Color

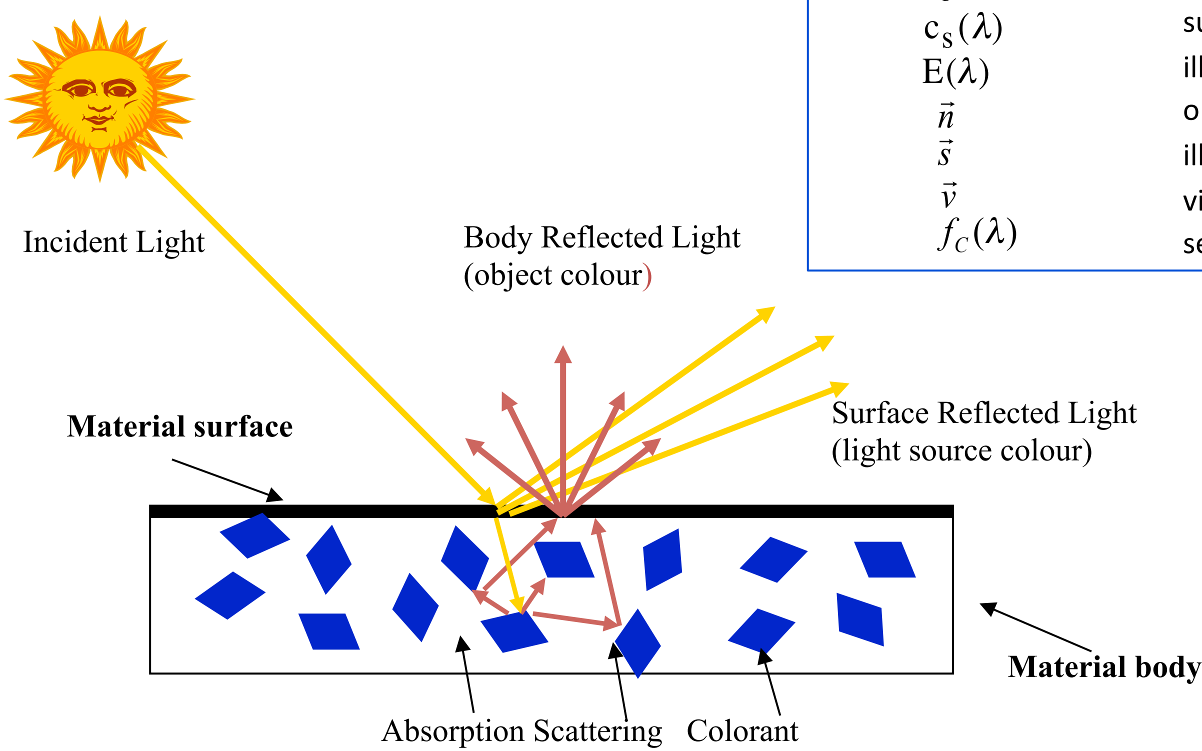
Object color formation

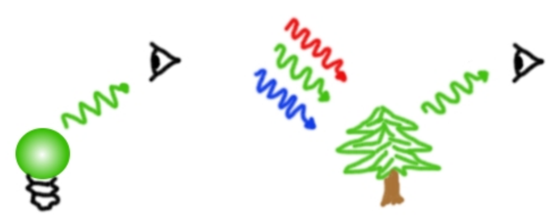
- The color of an object is determined by its reflectance $\rho(\lambda)$ and the visible wavelenghts of the light it is exposed with (and angle). Objects change their color due to different factors: changes in illumination intensity, changes of the color of the illumination source and conditions of interaction between light and object.

- Two basic components of $\rho(\lambda)$ are related to material body and material surface reflection terms:

$$C = m_b(\vec{n},\vec{s}) \int_{\lambda} f_C(\lambda)E(\lambda)c_b(\lambda)d\lambda + m_s(\vec{n},\vec{s},\vec{v}) \int_{\lambda} f_C(\lambda)E(\lambda)c_s(\lambda)d\lambda$$

$c_b(\lambda)$	body reflectance	object material dependent
$c_s(\lambda)$	surface albedo	scene & viewpoint invariant
$E(\lambda)$	illumination	scene dependent
$\vec{n}$	object surface normal	object shape variant
$\vec{s}$	illumination direction	scene dependent
$\vec{v}$	viewer's direction	viewpoint variant
$f_C(\lambda)$	sensor sensitivity	scene dependent

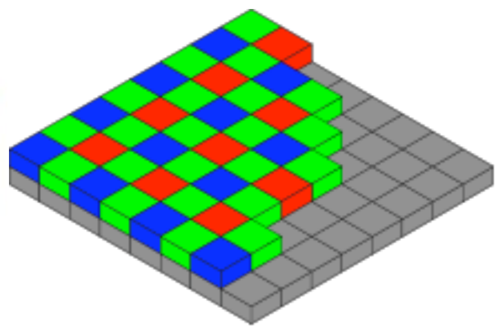


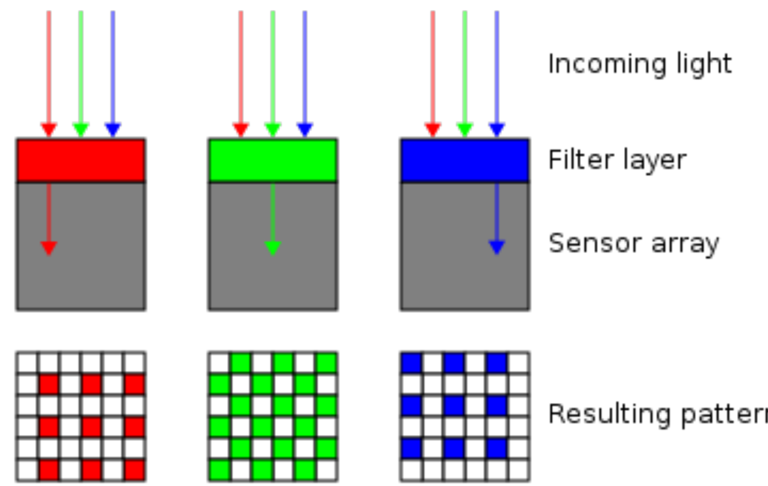


RGB cameras

- Digital images of real world objects are nowadays obtained from photographic digital cameras that use CMOS or CCD sensors to acquire the three color signals. 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.

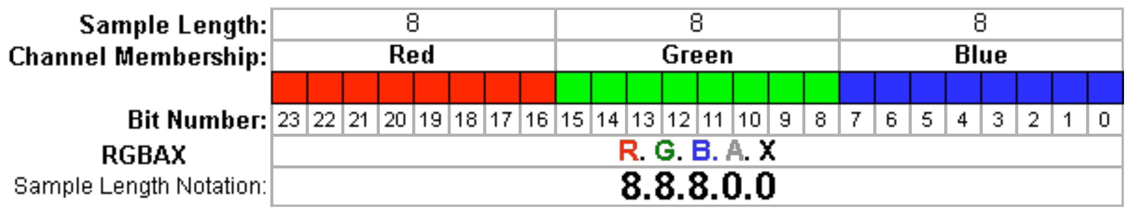
- The sensor has a grid of red, green, and blue detectors arranged so that the first row is RGRGRGRG, the next is GBGBGBGB, and that sequence is repeated in subsequent rows. For every channel, missing pixels are obtained by interpolation to build up the complete image.





- A pixel only records one color out of three and cannot determine the color of the reflected light. To obtain a full color image demosaicing algorithms are used that interpolate a set of complete green, red, blue values at each point. This is done in-camera producing a JPEG image.

