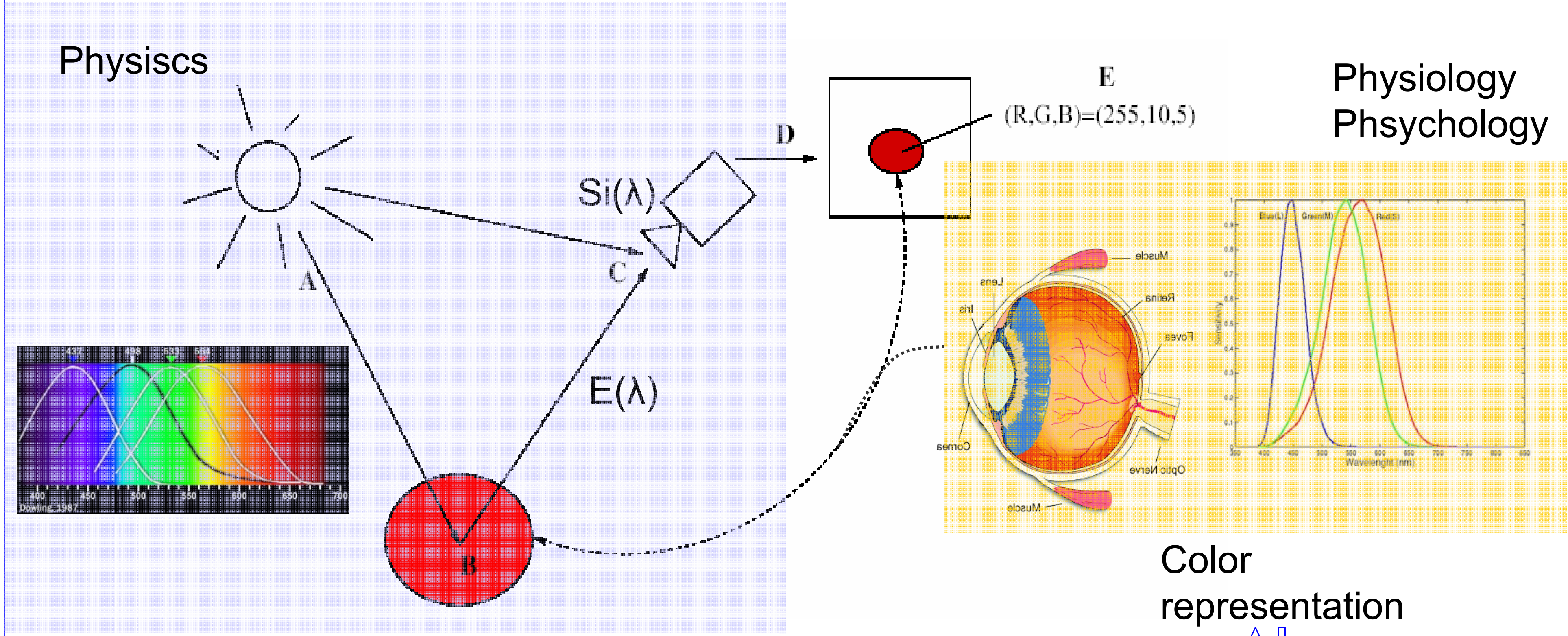
Color imaging

Color science

- Color vision
  - *Seeing* colors
  - Foundations of color vision
  - Trichromatic model
- Color naming
  - *Attaching labels* to colors
- Colorimetry & Photometry
  - *Measuring* colors: radiometric & photometric units
- Applications
  - Image rendering, cross-media color reproduction, image analysis, feature extraction, image classification, data mining...

What *is* color?

Physiscs



Physiology
Phsychology

Color
representation

⇧⇩

Modeling

⇧⇩

Color
perception

$$C_i = \int_{\lambda} E(\lambda) S_i(\lambda)\, d\lambda$$

$S_i(\lambda)$: sensitivity of the i^{th} sensor
$E(\lambda)$: Spectral Power Distribution (SPD) of the diffused light

What *is* color?

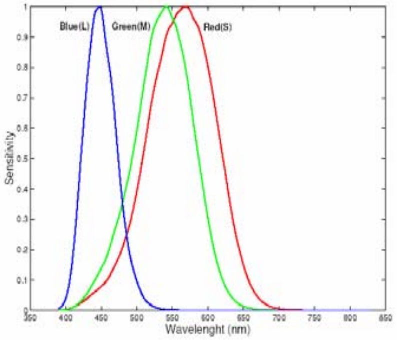
Radiometric quantities ⇔

Physics (EM)

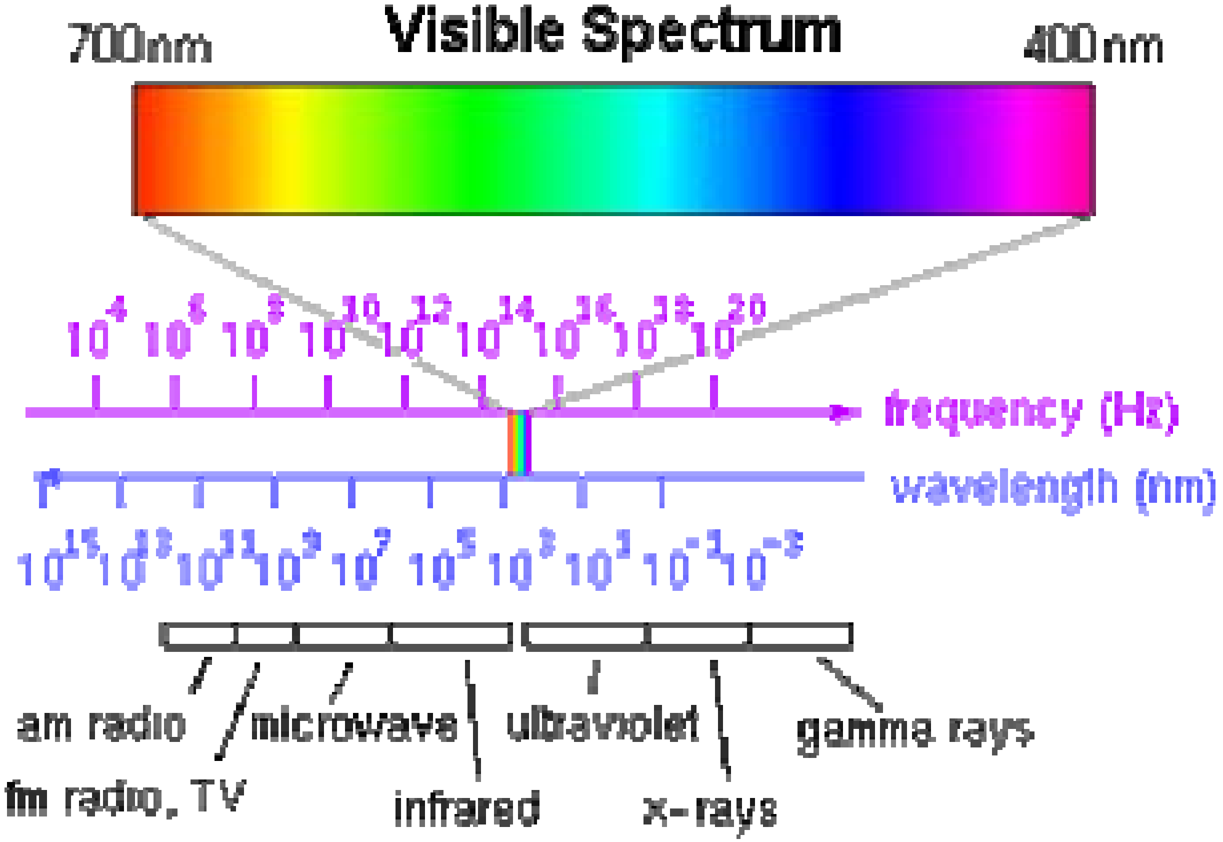
Photometry& Colorimetry

Neurophysiology (Color vision)

⇔ *Photometric* quantities (only concern the visible spectrum)



Colorimetry



Color models

- A color model is a 3D unique representation of a color
- There are different color models and the use of one over the other is problem oriented. For instance
  - RGB color model is used in hardware applications like PC monitors, cameras and scanners
  - CMY color model is used in color printers
  - YIQ model in television broadcast
  - In color image manipulation the two models widely used are HSI and HSV.

Color models

- Colorimetric color models
  - Based on the principles of trichromacy
  - Allow to predict if two colors match in appearance in given observation conditions
  - CIE XYZ
  - Perceptually uniform color models (CIELAB, CIELUV)

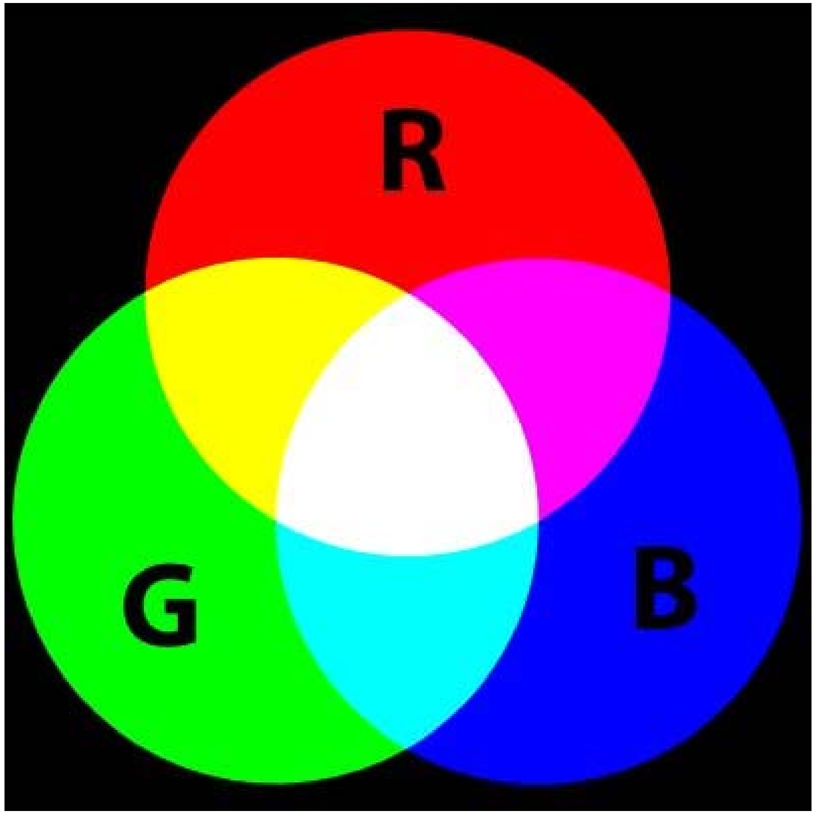
- User-oriented color models
  - Emphasize the intuitive color notions of brightness, hue and saturation
    - HSV (Hue, saturation, Value)
    - HSI (Hue, Saturation, Intensity)
    - HSL (Hue, Saturation, Lightness)

Color models

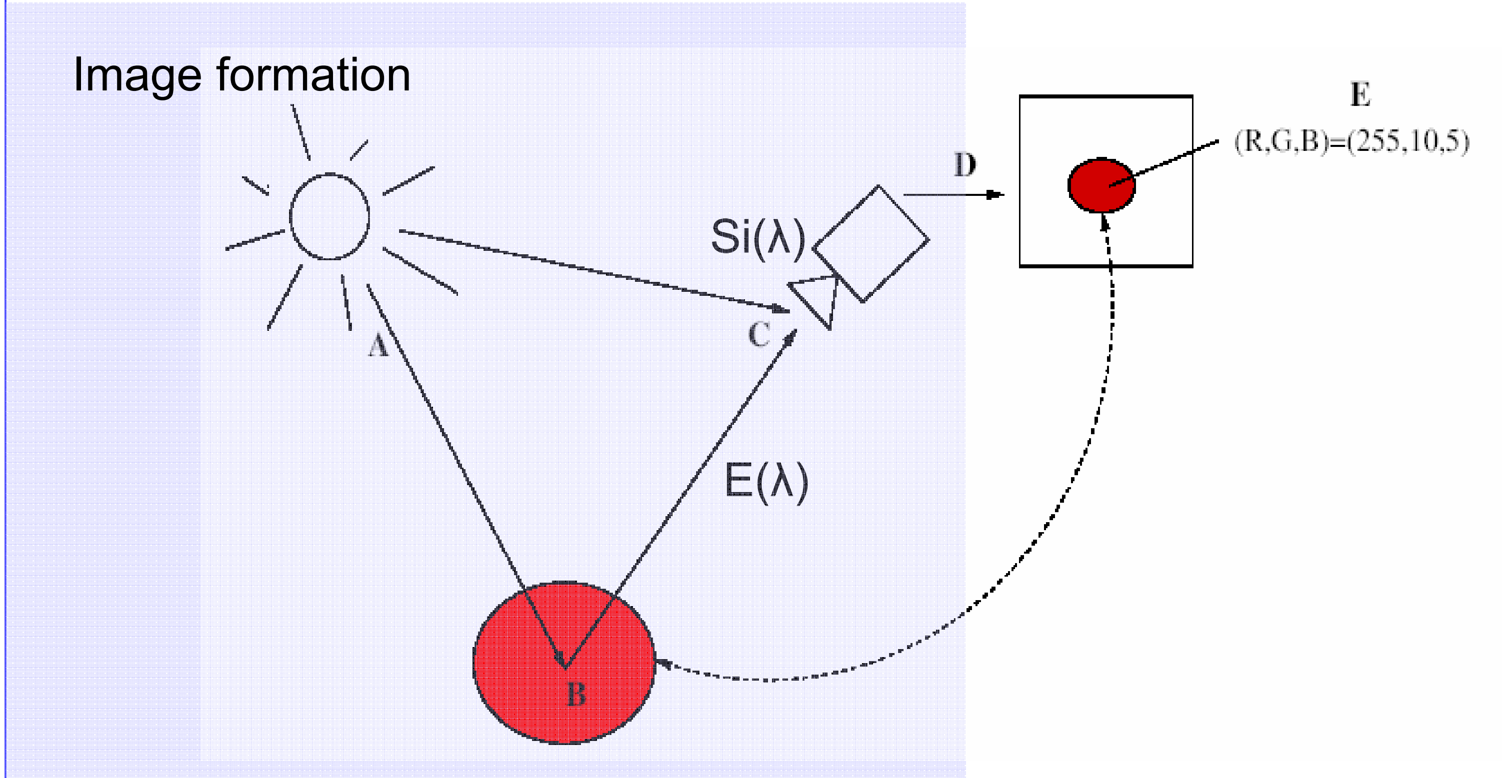
- Device-oriented color models
  - The color representation depends on the device.
- Concerns both acquisition and display devices
  - Acquisition
    - The value of the color numerical descriptors depend on the spectral sensitivity of the camera sensors
  - Display
    - A color with given numerical descriptors appears different if displayed on another device or if the set-up changes
    - In RGB for instance, the R,G and B components depend on the chosen red, green and blue primaries as well as on the reference white
    - Amounts of ink expressed in CMYK or digitized video voltages expressed in RGB
  - RGB, Y'CbCr,Y'UV, CMY, CMYK
  - Towards device independence: sRGB

RGB color model

- Additive color model
  - The additive reproduction process usually uses red, green and blue light to produce the other colors



