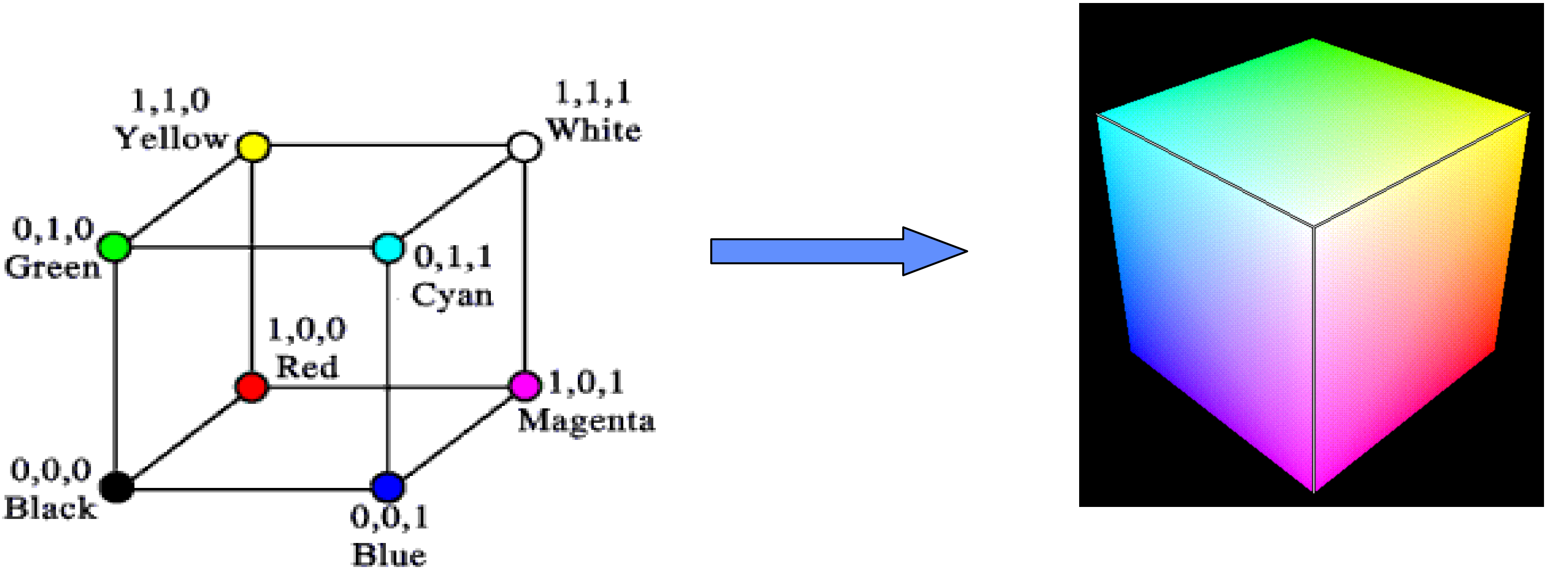
- 3f = use a RGB model, and the value of the component is float in C.

- Four-color (RGBA) system
- A is called alpha channel, stored in the frame buffer as are the RGB value

- The alpha value will be treated by OpenGL as an *opacity* or *transparency*
- **`glClearColor(1.0, 1.0, 1.0, 1.0)`**
  - solid and white

RGB Models

- To display a color, the monitor sends the right proportions of red, green, and blue
- **Color = a . Red + b . Green + c . Blue**
- Thus, a color is a point in a color cube



Using RGB Color with OpenGL

- void **glColor3**{b s i f d ub us ui} (**TYPE** *r*, **TYPE** *g*, **TYPE** *b*);
  - Specify a color for drawing the object
- void **glClearColor**(GLclampf **red**, GLclampf **green**, GLclampf **blue**, GLclampf **alpha**);
  - Specify a color for clearing the screen

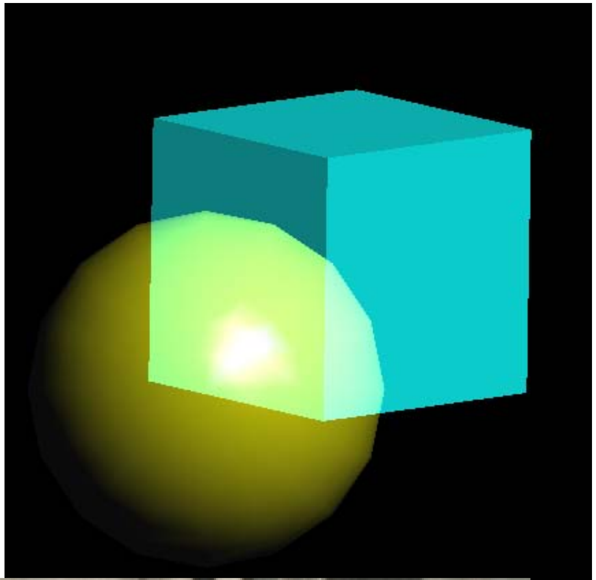
```
glClearColor(0, 0, 0, 0);  // black color
glClear(GL_COLOR_BUFFER_BIT);  // clear screen
glColor3f(1.0, 0.0, 0.0);  // red color
glBegin(GL_TRIANGLE)  // drawing a triangle red color
   glVertex2f (5.0, 5.0);
   glVertex2f (25.0, 5.0);
   glVertex2f (5.0, 25.0);
glEnd()
```

Transparency

- When drawing an object (car green window) atop another (car gray interior), what should be the effect? We should see both the window and the interior with appropriate colors.
- glColor4f(1, 1, 1, 0.75): what is the 4th parameter, or the alpha value, for?
- It is used for blending, i.e., combining the new color values (source) with the existing ones (destination), making translucent scenes
- Must enable blending:

  ```
  glEnable(GL_BLEND);
  glBlendFunc(sFactor,dFactor);
  ```

- Alpha value represents opacity of the object
  - Low alpha value: transparent or translucent objects
  - High alpha value: opaque objects



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