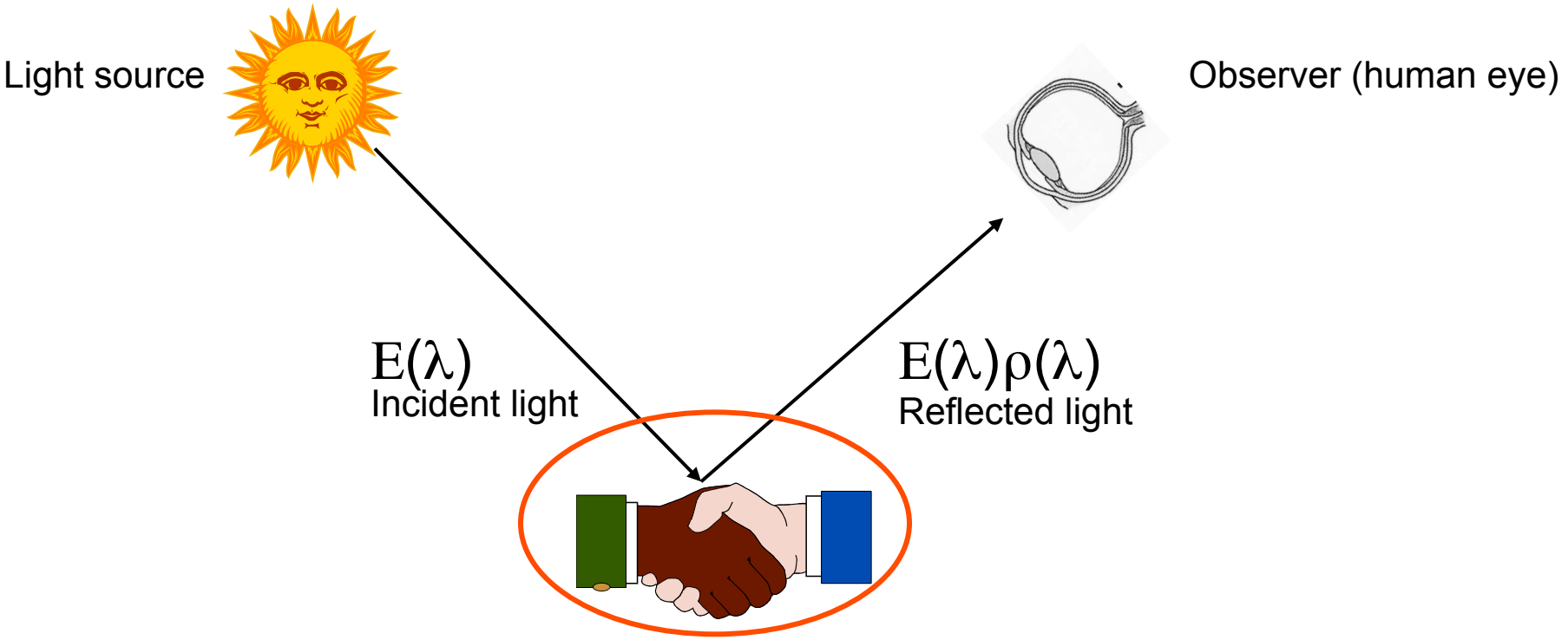
PPM PART I
Media and Media formats

- Images
  - A) COLOR IMAGES
    - A) Color spaces
    - B) Image Formats
  - B) IMAGE STANDARDS
    - A) JPEG
    - B) JPEG 2000

Color Images: color spaces

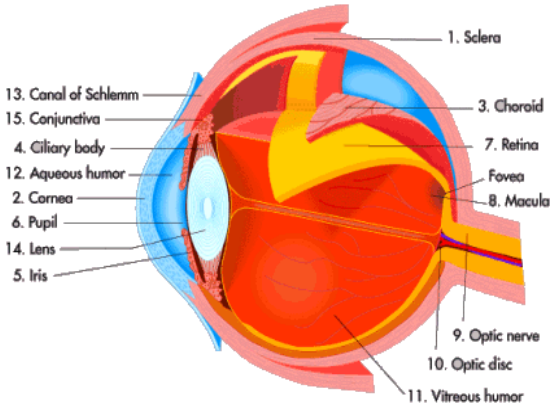
Color perception

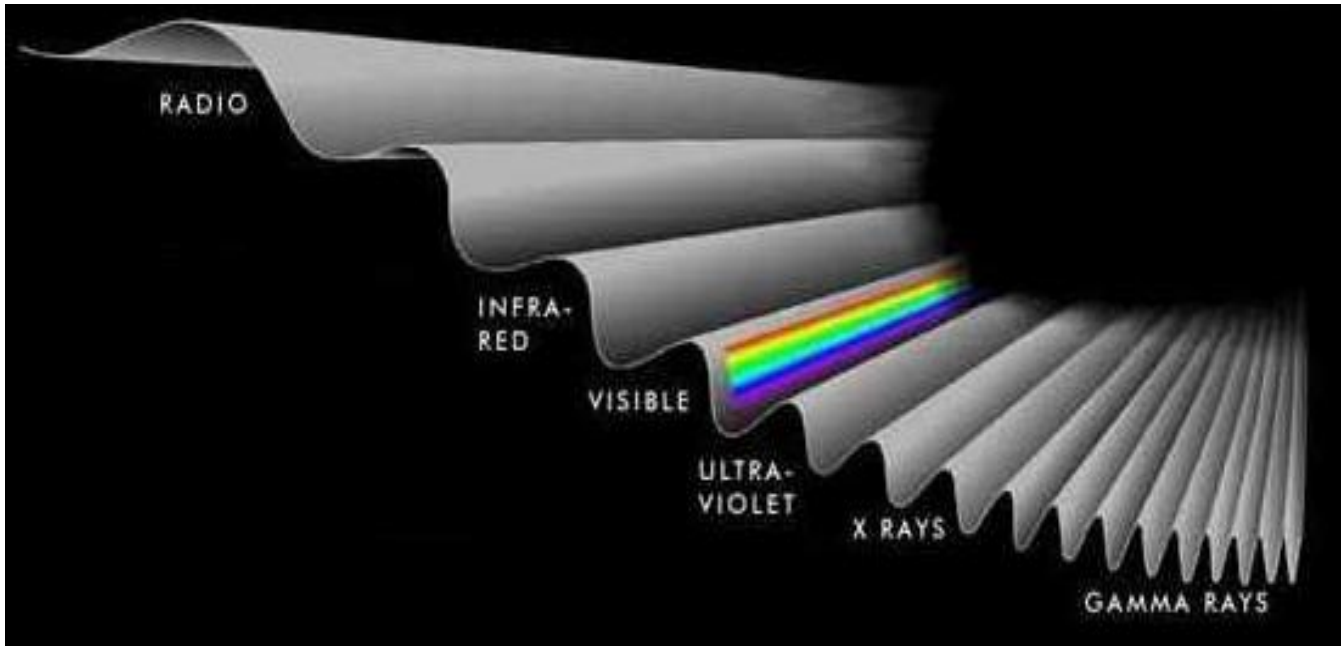


- Humans perceive color light through the eye sensor. Color is determined by the relative radiant power distribution of the incident light, the reflection of the materials and the characteristics of the observer.
- The appearance of an object is determined by its reflectance and the visible wavelenghts of the light it is exposed with (and angle).

