Color Vision

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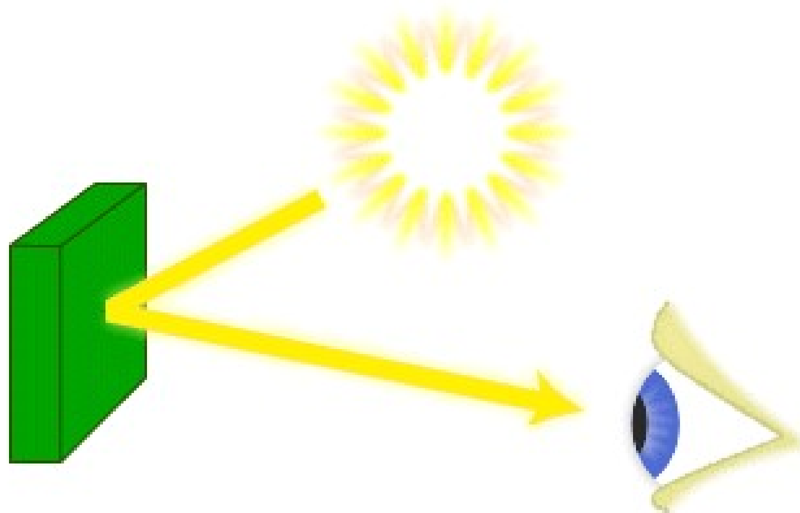
- Color perception is due to the physical interaction between emitted light and the objects encountered en route to the eye of the observer
- The percieved color is a function of the physical characteristics of the light reaching him/her



Newton

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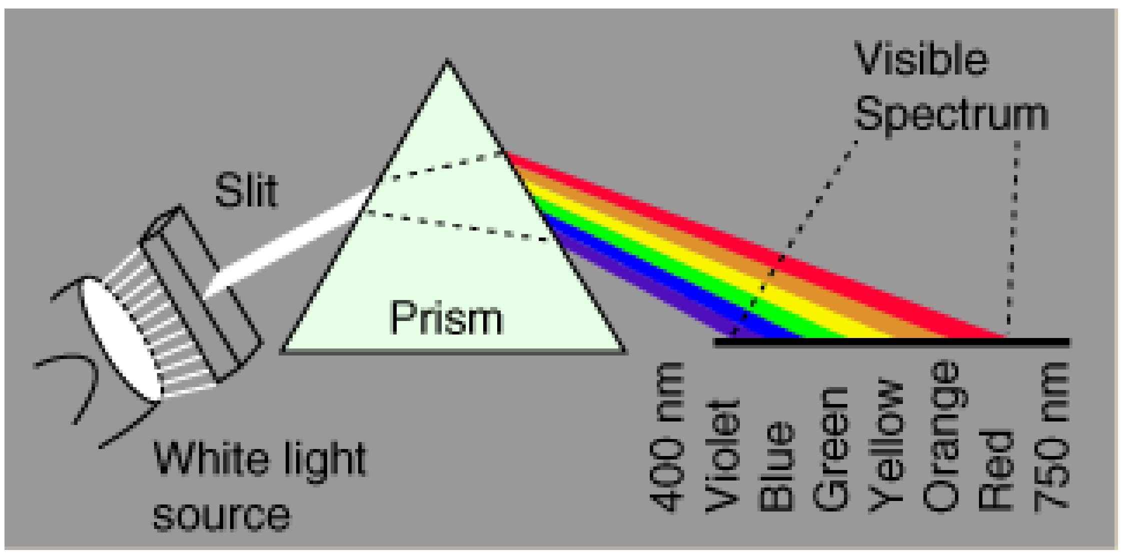
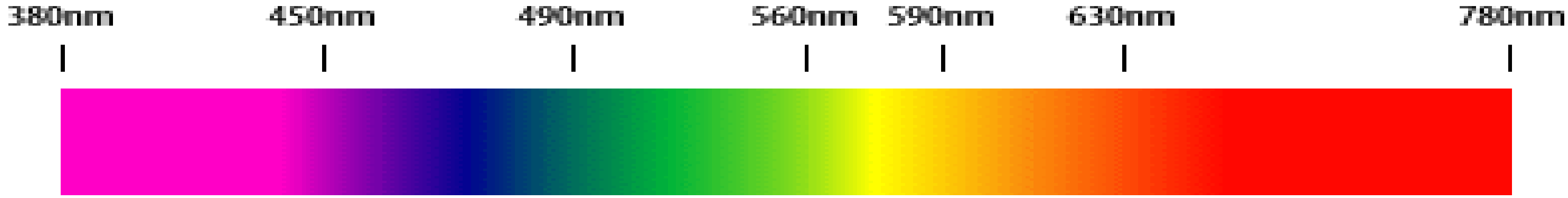
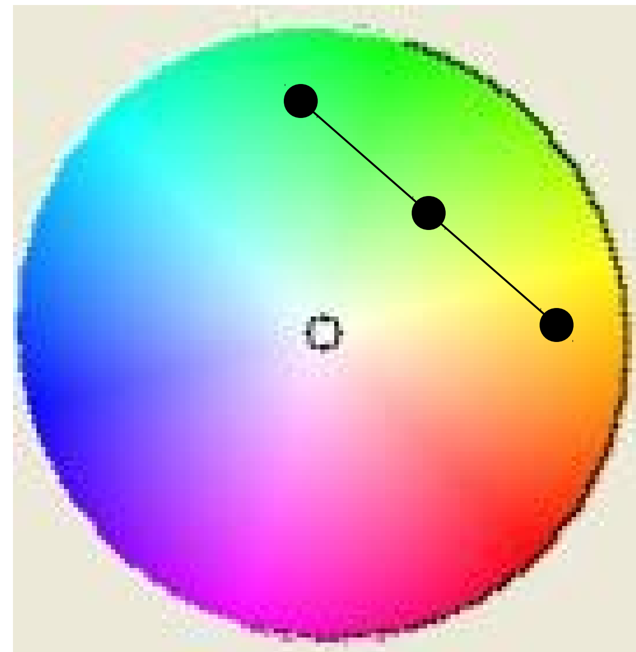
- The first coherent theory of the physical phenomenon linked with color perception was introduced by Newton
- If we let white light go through a prism, the light is separated in various colors.
- Newton's intuition is that white is not a "pure" color, but is the composition of several colors.



Additive synthesis

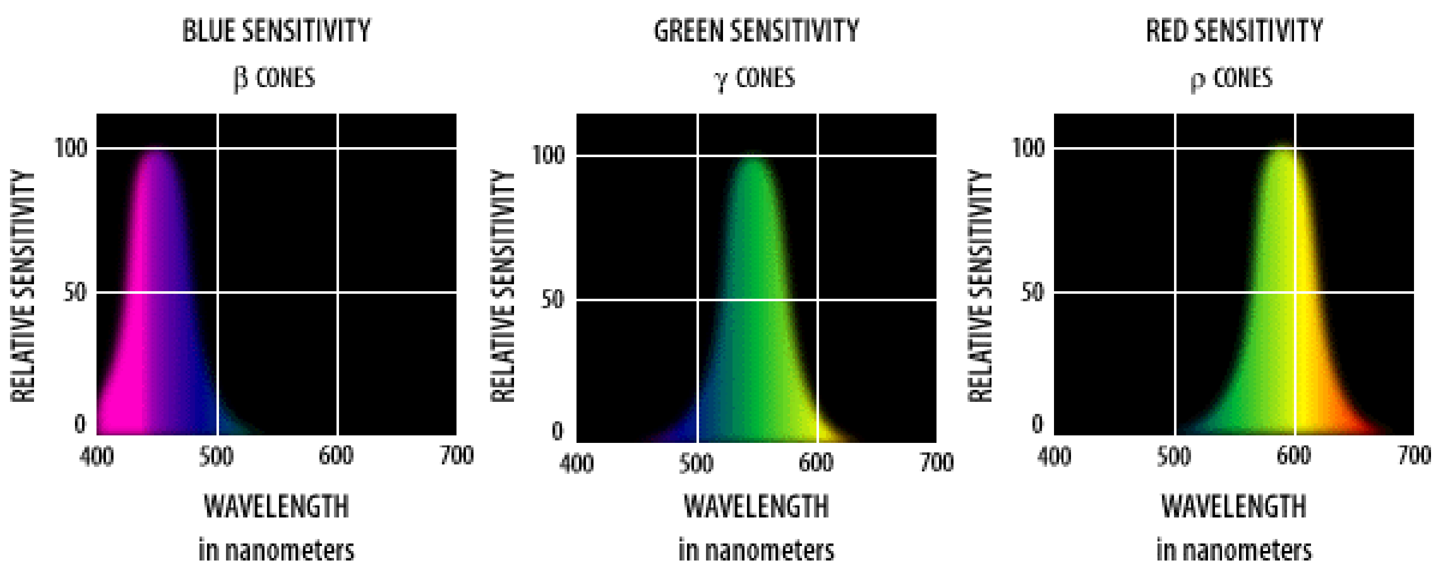


- Newton describes the algebra of colors through a circle (color wheel).
- Colors are placed around the circle in the same order in which we find them in the spectrum.
- The combination of equal parts of two colors is at the center of the segment joining them.



