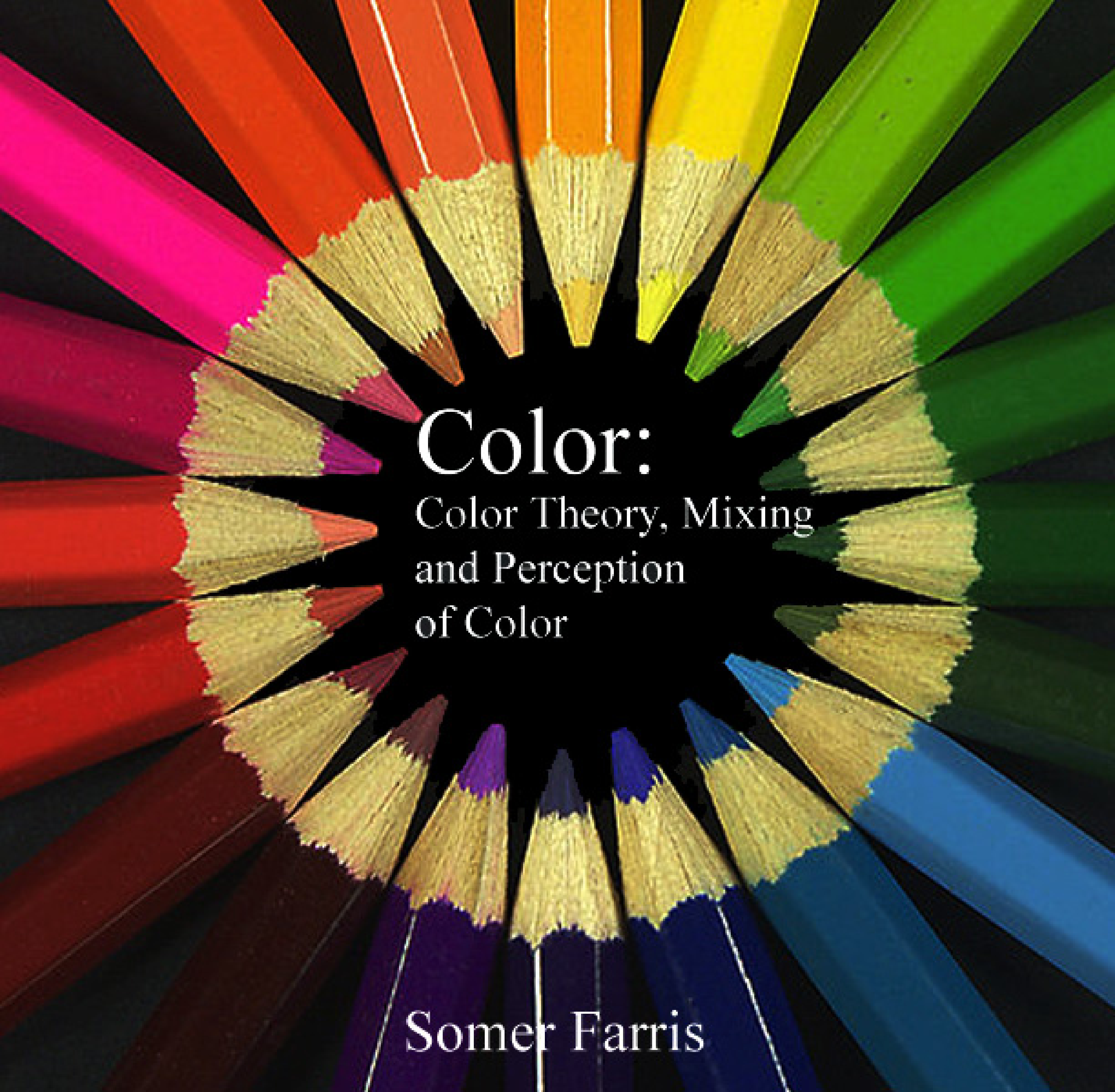

# Color:

## Color Theory, Mixing and Perception of Color

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**Chapter 1**

# Color

Color

**Color** or **colour** is the visual perceptual property corresponding in humans to the categories called *red*, *green*, *blue* and others. Color derives from the spectrum of light (distribution of light energy versus wavelength) interacting in the eye with the spectral sensitivities of the light receptors. Color categories and physical specifications of color are also associated with objects, materials, light sources, etc., based on their physical properties such as light absorption, reflection, or emission spectra. By defining a color space, colors can be identified numerically by their coordinates.

Because perception of color stems from the varying spectral sensitivity of different types of cone cells in the retina to different parts of the spectrum, colors may be defined and quantified by the degree to which they stimulate these cells. These physical or physiological quantifications of color, however, do not fully explain the psychophysical perception of color appearance.

The science of color is sometimes called ***chromatics***. It includes the perception of color by the human eye and brain, the origin of color in materials, color theory in art, and the physics of electromagnetic radiation in the visible range (that is, what we commonly refer to simply as *light*).

## Physics

**The colors of the visible light spectrum**

| color | wavelength interval | frequency interval |
|---|---|---|
| red | ~ 700–635 nm | ~ 430–480 THz |
| orange | ~ 635–590 nm | ~ 480–510 THz |
| yellow | ~ 590–560 nm | ~ 510–540 THz |
| green | ~ 560–490 nm | ~ 540–610 THz |
| blue | ~ 490–450 nm | ~ 610–670 THz |
| violet | ~ 450–400 nm | ~ 670–750 THz |

Continuous optical spectrum rendered into the sRGB color space.

**Color, wavelength, frequency and energy of light**

| Color | $\lambda$ (nm) | $\nu$ (THz) | $\nu_b$ (μm$^{-1}$) | $E$ (eV) | $E$ (kJ mol$^{-1}$) |
|---|---|---|---|---|---|
| Infrared | >1000 | <300 | <1.00 | <1.24 | <120 |
| Red | 700 | 428 | 1.43 | 1.77 | 171 |
| Orange | 620 | 484 | 1.61 | 2.00 | 193 |
| Yellow | 580 | 517 | 1.72 | 2.14 | 206 |
| Green | 530 | 566 | 1.89 | 2.34 | 226 |
| Blue | 470 | 638 | 2.13 | 2.64 | 254 |
| Violet | 420 | 714 | 2.38 | 2.95 | 285 |
| Near ultraviolet | 300 | 1000 | 3.33 | 4.15 | 400 |
| Far ultraviolet | <200 | >1500 | >5.00 | >6.20 | >598 |

Electromagnetic radiation is characterized by its wavelength (or frequency) and its intensity. When the wavelength is within the visible spectrum (the range of wavelengths humans can perceive, approximately from 390 nm to 750 nm), it is known as "visible light".

Most light sources emit light at many different wavelengths; a source's *spectrum* is a distribution giving its intensity at each wavelength. Although the spectrum of light arriving at the eye from a given direction determines the color sensation in that direction, there are many more possible spectral combinations than color sensations. In fact, one may formally define a color as a class of spectra that give rise to the same color sensation, although such classes would vary widely among different species, and to a lesser extent among individuals within the same species. In each such class the members are called *metamers* of the color in question.

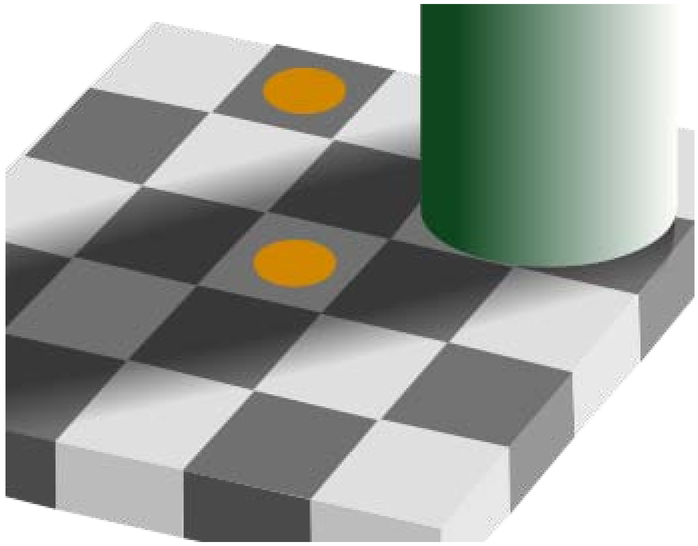
## Spectral colors

The familiar colors of the rainbow in the spectrum – named using the Latin word for *appearance* or *apparition* by Isaac Newton in 1671 – include all those colors that can be produced by visible light of a single wavelength only, the *pure spectral* or *monochromatic* colors. The table at right shows approximate frequencies (in terahertz) and wavelengths (in nanometers) for various pure spectral colors. The wavelengths are measured in air or vacuum.

The color table should not be interpreted as a definitive list – the pure spectral colors form a continuous spectrum, and how it is divided into distinct colors linguistically is a matter of culture and historical contingency (although people everywhere have been shown to *perceive* colors in the same way). A common list identifies six main bands: red, orange, yellow, green, blue, and violet. Newton's conception included a seventh color, indigo, between blue and violet. Optical scientists Hardy and Perrin list indigo as between 446 and 464 nm wavelength.

The *intensity* of a spectral color, relative to the context in which it is viewed, may alter its perception considerably; for example, a low-intensity orange-yellow is brown, and a low-intensity yellow-green is olive-green.

## Color of objects



The upper disk and the lower disk have exactly the same objective color, and are in identical gray surroundings; based on context differences, humans perceive the squares as having different reflectances, and may interpret the colors as different color categories.

The color of an object depends on both the physics of the object in its environment and the characteristics of the perceiving eye and brain. Physically, objects can be said to have the color of the light leaving their surfaces, which normally depends on the spectrum of the incident illumination and the reflectance properties of the surface, as well as potentially on the angles of illumination and viewing. Some objects not only reflect light, but also transmit light or emit light themselves, which contribute to the color also. And a viewer's perception of the object's color depends not only on the spectrum of the light leaving its surface, but also on a host of contextual cues, so that the color tends to be perceived as relatively constant: that is, relatively independent of the lighting spectrum, viewing angle, etc. This effect is known as color constancy.

Some generalizations of the physics can be drawn, neglecting perceptual effects for now:

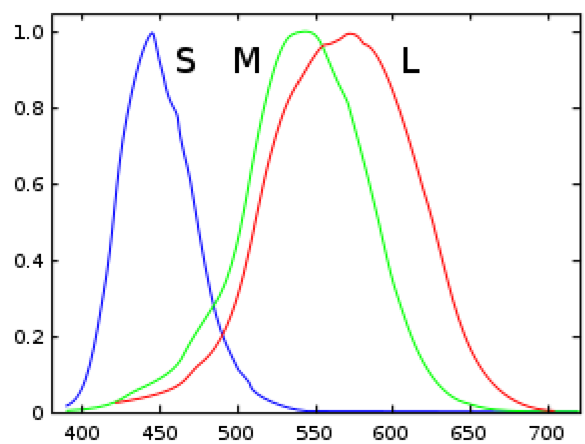
- Light arriving at an opaque surface is either reflected "specularly" (that is, in the manner of a mirror), scattered (that is, reflected with diffuse scattering), or absorbed – or some combination of these.
- Opaque objects that do not reflect specularly (which tend to have rough surfaces) have their color determined by which wavelengths of light they scatter more and which they scatter less (with the light that is not scattered being absorbed). If objects scatter all wavelengths, they appear white. If they absorb all wavelengths, they appear black.
- Opaque objects that specularly reflect light of different wavelengths with different efficiencies look like mirrors tinted with colors determined by those differences. An object that reflects some fraction of impinging light and absorbs the rest may

look black but also be faintly reflective; examples are black objects coated with layers of enamel or lacquer.

- Objects that transmit light are either *translucent* (scattering the transmitted light) or *transparent* (not scattering the transmitted light). If they also absorb (or reflect) light of varying wavelengths differentially, they appear tinted with a color determined by the nature of that absorption (or that reflectance).
- Objects may emit light that they generate themselves, rather than merely reflecting or transmitting light. They may do so because of their elevated temperature (they are then said to be *incandescent*), as a result of certain chemical reactions (a phenomenon called *chemoluminescence*), or for other reasons.
- Objects may absorb light and then as a consequence emit light that has different properties. They are then called *fluorescent* (if light is emitted only while light is absorbed) or *phosphorescent* (if light is emitted even after light ceases to be absorbed; this term is also sometimes loosely applied to light emitted because of chemical reactions).

To summarize, the color of an object is a complex result of its surface properties, its transmission properties, and its emission properties, all of which factors contribute to the mix of wavelengths in the light leaving the surface of the object. The perceived color is then further conditioned by the nature of the ambient illumination, and by the color properties of other objects nearby, via the effect known as color constancy and via other characteristics of the perceiving eye and brain.

## *Perception*




Normalized typical human cone cell responses (S, M, and L types) to monochromatic spectral stimuli

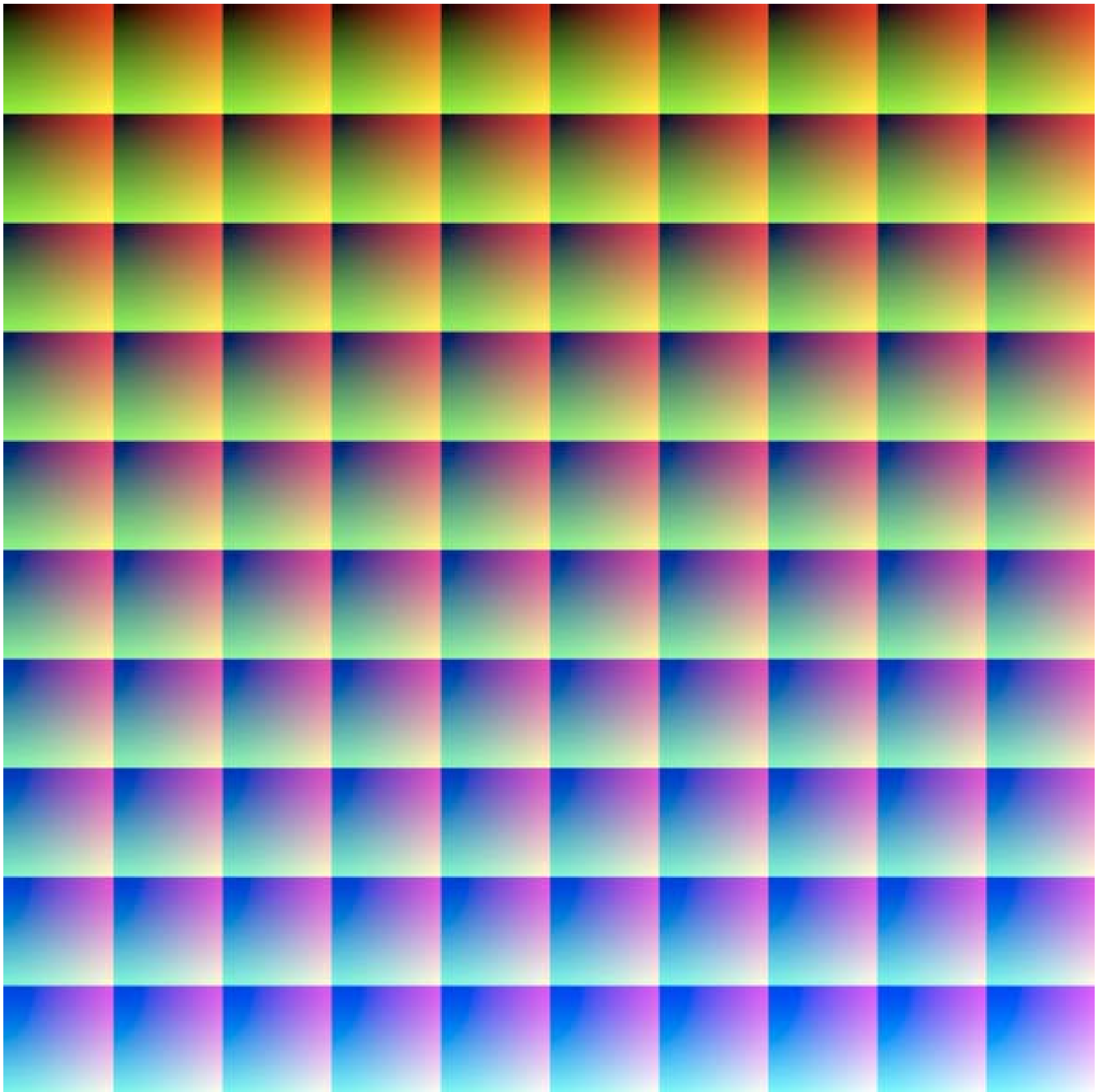
## Development of theories of color vision

Although Aristotle and other ancient scientists had already written on the nature of light and color vision, it was not until Newton that light was identified as the source of the color sensation. In 1810, Goethe published his comprehensive *Theory of Colors*. In 1801 Thomas Young proposed his trichromatic theory, based on the observation that any color could be matched with a combination of three lights. This theory was later refined by James Clerk Maxwell and Hermann von Helmholtz. As Helmholtz puts it, "the principles of Newton's law of mixture were experimentally confirmed by Maxwell in 1856. Young's theory of color sensations, like so much else that this marvellous investigator achieved in advance of his time, remained unnoticed until Maxwell directed attention to it."

At the same time as Helmholtz, Ewald Hering developed the opponent process theory of color, noting that color blindness and afterimages typically come in opponent pairs (red-green, blue-orange, yellow-purple, and black-white). Ultimately these two theories were synthesized in 1957 by Hurvich and Jameson, who showed that retinal processing corresponds to the trichromatic theory, while processing at the level of the lateral geniculate nucleus corresponds to the opponent theory.

In 1931, an international group of experts known as the *Commission internationale de l'éclairage* (CIE) developed a mathematical color model, which mapped out the space of observable colors and assigned a set of three numbers to each.

## Color in the eye



This image (when viewed in full size, 1000 pixels wide) contains 1 million pixels, each of a different color. The human eye can distinguish about 10 million different colors.

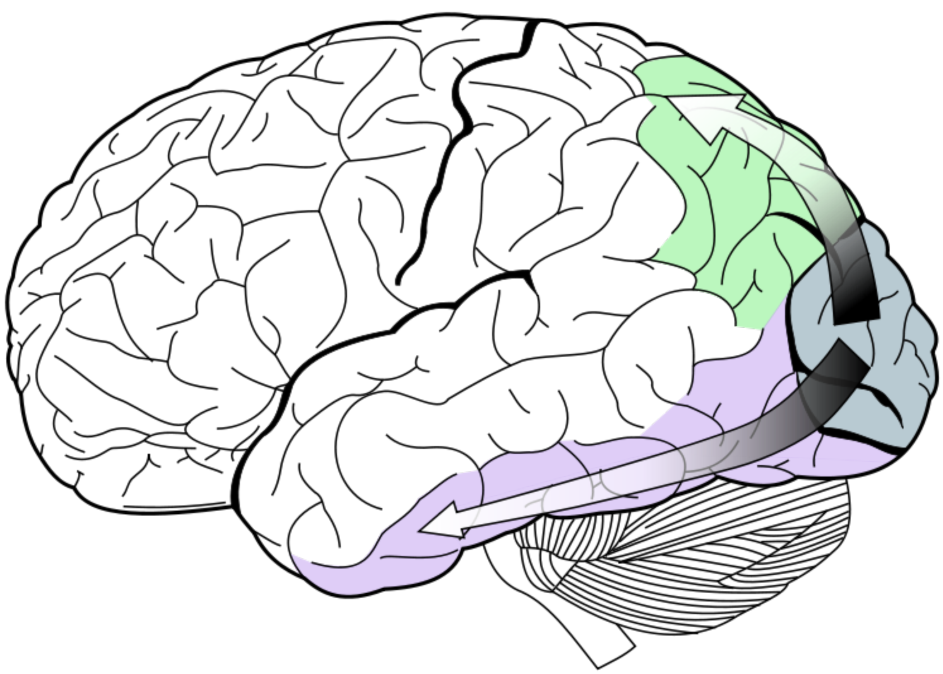
The ability of the human eye to distinguish colors is based upon the varying sensitivity of different cells in the retina to light of different wavelengths. The retina contains three types of color receptor cells, or cones. One type, relatively distinct from the other two, is most responsive to light that we perceive as violet, with wavelengths around 420 nm; cones of this type are sometimes called *short-wavelength cones*, *S cones*, or *blue cones*. The other two types are closely related genetically and chemically. One of them, sometimes called *long-wavelength cones*, *L cones*, or *red cones*, is most sensitive to light we perceive as greenish yellow, with wavelengths around 564 nm; the other type, known as *middle-wavelength cones*, *M cones*, or *green cones* is most sensitive to light perceived as green, with wavelengths around 534 nm.

Light, no matter how complex its composition of wavelengths, is reduced to three color components by the eye. For each location in the visual field, the three types of cones yield three signals based on the extent to which each is stimulated. These amounts of stimulation are sometimes called *tristimulus values*.

The response curve as a function of wavelength for each type of cone is illustrated above. Because the curves overlap, some tristimulus values do not occur for any incoming light combination. For example, it is not possible to stimulate *only* the mid-wavelength (so-called "green") cones; the other cones will inevitably be stimulated to some degree at the same time. The set of all possible tristimulus values determines the human *color space*. It has been estimated that humans can distinguish roughly 10 million different colors.

The other type of light-sensitive cell in the eye, the rod, has a different response curve. In normal situations, when light is bright enough to strongly stimulate the cones, rods play virtually no role in vision at all. On the other hand, in dim light, the cones are understimulated leaving only the signal from the rods, resulting in a colorless response. (Furthermore, the rods are barely sensitive to light in the "red" range.) In certain conditions of intermediate illumination, the rod response and a weak cone response can together result in color discriminations not accounted for by cone responses alone. These effects, combined, are summarized also in the Kruithof curve, that describes the change of color perception and pleasingness of light as function of temperature and intensity.

## Color in the brain



The visual dorsal stream (green) and ventral stream (purple) are shown. The ventral stream is responsible for color perception.

While the mechanisms of color vision at the level of the retina are well-described in terms of tristimulus values, color processing after that point is organized differently. A dominant theory of color vision proposes that color information is transmitted out of the eye by three opponent processes, or opponent channels, each constructed from the raw output of the cones: a red-green channel, a blue-yellow channel and a black-white "luminance" channel. This theory has been supported by neurobiology, and accounts for the structure of our subjective color experience. Specifically, it explains why we cannot perceive a "reddish green" or "yellowish blue," and it predicts the color wheel: it is the collection of colors for which at least one of the two color channels measures a value at one of its extremes.

The exact nature of color perception beyond the processing already described, and indeed the status of color as a feature of the perceived world or rather as a feature of our *perception* of the world, is a matter of complex and continuing philosophical dispute.

## Nonstandard color perception

### Color deficiency

If one or more types of a person's color-sensing cones are missing or less responsive than normal to incoming light, that person can distinguish fewer colors and is said to be *color deficient* or *color blind* (though this latter term can be misleading; almost all color deficient individuals can distinguish at least some colors). Some kinds of color deficiency are caused by anomalies in the number or nature of cones in the retina. Others (like *central* or *cortical achromatopsia*) are caused by neural anomalies in those parts of the brain where visual processing takes place.

### Tetrachromacy

While most humans are *trichromatic* (having three types of color receptors), many animals, known as *tetrachromats*, have four types. These include some species of spiders, most marsupials, birds, reptiles, and many species of fish. Other species are sensitive to only two axes of color or do not perceive color at all; these are called *dichromats* and *monochromats* respectively. A distinction is made between *retinal tetrachromacy* (having four pigments in cone cells in the retina, compared to three in trichromats) and *functional tetrachromacy* (having the ability to make enhanced color discriminations based on that retinal difference). As many as half of all women are retinal tetrachromats. The phenomenon arises when an individual receives two slightly different copies of the gene for either the medium- or long-wavelength cones, which are carried on the x-chromosome. To have two different genes, a person must have two x-chromosomes, which is why the phenomenon only occurs in women. For some of these retinal tetrachromats, color discriminations are enhanced, making them functional tetrachromats.

**Synesthesia**

In certain forms of synesthesia, perceiving letters and numbers (grapheme–color synesthesia) or hearing musical sounds (music–color synesthesia) will lead to the unusual additional experiences of seeing colors. Behavioral and functional neuroimaging experiments have demonstrated that these color experiences lead to changes in behavioral tasks and lead to increased activation of brain regions involved in color perception, thus demonstrating their reality, and similarity to real color percepts, albeit evoked through a non-standard route.

## Afterimages

After exposure to strong light in their sensitivity range, photoreceptors of a given type become desensitized. For a few seconds after the light ceases, they will continue to signal less strongly than they otherwise would. Colors observed during that period will appear to lack the color component detected by the desensitized photoreceptors. This effect is responsible for the phenomenon of afterimages, in which the eye may continue to see a bright figure after looking away from it, but in a complementary color.

Afterimage effects have also been utilized by artists, including Vincent van Gogh.

## Color constancy

There is an interesting phenomenon which occurs when an artist uses a limited color palette: the eye tends to compensate by seeing any grey or neutral color as the color which is missing from the color wheel. For example, in a limited palette consisting of red, yellow, black and white, a mixture of yellow and black will appear as a variety of green, a mixture of red and black will appear as a variety of purple, and pure grey will appear bluish.

The trichromatic theory discussed above is strictly true only if the whole scene seen by the eye is of one and the same color which, of course, is unrealistic. In reality, the brain compares the various colors in a scene to eliminate the effects of the illumination. If a scene is illuminated with one light, and then with another, as long as the difference between the light sources stays within a reasonable range, the colors in the scene appear constant to us. This was studied by Edwin Land in the 1970s and led to his retinex theory of color constancy.

## Color naming

Colors vary in several different ways, including hue (red vs. orange vs. blue), saturation, brightness, and gloss. Some color words are derived from the name of an object of that color, such as "orange" or "salmon", while others are abstract, like "red".

Different cultures have different terms for colors, and may also assign some color names to slightly different parts of the spectrum: for instance, the Chinese character 青

(rendered as *qīng* in Mandarin and *ao* in Japanese) has a meaning that covers both blue and green; blue and green are traditionally considered shades of "青." South Korea, on the other hand, differentiates between blue and green by using "綠 (녹)" for green and "靑 (청)" for blue.