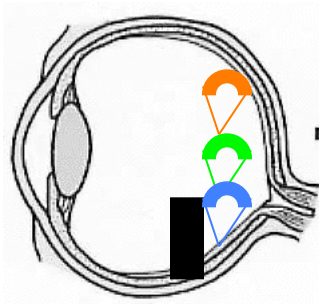
The human eye sensor

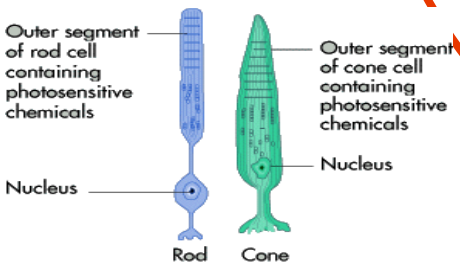
- The human eye sensor operates in the wavelenght interval 350nm - 780nm (infrared is beyond 780nm and ultraviolet below 350nm). The visible spectrum is therefore comprised between 384THz and 857THz (THz = 10^{12} Hz)

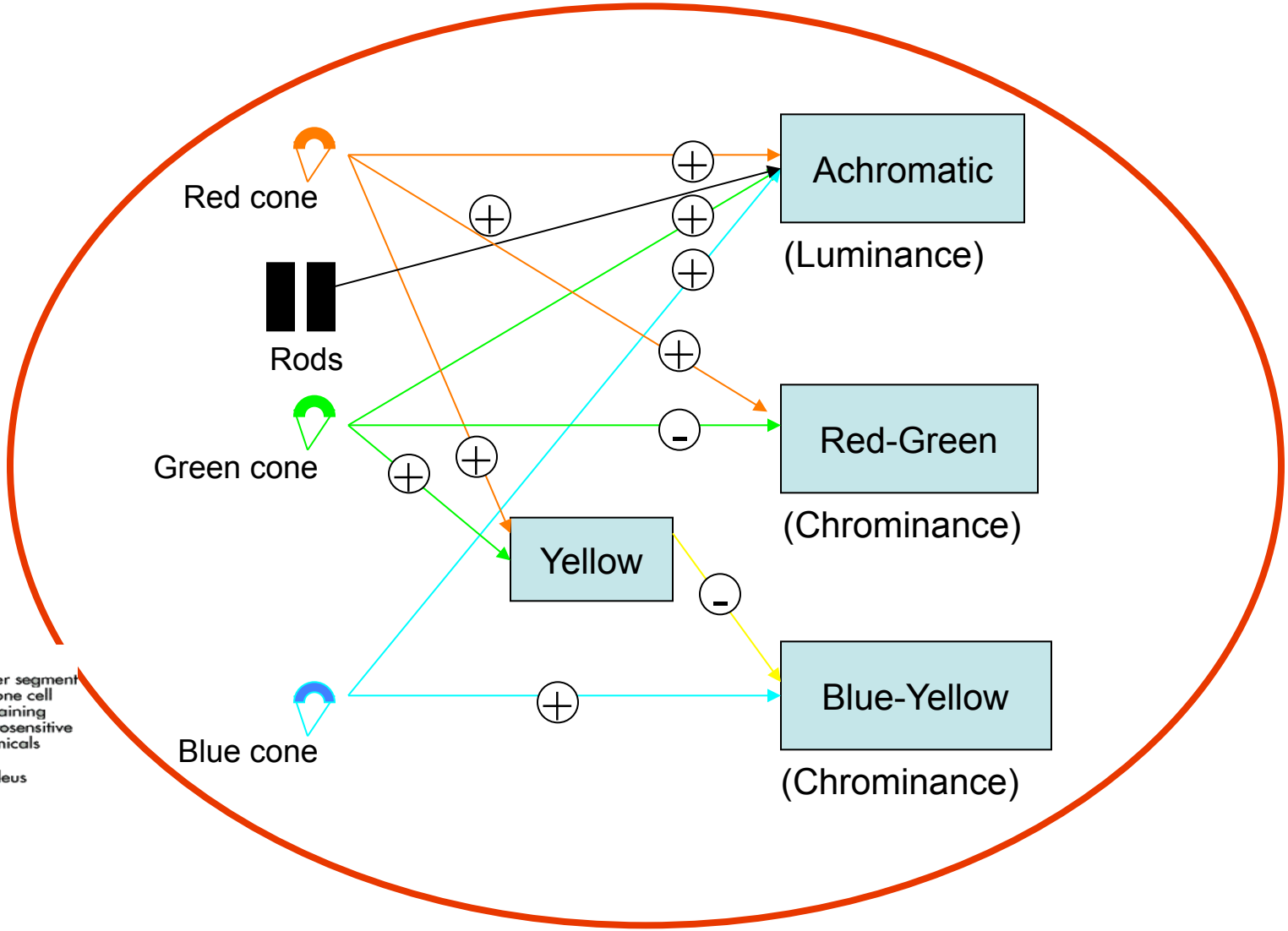




Eye response: Luminance and Chrominance



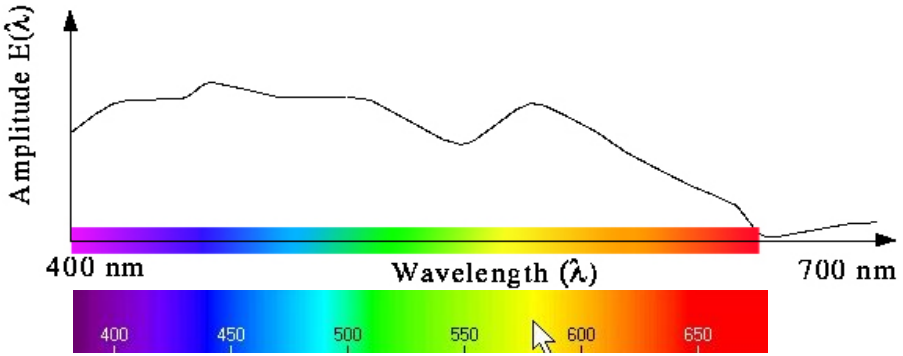




- Human eye rods and cones have sensitivity to Luminance and Chrominance, respectively. Eye has higher sensitivity for Luminance

Human eye spectral integration

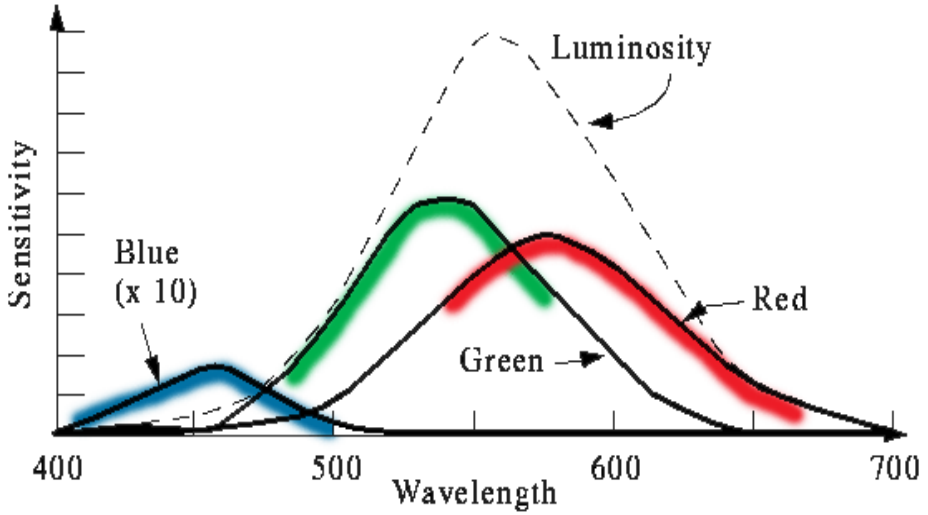
- Color sensation of humans is obtained from the combination of the responses of the three types of cones, according to the amount of light E the object reflectance ρ and the cone type sensibility S_t.



