Introduction to color theory

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Abstract

A short introduction to the physics, perception, specification, and use of color. This document is intended primarily for technical writers and user interface designers.

This publication is available in Web form[1] and also as a PDF document[2]. Please forward any comments to **`tcc-doc@nmt.edu`**.

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1. Why is color important?

A working understanding of the physics of color, and how humans perceive color, is most useful in technical writing and in engineering design.

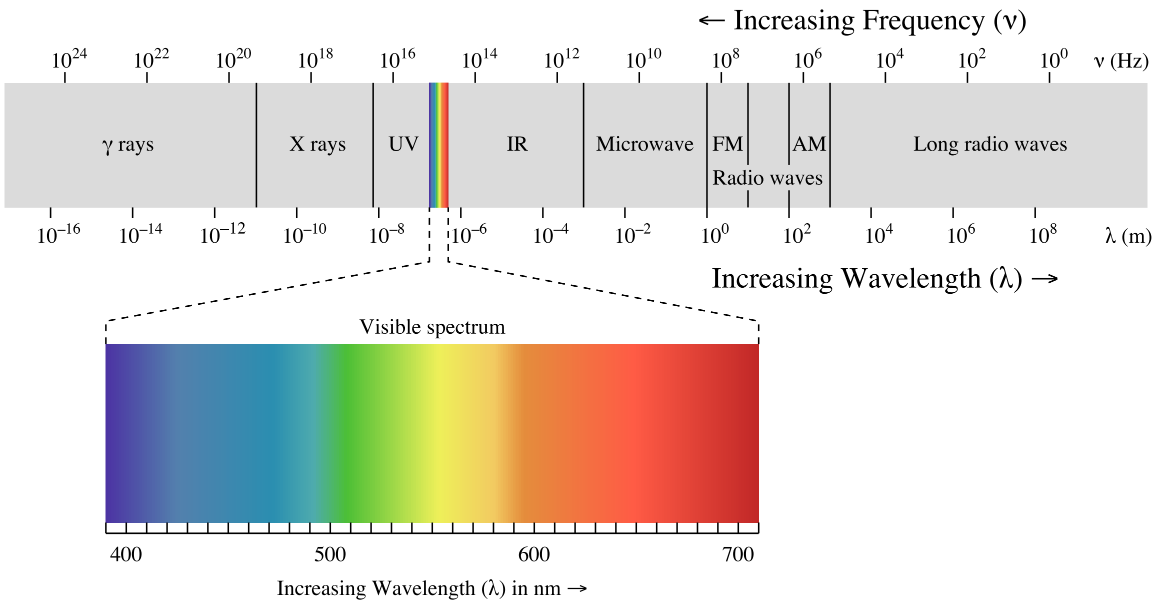
If you use color to convey information, in a user interface or in documentation, there are many things to keep in mind.

- Section 2, "The physics of color" (p. 2) discusses color from a scientific viewpoint.
- Section 3, "Color perception" (p. 2) discusses how we perceive color. Not everyone sees color the same way; a substantial fraction of humans have some form of color-blindness.
- There are several different useful ways to describe colors; see Section 4, "Modeling color space" (p. 3).
- Consider the cultural differences in the interpretation of color. In the USA, red often means *danger*, but in China, red is the color of good fortune.
- The legibility of text can be affected strongly by the contrast between foreground and background colors. Dark letters on a black background are hard to read. Some combinations of bright colors, such as bright green text on a pink background, are difficult to ignore, even annoying; this may be a good practice (as when you are trying to attract attention) or a bad practice (as when you would prefer that your readers or users not hate you).

[1] http://www.nmt.edu/tcc/help/pubs/colortheory/
[2] http://www.nmt.edu/tcc/help/pubs/colortheory/colortheory.pdf

- If you want your colors to be rendered in the same way on paper as on a display device, it is important to understand the limitations of printing and display devices. We touch on this problem in Section 4.5, "The CMYK model" (p. 6).

