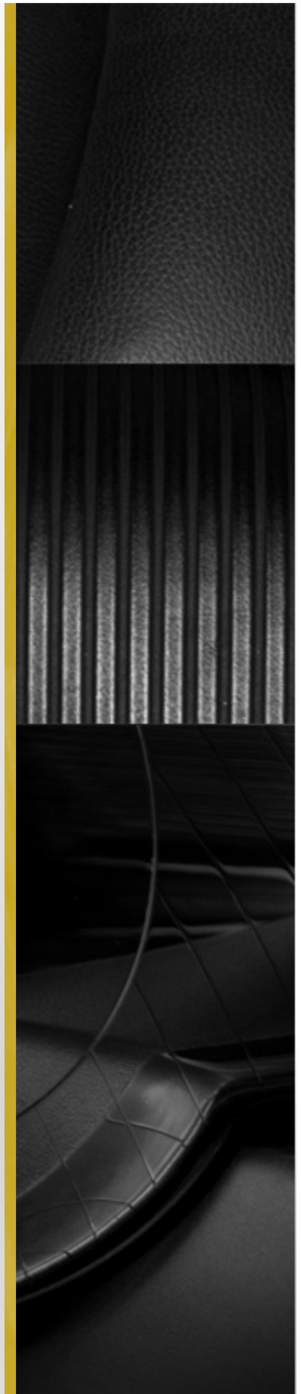
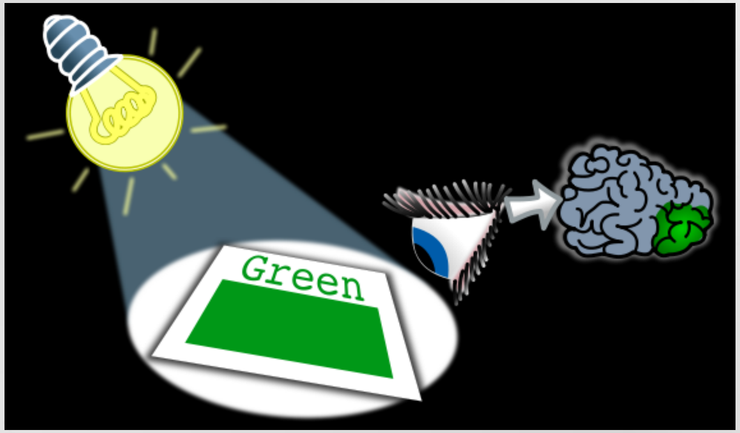
Color Theory

Computer Graphics



Introduction

- The **color of an object** depends on:
  - Object properties
  - Light source
  - Background color
  - Human visual system



- There is not a **universally accepted theory** about human color perception

Introduction

- Some materials reflect the light (plastic, wood…) while some others transmit it (glass, cellophane…)
  - A surface that only reflects **pure blue light**, illuminated with **pure red light**, appears…

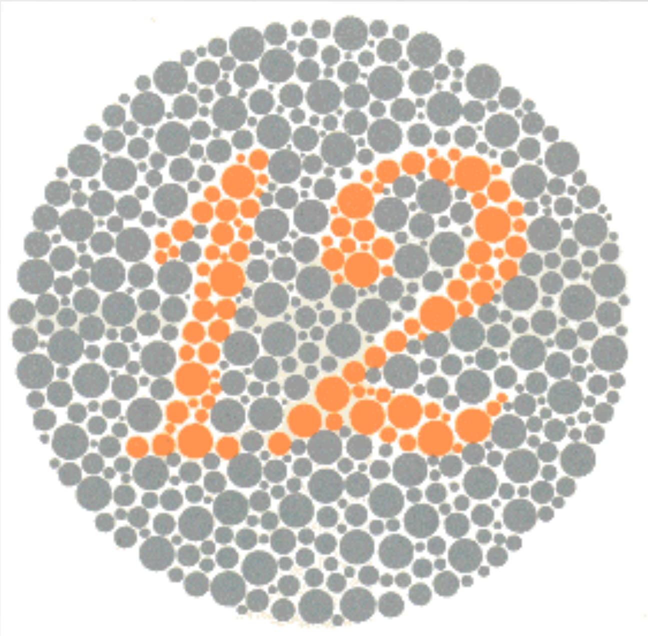
    Black

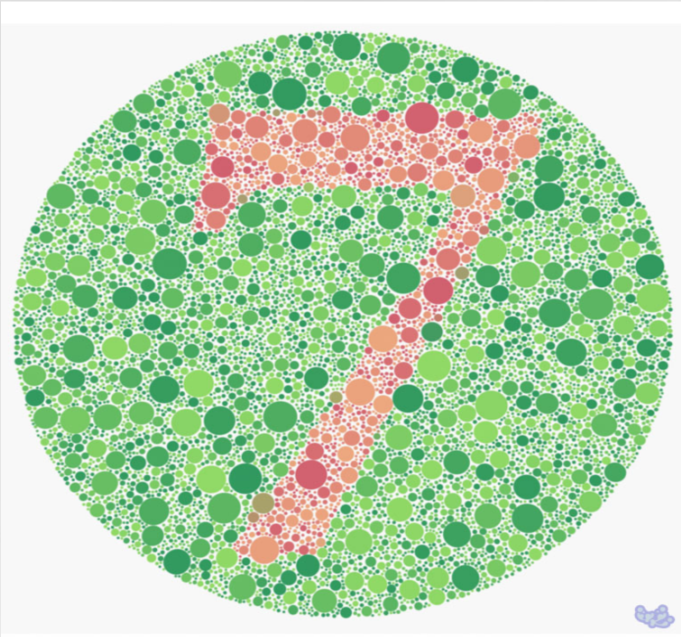
  - A **pure green light** source through glass that only transmits **pure red,** appears…

    Black

Introduction

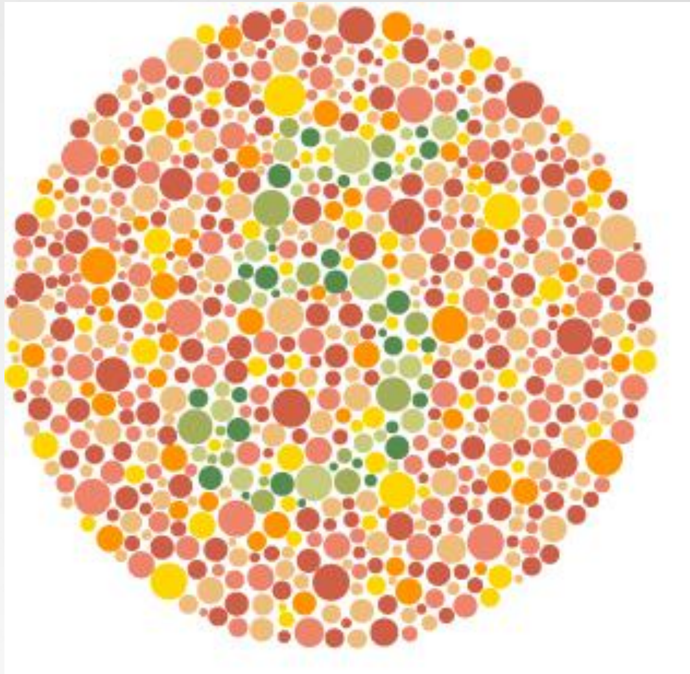
- 8% of men and 1% of women are blind to some colors
  - They generally can not distinguish between red and green
  - **Ishihara Test** – these are easy to see….