$$R = \rho \int E(\lambda)\, S_R(\lambda)\, d\lambda$$

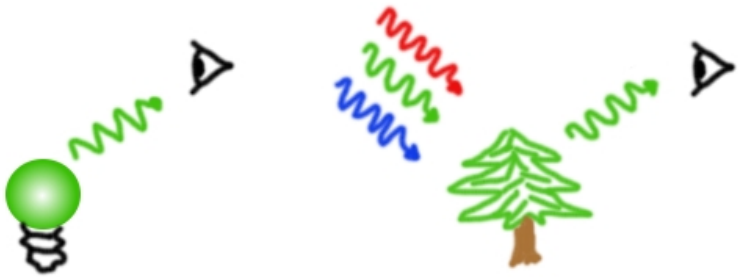
$$G = \rho \int E(\lambda)\, S_G(\lambda)\, d\lambda$$

$$B = \rho \int E(\lambda)\, S_B(\lambda)\, d\lambda$$

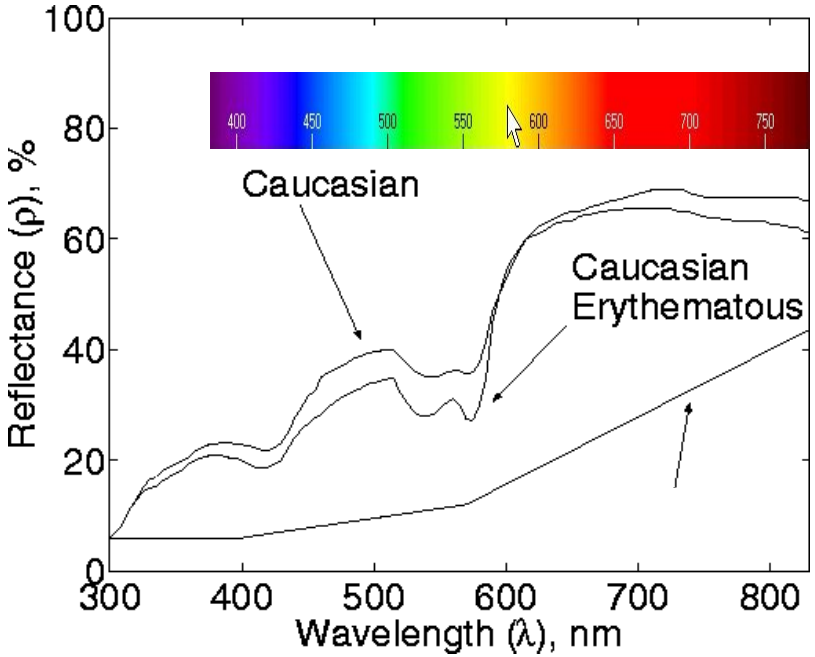


Radiant and illuminated objects

- Humans perceive colors according to two distinct processes, depending on whether the object observed is a light source object or is illuminated by an external source.
  - In the first case we perceive the light that is radiated by the object
  - In the second case we perceive the light that is not absorbed (i.e. is reflected). The color perceived is the color of the illuminant less the color absobed by the object.

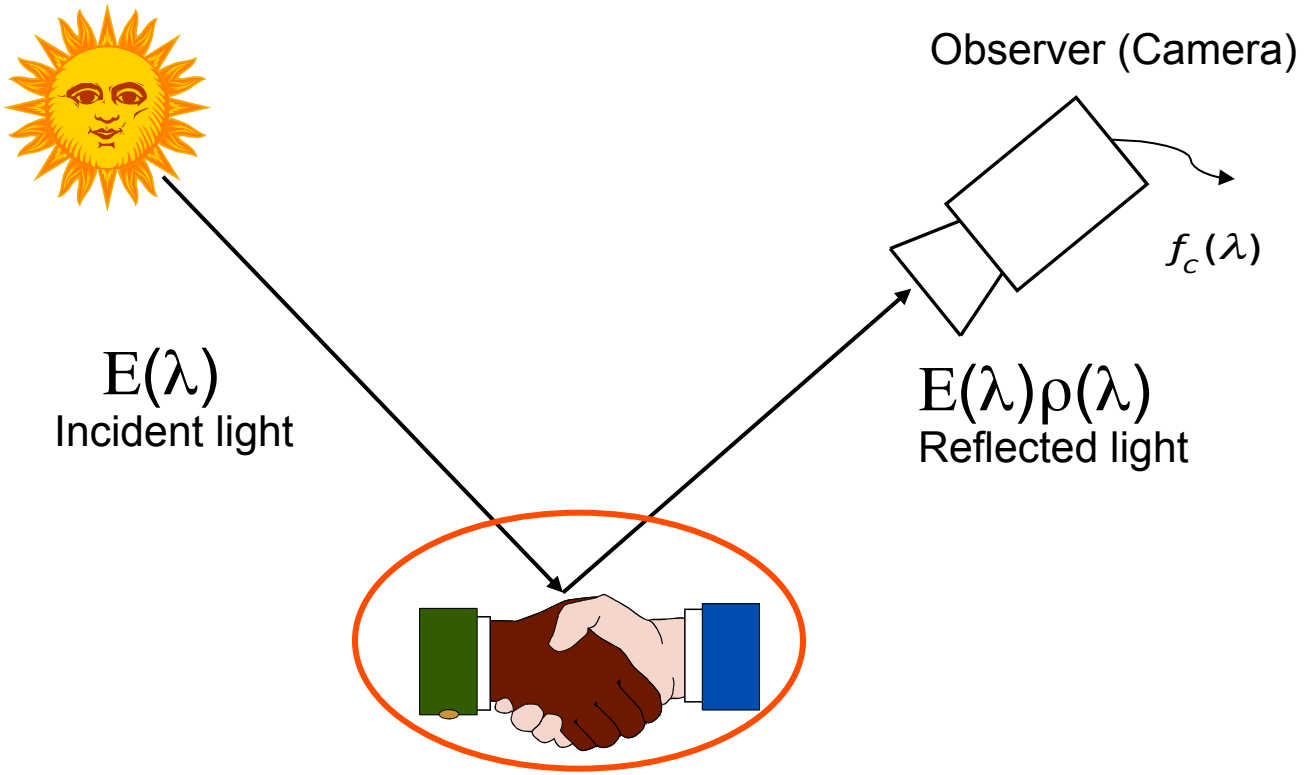


Reflectance of object surfaces $\rho(\lambda)$



- Different objects have different reflectances in the visible spectrum

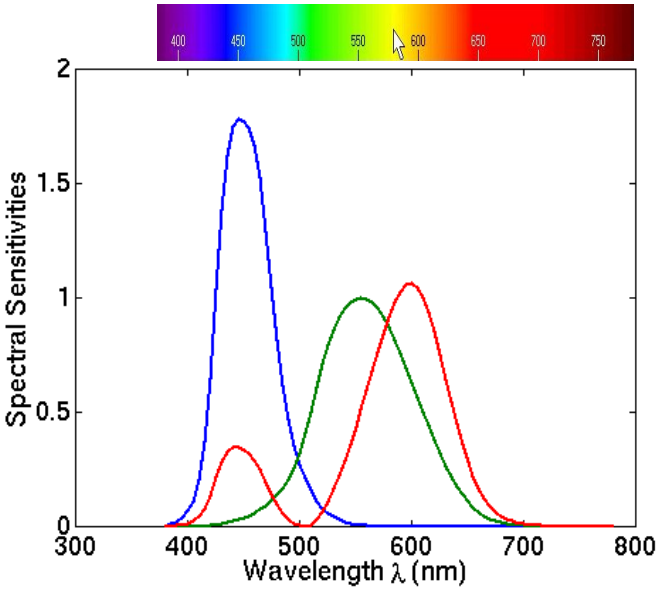
Colour image formation



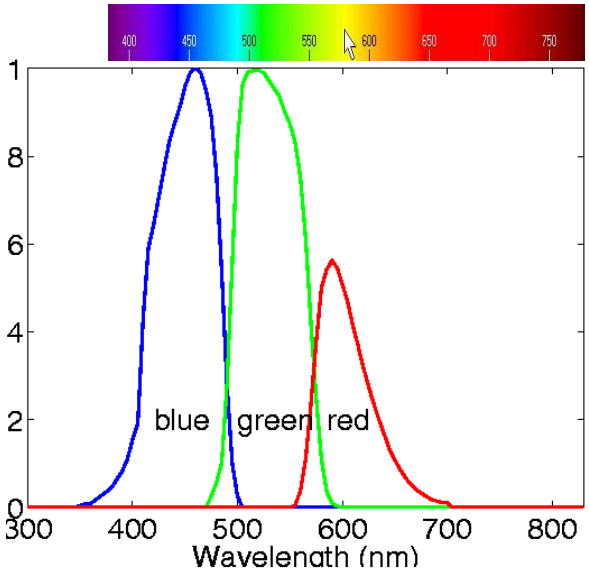
- Colour image formation is determined by the relative radiant power distribution of the incident light, the reflection of the materials and the characteristics of the observer camera device.
- The appearance of an object is determined by its reflectance and the visible wavelenghts of the light it is exposed with (and angle).