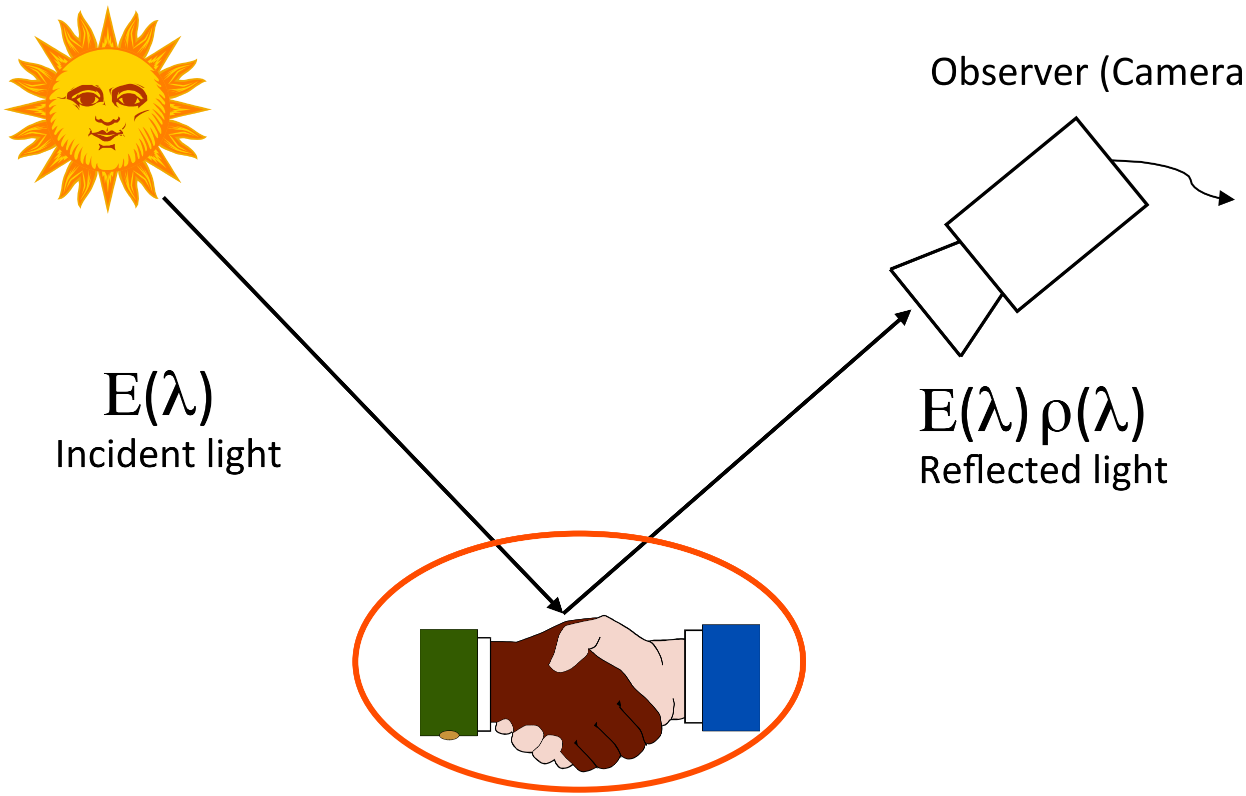
- Truecolor is a method of representing and storing graphical image information. Truecolor defines 256 (2^8) shades of red, green, and blue for each pixel of the digital picture, which results in 256^3 or 16,777,216 (approximately 16.7 million) color variations for each pixel.



- Many low- to medium-end consumer digital cameras and scanners convert the camera RGB measurements into a standard RGB color space referred to as sRGB

- Color image formation, color spaces and color standards are discussed in the following

Color Image Formation

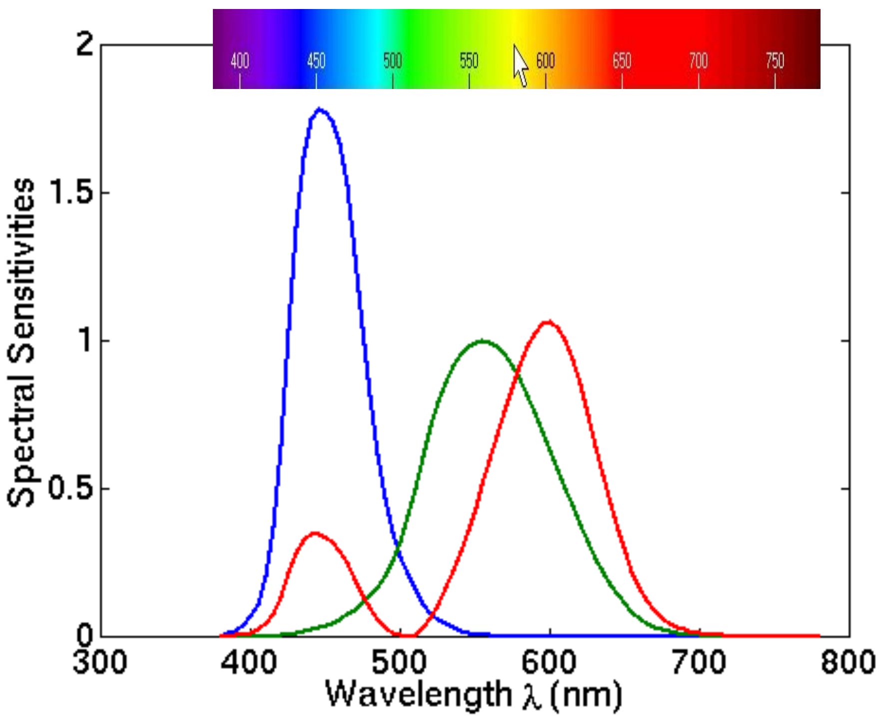


- Color image formation is determined by the relative radiant power distribution of the incident light, the reflection of the materials and the characteristics of the observer.

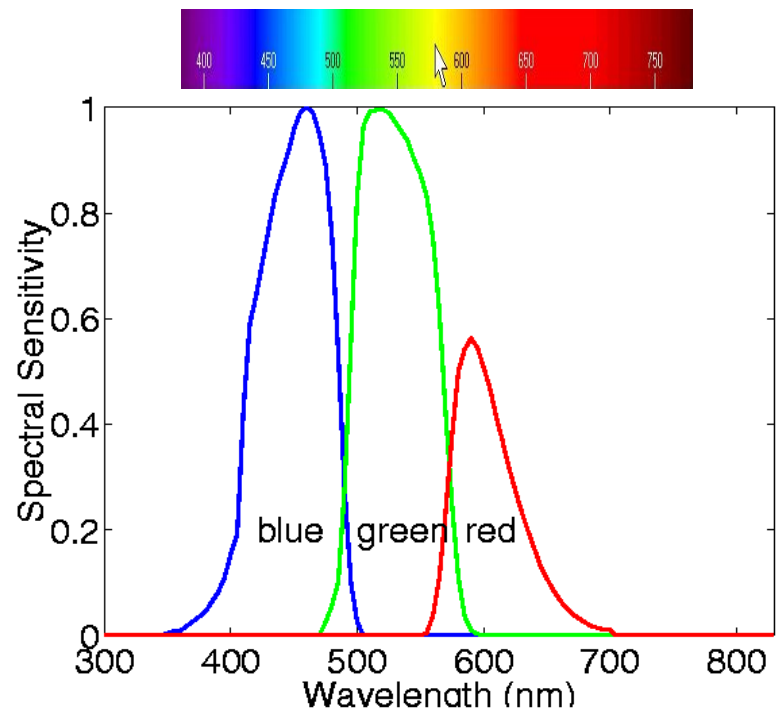
Observer/Sensor f (λ)

- Having the light spectrum and the spectral reflectance curve of the object the appearance of the object depends on the spectral sensitivity of the observer.
  Considering Tristimulus, RGB values of camera = Colour * Tristimulus.