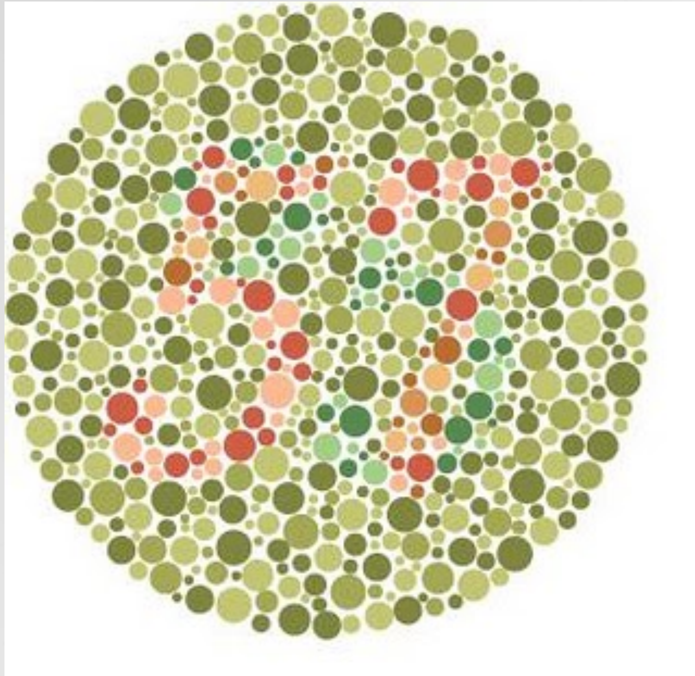




Introduction

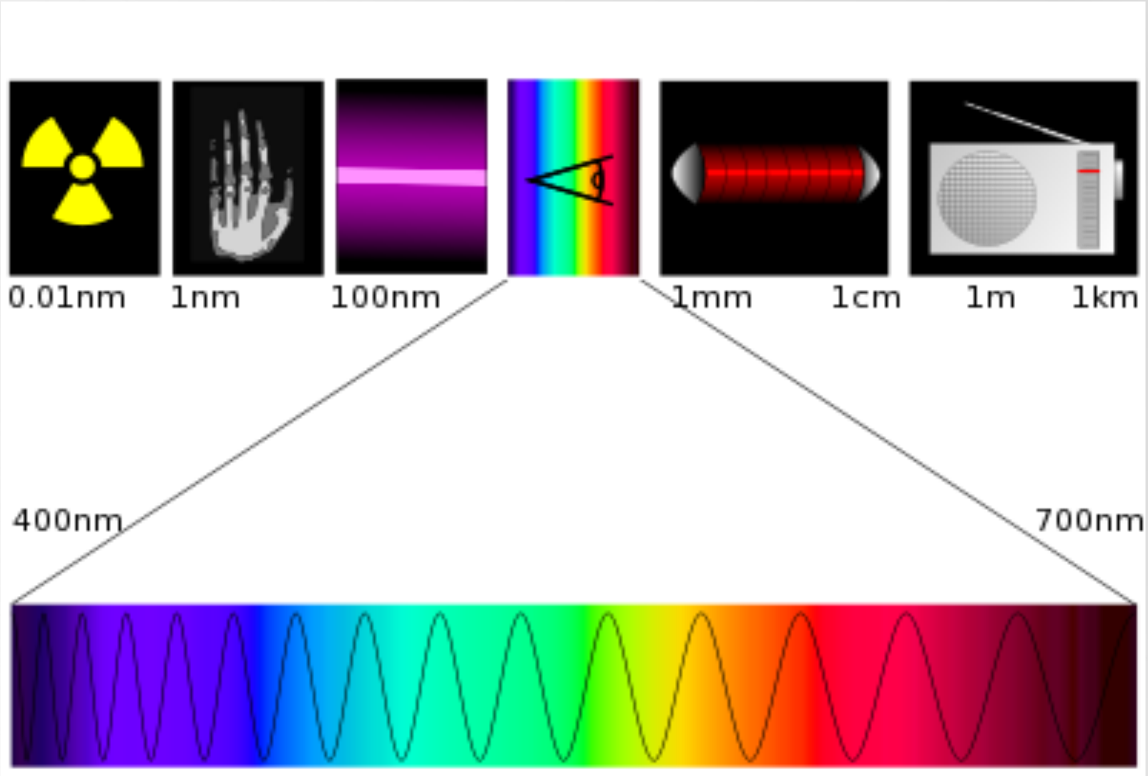
- A bit more difficult….





Color Characterization

- **Light** (colors spectrum) – wavelength band that is visible for us within the electromagnetic spectrum



Color Characterization

- A color can be described by its **wavelength** (λ **,** measured in nanometers) **or its wave frequency** (**f,** measured in hertz). They are related through

  $$c = \lambda f$$

  f is constant for all materials, but **c** and λ depend on the material

- A white light source (sun) emits all frequencies. When it hits an object, The object absorbs some wavelengths and reflects some others. The combination of reflected wavelengths determines the object color (tone, hue)

Color Characterization

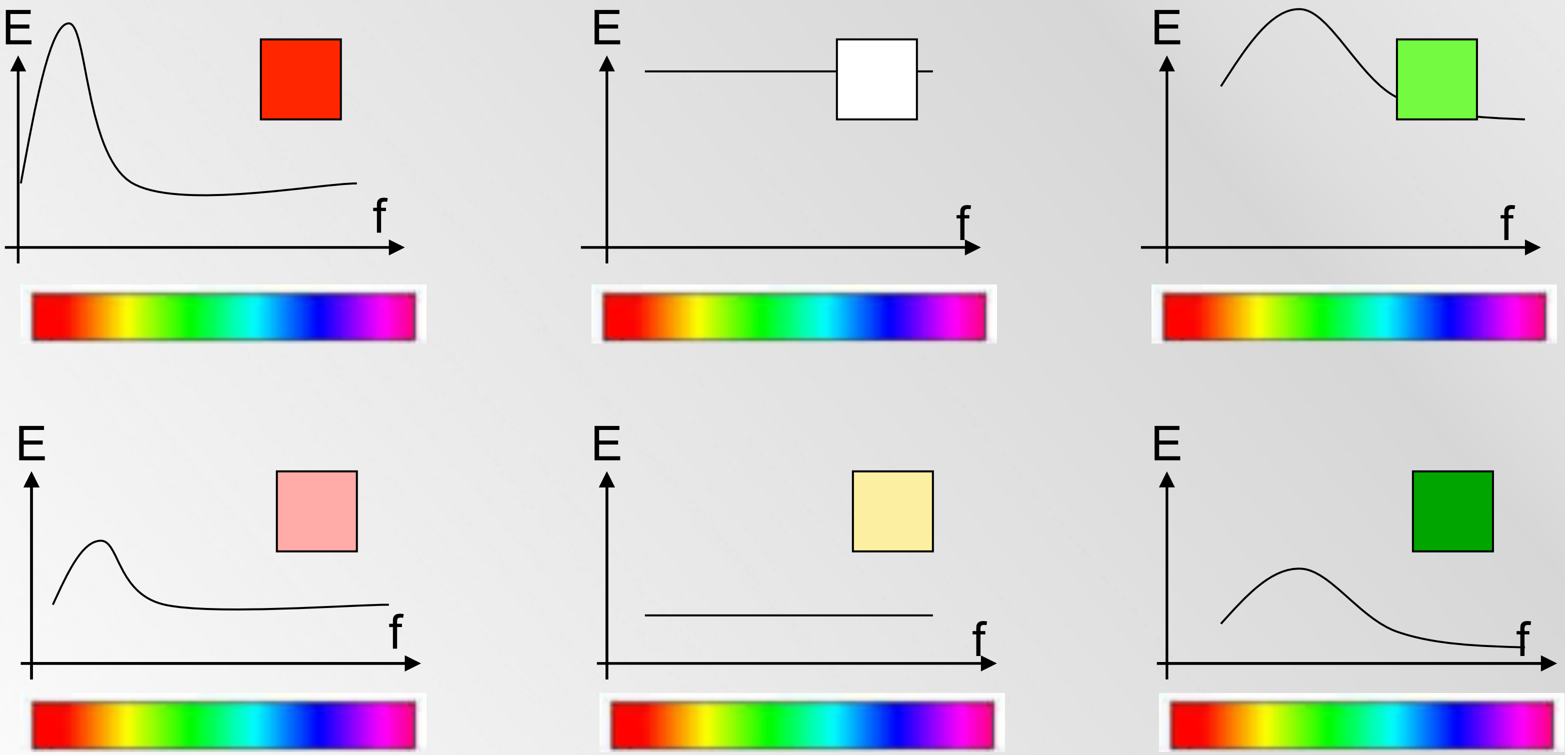
- **Color** is determined by **3 parameters**:
  - **Hue** or **Tone** – prevailing wave length (WL)
    - We can differentiate approximately 150 of them
  - **Saturation** or **Purity** = prevailing WL **–** white light WL (how far a color is from a gray with the same intensity)
    - Less saturated colors contain more white light
  - **Brightness** or **Luminance** – Light Intensity perceived
    - **Intensity** – energy emitted by time unit, solid angle unit and area source unit
- We can **distinguish around 7 million colors**

Color Characterization

Color Saturation (purity)

Color Characterization

Graphical representation of tone, saturation and brightness



Achromatic Light

- **Chromaticity quality of a color** considering **hue** and **saturation**

- **Achromatic light → quantity of light**
  - **Physical** sense
    Light intensity or luminance
  - **Psychological** sense
    Brightness
  - What we see on a B/W TV or monitor
    - many different grays at a single pixel position
  - **Scale of achromatic sensations** (light intensity values)
    - 0 ——— 1
    black *different grays* *white*