Observer/Sensor sensitivity f (λ)

Eye Response



Camera Response



$$R = \int_{\lambda} E(\lambda)\rho_{Skin}(\lambda)f_R(\lambda)d\lambda$$

$$G = \int_{\lambda} E(\lambda)\rho_{Skin}(\lambda)f_G(\lambda)d\lambda$$

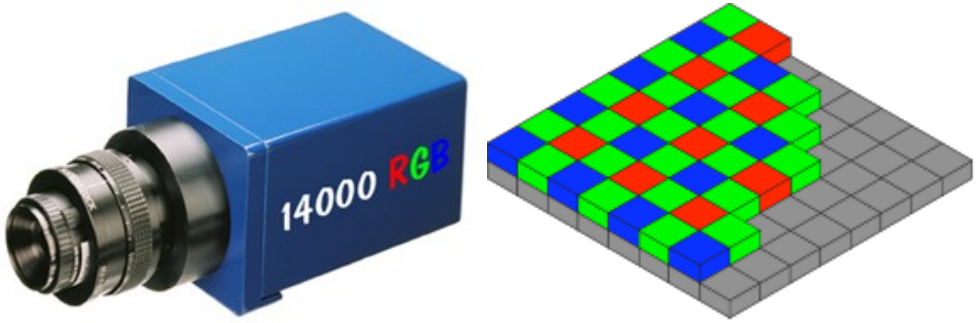
$$B = \int_{\lambda} E(\lambda)\rho_{Skin}(\lambda)f_B(\lambda)d\lambda$$

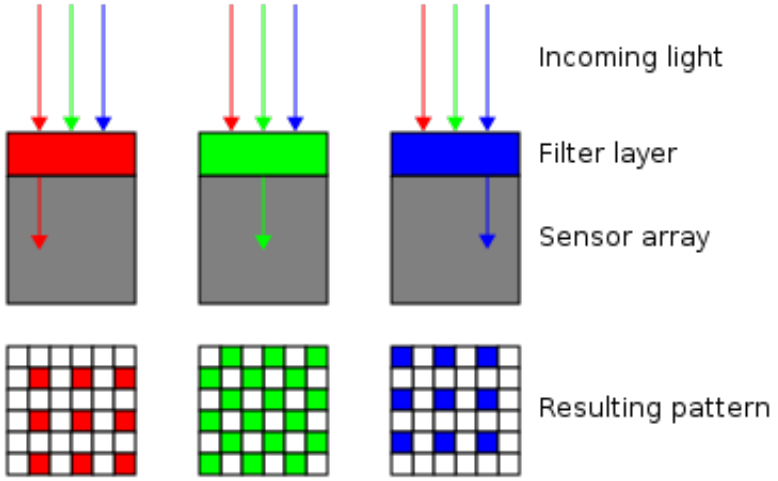
$$\int f(x)dx \approx \sum_{i=1}^{A/\Delta x} f(i\Delta x)\Delta x$$

- Reflected light spectrum can be represented by a 3 element vector, with values which are the proportions of each of the primary colors *red* (R), *green* (G) and *blue* (B) used to produce it. These are the *tristimulus* values.
- Considering Tristimulus: RGB values of camera = Colour * Tristimulus.

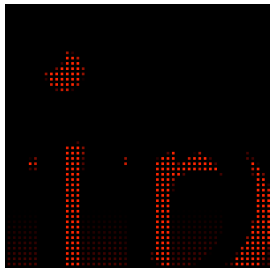
RGB cameras

- Digital images are nowadays obtained from photographic digital cameras that use CMOS or CCD sensors to acquire three color signals in the *red* (R) *green* (G) and *blue* (B) wavelenghts. These cameras often operate with a variation of the RGB space in a Bayer filter arrangement: *green* is given twice as many detectors as *red* and *blue* (ratio 1:2:1) in order to achieve higher luminance than chrominance resolution.
- The sensor has a grid of red, green, and blue detectors arranged so that the first row is GBGBGBGB, the next is RGRGRGRG and that sequence is repeated in subsequent rows.





Demosaicing algorithms



red



green



blue

Bayer filter samples

original





reconstructed after demosaicing

- A pixel only records one color out of three and cannot determine the color of the reflected light. For every channel, missing pixels are obtained by interpolation to build up the complete image.

- A demosaicing algorithm is needed to estimate for each pixel the color levels for all color components, rather than a single component. For example, demosaicing can be done with bilinear interpolation the red value of a non-red pixel is computed as the average of the two or four adjacent red pixels, and similarly for blue and green….
- This is done in-camera producing a JPEG image.

Truecolor representation

- Truecolor is a method of representing and storing graphical image information. Truecolor defines 256 (2^8) shades of red, green, and blue for each pixel of the digital picture, which results in 256^3 or 16,777,216 (approximately 16.7 million) color variations for each pixel.

Sample Length:	8								8								8							
Channel Membership:	**Red**								**Green**								**Blue**							
Bit Number:	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
RGBAX	**R. G. B. A. X**																							
Sample Length Notation:	**8.8.8.0.0**																							

Color spaces

- A color space is a three-dimensional definition of a color system. The attributes of the color system are mapped onto the coordinate axes of the color space.
- Different color spaces exist: each has advantages and disadvantages for color selection and specification for different applications:
  - Some color spaces are perceptually linear, a change in stimulus will produce the same change in perception wherever it is applied. Other colour spaces, e.g. computer graphics color spaces, are not linear.
  - Some color spaces are intuitive to use, i.e. it is easy for the user creating desired colors from space navigation. Other spaces require to manage parameters with abstract relationships to the perceived color.
  - Some color spaces are tied to specific equipments while others are equally valid on whatever device they are used.
  - …..

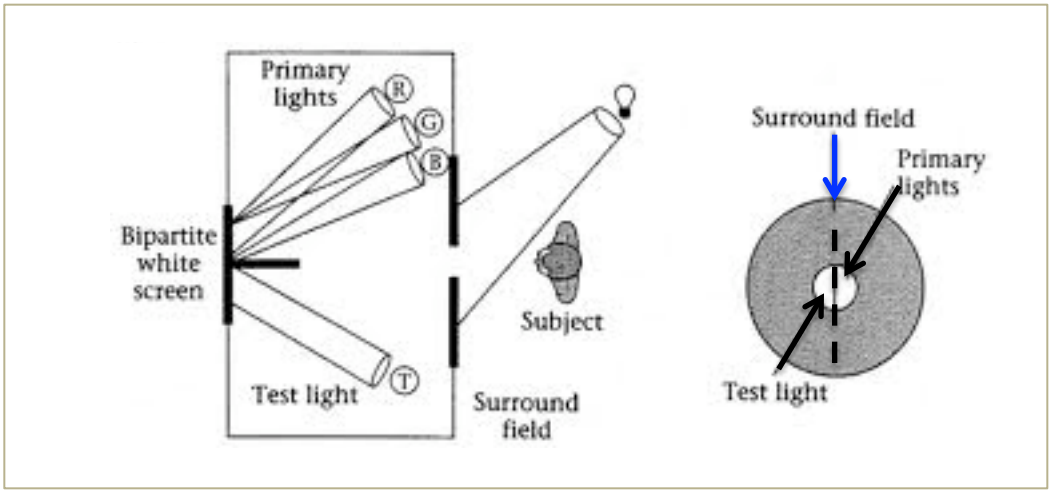
Models		Applications
CIE Colorimetiric	XYZ	Colorimetric calculations
Device-oriented	Non-uniform spaces RGB, YIQ, YCC	Storage, processing, analysis, coding, color TV
	Uniform spaces L*a*b*, L*u*v*	Color difference evaluation, analysis, color management systems
Device-oriented and User-oriented	HSI, HSV, HSL, $I_1I_2I_3$	Human color perception, computer graphics
Munsell		Human visual system

CIE color matching experiment

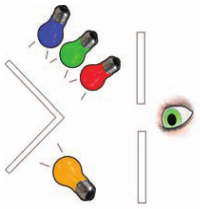
- The first color matching experiments were devised in late 1920s to characterize the relationship between the physical spectra and the perceived color, measuring the mixtures of different spectral distributions that are required for human observers to match colors

- The experiments were conducted by using a circular split screen 2° in size (the angular size of the cone distribution in 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, that was a mixture of three monochromatic (single-wavelength) primary colors, each with fixed chromaticity, but with adjustable brightness