Eye Response

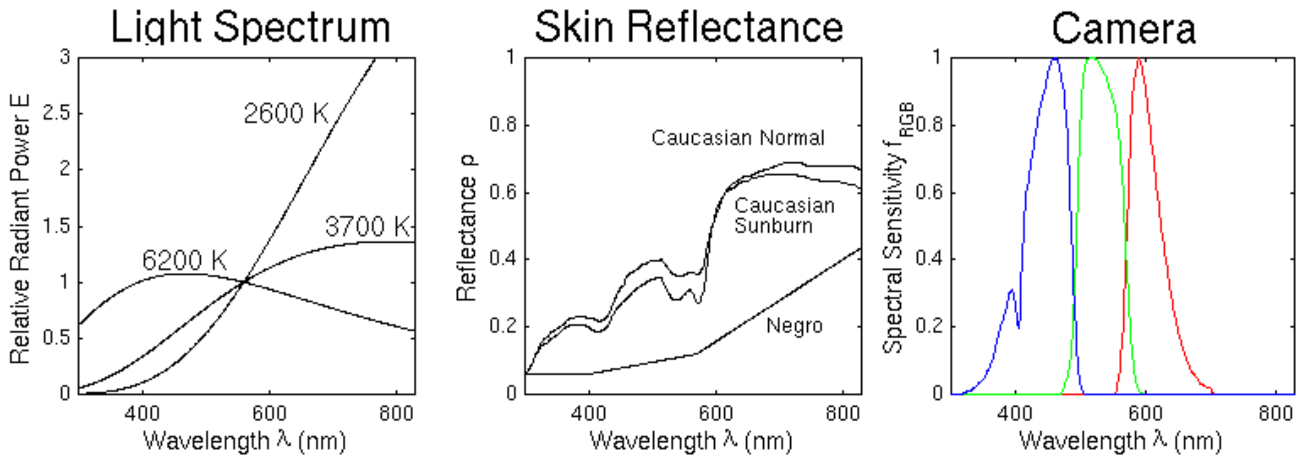


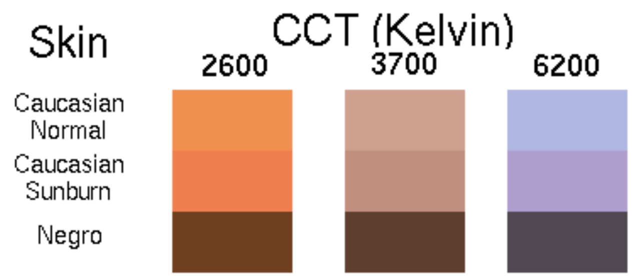
Camera Response



Camera spectral integration

- If the spectrum of the light source changes then the colour of the reflected light also changes.





- Reflected light spectrum is represented by a 3 element vector

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

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

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

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

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, i.e. 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 colours from space navigation. Other spaces require to manage parameters with abstract relationships to the perceived colour.
  - Some color spaces are tied to specific equipments while others are equally valid on whatever device they are used.
  - .....

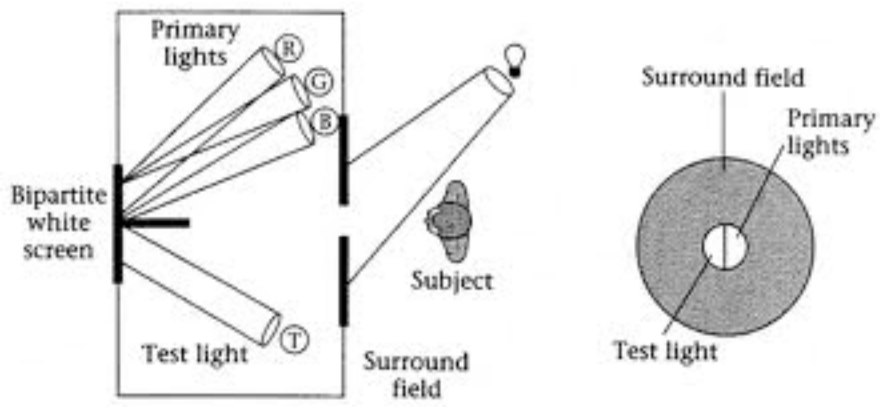
spaces		Applications
CIE Colorimetiric	XYZ	Colorimetric calculations
Device-oriented	Non-uniform spaces RGB, YIQ, YCC	Storage, processing, analysis, coding, color TV
	Uniform spaces L* a* b*, L* u* v*	Color difference evaluation, analysis, color management systems
Device-oriented and User-oriented	HSI, HSV, HSL, $I_1 I_2 I_3$	Human color perception, computer graphics
Munsell		Human visual system

CIE color matching experiment

- The first color matching experiment was devised in 1920 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.

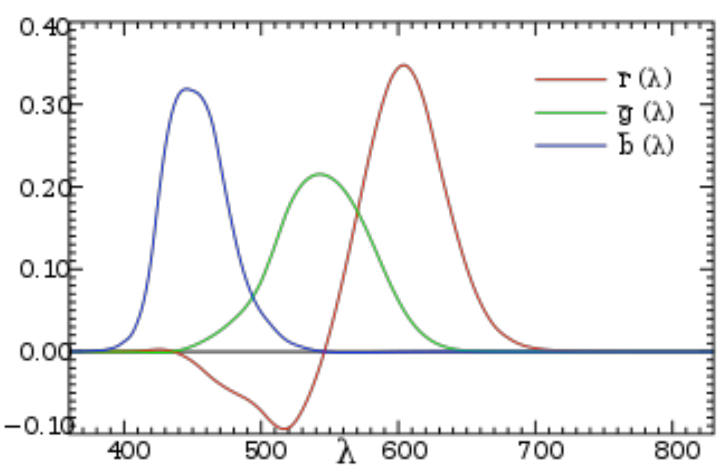


CIE RGB color space

- In 1931 CIE standardized the RGB color matching functions $\overline{r}(\lambda)\,\overline{g}(\lambda)\,\overline{b}(\lambda)$ 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 at the wavelenght shown on the horizontal scale. Rather than specifying the brightness of each primary, the curves were normalized (scaled) to have constant area under them.

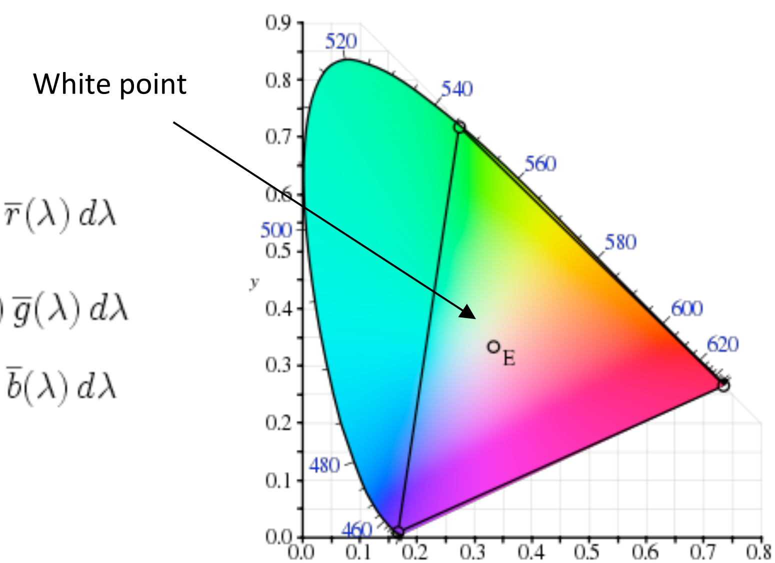
- The CIE RGB color space is one of many RGB color spaces, distinguished by a particular set of monochromatic primary colors. The RGB tristimulus values for a color with a spectral power distribution $I(\lambda)$ are given by integration of the scaled RGB color matching functions.
- The range of colors represented in such a space (*gamut*) is only part of the whole set of colors distinguishable by the human eye (the triangle in figure).



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

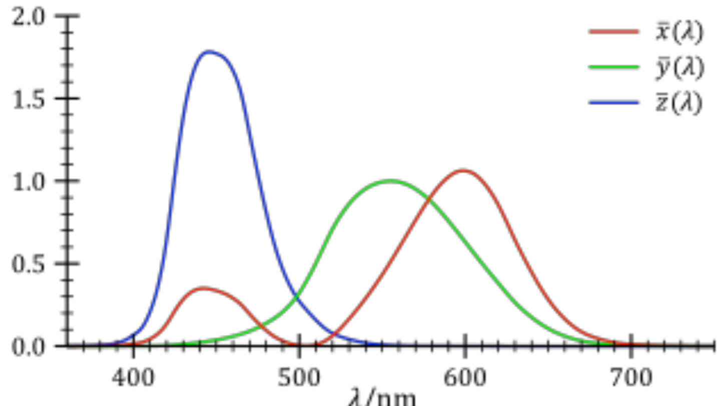
$$G = \int_0^\infty I(\lambda)\,\overline{g}(\lambda)\,d\lambda$$

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



CIE XYZ color space

- Having developed an RGB space of human vision using the CIE RGB matching functions, the Commission developed another color space that would relate to the CIE RGB color space by a linear transformation such that the *new color matching functions* $\overline{x}(\lambda)$ $\overline{y}(\lambda)$ $\overline{z}(\lambda)$ were to be everywhere greater than or equal to zero, and the $\overline{y}(\lambda)$ color matching function would be proportional to human sensitivity to luminance i.e. corresponding to the photopic luminous efficiency function for the *CIE standard observer*.