RGB color model

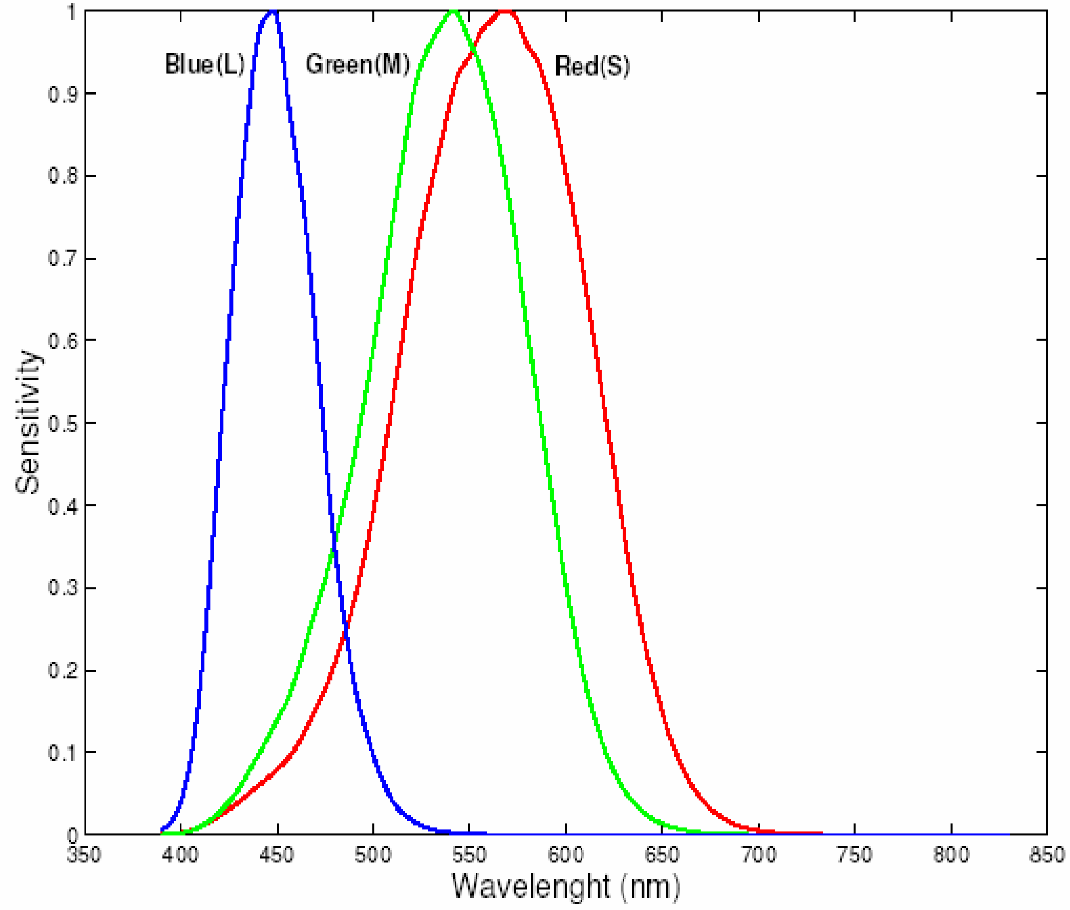


$$C_i = \int_{\lambda} E(\lambda) S_i(\lambda)\, d\lambda$$

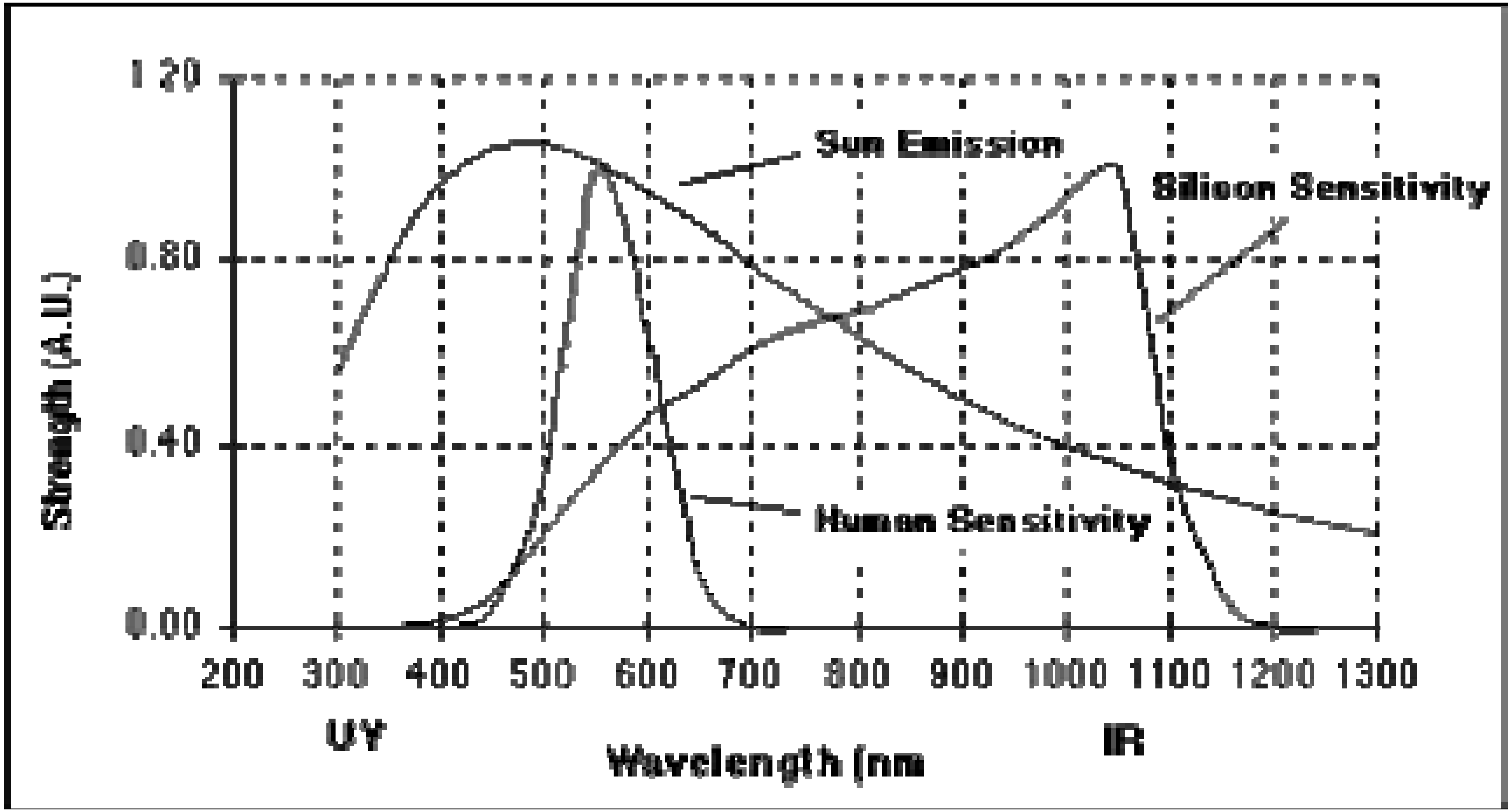
$S_i(\lambda)$: sensitivity of the i^{th} sensor
E(λ): Spectral Power Distribution (SPD) of the diffused light

Spectral sensitivities

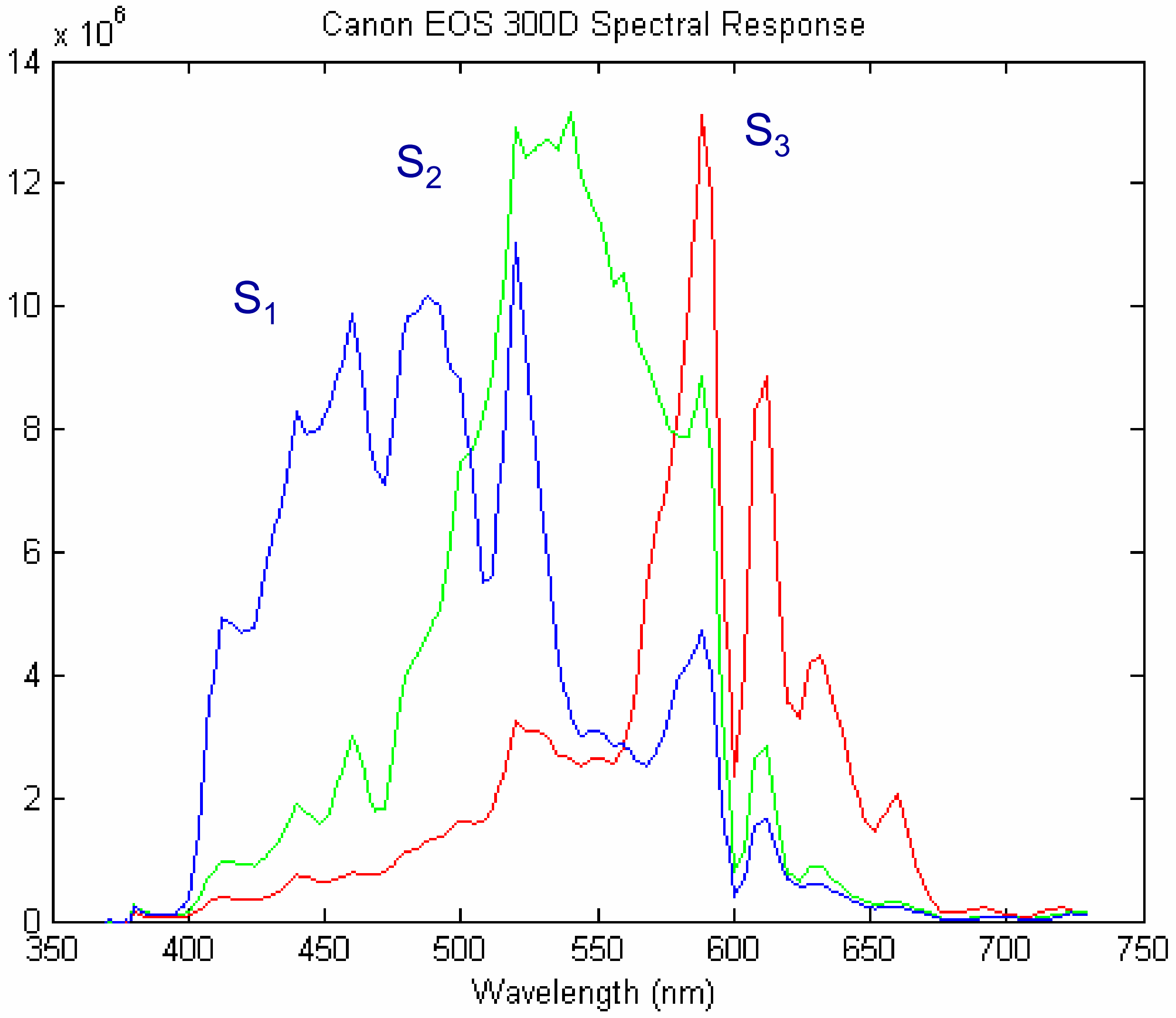
Target: spectral sensitivity of the eye



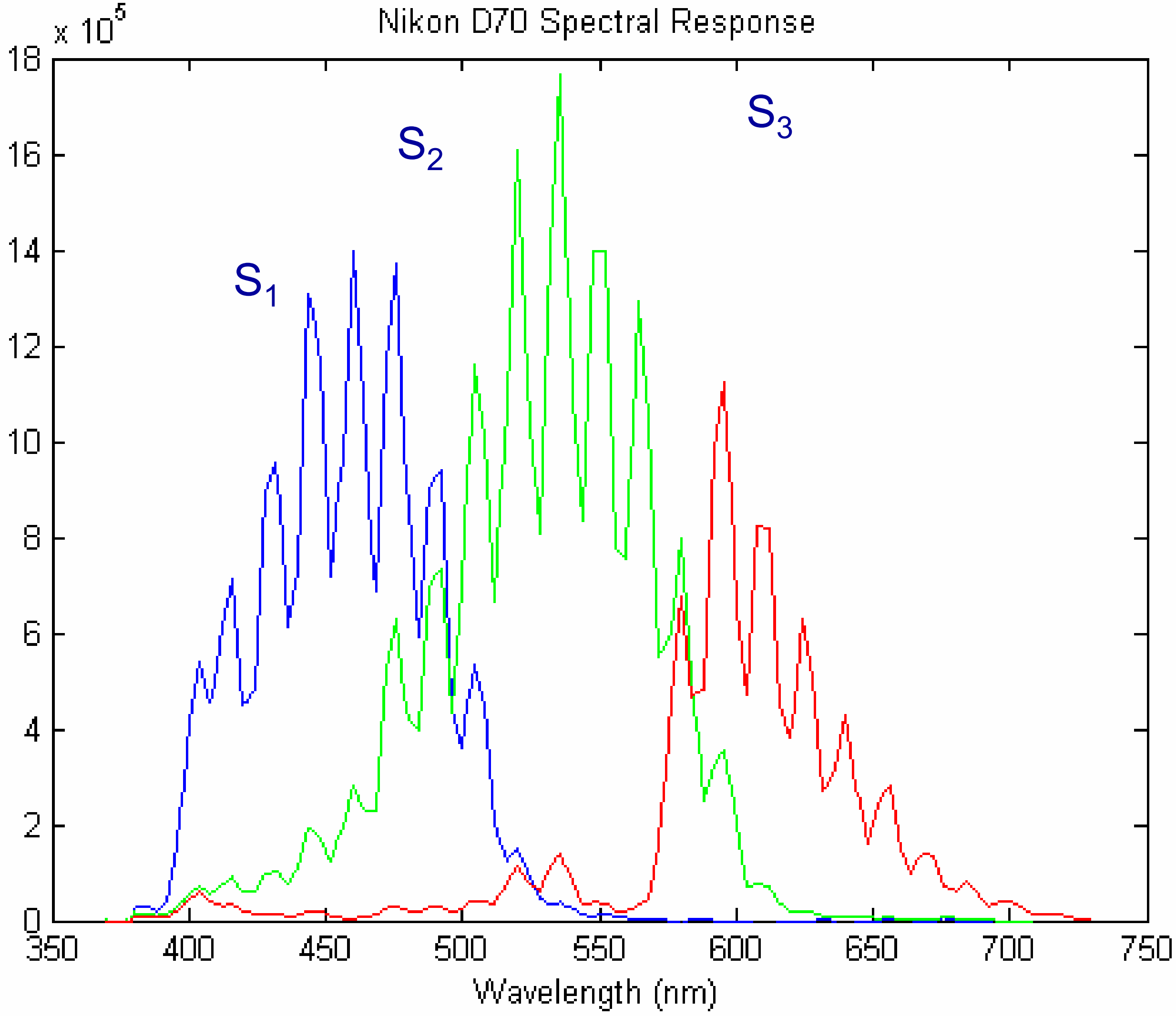
Broad range sensitivity



Sensor sensitivity: Ex. 1



Spectral sensitivity: Ex. 2



RGB model

$$C_i = \int_\lambda P(\lambda) S_i(\lambda)\, d\lambda$$

$P(\lambda)$: PSD (Power Spectral Density of the incident light)

