CSE 472
Light and Color

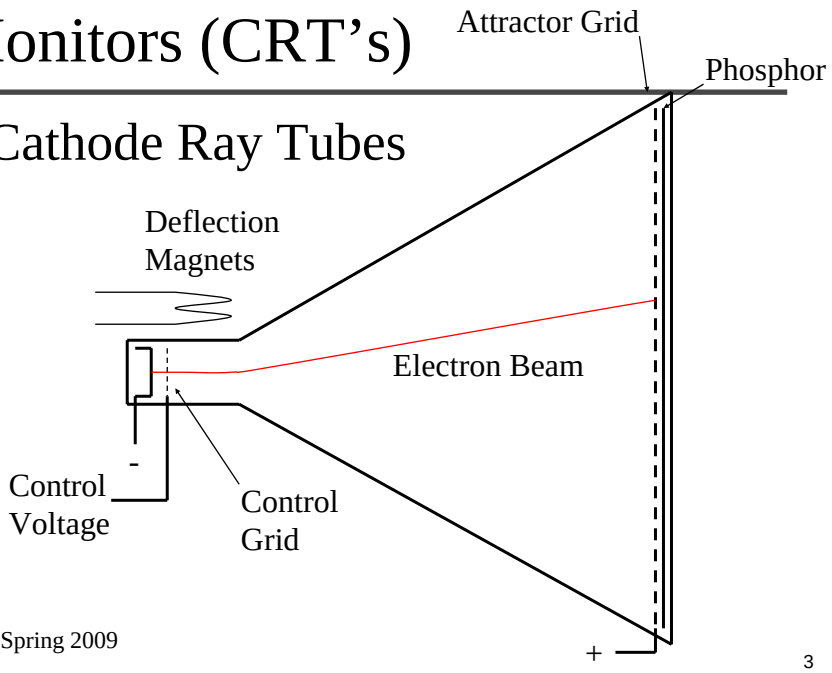
Achromatic Light

Achromatic light

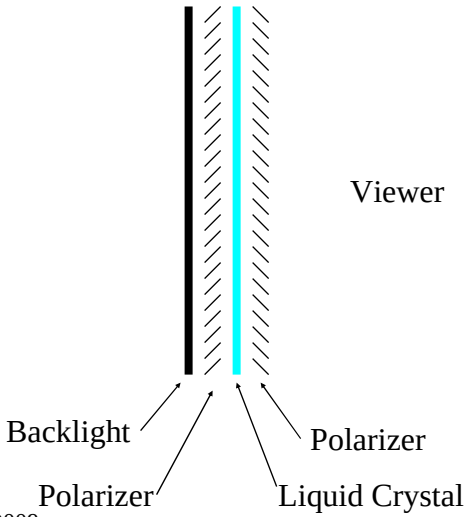
- shades of a single color.
- A B&W TV is an achromatic device.
- Light is described with a single parameter
  - Intensity or luminance
    - (physical properties)
  - Brightness (perceived)

Monitors (CRT's)

Cathode Ray Tubes



Monitors (LCD's)



Gamma

A CRT electron gun does not have a linear relationship between voltage and intensity. The relationship is:

$$I = kN^{\gamma}$$

- k - *constant of total intensity*
- N - number of electrons falling upon the phosphor.
- I - intensity.

The value γ is a parameter of the CRT and varies in the range 2.2-2.5 for most CRT's.

This is called gamma

LCD's have a similar property

Gamma Correction

If gamma is not corrected for, a non-linearity will appear in the output.

