Color Theory

In this short document, I will try to summarize the scientific aspects of colors.
There are other aspects, such as history and symbolic meaning of colors, that are too extensive or vague to be described here.

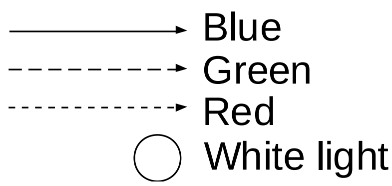
1. Physics and biology

Physically, light can be described as a number of small particles (photons) with different weight (frequency), leaving a source (like a lamp or the sun), possibly bouncing on surfaces, entering an eye and hitting the cones (cone cells) or rods (rod cells) of the retina. The rods send messages about the existence of light while the cones send chemical messages about the frequency of the light. The messages end up in the brain, which interprets the messages as colors.

The brain translates the lightest visible photons to red, followed by orange, yellow, green, blue and violet for the heaviest visible photons. These colors are called spectrum colors, and are visible in a rainbow or if you use a lens or prism.
Other colors appear when the brain interprets photons of different frequencies at the same spot. These colors cannot be found in a rainbow and include purple, pink and brown.

A color can be defined as all combinations of light which give rise to the same color sensation.

Even though light can have any weight (frequency), for now you can imagine that there are only three different weights; blue, green and red. Blue appears darker, while red and green has about the same brightness. If the eye detects two of these colors at the same spot, the brightness of the colors are added, resulting in a color that is lighter than the individual colors.

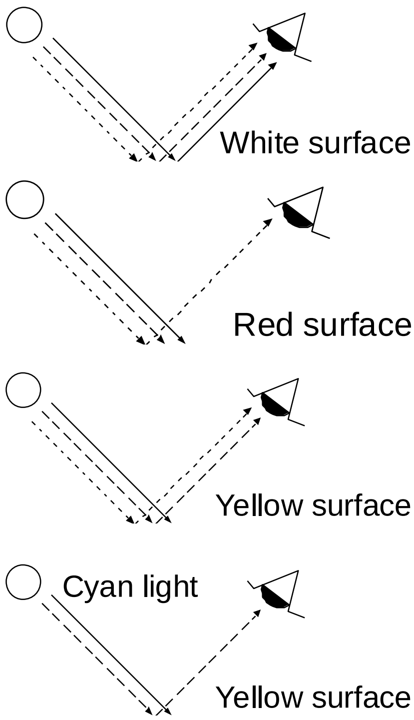


Blue and green creates cyan (which is brighter than either), blue and red creates magenta and red and green creates yellow.
If the brain cannot detect any difference between the amounts of frequencies, it is called white. Blue, green and red creates white.

If no light can be detected, the brain calls that black.
The brain also keeps track of how much blue, green and red there is, and calls the expected average value white or grey, depending on how much light there is. The expected value is found by the brain by contantly looking for a "dynamic equilibrium point", which is a process common for all sensory input.

You can test how ths works by looking at a large red dot on a white paper for a while. Your brain will now adjust its "white-balance" so that it expects more red for a white/grey-value at that spot, in effect reducing sensitivity to red. By doing this, the red becomes less vivid.
Now look at a pure white surface instead. A green-blue dot will appear where you used to see a red dot, since the actual white light from the surface contains less red than the brain expects. After a while the brain readjusts its white-balance, and the dot disappears.
You can get the same experience with colored sunglasses.
This effect can also be used for enhancing a color by surrounding it with its complementary color. A color will reduce local sensitivity for colors close to itself, and increase sensitivity to complementary colors. This is called simultaneous contrast.

2. Reflections



A white surface reflects all colors equally well, so that the reflection of white light appears white.

A red surface will absorb (delete) most of the blue and green light, so that there is more red light left than the others. Thus the surface looks red.

A yellow surface will absorb (delete) most blue light. The red and green light reaches the eye, and the brain interprets the result as yellow.

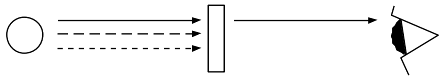
If the light is not white, but slightly cyan (blue and green), and the surface is yellow (absorbing blue), the eye will see green. Cyan light reflected on a red surface will look black.