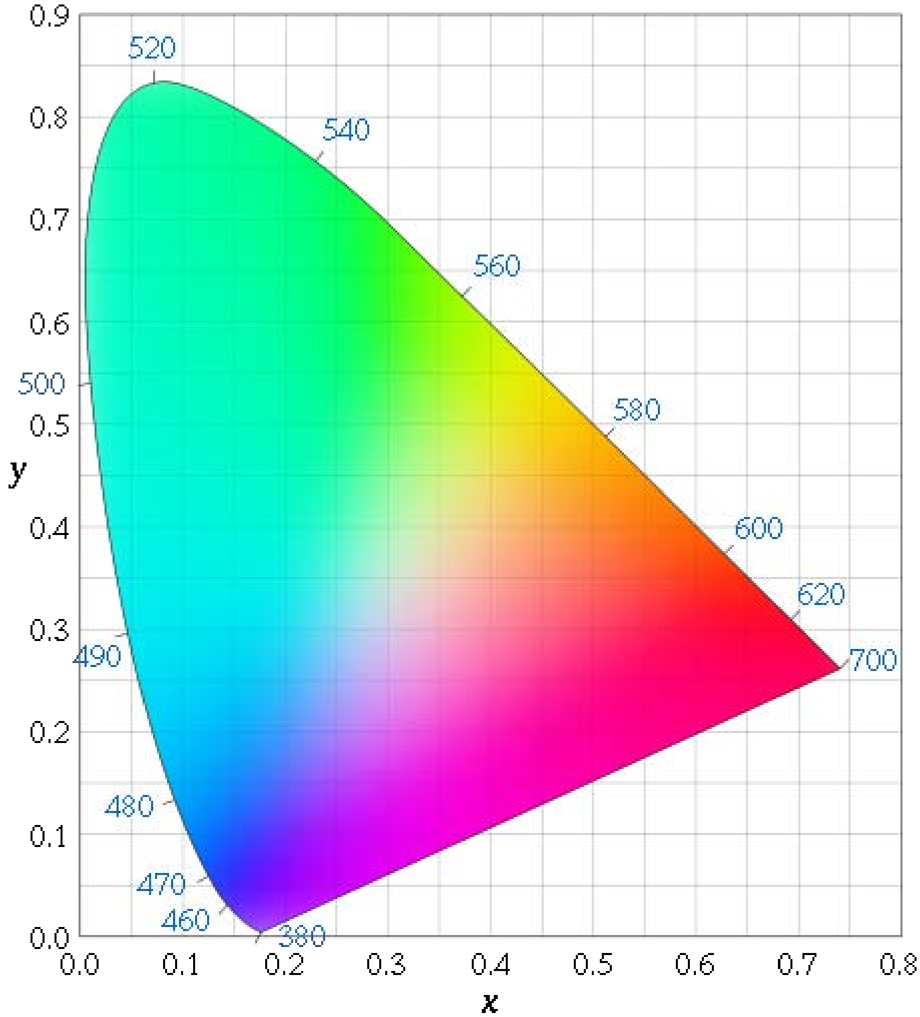
In the 1969 study Basic Color Terms: Their Universality and Evolution, Brent Berlin and Paul Kay describe a pattern in naming "basic" colors (like "red" but not "red-orange" or "dark red" or "blood red", which are "shades" of red). All languages that have two "basic" color names distinguish dark/cool colors from bright/warm colors. The next colors to be distinguished are usually red and then yellow or green. All languages with six "basic" colors include black, white, red, green, blue and yellow. The pattern holds up to a set of twelve: black, grey, white, pink, red, orange, yellow, green, blue, purple, brown, and azure (distinct from blue in Russian and Italian but not English).

## *Associations*

Individual colors have a variety of cultural associations such as national colors (in general described in individual color articles and color symbolism). The field of color psychology attempts to identify the effects of color on human emotion and activity. Chromotherapy is a form of alternative medicine attributed to various Eastern traditions. Colors have different associations in different countries and cultures.

Different colors have been demonstrated to have affects on cognition. For example, researchers at the University of Linz in Austria demonstrated that the color red significantly decreases cognitive functioning in men.

### *Spectral colors and color reproduction*




The CIE 1931 color space chromaticity diagram. The outer curved boundary is the spectral (or monochromatic) locus, with wavelengths shown in nanometers. Note that the colors depicted depend on the color space of the device on which you are viewing the image, and therefore may not be a strictly accurate representation of the color at a particular position, and especially not for monochromatic colors.

Most light sources are mixtures of various wavelengths of light. However, many such sources can still have a spectral color insofar as the eye cannot distinguish them from monochromatic sources. For example, most computer displays reproduce the spectral color orange as a combination of red and green light; it appears orange because the red and green are mixed in the right proportions to allow the eye's red and green cones to respond the way they do to orange.

A useful concept in understanding the perceived color of a non-monochromatic light source is the dominant wavelength, which identifies the single wavelength of light that produces a sensation most similar to the light source. Dominant wavelength is roughly akin to hue.

There are many color perceptions that by definition cannot be pure spectral colors due to desaturation or because they are purples (mixtures of red and violet light, from opposite ends of the spectrum). Some examples of necessarily non-spectral colors are the achromatic colors (black, gray and white) and colors such as pink, tan, and magenta.

Two different light spectra that have the same effect on the three color receptors in the human eye will be perceived as the same color. This is exemplified by the white light emitted by fluorescent lamps, which typically has a spectrum of a few narrow bands, while daylight has a continuous spectrum. The human eye cannot tell the difference between such light spectra just by looking into the light source, although reflected colors from objects can look different. (This is often exploited e.g., to make fruit or tomatoes look more intensely red.)

Similarly, most human color perceptions can be generated by a mixture of three colors called *primaries*. This is used to reproduce color scenes in photography, printing, television and other media. There are a number of methods or color spaces for specifying a color in terms of three particular primary colors. Each method has its advantages and disadvantages depending on the particular application.

No mixture of colors, though, can produce a fully pure color perceived as completely identical to a spectral color, although one can get very close for the longer wavelengths, where the chromaticity diagram above has a nearly straight edge. For example, mixing green light (530 nm) and blue light (460 nm) produces cyan light that is slightly desaturated, because response of the red color receptor would be greater to the green and blue light in the mixture than it would be to a pure cyan light at 485 nm that has the same intensity as the mixture of blue and green.

Because of this, and because the *primaries* in color printing systems generally are not pure themselves, the colors reproduced are never perfectly saturated colors, and so spectral colors cannot be matched exactly. However, natural scenes rarely contain fully saturated colors, thus such scenes can usually be approximated well by these systems. The range of colors that can be reproduced with a given color reproduction system is called the gamut. The CIE chromaticity diagram can be used to describe the gamut.

Another problem with color reproduction systems is connected with the acquisition devices, like cameras or scanners. The characteristics of the color sensors in the devices are often very far from the characteristics of the receptors in the human eye. In effect, acquisition of colors that have some special, often very "jagged," spectra caused for example by unusual lighting of the photographed scene can be relatively poor.

Species that have color receptors different from humans, e.g. birds that may have four receptors, can differentiate some colors that look the same to a human. In such cases, a color reproduction system 'tuned' to a human with normal color vision may give very inaccurate results for the other observers.

The different color response of different devices can be problematic if not properly managed. For color information stored and transferred in digital form, color management techniques, such as those based on ICC profiles, can help to avoid distortions of the reproduced colors. Color management does not circumvent the gamut limitations of particular output devices, but can assist in finding good mapping of input colors into the gamut that can be reproduced.

## *Pigments and reflective media*

Pigments are chemicals that selectively absorb and reflect different spectra of light. When a surface is painted with a pigment, light hitting the surface is reflected, minus some wavelengths. This subtraction of wavelengths produces the appearance of different colors. Most paints are a blend of several chemical pigments, intended to produce a reflection of a given color.

Pigment manufacturers assume the source light will be white, or of roughly equal intensity across the spectrum. If the light is not a pure white source (as in the case of nearly all forms of artificial lighting), the resulting spectrum will appear a slightly different color. Red paint, viewed under blue light, may appear black. Red paint is red because it reflects only the red components of the spectrum. Blue light, containing none of these, will create no reflection from red paint, creating the appearance of black.

## *Structural color*

Structural colors are colors caused by interference effects rather than by pigments. Color effects are produced when a material is scored with fine parallel lines, formed of one or more parallel thin layers, or otherwise composed of microstructures on the scale of the color's wavelength. If the microstructures are spaced randomly, light of shorter wavelengths will be scattered preferentially to produce Tyndall effect colors: the blue of the sky (Rayleigh scattering, caused by structures much smaller than the wavelength of light, in this case air molecules), the luster of opals, and the blue of human irises. If the microstructures are aligned in arrays, for example the array of pits in a CD, they behave as a diffraction grating: the grating reflects different wavelengths in different directions due to interference phenomena, separating mixed "white" light into light of different wavelengths. If the structure is one or more thin layers then it will reflect some wavelengths and transmit others, depending on the layers' thickness.

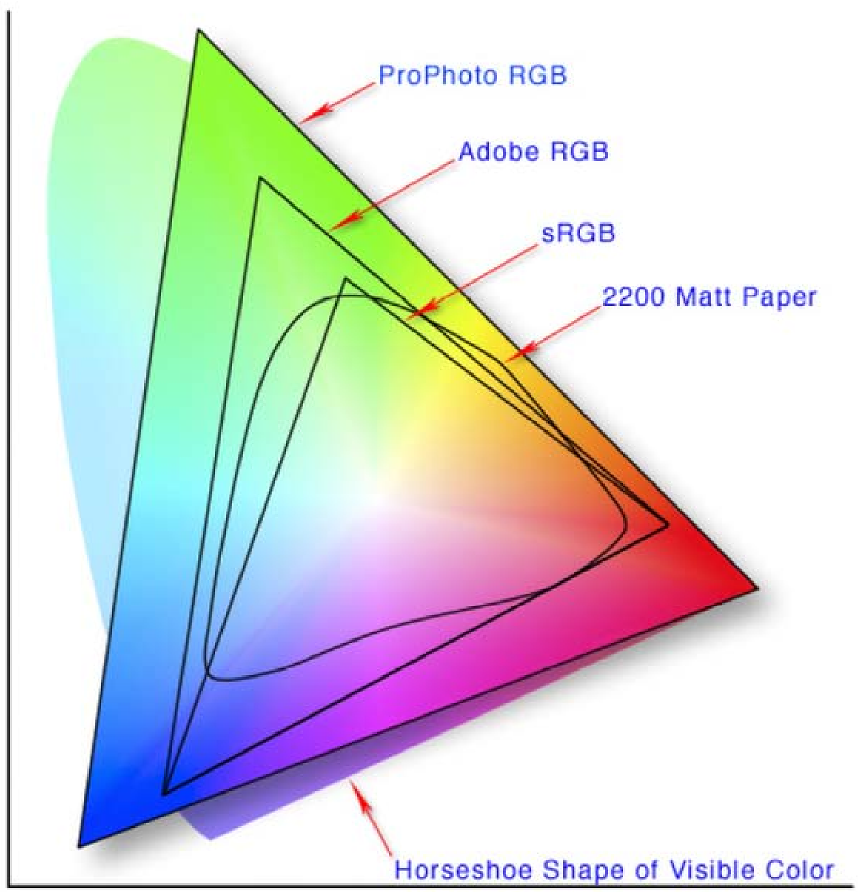
Structural color is studied in the field of thin-film optics. A layman's term that describes particularly the most ordered or the most changeable structural colors is iridescence. Structural color is responsible for the blues and greens of the feathers of many birds (the blue jay, for example), as well as certain butterfly wings and beetle shells. Variations in the pattern's spacing often give rise to an iridescent effect, as seen in peacock feathers, soap bubbles, films of oil, and mother of pearl, because the reflected color depends upon the viewing angle. Numerous scientists have carried out research in butterfly wings and beetle shells, including Isaac Newton and Robert Hooke. Since 1942, electron micrography has been used, advancing the development of products that exploit structural color, such as "photonic" cosmetics.

### *Additional terms*

- Colorfulness, chroma, purity, or saturation: how "intense" or "concentrated" a color is.
- Dichromatism: a phenomenon where the hue is dependent on concentration and/or thickness of the absorbing substance.
- Hue: the color's direction from white, for example in a color wheel or chromaticity diagram.
- Shade: a color made darker by adding black.
- Tint: a color made lighter by adding white.
- Value, brightness, lightness, or luminosity: how light or dark a color is.

Chapter 2

# Color Space



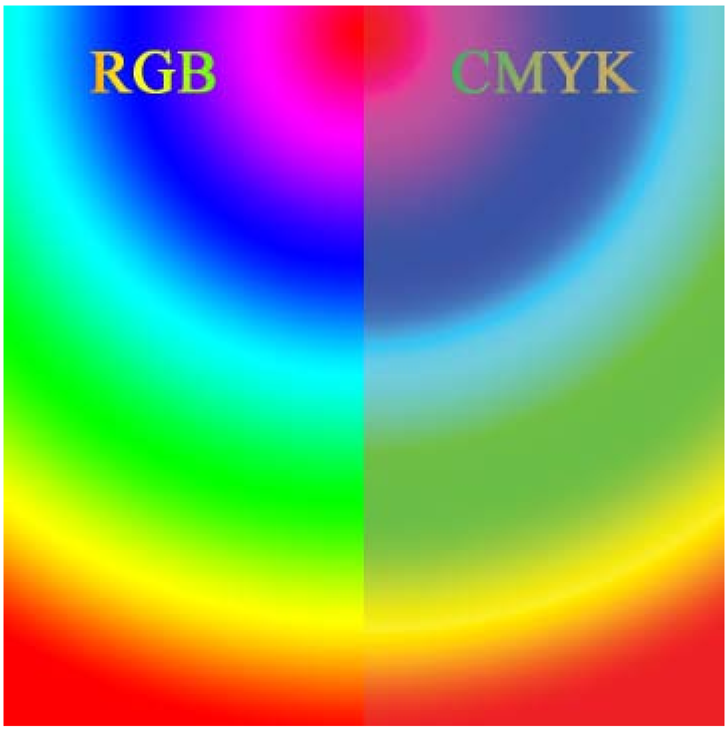

A comparison of the chromaticities enclosed by some color spaces.

A color model is an abstract mathematical model describing the way colors can be represented as tuples of numbers, typically as three or four values or *color components* (e.g. RGB and CMYK are color models). However, a color model with no associated mapping function to an absolute color space is a more or less arbitrary color system with no connection to any globally-understood system of color interpretation.

Adding a certain mapping function between the color model and a certain reference color space results in a definite "footprint" within the reference color space. This "footprint" is known as a gamut, and, in combination with the color model, defines a new **color space**. For example, Adobe RGB and sRGB are two different absolute color spaces, both based on the RGB model.

In the most generic sense of the definition above, color spaces can be defined without the use of a color model. These spaces, such as Pantone, are in effect a given set of names or numbers which are defined by the existence of a corresponding set of physical color swatches.

## *Understanding the concept*




A comparison of RGB and CMYK color models. This image demonstrates the difference between how colors will look on a computer monitor (RGB) compared to how they will reproduce in a CMYK print process.

A wide range of colors can be created by the primary colors of pigment (cyan (C), magenta (M), yellow (Y), and black (K)). Those colors then define a specific color space. To create a three-dimensional representation of a color space, we can assign the amount of magenta color to the representation's X axis, the amount of cyan to its Y axis, and the amount of yellow to its Z axis. The resulting 3-D space provides a unique position for every possible color that can be created by combining those three pigments.

However, this is not the only possible color space. For instance, when colors are displayed on a computer monitor, they are usually defined in the RGB (red, green and blue) color space. This is another way of making nearly the same colors (limited by the reproduction medium, such as the phosphor (CRT) or filters and backlight (LCD)), and red, green and blue can be considered as the X, Y and Z axes. Another way of making the same colors is to use their Hue (X axis), their Saturation (Y axis), and their brightness Value (Z axis). This is called the HSV color space. Many color spaces can be represented as three-dimensional (X,Y,Z) values in this manner, but some have more, or fewer dimensions, and some cannot be represented in this way at all.

### Notes

When formally defining a color space, the usual reference standard is the CIELAB or CIEXYZ color spaces, which were specifically designed to encompass all colors the average human can see.

Since "color space" is a more specific term for a certain *combination* of a color model plus a mapping function, the term "color space" tends to be used to also identify color models, since identifying a color space automatically identifies the associated color model. Informally, the two terms are often used interchangeably, though this is strictly incorrect. For example, although several specific color spaces are based on the RGB model, there is no such thing as *the* RGB color space.

Since any color space defines colors as a function of the absolute reference frame, color spaces, along with device profiling, allow reproducible representations of color, in both analogue and digital representations.

### Conversion

Color space conversion is the translation of the representation of a color from one basis to another. This typically occurs in the context of converting an image that is represented in one color space to another color space, the goal being to make the translated image look as similar as possible to the original.

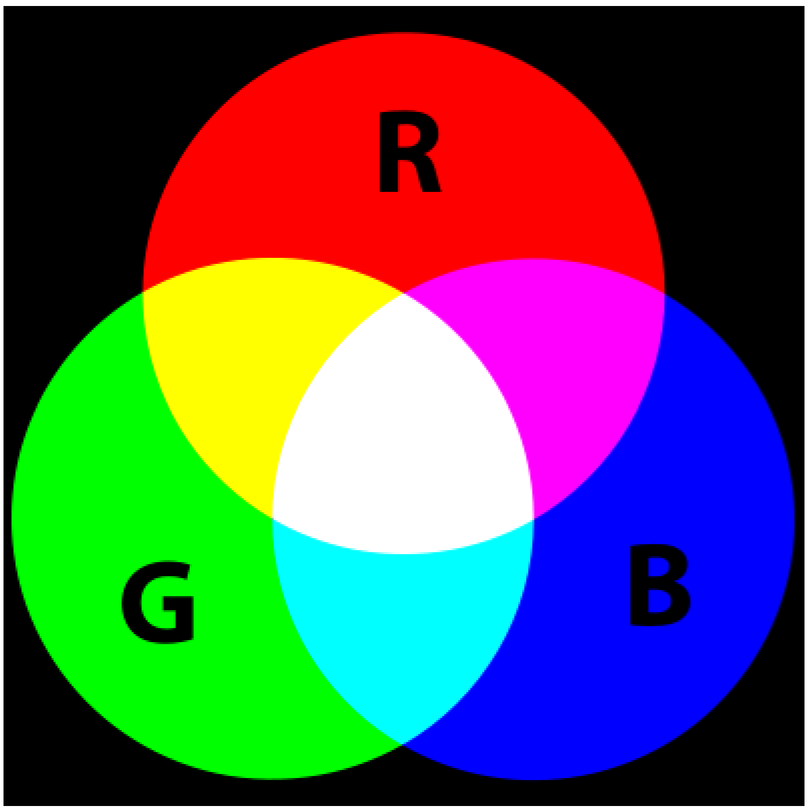
### Density

The RGB color model is implemented in different ways, depending on the capabilities of the system used. By far the most common general-used incarnation as of 2006 is the 24-bit implementation, with 8 bits, or 256 discrete levels of color per channel. Any color space based on such a 24-bit RGB model is thus limited to a range of $256 \times 256 \times 256 \approx 16.7$ million colors. Some implementations use 16 bits per component for 48 bits total, resulting in the same gamut with a larger number of distinct colors. This is especially important when working with wide-gamut color spaces (where most of the more common colors are located relatively close together), or when a large number of digital filtering algorithms are used consecutively. The same principle applies for any color space based on the same color model, but implemented in different bit depths.

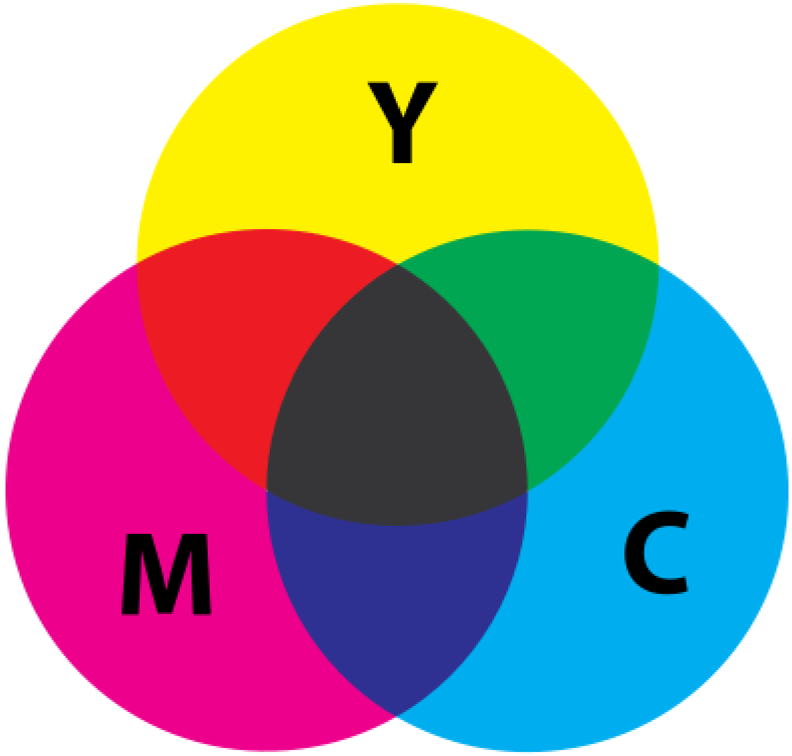
## *Partial list of color spaces*

CIE 1931 XYZ color space was one of the first attempts to produce a color space based on measurements of human color perception (earlier efforts were by James Clerk Maxwell, König & Dieterici, and Abney at Imperial College) and it is the basis for almost all other color spaces. Derivatives of the CIE XYZ space include CIELUV, CIEUVW, and CIELAB.

### Generic color models




Additive color mixing: Three overlapping lightbulbs in a vacuum, adding together to create white.




Subtractive color mixing: Three splotches of paint on white paper, subtracting together to turn the paper black.

RGB uses additive color mixing, because it describes what kind of *light* needs to be *emitted* to produce a given color. Light is added together to create form from out of the darkness. RGB stores individual values for red, green and blue. RGBA is RGB with an additional channel, alpha, to indicate transparency.

Common color spaces based on the RGB model include sRGB, Adobe RGB and ProPhoto RGB.

CMYK uses subtractive color mixing used in the printing process, because it describes what kind of inks need to be applied so the light *reflected* from the substrate and through the inks produces a given color. One starts with a white substrate (canvas, page, etc.), and uses ink to subtract color from white to create an image. CMYK stores ink values for cyan, magenta, yellow and black. There are many CMYK color spaces for different sets of inks, substrates, and press characteristics (which change the dot gain or transfer function for each ink and thus change the appearance).

YIQ was formerly used in NTSC (North America, Japan and elsewhere) television broadcasts for historical reasons. This system stores a luminance value with two chrominance values, corresponding approximately to the amounts of blue and red in the color. It is similar to the YUV scheme used in most video capture systems and in PAL (Australia, Europe, except France, which uses SECAM) television, except that the YIQ color space is rotated 33° with respect to the YUV color space. The YDbDr scheme used by SECAM television is rotated in another way.

YPbPr is a scaled version of YUV. It is most commonly seen in its digital form, YCbCr, used widely in video and image compression schemes such as MPEG and JPEG.

xvYCC is a new international digital video color space standard published by the IEC (IEC 61966-2-4). It is based on the ITU BT.601 and BT.709 standards but extends the gamut beyond the R/G/B primaries specified in those standards.

HSV (**h**ue, **s**aturation, **v**alue), also known as HSB (hue, saturation, **b**rightness) is often used by artists because it is often more natural to think about a color in terms of hue and saturation than in terms of additive or subtractive color components. HSV is a transformation of an RGB colorspace, and its components and colorimetry are relative to the RGB colorspace from which it was derived.

HSL (**h**ue, **s**aturation, **l**ightness/**l**uminance), also known as HLS or HSI (hue, saturation, **i**ntensity) is quite similar to HSV, with "lightness" replacing "brightness". The difference is that the *brightness* of a pure color is equal to the brightness of white, while the *lightness* of a pure color is equal to the lightness of a medium gray.

## Commercial color spaces

- Munsell color system
- Natural Color System (NCS)

## Special-purpose color spaces

- The RG Chromaticity space is used in Computer vision applications. It shows the color of light (red, yellow, green etc.), but not its intensity (dark, bright).

## Obsolete color spaces

Early color spaces had two components. They largely ignored blue light because the added complexity of a 3-component process provided only a marginal increase in fidelity when compared to the jump from monochrome to 2-component color.