2. The physics of color



Color is a property of light, and light is just a small slice of the entire electromagnetic spectrum, as shown above. In this figure, wavelength increases toward the right-hand side. The visible spectrum is roughly 400–700 nanometers, with the red end of the spectrum at the longer wavelengths.

The colors shown here are referred to as *pure* colors.

3. Color perception

Most humans can see a range of wavelengths from about 400–700nm. The peak sensitivity in the human eye is around 560 nanometers, roughly the yellow color that is the primary color of sunlight.

Humans perceive light through two different structures in the retina of the eye.

- *Rods* perceive brightness, not color. They are widely distributed in the eye, and quite sensitive.
- *Cones* perceive color. Their density is highest near the *fovea* (the center of where you are looking), and they are less sensitive, functioning well only with relatively high levels of light.

Most humans have three different types of cones, each with a peak sensitivity centered around a specific frequency:

Type of cone	Peak sensitivity
blue	440nm
green	545nm
blue	580nm

The blue cones are somewhat less sensitive.

When considering human color perception, one must always be aware that about 5% of humans have some form of color-blindness, caused by hereditary deficiencies in the eye. Refer to the Wikipedia article on color-blindness[3] for more details.

If you are designing a document or human interface, you can see how your color scheme looks to someone with one of the forms of color-blindness using a color-blindness simulator[4].

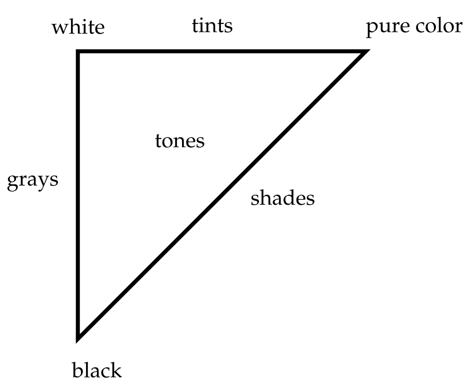
4. Modeling color space

There are many different ways to describe the different colors.

- Section 4.1, "The Ostwald diagram" (p. 3): Describing the lighter and darker versions of a single pure color.
- Section 4.2, "The color wheel and the RGB color model" (p. 4): The pure colors described in terms of red, green, and blue components.
- Section 4.3, "The hue-saturation-value (HSV) color model" (p. 5).
- Section 4.4, "The CMY model" (p. 6).
- Section 4.5, "The CMYK model" (p. 6).

4.1. The Ostwald diagram

Friedrich Wilhelm Ostwald[5] worked out a scheme for describing different colors as a practical guide for painters. The diagram below left shows the ways of modifying a pure color (such as green) by adding white or black to it. On the right is an example of the Ostwald diagram based on the pure color red.