- 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*. Almost any spectral composition can be achieved by a suitably chosen mix of these three monochromatic primaries. They yield the CIE XYZ *tristimulus values* X, Y, Z. The XYZ tristimulus values of a color with spectral distribution E(λ) are given in terms of the standard observer and are related to CIE RGB values by a linear transformation as

$$X = \int E(\lambda)\,\bar{x}(\lambda)\,d\lambda$$
$$Y = \int E(\lambda)\,\bar{y}(\lambda)\,d\lambda$$
$$Z = \int E(\lambda)\,\bar{z}(\lambda)\,d\lambda$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

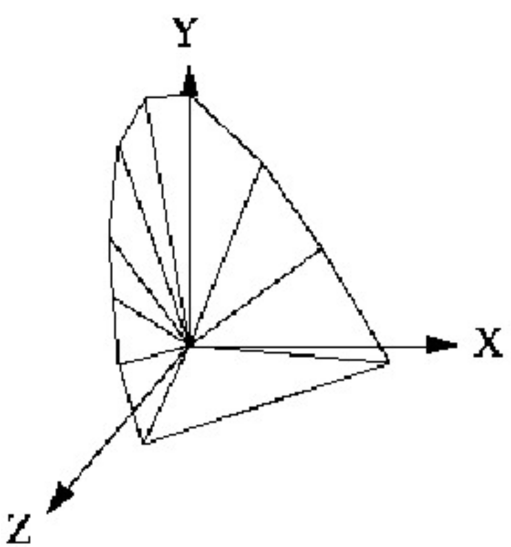
Illuminant D65

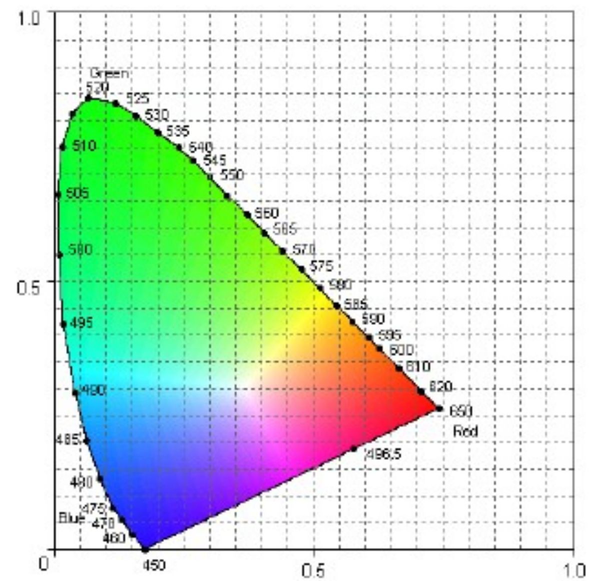
CIE xyY color space

- The CIE XYZ color space serves as a basis from which other color spaces are defined.
  By normalizing XYZ (i.e. dividing by X + Y + Z) derived values are obtained referred to as x,y,z .
  In that x + y + z = 1, the chromaticity of a color can be specified by two parameters x y, of the three normalized values.

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

- The xy diagram obtained by intersecting the XYZ space with plane X + Y + Z = 1 and projecting this intersection on the x-y 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 xy Y space is widely used in practice to represent colors.

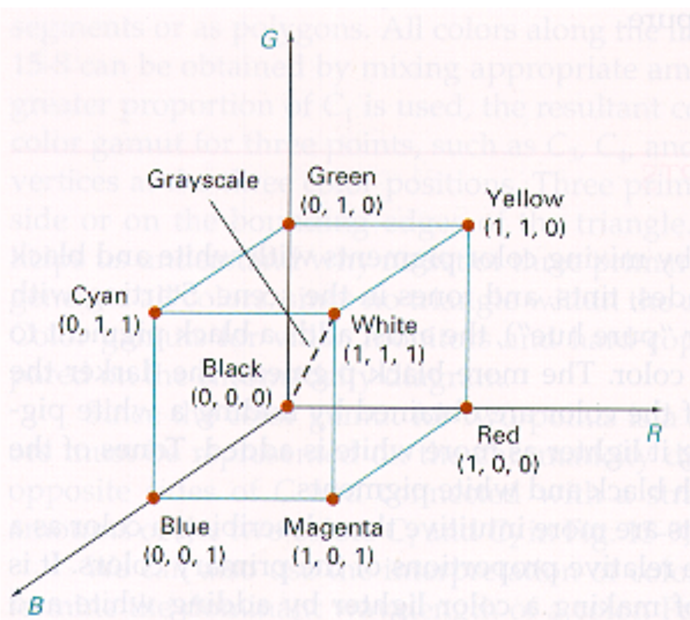


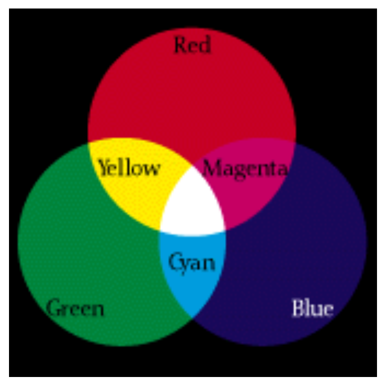


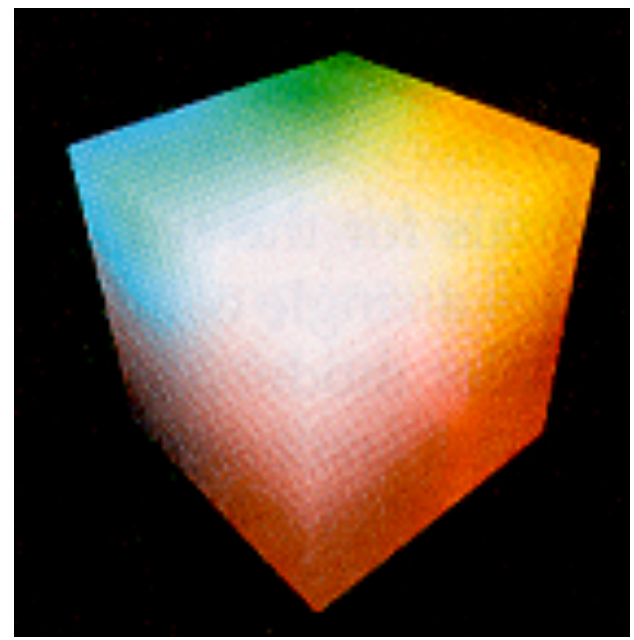
RGB color space

- 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 three-dimensional coordinate of the point of the given color within the cube or its faces or along its edges. This approach allows computations of the color similarity of two given RGB colors by simply calculating the distance between them: the shorter the distance, the higher the similarity.







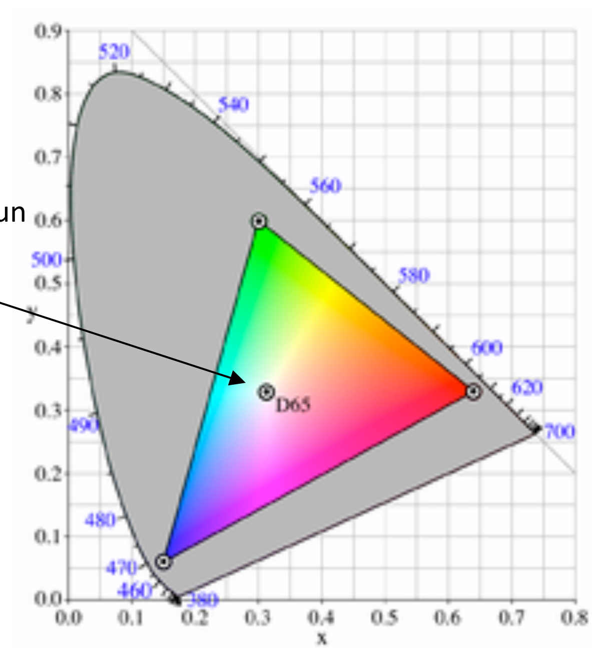
RGB color spaces

- RGB color space is hardware dependent. Therefore several RGB color spaces exist. The sRGB color space is the most widely used in practice.

Color Space	Gamut	White Point	Primaries					
			xR	yR	xG	yG	xB	yB
HDTV (ITU-R BT.709), sRGB	**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

……….

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



sRGB gamut

sRGB color space

- sRGB color space (created cooperatively by HP and Microsoft in 1996) 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.

- 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.