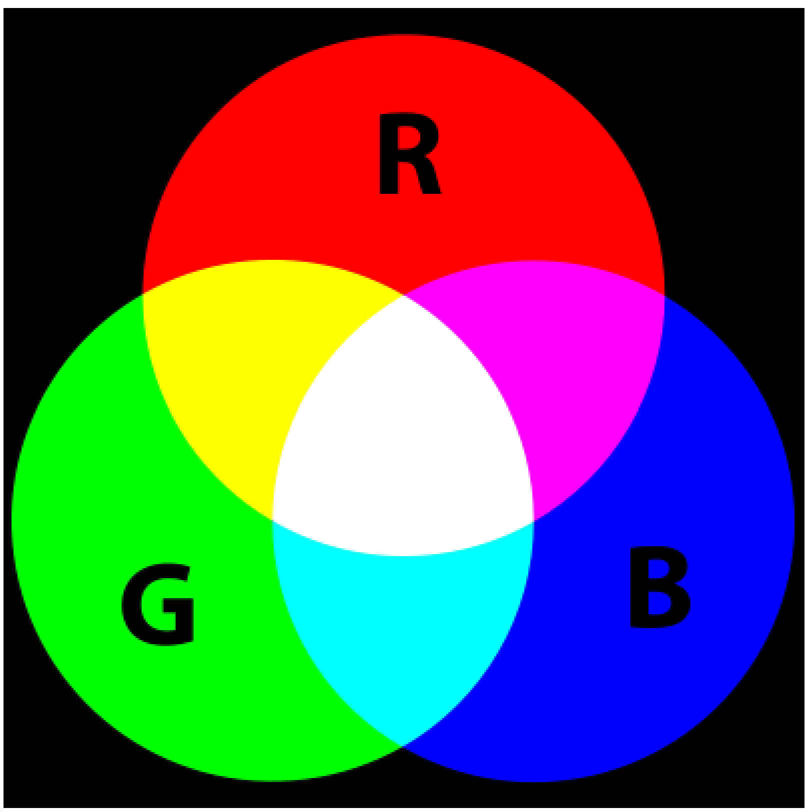
- RG for early Technicolor film
- RGK for early color printing

Chapter 3

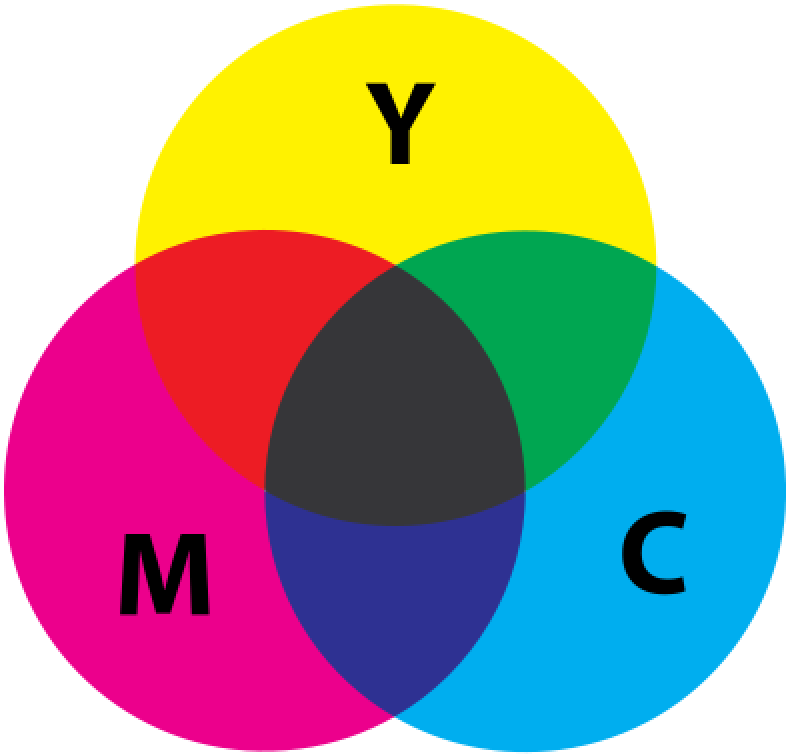
# Color Theory

In the visual arts, **color theory** is a body of practical guidance to color mixing and the visual impacts of specific color combinations. Although color theory principles first appeared in the writings of Leone Battista Alberti (c.1435) and the notebooks of Leonardo da Vinci (c.1490), a tradition of "colory theory" began in the 18th century, initially within a partisan controversy around Isaac Newton's theory of color (*Opticks*, 1704) and the nature of so-called primary colors. From there it developed as an independent artistic tradition with only superficial reference to colorimetry and vision science.

## *Color abstractions*




Additive color mixing




Subtractive color mixing

The foundations of pre-20th-century color theory were built around "pure" or ideal colors, characterized by sensory experiences rather than attributes of the physical world. This has led to a number of inaccuracies in traditional color theory principles that are not always remedied in modern formulations.

The most important problem has been a confusion between the behavior of light mixtures, called additive color, and the behavior of paint or ink or dye or pigment mixtures, called subtractive color. This problem arises because the absorption of light by material substances follows different rules from the perception of light by the eye.

A second problem has been the failure to describe the very important effects of strong luminance (lightness) contrasts in the appearance of surface colors (such as paints or inks) as opposed to light colors; "colors" such as browns or ochres cannot appear in light mixtures. Thus, a strong lightness contrast between a mid valued yellow paint and a surrounding bright white makes the yellow appear to be green or brown, while a strong brightness contrast between a rainbow and the surrounding sky makes the yellow in a rainbow appear to be a fainter yellow or white.

A third problem has been the tendency to describe color effects holistically or categorically, for example as a contrast between "yellow" and "blue" conceived as generic colors, when most color effects are due to contrasts on three relative attributes that define all colors:

1. lightness (light vs. dark, or white vs. black),
2. saturation (intense vs. dull), and
3. hue (e.g., red, orange, yellow, green, blue or purple).

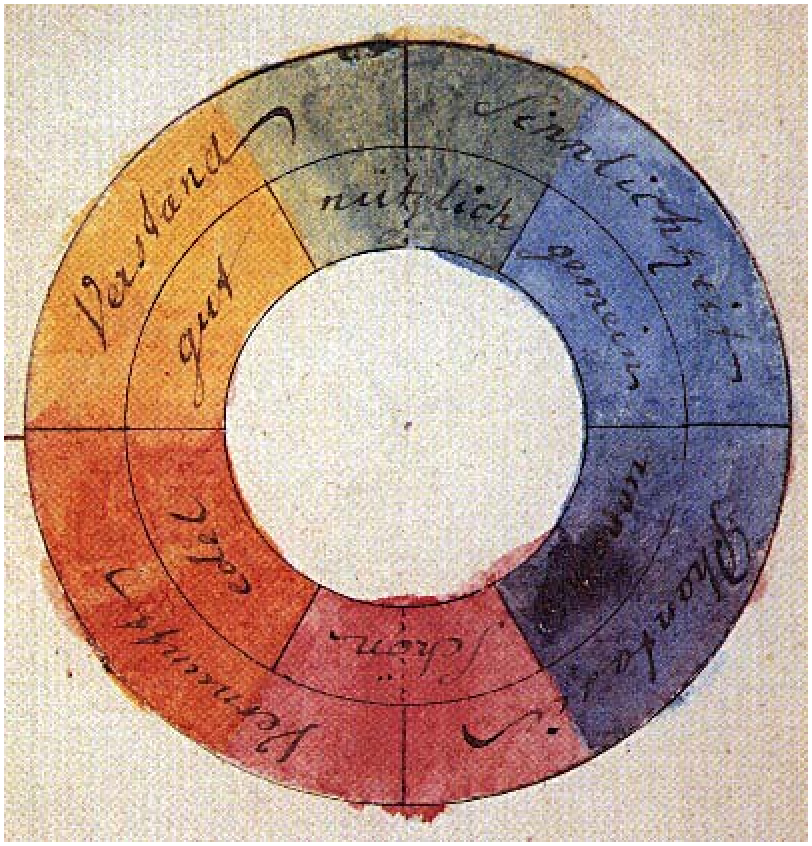
Thus, the visual impact of "yellow" vs. "blue" hues in visual design depends on the relative lightness and intensity of the hues.

These confusions are partly historical, and arose in scientific uncertainty about color perception that was not resolved until the late 19th century, when the artistic notions were already entrenched. However they also arise from the attempt to describe the highly contextual and flexible behavior of color perception in terms of abstract color sensations that can be generated equivalently by any visual media.

Many historical "color theorists" have assumed that three "pure" primary colors can mix *all possible colors*, and that any failure of specific paints or inks to match this ideal performance is due to the impurity or imperfection of the colorants. In reality, only imaginary "primary colors" used in colorimetry can "mix" or quantify all visible (perceptually possible) colors; but to do this the colors are defined as lying outside the range of visible colors: they cannot be seen. Any three real "primary" colors of light, paint or ink can mix only a limited range of colors, called a gamut, which is always smaller (contains fewer colors) than the full range of colors humans can perceive.

## Historical background

Color theory was originally formulated in terms of three "primary" or "primitive" colors—red, yellow and blue (RYB)—because these colors were believed capable of mixing all other colors. This color mixing behavior had long been known to printers, dyers and painters, but these trades preferred pure pigments to primary color mixtures, because the mixtures were too dull (unsaturated).

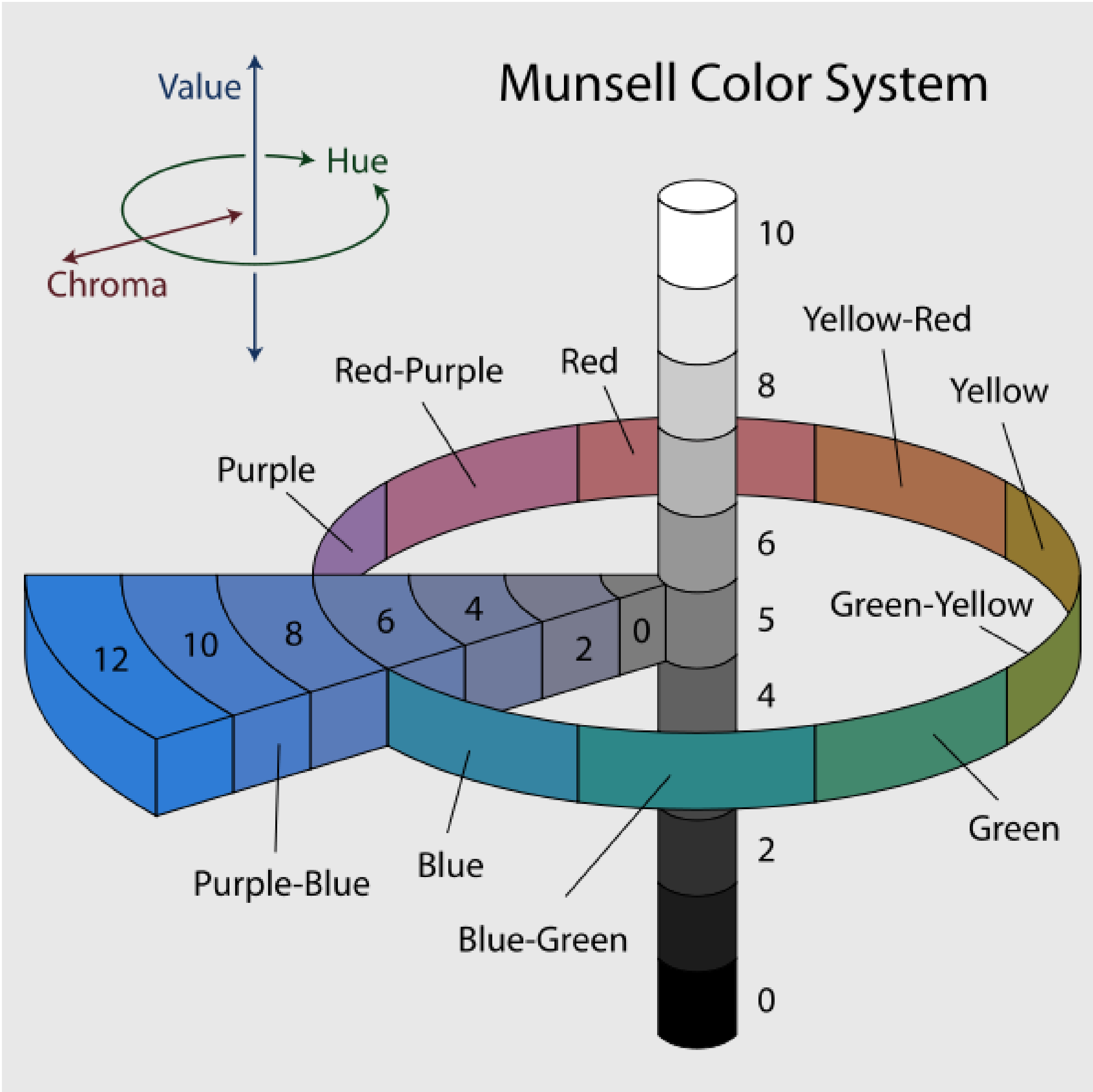



Goethe's color wheel from his 1810 *Theory of Colours*

The RYB primary colors became the foundation of 18th century theories of color vision, as the fundamental sensory qualities that are blended in the perception of all physical colors and equally in the physical mixture of pigments or dyes. These theories were enhanced by 18th-century investigations of a variety of purely psychological color effects, in particular the contrast between "complementary" or opposing hues that are produced by color afterimages and in the contrasting shadows in colored light. These ideas and many personal color observations were summarized in two founding documents in color theory: the *Theory of Colours* (1810) by the German poet and government minister Johann Wolfgang von Goethe, and *The Law of Simultaneous Color Contrast* (1839) by the French industrial chemist Michel Eugène Chevreul.

Subsequently, German and English scientists established in the late 19th century that color perception is best described in terms of a different set of primary colors—red, green and blue violet (RGB)—modeled through the additive mixture of three monochromatic lights. Subsequent research anchored these primary colors in the differing responses to light by three types of color receptors or *cones* in the retina (trichromacy). On this basis the quantitative description of color mixture or colorimetry developed in the early 20th century, along with a series of increasingly sophisticated models of color space and color perception, such as the opponent process theory.

Across the same period, industrial chemistry radically expanded the color range of lightfast synthetic pigments, allowing for substantially improved saturation in color mixtures of dyes, paints and inks. It also created the dyes and chemical processes necessary for color photography. As a result three-color printing became aesthetically and economically feasible in mass printed media, and the artists' color theory was adapted to primary colors most effective in inks or photographic dyes: cyan, magenta, and yellow (CMY). (In printing, dark colors are supplemented by a black ink, known as the CMYK system; in both printing and photography, white is provided by the color of the paper.) These CMY primary colors were reconciled with the RGB primaries, and subtractive color mixing with additive color mixing, by defining the CMY primaries as substances that *absorbed* only one of the retinal primary colors: cyan absorbs only red (−R+G+B), magenta only green (+R−G+B), and yellow only blue violet (+R+G−B). It is important to add that the CMYK, or process, color printing is meant as an economical way of producing a wide range of colors for printing, but is deficient in reproducing certain colors, notably orange and slightly deficient in reproducing purples. A wider range of color can be obtained with the addition of other colors to the printing process, such as in Pantone's Hexachrome printing ink system (six colors), among others.




Munsell's color system represented as a three-dimensional solid showing all three color making attributes: *lightness*, *saturation* and *hue*.

For much of the 19th century artistic color theory either lagged behind scientific understanding or was augmented by science books written for the lay public, in particular *Modern Chromatics* (1879) by the American physicist Ogden Rood, and early color atlases developed by Albert Munsell and Wilhelm Ostwald (Color Atlas, 1919). Major advances were made in the early 20th century by artists teaching or associated with the German Bauhaus, in particular Wassily Kandinsky, Johannes Itten, Faber Birren and Josef Albers, whose writings mix speculation with an empirical or demonstration-based study of color design principles.

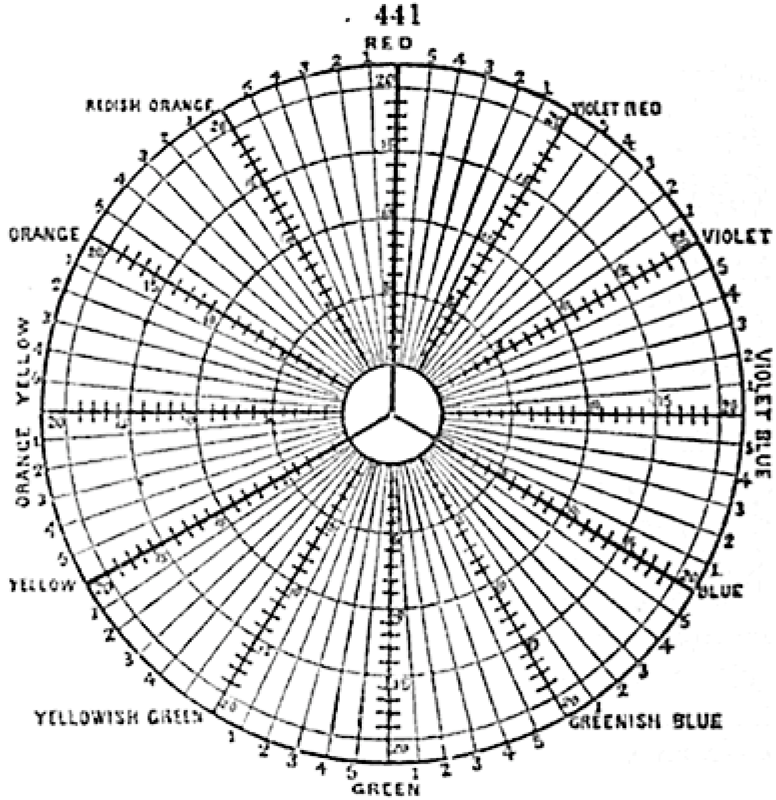
Contemporary color theory must address the expanded range of media created by digital media and print management systems, which substantially expand the range of imaging systems and viewing contexts in which color can be used. These applications are areas of intensive research, much of it proprietary; artistic color theory has little to say about these complex new opportunities.

## *Traditional color theory*

### Complementary colors

800. **Chevreul's classification of colors, and chromatic diagram.**—The chromatic diagram, of Chevreul, fig. 441, greatly

441

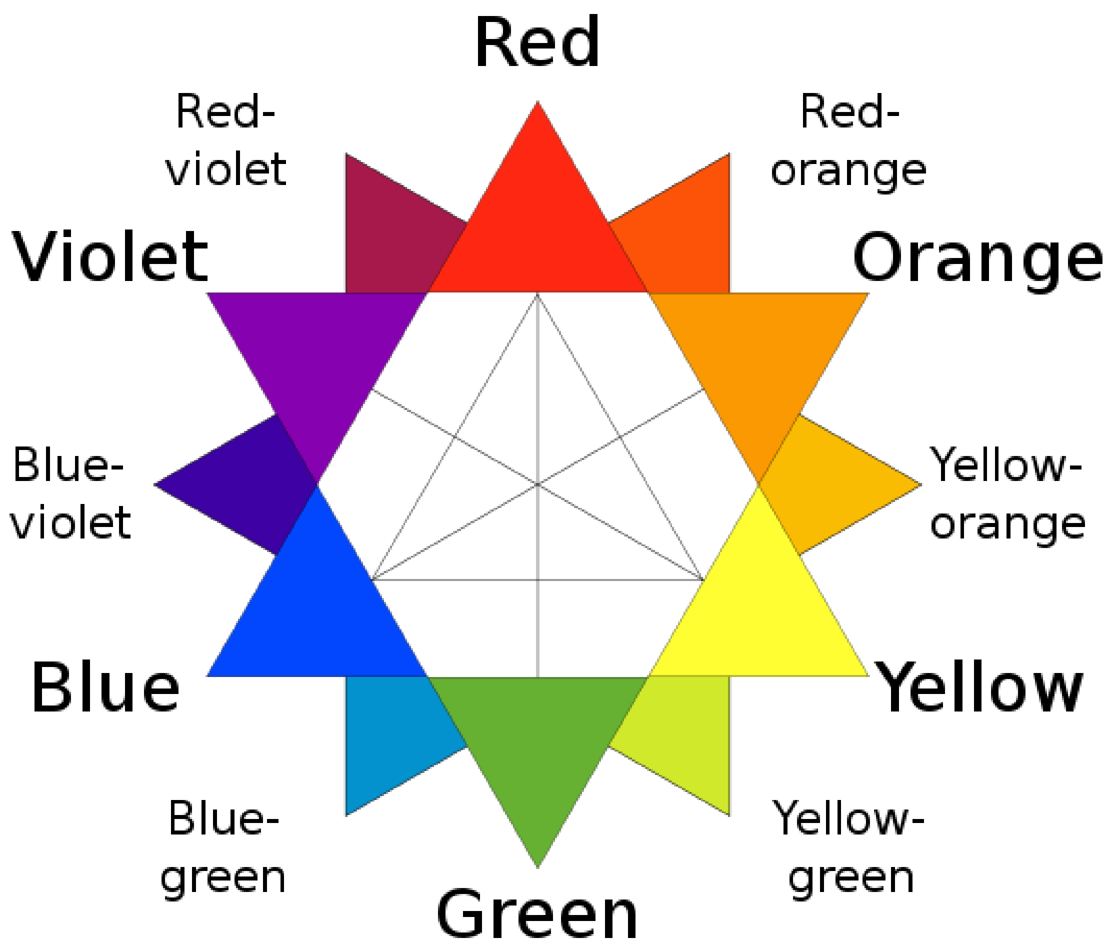



**facilitates the study of complementary colors, and the modifications produced by their mutual proximity.**

Chevreul's 1855 "chromatic diagram" based on the RYB color model, showing complementary colors and other relationships

For the mixing of colored light, Newton's color wheel is often used to describe complementary colors, which are colors which cancel each other's hue to produce an achromatic (white, gray or black) light mixture. Newton offered as a conjecture that colors exactly opposite one another on the hue circle cancel out each other's hue; this concept was demonstrated more thoroughly in the 19th century.

A key assumption in Newton's hue circle was that the "fiery" or maximum saturated hues are located on the outer circumference of the circle, while achromatic white is at the center. Then the saturation of the mixture of two spectral hues was predicted by the straight line between them; the mixture of three colors was predicted by the "center of gravity" or centroid of three triangle points, and so on.




Primary, secondary, and tertiary colors of the RYB color model

According to traditional color theory based on subtractive primary colors and the RYB color model, which is derived from paint mixtures, yellow mixed with violet, orange mixed with blue, or red mixed with green produces an equivalent gray and are the painter's complementary colors. These contrasts form the basis of Chevreul's law of color contrast: colors that appear together will be altered as if mixed with the complementary color of the other color. Thus, a piece of yellow fabric placed on a blue background will appear tinted orange, because orange is the complementary color to blue.

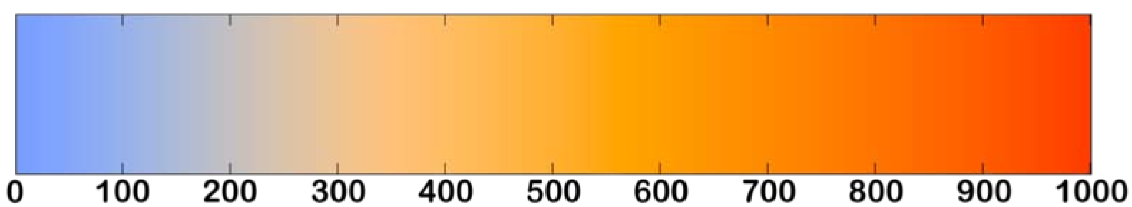
Unfortunately, the artists' primary colors are not the same as complementary colors defined by light mixtures. This discrepancy becomes important when color theory is applied across media. Digital color management uses a hue circle defined around the additive primary colors (the RGB color model), as the colors in a computer monitor are additive mixtures of light, not subtractive mixtures of paints.

## Warm vs. cool colors

The distinction between *warm* and *cool* colors has been important since at least the late 18th century but is generally not remarked in modern color science or colorimetry in reference to painting, but is still used in design practices today. The contrast, as traced by etymologies in the Oxford English Dictionary, seems related to the observed contrast in landscape light, between the "warm" colors associated with daylight or sunset and the "cool" colors associated with a gray or overcast day. Warm colors are often said to be hues from red through yellow, browns and tans included; cool colors are often said to be the hues from blue green through blue violet, most grays included. There is historical disagreement about the colors that anchor the polarity, but 19th century sources put the peak contrast between red orange and greenish blue.

Color theory has ascribed perceptual and psychological effects to this contrast. Warm colors are said to advance or appear more active in a painting, while cool colors tend to recede; used in interior design or fashion, warm colors are said to arouse or stimulate the viewer, while cool colors calm and relax. Most of these effects, to the extent they are real, can be attributed to the higher saturation and lighter value of warm pigments in contrast to cool pigments. Thus, brown is a dark, unsaturated warm color that few people think of as visually active or psychologically arousing.

Compare the traditional warm–cool association of color with the color temperature of a theoretical radiating black body, where the association of color with temperature is reversed. For instance, the hottest stars radiate blue light (i.e., with shorter wavelength and higher frequency) and the coolest radiate red.




The hottest radiating bodies (e.g. stars) have a "cool" color while the less hot bodies radiate with a "warm" color. (Image in mired scale.)

## Achromatic colors

Any color that lacks strong chromatic content is said to be *unsaturated*, *achromatic*, or near *neutral*. Pure achromatic colors include black, white and all grays; near neutrals include browns, tans, pastels and darker colors. Near neutrals can be of any hue or lightness.

*Neutrals* are obtained by mixing pure colors with either white or black, or by mixing two complementary colors. In color theory, neutral colors are colors easily modified by adjacent more saturated colors and they appear to take on the hue complementary to the saturated color. Next to a bright red couch, a gray wall will appear distinctly greenish.

Black and white have long been known to combine well with almost any other colors; black increases the apparent *saturation* or *brightness* of colors paired with it, and white shows off all hues to equal effect.

## Tints and shades

When mixing colored light (additive color models), the achromatic mixture of spectrally balanced red, green and blue (RGB) is always white, not gray or black. When we mix colorants, such as the pigments in paint mixtures, a color is produced which is always darker and lower in chroma, or saturation, than the parent colors. This moves the mixed color toward a neutral color—a gray or near-black. Lights are made brighter or dimmer by adjusting their brightness, or energy level; in painting, lightness is adjusted through mixture with white, black or a color's complement.

It is common among some painters to darken a paint color by adding black paint—producing colors called *shades*—or lighten a color by adding white—producing colors called *tints*. However it is not always the best way for representational painting, as an unfortunate result is for colors to also shift in hue. For instance, darkening a color by adding black can cause colors such as yellows, reds and oranges, to shift toward the greenish or bluish part of the spectrum. Lightening a color by adding white can cause a shift towards blue when mixed with reds and oranges. Another practice when darkening a color is to use its opposite, or complementary, color (e.g. purplish-red added to yellowish-green) in order to neutralize it without a shift in hue, and darken it if the additive color is darker than the parent color. When lightening a color this hue shift can be corrected with the addition of a small amount of an adjacent color to bring the hue of the mixture back in line with the parent color (e.g. adding a small amount of orange to a mixture of red and white will correct the tendency of this mixture to shift slightly towards the blue end of the spectrum).

## Split primary colors

In painting and other visual arts, two-dimensional color wheels or three-dimensional color solids are used as tools to teach beginners the essential relationships between colors. The organization of colors in a particular color model depends on the purpose of that model: some models show relationships based on Human color perception, whereas others are based on the color mixing properties of a particular medium such as a computer display or set of paints.

This system is still popular among contemporary painters, as it is basically a simplified version of Newton's geometrical rule that colors closer together on the hue circle will produce more vibrant mixtures. However, with the range of contemporary paints available, many artists simply add more paints to their palette as desired for a variety of practical reasons. For example, they may add a scarlet, purple and/or green paint to expand the mixable gamut; and they include one or more dark colors (especially "earth" colors such as yellow ochre or burnt sienna) simply because they are convenient to have premixed. Printers commonly augment a CYMK palette with spot (trademark specific) ink colors.