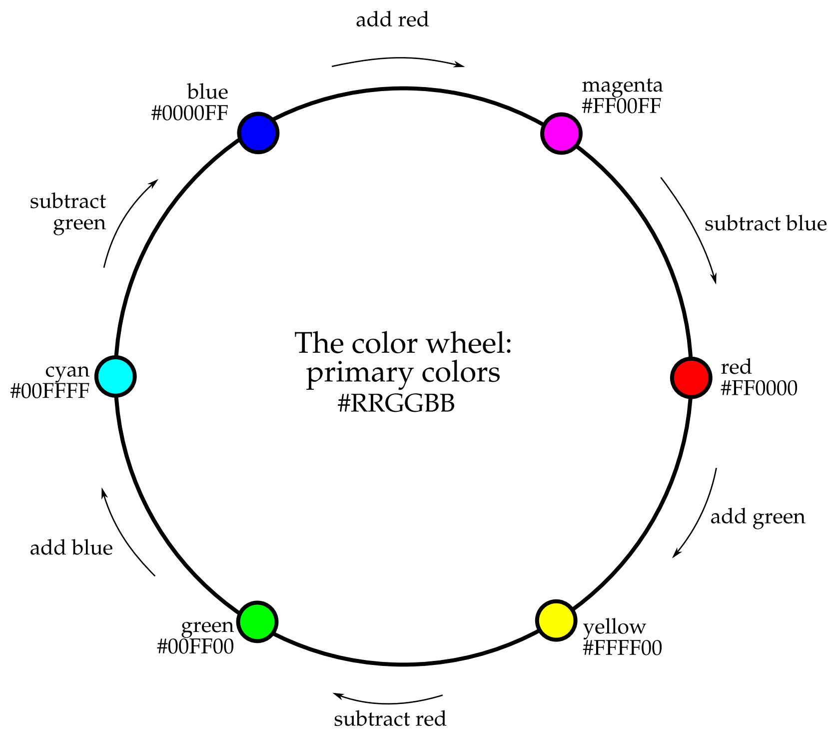


- Adding white pigment to a pure color produces a *tint*. For example, adding white to red makes pink.
- Adding black pigment to a pure color produces a *shade*. For example, adding black to red makes dark red.
- Adding both white and black to a pure color produces a *tone*.
- A mixture of white and black, with no color added, produces a shade of *gray*.

[3] http://en.wikipedia.org/wiki/Color-blindness
[4] http://www.etre.com/tools/colourblindsimulator/
[5] http://en.wikipedia.org/wiki/Wilhelm_Ostwald

4.2. The color wheel and the RGB color model

Considering only pure colors, we can arrange them in a circle called the *color wheel*.



In this view, we can characterize any pure color as a mixture of red, green, and blue light. This way of viewing colors is called the RGB model after the three component colors.

If you start with red light, as you add some green light, the color shifts toward yellow. From yellow, if you reduce the amount of red light, the color shifts toward green, and so forth around the circle.

This view of light will be familiar to anyone who has done theater lighting. Most theater lighting systems allow you to mix various amounts of red, green, and blue light to achieve a given color. For example, if you want a scene to look like it is taking place outdoors on a clear day, you would use a cyclorama (a large, featureless white sheet) in the background, and project blue light onto it, to resemble the sky.

The RGB color model is also the standard way of specifying colors on a Web page. In general, any color may be specified as a color name of the form "`#RRGGBB`". Within this color name, the *`RR`* part is a hexadecimal (base 16)[6] number between `00` and `FF` that specifies the amount of red in the color, where `00` means no red and `FF` means the maximum amount of red.

Similarly, the *`GG`* and *`BB`* parts of this color name specify the relative amount of green and blue.

For example, color `#FFFF00` means full intensity of red and green, but no blue, and gives you yellow. Any number of intermediate values are possible. For example, `#ff8000` is an orange hue: it specifies the maximum amount of red and half intensity of green, which puts it halfway between red and yellow on the color wheel.

[6] http://en.wikipedia.org/wiki/Hexadecimal

Red, green and blue are referred to as the *additive primary colors*: starting with black, you can add various amounts of these colors of light to move toward all the lighter colors.

4.3. The hue-saturation-value (HSV) color model

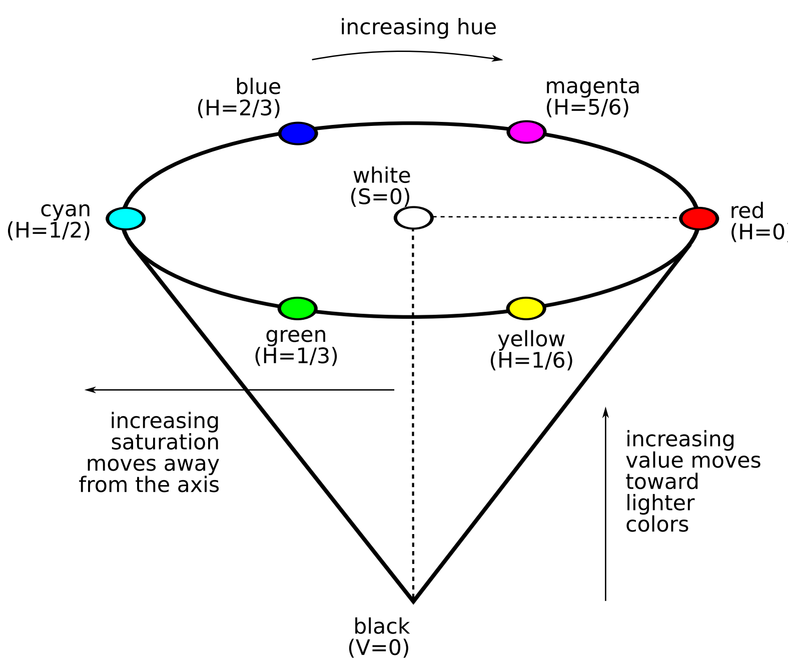
Another way to characterize a color is in terms of the HSV model.