This means that a painting will look different in different light. Also, two surfaces that look the same in white light, since the resulting reflection is interpreted by the brain as the same color, may look different in another light, for instance a green pigment compared to a yellow-blue mixture.
The higher the temperature of a light, the whiter it is. Lightbulb light is slightly red and flourecent light is yellow. There are daylight lamps that emits almost the same color as sunlight.

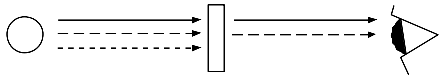
The retina is full of rods, detecting light in general, and cones, detecting color. The rods outnumber the cones by about twenty to one, especially far from the middle of the retina, and are much more sensitive. As the light grows dimmer, only the sensitive rods can detect the light, and thus color disappears.

The brain is constantly trying to detect lines and edges. Normally it uses the light-sensitive rods for this, but if the only thing that distinguishes one side of an edge from the other is color, like a red-green boundry with the same brightness, the cones must be used instead. Since the eye constantly moves around, even though you try to hold it still, the cones close to the edge will shift detection between red and green, sending the signal that the color is changing. The edge starts to vibrate. This can make paintings with constant brightness interesting.

3. Filters



Blue filter

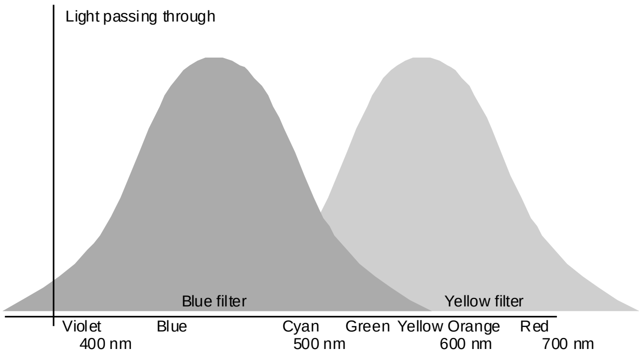


Cyan filter

Just as with reflecting surfaces, a filter, such as sunglasses, only lets certain colors through. For instance, a blue filter absorbs most red and green, letting most of the blue color through, while a cyan filter absorbs most red.

In reality, a blue filter does not let all blue light through. Neither does it stop all other light. It lets more light through the closer to blue it is. The same is true for other filters.

The figure to the right shows an example how much light a blue and a yellow filter may let through.

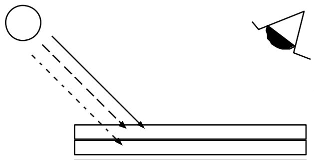


If white light, i.e. a ray of light that is a mixture of all frequencies from red through green to violet, passes a blue filter, most blue, some green and no red light will pass through, as seen in the leftmost bump. The resulting ray of light has a lot of blue, some cyan and a little bit of violet and green.

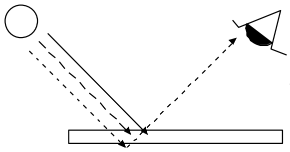
If a yellow filter follows, it will stop all remaining blue light and let some of the remaining green through. This means that the combination of a blue and a yellow filter will only let green light though. If the filter lets a lot of other colors through, it will look dirty and greyish.

Contrary to common belief, mixed yellow and blue light is white or grey.
You can view an example of this at *www.studiolab.se/tutorial/color*

4. Transparent paint



White surface with red and green transparent paint



White surface with red transparent paint

A transparent paint can be described as a filtering layer on top of a surface.

A red, transparent paint will absorb most blue and some green light. Most red and some green will be reflected by the surface below, be filtered again on the way back, and reach the eye.

If you put a green, transparent layer of paint on top of the red, it will absorb the red and blue light before it even reaches the red paint, which absorbs the green light.
The result is that most light is absorbed at some point, making the resulting surface grey or even black.