Achromatic Light

- **Light intensity levels distribution**
  - To avoid perceiving intensity discontinuities, it seems reasonable to select intensities evenly distributed along the [0,1] range, but…
  - **Human eye is sensitive to intensity levels ratios** instead of absolute values of intensity levels → we **perceive intensities in a logarithmic scale** (rather than linear)
    - 0.11 / 0.10 = 0.55 / 0.50
    - Log (0,11) – Log (0,10) = Log (0,55) – Log (0,50)
  - **Intensity levels must be logarithmically spaced out**

    quotient between successive intensity levels must be constant

Achromatic Light

- For *n+1* intensities, from the minimum (I_0) to the maximum (1), each intensity equals the prior intensity multiplied by a factor (r) :

$$I_0 = 0 + \varepsilon, \quad I_1 = I_0 r, \quad I_2 = I_0 r^2, \quad \dots \quad , \quad I_n = I_0 r^n = 1$$

- Therefore

$$\frac{I_{k+1}}{I_k} = r\ constant \ \rightarrow\ Log(r) = Log\left(\frac{I_{k+1}}{I_k}\right) = Log(I_{k+1}) - Log(I_k)\ constant$$

$$r = (1/I_0)^{1/n} \quad and \quad I_j = I_0^{(n-j)/n} \quad (0 < j < n)$$

- For example, To obtain 256 intensities (8 bit/pixel B/W monitor)

$$r = (1/I_0)^{1/255} \quad and \quad I_j = I_0^{(255-j)/255} \quad (0 < j < 255)$$

$$I_0 = 0,01 \rightarrow\ r = (1/I_0)^{1/255} = 1,01822$$

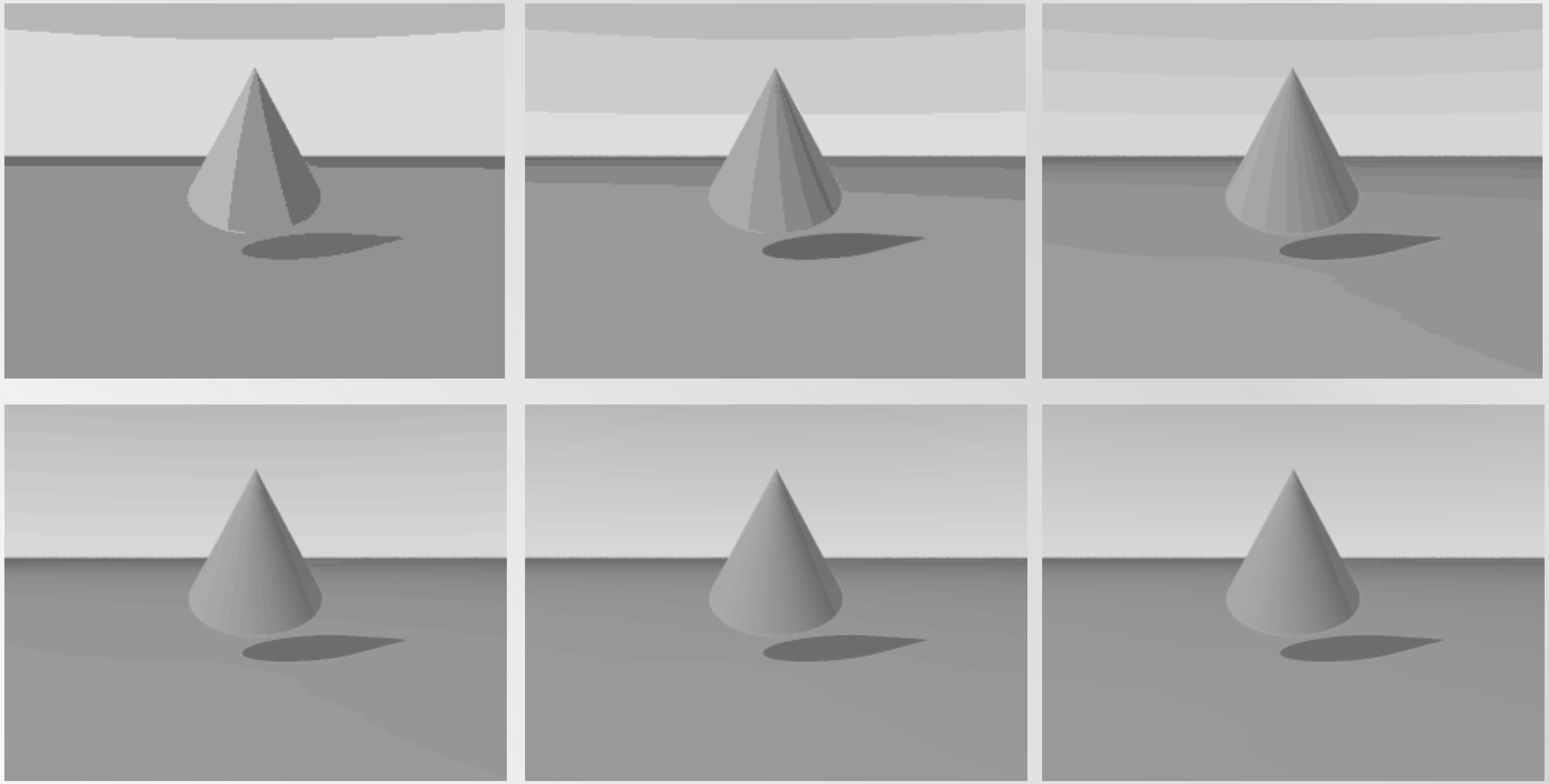
Achromatic Light

- **Minimum intensity in CRT monitors is between 0.005 and 0.025** (is not 0 because of light reflection from the phosphor)
- **Dynamic range** = ratio between maximum and minimum intensities (measured with a photometer; DR =$1/I_0$ in our case)
- Display these intensities on a CRT is a difficult task (even more so recording them on a film) because these devices emit light intensity in a non-linear way → the device "uses" a look-up table to assign light intensity to pixels is called **gamma correction**
- **How many intensities (n)** are enough to reproduce a continuous-tone B/W image so that the **reproduction appears to be continuous?** It can only be achieved when **r<1,01**

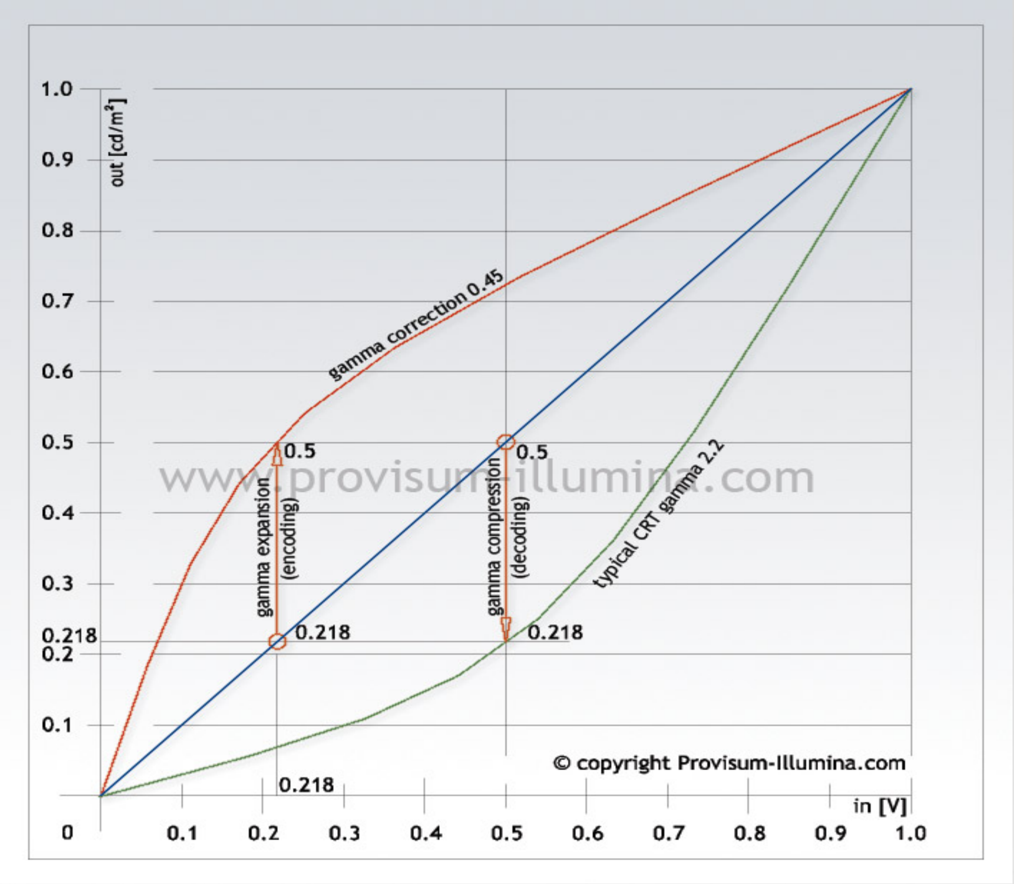
$$r = (1/I_0)^{1/n} \quad \rightarrow \quad r^n = \frac{1}{I_0} \quad \rightarrow \quad n = log_r\left(\frac{1}{I_0}\right)$$

