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Color Models

Color models are frameworks used to describe the properties and behavior of color in various contexts. Visible colors are contained within the electromagnetic spectrum with frequencies ranging from $4.3\times10^{14}\mathrm{Hz}$ to $7.5\times10^{14}\mathrm{Hz}$.

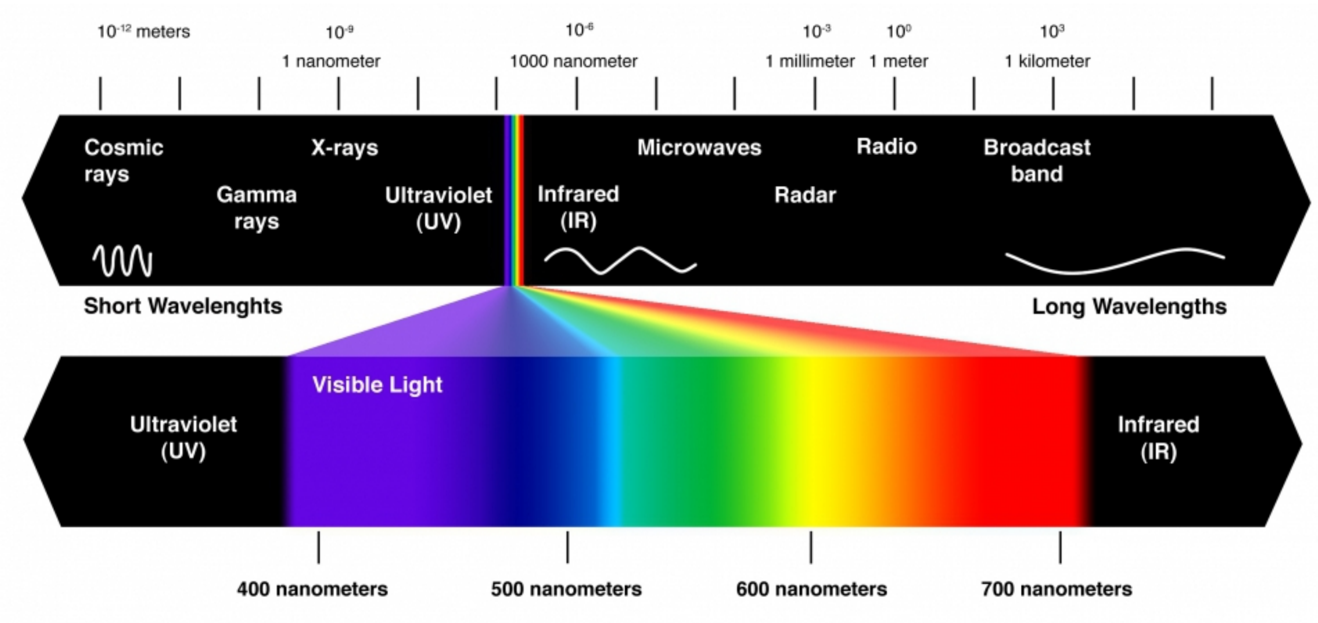


Illustration 1: The visible part of the electromagnetic spectrum

Light wavelength and frequency are inversely proportional and the governing relationship is given by $c=\lambda f$ where c is the speed of light (3.0×10^{8} meters per second), f is frequency, and λ is wavelength. In the visible spectrum, λ varies from 700 nm to 400 nm. White light is emitted by a source when all visible frequencies are emitted with equal power. When white light hits an object, some frequencies are absorbed while others are reflected, creating the perceived color. Below are some general definitions about color:

1. The hue (perceived color) is the dominant frequency of light, when present
2. The brightness is the intensity of the light
3. The saturation of light refers to its purity
4. If two colors combine to produce white light then they are complementary colors

5. Typically, three primary colors are used

6. There exists one set of imaginary primary colors that generate all possible colors

The CIE Standard

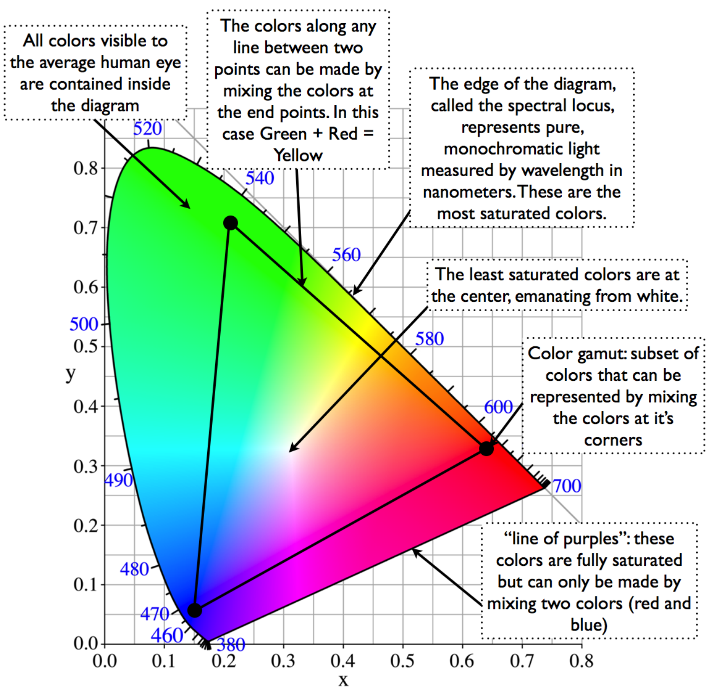
An international standard for primary colors was established by the *Commission Internationale de l'Eclairage*. In this standard three imaginary primary colors A, B, and C are used to define all the visible colors in a 3D color space. If $(\vec{X}, \vec{Y}, \vec{Z})$ represents 3D orthogonal vectors in this space, then any color can be expressed as:

$$c = A\vec{X} + B\vec{Y} + C\vec{Z}$$

Then, a normalization to eliminate the effect of luminance is applied as:

$$x = \frac{A}{A+B+C} \quad y = \frac{B}{A+B+C} \quad z = \frac{C}{A+B+C}$$

Since $x+y+z=1$, only two of these quantities are independent and any color may be represented with x and y only, on the CIE diagram below:



Anatomy of a CIE Chromaticity Diagram

The (x, y) index values addressing the diagram are referred to as chromaticity values and represent a combination of color purity and hue.