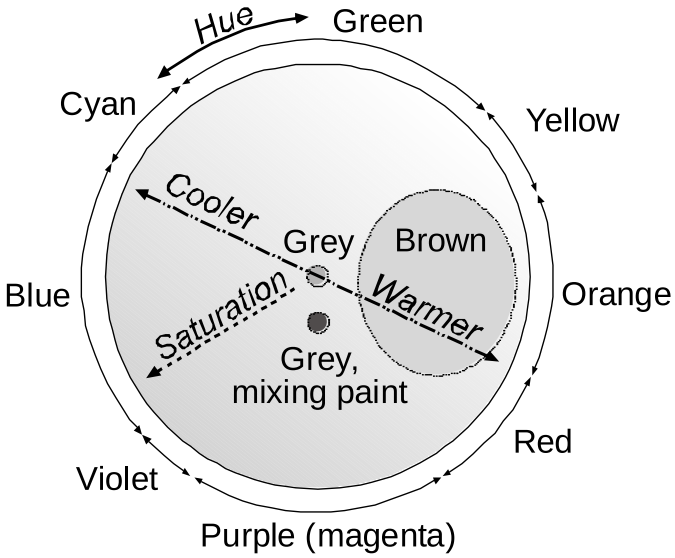
A yellow layer and a blue layer will look green, for the filtering reasons described above.

5. Opaque paint

An opaque paint is like a transparent paint, carrying its own reflecting surface. This means that the light is reflected at the top layer, not at the surface below. There is no real difference between opaque paint and a reflecting surface, as described above.

Most oil paint is semi-opaque to a varying degree, which means that some light is reflected and some light is filtered.

6. Color circle



A hue is the name of a color. The complementary hue is the one on the opposite side of the color circle. Complementary colors include yellow-ultramarine blue, red-cyan and green-magenta.

The saturation level is how far from the grey the color is. Less saturation means more greyness. For instance, brown is unsaturated yellow-orange-red.

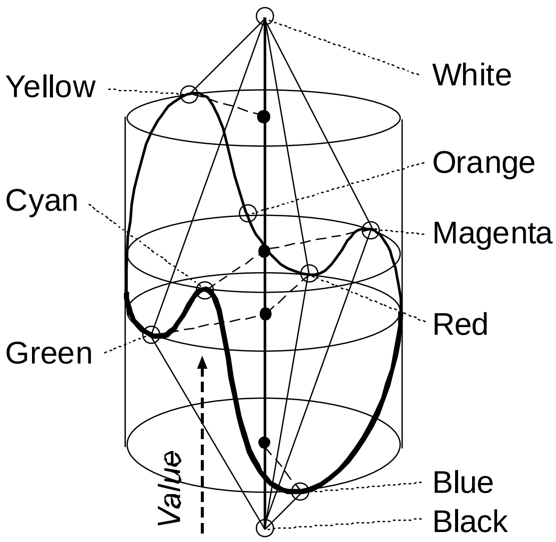
Light of a certain hue and light of its complement hue can be mixed until it has no saturation, i.e. becomes white, grey or black.

A color is called warmer if it comes closer to orange-red, and cooler if it is closer to blue-green. Warmer colors tend to appear moving toward the viewer while cold colors recede.

All spectrum colors are fully saturated.
Purple colors, including mauve, magenta, lilac, can be considered to be fully saturated but are created in the brain. No single-frequency light can create the same sensation as red and blue/violet light at the same spot.

Note that the color circle above applies to added light. You get a path of possible mixture colors by drawing a straight line between then two colors you mix.
If you mix paint, the grey point is moved a bit lower, due to the amount of light passing through filtering layers, as described above. For instance, the yellow-blue line passes the fairly unsaturated green area.

7. Trebard color diamond



There are three types of cone cells. They are used for detecting color relations, which can be translated into hue and saturation.
The rods are used for detecting brightness or value. Thus every color experience can be described using three coordinates in a color space. Computers normally use red-green-blue or hue-saturation-value triplets, and printers use cyan-magenta-yellow, although there are a number of other solutions.

If we add value as a third dimension to the color circle, the color space can be seen as a diamond-shaped volume, with white at the top and black at the bottom.

The height of a color is called the value of the color.