Gamma Correction

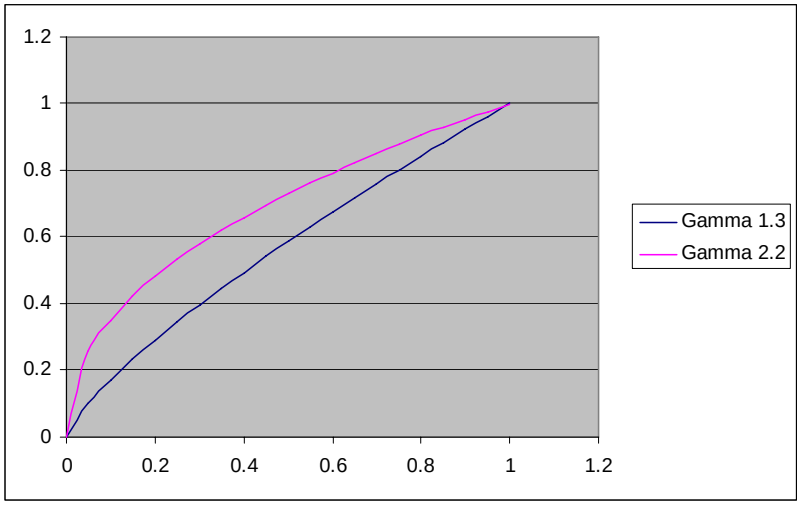
$$V = (I / K)^{1/\gamma}$$

K and γ are functions of the monitor design.

Real systems do this (c in range [0,1]):

$$I = 255 * c^{1/\gamma}$$

Gamma Correction Curves



Gamma Correction Values

Monitors typically range from 2.2-2.5

Correction values are often more like 1.3

Why?

Where should gamma correction be done?

When do we need it?

Intensity Levels

Graphics systems are typically discrete

- Fixed number of intensity steps
- How many do we need?

Dynamic range

- Ratio between largest and smallest value
- If min=light of one candle and max=light of the sun, even 65536 steps will be very perceptible

Common Bit Sizes Used

Computer graphics

- 8 bits = 256 steps
- You can see the steps

Commercial television

- 10 bits = 1024 steps

Motion pictures

- 10-12 bits = 1024-4096 steps
- Generally imperceptible

Chromatic Light

So much for B&W
The real issue is COLOR!!!

Color Perception

- *Hue* - Hue distinguishes colors in the spectrum.
- *Saturation* - How far a color is from gray of the same intensity.
- *Lightness* - The perceived intensity of the light reflected from an object. When the object radiates, we call this *brightness*.

Psychophysics

Psychophysics is concerned with the perception of light.

- This is distinct from *colorimetry* which is concerned with more physical qualities (wavelength, luminance, etc.)

Dominant Wavelength

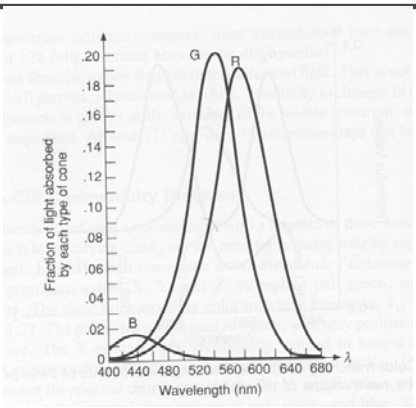
- When we look at any color, we see one wavelength more than any other.
- Note that we see "wavelengths" which really don't exist. The dominant wavelength corresponds to the hue.
- There are an infinite number of wavelengths and we can't put infinite number of pigment colors in a CRT

Tristimulus Theory *of color perception*

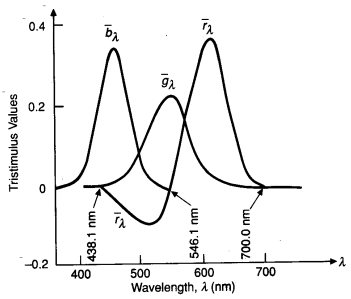
There are three kinds of light sensors (cones) in the eyes.

- Sensitive to wavelengths around red, green, and blue
- Color is represented to our brain as a *triple* indicating the excitation of these three sensors.