Achromatic Light

- Increasing number of intensities → 8, 16, 32, 64, 128, 256



Gamma correction



$$\boxed{V_{out} = C \cdot V_{in}^{\gamma}}$$

Devices

- The number of intensities and colors (*gamut*) shown by a device is not always the same

Device	Dynamic Range	Nº of Intensities
CRT	50-200	400-530
Photograph	100	465
Slide	1000	700
B/W Impression	100	465
Color Impression	50	400
B/W newspaper	10	234

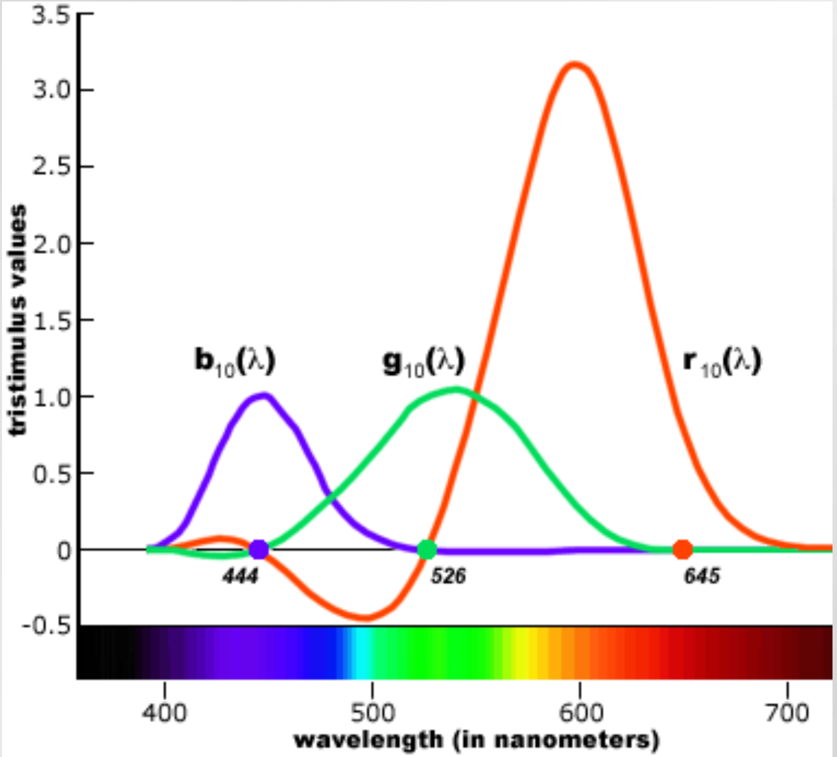
Color Characterization

- **Primary colors** – can not be obtained by mixing of other colors
- **Complementary colors** – those producing white light when combined
  - Red-Cyan, Green-Magenta, Blue-Yellow
- We can **combine 2 light sources** with different color by suitably selecting intensities to obtain the desired color range
- A finite (or even real) number of primary colors can not be combined to arrive at all possible visible colors
- Color **models generally use 3 primary colors** to obtain the colors spectrum (gamut) associated to that model

Color Characterization

- Mixture of 3 primary colors (blue, red & green from RGB model) to generate all colors in the spectrum (average)
- A RGB color monitor cannot display colors close to 500nm (between 438-546nm we need to "extract" the red color)

- ***Matching-Color Functions***



Primary colors

- **Additive** Colors
  - We generate white mixing them
  - Blue, Green, Red
  - Type of colors for the TV and a computer screen

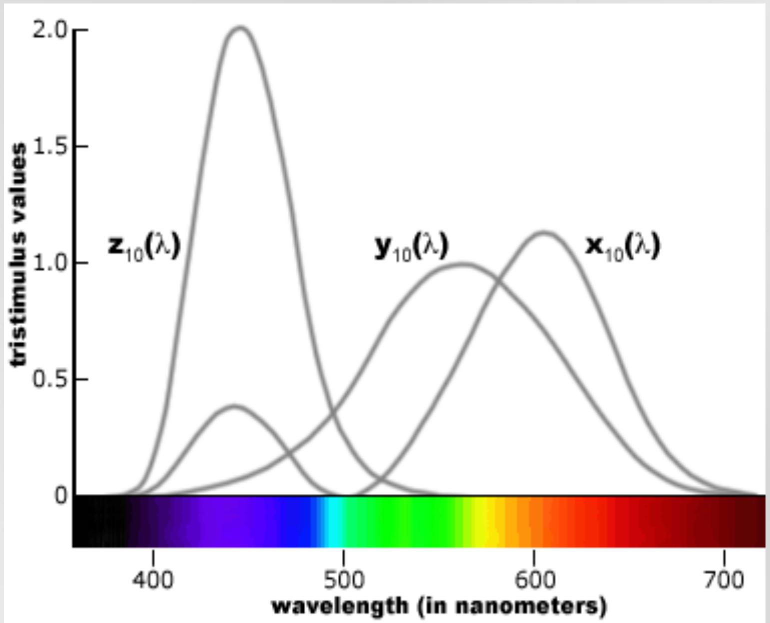
Primary colors

- **Subtractive** Colors
  - Cyan, Yellow and Magenta
  - Filters absorbing the light
  - Printers

Standard Primary colors

CIE (1936) defines a 3-additive color standard

- Imaginary colors: X,Y,Z (3D vectors)
- Mathematically defined with color-matching functions
  → No need to “subtract”
- They generate all the spectrum



Primary Color Standard – X, Y, Z model

- A color is specified as:

$$C_\lambda = xX + yY + zZ$$

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}$$

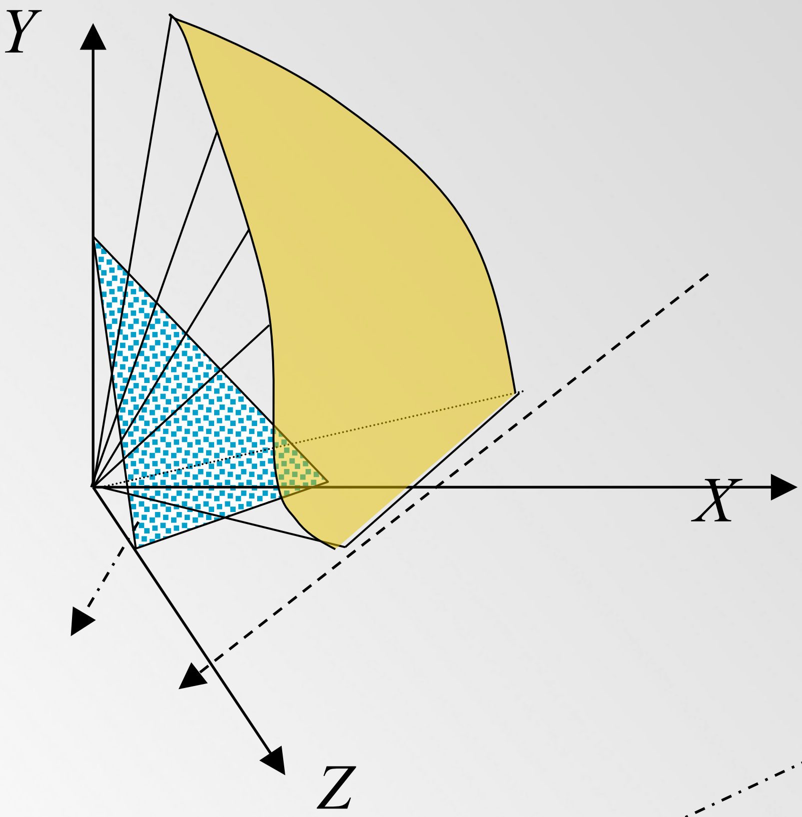
$$x + y + z = 1$$

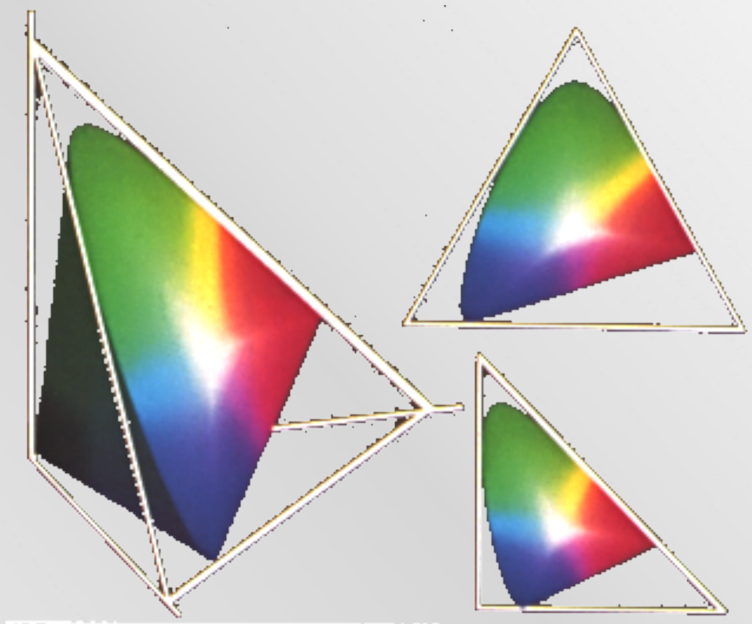
x, y, z are normalized amounts within the x + y + z = 1 plane

- z value can be calculated from a (x , y) pair of values
- X,Y,Z cannot be calculated with x e y → we need to know Y
- With a luminance fixed value , Y, all colors can be obtained assigning values to x and y: **Chromaticity Diagram**

$$X = \frac{x}{y}Y, \quad Z = \frac{z}{y}Y, \quad z = 1 - x - y$$

Chromaticity Diagram, CIE



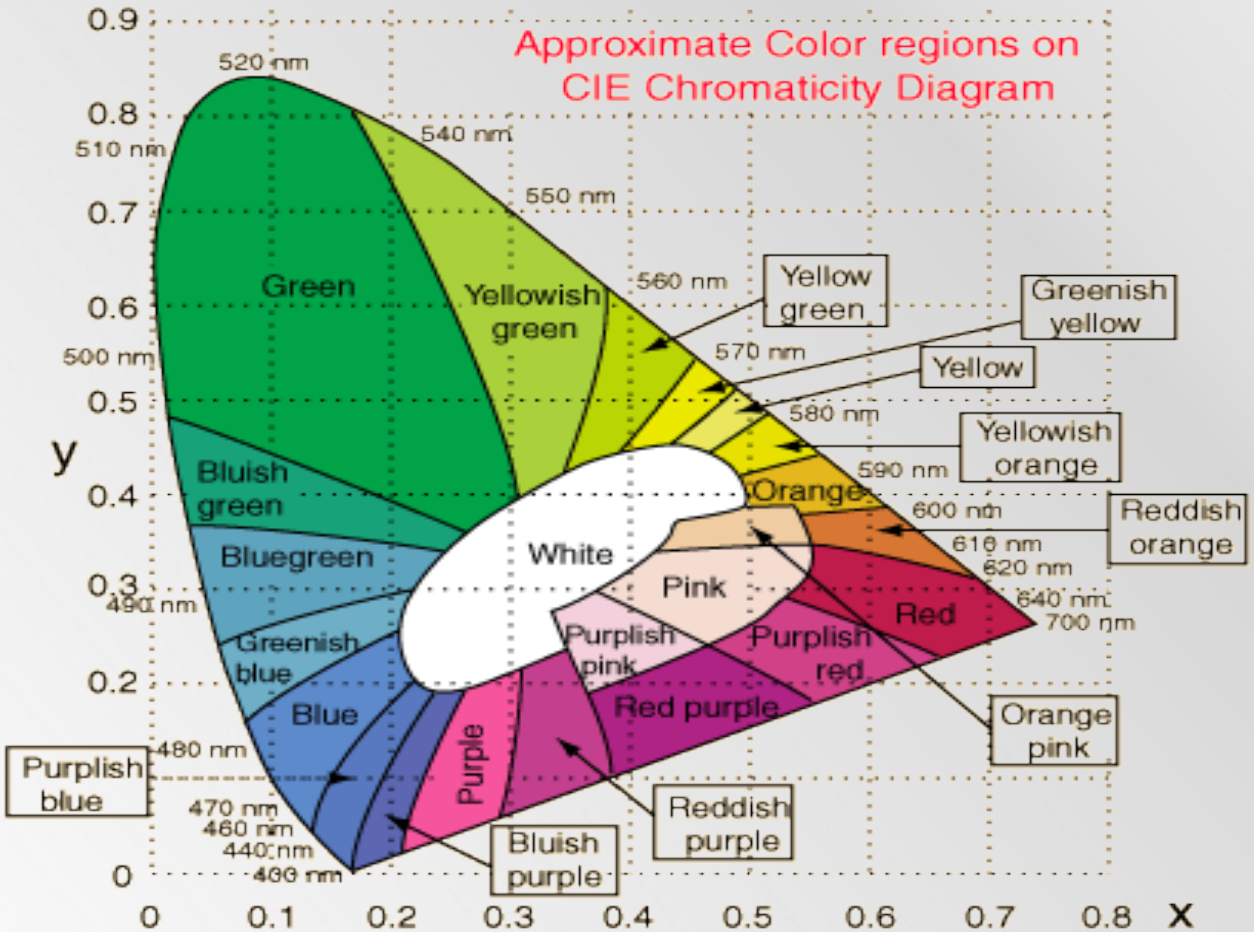


Chromaticity Diagram: $X+Y+Z=1$ plane projected on plane XZ

Chromaticity Diagram (CIE)

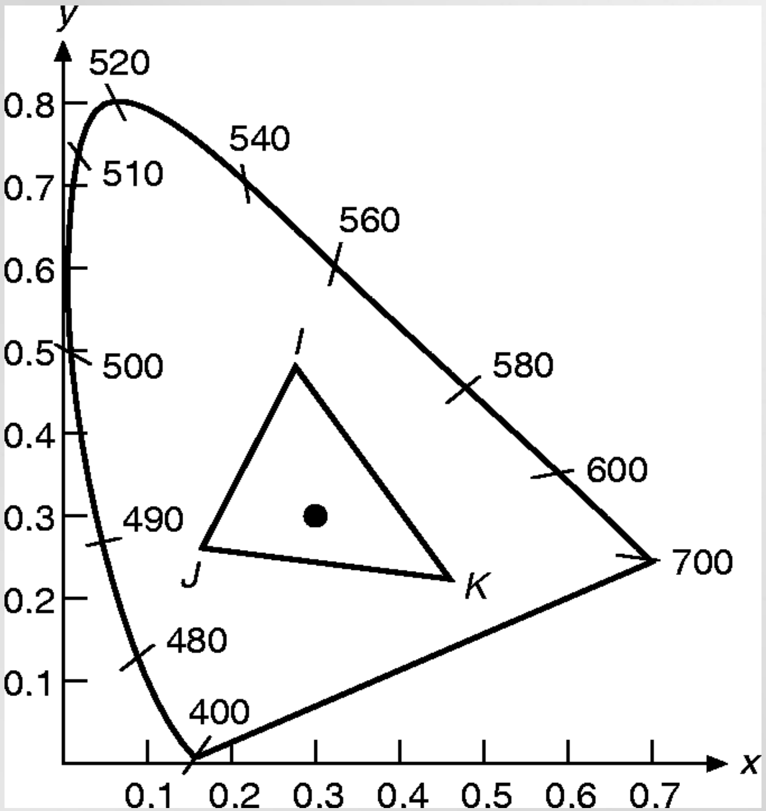
- Applications
  - Name colors
  - Mixture of colors
  - Identify complementary colors
  - Determine prevailing frequency
  - Compare devices gamut
- Properties
  - Edge colors are pure

Chromaticity Diagram (CIE)