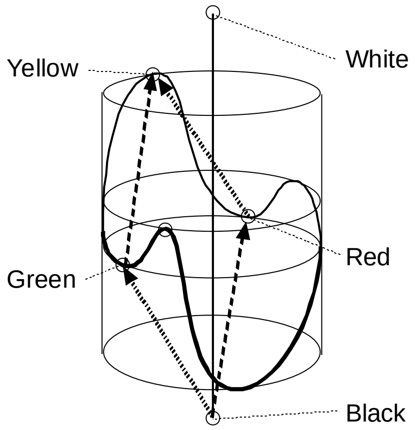
Each existing color can be defined with hue (angle), saturation (distance from middle axis) and value (brightness).

The fully saturated colors are located along a path on a cylinder enclosing all possible colors. Since blue is darker than both red and green, it is located lower. Cyan and magenta are lighter than red and green, so they are higher. Yellow is the lightest, fully saturated existing color, so it is the highest existing color on the enclosing cylinder.

Note that if you look at the diamond from above, you see the color circle. Also note that there is only one value at maximum saturation for each hue. All other values with that hue (color) has a bit of white/grey/black in them. If you draw a straight line between each fully saturated color and white, and another to black, you get a volume that encloses every existing color.

Since I have never seen this diamond shape anywhere in literature, I call it the *Trebard color diamond*. It has some resemblance to color space description made by Garritsen.

8. Mixing light



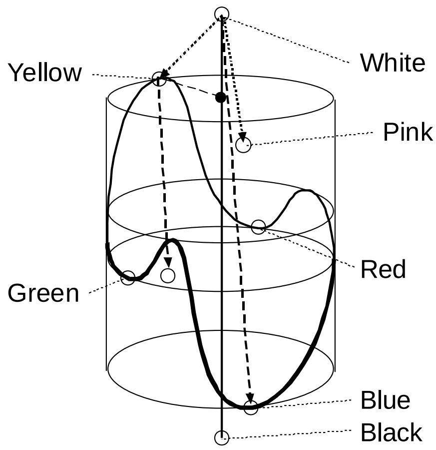
Mixing light adds value.

If you mix light, e.g. by pointing two spotlights with different colors to the same spot, you add part of the vectors (arrows) from black to the individual colors to get the result, as long as it is within the possible color space. For instance, mixed red and green light can become yellow.

You can get most colors by mixing red, green and blue, as computer and television monitors normally do, but there are places you cannot reach by adding these three colors, like a number of greens, oranges and violets. This is why digital cameras, which often detect only these three colors, cannot capture all colors of paintings or nature.

In my examples above, I have used only three colors, blue, green and red, but in reality all frequencies are used, and the cones react more or less to all frequencies. With all spectrum frequencies available, you can reach every possible color of the diamond.

9. Mixing transparent paint

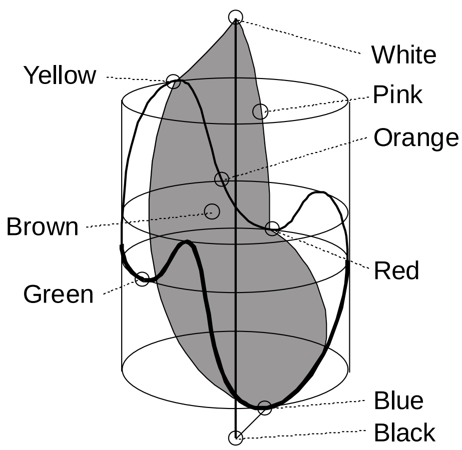


Mixing transparent paint reduces value.

If you mix transparent colors or filter light, you add vectors from white (or whatever color you start with) to each color. Each new color will reduce the value. A small amount of red on a white surface becomes pink. The more red color you add, the more red the surface becomes, until only red remains, and the color is saturated.
Since filters do not only let only one frequency through, all vectors after the first will be slightly shifted, often towards green. This way yellow and blue becomes green.