- Not all test colors could be matched using this technique. When this was the case, a variable amount of one of the primaries was allowed to add to the test color. The amount of the primary added to the test color was considered to be a negative value



Primary color composition



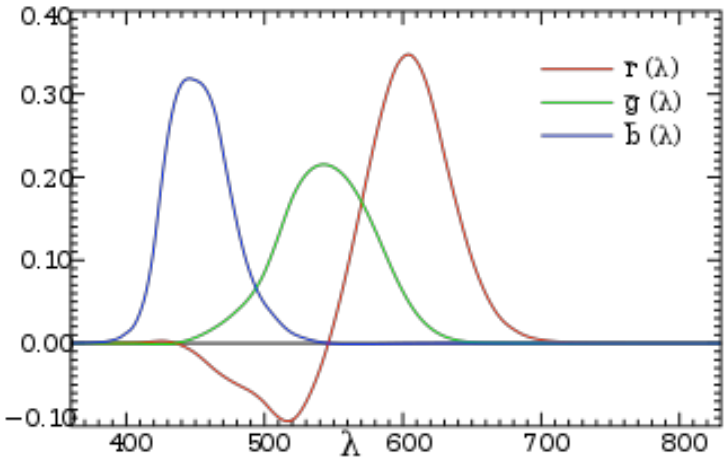
Primary color subtraction



CIE primaries and color matching functions

- In 1931 CIE standardized the RGB color matching functions $\bar{r}(\lambda)\ \bar{g}(\lambda)\ \bar{b}(\lambda)$ obtained using three monochromatic primaries at 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.

- Rather than specifying the brightness of each primary, the curves were normalized (scaled) to have constant area under them. The tabulated numerical values of these functions are known as the CIE standard observer (CIE 1931 2° standard observer). They roughly correspond to colour sensations of *red*, *green* and *blue*.



$$R = \int_0^\infty I(\lambda)\,\bar{r}(\lambda)\,d\lambda$$

$$G = \int_0^\infty I(\lambda)\,\bar{g}(\lambda)\,d\lambda$$

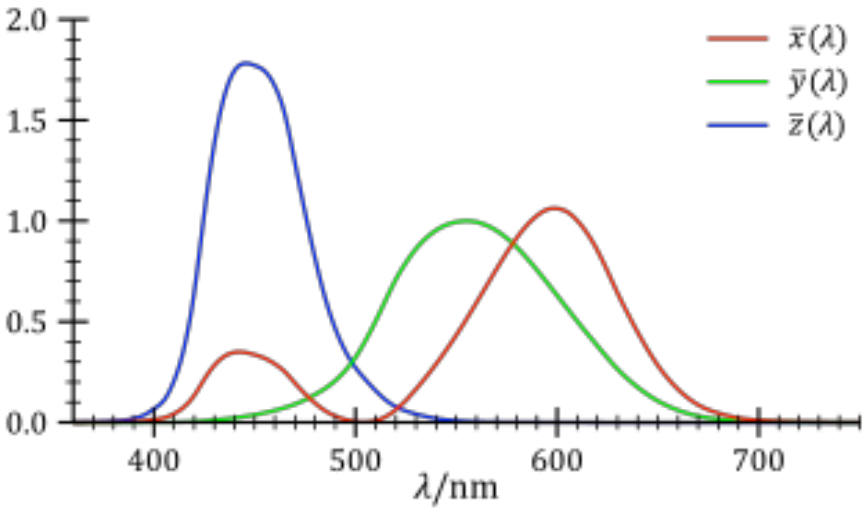
$$B = \int_0^\infty I(\lambda)\,\bar{b}(\lambda)\,d\lambda$$

CIE XYZ color space

- To avoid the presence of negative values of the CIE RGB matching functions, the Commission developed the CIE XYZ color space that would relate to the CIE RGB color space by a linear transformation such that the new color matching functions $\bar{x}(\lambda)\ \bar{y}(\lambda)\ \bar{z}(\lambda)$ were to be everywhere greater than or equal to zero. The XYZ values for a color with a spectral power distribution $E(\lambda)$ are given by integration of the scaled new color matching functions

- The transformation was deliberately designed such that:
  - Y was a measure of the *brightness* or *luminance* of a color,
  - Z was quasi-equal to *blue* stimulation,
  - X is a linear combination of cone response curves chosen to be nonnegative (roughly *red*).

- The CIE XYZ color space serves as a basis from which other color spaces are defined.



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

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

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

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4887180 & 0.3106803 & 0.2006017 \\ 0.1762044 & 0.8129847 & 0.0108109 \\ 0.0000000 & 0.0102048 & 0.9897952 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE xyY color space

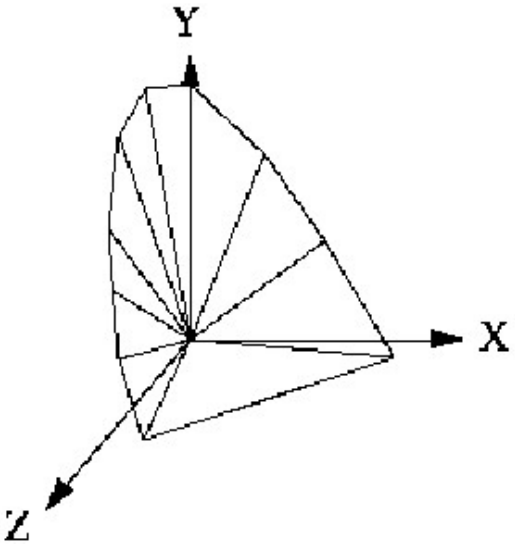
- By normalizing XYZ (i.e. dividing by X+Y+Z) derived values are obtained referred to as x,y,z .

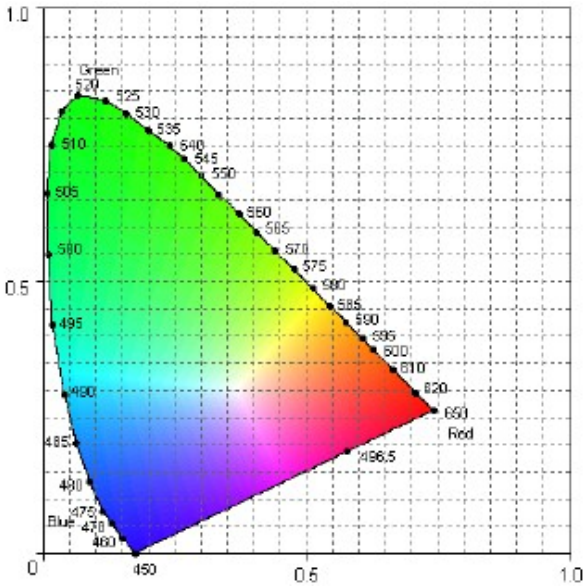
$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z} = 1 - x - y$$

- In that x+y+z = 1 the chromaticity of a color can be specified by two parameters x y, of the three normalized values.

- The x y diagram obtained by intersecting the XYZ space with plane X+Y+Z = 1 and projecting this intersection on the xy plane is referred to as CIE Chromaticity diagram and the xy values are referred to as chromaticity values . They represent all the colors that are visible by the human eye with constant intensity equal to 1. The degree of luminance can be espressed in percentage referring to the Y coordinate of XYZ.

- The x y Y space is widely used in practice to represent colors.