## Color harmony and color meaning

It has been suggested that "Colors seen together to produce a pleasing affective response are said to be in harmony". However, color harmony is a somewhat misleading notion in that responses to color can be influenced by a range of different factors including individual differences (age, gender, etc.); cultural and social differences; as well as contextual, temporal and perceptual factors. The following conceptual model illustrates this approach to color harmony:

$$\text{Color harmony} = f(\text{Col } 1, 2, 3\ldots n) * (ID+CE+CX+P+T)$$

Wherein color harmony is a function (*f*) of the interaction between color/s (Col1,2,3...n) and the factors that influence positive aesthetic response to color: individual differences (ID) such as age, gender, personality and affective state; cultural experiences (CE), the prevailing context (CX) which includes setting and ambient lighting; intervening perceptual effects (P) and the effects of time (T) in terms of prevailing social trends.

In addition, given that humans can perceive over 2.8 million different hues, it has been suggested that the number of possible color combinations is virtually infinite thereby implying that predictive color harmony formulae are fundamentally unsound. Despite this, many color theorists have devised formulae, principles or guidelines for color combination with the aim being to predict or specify positive aesthetic response or 'color harmony'. Color wheel models have often been used as a basis for color combination principles or guidelines and for defining relationships between colors. Some theorists and artists believe juxtapositions of complementary color will produce strong contrast, a sense of visual tension as well as 'color harmony'; while others believe juxtapositions of analogous colors will elicit positive aesthetic response. Color combination guidelines suggest that colors next to each other on the color wheel model (analogous colors) tend to produce a single-hued or monochromatic color experience and some theorists also refer to these as 'simple harmonies'. In addition, split complementary color schemes usually depict a range of analogous hues plus a key complementary color. A triadic color scheme adopts any three colors approximately equidistant around a color wheel model. Feisner and Mahnke are among a number of authors who provide color combination guidelines in greater detail.

Color combination formulae and principles may provide some guidance but have limited practical application. This is because of the influence of contextual, perceptual and temporal factors which will influence how color/s are perceived in any given situation, setting or context. Such formulae and principles may be useful in fashion, interior and graphic design, but much depends on the tastes, lifestyle and cultural norms of the viewer or consumer.

As early as the ancient Greek philosophers, many theorists have devised color associations and linked particular connotative meanings to specific colors. However, connotative color associations and color symbolism tends to be culture-bound and may also vary across different contexts and circumstances. For example, red has many different connotative and symbolic meanings from exciting, arousing, sensual, romantic and feminine; to a symbol of good luck; and also acts as a signal of danger. Such color associations tend to be learned and do not necessarily hold irrespective of individual and cultural differences or contextual, temporal or perceptual factors. It is important to note that while color symbolism and color associations exist, their existence does not provide evidential support for color psychology or claims that color has therapeutic properties.

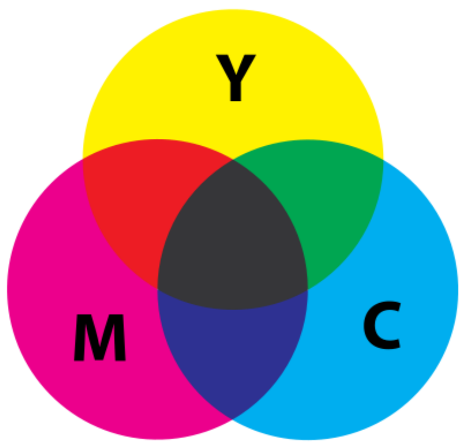
## *Current status*

Color theory has not developed an explicit explanation of how specific media affect color appearance: colors have always been defined in the abstract, and whether the colors were inks or paints, oils or watercolors, transparencies or reflecting prints, computer displays or movie theaters, was not considered especially relevant. Josef Albers investigated the effects of relative contrast and color saturation on the illusion of transparency, but this is an exception to the rule.

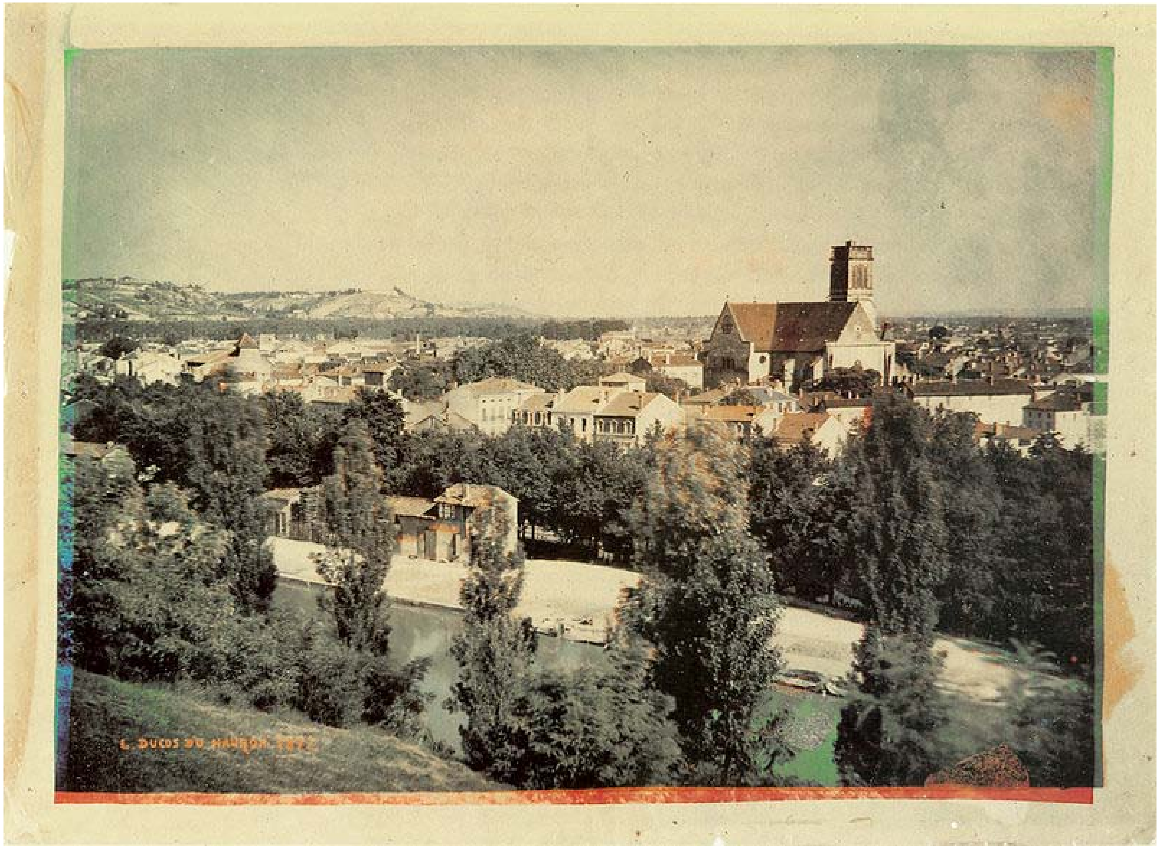
Chapter 4

# Subtractive Color & Additive Color

## Subtractive Color




Subtractive color mixing




An 1877 color photo by Louis Ducos du Hauron, a French pioneer of color photography. The overlapping, subtractive yellow, cyan and red (magenta) image elements can clearly be seen.

A **subtractive color** model explains the mixing of paints, dyes, inks, and natural colorants to create a full range of colors, each caused by subtracting (that is, absorbing) some wavelengths of light and reflecting the others. The color that a surface displays depends on which colors of the electromagnetic spectrum are reflected by it and therefore made visible.

Subtractive color systems start with light, presumably white light. Colored inks, paints, or filters between the viewer and the light source or reflective surface *subtract* wavelengths from the light, giving it color. If the incident light is other than white, our visual mechanisms are able to compensate well, but not perfectly, often giving a flawed impression of the "true" color of the surface.

Conversely, additive color systems start without light (black). Light sources of various wavelengths combine to make a color. In either type of system, three primary colors are combined to stimulate humans' trichromatic color vision, sensed by the three types of cone cells in the eye, giving an apparently full range.

## *RYB*

Standard RYB Color Wheel

RYB (Red, Yellow, Blue) is the formerly standard set of subtractive primary colors used for mixing pigments. It is used in art and art education, particularly in painting. It predated modern scientific color theory.

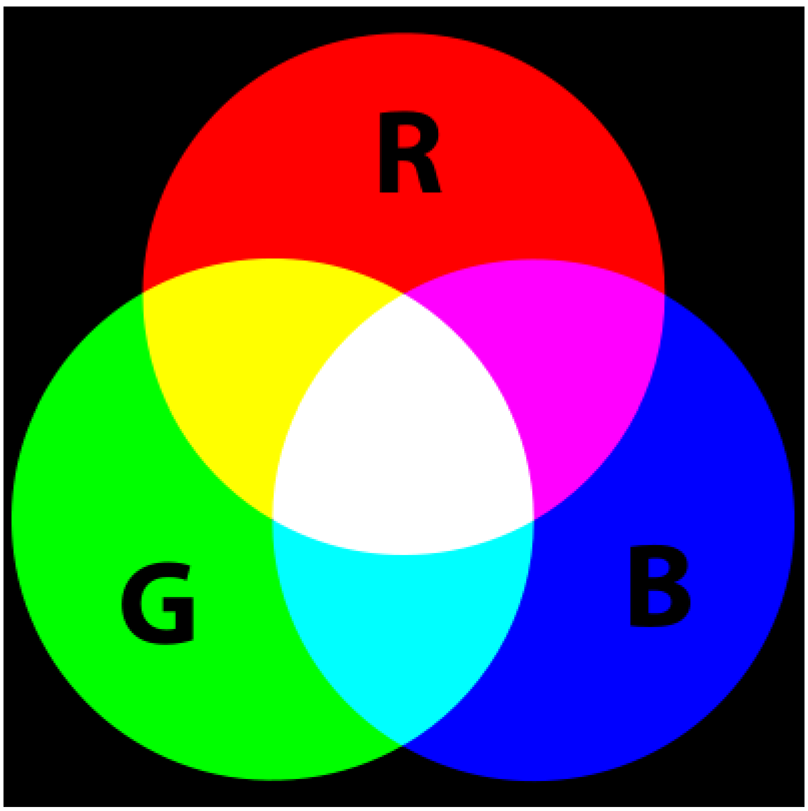
Red, yellow, and blue are the primary colors of the standard color "wheel". The secondary colors, violet (or purple), orange, and green (VOG) make up another triad, formed by mixing equal amounts of red and blue, red and yellow, and blue and yellow, respectively.

The RYB primary colors became the foundation of 18th century theories of color vision as the fundamental sensory qualities blended in the perception of all physical colors and equally in the physical mixture of pigments or dyes. These theories were enhanced by 18th-century investigations of a variety of purely psychological color effects, in particular the contrast between "complementary" or opposing hues produced by color afterimages and in the contrasting shadows in colored light. These ideas and many personal color observations were summarized in two founding documents in color theory: the *Theory of Colors* (1810) by the German poet and government minister Johann Wolfgang von Goethe, and *The Law of Simultaneous Color Contrast* (1839) by the French industrial chemist Michel-Eugène Chevreul.

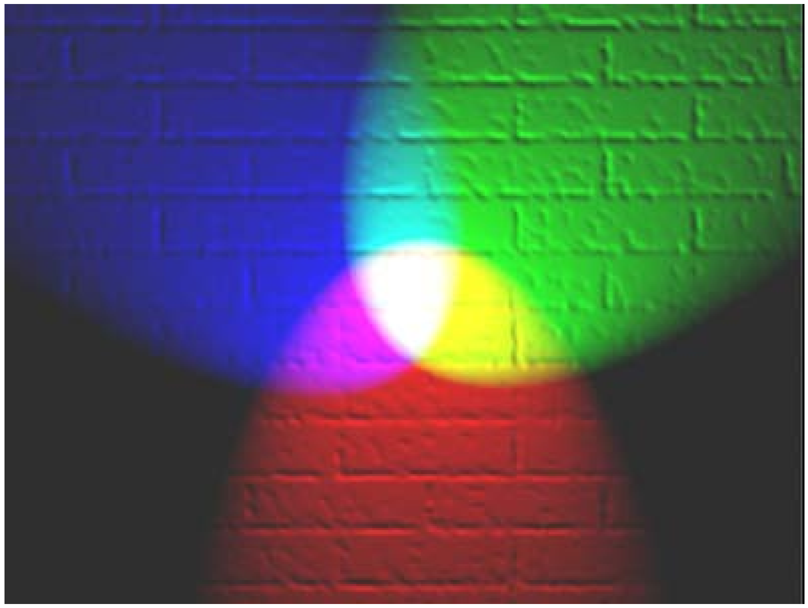
### *CMYK printing process*

In most color printing, the primary ink colors used are cyan, magenta, and yellow. Cyan is the complement of red, meaning that cyan acts like a filter that absorbs red. The amount of cyan applied to a paper will control how much red will show. Magenta is the complement of green, and yellow the complement of blue. Combinations of different amounts of the three inks can produce a wide range of colors; this is how artwork reproductions are mass-produced, although an under-toning of black ink is usually used as well. This mixture is called CMYK.

## Additive Color




Additive color mixing: adding red to green yields yellow; adding all three primary colors together yields white.

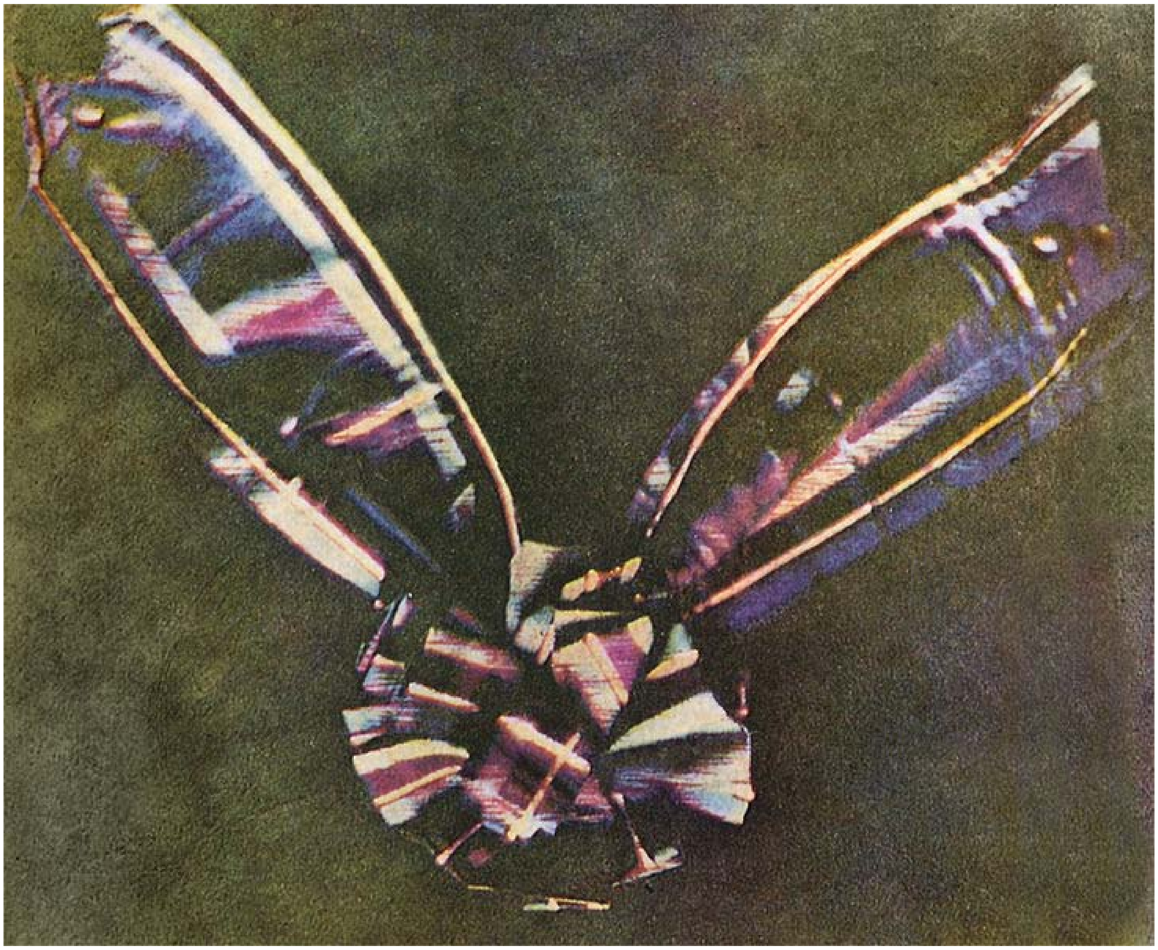


A rendered model, showing red, green and blue lights combining.

An **additive color** model involves light emitted directly from a source or illuminant of some sort. The additive reproduction process usually uses red, green and blue light to produce the other colors. Combining one of these additive primary colors with another in equal amounts produces the additive secondary colors cyan, magenta, and yellow. Combining all three primary lights (colors) in equal intensities produces white. Varying the luminosity of each light (color) eventually reveals the full gamut of those three lights (colors).

Computer monitors and televisions use a system called optical mixing and cannot be considered additive light because the colors do not overlap. The red green and blue pixels are side-by-side. When a green color appears, only the green pixels light up. When a cyan color appears, both green and blue pixels light up. When white appears all the pixels light up. Because the pixels are so small and close together our eyes blend them together, having a similar effect as additive light. Another common use of additive light is the projected light used in theatrical lighting (plays, concerts, circus shows, night clubs, etc.).

Results obtained when mixing additive colors are often counterintuitive for people accustomed to the more everyday subtractive color system of pigments, dyes, inks and other substances which present color to the eye by reflection rather than emission. For example, in subtractive color systems green is a combination of yellow and blue; in additive color, red + green = yellow and no simple combination will yield green. Additive color is a result of the way the eye detects color, and is not a property of light. There is a vast difference between yellow light, with a wavelength of approximately 580 nm, and a mixture of red and green light. However, both stimulate our eyes in a similar manner, so we do not detect that difference.



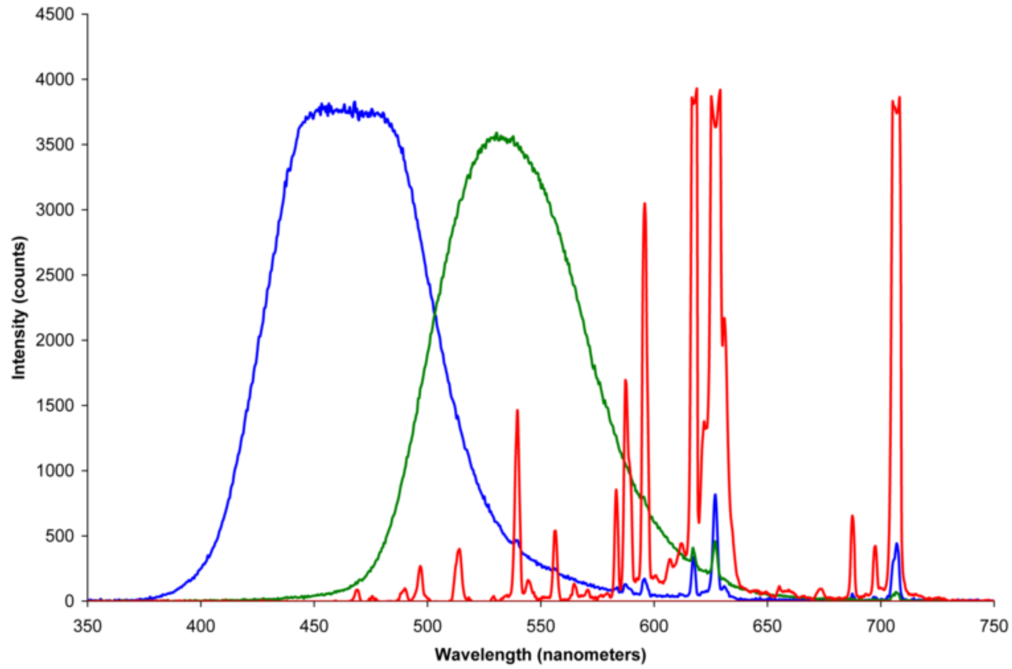
The first permanent color photograph, taken by James Clerk Maxwell in 1861.

James Clerk Maxwell with his color top that he used for investigation of color vision and additive color

James Clerk Maxwell is credited as being the father of additive color. He had the photographer Thomas Sutton photograph a tartan ribbon on black-and-white film three times, first with a red, then green, then blue color filter over the lens. The three black-and-white images were developed and then projected onto a screen with three different projectors, each equipped with the corresponding red, green, or blue color filter used to take its image. When brought into alignment, the three images (a black-and-red image, a black-and-green image and a black-and-blue image) formed a full color image, thus demonstrating the principles of additive color.

Chapter 5

# Primary Color




The emission spectra of the three phosphors that define the **additive primary colors** of a CRT color video display. Unlike subtractive systems that mix red, yellow, and blue paints, or magenta, yellow, and cyan inks, additive systems such as computer displays mix red, green, and blue light to make all colors.

**Primary colors** are sets of colors that can be combined to make a useful range of colors. For human applications, three primary colors are usually used, since human color vision is trichromatic.

For additive combination of colors, as in overlapping projected lights or in CRT displays, the primary colors normally used are red, green, and blue. For subtractive combination of colors, as in mixing of pigments or dyes, such as in printing, the primaries normally used are cyan, magenta, and yellow, though the set of red, yellow, blue is popular among artists.

Any choice of primary colors is essentially arbitrary; for example, an early color photographic process, autochrome, typically used orange, green, and violet primaries. However, unless negative amounts of a color are allowed the gamut will be restricted by the choice of primaries.

The combination of any two primary colors creates a secondary color.

The most commonly used additive color primaries are the secondary colors of the most commonly used subtractive color primaries, and vice versa.

## *Biological basis*

Primary colors are not a fundamental property of light but are often related to the physiological response of the eye to light. Fundamentally, light is a continuous spectrum of the wavelengths that can be detected by the human eye, an infinite-dimensional stimulus space. However, the human eye normally contains only three types of color receptors, called cone cells. Each color receptor responds to different ranges of the color spectrum. Humans and other species with three such types of color receptors are known as trichromats. These species respond to the light stimulus via a three-dimensional sensation, which generally can be modeled as a mixture of three primary colors.

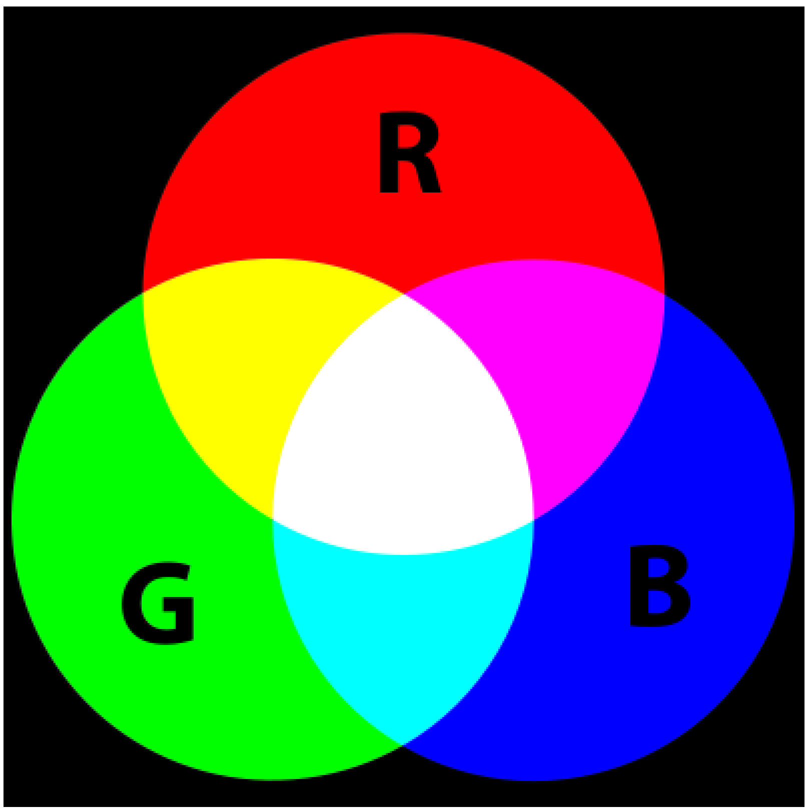
Before the nature of colorimetry and visual physiology were well understood, scientists such as Thomas Young, James Clark Maxwell, and Hermann von Helmholtz expressed various opinions about what should be the three primary colors to describe the three primary color sensations of the eye. Young originally proposed red, green, and violet, and Maxwell changed violet to blue; Helmholtz proposed "a slightly purplish red, a vegetation-green, slightly yellowish (wave-length about 5600 tenth-metres), and an ultramarine-blue (about 4820)". In modern understanding, the human cone cells do not correspond to any real primary colors.

Species with different numbers of receptor cell types would have color vision requiring a different number of primaries. For example, for species known as tetrachromats, with four different color receptors, one would use four primary colors. Since humans can only see to 380 nanometers (violet), but tetrachromats can see into the ultraviolet to about 300 nanometers, this fourth primary color for tetrachromats is located in the shorter-wavelength range.