Normally, color-printers uses cyan, magenta and yellow, since these are approximately the complementary colors of red, green and blue. Yellow and cyan transparent paint produces green, yellow and magenta becomes red and cyan and magenta becomes blue. Printers often add black ink as well, since the colors seldom are fully transparent. Printing with these colors excludes a number of colors, which is why prints of paintings seldom looks quite like the original.

10. Mixing opaque paint



Mixing opaque paint shares value, since the pigments both add their own value at the surface and block light from underlying pigments.

If you mix opaque colors, like most oil paint, you draw curved lines between the individual colors. The color space surrounded by these lines define all possible color resulting from the mixing. It does not describe the required amounts though.

Mixing just two colors will result in a line of possibilities. Mixing two complementary colors will result in a line passing through the grey axis.
The image shows the mixture of blue, red, yellow and white. The result includes a number of browns. Adding orange will extend the possible number of colors with a set of warmer browns.

Oil colors often are semi-transparent. Since transparent colors reduce value, mixing brown with semi-transparent blue may result in an almost black color.

A cold (bluish) red and a warm (reddish) blue will mix to become a fairly saturated violet or purple, while a warm red and a cold blue will be grayish (less saturated).
You can draw a line between the colors to see this phenomenon.

You cannot get fully saturated colors by mixing opaque pigments, and this does apply not only to the "primary" colors yellow, red and blue. For instance, there are many greens you cannot get by mixing yellow and blue. However, yellow must be very saturated to be called yellow, while green, orange and violet are called those names even as the saturation drops considerably. This is a reason yellow, red and blue are called primary colors.
On the other hand, painting with a few properly mixed colors can bring a certain kind of harmony to your painting. Personally, I use Windsor & Newton Artisan series Permanent Rose, Lemon Yellow, Phtalo Blue, Cadmium Orange Hue, Titanium White and Ivory Black.

11. Color contrasts

We constantly try to identify contrasts and harmonies in what we see. It is in our nature, and is usually not a conscious choice. A description of color must include this level as well. Johannes Itten (1888-1967) defined seven strategies for color combinations.

The contrast of hue
In contrast of hue, the colors on the wheel are used in such a way as to proclaim their separate identities. The greater the distance between hues on a color wheel, the greater the contrast.

The contrast of temperature
The contrast is formed by the juxtaposition of hues considered warm or cool.

The contrast of intensity
Contrast of intensity refers to the variation of saturation chiefly in a single hue or in closely related hues.

The contrast of extension
Also known as the contrast of proportion. The contrast is formed by assigning proportional field sizes in relation to the visual weight of a color.

Goethe suggested the following visual weights:

Yellow	9	Orange	8	Red	6
Violet	3	Blue	4	Green	6

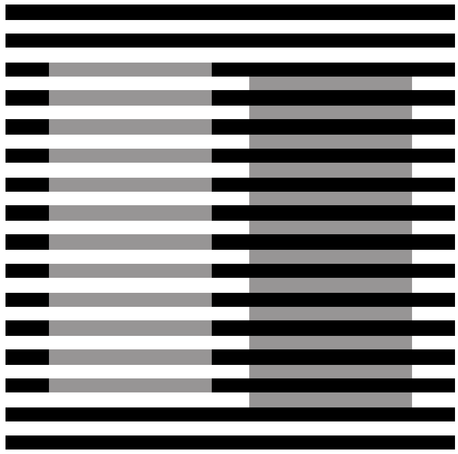
For instance, yellow/violet 9:3 = 3:1, i.e. violet must occupy three times as large area as yellow to create perfect harmony. The orange/blue ratio is 2:1 and the red/green 1:1.

The contrast of value
The contrast is formed by the juxtaposition of light and dark values. The use of chiaroscuro (light-shade) and the use of color in paintings has always been an uneasy relationship. The use of one in a painting seems to require suppression of the other. It is better, therefore, that the artist choose one or the other, for the most unfortunate results come from the failure to make a choice: too much value contrast having compromised form, and so on.

The contrast of complements
The contrast is formed by the juxtaposition of color wheel or perceptual opposites.