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

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

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

where a = 0.055

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

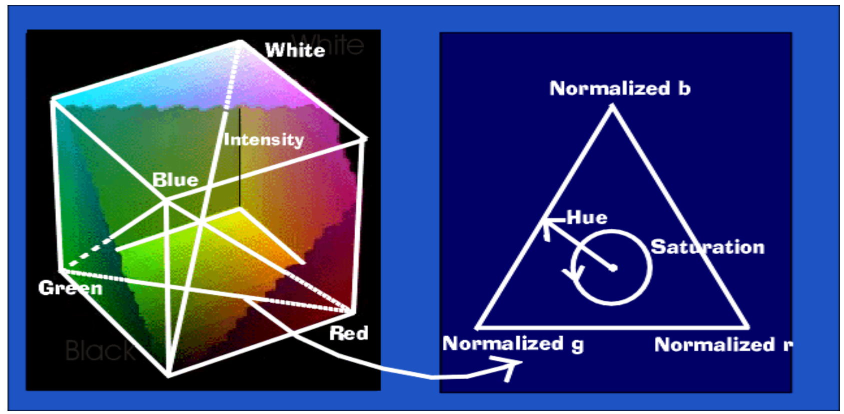
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix}$$

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}.

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

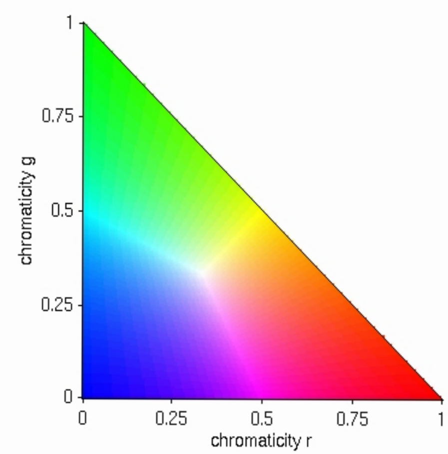
$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} \dfrac{R}{R+G+B} \\ \dfrac{G}{R+G+B} \\ \dfrac{B}{R+G+B} \end{pmatrix}$$



- 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.

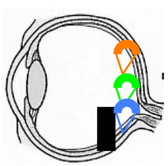
$$r = \frac{R}{R+G+B},$$

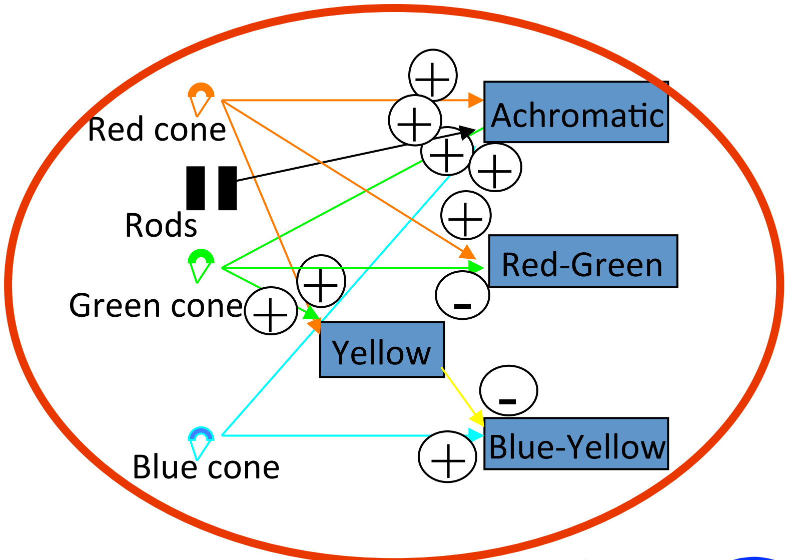
$$g = \frac{G}{R+G+B}.$$



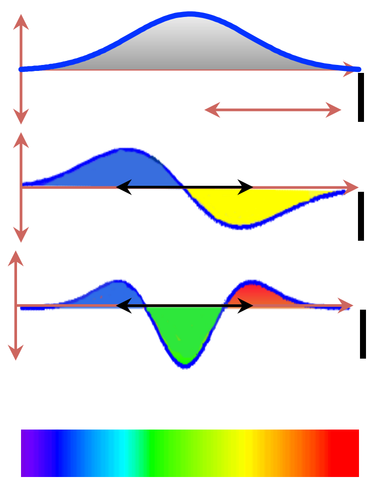
Opponent color space

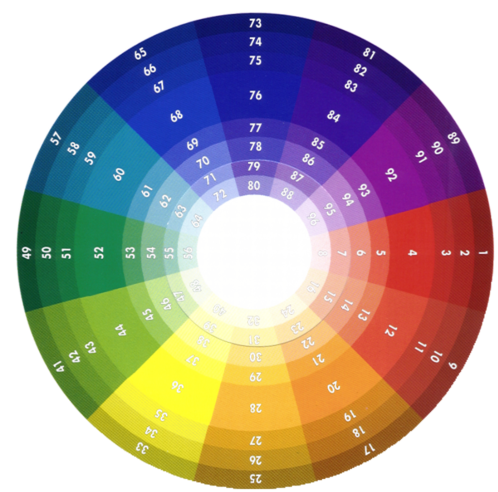
- Human perception combines R, G and B response of the eye in opponent colours. Opponent colours can be hence expressed in RGB space.





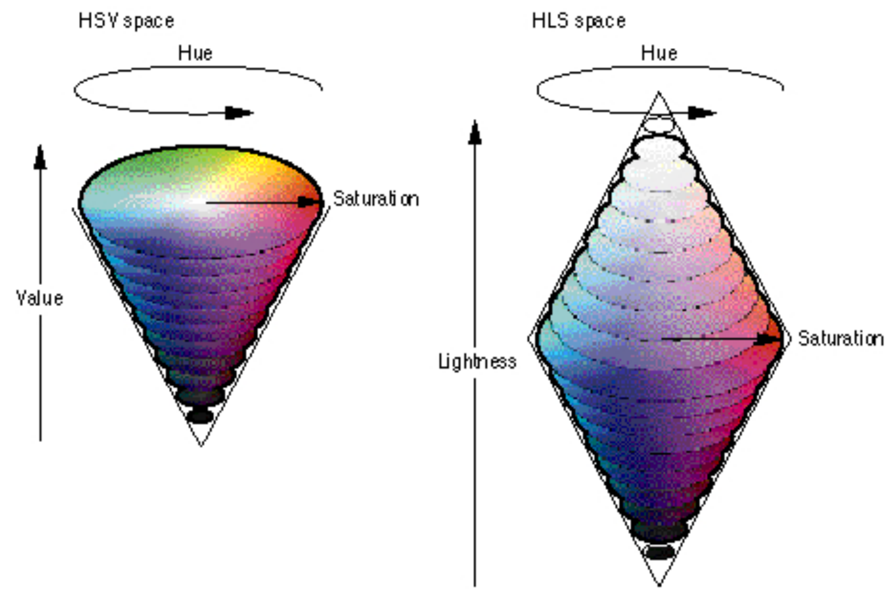
$$\begin{pmatrix} \text{Luminance} \\ \text{Red - Green} \\ \text{Blue - Yellow} \end{pmatrix} = \begin{pmatrix} R+G+B \\ R-G \\ B-(R+G) \end{pmatrix}$$





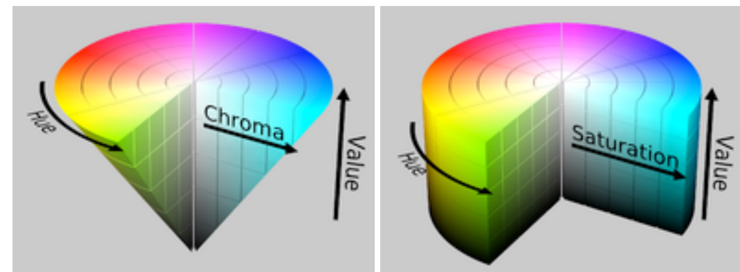
HSB – HLS - HSV color spaces

- 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) and *luminance* (the amount of gray) closely to human perception.



HSV color space

- HSV can be represented both as a cylinder or a cone space depending on whether the term S refers to *saturation* (*colorfulness wrt its own brightness*) or *chroma* (*colorfulness wrt the brightness of another colour which appears white under similar viewing conditions*).