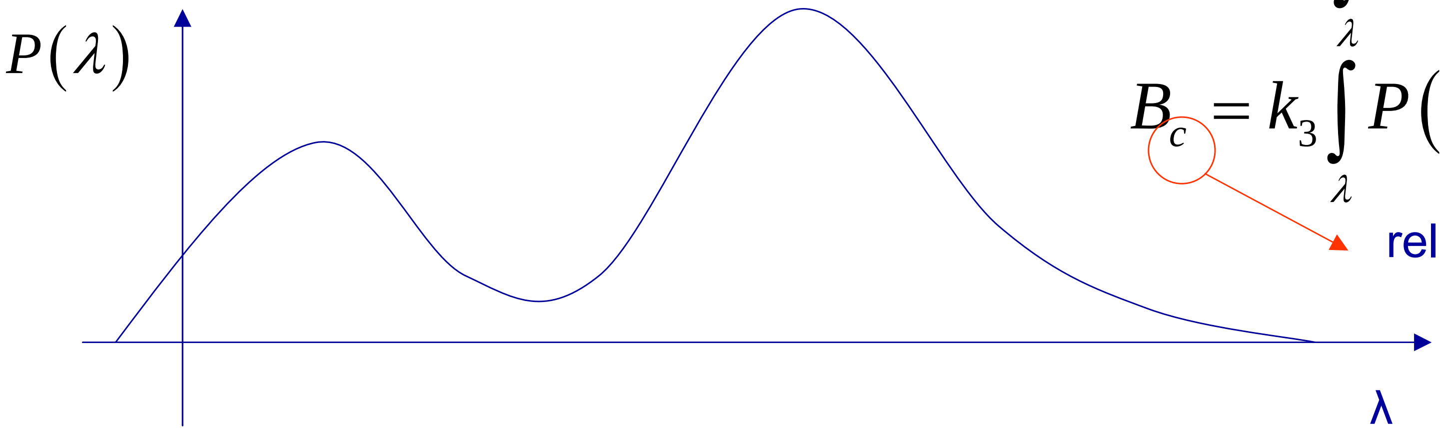
$S_i(\lambda)$: spectral sensitivity of the "red", "green" and "blue" sensors

$$R_c = k_1 \int_\lambda P(\lambda) S_1(\lambda)\, d\lambda$$

$$G_c = k_2 \int_\lambda P(\lambda) S_2(\lambda)\, d\lambda$$

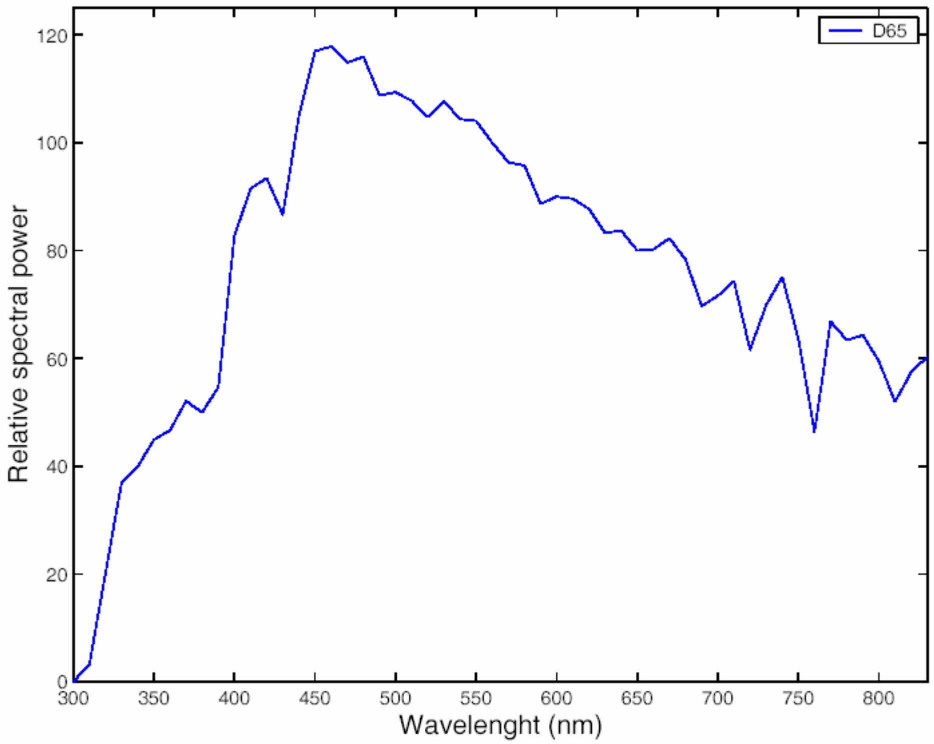
$$B_c = k_3 \int_\lambda P(\lambda) S_3(\lambda)\, d\lambda$$

relative to the camera



Reference white

- The reference white is the light source that is chosen to approximate the white light
  - D65, D50



Reference white

- The reference white, E(λ), will be given the maximum tristimulus values in all channels (R=G=B=255)
- The numerical values of the R,G,B coordinates of a generic PSD P(λ) will depend on the choice of E(λ)

$$
\begin{aligned}
R_{Ec} &= k_1 \int_{\lambda} E(\lambda) S_1(\lambda)\, d\lambda = 255 \\
G_{Ec} &= k_2 \int_{\lambda} E(\lambda) S_2(\lambda)\, d\lambda = 255 \rightarrow k_1, k_2, k_3 \\
B_{Ec} &= k_3 \int_{\lambda} E(\lambda) S_3(\lambda)\, d\lambda = 255
\end{aligned}
$$

RGB tristimulus values

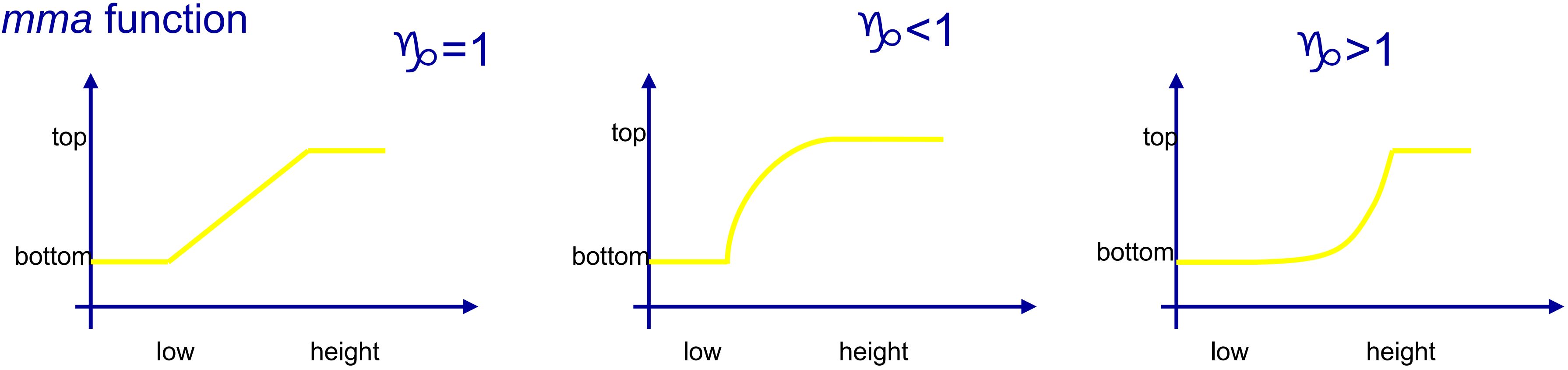
- The R,G,B coordinates does not have an absolute meaning, as their value depend on
  - The spectral sensitivity of the sensors that are used in the capture device
  - The reference white
- Thus, R,G,B values of the same physical stimulus (image) acquired with different cameras are different, in general
- Gamut: set of colors that is “manageable” by the device
  - Acquisition devices: set of colors that are represented by the device
  - → gamut mapping

RGB model

- Similar considerations apply to rendering devices: the rendering of a color with given tristimulus coordinares (R,G,B) will depend on
  - The spectral responses of the emitters
    - phosphors for a CRT
    - color filters in a LCD
  - The calibration of the device
    - As for the acquisition devices, the color corresponding to the rendered white must be set
    - To define the entire gamut for a monitor, you only need mark the points on the diagram that represent the colors the monitor actually produces. You can measure these colors with either a colorimeter or a photospectrometer along with software that ensures the monitor is showing 100 percent red for the red measurement, 100 percent green for the green measurement, and 100 percent blue for the blue measurement.
  - The linearity of the monitor transfer function (gamma)

Gamma function

Gamma function

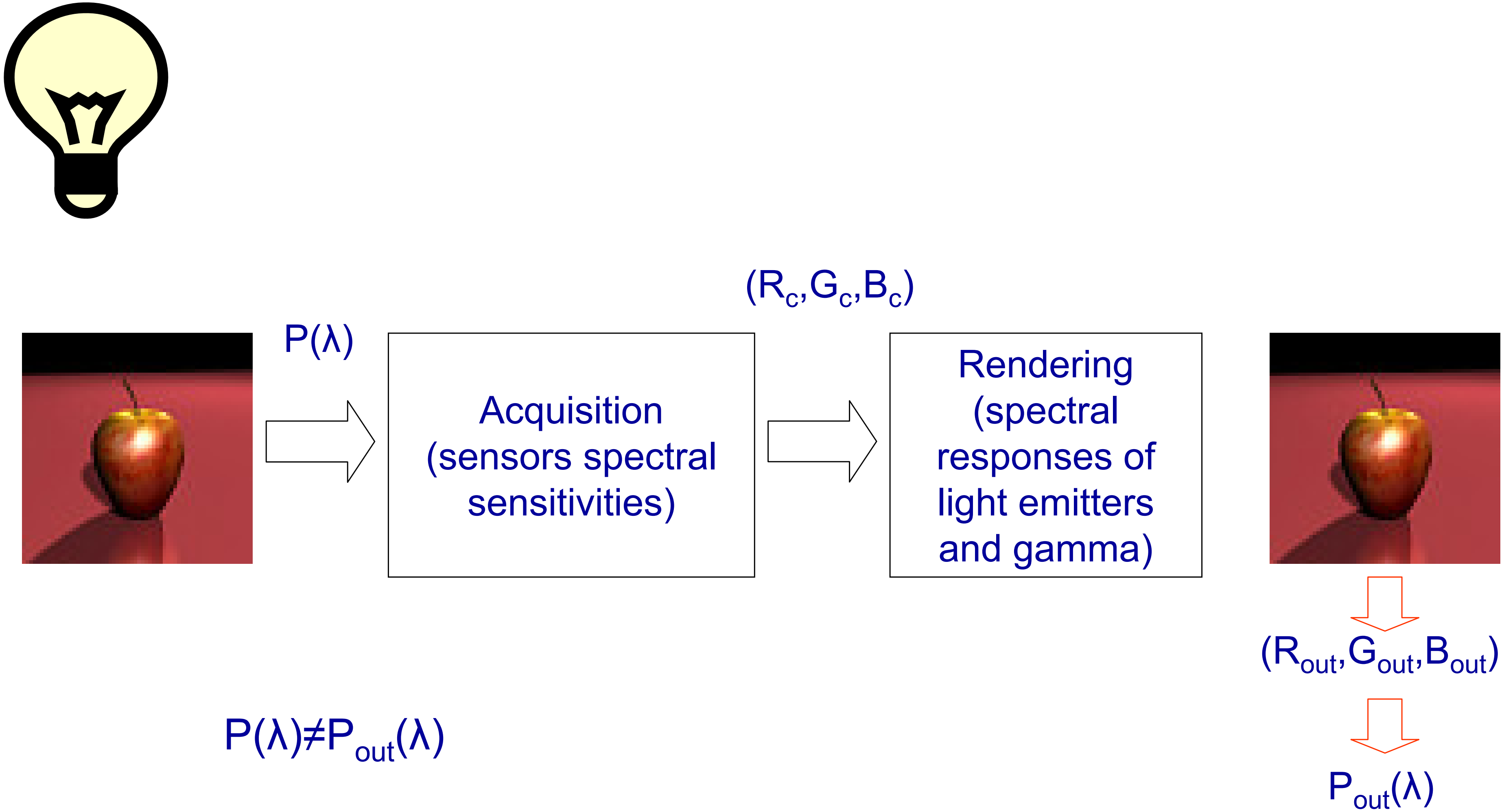


- Typical CRT monitors: gamma=2.2
- The non-linearity of the monitor can be compensated by non-uniform scaling of the RGB coordinates at input (*RGB linearization*)
- This led to the definition of the sRGB color model

RGB model: rendering ex.

- The RGB values depend on the phosphores coordinates
  - Different for the different reproduction media (CRT, television displays)
  - Example:
    - Red phosphore: x=0.68, y=0.32
    - Green phosphore: x=0.28, y=0.60
    - Blue phosphore: x=0.15, y=0.07
  - Given the x,y coordinates of the phosohores, the reference white point and the illuminant (D65), the RGB coordinates can be calculated
  - Calibration
    - the R=G=B=100 points must match in appearance with the white color as observed by 10 deg observer under the D65 illuminant
    - The brightness of the three phosphores is non linear with the RGB values. A suitable correction factor must be applied (Gamma correction)

RGB model



$P(\lambda)$

Acquisition (sensors spectral sensitivities)

(R_c,G_c,B_c)

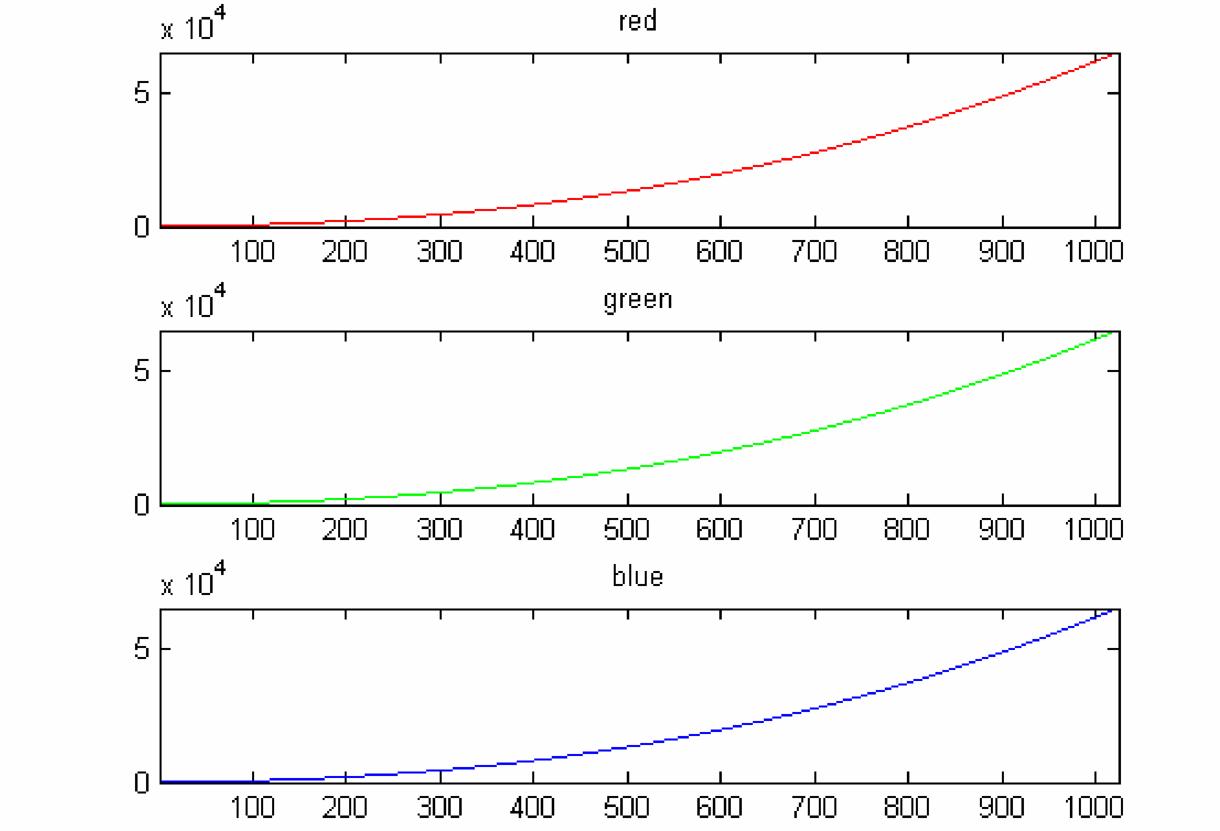
Rendering (spectral responses of light emitters and gamma)