Simultaneous contrast
As described above, the dynamic equilibrium will adjust the surrounding of a saturated color with its complementary color. The contrast is formed when the boundaries between colors perceptually vibrate. Some interesting illusions are accomplished with this contrast.

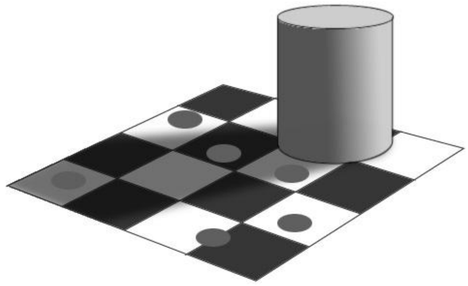
12. Light contrast



Black and white are not absolute values. They depend very much on their surroundings. Apparently, the eye tries to decipher the scene into coherent fractions, finds a "whiteness anchor-point" for each part, and evaluates surrounding parts of the scene fraction based on this anchor point.

For instance, the gray areas on the image to the right actually have the same absolute lightness, although the left ones seem much lighter than the left ones.

In the chessboard scene, the grey ovals have the same lightness, although the one on the black squares in the shadow seems lighter than the ones on white square in the light.

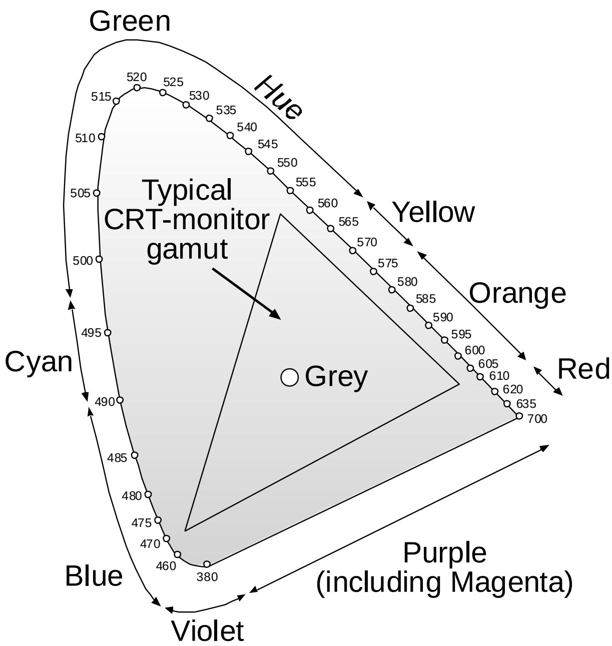


13. Color horseshoes and crystals

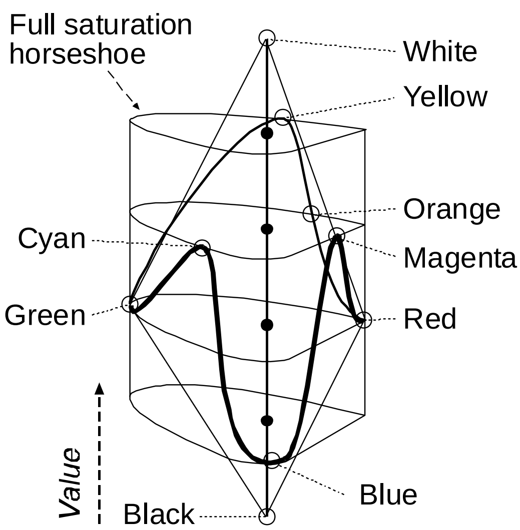
Most descriptions above are naturally very simplified.

For instance, the color circle and diamond are actually simplified versions of something that more resembles a horseshoe and an oddshaped crystal. The translation from horseshoe to circle is the reason why the lines in the Trebard color diamond can be curved when you calculate the result of adding colors. The horseshoe is displayed here with wavelengths in nanometer, and is based on a huge international study of human perception around 1930.

