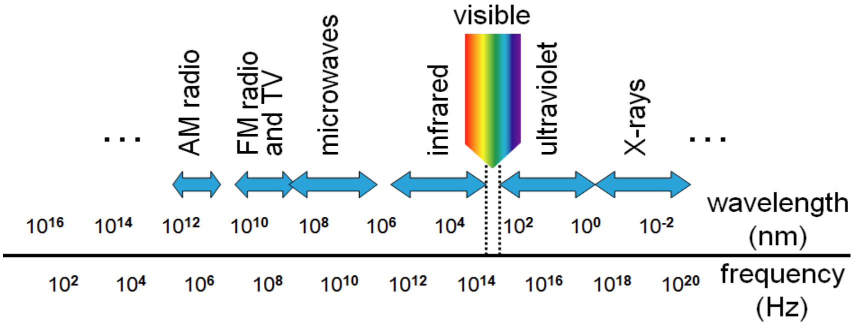
Colors and Color Models

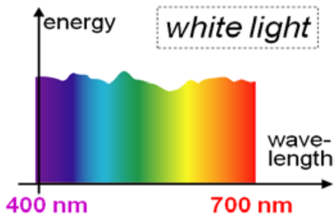
Color is one of the essential ingredients of computer graphics. To understand and handle color correctly is a basic tool for people dealing with computer graphics. However, the often used RGB-model cannot depict all colors and is also only very approximative. Many color calculations are mostly done approximatively only (which is often good enough) and the exact science of colors is very complex.

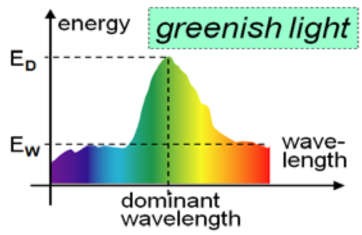
What is Color?



Our eyes can recognize electromagnetic rays in the frequency range between circa $3.8 \cdot 10^{14}$ Hz (~780 nm) and $7.8 \cdot 10^{14}$ Hz (~380 nm). Thus, we perceive this radiation as *light*. This visible range varies from person to person and many animals have different borders. Other electromagnetic frequency ranges are used for other purposes (see graph). Within the visible range our eyes can even distinguish which frequency the radiation has, which we perceive as different *colors*. Light with a long wavelength (therefore low frequency) appears red to us, whereas light with a short wavelength (therefore high frequency) appears blue or violet to us; the prismatic colors are in between.

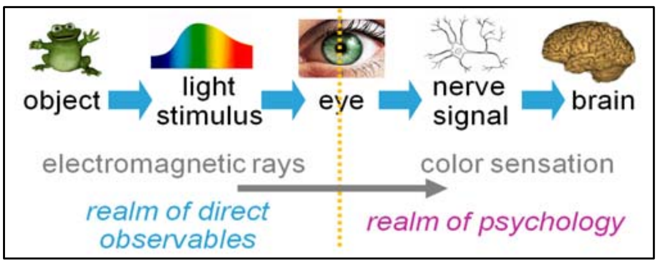
[as a reminder: $c = \lambda \cdot f$, where c…speed of light, λ …wavelength, f…frequency]





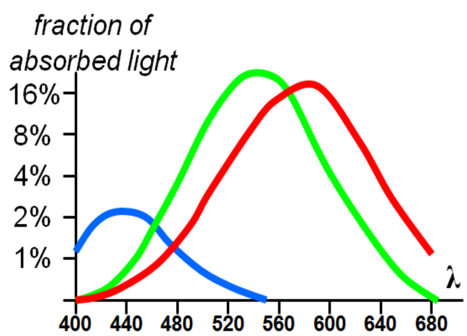
In nature pure spectral light consisting of a single wavelength is very rare, mostly we see a mix of many colors (*spectrum*). Frequencies with more energy determine which color we perceive – we talk about *dominant wavelength*. If all the spectrum's wavelengths have about the same intensity, we see colorless light, i.e. white or gray. Let E_D denote the energy of the dominant wavelength and E_W be the average energy of the other wavelengths, then $(E_D - E_W) / E_D$ is called a color's *purity*. The *brightness* results from the integral under the spectral curve.

Colorimetry



Colorimetry is the science of the technical description of color. However, since color is a visual sensation rather than a physically directly measurable quantity, only the visual stimulus can be defined numerically such that

- stimuli with the same specification look the same under the same conditions,
- stimuli that look the same have the same specification,
- the numbers used for specification are continuous functions of the physical parameters.