Cones

- The color space described by Newton has 3 dimensions (luminosity + 2 for the color wheel)
- Physiologic research showed that in the human cornea there are three types of receptors for daylight vision (cones) sensible in different ways to the various frequencies of the electromagnetic radiation



Color perception

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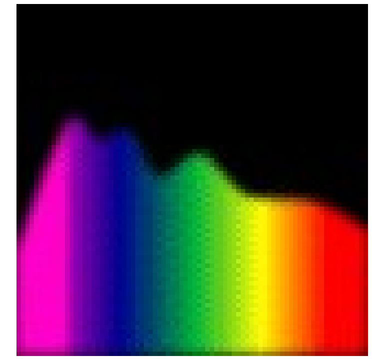
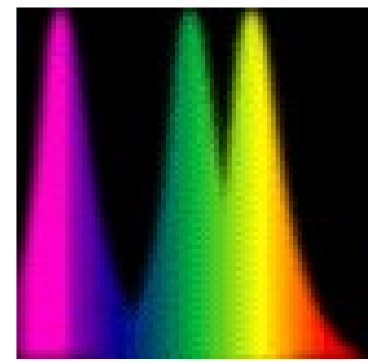
- Color perception is determined by the response of these receptors.

$$\beta = \int \ell(v)\beta(v)\,dv$$
$$\gamma = \int \ell(v)\gamma(v)\,dv$$
$$\rho = \int \ell(v)\rho(v)\,dv$$

- Two lights with different spectra that produce the same response from these 3 types of receptors are perceved being of the same color.





Color Matching

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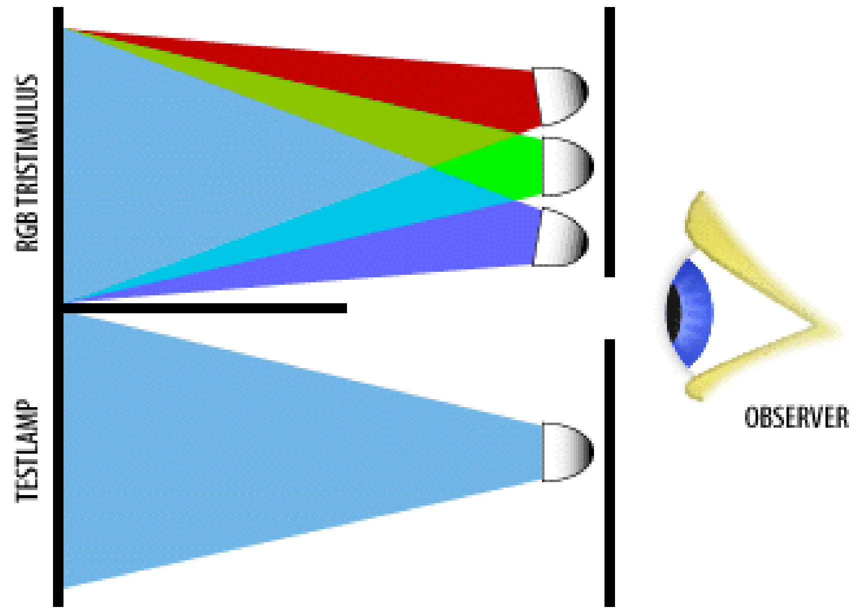
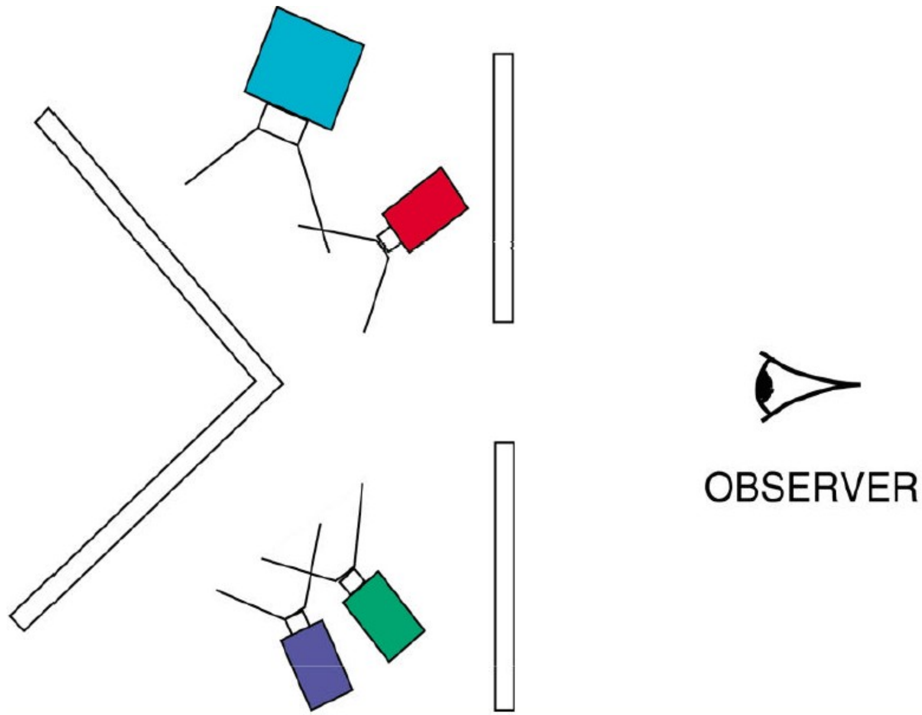
- We can do a simple experiment:
  - An observer controls three lights “centered” on the frequencies of maximum response of the three cones.
  - Controlling the proportion of the luminosity of the three lighs the observer tries to reproduce the same chromatic perception of a test light.

- If the three lights can reproduce the same activation responses from the three types of cones, then the percieved color should be matched perfectly.



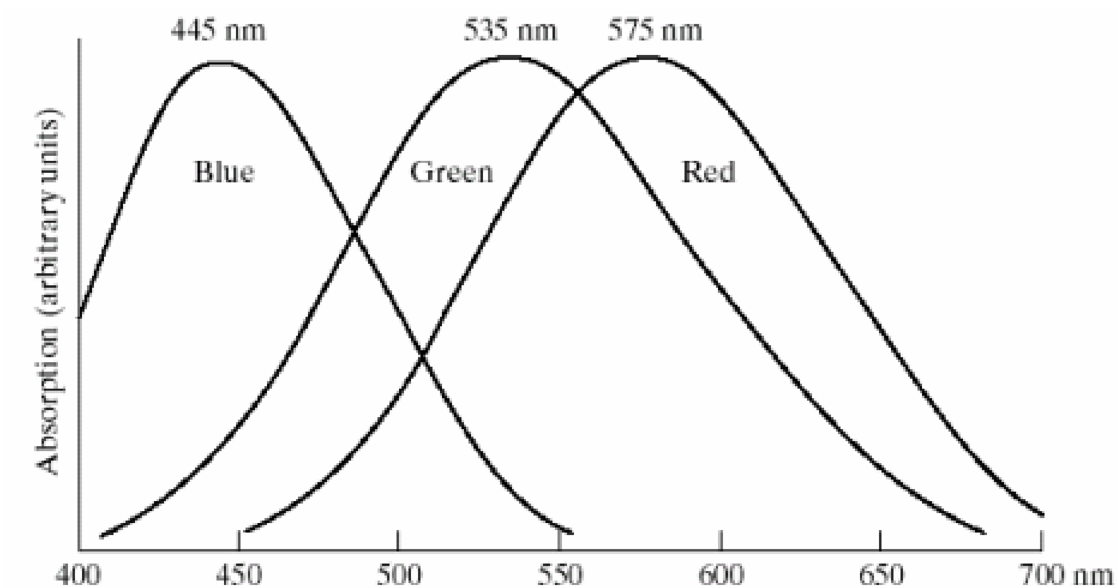
Color Matching

- Almost all colors can be matched this way.
- There are some shades between blue and green that cannot be reproduced this way.
- If we add some red to the test light, than we can match it using only green and blue.
- We have to add a negative quantity of red!