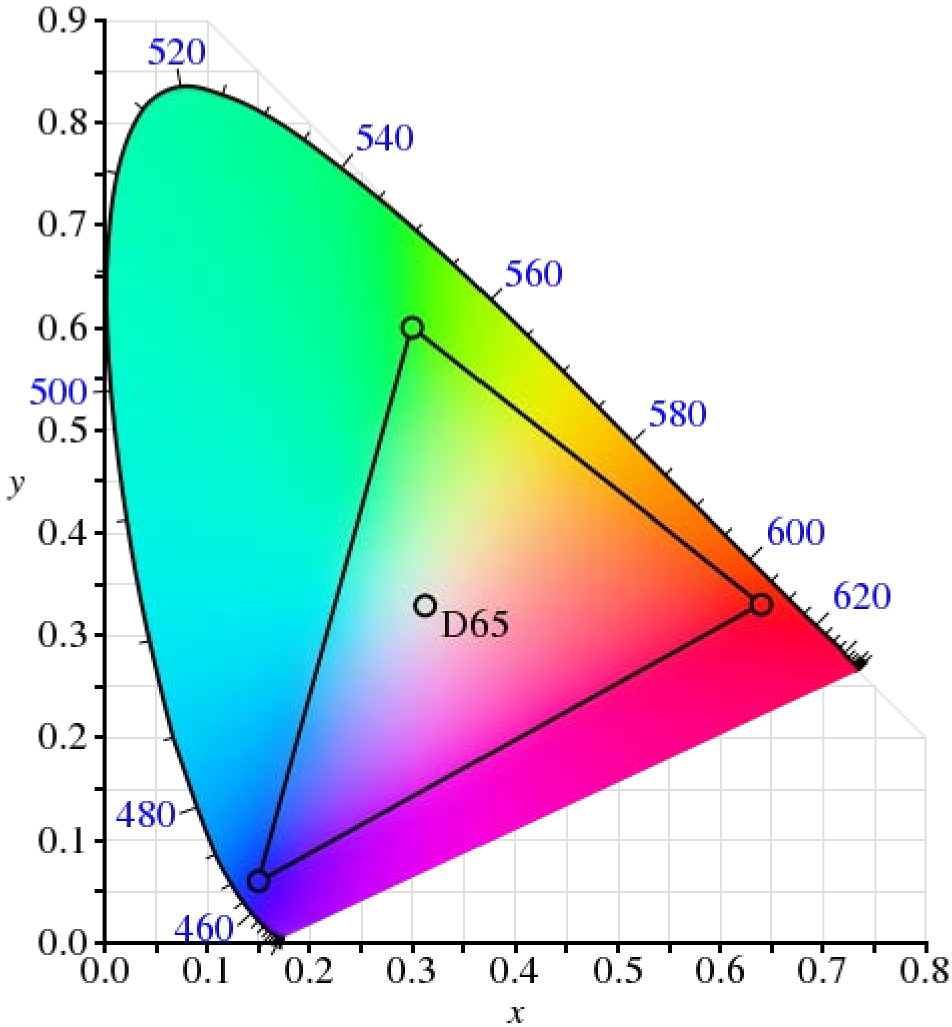
Many birds and marsupials are tetrachromats, and it has been suggested that some human females are tetrachromats as well, having an extra variant version of the long-wave (L) cone type. The peak response of human color receptors varies, even among individuals with "normal" color vision; in non-human species this polymorphic variation is even greater, and it may well be adaptive. Most mammals other than primates have only two types of color receptors and are therefore dichromats; to them, there are only two primary colors.

It would be incorrect to assume that the world "looks tinted" to an animal (or human) with anything other than the human standard of three color receptors. To an animal (or human) born that way, the world would look normal to it, but the animal's ability to detect and discriminate colors would be different from that of a human with normal color vision. If a human and an animal both look at a natural color, they see it as natural; however, if both look at a color reproduced via primary colors, such as on a color television screen, the human may see it as matching the natural color, while the animal does not, since the primary colors have been chosen to suit human capabilities.

### *Additive primaries*



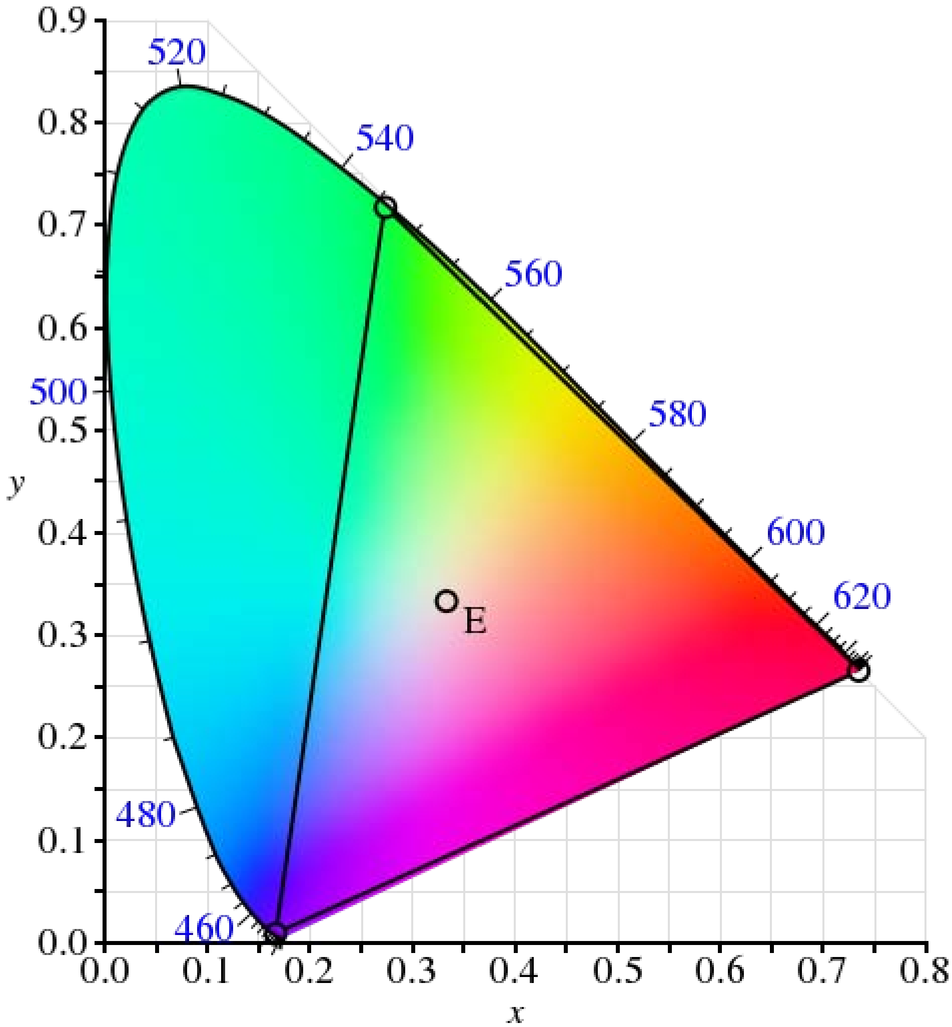

Additive color mixing




The sRGB color triangle

Media that combine emitted lights to create the sensation of a range of colors are using the additive color system. Typically, the primary colors used are red, green, and blue.

Television and other computer and video displays are a common example of the use of additive primaries and the RGB color model. The exact colors chosen for the primaries are a technological compromise between the available phosphors (including considerations such as cost and power usage) and the need for large color triangle to allow a large gamut of colors. The ITU-R BT.709-5/sRGB primaries are typical.




CIE 1931 RGB color triangle with monochromatic primaries

Additive mixing of red and green light produces shades of yellow, orange, or brown. Mixing green and blue produces shades of cyan, and mixing red and blue produces shades of purple, including magenta. Mixing nominally equal proportions of the additive primaries results in shades of grey or white; the color space that is generated is called an RGB color space.

The CIE 1931 color space defines *monochromatic* primary colors with wavelengths of 435.8 nm (violet), 546.1 nm (green) and 700 nm (red). The corners of the color triangle are therefore on the spectral locus, and the triangle is about as big as it can be. No real display device uses such primaries, as the extreme wavelengths used for violet and red result in a very low luminous efficiency.

## *Subtractive primaries*

Media that use reflected light and colorants to produce colors are using the subtractive color method of color mixing.

### Traditional

RYB (red, yellow, and blue) is a historical set of subtractive primary colors. It is primarily used in art and art education, particularly painting. It predates modern scientific color theory.

RYB color wheel

RYB make up the primary colors in a painter's color wheel; the secondary colors VOG (violet, orange, and green) make up another triad. Triads are formed by 3 equidistant colors on a particular color wheel; neither RYB nor VOG is equidistant on a perceptually uniform color wheel, but rather have been *defined* to be equidistant in the RYB wheel.

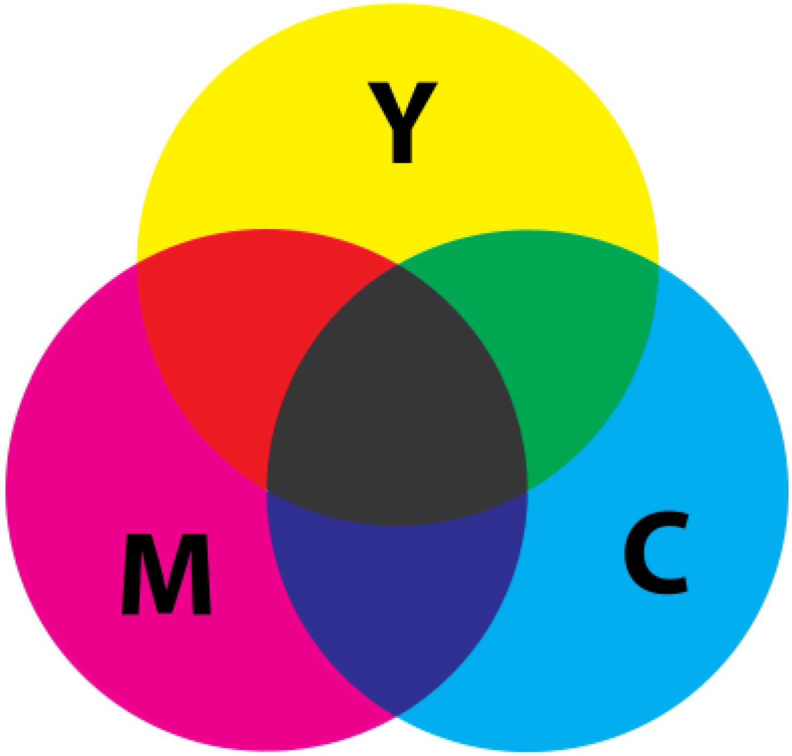
Painters have long used more than three "primary" colors in their palettes—and at one point considered red, yellow, blue, and green to be the *four* primaries. Red, yellow, blue, and green are still widely considered the four psychological primary colors, though red, yellow, and blue are sometimes listed as the *three* psychological primaries, with black and white occasionally added as a fourth and fifth.

During the 18th century, as theorists became aware of Isaac Newton's scientific experiments with light and prisms, red, yellow, and blue became the canonical primary colors—supposedly the fundamental sensory qualities that are blended in the perception of all physical colors and equally in the physical mixture of pigments or dyes. This theory became dogma, despite abundant evidence that red, yellow, and blue primaries cannot mix all other colors, and has survived in color theory to the present day.

Using red, yellow, and blue as primaries yields a relatively small gamut, in which, among other problems, colorful greens, cyans, and magentas are impossible to mix, because red, yellow, and blue are not well-spaced around a perceptually uniform color wheel. For this reason, modern three- or four-color printing processes, as well as color photography, use cyan, yellow, and magenta as primaries instead. Most painters include colors in their palettes which cannot be mixed from yellow, red, and blue paints, and thus do not fit within the RYB color model. Some who do use a three-color palette opt for the more evenly spaced cyan, yellow, and magenta used by printers, and others paint with 6 or more colors to widen their gamuts. The cyan, magenta, and yellow used in printing are sometimes known as "process blue," "process red," and "process yellow."

## CMYK color model, or four-color printing

In the printing industry, to produce the varying colors the **subtractive primaries** cyan, magenta, and yellow are applied together in varying amounts. Before the color names *cyan* and *magenta* were in common use, these primaries were often known as blue-green and purple, or in some circles as blue and red, respectively, and their exact color has changed over time with access to new pigments and technologies.




Subtractive color mixing – the magenta and cyan primaries are sometimes called purple and blue-green, or red and blue

Mixing yellow and cyan produces green colors; mixing yellow with magenta produces reds, and mixing magenta with cyan produces blues. In theory, mixing equal amounts of all three pigments should produce grey, resulting in black when all three are applied in sufficient density, but in practice they tend to produce muddy brown colors. For this reason, and to save ink and decrease drying times, a fourth pigment, black, is often used in addition to cyan, magenta, and yellow.

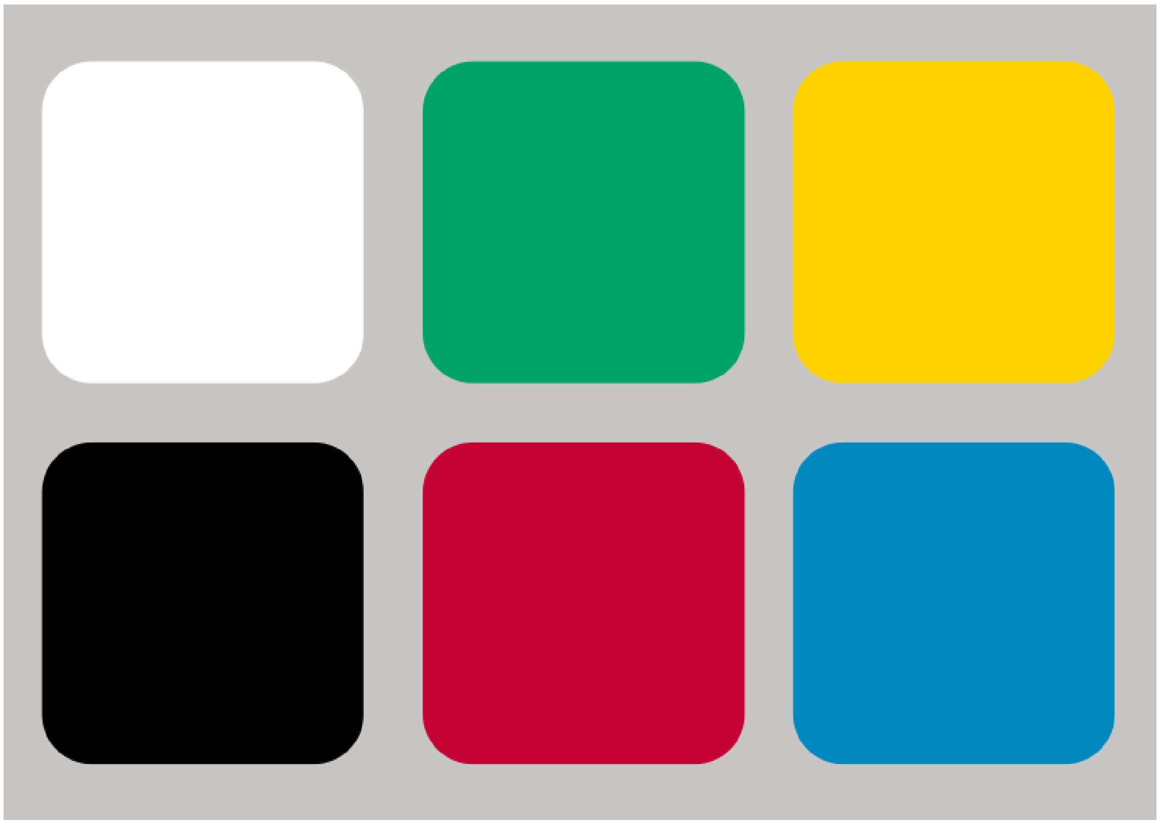
The resulting model is the so-called CMYK color model. The abbreviation stands for **c**yan, **m**agenta, **y**ellow, and **k**ey—black is referred to as the *key* color, a shorthand for the *key printing plate* that impressed the artistic detail of an image, usually in black ink.

In practice, colorant mixtures in actual materials such as paint tend to be more complex. Brighter or more saturated colors can be created using natural pigments instead of mixing, and natural properties of pigments can interfere with the mixing. For example, mixing magenta and green in acrylic creates a dark cyan—something which would not happen if the mixing process were perfectly subtractive.

In the subtractive model, adding white to a color, whether by using less colorant or by mixing in a reflective white pigment such as zinc oxide, does not change the color's hue but does reduce its saturation. Subtractive color printing works best when the surface or paper is white, or close to it.

A system of subtractive color does not have a simple chromaticity gamut analogous to the RGB color triangle, but a gamut that must be described in three dimensions. There are many ways to visualize such models, using various 2D chromaticity spaces or in 3D color spaces.

### *Psychological primaries*



Approximations within the sRGB gamut to the "aim colors" of the Natural Color System, a model based on the opponent process theory of color vision.

The opponent process is a color theory that states that the human visual system interprets information about color by processing signals from cones and rods in an antagonistic manner. The three types of cones have some overlap in the wavelengths of light to which they respond, so it is more efficient for the visual system to record *differences* between the responses of cones, rather than each type of cone's individual response. The opponent color theory suggests that there are three opponent channels: red versus green, blue versus yellow, and black versus white. Responses to one color of an opponent channel are antagonistic to those of the other color. The particular colors considered by an observer to be uniquely representative of the concepts red, yellow, green, blue, white, and black might be called "psychological primary colors", because any other color can be described in terms of some combination of these.

Chapter 6

# Colorfulness & Color Mixing

## Colorfulness

Original image, with relatively muted colors

L*C*h (CIELAB) chroma increased 50%

HSL saturation increased 50%; notice that changing HSL saturation also affects the perceived lightness of a color

CIELAB lightness preserved, with $a^*$ and $b^*$ stripped, to make a grayscale image

In colorimetry and color theory, **colorfulness**, **chroma**, and **saturation** are related but distinct concepts referring to the perceived intensity of a specific color. *Colorfulness* is the difference between a color against gray. *Chroma* is the colorfulness relative to the brightness of another color which appears white under similar viewing conditions. Saturation is the colorfulness of a color relative to its own brightness. Though this general concept is intuitive, terms such as *chroma*, *saturation*, *purity*, and *intensity* are often used without great precision, and even when well-defined depend greatly on the specific color model in use.

A highly colorful stimulus is vivid and intense, while a less colorful stimulus appears more muted, closer to gray. With no colorfulness at all, a color is a "neutral" gray (an image with no colorfulness in any of its colors is called *grayscale*). With three attributes—colorfulness (or chroma or saturation), lightness (or brightness), and hue—any color can be described.

### *Saturation*

Scale of saturation (0% at bottom).

Saturation is one of three coordinates in the HSL and HSV color spaces. Note that virtually all computer software implementing these spaces use a very rough approximation to calculate the value they call "saturation", such as the formula described for HSV and this value has little, if anything, to do with the description shown here.

The saturation of a color is determined by a combination of light intensity and how much it is distributed across the spectrum of different wavelengths. The purest color is achieved by using just one wavelength at a high intensity, such as in laser light. If the intensity drops, so does the saturation. To desaturate a color in a subtractive system (such as watercolor), one can add white, black, gray, or the hue's complement.

Various correlates of saturation follow.

CIELUV

The *chroma* normalized by the lightness:

$$s_{uv} = \frac{C^*_{uv}}{L^*} = 13\sqrt{(u' - u'_n)^2 + (v' - v'_n)^2}$$

where $(u'_n, v'_n)$ is the chromaticity of the white point, and chroma is defined below.

By analogy, in CIELAB this would yield:

$$s_{ab} = \frac{C^*_{ab}}{L^*} = \frac{\sqrt{{a^*}^2 + {b^*}^2}}{L^*}$$

The CIE has not formally recommended this equation since CIELAB has no chromaticity diagram, and this definition therefore lacks direct correlation with older concepts of saturation. Nevertheless, this equation provides a reasonable predictor of saturation, and demonstrates that adjusting the lightness in CIELAB while holding ($a^*$, $b^*$) fixed does affect the saturation.

But the following formula is in agreement with the human perception of saturation: The formula proposed by Eva Lübbe is in agreement with the verbal definition of Manfred Richter: Saturation is the proportion of pure chromatic color in the total color sensation.

$$S_{ab} = \frac{C^*_{ab}}{\sqrt{{C^*_{ab}}^2 + {L^*}^2}} 100\%$$

where $S_{ab}$ is the saturation, $L^*$ the lightness and $C^*_{ab}$ is the chroma of the color.

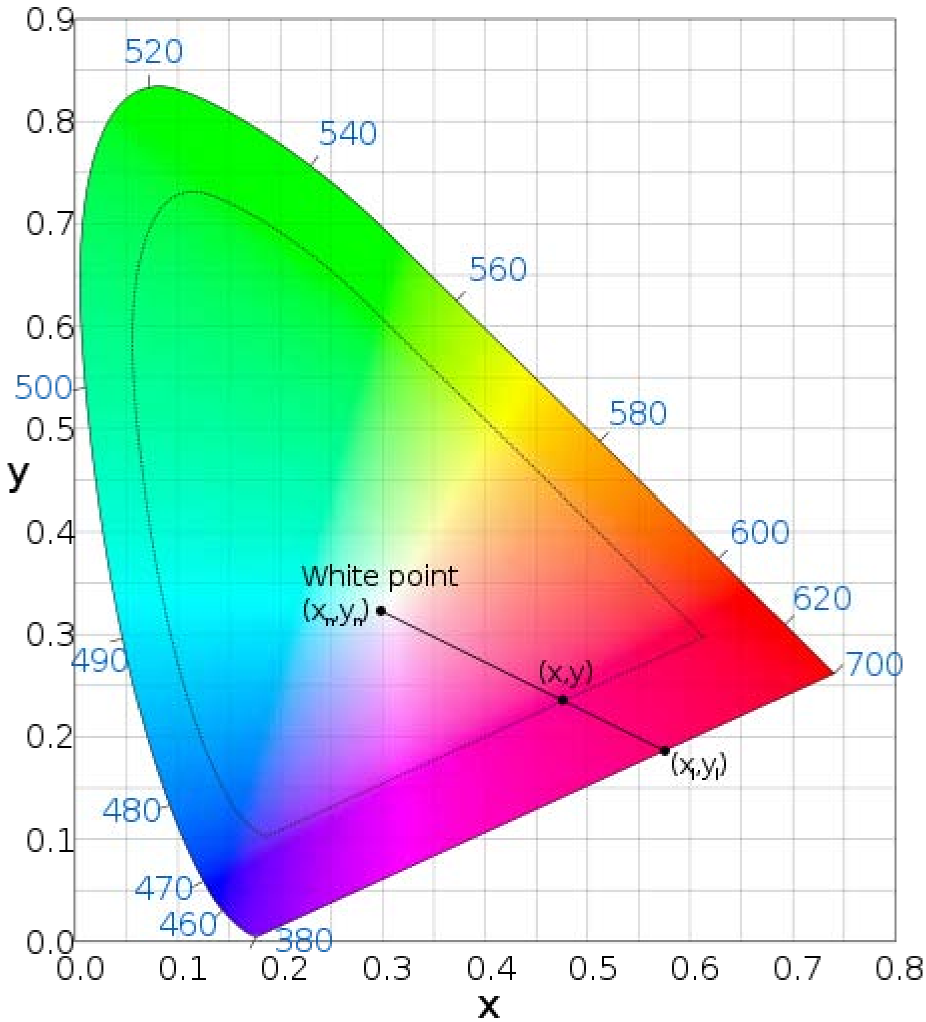
CIECAM02

The square root of the *colorfulness* divided by the *brightness*:

$$s = \sqrt{M/Q}$$

This definition is inspired by experimental work done with the intention of remedying CIECAM97s's poor performance. $M$ is proportional to the chroma $C$ ($M = CF_L^{0.25}$), thus the CIECAM02 definition bears some similarity to the CIELUV definition. An important difference is that the CIECAM02 model accounts for the viewing conditions through the parameter $F_L$.

### *Excitation purity*




**Excitation purity** is the relative distance from the white point. Contours of constant purity can be found by shrinking the spectral locus about the white point. The points along the line segment have the same hue, with $p_e$ increasing from 0 to 1 between the white point and position on the spectral locus (position of the color on the horseshoe shape in the diagram) or (as at the saturated end of the line shown in the diagram) position on the line of purples.

The **excitation purity** (purity for short) of a stimulus is its difference from the illuminant's white point relative to the furthest point on the chromaticity diagram with the same hue (dominant wavelength for monochromatic sources); using the CIE 1931 color space:

$$p_e = \sqrt{\frac{(x - x_n)^2 + (y - y_n)^2}{(x_I - x_n)^2 + (y_I - y_n)^2}}$$

where $(x_n, y_n)$ is the chromaticity of the white point and $(x_I, y_I)$ is the point on the perimeter whose line segment to the white point contains the chromaticity of the stimulus. Different color spaces, such as CIELAB or CIELUV may be used, and will yield different results.

## *Chroma in CIE 1976 L*a*b* and L*u*v* color spaces*

The naïve definition of saturation does not specify its response function. In the CIE XYZ and RGB color spaces, the saturation is defined in terms of additive color mixing, and has the property of being proportional to any scaling centered at white or the white point illuminant. However, both color spaces are nonlinear in terms of psychovisually perceived color differences. It is also possible, and sometimes desirable to define a saturation-like quantity that is linearized in term of the psychovisual perception.

In the CIE 1976 L*a*b* and L*u*v* color spaces, the unnormalized **chroma** is the radial component of the cylindrical coordinate CIE L*C*h (lightness, chroma, hue) representation of the L*a*b* and L*u*v* color spaces, also denoted as CIE L*C*h(a*b*) or CIE L*C*h for short, and CIE L*C*h(u*v*). The transformation of $(a^*, b^*)$ to $(C^*_{ab}, h_{ab})$ is given by:

$$C^*_{ab} = \sqrt{a^{*2} + b^{*2}}$$
$$h_{ab} = \arctan \frac{b^*}{a^*}$$

and analogously for CIE L*C*h(u*v*).

The chroma in the CIE L*C*h(a*b*) and CIE L*C*h(u*v*) coordinates has the advantage of being more psychovisually linear, yet they are non-linear in terms of linear component color mixing. And therefore, chroma in CIE 1976 L*a*b* and L*u*v* color spaces is very much different from the traditional sense of "saturation".