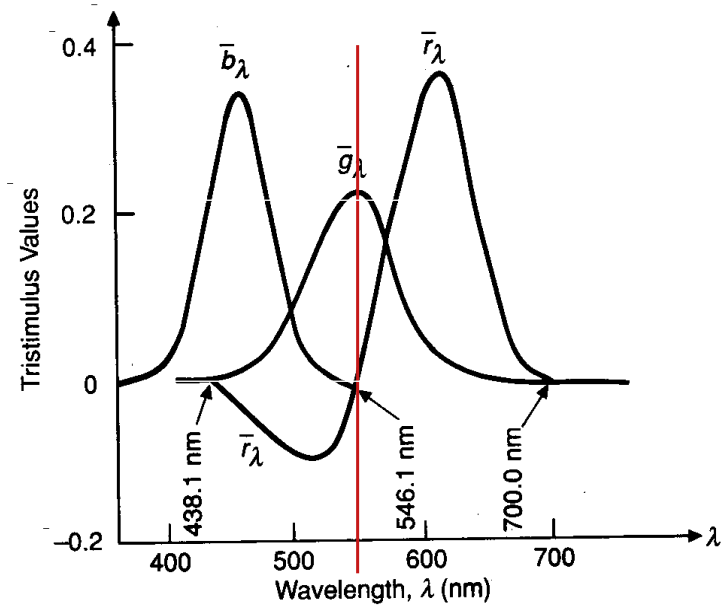
Eye Sensitivity to Colors



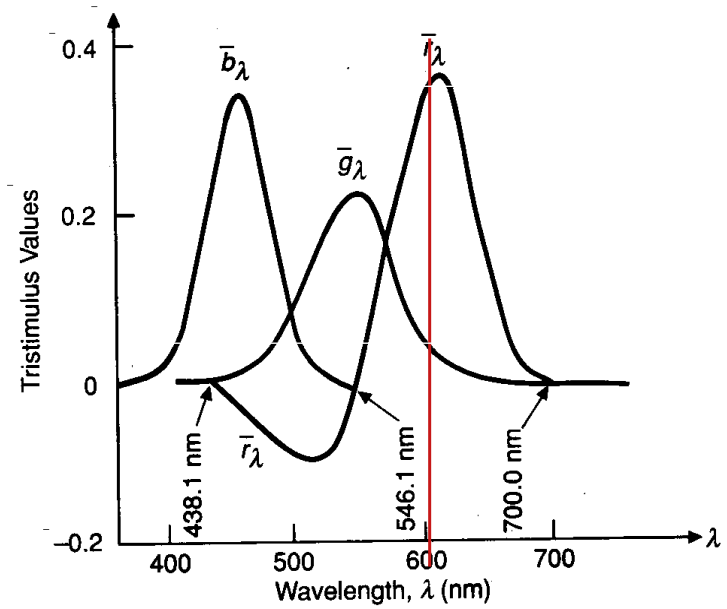
Spectral-response functions for the three types of cones in the human retina



Amounts of three primaries needed to match all wavelengths of the spectrum


0.4
0.2
0
–0.2
Tristimulus Values
$\bar{b}_\lambda$
$\bar{g}_\lambda$
$\bar{r}_\lambda$
$\bar{r}_\lambda$
438.1 nm
546.1 nm
700.0 nm
400
500
600
700
λ
Wavelength, λ (nm)

550 nm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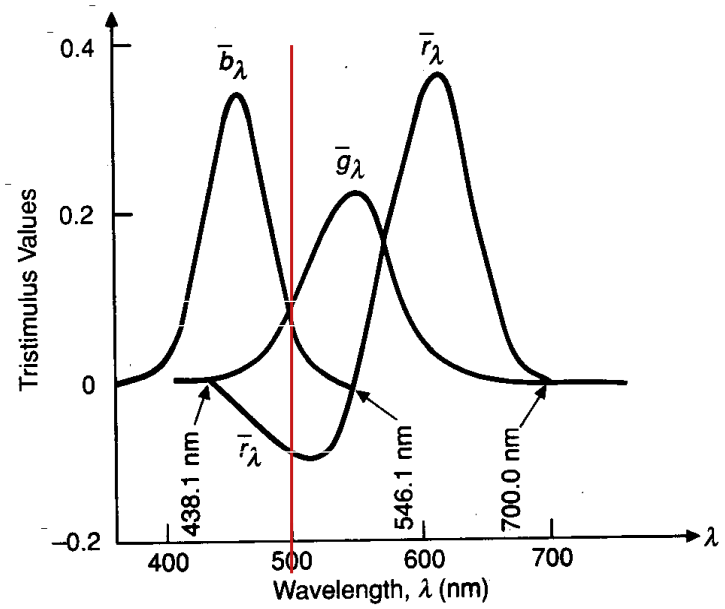
600 nm