$(R_{out},G_{out},B_{out})$

$P_{out}(\lambda)$

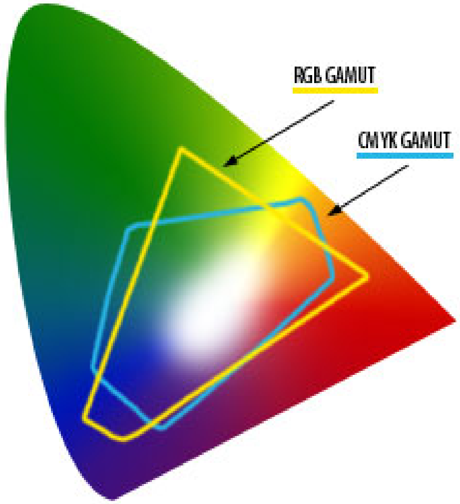
$P(\lambda) \neq P_{out}(\lambda)$

sRGB


x 10^4
red
5
0
100
200
300
400
500
600
700
800
900
1000
x 10^4
green
5
0
100
200
300
400
500
600
700
800
900
1000
x 10^4
blue
5
0
100
200
300
400
500
600
700
800
900
1000

sRGB

- RGB specification that is based on the average performance of personal computer displays. This solution is supported by the following observations:
  - Most computer monitors are similar in their key color characteristics - the phosphor chromaticities (primaries) and transfer function → RGB primaries, γ value
  - Reference viewing environments are defined for standard RGB
    - Luminance level 80 cd/m2
    - Illuminant White *x* = 0.3127, *y* = 0.3291 (D65)
    - Image surround 20% reflectance
    - Encoding Ambient Illuminance Level 64 lux
    - Encoding Ambient White Point x = 0.3457, y = 0.
    - Encoding Viewing Flare 1.0%
    - Typical Ambient Illuminance Level 200 lux
    - Typical Ambient White Point *x* = 0.3457, *y* = 0.35
    - Typical Viewing Flare 5.0%



RGB standard observer

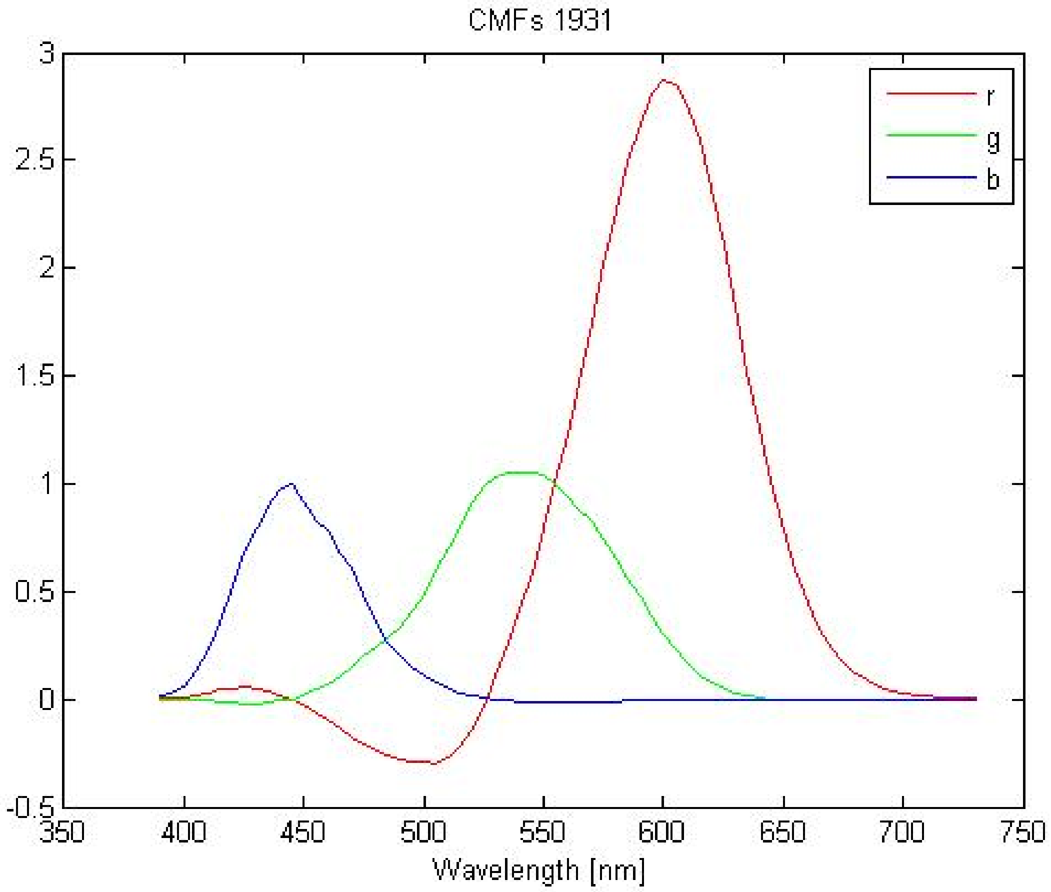
- Spectral sensitivities for the human eye have been measured in reference conditions by a very large number of observers
- Performed by the CIE (Commission Intérnationale d'Eclairage) standardization committee
- Such curves are called Color Matching Functions (CMFs) after the type of experiment
- The so-derived tristimulus values
  - Are not device dependent
  - Are still relative as they depend on (1) the choice of the red, green and blue monochromatic primaries that were used (2) the reference white and (3) the experimental conditions

CIE - RGB

$$R = \int_{\lambda} P(\lambda)\bar{r}(\lambda)\,d\lambda$$

$$G = \int_{\lambda} P(\lambda)\bar{g}(\lambda)\,d\lambda$$

$$B = \int_{\lambda} P(\lambda)\bar{b}(\lambda)\,d\lambda$$



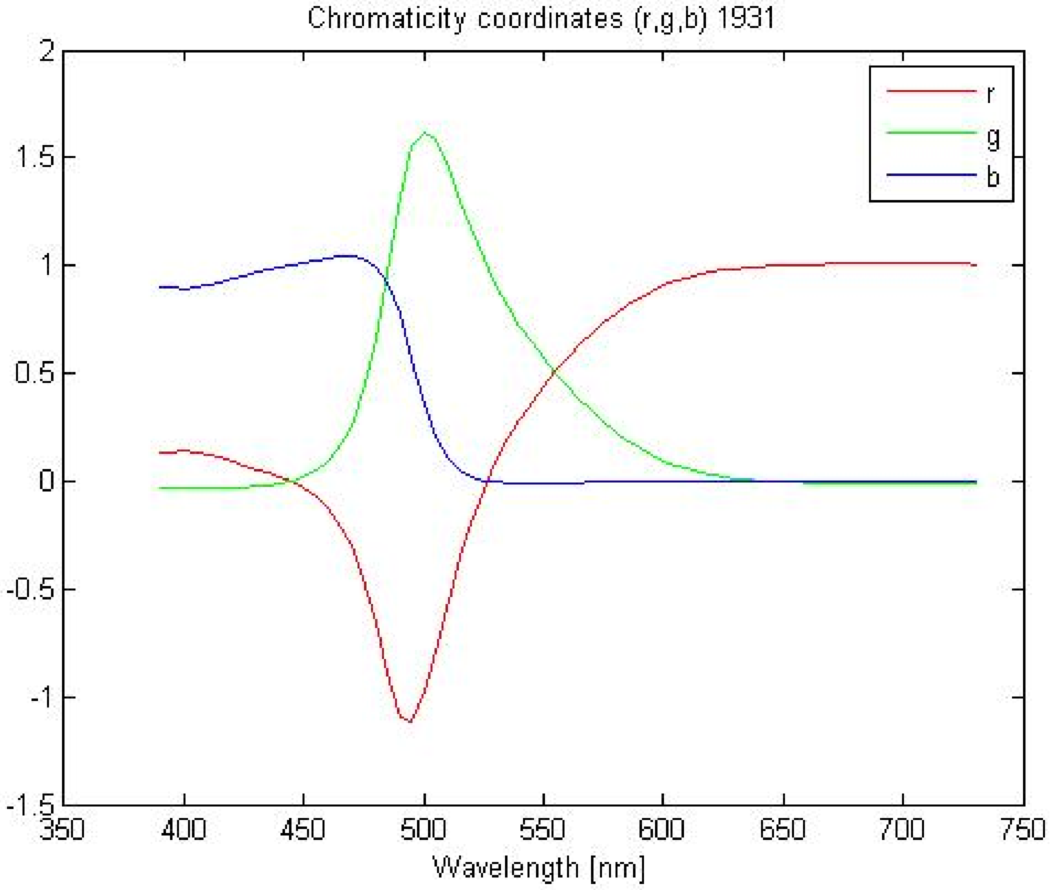
Chromaticity coordinates

$$r(\lambda)=\frac{\bar{r}(\lambda)}{\bar{r}(\lambda)+\bar{g}(\lambda)+\bar{b}(\lambda)}$$

$$g(\lambda)=\frac{\bar{g}(\lambda)}{\bar{r}(\lambda)+\bar{g}(\lambda)+\bar{b}(\lambda)}$$

$$b(\lambda)=\frac{\bar{b}(\lambda)}{\bar{r}(\lambda)+\bar{g}(\lambda)+\bar{b}(\lambda)}$$

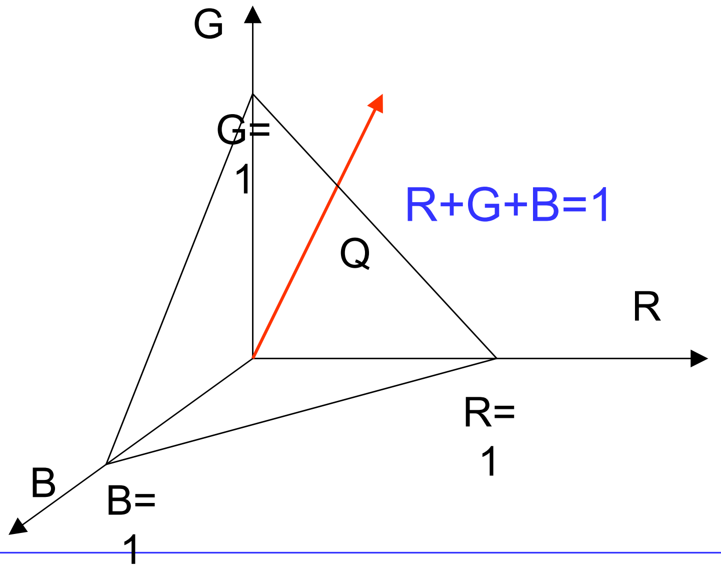
$$r(\lambda)+g(\lambda)+b(\lambda)=1$$



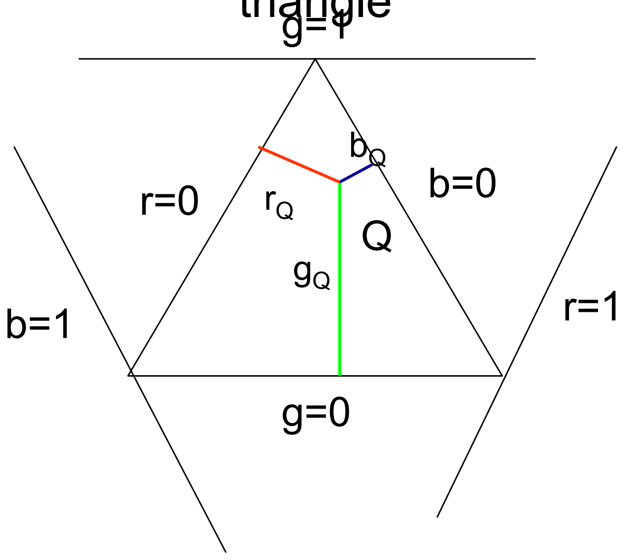
Chromaticity coordinates

Chromaticity coordinates

$$r = \frac{R}{R+G+B}$$
$$g = \frac{G}{R+G+B} \quad \Longrightarrow \quad r+g+b=1$$
$$b = \frac{B}{R+G+B}$$



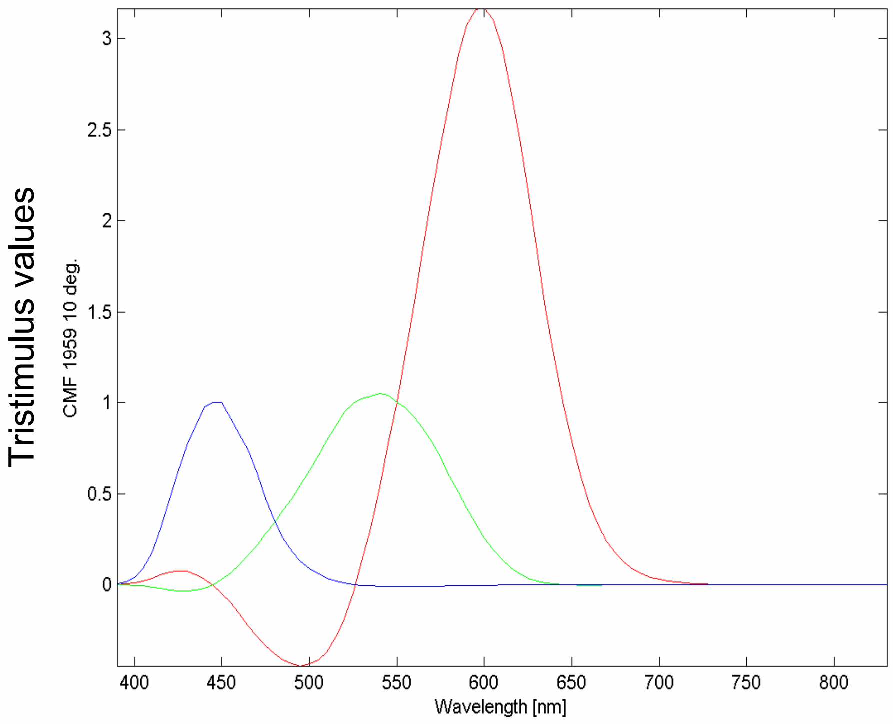
Maxwell color triangle



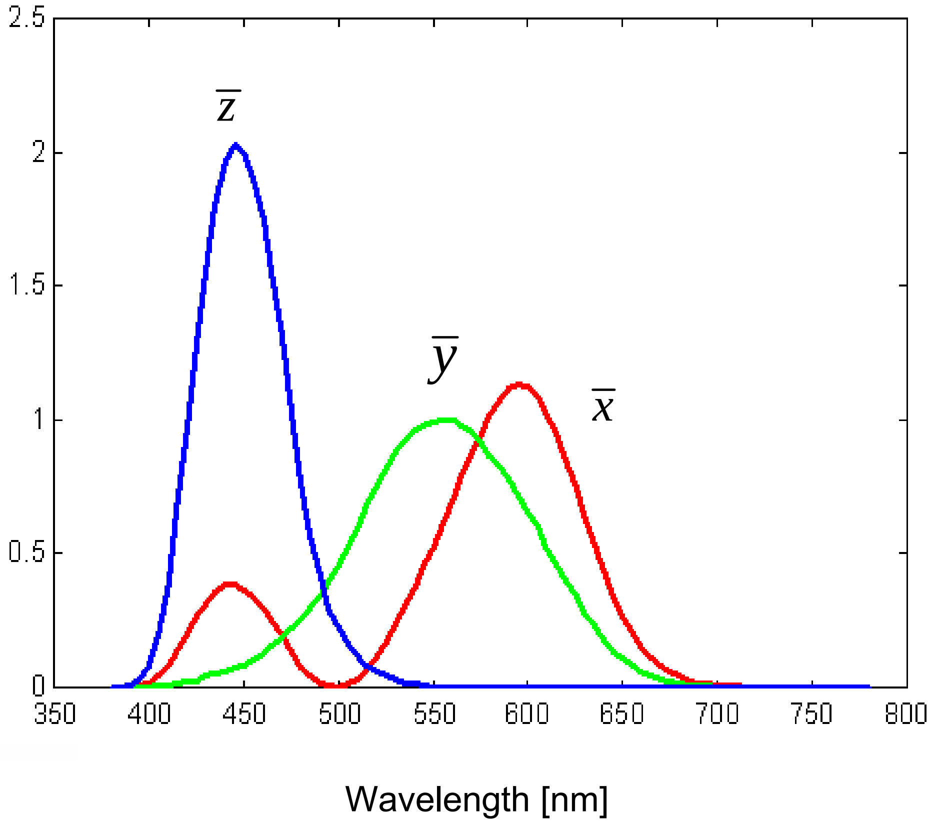
(r,g) specify the *hue and saturation* of the color while the information about the luminance is lost