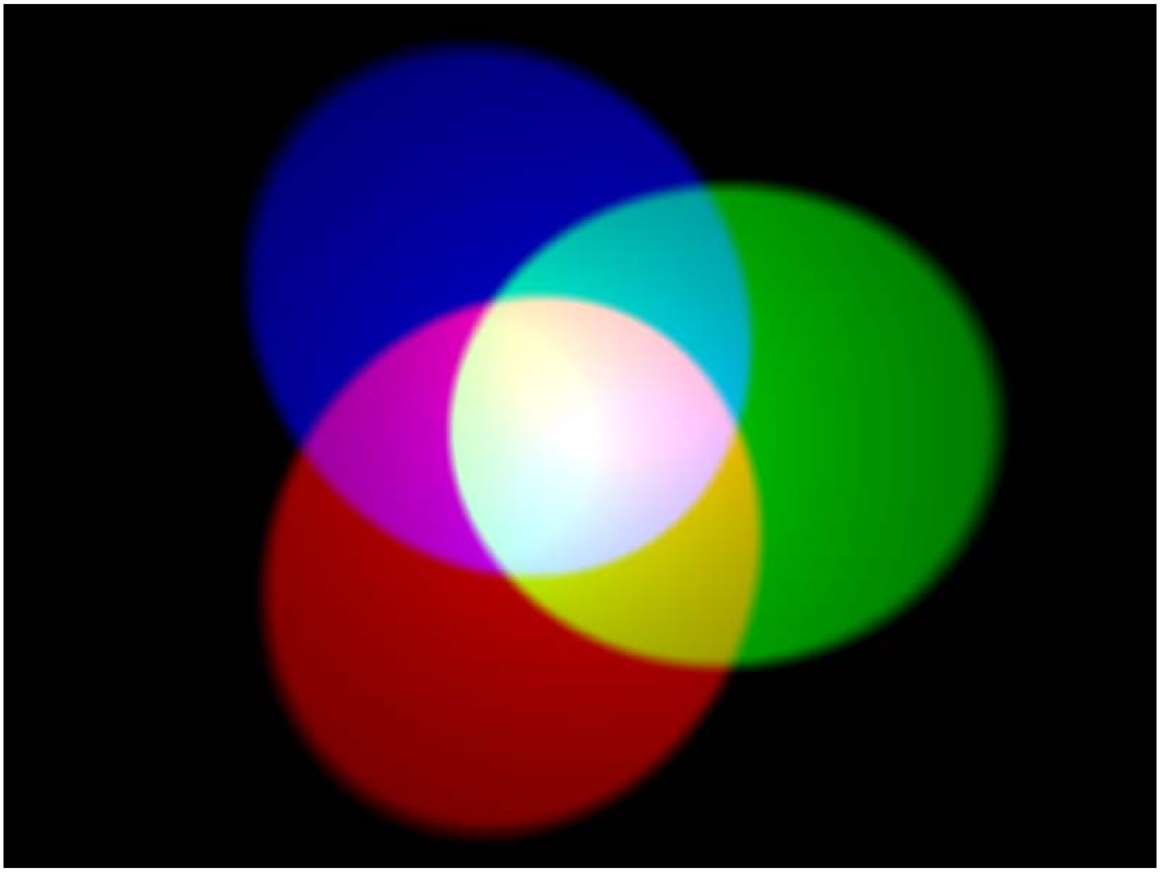
### Chroma in color appearance models

Another, psychovisually even more accurate, but also more complex method to obtain or specify the saturation is to use the color appearance model, like CIECAM. The **chroma** component of the LCh (lightness, chroma, hue) coordinate, and becomes a function of parameters like the chrominance and physical brightness of the illumination, or the characteristics of the emitting/reflecting surface, which is also psychovisually more sensible.

# Color Mixing

White light split by a prism. The additive primary colors are clearly visible.

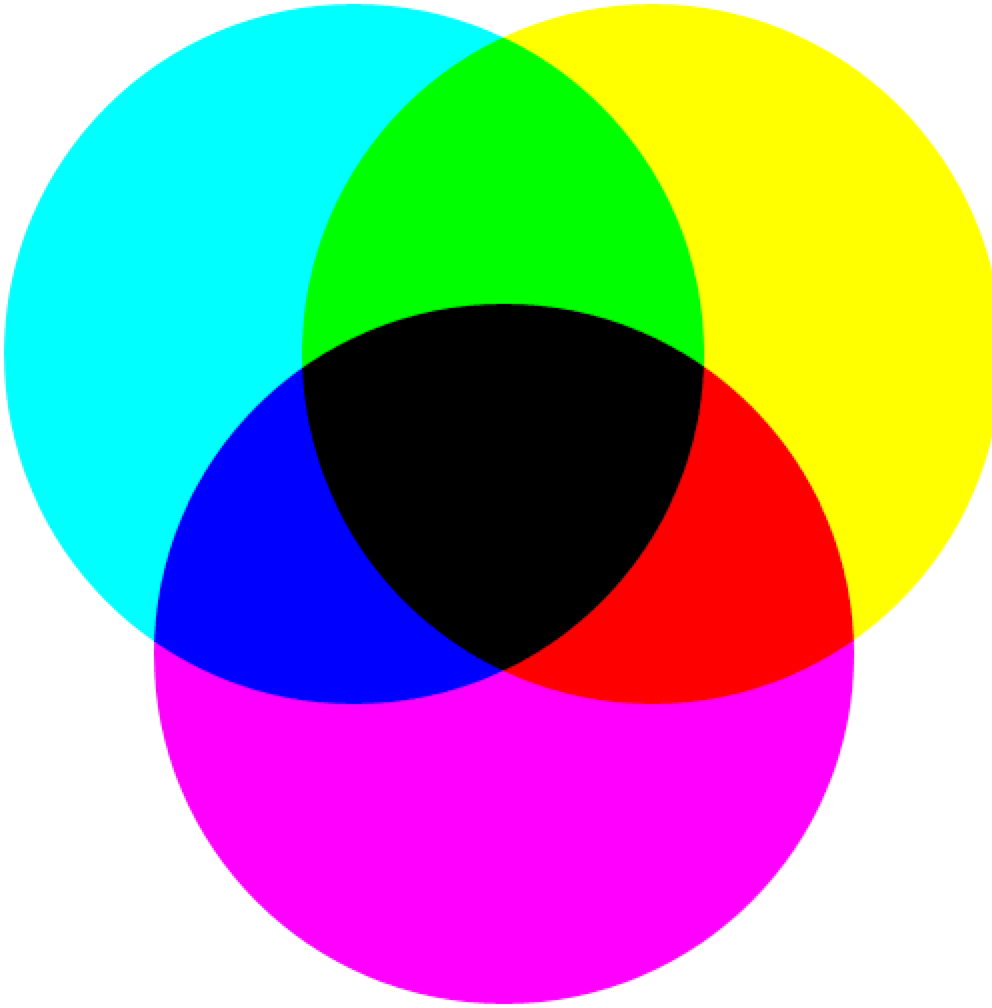
There are two types of **color mixing**: *Additive* and *Subtractive*. In both cases there are three primary colors, three secondary colors (colors made from 2 of the three primary colors in equal amounts), and one tertiary color made from all three primary colors.



A simulated example of additive color mixing

### *Additive Mixing*

Additive mixing of colors generally involves mixing colors of light. In additive mixing of colors there are three primary colors: red, green, and blue. In the absence of color or, when no colors are showing, the result is black. If all three primary colors are showing, the result is white. When red and green combine, the result is yellow. When red and blue combine, the result is magenta. Additive mixing is used in television and computer monitors to produce a wide range of colors using only three primary colors.



A simulated example of subtractive color mixing

### *Subtractive Mixing*

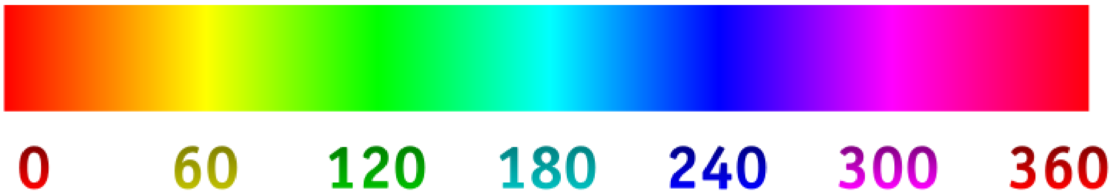
Subtractive mixing is done by selectively removing certain colors, for instance with optical filters. The three primary colors in subtractive mixing are yellow, magenta, and cyan. In subtractive mixing of color, the absence of color is white and the presence of all three primary colors is black. In subtractive mixing of colors, the secondary colors are the same as the primary colors from additive mixing, and vice versa. Subtractive mixing is used to create a variety of colors when printing on paper by combining a small number of ink colors, and also when painting. The mixing of pigments does not produce perfect subtractive color mixing because some light from the subtracted color is still being reflected. This results in a darker and desaturated color compared to the color that would be achieved with ideal filters.

### *Importance to vision*

Additive color mixing—red and green combining to make yellow, for example, or blue and yellow producing white—runs counter to the commonsense observation that, for example, yellow paint plus cyan paint makes green paint. In this case, one must understand that the wavelengths of light that reach the eye are often selected via these more intuitive subtractive processes: for example, cyan paint appears to our eye as cyan because it absorbs **red** wavelengths, and a yellow paint appears yellow because it absorbs **blue** wavelengths. When white light falls on a combination of cyan and yellow, then, both **red and blue** are absorbed, and green is reflected to the eye.

Chapter 7

# Hue




Hue in the HSB/HSL encodings of RGB

An image with the hues cyclically shifted in HSL space.

The hues in the image of this Painted Bunting are cyclically rotated with time.

**Hue** is one of the main properties of a color, defined technically (in the CIECAM02 model), as "the degree to which a stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow," (the unique hues). The other main correlatives of color appearance are colorfulness, chroma, saturation, lightness, and brightness.

Usually, colors with the same hue are distinguished with adjectives referring to their lightness and/or chroma, such as with "light blue", "pastel blue", "vivid blue". Exceptions include brown, which is a dark orange, and pink, a light red with reduced chroma.

In painting color theory, a **hue** refers to a *pure* color—one without tint or shade (added white or black pigment, respectively). A hue is an element of the color wheel. Hues are first processed in the brain in areas in the extended V4 called globs.

## Computing hue

In opponent color spaces in which two of the axes are perceptually orthogonal to lightness, such as the CIE 1976 ($L^*$, $a^*$, $b^*$) (CIELAB) and 1976 ($L^*$, $u^*$, $v^*$) (CIELUV) color spaces, hue may be computed together with chroma by converting these coordinates from rectangular form to polar form. Hue is the angular component of the polar representation, while chroma is the radial component.

Specifically, in CIELAB:

$$h_{ab} = \operatorname{atan2}(b^*, a^*)$$

while, analogously, in CIELUV:

$$h_{uv} = \operatorname{atan2}(v^*, u^*) = \operatorname{atan2}(v', u')$$

Where, atan2 is a two-argument inverse tangent.

### Computing hue from RGB

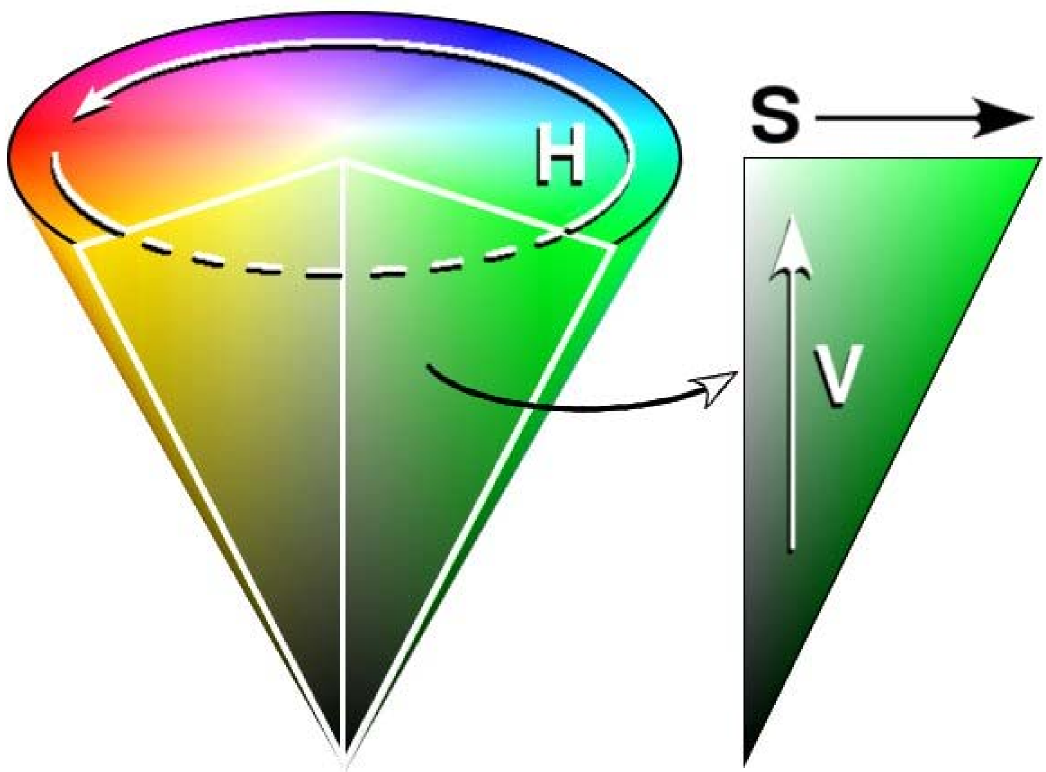
Preucil describes a color hexagon, similar to a trilinear plot described by Evans, Hanson, and Brewer, which may be used to compute hue from RGB. To place red at 0°, green at 120°, and blue at 240°.

$$h_{rgb} = \operatorname{atan2}\left(2 \cdot R - G - B, \sqrt{3} \cdot (G - B)\right)$$

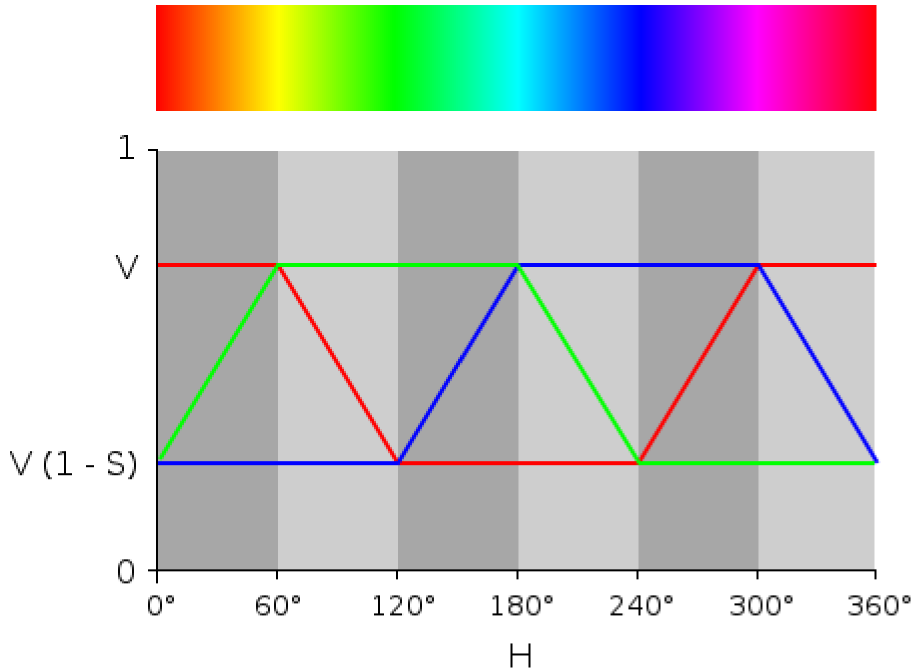
Equivalently, one may solve:

$$\tan(h_{rgb}) = \frac{\sqrt{3} \cdot (G - B)}{2 \cdot R - G - B}$$

Preucil used a polar plot, which he termed a color circle. Using R, G, and B, one may compute hue angle using the following scheme: determine which of the six possible orderings of R, G, and B prevail, then apply the formula given in the table below.




HSV color space as a conical object




An illustration of the relationship between the "hue" of colors with maximal saturation in HSV and HSL with their corresponding RGB coordinates.

| Ordering | Hue Region | Formula |
|---|---|---|
| $R \geq G \geq B$ | Red-Yellow | $h_{Preucil\ circle} = 60^\circ \cdot \frac{G-B}{R-B}$ |
| $G > R \geq B$ | Yellow-Green | $h_{Preucil\ circle} = 60^\circ \cdot \left(2 - \frac{R-B}{G-B}\right)$ |
| $G \geq B > R$ | Green-Cyan | $h_{Preucil\ circle} = 60^\circ \cdot \left(2 + \frac{B-R}{G-R}\right)$ |
| $B > G > R$ | Cyan-Blue | $h_{Preucil\ circle} = 60^\circ \cdot \left(4 - \frac{G-R}{B-R}\right)$ |
| $B > R \geq G$ | Blue-Magenta | $h_{Preucil\ circle} = 60^\circ \cdot \left(4 + \frac{R-G}{B-G}\right)$ |
| $R \geq B > G$ | Magenta-Red | $h_{Preucil\ circle} = 60^\circ \cdot \left(6 - \frac{B-G}{R-G}\right)$ |

Note that in each case the formula contains the fraction $\frac{M-L}{H-L}$, where H is the highest of R, G, and B; L is the lowest, and M is the mid one between the other two. This is referred to as the Preucil Hue Error, and was used in the computation of mask strength in photomechanical color reproduction.

Hue angles computed for the Preucil circle agree with the hue angle computed for the Preucil Hexagon at integer multiples of 30 degrees (red, yellow, green, cyan, blue, magenta, and the colors mid-way between contiguous pairs), and differ by approximately 1.2 degrees at odd integer multiples of 15 degrees (based on the circle formula), the maximum divergence between the two.

The process of converting an RGB color into an HSL color space or HSV color space is usually based on a 6-piece piecewise mapping, treating the HSV cone as a hexacone, or the HSL double cone as a double hexacone. The formulae used are those in the table above.

### Specialized hues

The hues exhibited by caramel colorings and beers are fairly limited in range. The Linner hue index is used to quantify the hue of such products.

### Hue as a qualification in the names of artist's colors

Manufacturers of pigments use the word hue e.g. 'Cadmium Yellow (hue)' to indicate that the original pigmentation ingredient, often toxic, has been replaced by safer (or cheaper) alternatives whilst retaining the hue of the original. Replacements are often used for chromium, cadmium and alizarin.

### Hue vs. dominant wavelength

Dominant wavelength (or sometimes equivalent wavelength) is a physical analog to the perceptual attribute hue. On a chromaticity diagram, a line is drawn from a white point through the coordinates of the color in question, until it intersects the spectral locus. The wavelength at which the line intersects the spectrum locus is identified as the color's dominant wavelength if the point is on the same side of the white point as the spectral locus, and as the color's complementary wavelength if the point is on the opposite side.

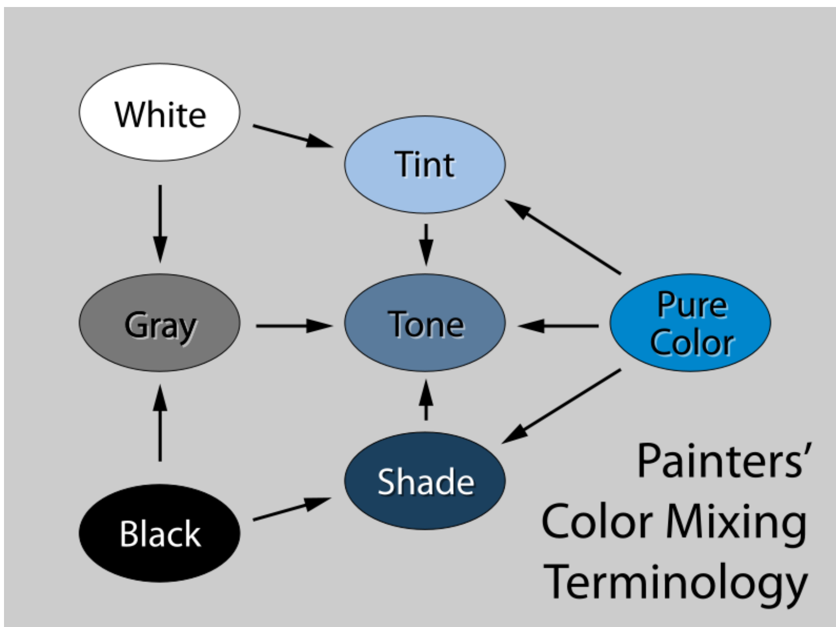
### Hue difference: Δh or ΔH * ?

There are two main ways in which hue difference is quantified. The first is the simple difference between the two hue angles. The symbol for this expression of hue difference is $\Delta h_{ab}$ in CIELAB and $\Delta h_{uv}$ in CIELUV. The other is computed as the residual total color difference after Lightness and Chroma differences have been accounted for; its symbol is $\Delta H^*_{ab}$ in CIELAB and $\Delta H^*_{uv}$ in CIELUV.

Chapter 8

# Tints and Shades & Dichromatism

## Tints and Shades

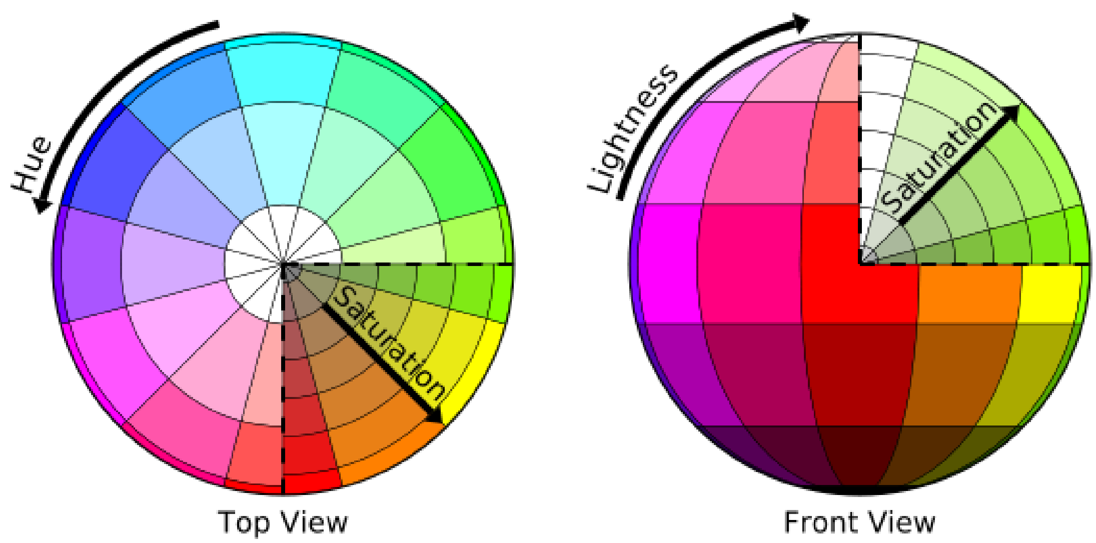



Some shades of blue

In color theory, a **tint** is the mixture of a color with white, which increases lightness, and a **shade** is the mixture of a color with black, which reduces lightness. Mixing a color with any neutral color, including black and white, reduces the chroma, or colorfulness, while the hue remains unchanged.

When mixing colored light (additive color models), the achromatic mixture of spectrally balanced red, green and blue (RGB) is always white, not gray or black. When we mix colorants, such as the pigments in paint mixtures, a color is produced which is always darker and lower in chroma, or saturation, than the parent colors. This moves the mixed color toward a neutral color—a gray or near-black. Lights are made brighter or dimmer by adjusting their brightness, or energy level; in painting, lightness is adjusted through mixture with white, black or a color's complement.

It is common among some artistic painters to darken a paint color by adding black paint—producing colors called *shades*—or to lighten a color by adding white—producing colors called *tints*. However, this is not always the best way for representational painting, since an unfortunate result is for colors to also shift in their hues. For instance, darkening a color by adding black can cause colors such as yellows, reds and oranges, to shift toward the greenish or bluish part of the spectrum. Lightening a color by adding white can cause a shift towards blue when mixed with reds and oranges. Another practice when darkening a color is to use its opposite, or complementary, color (e.g. purplish-red added to yellowish-green) in order to neutralize it without a shift in hue, and darken it if the additive color is darker than the parent color. When lightening a color this hue shift can be corrected with the addition of a small amount of an adjacent color to bring the hue of the mixture back in line with the parent color (e.g. adding a small amount of orange to a mixture of red and white will correct the tendency of this mixture to shift slightly towards the blue end of the spectrum).




An extension of the color wheel: the color sphere. Colors nearest the center or the poles are most *achromatic*. Colors of the same lightness and saturation are of the same *nuance*. Colors of the same hue and saturation, but of different lightness, are said to be *tints* and *shades*. Colors of the same hue and lightness, but of varying saturation, are called *tones*.

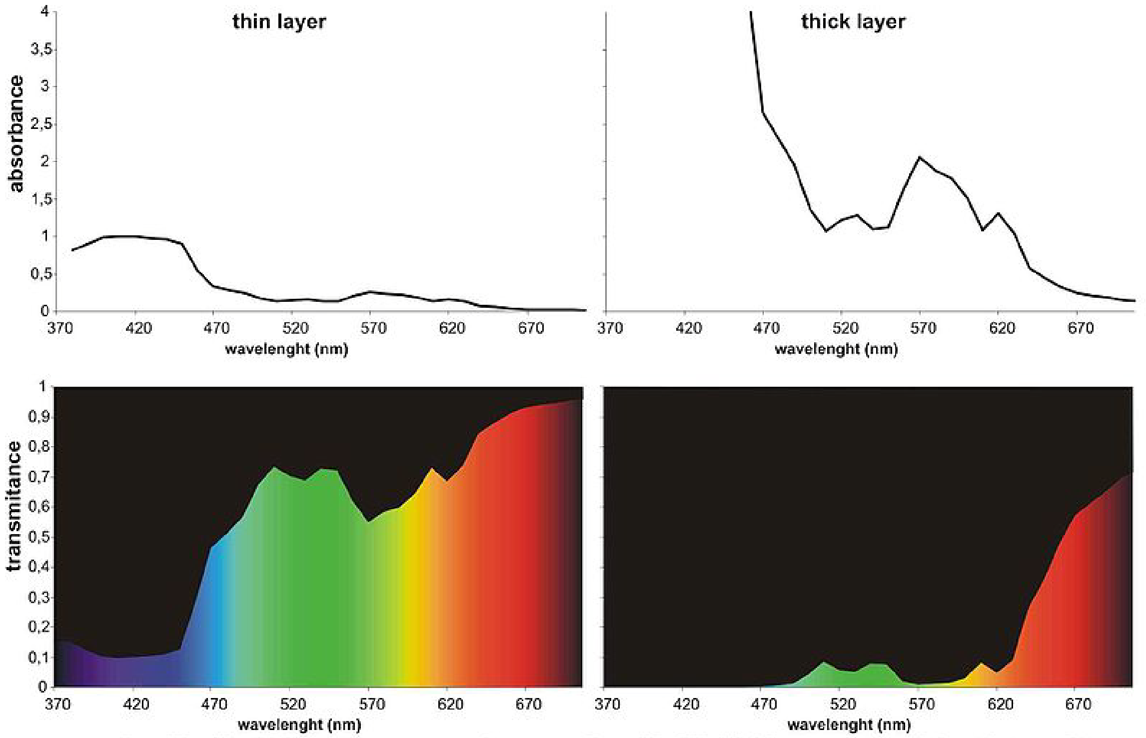
# Dichromatism

**Dichromatism** (or polychromatism) is a phenomenon where the hue of the colour in materials or solutions are dependent on both the concentration of the absorbing substance and the depth or thickness of the medium traversed. In most substances which are not dichromatic, only the brightness and saturation of the colour depend on their concentration and layer thickness.