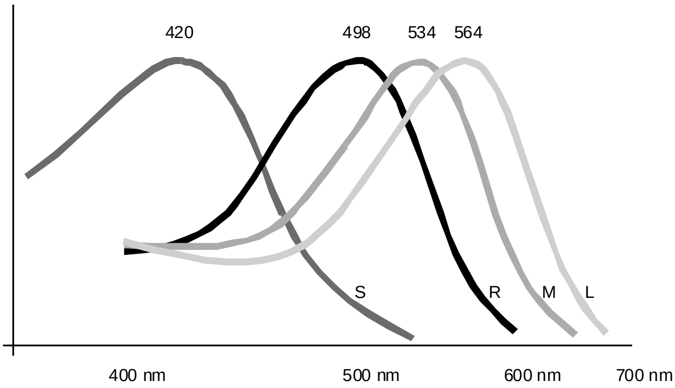
If you draw straight lines between all colors you mix, the area will enclose all possible resulting colors. The triangle in the horseshoe is a typical range of colors (gamut) of a CRT computer monitor. You can see that you exclude many greens and blues, but not so many yellows and oranges, by mixing the computer monitor "primaries", defined by the corners of the triangle.



You can also see that you can get almost all oranges by mixing spectral red and yellow, and all purples by mixing red and spectral violet. Greens and blues are more difficult to attain by mixture.



14. Extended biology

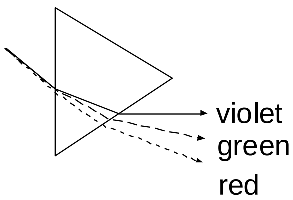


There are three types of color-sensitive cones and one type of brightness-sensitive rods.

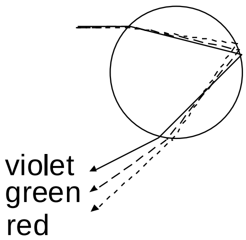
The image to the right shows how the cones
(S = short, M = medium, L = long) and the rods (R) react to light. The cones thus react most to blue-violet, green respectively green-yellow light.

For instance, pure blue light with "lightness" of 420 nm will cause the "heavy" blue (short wavelength) cones to react, while the rods and the other cones react much less, resulting in a sensation of blue color. Pure yellow will cause all cones to react in the same way as an equal amount of green and red light will, with a sensation of yellow in both cases.
An equal reaction (after the white-balance effect described above) of all cones at one spot on the retina will be interpreted as white or grey.

15. Rainbows and skies

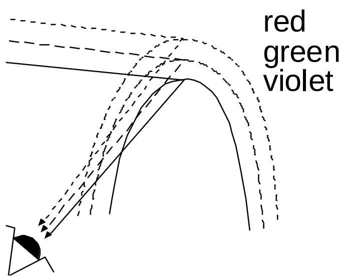


When light hits water or glass, in this case a triangular prism, at an angle, the light changes direction. This is why a vase will shift the background, and why a water surface seems to move the objects beneath. Violet light changes directions more than red.



In the same manner, if light hits a drop of water, the light changes direction as well. It is reflected at the back of the drop as well. As you see, the red is reflected downwards at a greater angle. This is the cause of rainbows, with red at the top.
Sometimes you can see an additional, weaker rainbow above the primary rainbow. This is the result of light bouncing twice, first below the center and then above, and the order of the colors is reversed.

The sky is blue since blue light more easily changes direction (towards the spectator) as it hits the air and other small particles on its way through the atmosphere.
This is also the reason why the sunsets and sunrises are red, as the blue light is scattered away.



16. English- swedish translation

Cone cells	Tappar
Rod cells	Stavar
Retina	Näthinna
Hue	Kulör, färg, nyans, färgton
Saturation	Mättnad
Value	Valör, ljushet
Transparent	Genomskinlig
Opaque	Ogenomskinlig
Juxtaposition	Ställa bredvid varandra
e.g.	t ex
i.e.	dvs

17. References

Garritsen - Evolution in color
John Gage - Color and culture, Color and meaning
Ramon Kelley - The 5 essentials in every powerful painting
Seeing in black and white - Scientific American Mind June/July 2006

18. Links

http://en.wikipedia.org/wiki/Color
http://webexhibits.org/colorart/
http://www.worqx.com/color/itten.htm
http://www.noteaccess.com/ELEMENTS/Color.htm