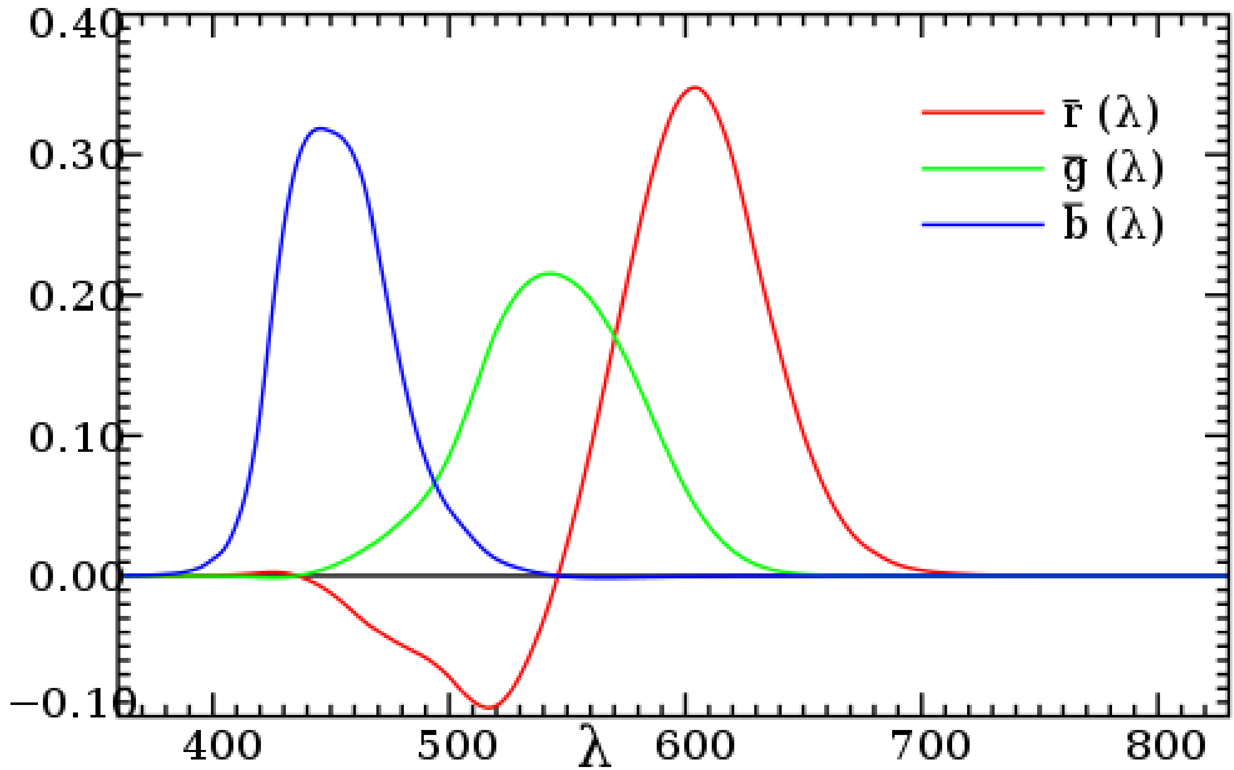
Interpretation

- The sensitivity regions of the three classes of cones overlap.
- The green light activates the red receptor more than the test light (cyan).
- To obtain the same response we need to reduce the activation of the red cones
  (subtract some red)



Color Matching functions

- Color matching functions indicate the quantity of base colors needed to reproduce the chromatic perception of a light of a given wavelength



CIE Standard

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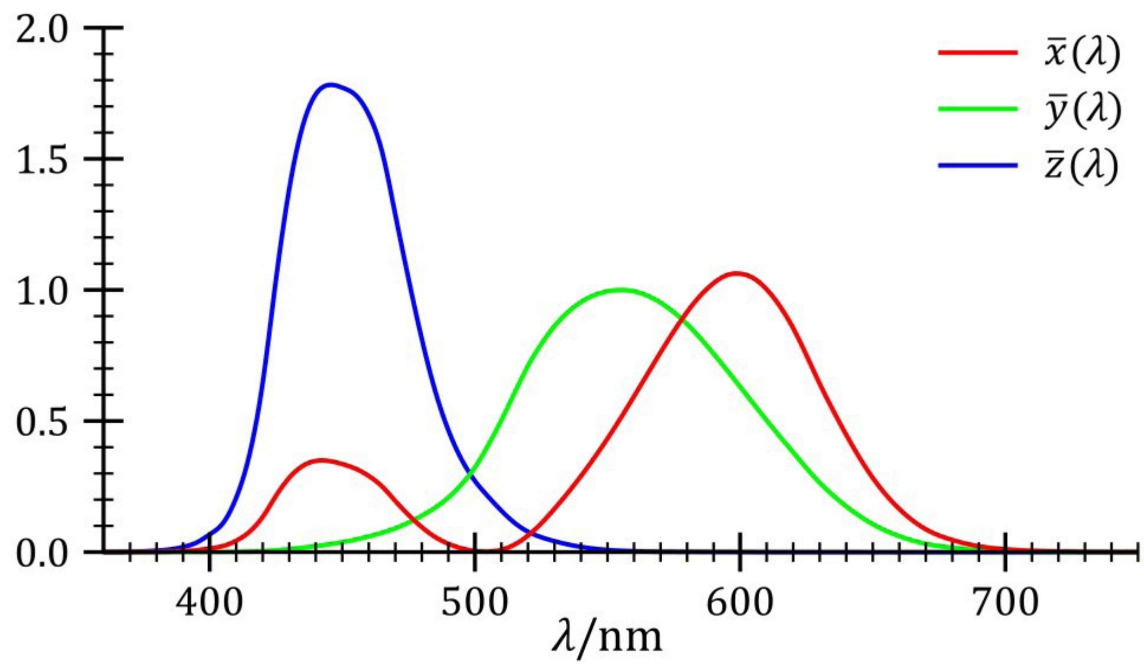
- 1931 CIE standar defines three virtual colors XYZ.
- These colors do not correspond to any real light, but the color perception of any light radiation can bbe matched with a positive combination of these virtual colors.



CIE Standard

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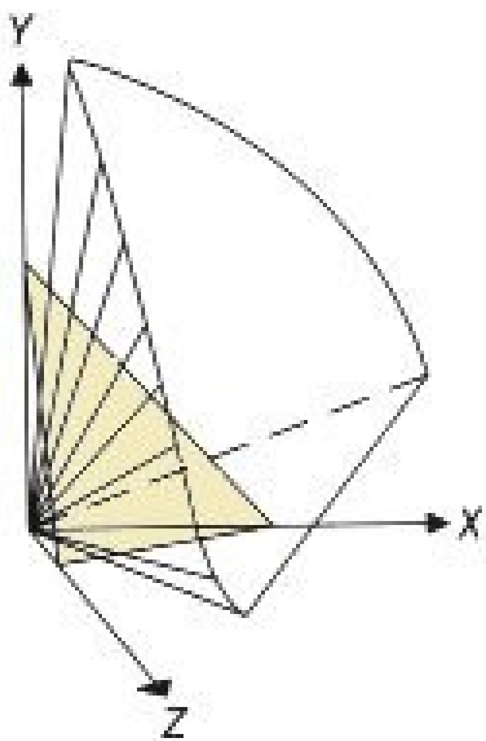
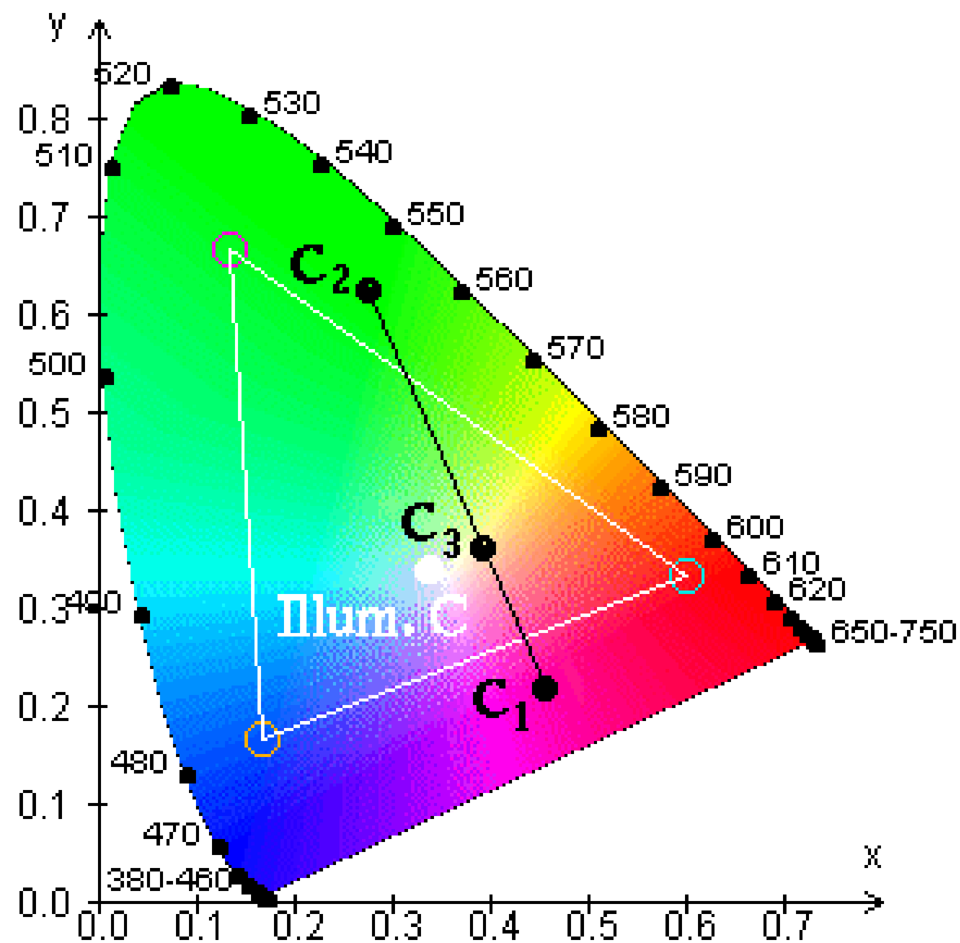
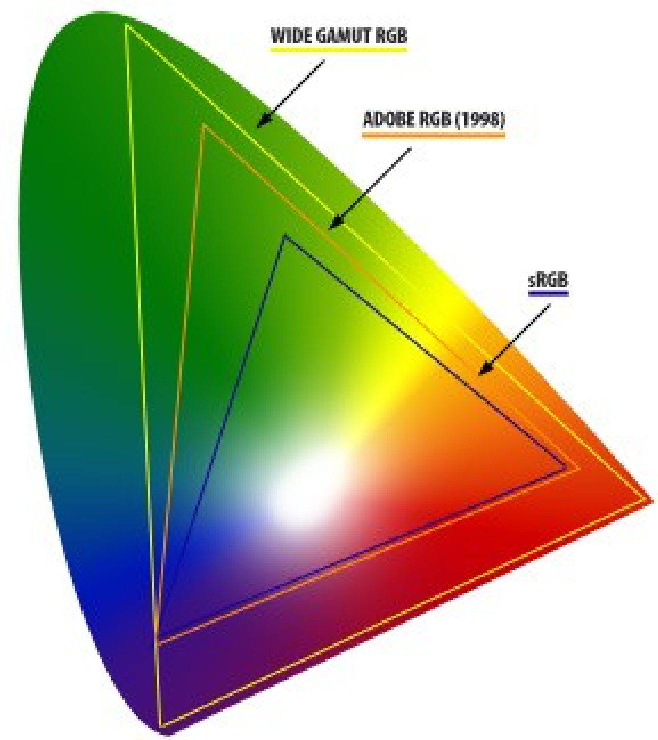