Examples of dichromatic substances are pumpkin seed oil, bromophenol blue and resazurin. When the layer of pumpkin seed oil is less than 0.7 mm thick, the oil appears bright green, and in layer thicker than this, it appears bright red.

The physicochemical–physiological basis of this phenomenon was recently explicated. Dichromatic properties can be explained by the Beer-Lambert law and by the excitation characteristics of the three types of cone photoreceptors in the human retina. Dichromatism is potentially observable in any substance that has an absorption spectrum with one wide but shallow local minimum and one narrow but deep local minimum. The apparent width of the deep minimum may also be limited by the end of the visible range of human eye; in this case, the true full width may not necessarily be narrow. As the thickness of the substance increases, the perceived hue changes from that defined by the position of the wide-but-shallow minimum (in thin layers) to the hue of the deep-but-narrow minimum (in thick layers).

The absorbance spectrum of pumpkin seed oil has the wide-but-shallow minimum in the green region of the spectrum and deep local minimum in the red region. In thin layers, the absorption at any specific green wavelength is not as low as it is for the red minimum, but a broader band of greenish wavelengths are transmitted, and hence the overall appearance is green. The effect is enhanced by the greater sensitivity to green of the photoreceptors in the human eye, and the narrowing of the red transmittance band by the long-wavelength limit of cone photoreceptor sensitivity. According to the Beer-Lambert law, when viewing through the coloured substance (and thus ignoring reflection), the proportion of light transmitted at a given wavelength, *T*, decreases exponentially with thickness *t*, $T = e^{-at}$, where *a* is the absorbance at that wavelength. Let $Ge^{-a_G t}$ be the green transmittance and $Re^{-a_R t}$ be the red transmittance. The ratio of the two transmitted intensities is then $(G/R)e^{(a_R - a_G)t}$. If the red absorbance is less than the green, then as the thickness *t* increases, so does the ratio of red to green transmitted light, which causes the apparent hue of the colour to switch from green to red.




Pumpkin oil in thin layer appears green, since not only green light, but also combination of blue and yellow light contributes to green appearance

Pumpkin oil in thick layer appears red since the transmittance of blue, green and yellow light, is almost zero. The transmittance of red light did not change much in comparison to thin layer.

## *Quantification*

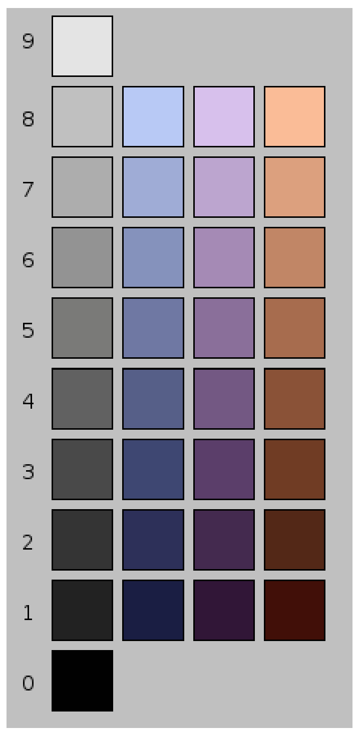
The extent of dichromatism of material can be quantified by the Kreft's dichromaticity index (DI). It is defined as the difference in hue angle ($\Delta h_{ab}$) between the color of the sample at the dilution, where the chroma (color saturation) is maximal and the color of four times more diluted (or thinner) and four times more concentrated (or thicker) sample. The two hue angle differences are called dichromaticity index towards lighter (Kreft's $DI_L$) and dichromaticity index towards darker (Kreft's $DI_D$) respectively. Kreft's dichromaticity index $DI_L$ and $DI_D$ for pumpkin oil, which is one of the most dichromatic substances, are −9 and −44, respectively. This means that pumpkin oil changes its color from green-yellow to orange-red (for 44 degrees in Lab color space) when the thickness of the observed layer is increased from cca 0.5 mm to 2 mm; and it changes slightly towards green (for 9 degrees) if its thickness is reduced for 4-fold.

## *History*

A record by William Herschel (1738–1822), shows he observed dichromatism with a solution of ferrous sulphate in 1801 when working on an early solar telescope, but he did not recognize the effect.

Chapter 9

# Lightness (Color)




Three hues in the Munsell color model. Each color differs in value from top to bottom in equal perception steps. The right column undergoes a dramatic change in perceived color.

**Lightness** (sometimes called **value** or **tone**) is a property of a color, or a dimension of a color space, that is defined in a way to reflect the subjective brightness perception of a color for humans along a lightness–darkness axis. A color's lightness also corresponds to its amplitude.

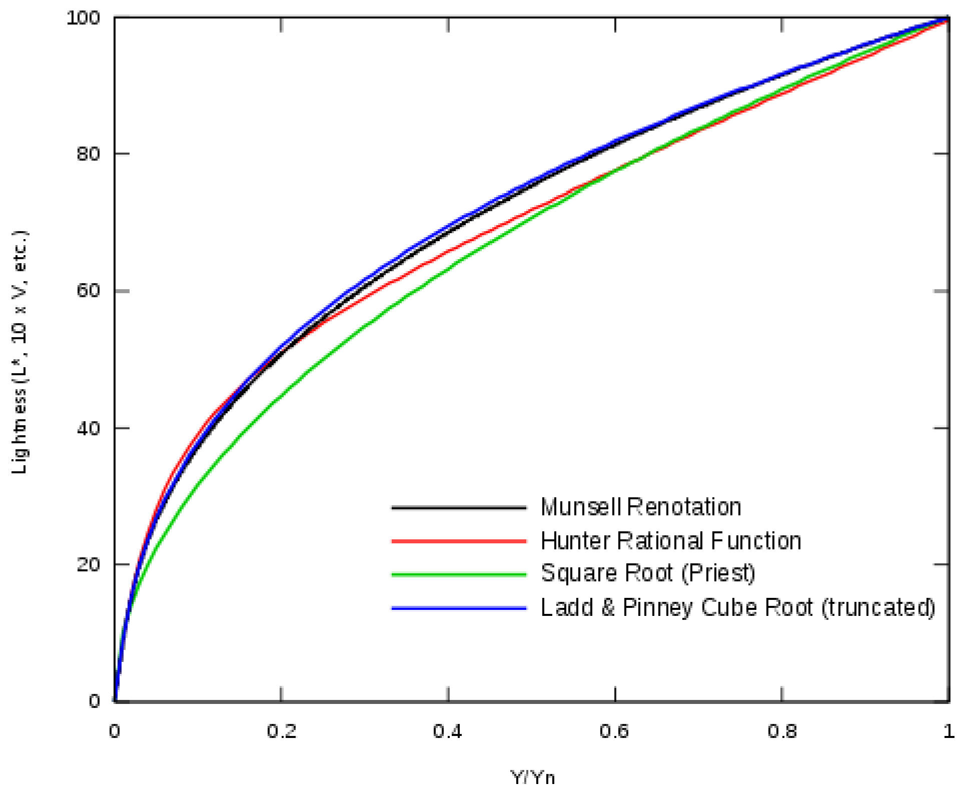
Various color models have an explicit term for this property. The Munsell color model uses the term *value*, while the HSL color model and Lab color space use the term *lightness*. The HSV model uses the term *value* a little differently: a color with a low value is nearly black, but one with a high value is the pure, fully-saturated color.

In subtractive color (i.e. paints) value changes can be achieved by adding black or white to the color. However, this also reduces saturation. Chiaroscuro and Tenebrism both take advantage of dramatic contrasts of value to heighten drama in art. Artists may also employ shading, subtle manipulation of value.

## *Relationship between lightness, value, and luminance*

The Munsell value has long been used as a perceptually uniform lightness scale. A question of interest is the relationship between the Munsell value scale and the relative luminance. Aware of the Weber–Fechner law, Munsell remarked "Should we use a logarithmic curve or curve of squares?" Neither option turned out to be quite correct; scientists eventually converged on a roughly cube-root curve, consistent with the Stevens power law for brightness perception, reflecting the fact that lightness is proportional to the number of nerve impulses per nerve fiber per unit time. The remainder of this section is a chronology of lightness approximations, leading to CIELAB.

*Note*: Munsell's V runs from 0 to 10, while Y typically runs from 0 to 100 (often interpreted as a percent). Typically, the relative luminance is normalized so that the "reference white" (say, magnesium oxide) has a tristimulus value of Y=100. Since the reflectance of magnesium oxide (MgO) relative to the perfect reflecting diffuser is 97.5%, V=10 corresponds to Y=100/97.5%≈102.6 if MgO is used as the reference.




Observe that the lightness is 50% for a luminance of around 18% relative to the reference white.

1920

Priest *et al.* provide a basic estimate of the Munsell value (with Y running from 0 to 1 in this case):

$V = 10\sqrt{Y}$

1933

Munsell, Sloan, and Godlove launch a study on the Munsell neutral value scale, considering several proposals relating the relative luminance to the Munsell value, and suggest:

$V^2 = 1.4742Y - 0.004743Y^2$

1943

Newhall, Nickerson, and Judd prepare a report for the Optical Society of America. They suggest a quintic parabola (relating the reflectance in terms of the value):

$Y = 1.2219V - 0.23111V^2 + 0.23951V^3 - 0.021009V^4 + 0.0008404V^5$

1943

Using Table II of the O.S.A. report, Moon and Spencer express the value in terms of the luminance:

$V = 5(Y / 19.77)^{0.426} = 1.4Y^{0.426}$

1944

Saunderson and Milner introduce a subtractive constant in the previous expression, for a better fit to the Munsell value. Later, Jameson and Hurvich claim that this corrects for simultaneous contrast effects.

$V = 2.357Y^{0.343} - 1.52$

1955

Ladd and Pinney of Eastman Kodak are interested in the Munsell value as a perceptually uniform lightness scale for use in television. After considering one logarithmic and five power-law functions (per Stevens' power law), they relate value to reflectance by raising the reflectance to the power of 0.352:

$V = 2.217Y^{0.352} - 1.324$

Realizing this is quite close to the cube root, they simplify it to:

$V = 2.468Y^{1/3} - 1.636$

1958

Glasser *et al.* define the lightness as ten times the Munsell value (so that the lightness ranges from 0 to 100):

$L^* = 25.29Y^{1/3} - 18.38$

1964

Wyszecki simplifies this to:

$W^* = 25Y^{1/3} - 17$

This formula approximates the Munsell value function for $1\% < Y < 98\%$ (it is not applicable for Y<1%) and is used for the CIE 1964 color space.

1976

CIELAB uses the following formula:

$L^* = 116(Y / Y_n)^{1/3} - 16$

where $Y_n$ is the Y tristimulus value of a "specified white object" and is subject to the restriction $Y / Y_n > 0.01$. Pauli removes this restriction by computing a linear extrapolation which maps $Y/Y_n=0$ to $L^*=0$ and is tangent to the formula above at the point at which the linear extension takes effect. First, the transition point is determined to be $Y/Y_n = (6/29)^3 \approx 0.008856$, then the slope of $(29/3)^3 \approx 903.3$ is computed. This gives the two-part function:

$$f(u) = \begin{cases} \frac{841}{108}u + \frac{4}{29}, & u \le (6/29)^3 \\ u^{1/3}, & u > (6/29)^3 \end{cases}$$

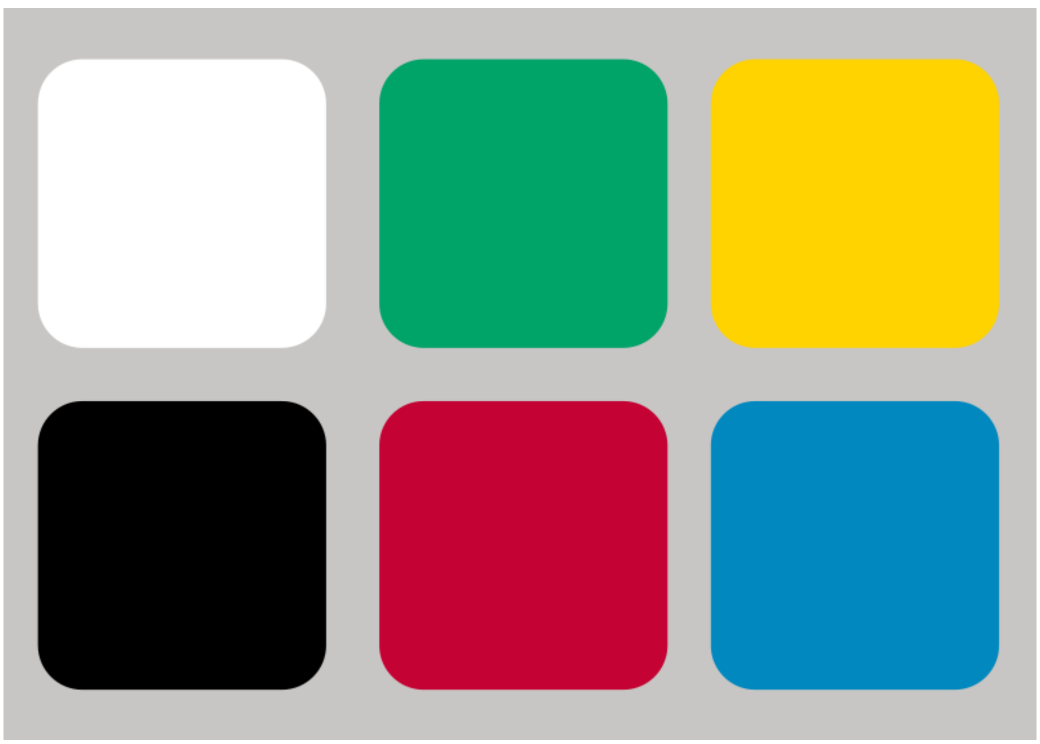
The lightness is then $L^* = 116f(Y / Y_n) - 16$.

At first glance, you might approximate the lightness function by a cube root, an approximation that is found in much of the technical literature. However, the linear segment near black is significant. The best-fit pure power function has an exponent of about 0.42, far from 1/3.

An 18% grey card, having a reflectance of 0.18, has lightness very close to 50. It is called "mid grey" because its lightness is midway between black and white.

Chapter 10

# Opponent Process



Opponent colors based on experiment. Deuteranopes see little difference between the two colors in the central column.

The color **opponent process** is a color theory that states that the human visual system interprets information about color by processing signals from cones and rods in an antagonistic manner. The three types of cones (L for long, M for medium and S for short) have some overlap in the wavelengths of light to which they respond, so it is more efficient for the visual system to record *differences* between the responses of cones, rather than each type of cone's individual response. The opponent color theory suggests that there are three opponent channels: red versus green, blue versus yellow, and black versus white (the latter type is achromatic and detects light-dark variation, or luminance). Responses to one color of an opponent channel are antagonistic to those to the other color. That is, since one color produces an excitatory effect and the other produces an inhibitory effect, the opponent colors are never perceived at the same time (the visual system cannot be simultaneously excited and inhibited).

While the trichromatic theory defines the way the retina of the eye allows the visual system to detect color with three types of cones, the opponent process theory accounts for mechanisms that receive and process information from cones. Though the trichromatic and opponent processes theories were initially thought to be at odds, it later came to be understood that the mechanisms responsible for the opponent process receive signals from the three types of cones and process them at a more complex level.

Besides the cones, which detect light entering the eye, the biological basis of the opponent theory involves two other types of cells: bipolar cells, and ganglion cells. Information from the cones is passed to the bipolar cells in the retina, which may be the cells in the opponent process that transform the information from cones. The information is then passed to ganglion cells, of which there are two major classes: magnocellular, or large-cell layers, and parvocellular, or small-cell layers. Parvocellular cells, or P cells, handle the majority of information about color, and fall into two groups: one that processes information about differences between firing of L and M cones, and one that processes differences between S cones and a combined signal from both L and M cones. The first subtype of cells are responsible for processing red-green differences,and the second process blue-yellow differences. P cells also transmit information about intensity of light (how much of it there is) due to their receptive fields.

## *History*

Johann Wolfgang von Goethe first studied the physiological effect of opposed colors in his *Theory of Colours* in 1810. Goethe arranged his color wheel symmetrically, "for the colours diametrically opposed to each other in this diagram are those which reciprocally evoke each other in the eye. Thus, yellow demands purple; orange, blue; red, green; and vice versa: thus again all intermediate gradations reciprocally evoke each other."

Ewald Hering proposed opponent color theory in 1892. He thought that the colors red, yellow, green, and blue are special in that any other color can be described as a mix of them, and that they exist in opposite pairs. That is, either red or green is perceived and never greenish-red; although yellow is a mixture of red and green in the RGB color theory, the eye does not perceive it as such.

In 1957, Hurvich and Jameson provided quantitative data for Hering's color opponency theory. Their method was called "hue cancellation". Hue cancellation experiments start with a color (e.g. yellow) and attempt to determine how much of the opponent color (e.g. blue) of one of the starting color's components must be added to eliminate any hint of that component from the starting color (Wolfe, Kluender, & Levi, 2009).

Griggs expanded the concept to reflect a wide range of opponent processes for biological systems in this book Biological Relativity (c) 1967.

In 1970, Solomon expanded Hurvich's general neurological opponent process model to explain emotion, drug addiction, and work motivation.

The opponent color theory can be applied to computer vision and implemented as the "Gaussian color model."

## *Subjective color and new colors*

### Reddish green and yellowish blue

Under normal circumstances, there is no hue one could describe as a mixture of opponent hues; that is, as a hue looking "redgreen" or "yellowblue". However, in 1983 Crane and Piantanida carried out an experiment under special viewing conditions in which red and green stripes (or blue and yellow stripes) were placed adjacent to each other and the image held in the same position relative to the viewer's eyes (using an eye tracker to compensate for minor muscle movements). Under such conditions, the borders between the stripes seem to disappear and the colors flowed into each other, making it apparently possible to override the opponency mechanisms and, for a moment, get some people to perceive novel colors. :

"[*s*]*ome observers indicated that although they were aware that what they were viewing was a color (that is, the field was not achromatic), they were unable to name or describe the color. One of these observers was an artist with a large color vocabulary. Other observers of the novel hues described the first stimulus as a reddish-green.*"

However, some subjects in the Crane and Piantanida study merely reported seeing hallucinatory textures, such as blue specks on a yellow backdrop. A possible explanation is that the study did not control for variations in the perceived luminance of the colors from subject to subject (two colors are equiluminant for an observer when rapidly alternating between the colors produces the least impression of flickering). To investigate this, Vincent Billock, Gerald Gleason and Brian Tsou set up a similar experiment which controlled for luminance. They had the following observation:

*"We found that when colors were equiluminant, subjects saw reddish greens, bluish yellows, or a multistable spatial color exchange (an entirely novel perceptual phenomena); when the colors were nonequiluminant, subjects saw spurious pattern formation."*

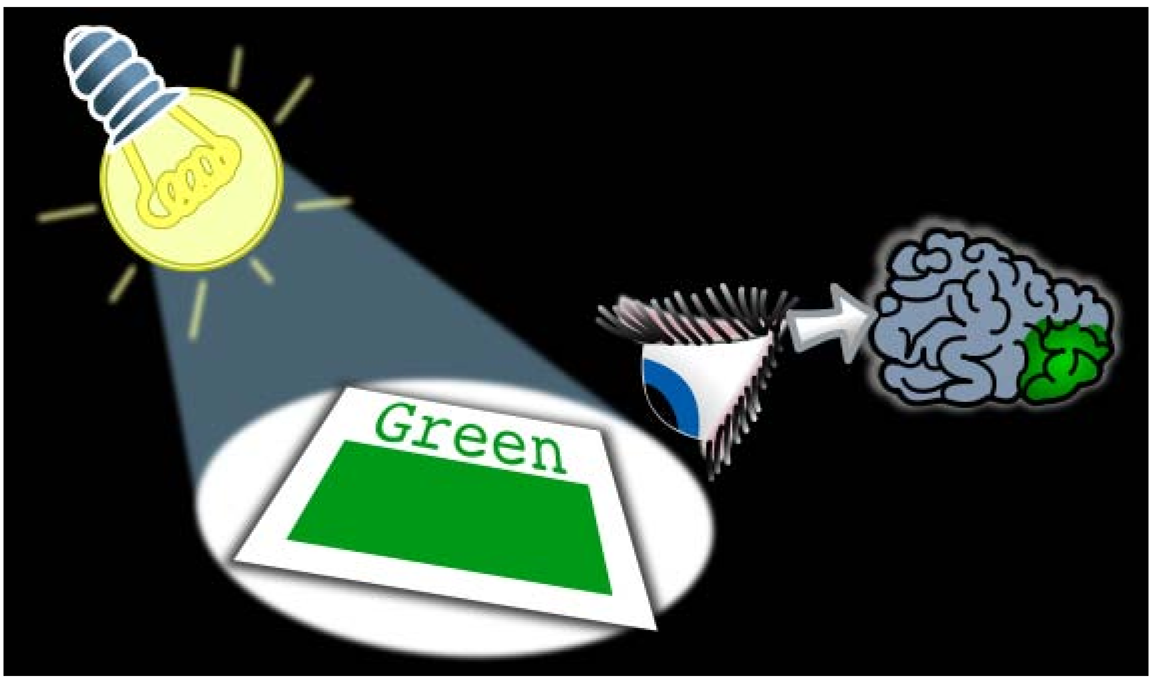
This led them to propose a 'soft-wired model of cortical color opponency', in which populations of neurons compete to fire and in which the 'losing' neurons go completely silent. In this model, eliminating competition by, for instance, inhibiting connections between neural populations can allow mutually exclusive neurons to fire together.

### *Other uses*

Opponent processes have also been used to explain pain, touch, facial expression of emotion, smell, taste, and balance.

Chapter 11

# Color Vision




Colorless, green and red photographic filters as imaged ("perceived") by digital camera

**Color vision** is the capacity of an organism or machine to distinguish objects based on the wavelengths (or frequencies) of the light they reflect, emit, or transmit. The nervous system derives color by comparing the responses to light from the several types of cone photoreceptors in the eye. These cone photoreceptors are sensitive to different portions of the visible spectrum. For humans, the visible spectrum ranges approximately from 380 to 740 nm, and there are normally three types of cones. The visible range and number of cone types differ between species.

A 'red' apple does not emit red light. Rather, it simply absorbs all the frequencies of visible light shining on it except for a group of frequencies that is perceived as red, which are reflected. An apple is perceived to be red only because the human eye can distinguish between different wavelengths. The advantage of color, which is a quality constructed by the visual brain and not a property of objects as such, is the better discrimination of surfaces allowed by this aspect of visual processing. In some dichromatic substances (e.g. pumpkin seed oil) the color hue depends not only on the spectral properties of the substance, but also on its concentration and the depth or thickness.

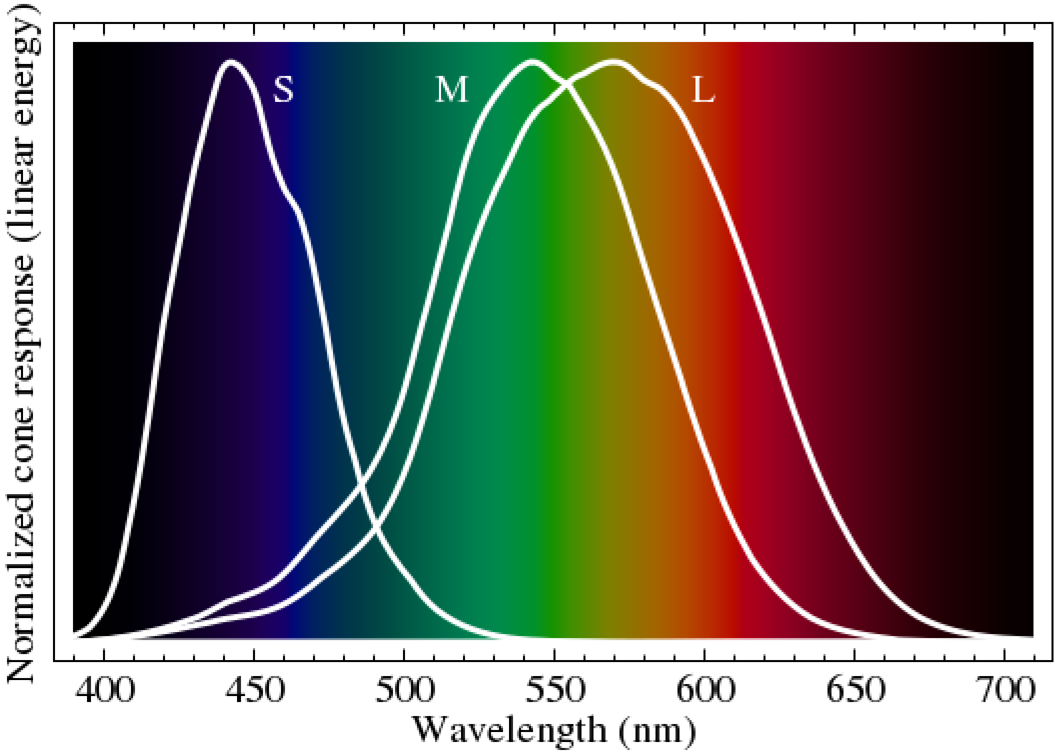
### *Wavelength and hue detection*

Isaac Newton discovered that white light splits into its component colors when passed through a prism, but that if those bands of colored light pass through another and rejoin, they make a white beam. The characteristic colors are, from low to high frequency: red, orange, yellow, green, cyan, blue, violet. Sufficient differences in frequency give rise to a difference in perceived hue; the just noticeable difference in wavelength varies from about 1 nm in the blue-green and yellow wavelengths, to 10 nm and more in the red and blue. Though the eye can distinguish up to a few hundred hues, when those pure spectral colors are mixed together or diluted with white light, the number of distinguishable chromaticities can be quite high.