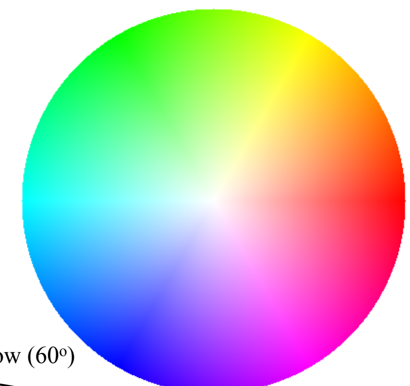
- Values can be derived by the RGB values:

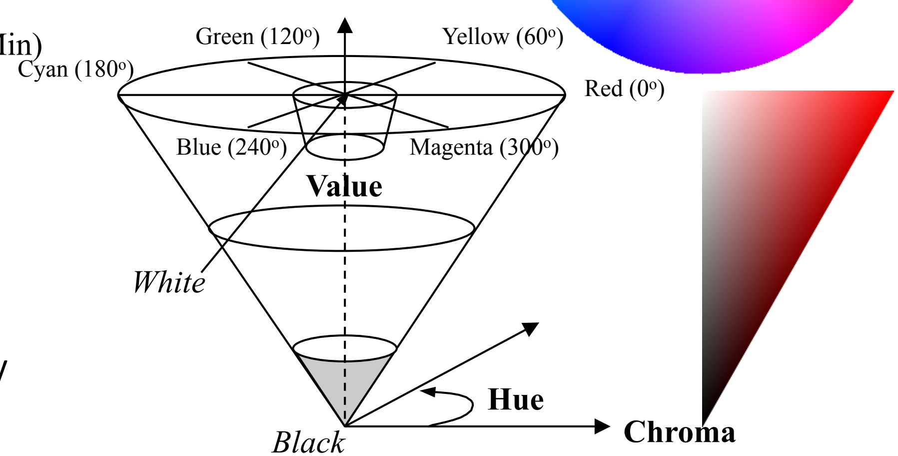
Max = max (R, G, B);   Min = min (R, G, B);

- **V - 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))

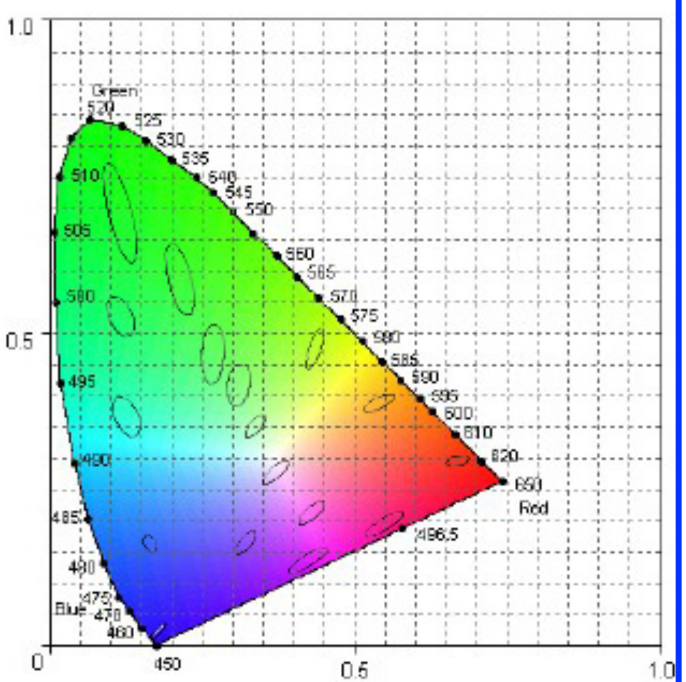




Colorfulness is the difference between a colour and gray

Distances in color space

- Hardware oriented color spaces 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 does not 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 as perceived by humans 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 in the chromaticity diagram xy, colors corresponding to points that have the same distance from a certain point are not perceived as similar colors by humans.
- Mac Adams ellipses account for this phenomenon. Ellipses are such that colors inside them are not distinguishable from the color in the center.

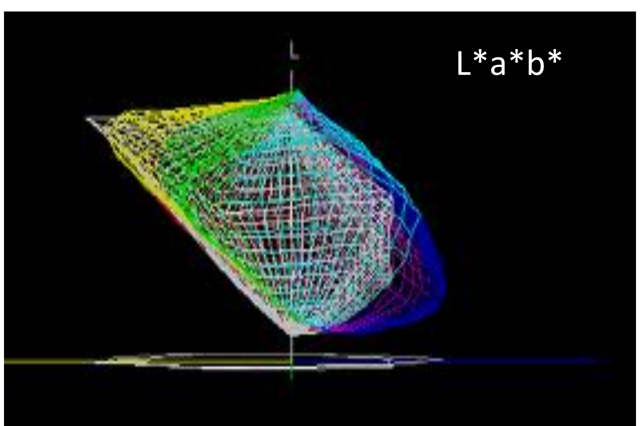
Perceptual color spaces

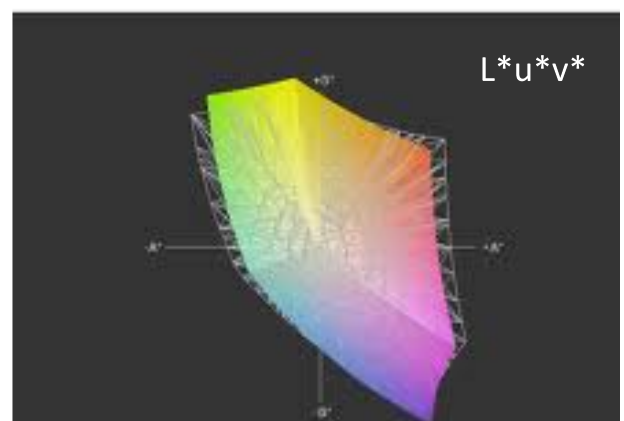
- CIE solved this problem in 1976 with the development of the L*a*b* perceptual color space. Other perceptual spaces are L*u*v* and L*c*h*. All are based on transformations that approximate the XYZ Riemann space into an Euclidean space. These spaces are less distorted than CIE XYZ space although they 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:

$$D(c1,c2) = [\ (L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2\ ]^{1/2}$$
$$D(c1,c2) = [\ (L^*_1 - L^*_2)^2 + (u^*_1 - u^*_2)^2 + (v^*_1 - v^*_2)^2\ ]^{1/2}$$

- 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

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

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

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

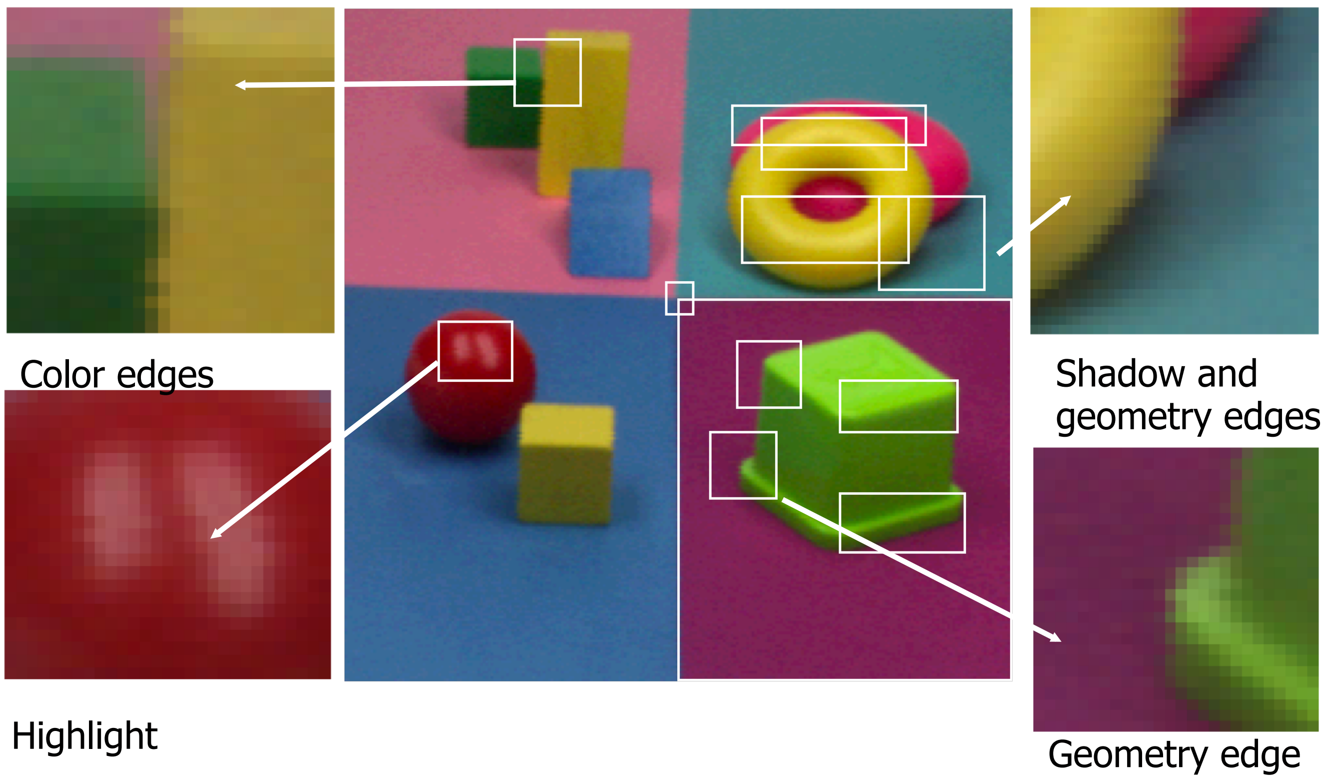
$$f(t) = (t)^{1/3} \quad \text{for } t \text{ GT } 0.008856$$
$$7.787\ t + 16/116 \quad \text{otherwise}$$