From rgb to xyz

rgb



xyz (CIE-1931)



rgb2xyz

- Chromaticity coordinates

$$x = \frac{0.49r + 0.31g + 0.2b}{0.66697r + 1.1324g + 1.20063b}$$

$$y = \frac{0.17697r + 0.81240g + 0.01063b}{0.66697r + 1.1324g + 1.20063b}$$

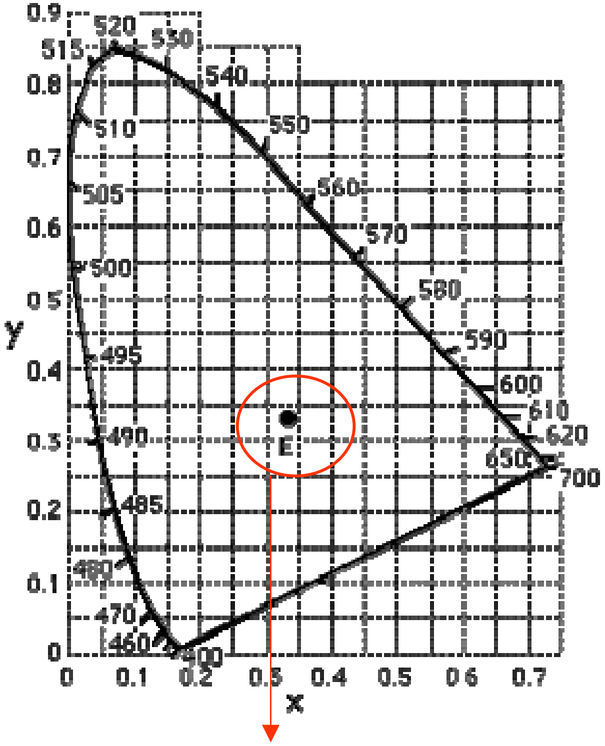
$$z = \frac{0.0r + 0.01g + 0.99b}{0.66697r + 1.1324g + 1.20063b}$$

- Tristimulus values

$$X = \frac{x}{y}V \quad \boxed{Y = V} \quad Z = \frac{z}{y}V$$

luminance

(x,y) chromaticity diagram



reference white

$$x_E = y_E = \frac{1}{3}$$

CIE Chromaticity Coordinates

- (X,Y,Z) tristimulus values

$$X = \int P_\lambda \bar{x}(\lambda) d\lambda$$

$$Y = \int P_\lambda \bar{y}(\lambda) d\lambda$$

$$Z = \int P_\lambda \bar{z}(\lambda) d\lambda$$

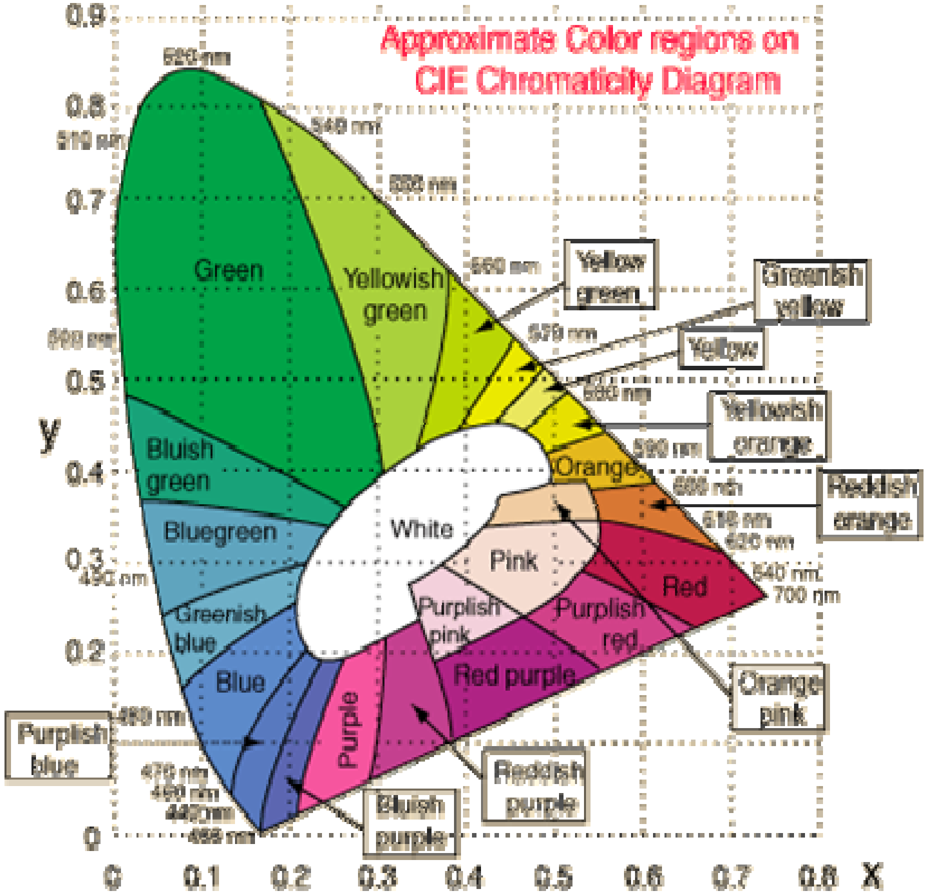
- Chromaticity coordinates

$$x(\lambda) = \frac{\bar{x}(\lambda)}{\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)}$$

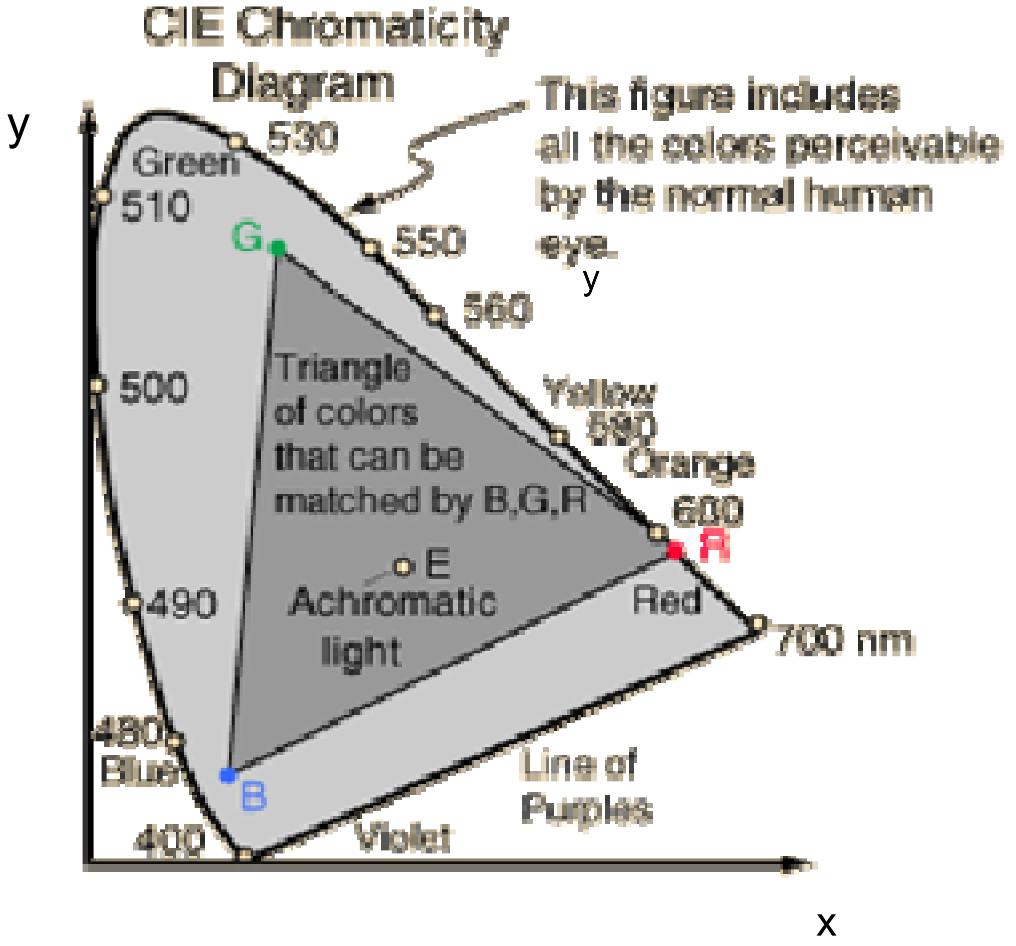
$$y(\lambda) = \frac{\bar{y}(\lambda)}{\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)}$$

$$z(\lambda) = \frac{\bar{z}(\lambda)}{\bar{x}(\lambda) + \bar{y}(\lambda) + \bar{z}(\lambda)}$$

$x(\lambda) + y(\lambda) + z(\lambda) = 1$ x - y chromaticity diagram

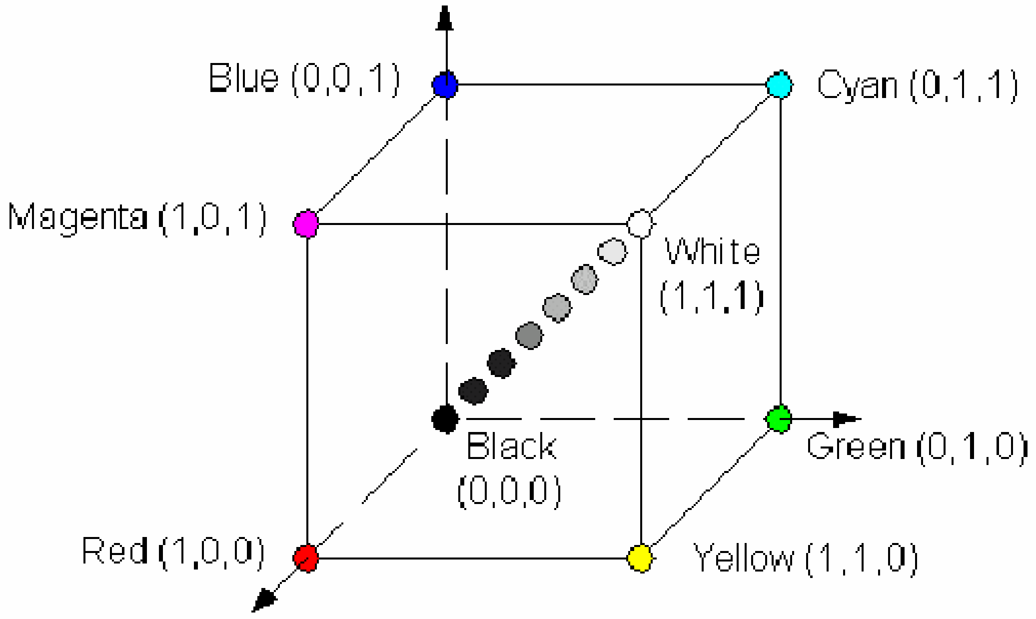


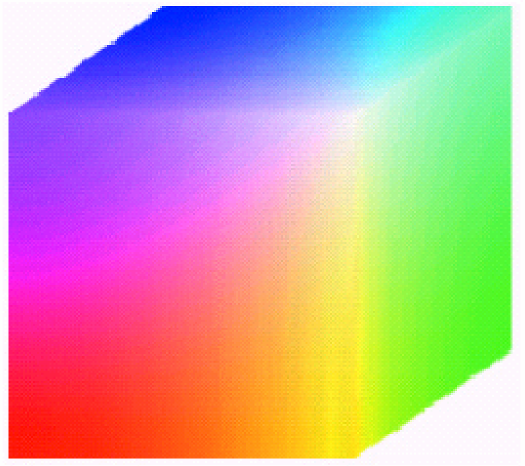
Gamut mapping



The CIE coordinates provide a device independent framework for performing color related processing

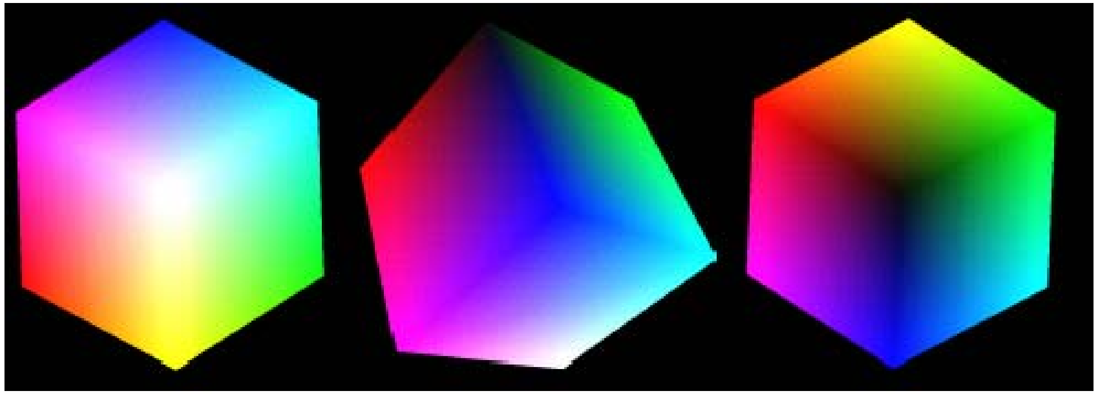
RGB model


Blue (0,0,1)
Cyan (0,1,1)
Magenta (1,0,1)
White
(1,1,1)
Black
(0,0,0)
Green (0,1,0)
Red (1,0,0)
Yellow (1,1,0)