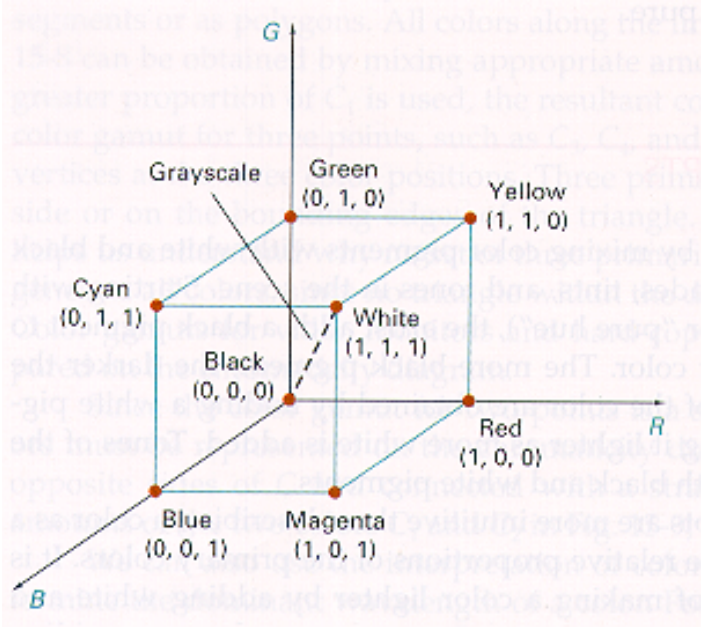


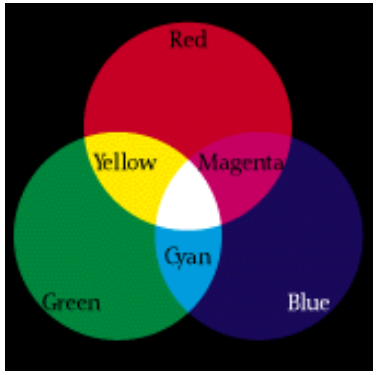
RGB color space

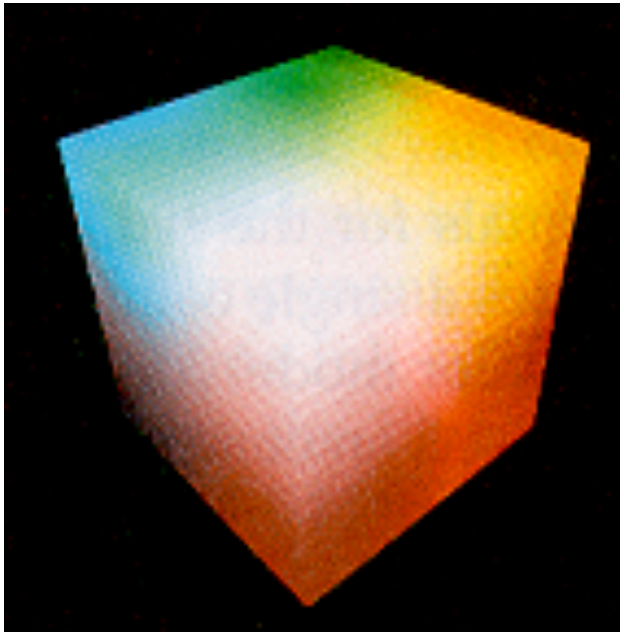
- RGB coordinates can be directly derived from XYZ using a linear transformation. This is defined by fixing the coordinates of the white color and the three primaries.

- The RGB space is usually represented by a cube using non-negative values within a 0–1 range, assigning black to the origin at the vertex (0, 0, 0), and with increasing intensity values running along the three axes up to white at the vertex (1, 1, 1), diagonally opposite black.

- An RGB triplet represents the point of the given color within the cube. Computations of the color similarity of two given RGB colors is obtained by simply calculating the distance between them.







RGB color spaces

- RGB color space is hardware dependent. Therefore several RGB color spaces exist.
  The sRGB color space (created cooperatively by HP and Microsoft in 1996) is the most widely used in practice
- The sRGB color space uses the same primaries as the ITU-R BT.709 primaries, standardized for studio monitors and HDTV. It is the reference standard used for monitors, printers and on the Internet. LCDs, digital cameras, printers, and scanners all follow the sRGB standard

Color Space	Gamut	White Point	Primaries					
			xR	yR	xG	yG	xB	yB
sRGB , HDTV (ITU-R BT.709),	**CRT**	**D65**	**0.64**	**0.33**	**0.30**	**0.60**	**0.15**	**0.06**
scRGB	Unlimited (signed)	D65	0.64	0.33	0.30	0.60	0.15	0.06
ROMM RGB	Wide	D50	0.7347	0.2653	0.1596	0.8404	0.0366	0.0001
Adobe RGB 98	CRT	D65	0.64	0.33	0.21	0.71	0.15	0.06
Apple RGB	CRT	D65	0.625	0.34	0.28	0.595	0.155	0.07
CIE (1931)	Wide	E	0.7347	0.2653	0.2738	0.7174	0.1666	0.0089

…….

- For this reason, one can generally assume, in the absence of any other information, that any 8-bit-per-channel image file or any 8-bit-per-channel image API or device interface can be treated as being in the sRGB color space.

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sRGB color space

- The transformation between XYZ and sRGB and viceversa is obtained applying a linear transformation followed by a second transformation as below:

$$\begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$C_{\text{srgb}} = \begin{cases} 12.92 C_{\text{linear}}, & C_{\text{linear}} \leq 0.0031308 \\ (1+a) C_{\text{linear}}^{1/2.4} - a, & C_{\text{linear}} > 0.0031308 \end{cases}$$

$$C_{\text{linear}} = \begin{cases} \frac{C_{\text{srgb}}}{12.92}, & C_{\text{srgb}} \leq 0.04045 \\ \left(\frac{C_{\text{srgb}}+a}{1+a}\right)^{2.4}, & C_{\text{srgb}} > 0.04045 \end{cases}$$

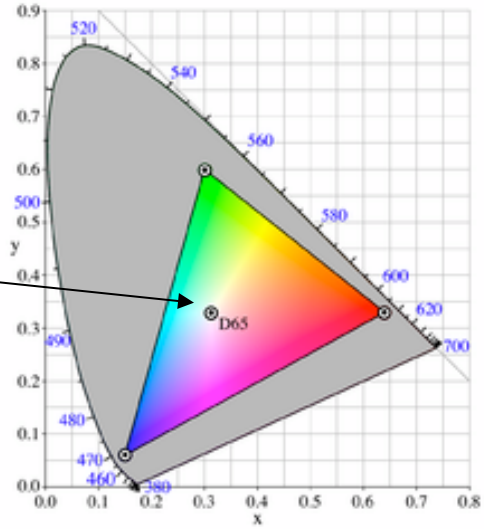
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix}$$

$a = 0.055$

where: R_{linear}, G_{linear} and B_{linear} for in-gamut colors are defined to be in the range [0,1]
C_{linear} is R_{linear}, G_{linear}, or B_{linear}, and C_{srgb} is R_{srgb},G_{srgb} or B_{srgb}.

Standard daylight illuminant
White surface illuminated by average midday sun
in western Europe/northern Europe

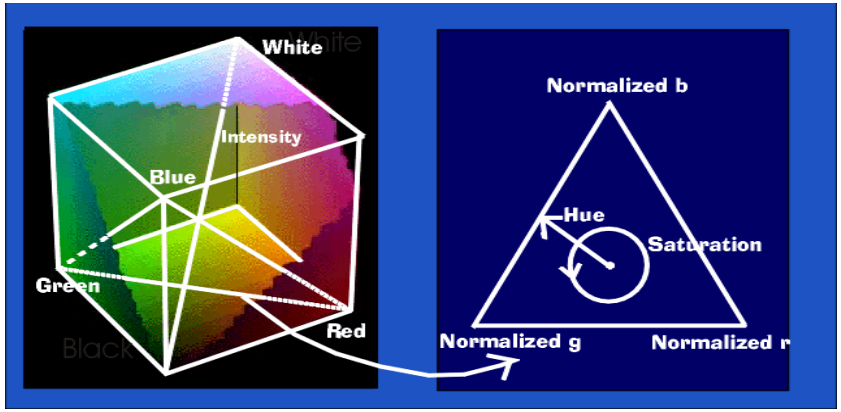
sRGB gamut



rgb color space

- The rgb color space (RGB normalized) aims to separate the chromatic components from the brightness components. It is used to eliminate the influence of varying illumination. The red, green and blue channel can be transformed to their normalized counterpart r, g, b according to:

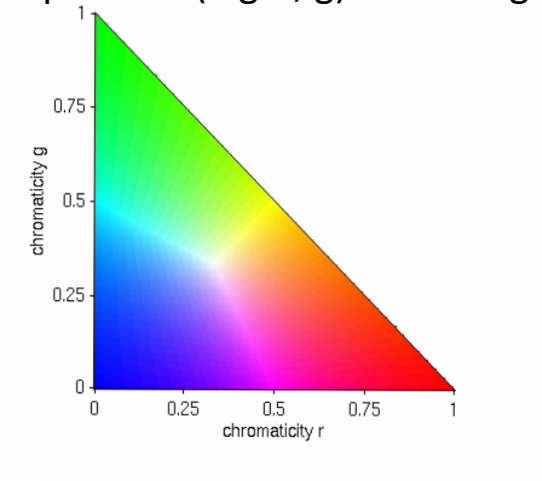
$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} \frac{R}{R+G+B} \\ \frac{G}{R+G+B} \\ \frac{B}{R+G+B} \end{pmatrix}$$



- One of these normalised channels is redundant since r + g + b = 1. Therefore the normalised RGB space is sufficiently represented by two chromatic components (e.g. r, g) and a brightness component

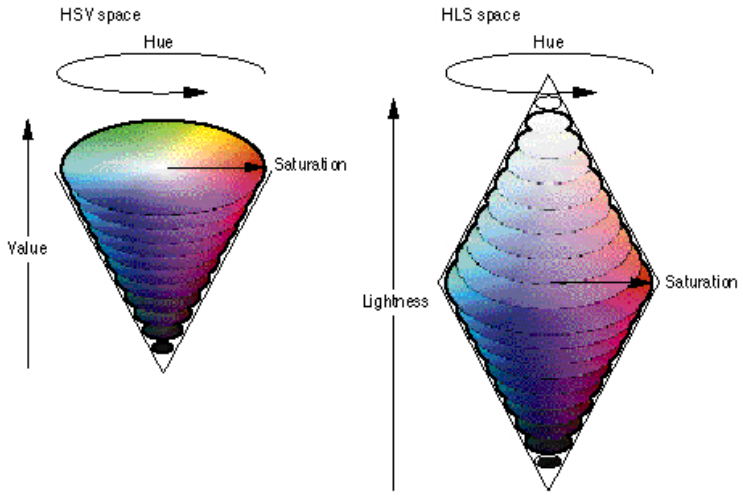
$$r = \frac{R}{R+G+B},$$

$$g = \frac{G}{R+G+B}.$$



HSB – HLS - HSV color models

- HSI (*Hue, Saturation, Intensity*), HLS (*Hue, Saturation, Luminance*) and
- HSV (*Hue, Saturation, Value*) ….. all specify colors using three values:
  - *hue* (the color dominant wavelenght),
  - *saturation* (how much the color spectral distribution is around a certain wavelenght)
  - *luminance* (the amount of gray) closely to human perception.



HSV color space

- HSV values can be derived by the RGB values:

Max = max (R, G, B); Min = min (R, G, B)

V - Value

Value = max (R, G, B)

S - Chroma

if (Max = 0) then Chroma= 0

else Chroma = (Max - Min) / Max

H - Hue

if (Max = Min) then Hue is undefined (achromatic color)

otherwise:

if (Max = R & G > B) Hue = 60 * (G - B) / (Max-Min)

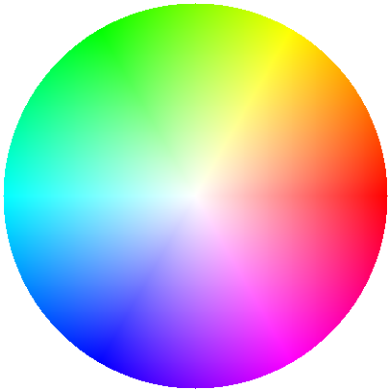
else

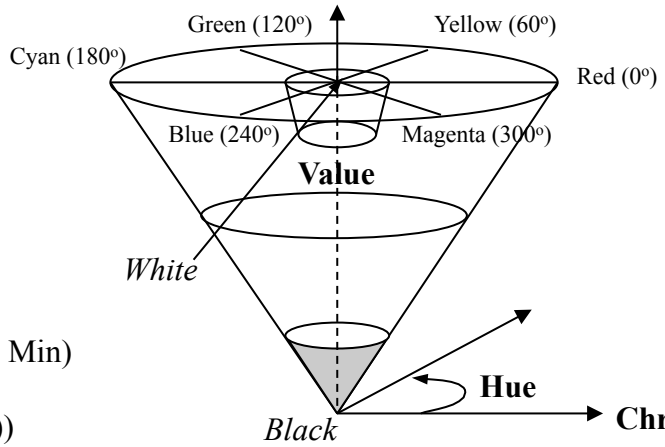
if (Max = R & G < B) Hue = 360 + 60 * (G - B) / (Max - Min)

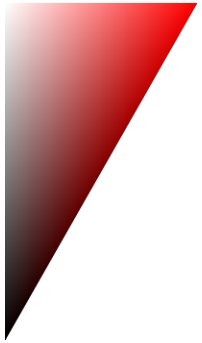
else

if (G = Max) Hue = 60 * (2.0 + (B - R) / (Max - Min))

else Hue = 60 * (4.0 + (R - G) / (Max - Min))



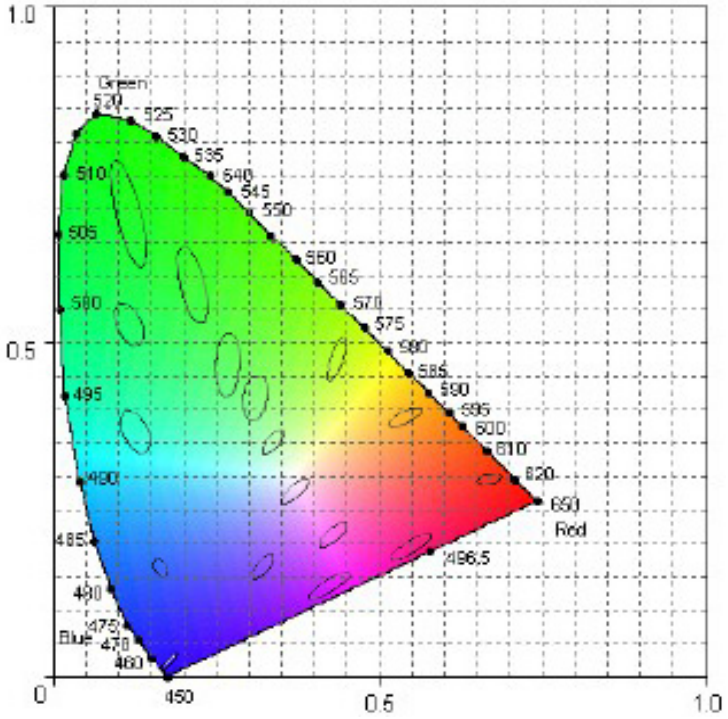




Distances in color space

- Hardware oriented color models such as RGB, HSV, HSI…are not perceptually uniform: uniform quantization of these spaces results into perceptually redundant bins and perceptual holes and a distance function such as the Euclidean doesnot provide satisfactory results

- A difference between green and greenish-yellow is relatively large, whereas the distance distinguishing blue and red is quite small.



- If infinitesimal distances between two colors were constant, the color space would be Euclidean and the distance between two colors would be proportional to the lenght of their connecting line. Instead colors corresponding to points that have the same distance from a certain point are not perceived as similar colors.

- Mac Adams ellipses account for this phenomenon. Ellipses are such that colors inside them are not distinguishable from the color in the center.