The RGB Color Model

The Red-Green-Blue color model uses these colors are primaries. All colors available on video, monitors, and television can be expressed using this model. Hence, colors can be addressed using three values comprised between 0 and 1. In general, each primary color is expressed with 256 values for its intensity (this can vary, depending on the hardware on which the RGB model is constructed). With 256 intensity values per primary color, a total of 256^3 different colors are available. The RGB cube is displayed below:

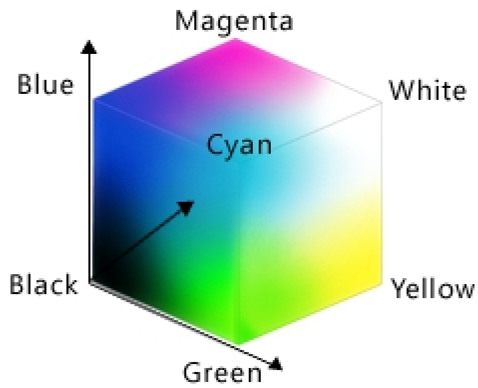


Illustration 2: The RGB cube

The HSV Model

This model, not unlike the RGB one, requires three parameters to specify a color. They are Hue, Saturation, and Value.

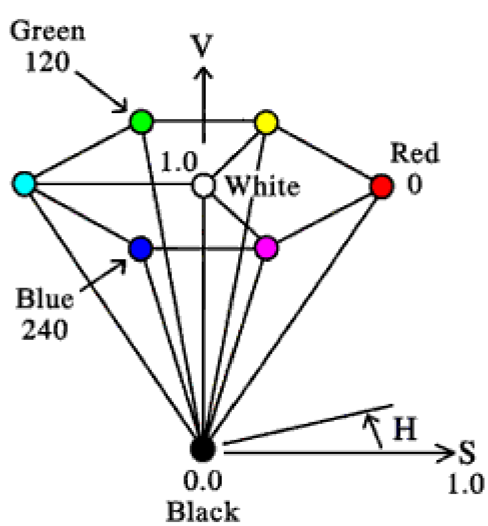


Illustration 3: An illustration of the HSV color model

To obtain the hexagon shape of the HSV model one needs to view the RGB cube along the diagonal monochromatic line from $(0,0,0)$ to $(1,1,1)$ from black to white.

The hue is represented as an angle H from 0° to 360°. The following colors are obtained for listed angular values below:

Red	0°
Yellow	60°
Green	120°
Cyan	180°
Blue	240°
Magenta	300°

Saturation (purity) is represented by a number $S \in [0,1]$ such that when $S=1$ the maximum color purity is obtained (at the edge of the hex-cone). When $S=0$, a gray value is obtained (the center of the hex-cone along its vertical axis).

Intensity is represented by a number $V \in [0,1]$ such that when $V=1$ maximum color intensity is obtained. When $V=0$ black is obtained, no matter what values the other parameters are given.

This model allows us to think of color as an artist would. Within the confines of this model, one can mix colors with shades of gray to form shades, tints, and tones. The artistic approach to light is based on pigments (such as in paint, see next section), as opposed to physics, where light is considered as an electromagnetic wave. In the HSV model:

1. given a pure color, add a bit of black to obtain different shades
2. or add a bit of white to obtain different tints
3. add both black and white to a pure color to form tones

Many people find these color concepts more intuitive than describing color as a some proportion of primary colors. Interestingly, humans can distinguish around 128 hues, 130 tints, and anywhere between 16 to 23 shades.

Additive and Subtractive Modes

When one mixes the primary colors of light, a white light is obtained and this is known as an additive light mixing mode. A subtractive light model occurs when one mixes color pigments (such as paint). In the additive mode, the three primary colors are the usual red, green, and blue (RGB), and the secondary colors are the result of adding two primaries together, such as below:

Red and Blue	Magenta
Green and Blue	Cyan

Red and Green	Yellow

In the case of pigment color, a primary pigment color is defined as one that subtracts or absorbs a primary light color and reflects or transmits the other two primary light colors. For instance, a magenta pigment reflects both red and blue, and absorbs green. This is the fundamental reason why pigment colors are subtractive, as opposed to light color.

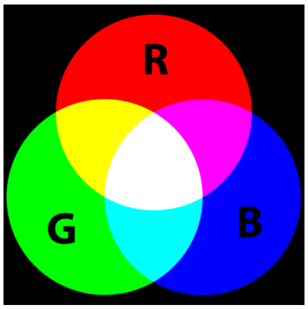


Illustration 5: Primary light colors and how the produce secondary colors

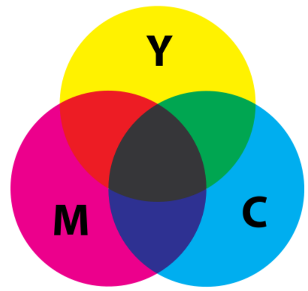


Illustration 4: Primary pigment colors and how they produce secondary colors