- The *hue* (H) of a color refers to which pure color it resembles. All tints, tones and shades of red have the same hue.

  Hues are described by a number that specifies the position of the corresponding pure color on the color wheel, as a fraction between 0 and 1. Value 0 refers to red; 1/6 is yellow; 1/3 is green; and so forth around the color wheel.

- The *saturation* (S) of a color describes how white the color is. A pure red is fully saturated, with a saturation of 1; tints of red have saturations less than 1; and white has a saturation of 0.
- The *value* (V) of a color, also called its *lightness*, describes how dark the color is. A value of 0 is black, with increasing lightness moving away from black.

This diagram, called the *single-hexcone model of color space*, can help you visualize the meaning of the H, S, and V parameters.



- The outer edge of the top of the cone is the color wheel, with all the pure colors. The H parameter describes the angle around the wheel.
- The S (saturation) is zero for any color on the axis of the cone; the center of the top circle is white. An increase in the value of S corresponds to a movement away from the axis.
- The V (value or lightness) is zero for black. An increase in the value of V corresponds to a movement away from black and toward the top of the cone.

The Ostwald diagram corresponds to a slice of this cone. For example, the triangle between red, white, and black is the Ostwald diagram for the varieties of red.

4.4. The CMY model

Note on the diagram of the color wheel that each of the three colors cyan, magenta, and yellow are opposite one of the additive primary colors: red is opposite cyan, green is opposite magenta, and yellow is opposite blue. These pairs are called *complementary colors*.

For example, if you take white light and filter out red, the result is cyan; if you take white light and filter out blue, you get yellow.

You can use the CMY model, like the HSV and RGB models, to characterize any color by specifying the amount of cyan, magenta, and yellow. The three values of a color in the CMY system are the opposite of the values in the RGB system. If each value is expressed as a value between 0 and 1, the C value of a color is $(1-R)$, and also $M = (1-G)$ and $Y = (1-B)$.

These colors are sometimes called the *subtractive primary colors*: if you start with white light, you can filter out various amounts of cyan, yellow, and magenta to produce any color.

4.5. The CMYK model

The term *gamut* refers to the range of colors that can be reproduced by a given process. When considering colors for display either on paper or on a display device, it is important to consider the gamut of that process. Computer monitors can usually produce brighter colors than ink on paper.

Colored inks on paper act to filter out reflected colors. The subtractive primaries (cyan, yellow, and magenta), when combined on a printed page, act to remove colors from the light reflected from them. Yellow ink absorbs blue; magenta ink absorbs green; and cyan ink absorbs red.

In theory, if all three subtractive colors are printed on a page, the result should be black. However, in practice, the combination of these colors does not produce a completely black page. Hence, all quality printing processes use four colors: cyan, magenta, yellow, and black. The black ink is applied to the darkest areas of the page, where the sum of the other three ink colors does not produce a dark enough color.

If you are involved in the production of printed documents, it is important to work with the printer to understand the gamut of their process. Experienced print shops can help you select colors so that the differences between a given color on a display device are as close as possible to the colors printed on the page.