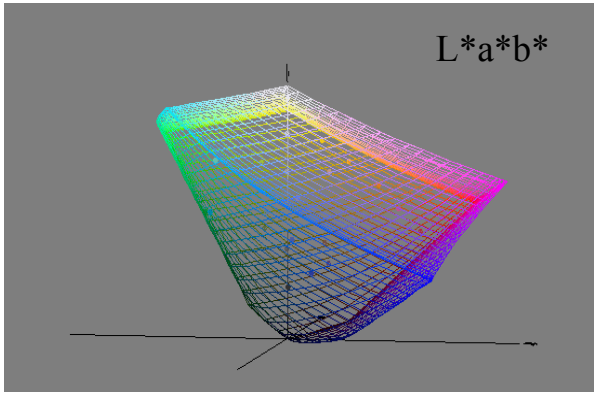
Perceptual color spaces

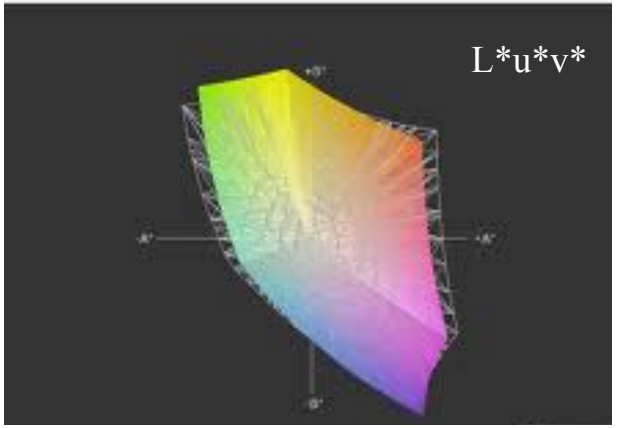
- CIE solved this problem in 1976 with the development of the L*a*b* perceptual color space. Other perceptual spaces are L*u*v* and L*c*h*. All are based on transformations that approximate the XYZ Riemann space into an Euclidean space. These spaces are less distorted than CIE XYZ space although they are not completely free of distortion (Mac Adam's ellipses become nearly circular here).

- In the L*a*b* and L*u*v* color spaces distances can be computed as Euclidean distances:

$$D(c_1,c_2) = [\ (L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2\ ]^{1/2}$$
$$D(c_1,c_2) = [\ (L^*_1 - L^*_2)^2 + (u^*_1 - u^*_2)^2 + (v^*_1 - v^*_2)^2\ ]^{1/2}$$

- Mathematical approximations introduced cause deviations from this property in certain parts of the spaces:
  - In L*u*v* Red is more represented than Green and Blue.
  - In L*a*b* there is a greater sensibility to Green than to Red and Blue. Blue is however more represented than in L*u*v* .





L*u*v* and L*a*b* color spaces

$$L^* = \begin{cases} 903{,}3\ Y/Y_n & \text{if } Y/Y_n < 0{,}008856 \\ 116\ (Y/Y_n)^{1/3} & \text{otherwise} \end{cases}$$

$$u^* = 13L^*\ (u' - u'_n)$$

$$v^* = 13L^*\ (v' - v'_n)$$

$$u' = 4X / (X+15Y+3Z)$$

$$v' = 9Y / (X+15Y+3Z)$$

$Y_n\ u_n\ v_n$ are the values of the reference white

$$L^* = \begin{cases} 903{,}3\ Y/Y_n & \text{if } Y/Y_n < 0{,}008856 \\ 116\ (Y/Y_n)^{1/3} & \text{otherwise} \end{cases}$$

$$a^* = 500\ [f(X/X_n) - f(Y/Y_n)\ ]$$

$$b^* = 200\ [f(Y/Y_n) - f(Z/Z_n)\ ]$$

$$f(t) = (t)^{1/3}$$

for t GT 0.008856

$$7.787\ t\ + 16/116 \quad \text{otherwise}$$

$X_n\ Y_n\ Z_n$ are the XYZ values of the reference white

Color space to use

- sRGB (Red Green Blue)
  - easy to implement but non-linear with visual perception.
  - device dependent with semi-intuitive specification of colours.
  - sRGB is intended as a common color space for the creation of images for viewing on the Internet and World Wide Web

- HSV
  - Used by artists because it is often more natural to think about a color in terms of hue and saturation than in terms of additive or subtractive color components. HSV is a transformation of an RGB color space, and its components and colorimetry are relative to the RGB colorspace from which it was derived.

CIE L*u*v*

- based directly on CIE XYZ.
- attempt to linearise the perceptibility of unit vector color differences.
- The non-linear relationship for L* is intended to mimic the logarithmic response of the eye.
- The CIELUV space is especially useful for additive mixtures of lights

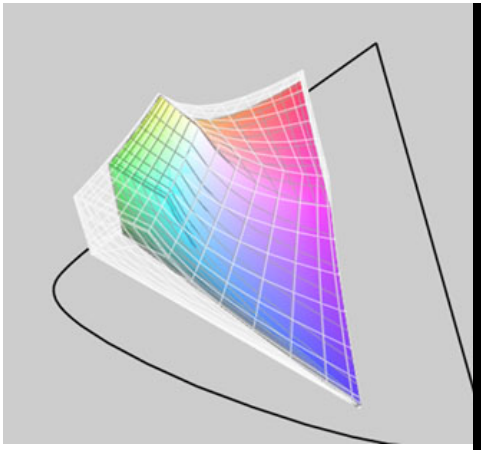
CIE L*a*b*

- based directly on CIE XYZ.
- attempt to linearise the perceptibility of unit vector color differences.
- The non-linear relationships for L* a* and b* are the same as for CIELUV and are intended to mimic the logarithmic response of the eye.
- This space is commonly used for surface colors, but not for mixtures of (transmitted) light

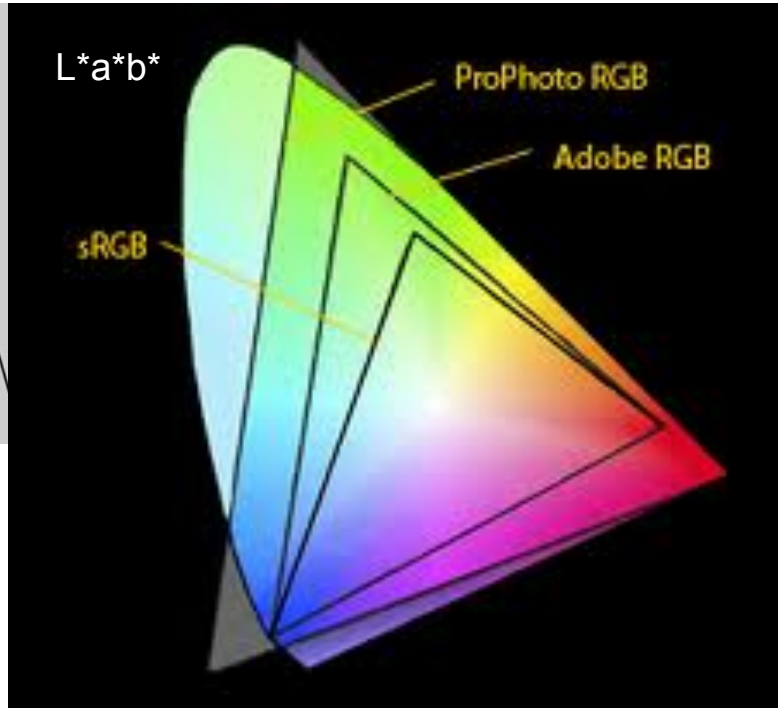
Some gamut comparisons

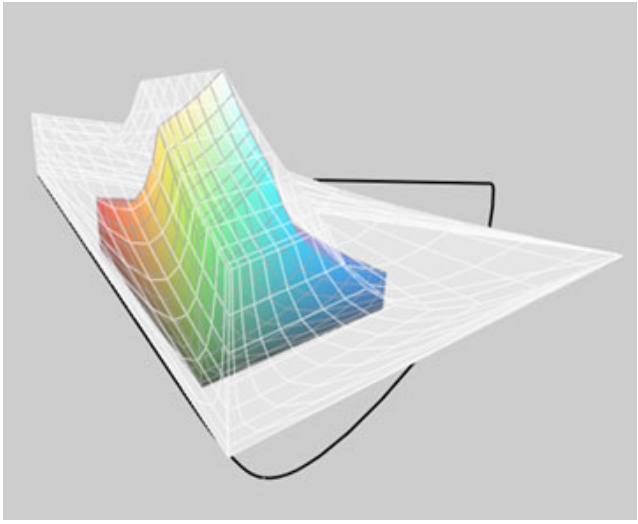
- Adobe RGB 98 gamut is much larger than sRGB especially in green, red and orange range.
- Kodak Prophoto RGB gamut is the closest to Lab

- But we must consider how much able are monitors to visualize the color space….



Adobe RGB vs sRGB





Powerbook vs ProPhotoRGB