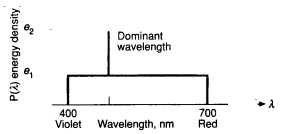


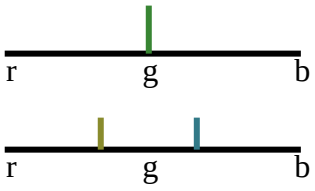
500 nm

Many-to-one mappings

An infinite number of different spectral distributions will appear the same since they all reduce to the same triple. This is a many-to-one mapping.

- We can use three colors in combination, then, to represent many possible colors! We'll call these three colors *primaries*..





Some Perceptual Issues

Most sensitive: green

Least sensitive: blue

- We can see less detail in blue

Color sensitivity decreases as light dims

The eye can recognize hundreds of thousands of colors and about 128 saturated hues.

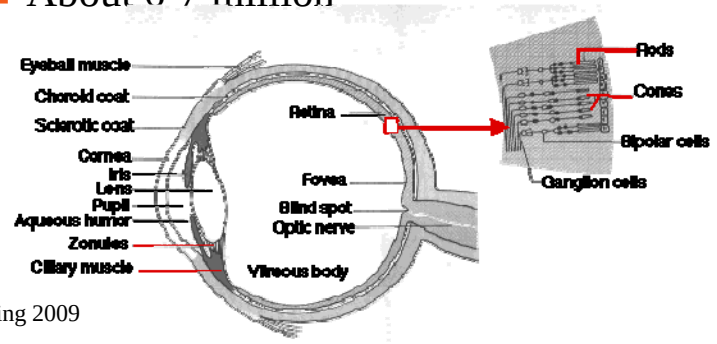
Eye characteristics

Rods – luminance sensors

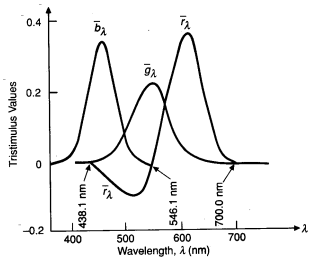
- About 120 million

Cones – color sensors

- About 6-7 million



Amazing Fact



The curves represented by the cone's reception are not simple peaks. They are, instead, quite complex curves.

- They even go negative!

RGB is not capable of reproducing every single color we can see.

CIE Chromaticity Diagram

Every color must be represented, somehow

The Commission Internationale de l'Éclairage (CIE) in 1931 defined three standard primaries which could define every light we can possibly see.

- These primaries are called X, Y, and Z. These primaries are designed to reproduce every visible color with equal luminance. These primaries do not actually exist!

Colors are represented using a triple (X,Y,Z)

- But, we are mostly interested in the color in CIE, not the luminance
- So, we normalize to a single luminance of 1

CIE Chromaticity Diagram

Chromaticity values:

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

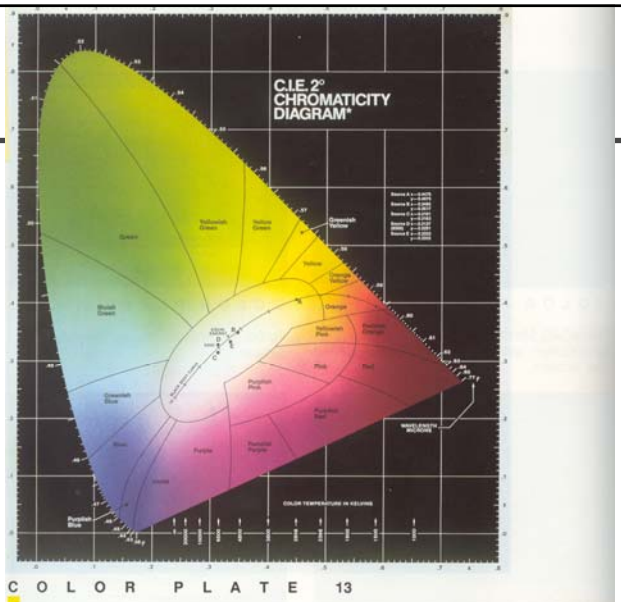
Note: x+y+z=1, we don't need z.

CIE chromaticity values are represented as:

- (x,y)
- All chromaticity values can be plotted in 2D!

CIE colors are represented as:

- (x,y,Y)



C O L O R P L A T E 13

The C. I. E. Chromaticity Diagram is an industry standard for describing the color reproduction capability of a color monitor. Shown here are all perceivable colors in a two-dimensional arrangement. The pure colors are located on the upper boundary of the curve. In nature most colors are mixtures of pure colors and correspond to the ones found within the boundaries of the curve. Color intensity is ignored in this diagram, that is why colors such as brown and gray are not visible. (Courtesy Photo Research)

Mixing Colors in CIE

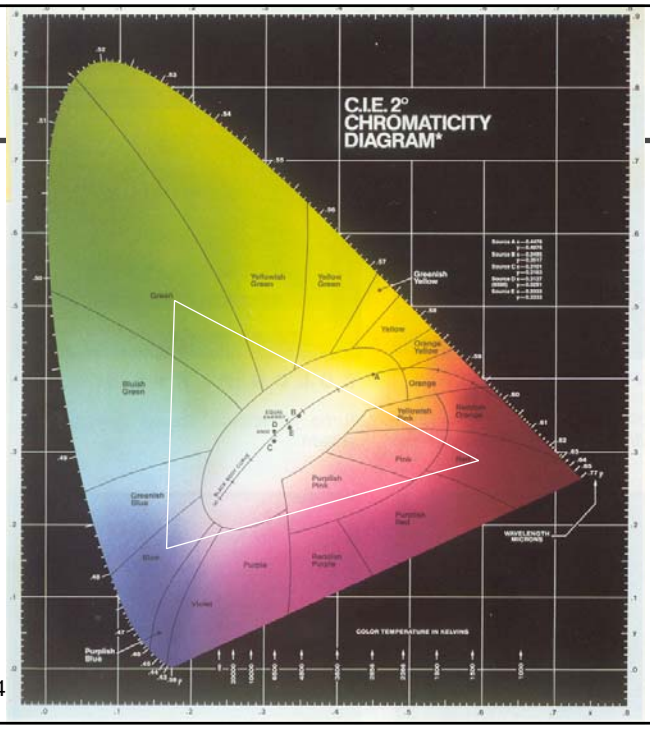
Mixing colors: If two colors are plotted on the CIE chart, the color produced by adding these colors will be on a line between them on the chart.

Given any set of colors, any combination of these colors will be in the convex hull of the points on the CIE diagram