X_n Y_n Z_n are the XYZ values of the reference white

Color space invariance to light-object interaction

- Interactions between light and object may produce highlighting and shadowing. Highlighting and shadowing depend on geometry, body and surface reflectance and illumination conditions. Highlighting and shadowing can highly impair image matching.

- The appropriate selection of color spaces can filter out or account of these effects to provide a transformed and more useful image.



- rgb color space is photometric (shadowing/ highlighting) invariant
  - Considering the body reflection term: $C_W = E\, m_b(\vec{n},\vec{s}) \int f_C(\lambda) c_b(\lambda) d\lambda = e\, m_b(\vec{n},\vec{s})\, k_C$

$$r(R_b, G_b, B_b) = \frac{e m_b(\vec{n},\vec{s}) k_R}{e m_b(\vec{n},\vec{s})(k_R + k_G + k_B)} = \frac{k_R}{(k_R + k_G + k_B)}$$

$$g(R_b, G_b, B_b) = \frac{e m_b(\vec{n},\vec{s}) k_G}{e m_b(\vec{n},\vec{s})(k_R + k_G + k_B)} = \frac{k_G}{(k_R + k_G + k_B)}$$

$$b(R_b, G_b, B_b) = \frac{e m_b(\vec{n},\vec{s}) k_B}{e m_b(\vec{n},\vec{s})(k_R + k_G + k_B)} = \frac{k_B}{(k_R + k_G + k_B)}$$

  - Similarly for the surface reflection term.

- Hue of HSI color space is photometric (shadowing/ highlighting) invariant

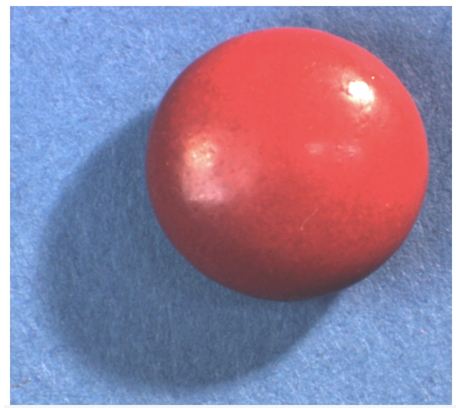
$l_1l_2l_3$ color space

- $l_1l_2l_3$ color space is obtained from RGB manipulation and is invariant to highlighting effects of light interaction particularly for shiny objects

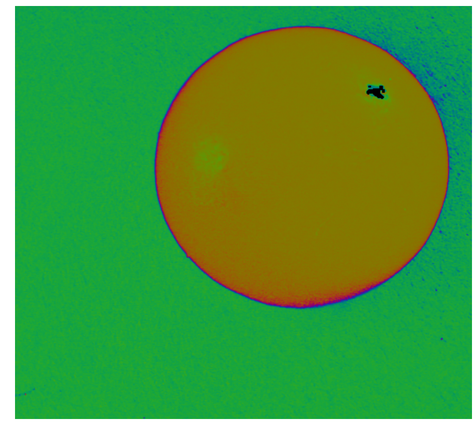
$$l1(R,G,B)=\frac{(R-G)^2}{(R-G)^2+(R-B)^2+(G-B)^2}$$

$$l2(R,G,B)=\frac{(R-B)^2}{(R-G)^2+(R-B)^2+(G-B)^2}$$

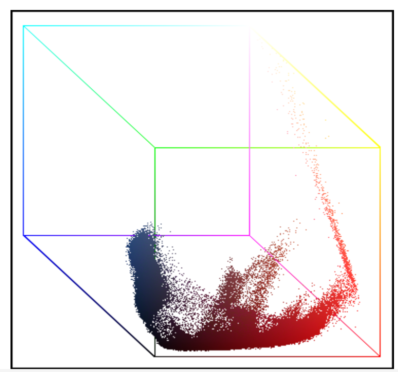
$$l3(R,G,B)=\frac{(G-B)^2}{(R-G)^2+(R-B)^2+(G-B)^2}$$



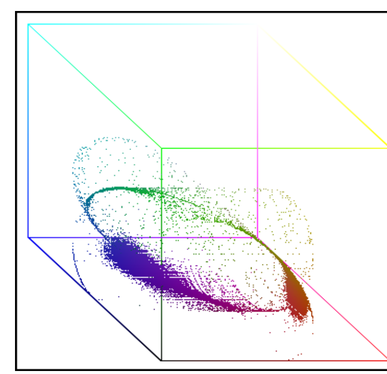
Original RGB image



$l_1l_2l_3$ image



3D plot of RGB image



3D plot of $l_1l_2l_3$ image

$c_1c_2c_3$ color space

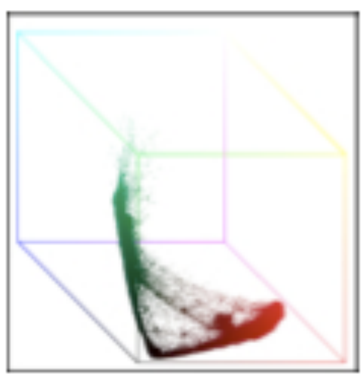
- $c_1c_2c_3$ color space is obtained from RGB manipulation and is invariant to shadowing effects of light interaction particularly for matte objects

$$c_1(R,G,B) = \arctan \frac{R}{\max\{G,B\}}$$

$$c_2(R,G,B) = \arctan \frac{G}{\max\{R,B\}}$$

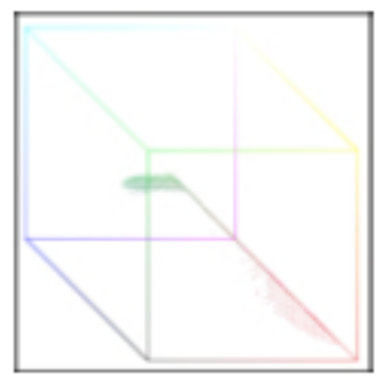
$$c_3(R,G,B) = \arctan \frac{B}{\max\{R,G\}}$$

Original RGB image



3D plot of RGB image

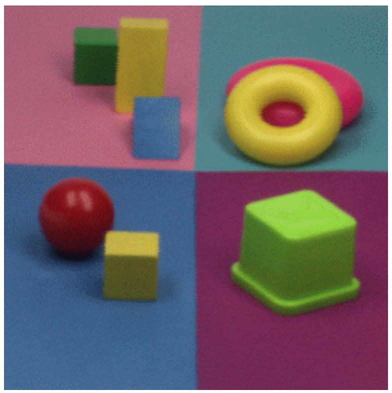
c1c2c3 image

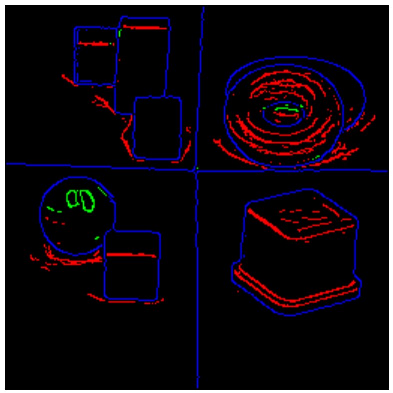


3D plot of $c_1c_2c_3$ image

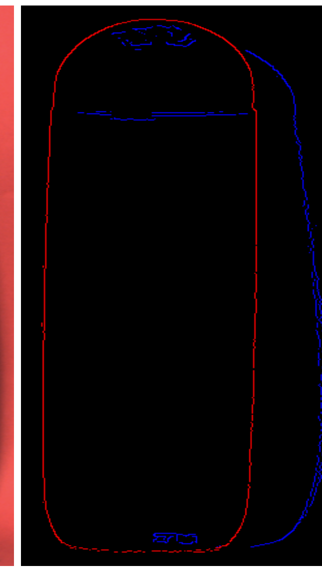
Classification of object color edges

- Local structures of objects like edges, corners and junctions depend on geometry, surface reflectance and illumination conditions. Properties of color spaces can be used for their classification