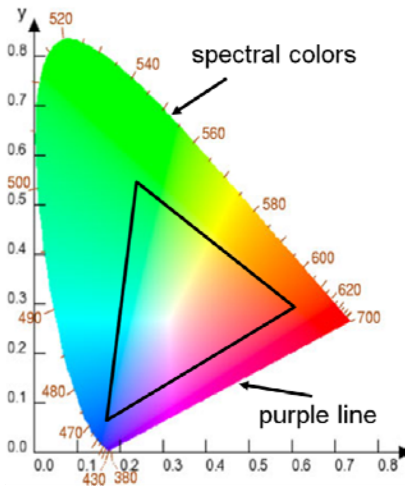
The eye's retina is the light-sensitive layer located in the inner rear part of the eyeball; it consists of rods and cones. Rods cannot distinguish between colors, in return they are very sensitive to light. Retinal cones are less sensitive but they come in three kinds with each one being sensitive to another wavelength-range.

Therefore our color perception is made up of the combination of three separate "achromatic" signals. This is the reason why the human perception of color is called *tristimulus*. The sensitivity curves of the three cone-types have their maxima at red, green and blue, respectively, so it is appropriate to talk about red, green and blue cones. Only our brain combines the 3 values to produce a color. So for the eye every "perceivable" color is made up of a mix of only 3 primary colors. If we place small red, green and blue light dots tightly next to each other, we see them as one dot, having the *additively* mixed color.

Color Blindness

Some people lack one (or even two) kinds of cones or their cones' sensitivity curves are not sufficiently distinct from each other. Then they do not have the ability to distinguish between as many colors as most people. This is called color deficiency or color blindness. The most common deficiency is red-green color blindness, which is caused by red and green cones reacting to (almost) the same wavelengths. Approximately 8% of all men have at least slight difficulties distinguishing colors!

Color Models

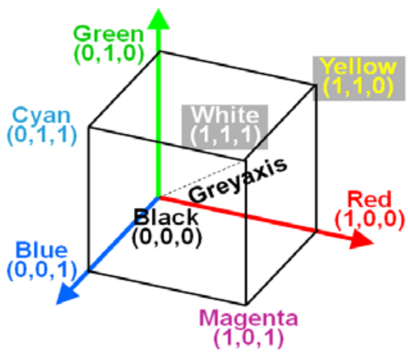


CIE 1931 XYZ Color Model

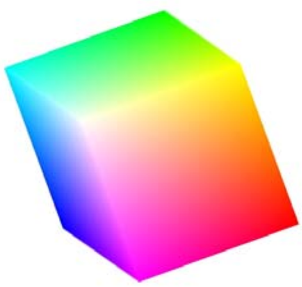
The XYZ color model is directly derived from the tristimulus theory. With color comparison experiments it can be determined which combinations of the three primary colors produce which color. Since some colors cannot be created by such a combination, we sometimes also have to use negative components which is done by adding a certain amount of light to the color to be generated. We end up with virtual base colors X, Y and Z, which do not exist in reality. By normalizing the brightness of the generated colors to 1 and projecting the result to the XY-plane, we get the CIE-graph, which was standardized by the international ***C***ommission ***I***nternationale d'***E***clairage in 1931. Colors are described by coordinates (x,y), and from x+y+z=1 follows z. Additionally, we can set the brightness, which is called Y. Finally, we get a complete color definition through (x,y,Y).

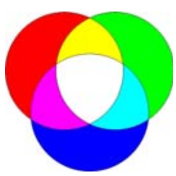
In the CIE 1931 graph all pure colors of the spectrum lie on the U-shaped outer edge. The so-called purple line (or crimson line) which contains the complementary colors to the pure spectral colors runs between the endpoints of the edge mentioned above. However, these complementary colors do not consist of a single wavelength. Each point in the graph describes a different color. Every linear combination of any two colors lies on the straight line between those two colors. White is found approximately in the middle. Complementary colors lie on opposite sides of straight lines that pass through the white point. The colors which an RGB monitor can display, i.e. the linear combinations of red, green and blue that the monitor can generate, are all inside the triangle given by the 3 points (see figure). Since there are no three colors containing the whole graph, no monitor can display all colors.

RGB Color Model



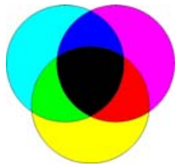
Beside color spaces (actually color space descriptions) like the CIE model, which can describe all colors, there are also color spaces for describing the colors of a device. The RGB model is usually used for monitors: a pixel is made up of three small colored dots and their sum of light (*additive color mixture*!) creates a color sensation. Depending on the employed technology and the specific material, each monitor has slightly different primary colors, from which different subsets of all colors can be generated. The space of all reproducible colors of a device is called its *gamut*.