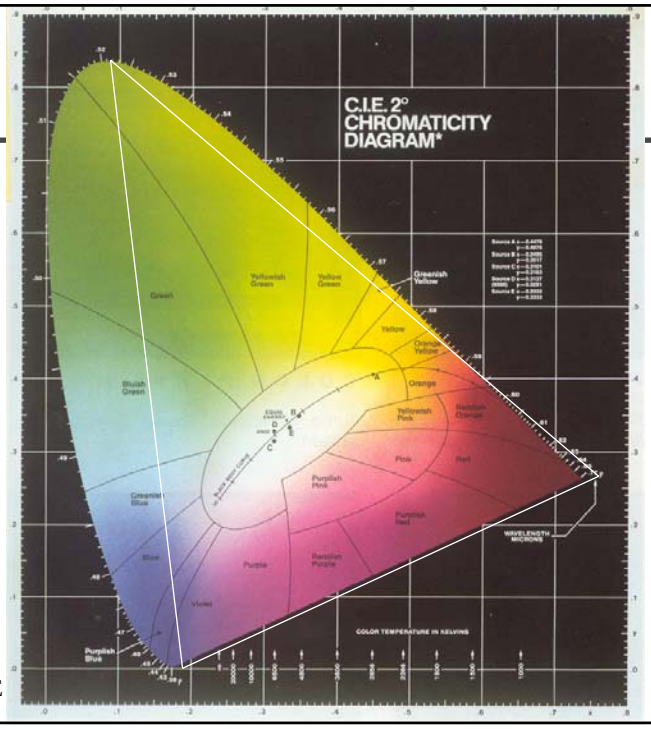
- This is called a *color gamut* or *color range*.

Devices using three primaries (of any kind) to produce colors will have a triangular color gamut on the CIE chart.

- No triangle with primaries within the chart can cover the entire chart. The CIE primaries don't really exist!



RGB
Color Gamut



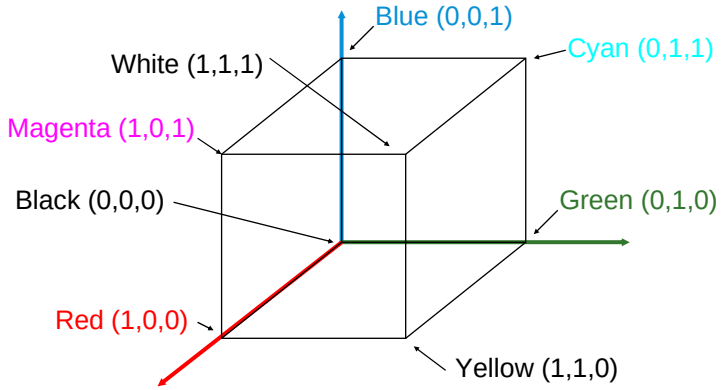
Best RGB we can do

Non-spectral Colors

The CIE chart reproduces colors which are non-spectral, which do not exist in the spectrum, but are only perceived.

RGB

We are pretty happy with a subset based on Red, Green, and Blue primaries



The RGB Color Cube

CMY

RGB assumes we are adding primaries

Reflective surfaces do the opposite, actually

- They have *subtractive primaries*
- Examples: Cyan, Magenta, Yellow
- Cyan (0,1,1) = -Red (1,0,0)
- Magenta (1,0,1) = -Green (0,1,0)
- Yellow (1,1,0) = -Blue (0,0,1)

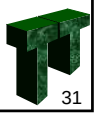
RGB to CMY conversion

Simple enough:

- C = 1 – R
- M = 1 – G
- Y = 1 – B

And the inverse:

- R = 1 – C
- G = 1 – M
- B = 1 - Y



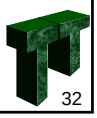
CMYK

Black ink is cheaper than colors

K is “black”

CMY to CMYK

- K=min(C,M,Y)
- C’=C-K
- M’=M-K
- Y’=Y-K



Alternative color systems

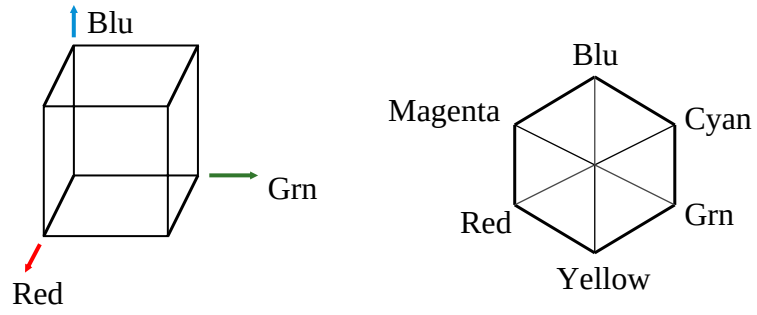
RGB is a poor perceptual system

HLS is better for human color selection

- H = Hue – the color
- S = Saturation – How pure the color is
- L = Luminance – the Brightness