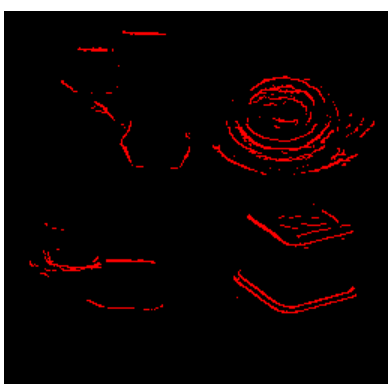




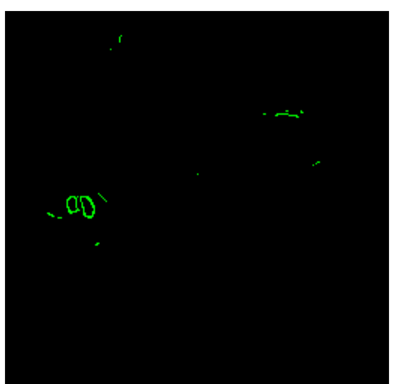
colour edge maxima by type



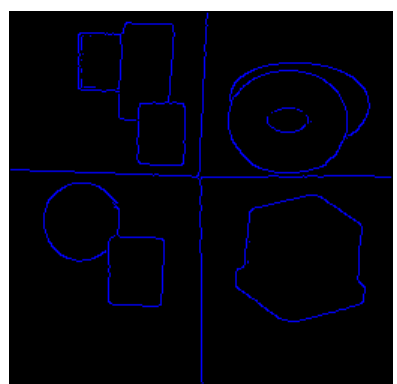
material shadow or geometry



shadows and geometry

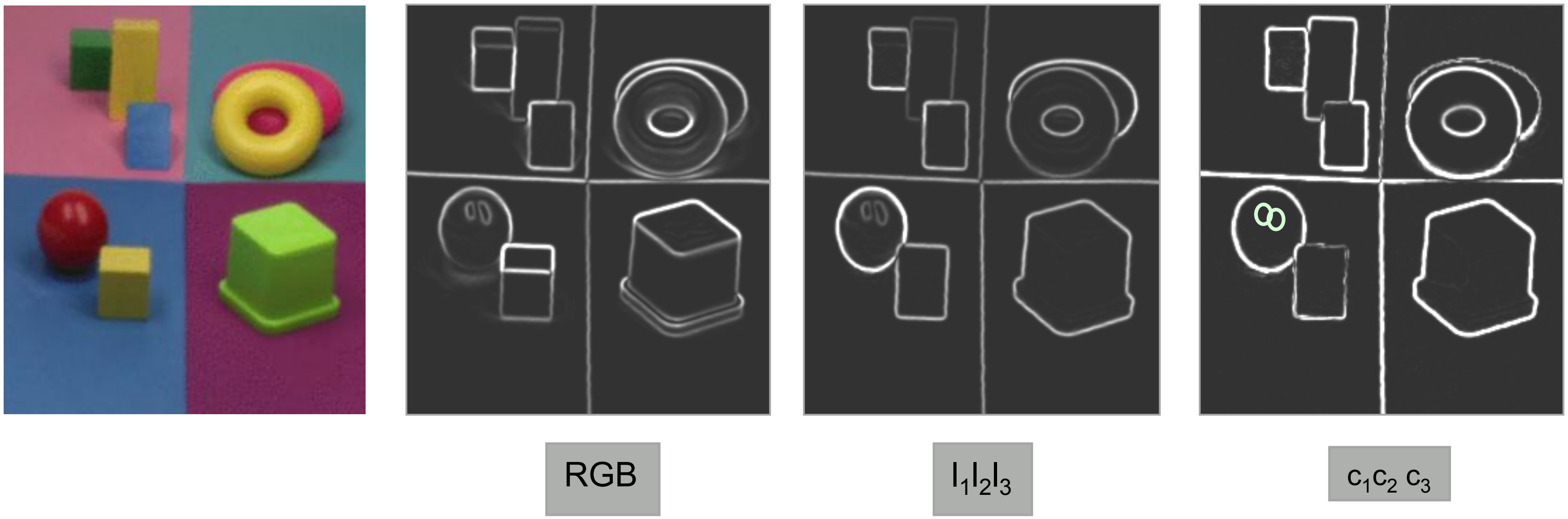


highlights



colour edges

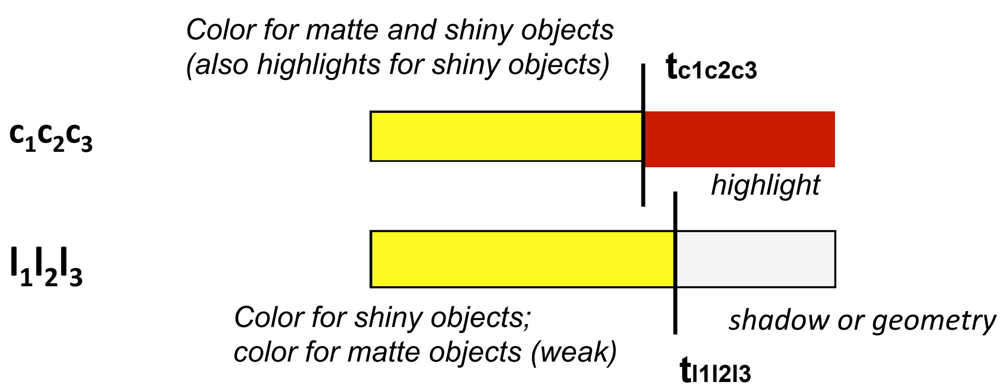
Edge classification by color spaces



- Using both $c_1c_2c_3$ and $l_1l_2l_3$ color spaces:

if $(|\nabla C_{c_1c_2c_3}| \geq t_{c_1c_2c_3}\ \&\ |\nabla C_{l_1l_2l_3}| < t_{l_1l_2l_3})$ then classify as highlight edge

else if $(|\nabla C_{l_1l_2l_3}| \leq t_{l_1l_2l_3})$ then classify as color edge else classify as shadow or geometry edge



Summary of color space properties

RGB (Red Green Blue)

- additive color system based on tri-chromatic theory.
- easy to implement but non-linear with visual perception.
- device dependent with semi-intuitive specification of colours.
- very common, used in virtually every computer system, television, video etc.

HSL (Hue Saturation and Lightness), HSI (Intensity), …

- intuitive specification of color.
- Obtained as linear transform from RGB and therefore device dependent and non-linear.
- Appropriate only for moderate luminance levels. Real world environments are not suitably represented in this space.

HSV HSL HSI (Hue component)

- Invariant under the orientation of the object to the illumination and camera direction.

Opponent color axes

- Advantage of isolating the brightness information on the third axis.
- Invariant to changes in illumination intensity and shadows.

$c_1c_2c_3$ color space

- Invariant to shadowing effects (for matte objects)

$l_1l_2l_3$ color space

- Invariant to highlighting effects

CIE L*u*v*

- based directly on CIE XYZ, attempts to linearise the perceptibility of unit vector color differences. Non-linear transformation but the conversions are reversible.
- The non-linear relationship for L* u* v* is intended to mimic the logarithmic response of the eye.

- CIE L*a*b*
  - based directly on CIE XYZ, attempts to linearise the perceptibility of unit vector color differences. Non-linear transformation but the conversions are reversible.
  - The non-linear relationships for L* a* and b* are intended to mimic the logarithmic response of the eye.
  - Suitable for real world scene color representation

Invariance properties of color spaces

	shadowing	highlights	ill. intensity	color ill. sou.
RGB	-	-	-	-
rgb	+	-	+	-
Hue	+	+	+	-
$c_1c_2c_3$	+	-	+	-
$l_1l_2l_3$	+	+	+	-

- no invariance
+ invariance