Gamut

- The chromaticity diagram gives us a tool to analyze the color matching problem.
- Any device that reproduces colors by mixing a fixed set of basic colors can only reproduce the colors within the convex envelope of their basis.
- The area of the envelope measures the quantity of reproducible colors and is called **Gamut**



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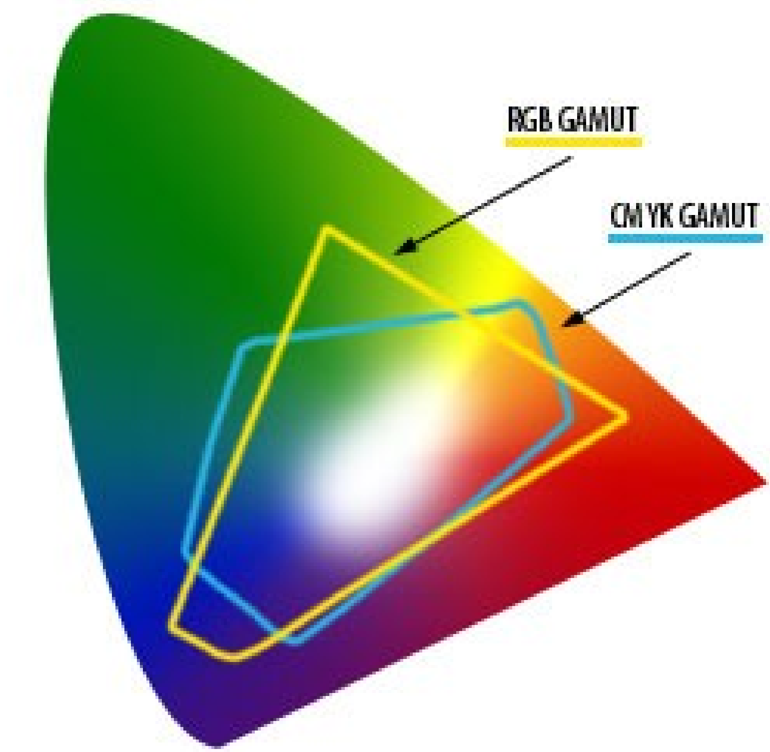
Gamut

- Different devices can use differen colors (print typically uses cyan, yellow, and magenta instrad of red, green, and blue), but the reproducible colors are always limited by the gamut of the device.
- Passing from one device to another we need to map non-reproducible colors within the gamut of the other device.



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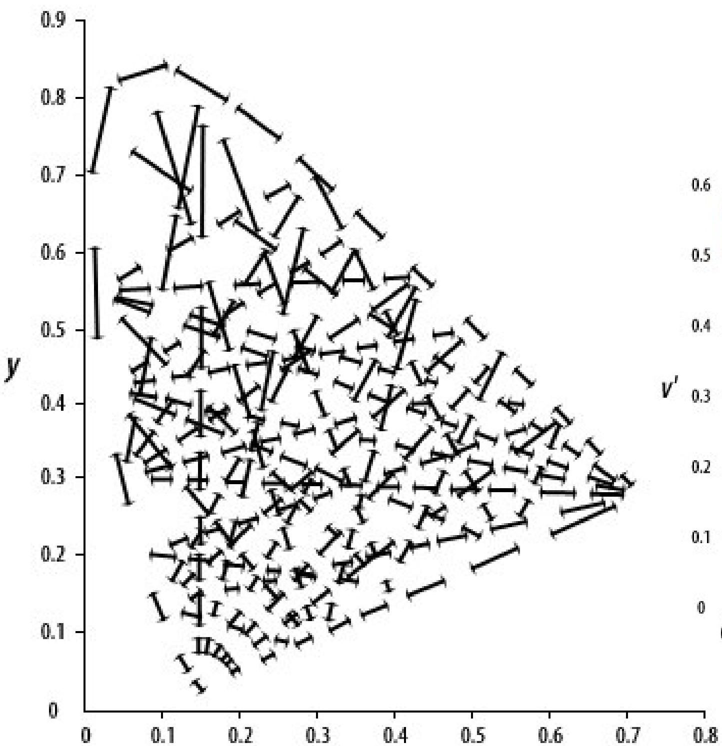
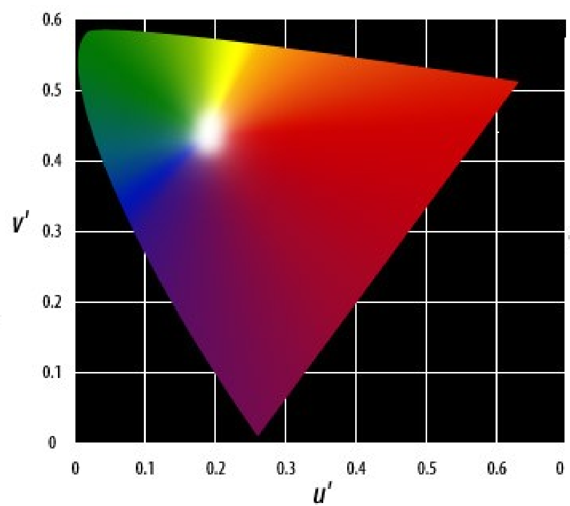
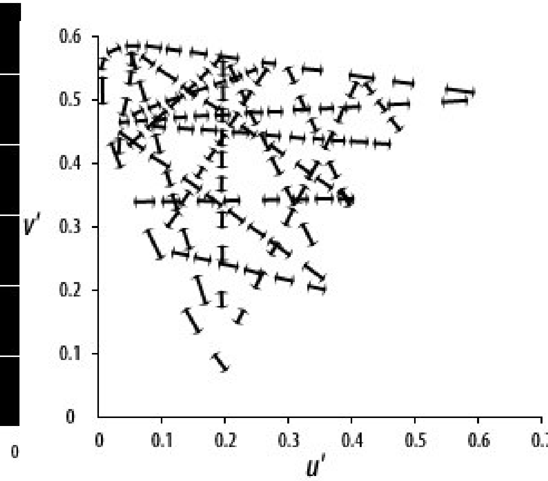
CIE L*u*v*

- There is no correspondence between the distance in the XYZ space and th percieved difference between the corresponding colors.
- CIE L*u*v* (1976) is a “deformation” of XYZ that reduces the discrepancy between spatial distance and perceptual difference.