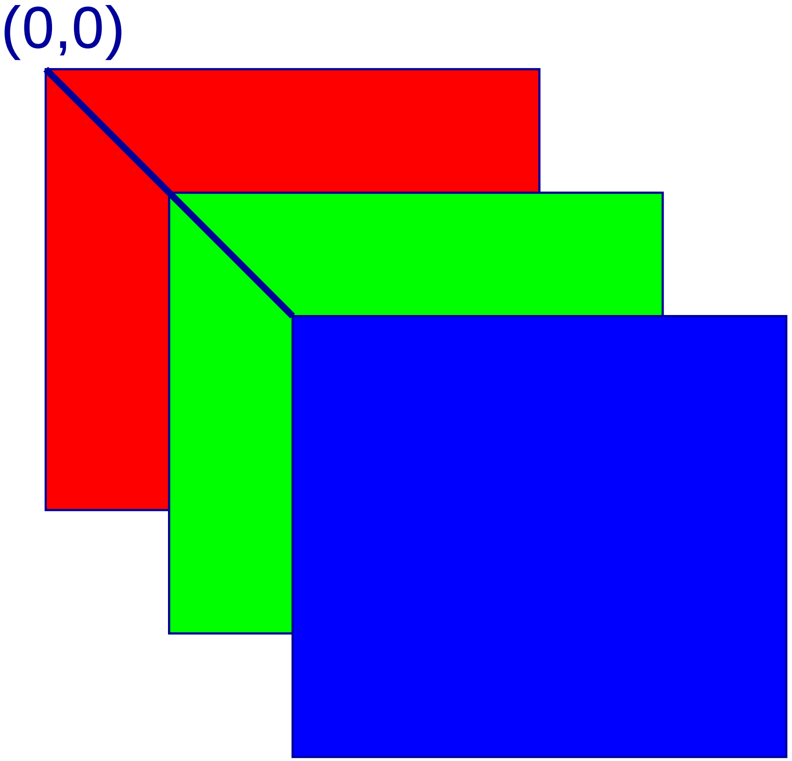


RGB model

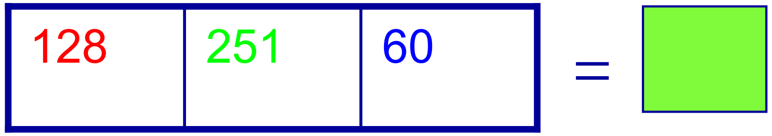
- Normalized values in [0,1] (chromaticity coordinates) may be convenient for some applications
- For a given device, the set of manageable colors lies inside the RGB cube
  - The R,G,B values must be represented as CIE coordinates



RGB model



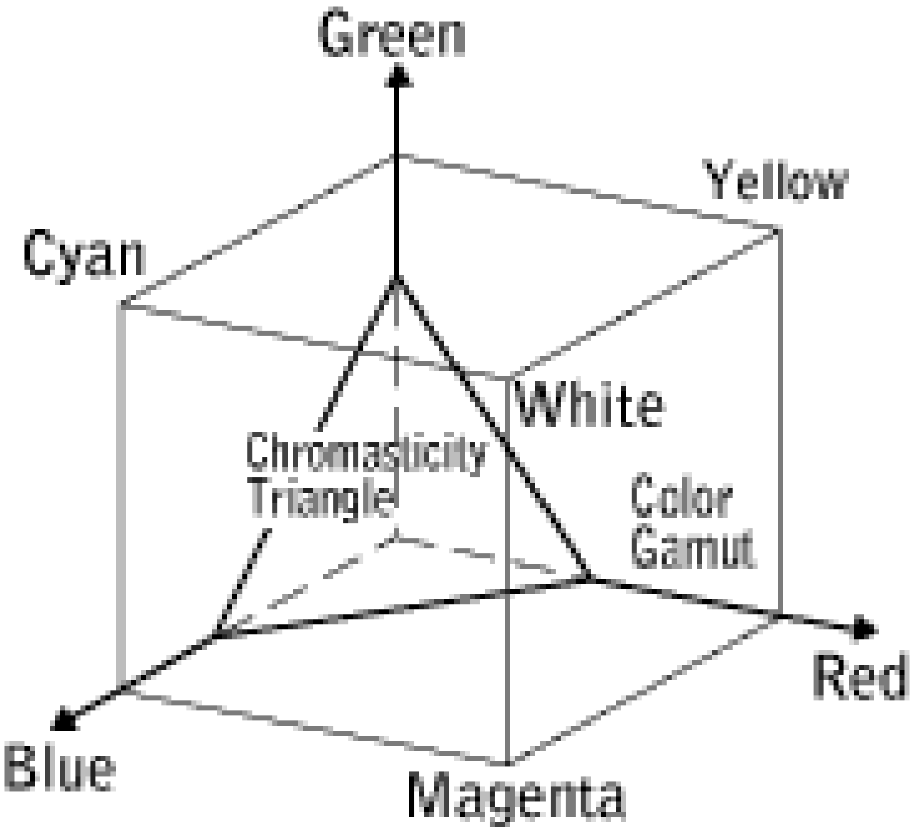
A single pixel consists of three components.



Final pixel in the image

If R,G, and B are represented with 8 bits (24-bit RGB image), the total number of colors is 256^3=16,777,216

RGB Color Space



Example RGB

Original Image

R-Component

G-Component

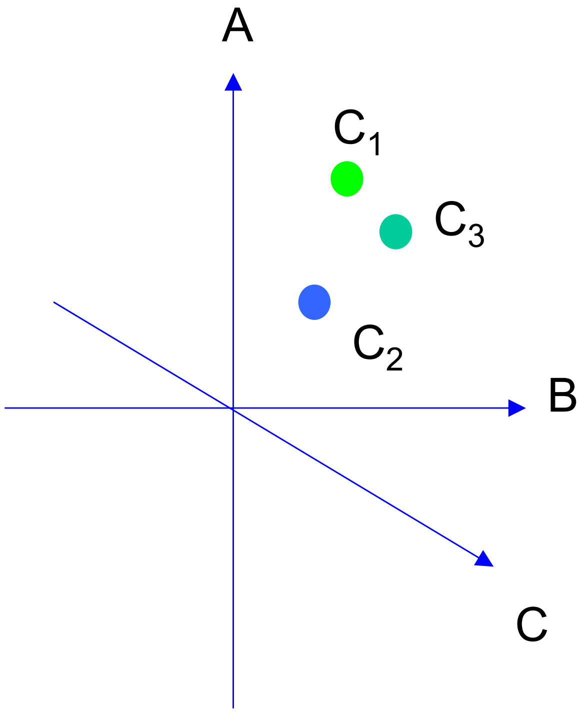
B-Component

Uniform color scales

Attributes: hue, saturation (chroma), brightness (lightness)

- Brightness
  - The attribute of a visual sensation according to which a visual stimulus appears to be more or less “intense”, or to emit more or less light
  - Ranges from “bright” to “dim”
- Lightness
  - The attribute of a visual sensation according to which a visual stimulus appears to be more or less “intense”, or to emit more or less light *in proportion to that emitted by a similarly illuminated area perceived as “white”*
  - Relative brightness
  - Ranges from “light” to “dark”
- Colorfulness
  - The attribute of a visual sensation according to which a visual stimulus appears to be more or less “chromatic”
- Chroma
  - The attribute of a visual sensation which permits a judgment to be made of the degree to which a chromatic stimulus differs from an “achromatic” stimulus of the same brightness
- Saturation
  - The attribute of a visual sensation which permits a judgment to be made of the degree to which a chromatic stimulus differs from an “achromatic” stimulus regardless of their brightness
- Chroma and saturation are often considered as equivalent

Perceptually uniform color models



Perceptual distance:

- Scaling the perceptual similarity among color samples
  - C1 is most similar to C3 than it is to C2

Measurable distance

- Metric in the color space
  - Euclidean distance among the color samples

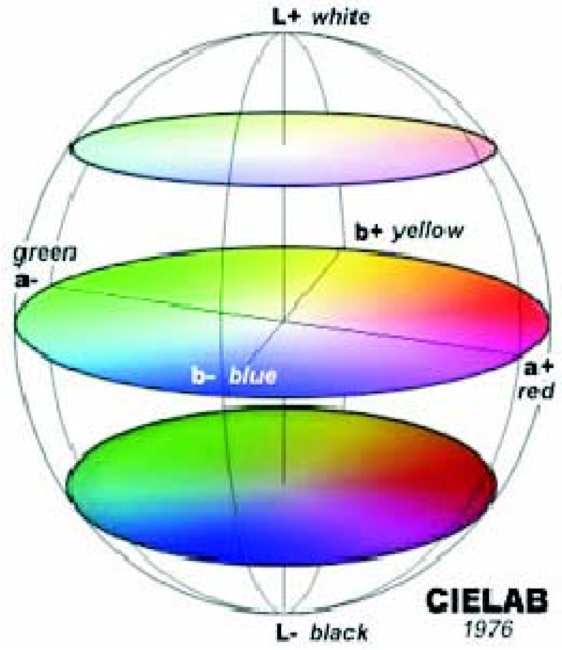
Does the perceptual distance match with the measurable distance among colors?

$$d\left(C_1C_3\right)\overset{?}{\leq}d\left(C_1C_2\right)$$

Color models whose metric is representative of the perceptual distance are *perceptually uniform*

Perceptually uniform Color models: Lab

CIE 1976 L*a*b* (CIELAB)



For: $$\frac{Y}{Y_n}, \frac{X}{X_n}, \frac{Z}{Z_n} \geq 0.01$$

$$\begin{aligned} L^* &= 116(Y/Y_n)^{1/3} - 16 \\ a^* &= 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}] \\ b^* &= 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}] \end{aligned}$$

otherwise

$$\begin{aligned} L^* &= 116\left[f\left(\frac{Y}{Y_n}\right) - \frac{16}{116}\right] \\ a^* &= 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right] \\ b^* &= 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right] \end{aligned}$$

$$f\left(\frac{Y}{Y_n}\right) = \begin{cases} \left(\frac{Y}{Y_n}\right)^{1/3} & for \quad \frac{Y}{Y_n} > 0.008856 \\ 7.787\frac{Y}{Y_n} + \frac{16}{116} & for \quad \frac{Y}{Y_n} \leq 0.008856 \end{cases}$$

X_n, Y_n, Z_n : *reference white*
Tristimulus values for a nominally white object-color stimulus. Usually, it corresponds to the spectral radiance power of one of the CIE standard illuminants (as D65 or A), reflected into the observer's eye by a perfect reflecting diffuser. Under these conditions, X_n, Y_n, Z_n are the tristimulus values of the standard illuminant with Y_n=100.

Hint: the diffuse light (✹ color) depends on both the physical properties of the surface and the illuminant

User-oriented CM

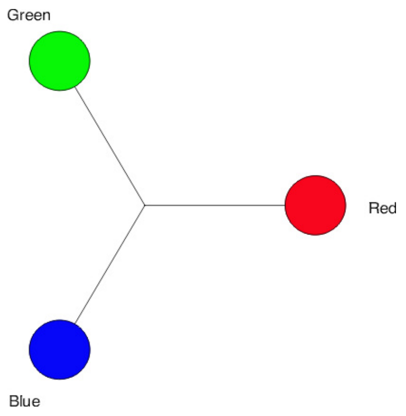
- HSV (Hue, Saturation, and Value). Sometimes variations include HSB (Brightness), HSL (Lightness/Luminosity), HIS (Intensity)
  - The hue of a color places it on the color wheel where the color spectrum (rainbow) is evenly spaced
  - The saturation or chroma of a hue defines its intensity
    - Decreasing the saturation via a contrast control adds gray.
  - The value of a hue defines how bright or dark a color is

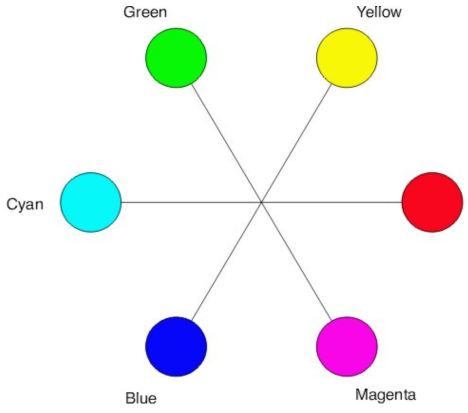
  - They all are effectively the RGB space twisted so that the neutral diagonal becomes the lightness axis, the saturation the distance from the central lightness axis and the hue the position around the center.
  - The only difference between these models is the measurement of saturation, or the strength of the colour

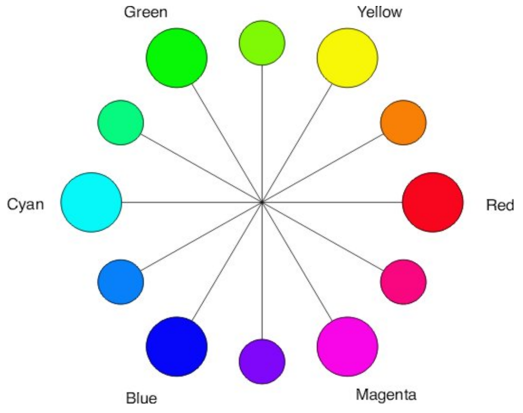
User-oriented CM

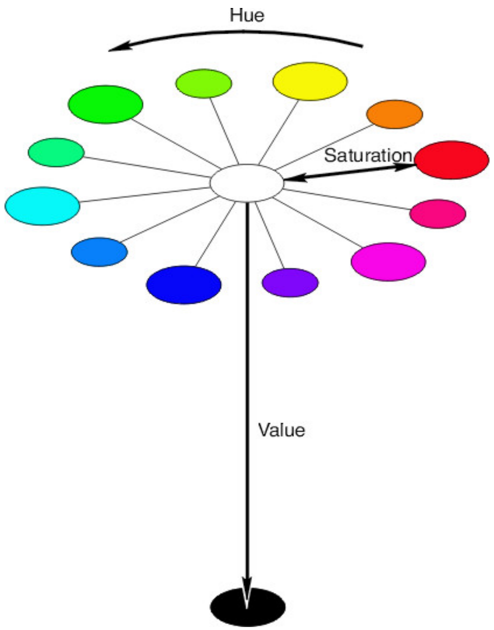
- Drawbacks
    - Singularities in the transform (such as undefined hue for achromatic points)
    - Sensitivity to small deviations of RGB values near the singularities
    - Numerical instability when operating on hue due to its angular nature

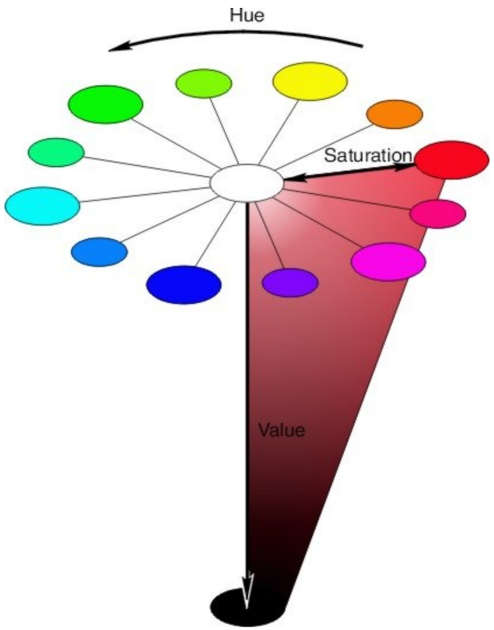
User-oriented CM: HSV







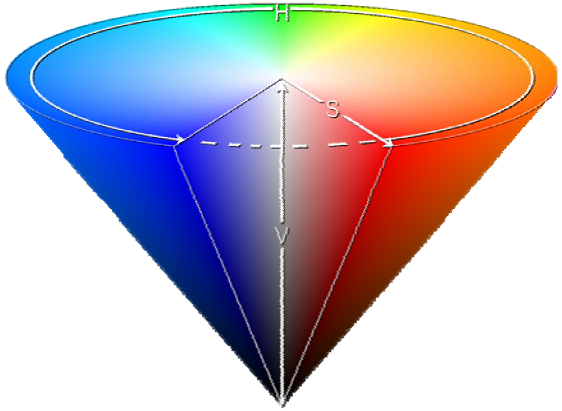




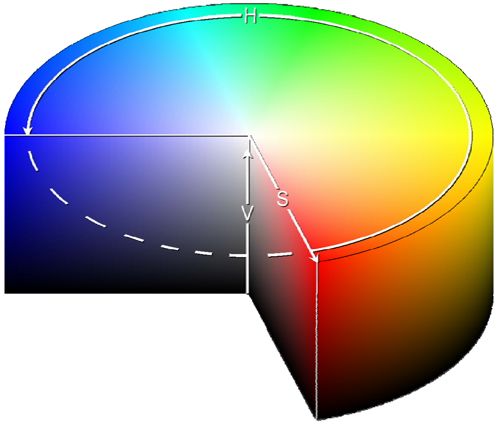
HSV, HSL

Hue, Saturation, Value (Brightness)