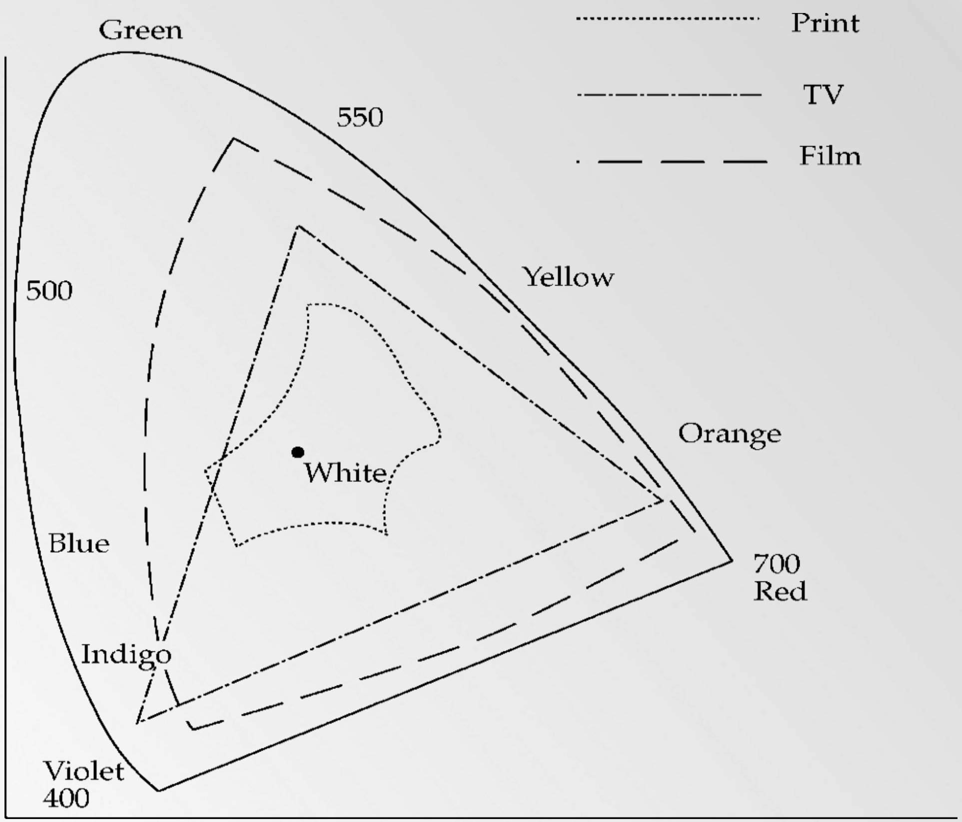
Chromaticity Diagram (CIE)

- Mixture of colors
  - Mixing colors I,J the full colors spectrum on the IJ segment can be obtained
  - With colors I,J,K all colors within the triangle can be obtained



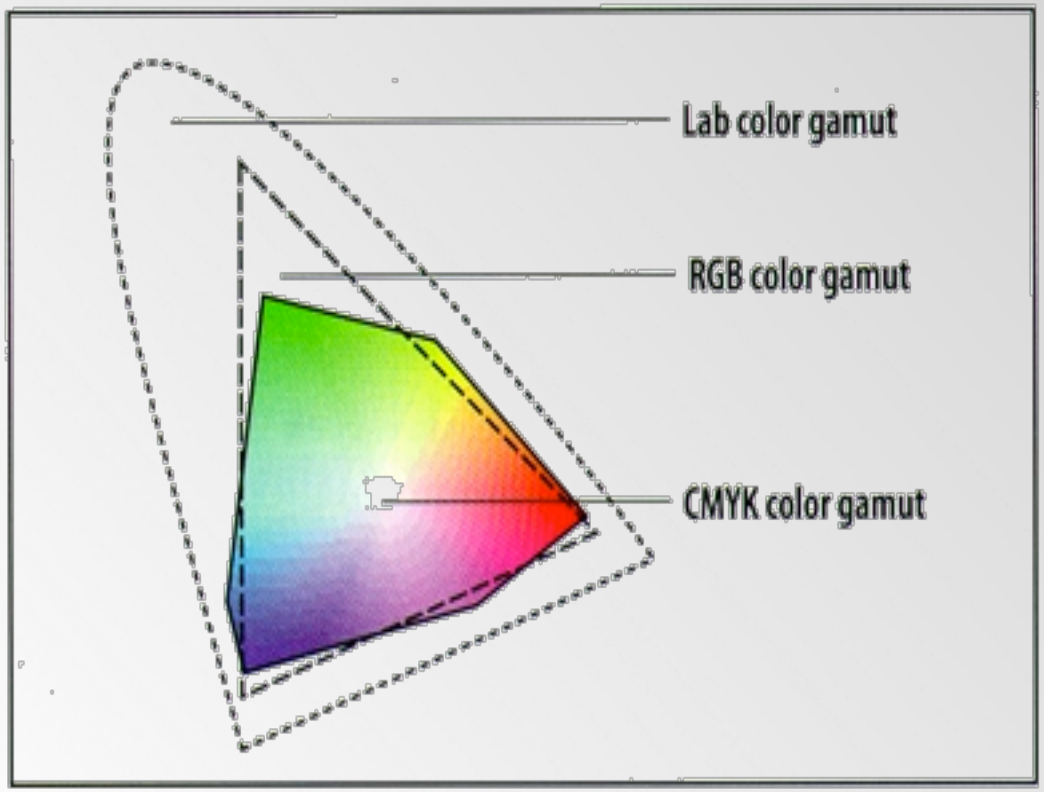
Chromaticity Diagram (CIE)

- **Gamut in different devices**



Chromaticity Diagram (CIE)

- **Gamut with different color models**

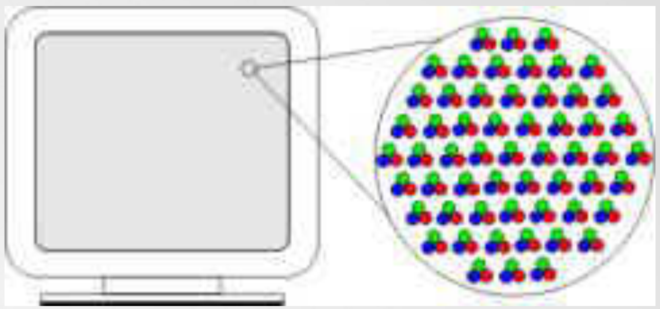


Color models for the raster

- **Hardware oriented** models – no relation to tone, saturation and brightness colors (non-intuitive)
  - **RGB** – used on screens
  - **YIQ** – TV North American system
  - **CMY** (cyan, magenta, yellow) – color impression
  - **CMYK** (cyan, magenta, yellow, black) – color impression
- **User oriented** models
  - **HSV** (hue, saturation, value), also called **HSB** (hue, saturation, brightness)
  - **HLS** (hue, lightness, saturation)
  - The **Munsell system**
  - **CIE Lab**

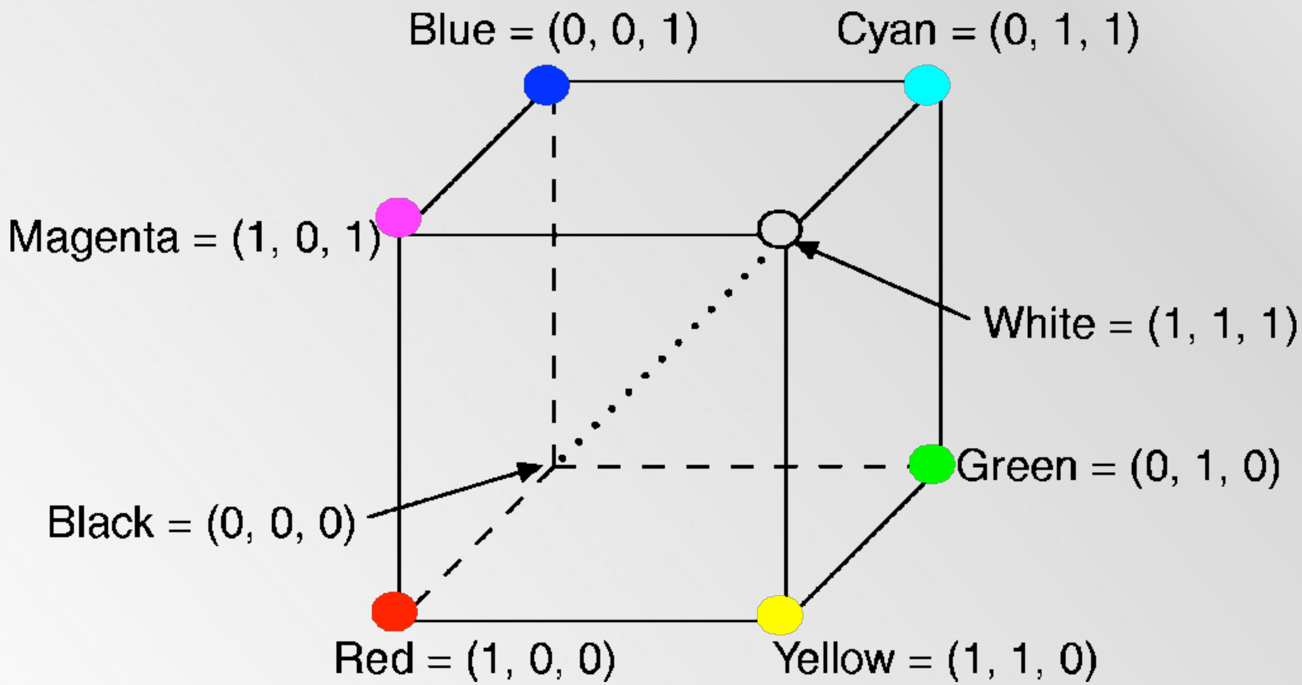
RGB Model

- Based on the fact that our eye has 3 types of cellules photosensitive each one of RGB colors
- Used by video devices
- **Additive model** – primary colors intensities are sumed to obtain other colors
- We obtain each color point on the cube frontier by adding its coordenates values (R, G, B), each ranging between [0, 1]
- Differences among adjacent colors can not be perceived