CIE L*u*v*

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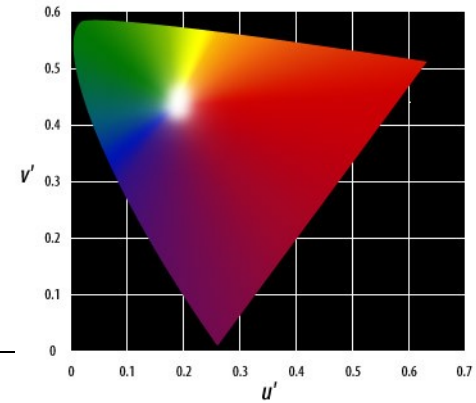

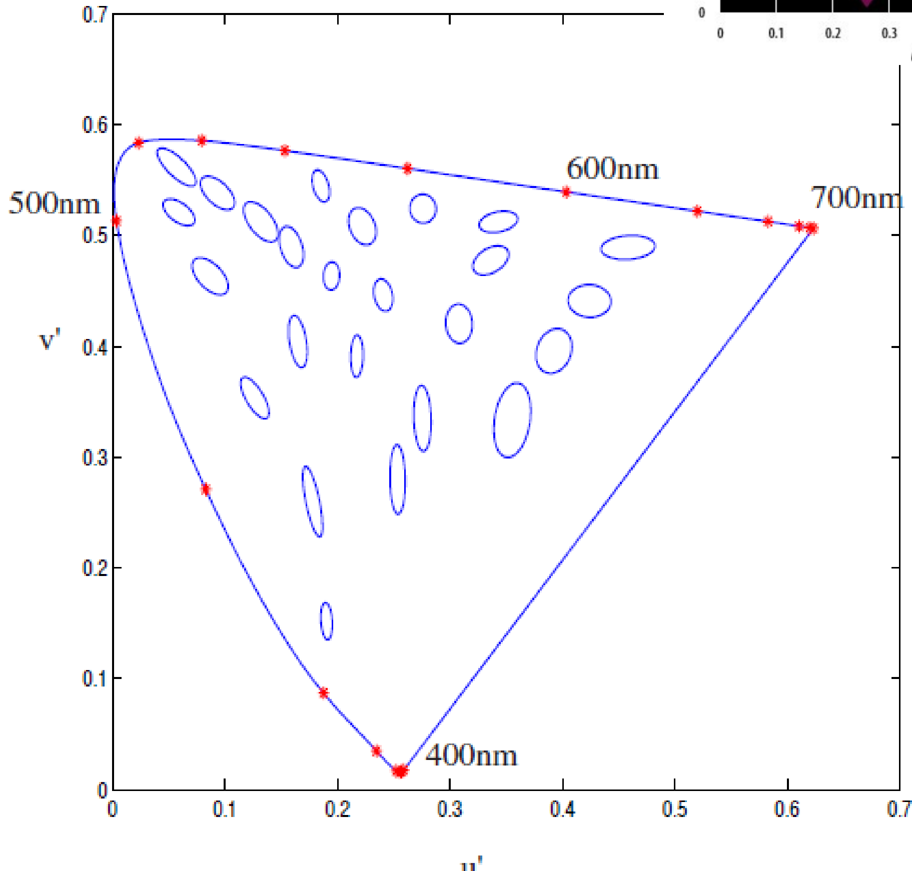

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

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

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

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

Additive-Subtractive synthesis

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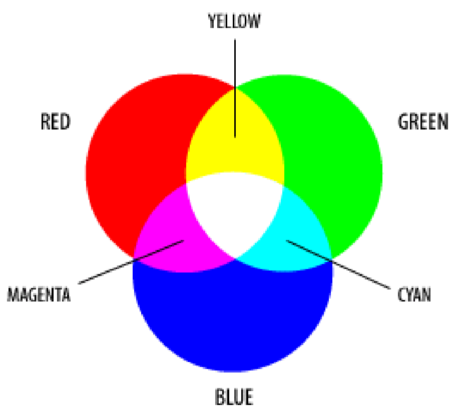
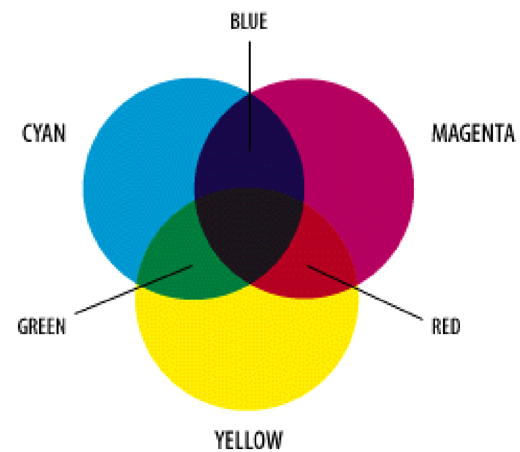
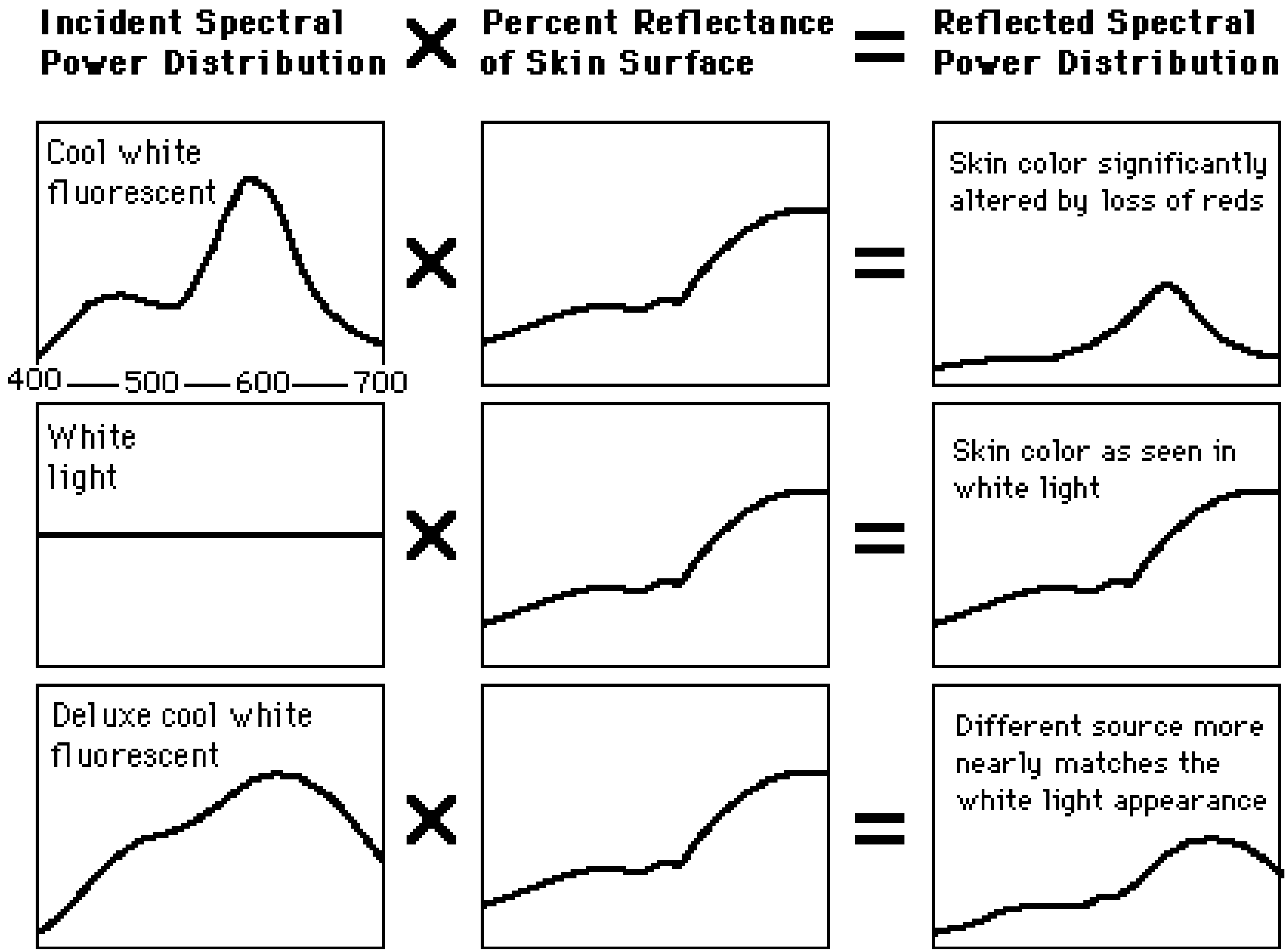




Effects of Illumination



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Perception beyond the retina