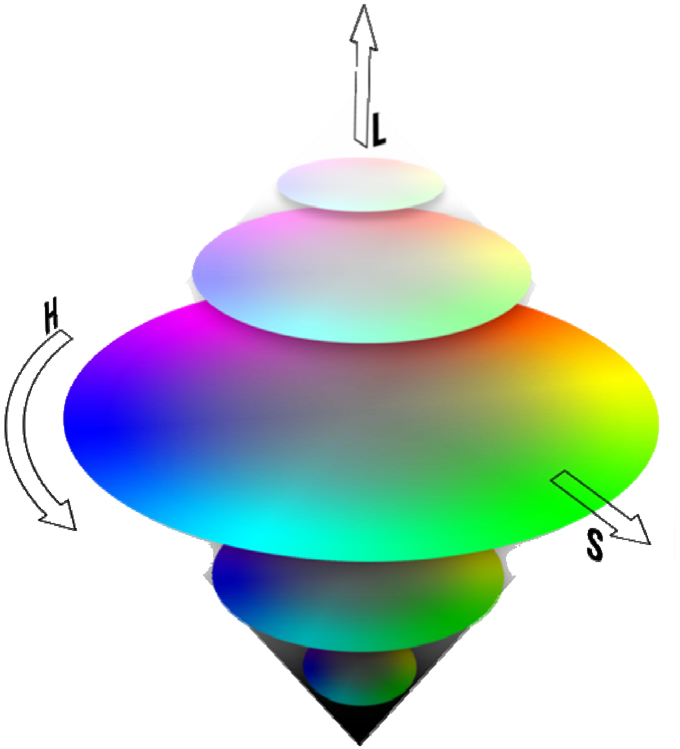
HSV cone



HSV cylinder



Hue, Saturation, Lightness



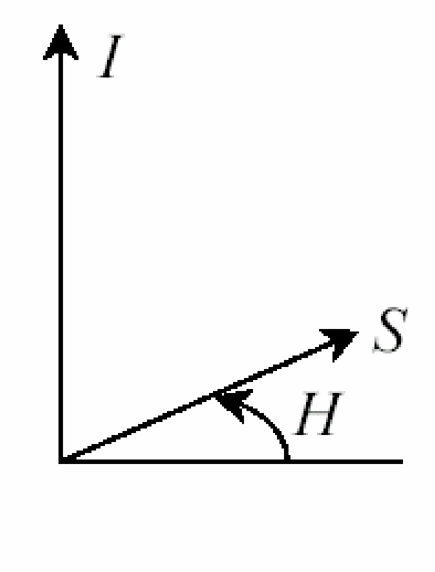
HSI (HSV, HSL) Color Space

- Recall:
  - Hue is color attribute that describes a pure color
  - Saturation gives the measure to which degree the pure color is diluted by white light.

1. Intensity (Value or Lightness) component I (V,L), is decoupled from the cromaticity information!
2. Hue and saturation can be accessed independently from illumination

HSI model

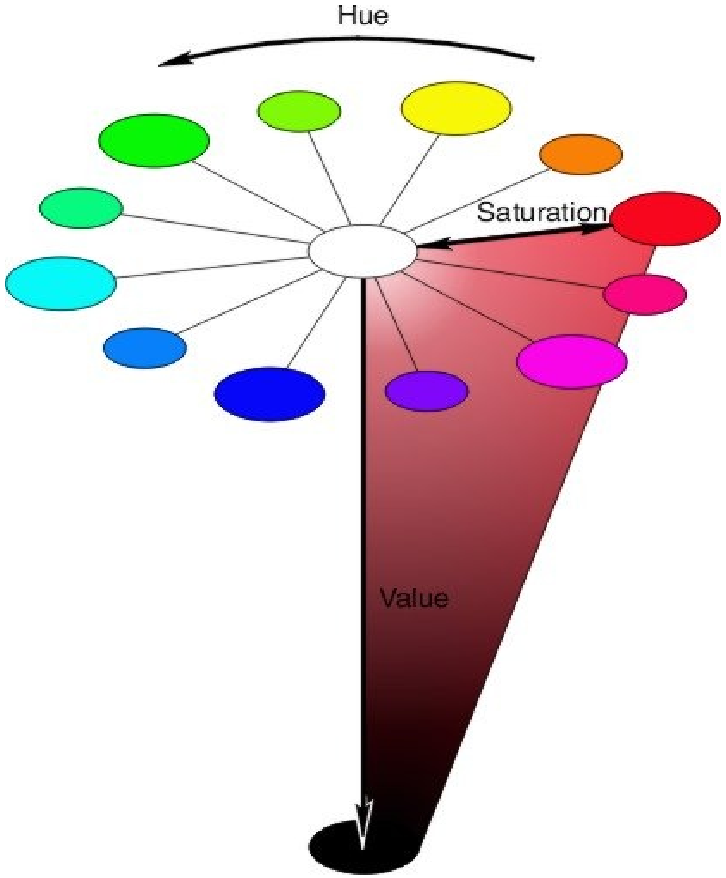
- Two values (H & S) encode *chromaticity*
- Convenient for *designing* colors
- Hue H is defined by and angle between 0 and 2π:
  - "red" at angle of 0;
  - "green" at 2π/3;
  - "blue" at 4π/3

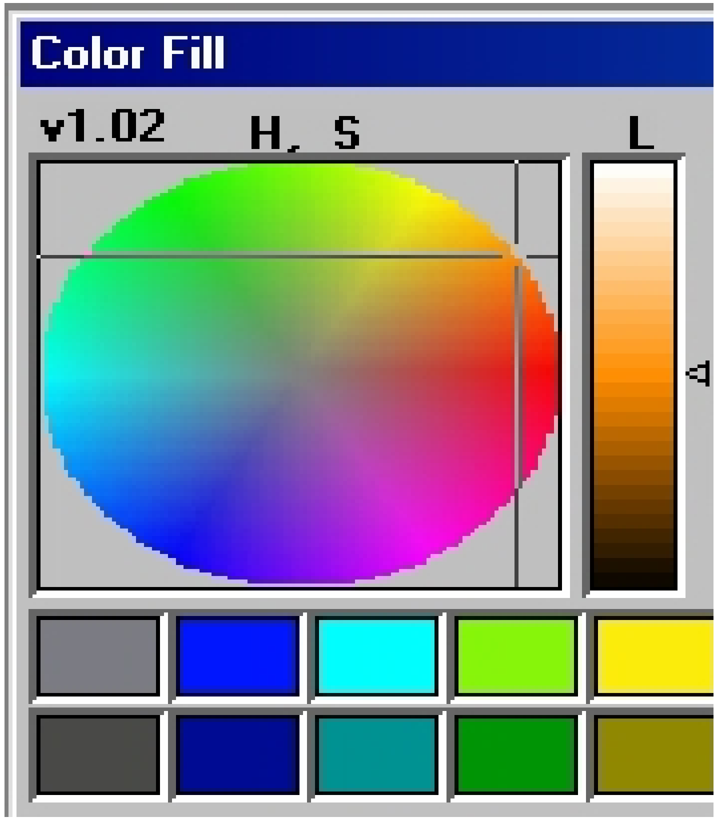


- Saturation S models the *purity* of the color
  - S=1 for a completely pure or saturated color
  - S=0 for a shade of "gray"

HSI-like model

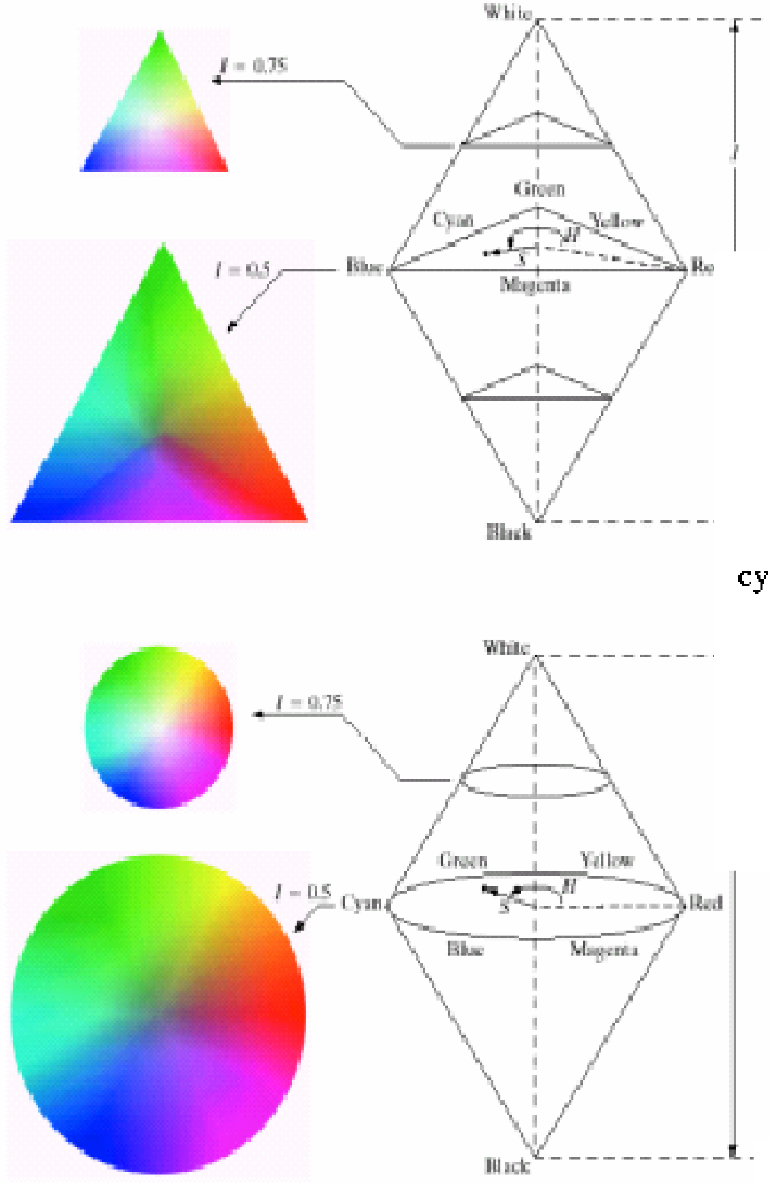
- Hue, Saturation, Value (HSV) model

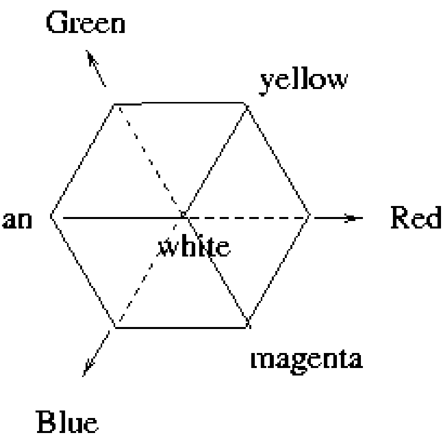


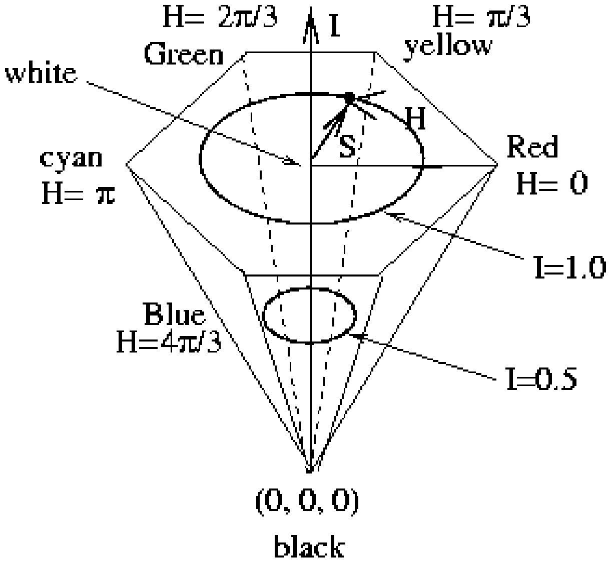


from http://www2.ncsu.edu/scivis/lessons/colormodels/color_models2.html#saturation.

Variations on the theme

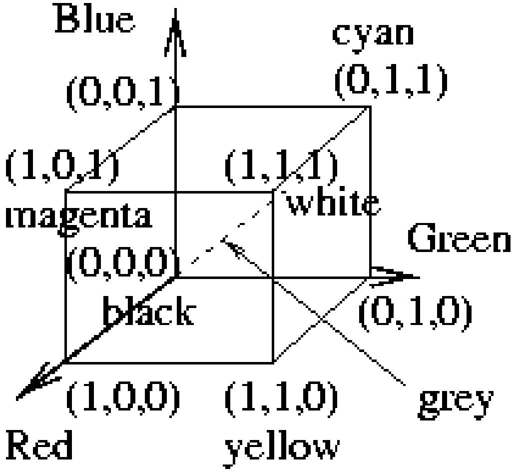




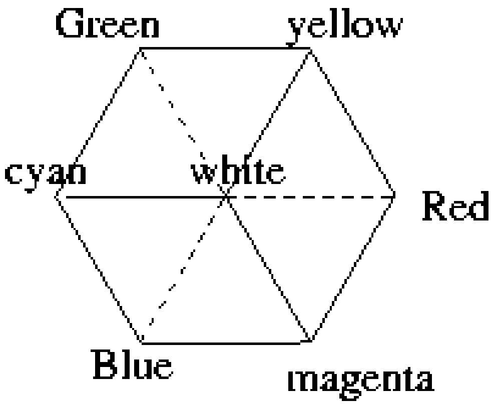


Color hexagon for HSI (HSV)

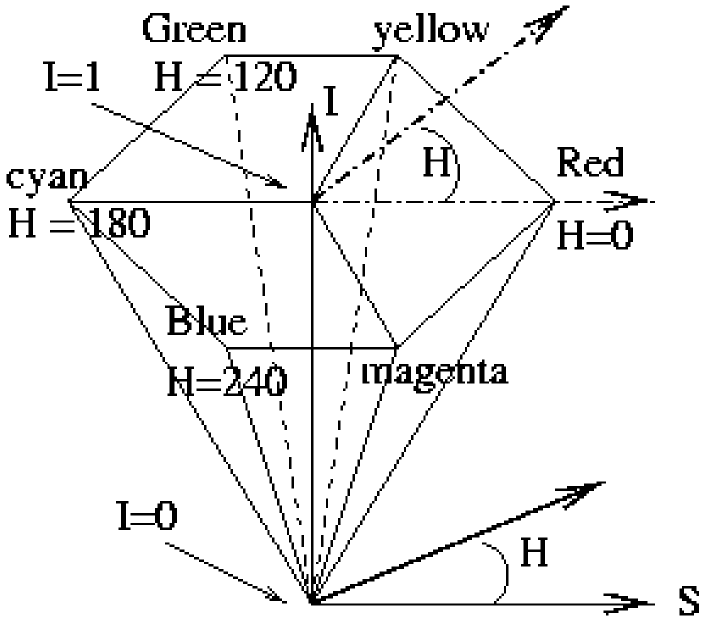
- Color is coded relative to the diagonal of the color cube. Hue is encoded as an angle, saturation is the relative distance from the diagonal, and intensity is height.