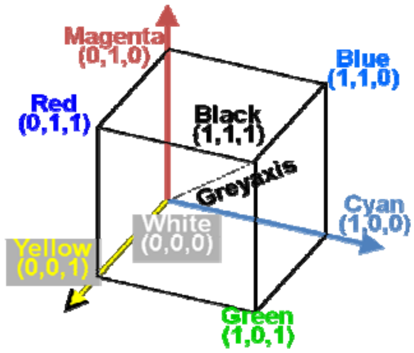




CMY Color Model

Mixing colored ink on a sheet of paper is subject to completely different rules than the additive color mixture of light. The more ink we use, the darker the result, because we actually apply a filter to the passively reflecting paper, thus we talk about *subtractive color mixture*. The according CMY model is the complement of RGB space. Thus, for simple applications we have





[C,M,Y] = [1,1,1] – [R,G,B]

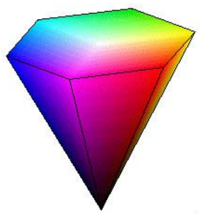
In many cases we also come across the *CMYK model*, where K stands for key, which corresponds to black. In printing, all shades of gray are printed separately with black color instead of generating them more costly and in lower quality by using equal amounts of cyan, magenta and yellow.

HSV and HLS Color Models

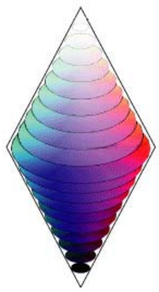
Beside the color spaces useful for devices, there are other descriptions of colors, which are better suited for humans. Describing a target color with the components R, G, B or C, M, Y is very difficult and takes a lot of practice. Our usual color descriptions are made up of qualities like words for a color, a brightness and a color-purity. Therefore, user interfaces use color systems which work in those 3 dimensions to define colors. Some examples for such color systems are HLS, HSV, Munsell, RAL, NCS, Coloroid.

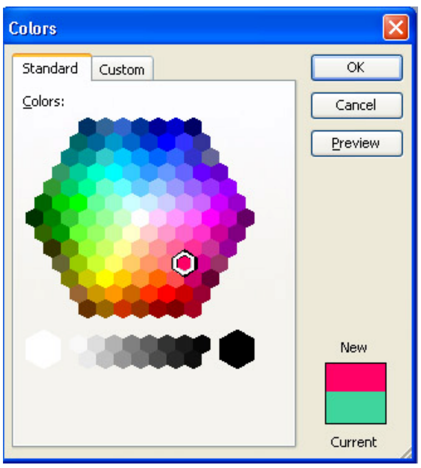
HSV stands for ***Hue***, ***Saturation*** and ***Value***. Hue means *tone* and depicts colors along the color wheel, which runs from red to orange, yellow, green, cyan, blue, violet and magenta until it eventually reaches red again. When we look at the RGB-cube exactly along its gray-axis, we see this color circle as the resulting hexagon's border. *Saturation* is a measure for a color's purity, i.e. how much it differs from gray. Value denotes something like a color's *brightness*.

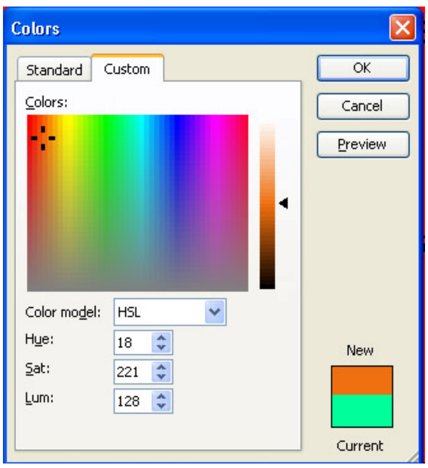
The darker a color is, the less shades of saturation exist. Due to that we can arrange all colors in a pyramid, with black at its tip and the color hexagon as its base plane. Color is specified in degrees along the base edge (red=0°, green=120°, blue=240°), saturation is given by the percentage of the distance to the pyramid axis and brightness is given by the percentage of the distance between the base plane and the tip. Therefore, a medium bright, fully saturated yellow has the HSV value (60, 1, 0.5).



The HLS system (also HSL) works pretty similarly. HLS stands for ***Hue***, ***Lightness*** or ***Luminance*** and ***Saturation***. This time the corresponding model is a double-cone though, where the upper tip is white and the lower tip is black. This is due to the assumption that white is much brighter than any pure color.







When we take a look at typical color-dialogues of a desktop application now, we will recognize the utilization of these user-oriented color-systems.

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