Perception

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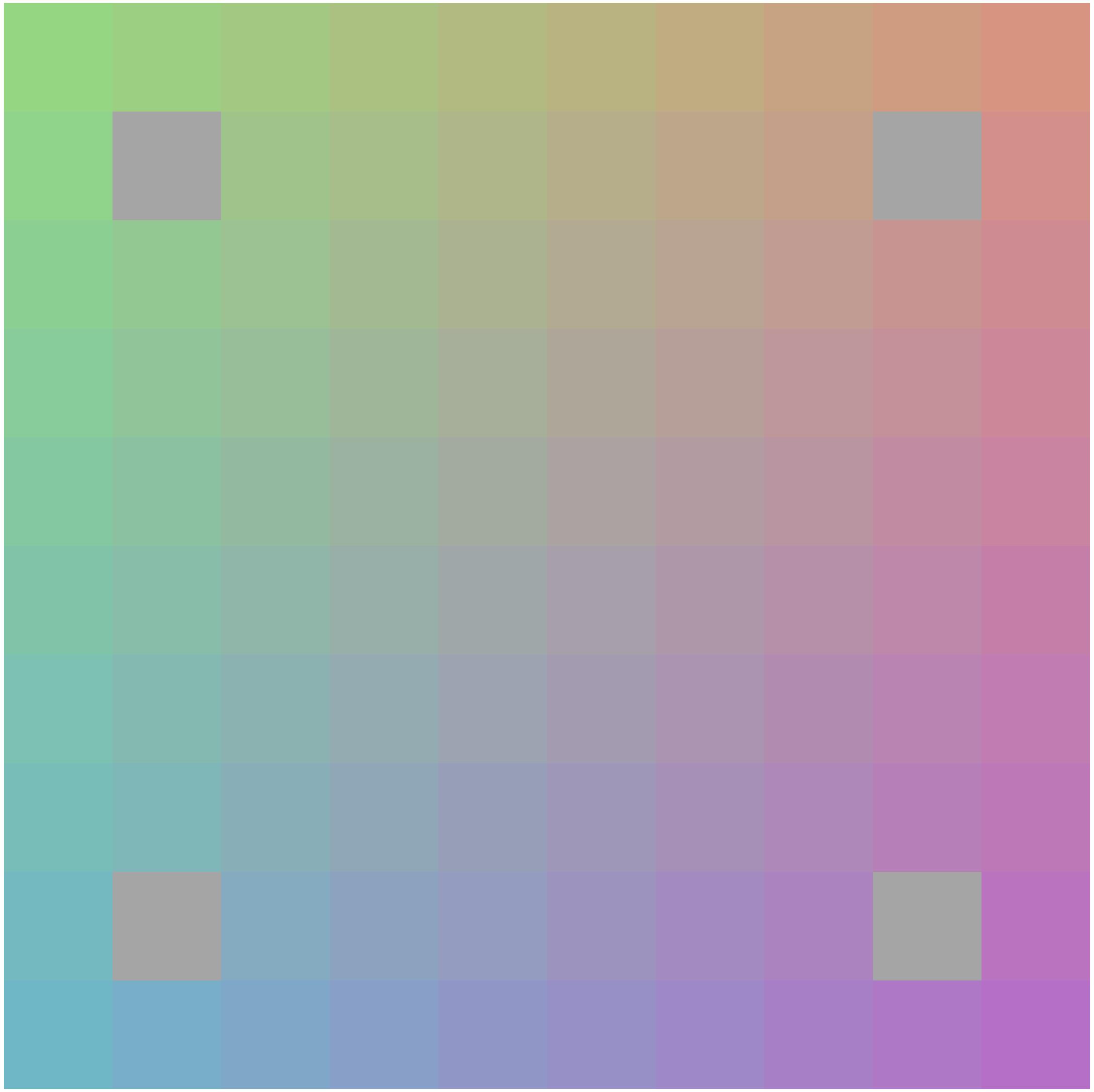
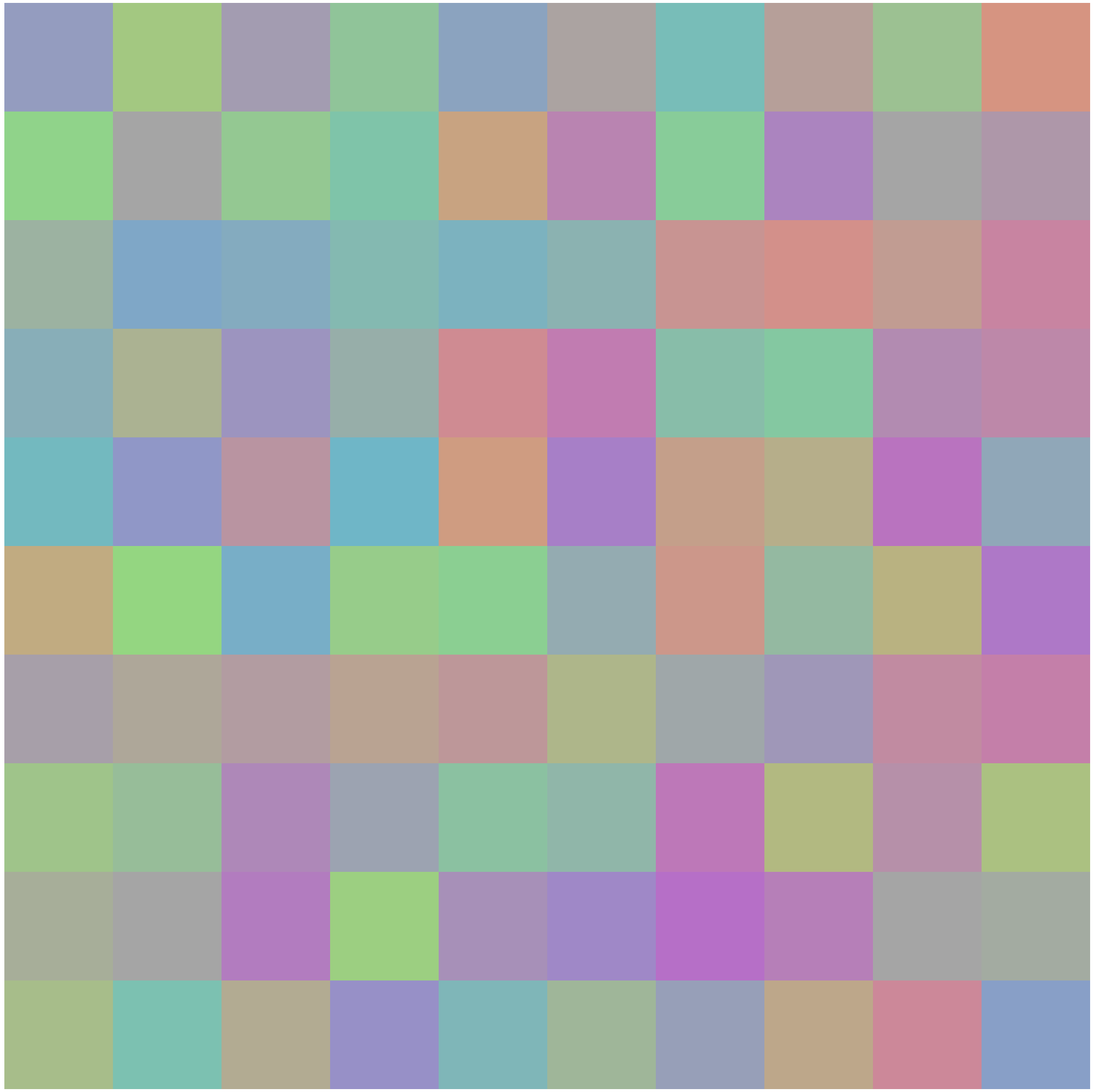
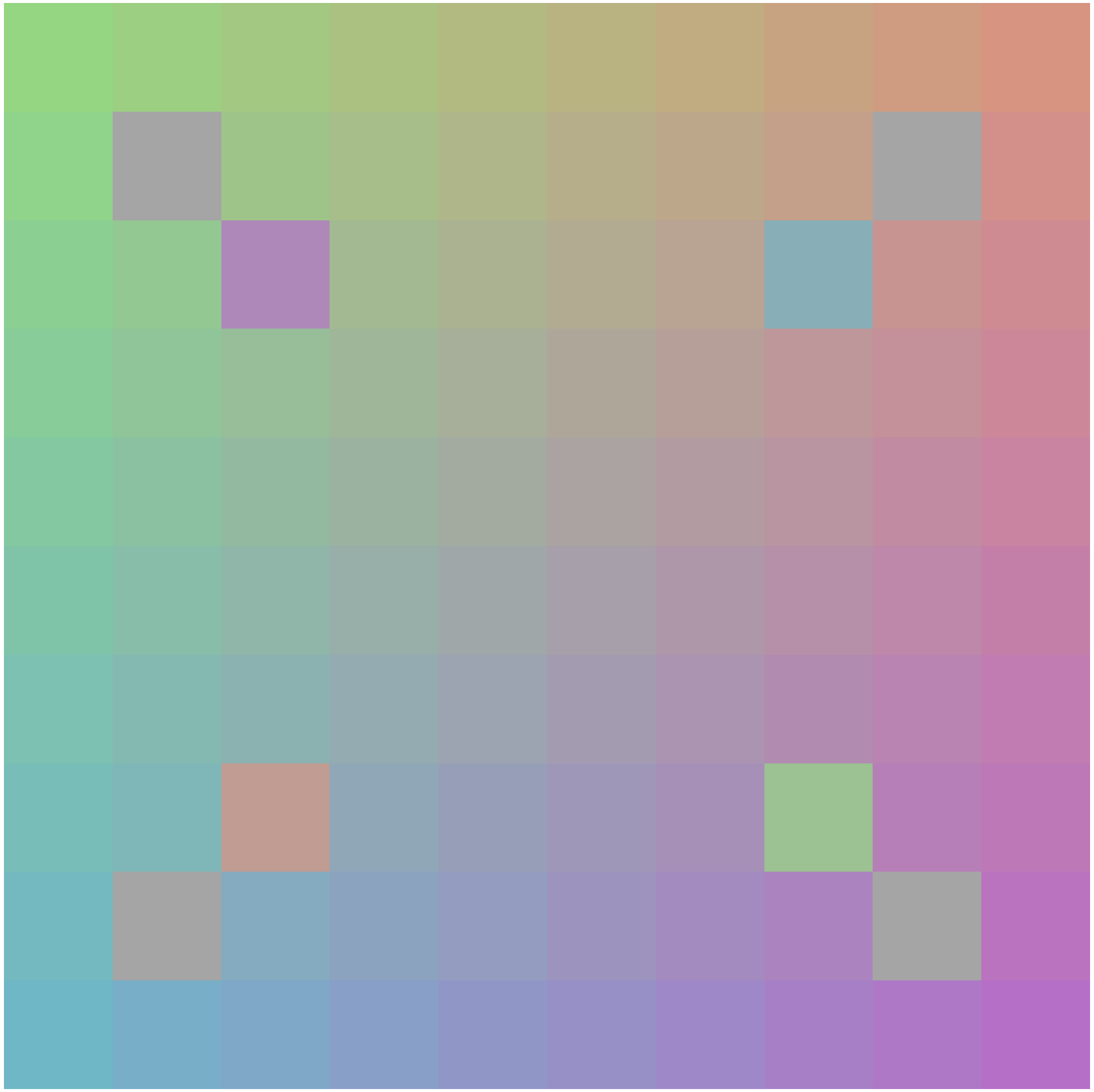