RGB Color cube

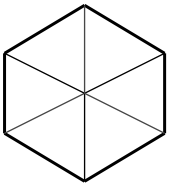
looking down the gray line

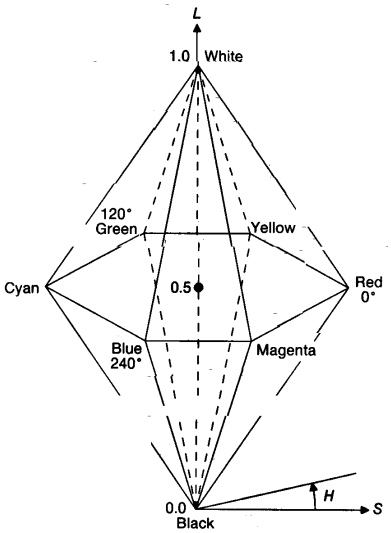


The Dual Hexacone HLS model

Parameters

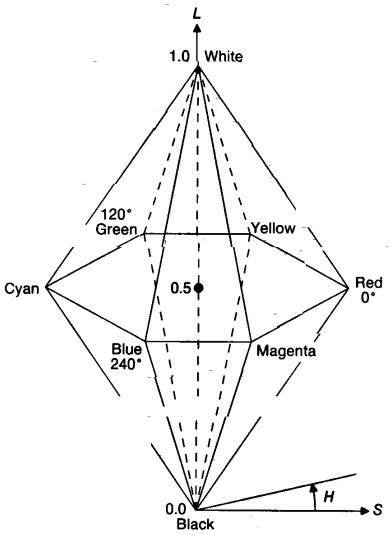
- H – Angle relative to red
- L – Height from black
- S – Percentage of way from center





Some example colors in HLS

Red – (0, 0.5, 1.0)
Blue – (240, 0.5, 1.0)
White – (*, 1.0, *)



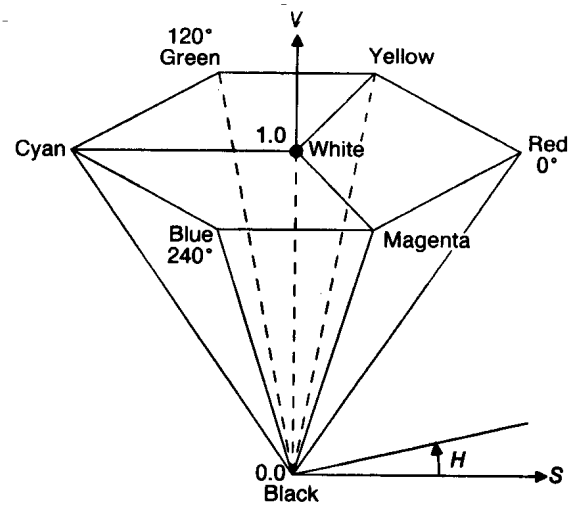
HSV

H - Hue. This is an angle from 0 to 360 degrees and represents the angle of a vector from the center to the color where red is the 0 degree direction. For the center line (the gray line) hue is undefined.

S - Saturation. This is how far from the center line we are, where the hexcone face is normalized to 1.0. For black this value is ignored, but is usually set to 0.

V - Value. This is how far we are vertically from black. It's basically brightness, but nor all equal V values will be equally right. Why?

HSV Hexacone



Internal Colors in Graphics Systems

Generally we use RGB internally

- Why not HSV or HLS?