RGB Model

- Cube varies among screens



YIQ Model

- Luminance is in Y (same as with XYZ model) while I and Q incorporate chromaticity
  - **I** codifies tones between **orange and cyan** (skin)
  - **Q** codifies tones between **green and magenta**
- A intensity combination from RGB is selected to obtain parameter Y (B/W TVs only need Y)
- Conversion from RGB to YIQ:

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.144 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

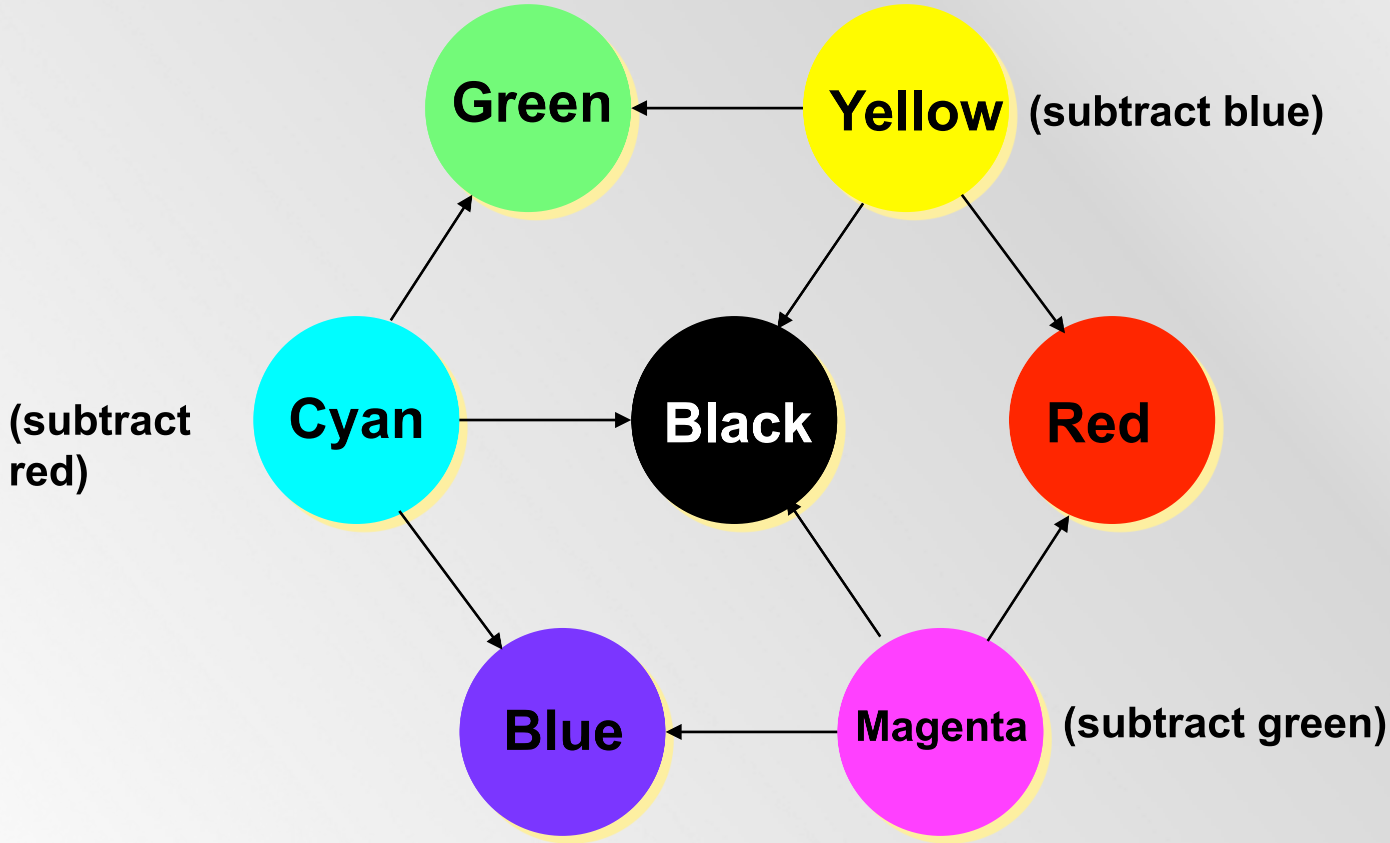
- I, Q information is applied on the Y signal

CMY Model

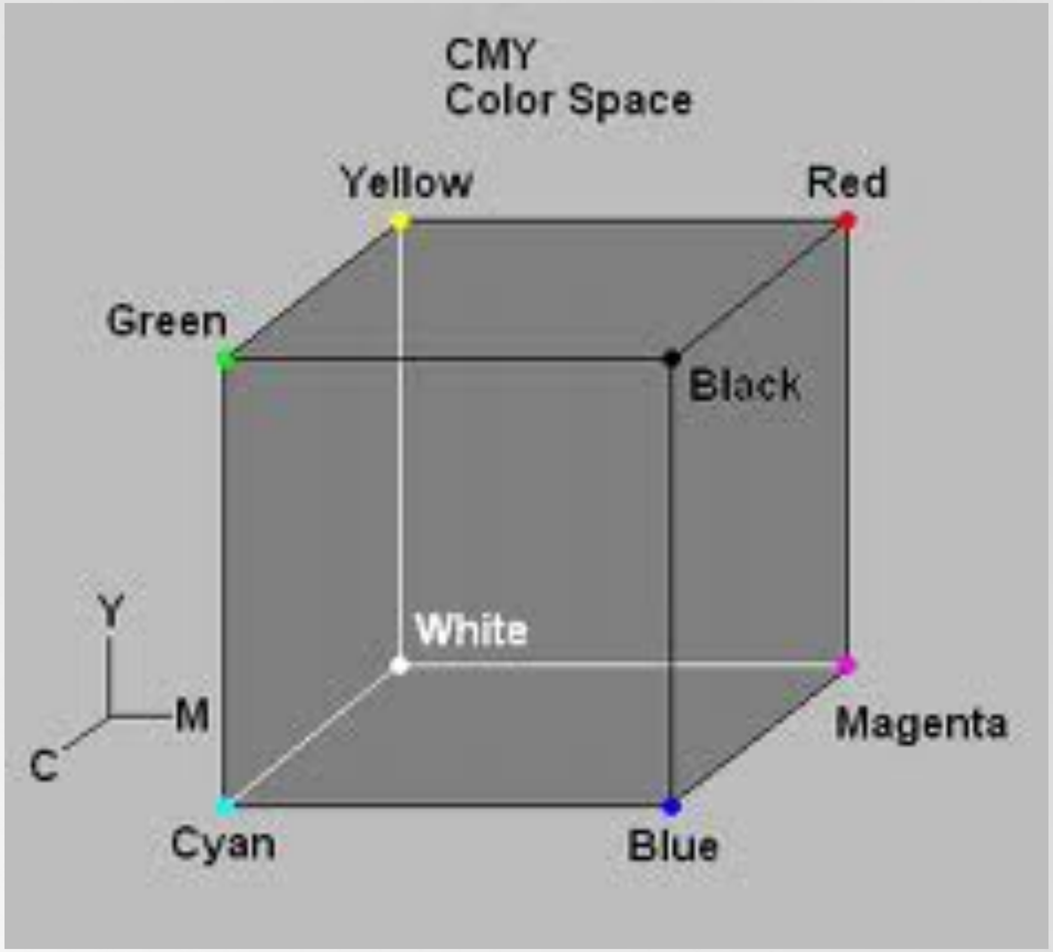
- "Subtractive" model defined with cyan, magenta and yellow
- Employed by printers (useful to save ink)
- CMY(K) is a CMY variant
- A color point is generated through a 4 points set
  - K = min(C, M, Y) is black
  - C' = C - K
  - M' = M - K
  - Y' = Y - K
  - (C', M' or Y' = zero)