Perception



Perception



White Balance

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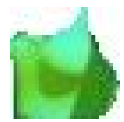
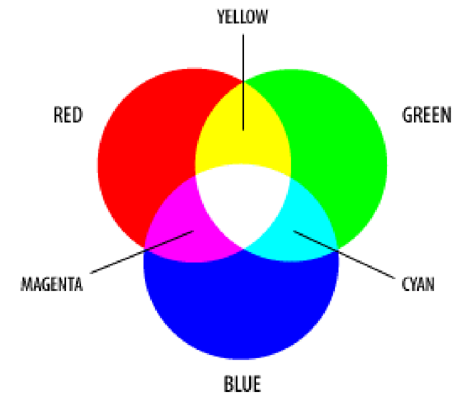
White Balance

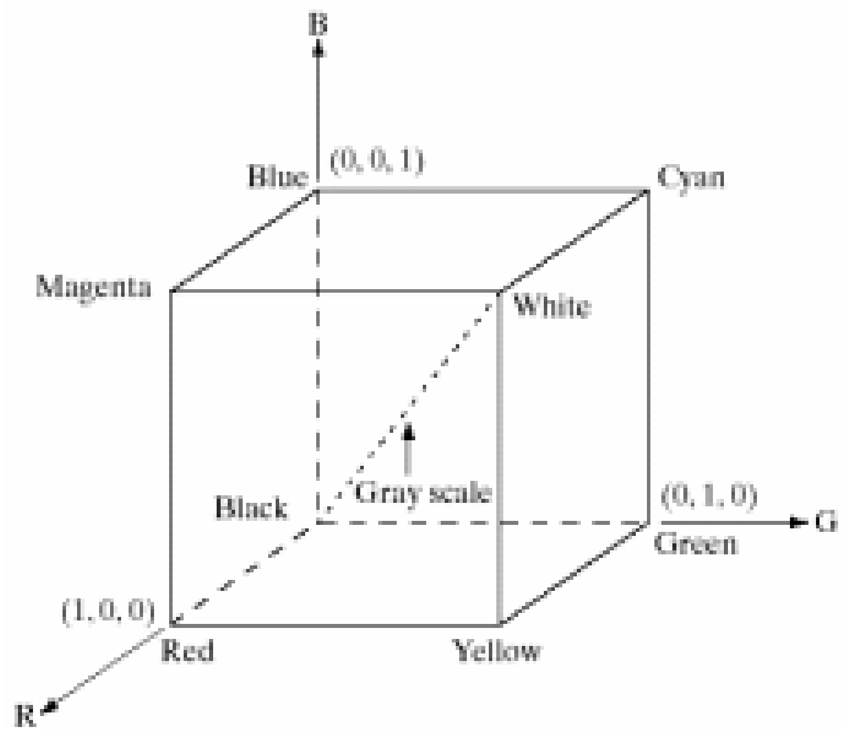


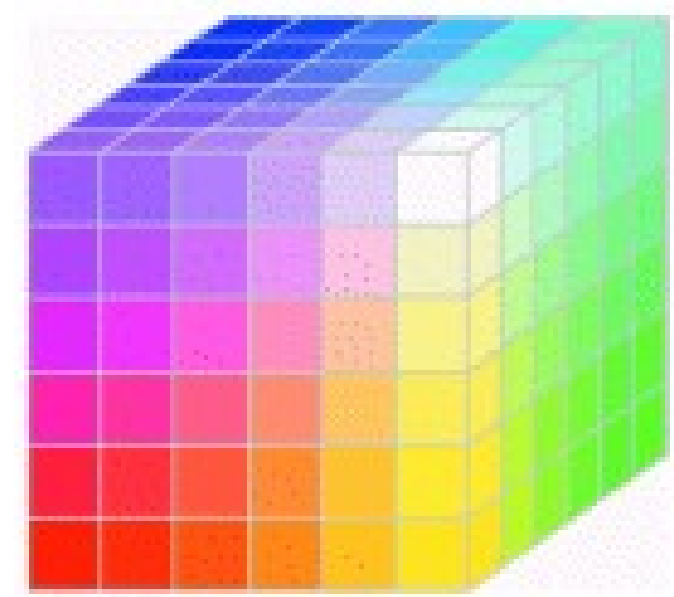
Color Spaces

RGB

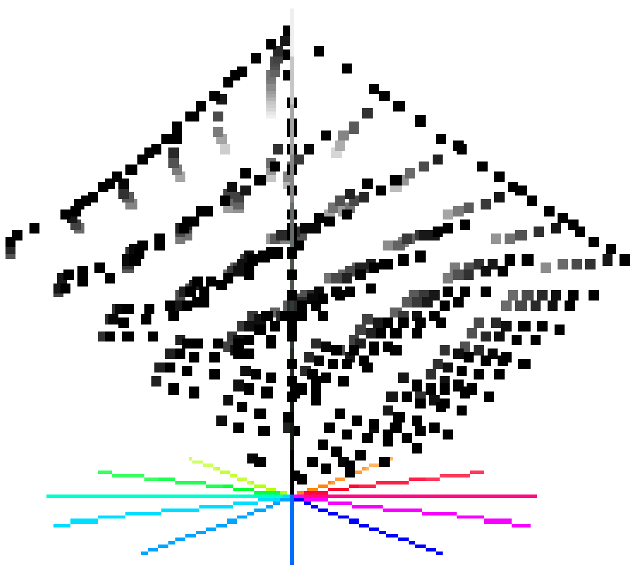
- Color space defined by the intensities of reference red, green, and blue lights
- The color space is contained in a cube

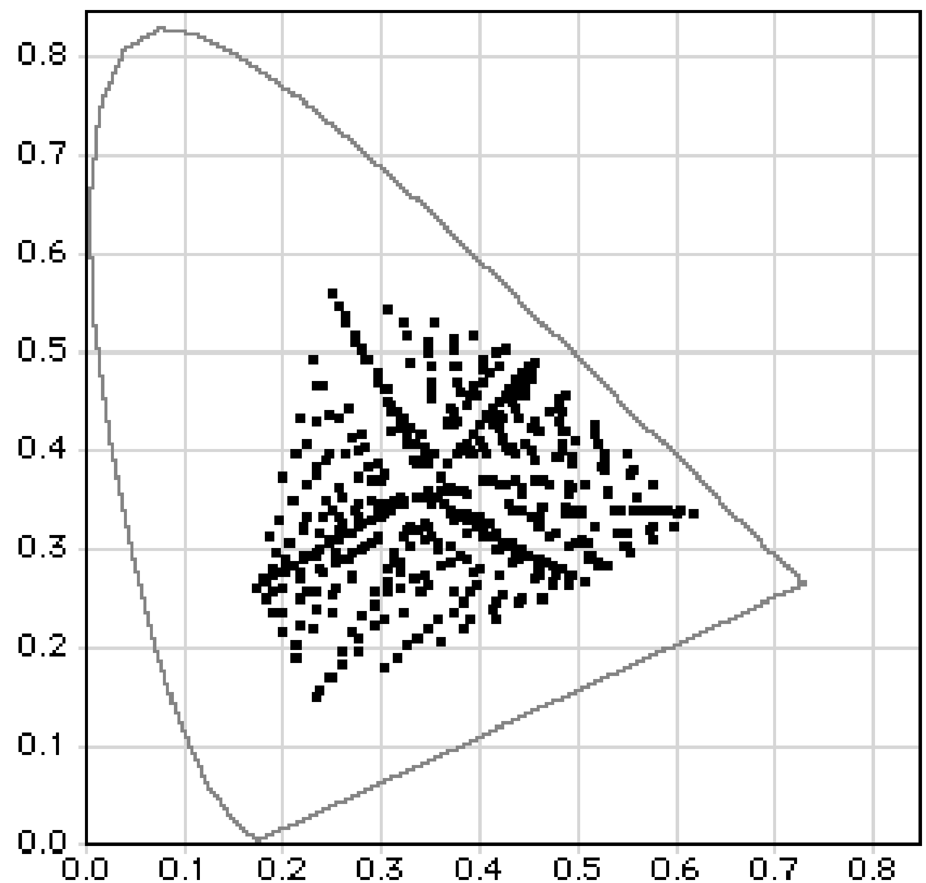






Quantization Effects

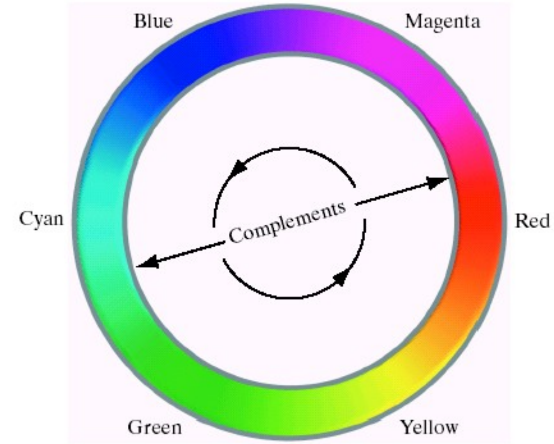




CYM e CYMK

- Complementary basis to RGB: cyan, yellow, and magenta.
- Subtractive synthesis (0 is white)