(a) RGB color cube



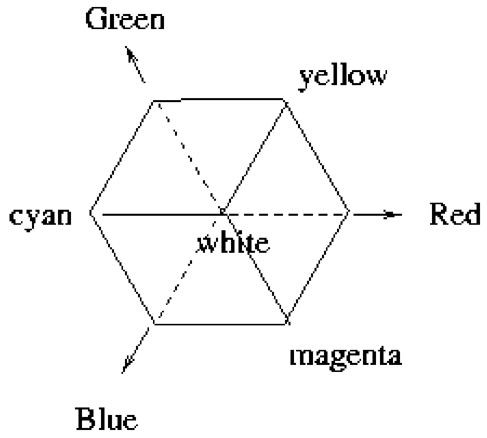
(b) view on diagonal
from white to black

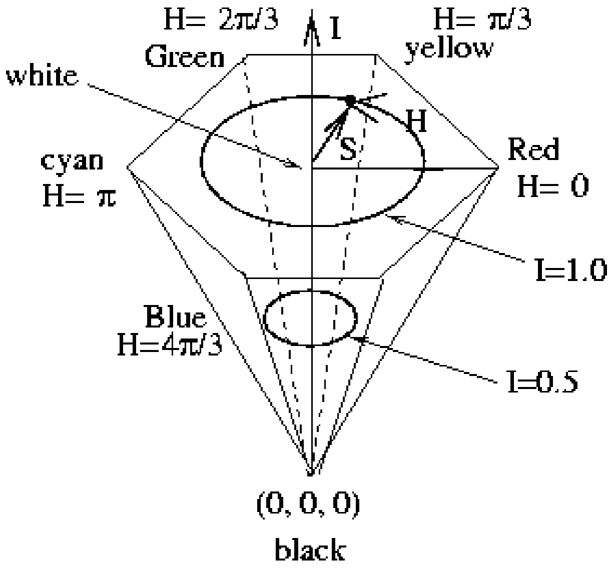


(c) single hexacone HSI model

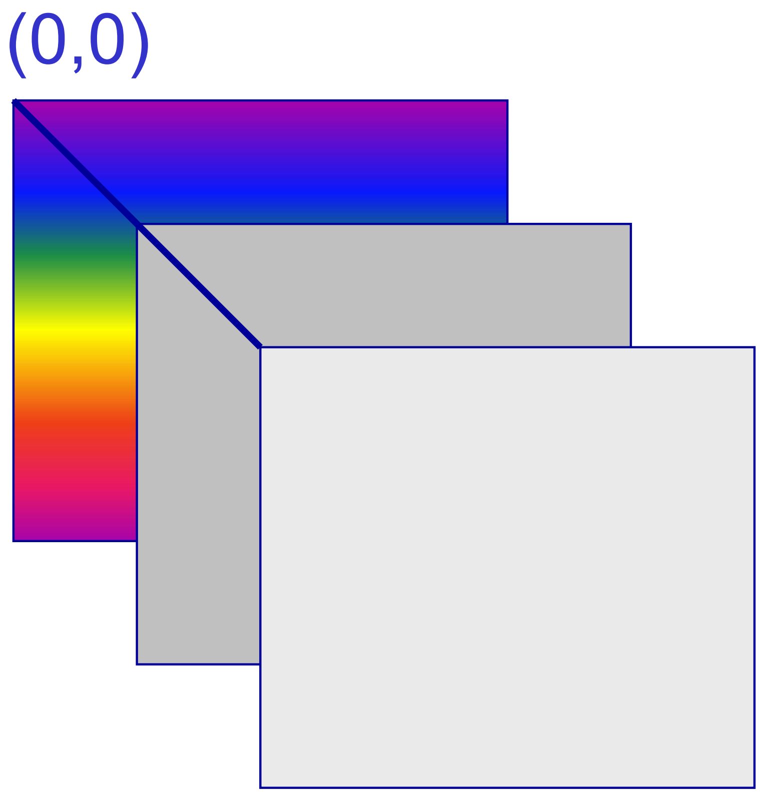
Color hexacone for HSI (HSV)

- (Left) Projection of RGB cube perpendicular to the diagonal (0,0,0) – (1,1,1).
- Color names now at vertices of a hexagon.
- Colors in HIS :
  - intensity I is vertical axis
  - hue H is angle with R at 0
  - saturation is 1 at periphery and 0 on I axis



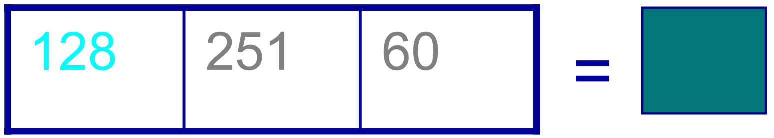


HSI Represention



A single pixel consists of three components.

Each pixel is a **Vector** / **Array.**



128	251	60

=

Pixel-Vector in the computer memory

Final pixel in the image

Caution! Sometimes pixels are not stored as vectors. Instead, first is stored the complete hue component, then the complete sat., then the intensity.

HSI Examples

Original Image

Hue

Saturation

Intensity

Editing saturation of colors

(Left) Image of food originating from a digital camera;

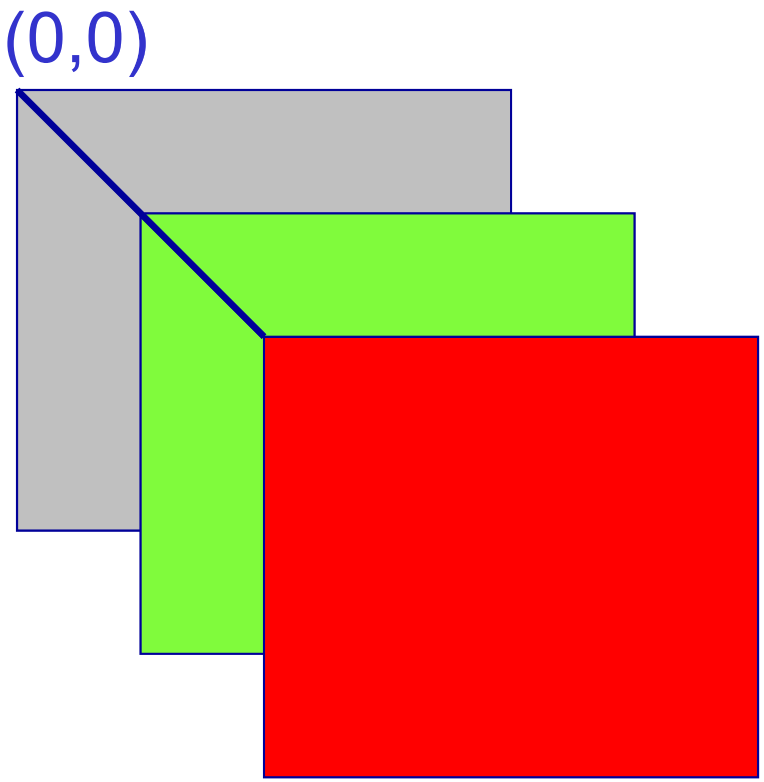
(center) saturation value of each pixel decreased 20%;

(right) saturation value of each pixel increased 40%.

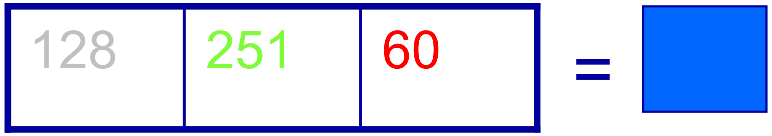
YUV Color model

- PAL TV standard
  - YCbCr similar, used in JPEG and MPEG
  - YIQ (similar) used in NTSC
- Color channels
  - Y: luminance
  - UV: chrominance. These are often downsampled exploiting the lowers cutting frequency and sensitivity of the human visual system with respect to the luminance component

YUV reppresentation



A single pixel consists of three components.
Each pixel is a Vector / Array.



Pixel-Vector in the computer memory

Final pixel in the image

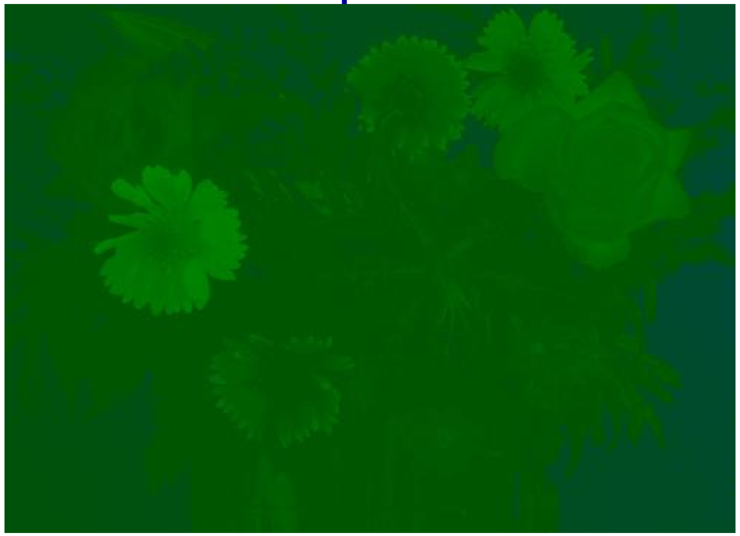
Same Caution as before applies here!

YUV example

Original Image

Y-Component

U-Component



V-Component

YIQ model

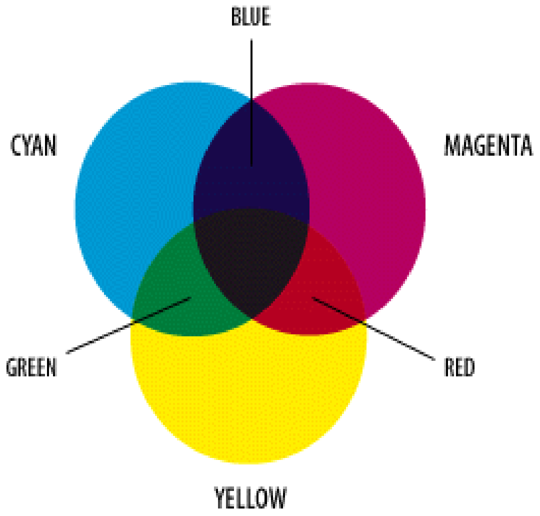
- NTSC
- Y is the luminance
- Chromaticity is represented by I and Q
  - in phase and in quadrature components
- RGB2YIQ

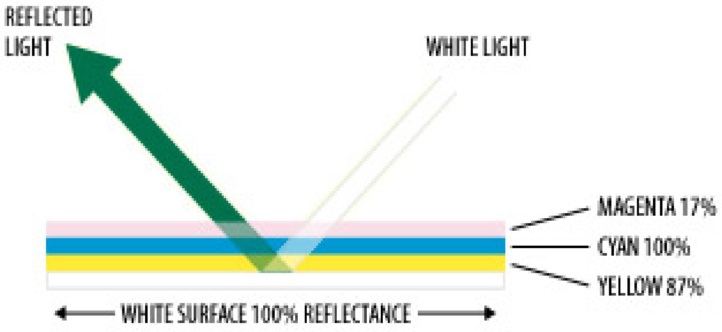
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Device-oriented color models: CMY(K)

- Color subtraction
  - Cyan, Magents, Yellow filters
    - The Y filter removes B and transmits the R ang G
    - The M filter removes G and transmits R and B
    - The C filter removes R and transmits G and B
  - Adjusting the transparency of these filters the amounts of R, G and B can be controlled

cyan=white-red
magenta=white-green
yellow=white-blue

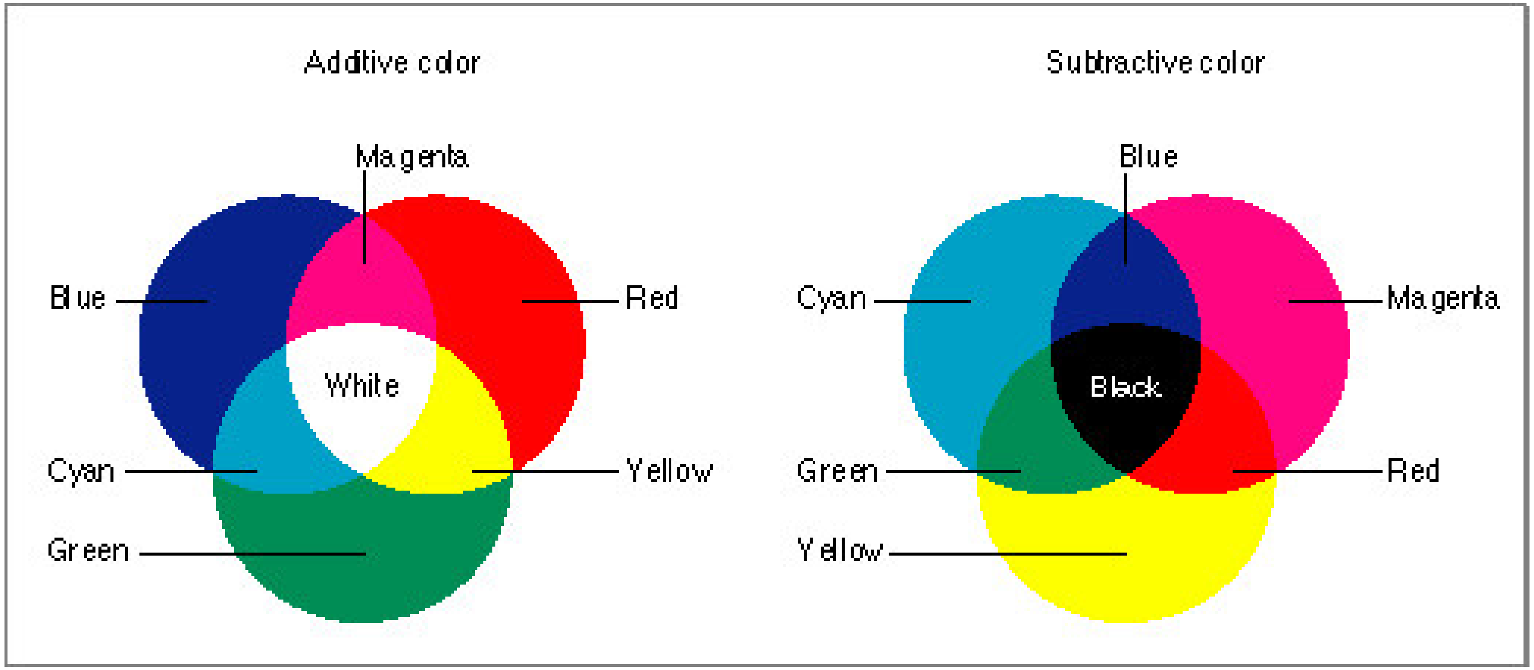




CMY model

- CMY (Cyan, Magenta, Yellow)
- Used in printing devices
- Subractive color synthesis
- CMYK: adding the black ink
  - Equal amounts of C,M and Y should produce black, but in practice a dark brown results. A real black ink is then added to the printer

CYM(K)



- cyan (C) absorbs **red**
- magenta (M) absorbs **green**
- yellow (Y) absorbs **blu**

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

CMY(K) model

- Red, Green, Blue are the primary colors of light
- Cyan, Magenta, Yellow are the
  - Secondary colors of light
  - Primary colors of pigments
- When a cyan-colored object is illuminated with white light, no red light will be reflected from its surface! *Cyan subtracts red!*
- *The pigment when illuminated with white light absorbs its complementary color and reflects the others*

Summary

- References
  - B. Wandell, “Foundations of visions”
  - Wyszecki&Stiles, “Color science, concepts, methods, quantitative data and formulae”, Wiley Classic Library
  - D. Malacara, “Color vision and colorimertry, theory and applications”, SPIE Press