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

CMY Model


Green
Yellow
(subtract blue)
(subtract
red)
Cyan
Black
Red
Blue
Magenta
(subtract green)

CMY model

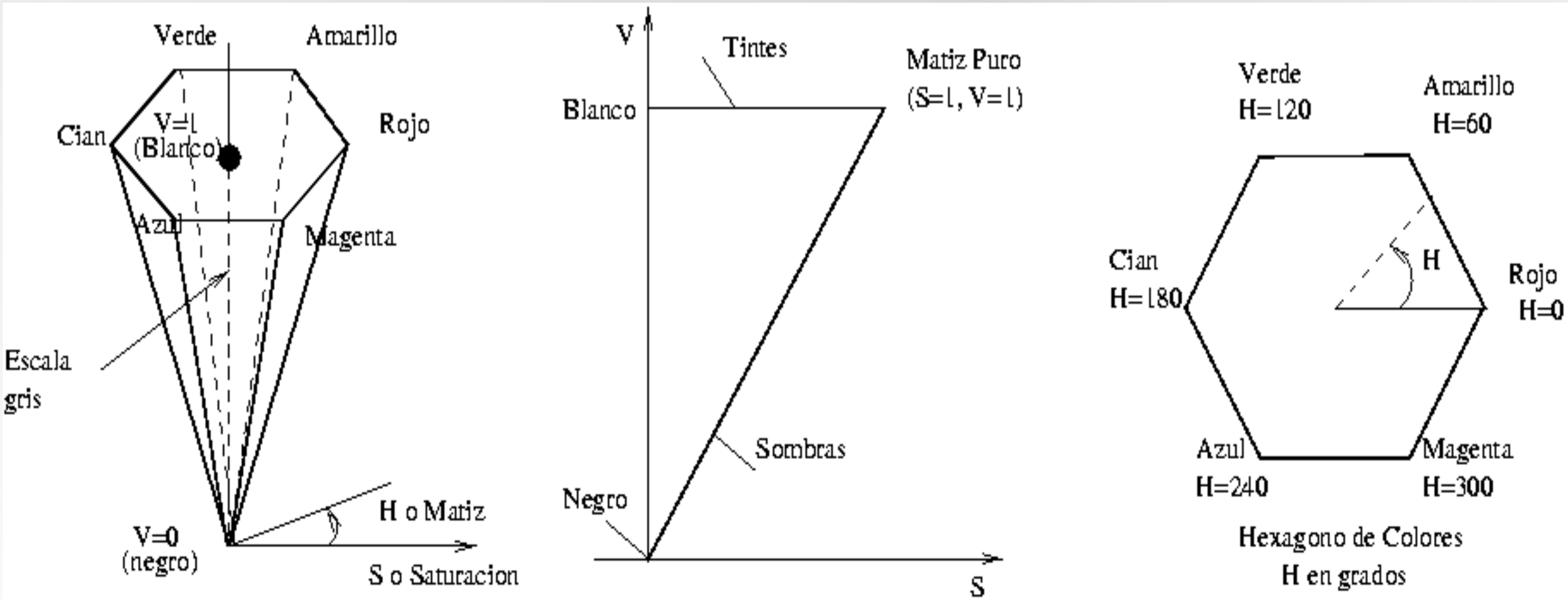

CMY
Color Space
Yellow
Red
Green
Black
Y
White
M
Magenta
C
Cyan
Blue

HSV model (or HSB)

- It simulates the way painters work
- Parameters
  - **Hue** – represented along the vertical axis
  - **Saturation** – along horizontal axis

    Varies between 0 and 1
  - **Value** (brightness) – varies between 0 (vertical axis bottom) and 1 (vertical axis top)

HSV, HSB Model



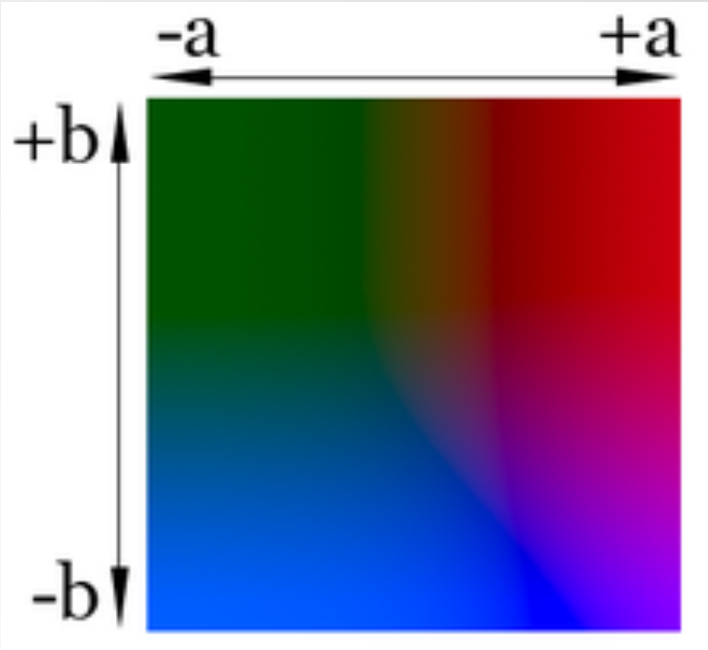
CIE Lab Model

- Created in1976 to describe all colors perceivable by a human eye
- Created to measure reflectivity and transmittance
  - **Luminosity** (L),
  - **Position between red/magenta and green** (a, negative values indicate green and positive indicate magenta)

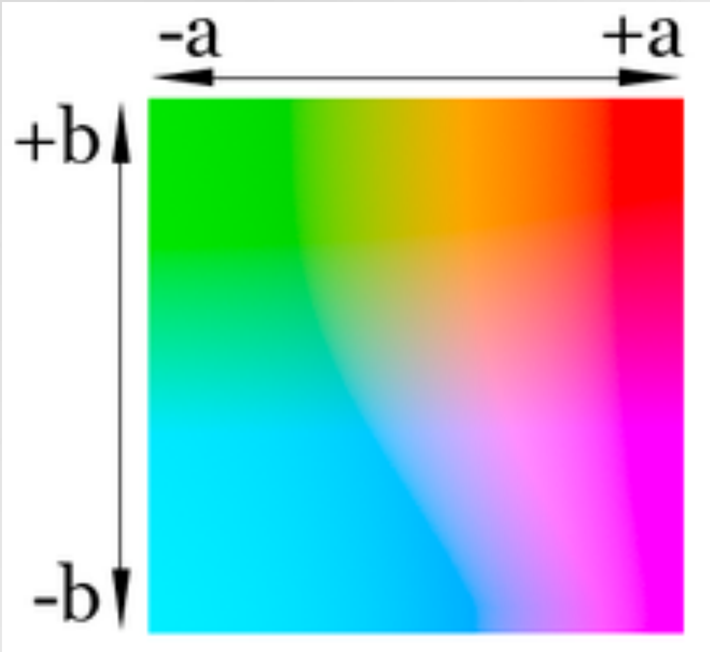
    Position between blue and yellow (b, negative values indicate blue and positive indicate yellow)

CIE Lab Model

Luminance 25%



Luminance 75%



Color models pros & cons

- **RGB**
  - + Cartesian coordinates system
  - + Linear
  - + Based on hardware (easy transformation to video)
  - + Based on visual perception
  - - Hard to use and name colors
  - - Does not cover the perceived colors gamut
  - - Non uniform: equal geometric distances → different perceptive distance

Color models pros & cons

- **CIE**
  - + It covers the perceived colors gamut
  - + It covers all possibilities of color
  - + Based on color human perception
  - + Linear
  - - Non-uniform (almost uniform)
  - - Color graphics do not incorporate luminance

Color models pros & cons

- **HSV**
  - \+ Easy conversion to RGB
  - \+ Easy to specify colors
  - \- Non-Linear
  - \- It covers the perceived colors gamut
  - \- Non-uniform

Alfa Channel

- We add another channel to the colors channel
  - **α-channel**
- It ranges between 0 and 1, being:
  - 1 = completely opaque
  - 0 = completely transparent