  C=1-R Y=1-B M=1-G



- It is hard to get a "nice" black mixing the bais, so in print black ink is added

  K=min(1-R,1-G,1-B)
  C=1-R-K
  Y=1-B-K
  M=1-G-K

  (one among C,Y and M will be 0)

HSV

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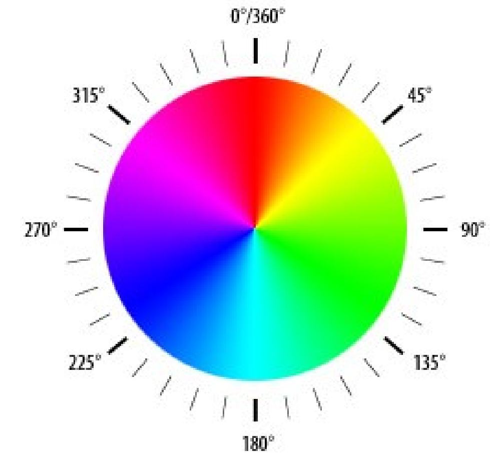
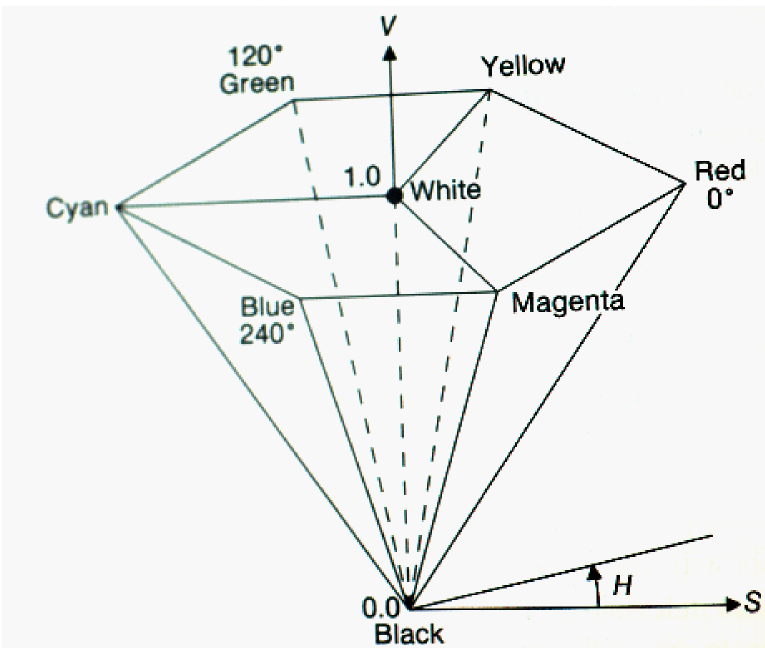
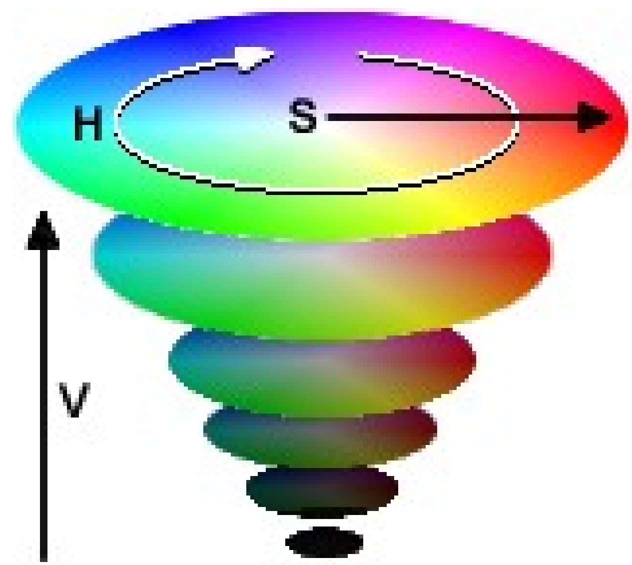
- Natural color space based on hue, saturation, and value (proportion of luminosity wrt the maximum for a give hue and saturation)

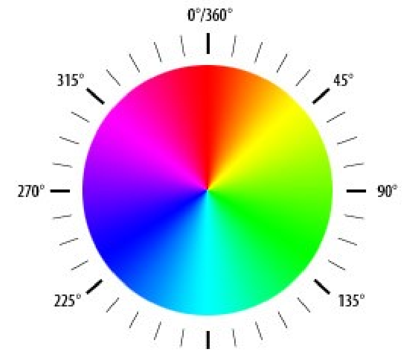


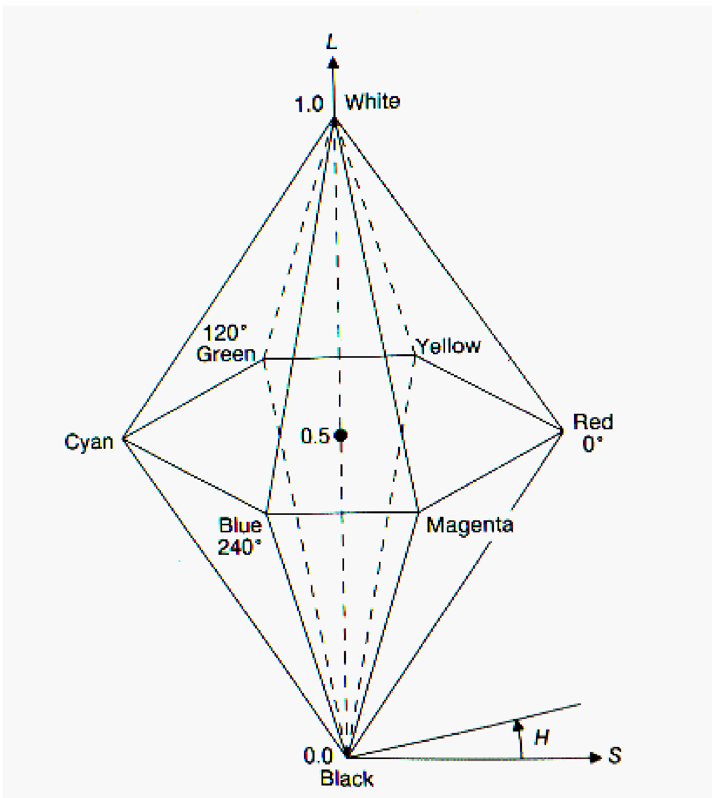


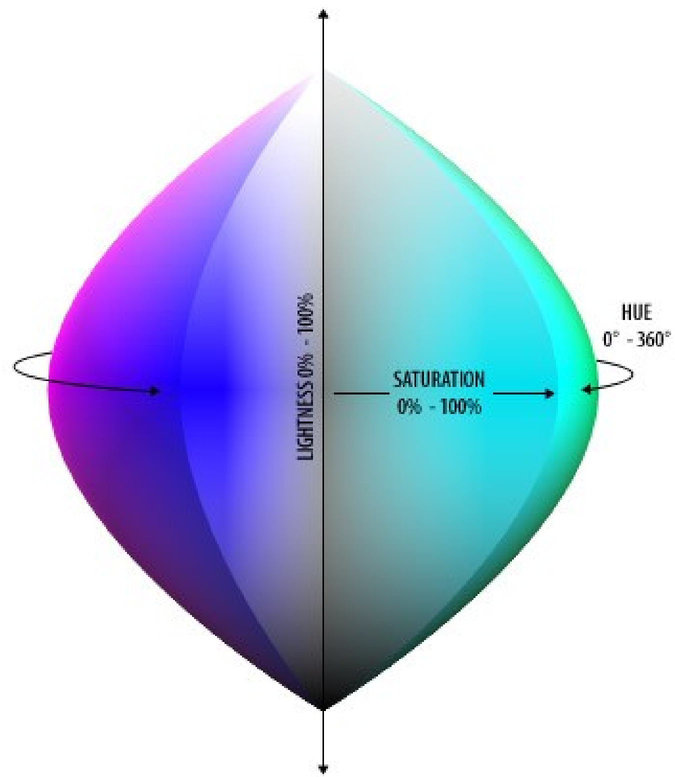


HSL

- Similar to HSV, but now it is the saturation that is relative to the maximum for a given hue and intensity.







YCbCr

- **YCbCr (YUV)** (TV, JPEG, ...)

$$Y = Kr\,R + Kb\,B + (1-Kr-Kb)\,G$$
$$Cb = 0.5(B-Y)/(1-Kb)$$
$$Cr = 0.5(R-Y)/(1-Kr)$$

$Kr = 0.114 \quad Kb = 0.299$