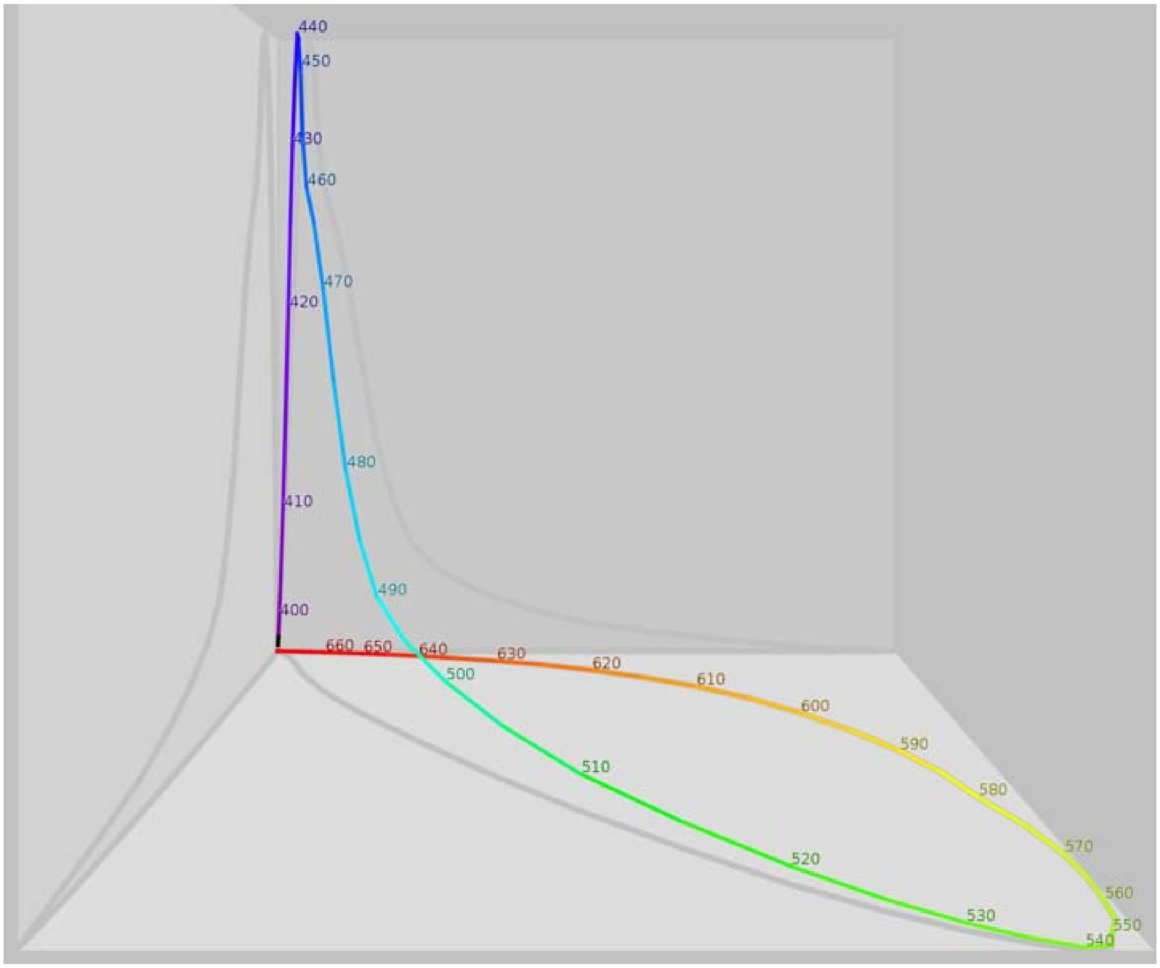
In very low light levels, vision is scotopic: light is detected by rod cells of the retina. Rods are maximally sensitive to wavelengths near 500 nm, and play little, if any, role in color vision. In brighter light, such as daylight, vision is photopic: light is detected by cone cells which are responsible for color vision. Cones are sensitive to a range of wavelengths, but are most sensitive to wavelengths near 555 nm. Between these regions, mesopic vision comes into play and both rods and cones provide signals to the retinal ganglion cells. The shift in color perception from dim light to daylight gives rise to differences known as the Purkinje effect.

The perception of "white" is formed by the entire spectrum of visible light, or by mixing colors of just a few wavelengths, such as red, green, and blue, or by mixing just a pair of complementary colors such as blue and yellow.

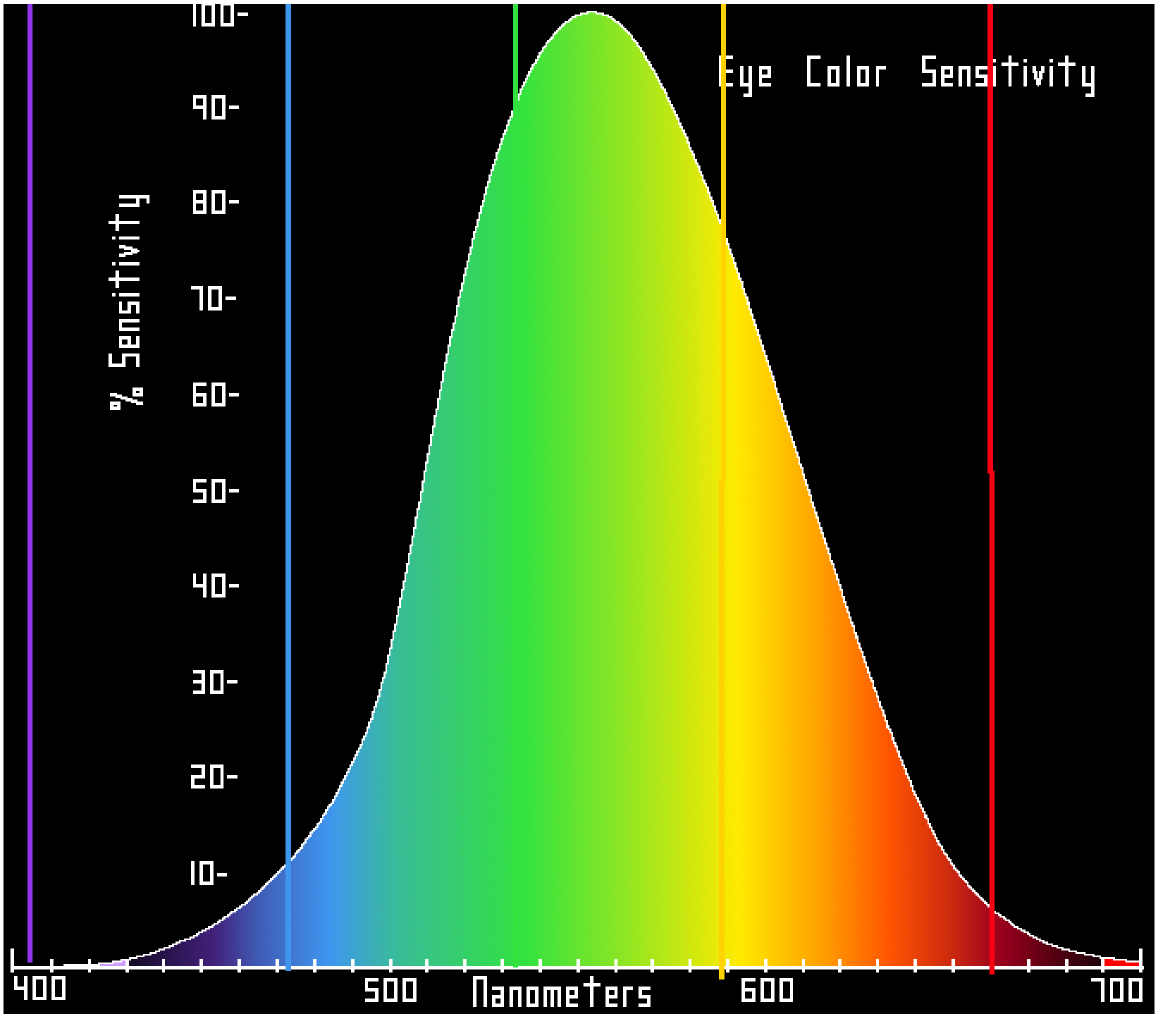
### *Physiology of color perception*




Normalized response spectra of human cones, S, M, and L types, to monochromatic spectral stimuli, with wavelength given in nanometers.




The same figures as above represented here as a single curve in three (normalized cone response) dimensions




Single color sensitivity diagram of the human eye.

Perception of color is achieved in mammals through color receptors containing pigments with different spectral sensitivities. In most Catarrhini (primates closely related to humans) there are three types of color receptors (known as cone cells), resulting in trichromatic color vision. These primates, like humans, are known as trichromats. Many other primates and other mammals are dichromats, and many mammals have little or no color vision. Trichromat mammals are rare, with most mammals having only rods in their retinas, or rod-dominated retinas.

The cones are conventionally labeled according to the ordering of the wavelengths of the peaks of their spectral sensitivities: short (S), medium (M), and long (L) cone types, also sometimes referred to as blue, green, and red cones. While the L cones are often referred to as the red receptors, microspectrophotometry has shown that their peak sensitivity is in the greenish-yellow region of the spectrum. Similarly, the S- and M-cones do not directly correspond to blue and green, although they are often depicted as such (such as in the graph to the right). It is important to note that the RGB color model is merely a convenient means for representing color, and is not directly based on the types of cones in the human eye.

The peak response of human color receptors varies, even amongst individuals with 'normal' color vision; in non-human species this polymorphic variation is even greater, and it may well be adaptive.

## Theories of color vision

Two complementary theories of color vision are the trichromatic theory and the opponent process theory. The trichromatic theory, or Young–Helmholtz theory, proposed in the 19th century by Thomas Young and Hermann von Helmholtz, as mentioned above, states that the retina's three types of cones are preferentially sensitive to blue, green, and red. Ewald Hering proposed the opponent process theory in 1872. It states that the visual system interprets color in an antagonistic way: red vs. green, blue vs. yellow, black vs. white. We now know both theories to be correct, describing different stages in visual physiology.

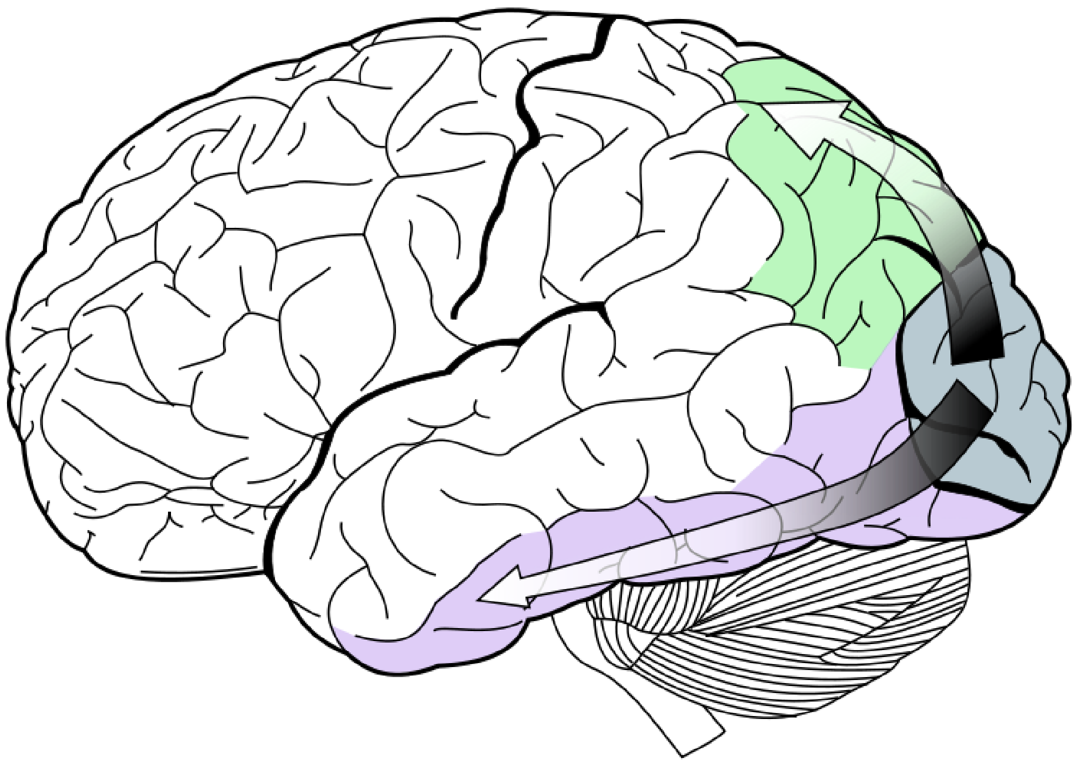
## Cone cells in the human eye

| Cone type | Name | Range | Peak wavelength |
|---|---|---|---|
| S | β | 400–500 nm | 420–440 nm |
| M | γ | 450–630 nm | 534–555 nm |
| L | ρ | 500–700 nm | 564–580 nm |

A range of wavelengths of light stimulates each of these receptor types to varying degrees. Yellowish-green light, for example, stimulates both L and M cones equally strongly, but only stimulates S-cones weakly. Red light, on the other hand, stimulates L cones much more than M cones, and S cones hardly at all; blue-green light stimulates M cones more than L cones, and S cones a bit more strongly, and is also the peak stimulant for rod cells; and blue light stimulates S cones more strongly than red or green light, but L and M cones more weakly. The brain combines the information from each type of receptor to give rise to different perceptions of different wavelengths of light.

The opsins (photopigments) present in the L and M cones are encoded on the X chromosome; defective encoding of these leads to the two most common forms of color blindness. The OPN1LW gene, which codes for the opsin present in the L cones, is highly polymorphic (a recent study by Verrelli and Tishkoff found 85 variants in a sample of 236 men). Many women have an extra type of color receptor because they have different alleles for the gene for the L opsin on each X chromosome. X chromosome inactivation means that only one opsin is expressed in each cone cell, and some women may therefore show a degree of tetrachromatic color vision. Variations in OPN1MW, which codes the opsin expressed in M cones, appear to be rare, and the observed variants have no effect on spectral sensitivity.

## Color in the human brain



Visual pathways in the human brain. The ventral stream (purple) is important in color recognition. The dorsal stream (green) is also shown. They originate from a common source in the visual cortex.

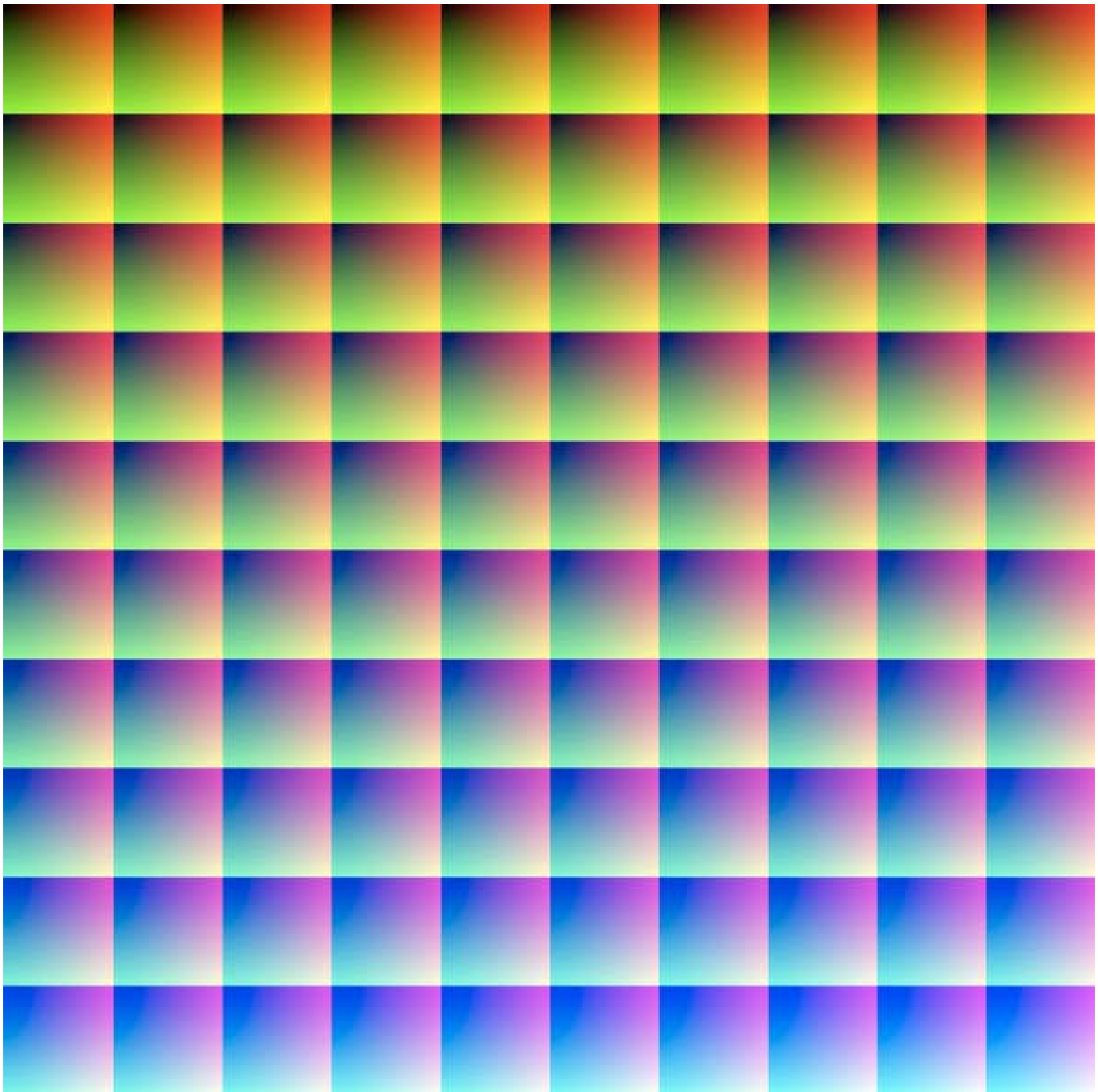
Color processing begins at a very early level in the visual system (even within the retina) through initial color opponent mechanisms. Both Helmholtz's trichromatic theory, and Hering's opponent process theory are therefore correct, but trichromacy arises at the level of the receptors, and opponent processes arise at the level of retinal ganglion cells and beyond. In Hering's theory opponent mechanisms refer to the opposing color effect of red-green, blue-yellow, and light-dark. However, in the visual system, it is the activity of the different receptor types that are opposed. Some midget retinal ganglion cells oppose L and M cone activity, which corresponds loosely to red-green opponency, but actually runs along an axis from blue-green to magenta. Small bistratified retinal ganglion cells oppose input from the S cones to input from the L and M cones. This is often thought to correspond to blue-yellow opponency, but actually runs along a color axis from lime green to violet.

Visual information is then sent to the brain from retinal ganglion cells via the optic nerve to the optic chiasma: a point where the two optic nerves meet and information from the temporal (contralateral) visual field crosses to the other side of the brain. After the optic chiasma the visual tracts are referred to as the optic tracts, which enter the thalamus to synapse at the lateral geniculate nucleus (LGN).

The LGN is divided into laminae (zones), of which there three types: the M-laminae, consisting primarily of M-cells, the P-laminae, consisting primarily of P-cells, and the koniocellular laminae. M- and P-cells received relatively balanced input from both L- and M-cones throughout most of the retina, although this seems to not be the case at the fovea, with midget cells synapsing in the P-laminae. The koniocellular laminae receive axons from the small bistratified ganglion cells.

After synapsing at the LGN, the visual tract continues on back to the primary visual cortex (V1) located at the back of the brain within the occipital lobe. Within V1 there is a distinct band (striation). This is also referred to as "striate cortex", with other cortical visual regions referred to collectively as "extrastriate cortex". It is at this stage that color processing becomes much more complicated.

In V1 the simple three-color segregation begins to break down. Many cells in V1 respond to some parts of the spectrum better than others, but this "color tuning" is often different depending on the adaptation state of the visual system. A given cell that might respond best to long wavelength light if the light is relatively bright might then become responsive to all wavelengths if the stimulus is relatively dim. Because the color tuning of these cells is not stable, some believe that a different, relatively small, population of neurons in V1 is responsible for color vision. These specialized "color cells" often have receptive fields that can compute local cone ratios. Such "double-opponent" cells were initially described in the goldfish retina by Nigel Daw; their existence in primates was suggested by David H. Hubel and Torsten Wiesel and subsequently proven by Bevil Conway. As Margaret Livingstone and David Hubel showed, double opponent cells are clustered within localized regions of V1 called blobs, and are thought to come in two flavors, red-green and blue-yellow. Red-green cells compare the relative amounts of red-green in one part of a scene with the amount of red-green in an adjacent part of the scene, responding best to local color contrast (red next to green). Modeling studies have shown that double-opponent cells are ideal candidates for the neural machinery of color constancy explained by Edwin H. Land in his retinex theory.



This image (when viewed in full size, 1000 pixels wide) contains 1 million pixels, each of a different color. The human eye can distinguish about 10 million different colors.

From the V1 blobs, color information is sent to cells in the second visual area, V2. The cells in V2 that are most strongly color tuned are clustered in the "thin stripes" that, like the blobs in V1, stain for the enzyme cytochrome oxidase (separating the thin stripes are interstripes and thick stripes, which seem to be concerned with other visual information like motion and high-resolution form). Neurons in V2 then synapse onto cells in the extended V4. This area includes not only V4, but two other areas in the posterior inferior temporal cortex, anterior to area V3, the dorsal posterior inferior temporal cortex, and posterior TEO. (Area V4 was identified by Semir Zeki to be exclusively dedicated to color, but this has since been shown not to be the case. Color processing in the extended V4 occurs in millimeter-sized color modules called globs. This is the first part of the brain in which color is processed in terms of the full range of hues found in color space.

Anatomical studies have shown that neurons in extended V4 provide input to the inferior temporal lobe . "IT" cortex is thought to integrate color information with shape and form, although it has been difficult to define the appropriate criteria for this claim. Despite this murkiness, it has been useful to characterize this pathway (V1 > V2 > V4 > IT) as the ventral stream or the "what pathway", distinguished from the dorsal stream ("where pathway") that is thought to analyze motion, among many other features.

## In other animals

Many invertebrates have color vision. Honey- and bumblebees have trichromatic color vision, which is insensitive to red but sensitive in ultraviolet. *Papilio* butterflies possess six types of photoreceptors and may have pentachromatic vision. The most complex color vision system in animal kingdom has been found in stomatopods (such as the mantis shrimp) with up to 12 different spectral receptor types thought to work as multiple dichromatic units.

Vertebrate animals such as tropical fish and birds sometimes have more complex color vision systems than humans. In the latter example, tetrachromacy is achieved through up to four cone types, depending on species. Brightly colored oil droplets inside the cones shift or narrow the spectral sensitivity of the cell. It has been suggested that it is likely that pigeons are pentachromats.

Reptiles and amphibians also have four cone types (occasionally five), and probably see at least the same number of colors that humans do, or perhaps more. In addition, some nocturnal geckos have the capability of seeing color in dim light.

In the evolution of mammals, segments of color vision were lost, then for a few species of primates, regained by gene duplication. Eutherian mammals other than primates (for example, dogs, cats, mammalian farm animals) generally have less-effective two-receptor (dichromatic) color perception systems, which distinguish blue, green, and yellow—but cannot distinguish reds. The adaptation to see reds is particularly important for primate mammals, since it leads to identification of fruits, and also newly sprouting leaves, which are particularly nutritious.

However, even among primates, full color vision differs between new-world and old-world monkeys. Old-world primates, including monkeys and all apes, have vision similar to humans. New World Monkeys may or may not have color sensitivity at this level: in most species, males are dichromats, and about 60% of females are trichromats, but the owl monkeys are cone monochromats, and both sexes of howler monkeys are trichromats. Visual sensitivity differences between males and females in a single species is due to the gene for yellow-green sensitive opsin protein (which confers ability to differentiate red from green) residing on the X sex chromosome.

Several marsupials such as the fat-tailed dunnart (*Sminthopsis crassicaudata*) have been shown to have trichromatic color vision.

Marine mammals, adapted for low-light vision, have only a single cone type and are thus monochromats.

## Evolution

Color perception mechanisms are highly dependent on evolutionary factors, of which the most prominent is thought to be satisfactory recognition of food sources. In herbivorous primates, color perception is essential for finding proper (immature) leaves. In hummingbirds, particular flower types are often recognized by color as well. On the other hand, nocturnal mammals have less-developed color vision, since adequate light is needed for cones to function properly. There is evidence that ultraviolet light plays a part in color perception in many branches of the animal kingdom, especially insects. In general, the optical spectrum encompasses the most common electronic transitions in matter and is therefore the most useful for collecting information about the environment.

The evolution of trichromatic color vision in primates occurred as the ancestors of modern monkeys, apes, and humans switched to diurnal (daytime) activity and began consuming fruits and leaves from flowering plants. Color vision, with UV discrimination, is also present in a number of arthropods – the only terrestrial animals besides the vertebrates to possess this trait.

Some animals can distinguish colors in the ultraviolet spectrum. The UV spectrum falls outside the human visible range, except for some cataract surgery patients. Birds, turtles, lizards, and fish have UV receptors in their retinas. These animals can see the UV patterns found on flowers and other wildlife that are otherwise invisible to the human eye. So far, there has not been enough evidence to show that any mammals are capable of UV vision.

UV and multi-dimensional vision is an especially important adaptation in birds. It allows birds to spot small prey from a distance, navigate, avoid predators, and forage while flying at high speeds. Birds also utilize their broad spectrum vision to recognize other birds, and in sexual selection.

## Mathematics of color perception

A "physical color" is a combination of pure spectral colors (in the visible range). Since there are, in principle, infinitely many distinct spectral colors, the set of all physical colors may be thought of as an infinite-dimensional vector space, in fact a Hilbert space. We call this space $H_{\text{color}}$. More technically, the space of physical colors may be considered to be the (mathematical) cone over the simplex whose vertices are the spectral colors, with white at the centroid of the simplex, black at the apex of the cone, and the monochromatic color associated with any given vertex somewhere along the line from that vertex to the apex depending on its brightness.

An element $C$ of $H_{\text{color}}$ is a function from the range of visible wavelengths—considered as an interval of real numbers $[W_{\text{min}}, W_{\text{max}}]$—to the real numbers, assigning to each wavelength $w$ in $[W_{\text{min}}, W_{\text{max}}]$ its intensity $C(w)$.

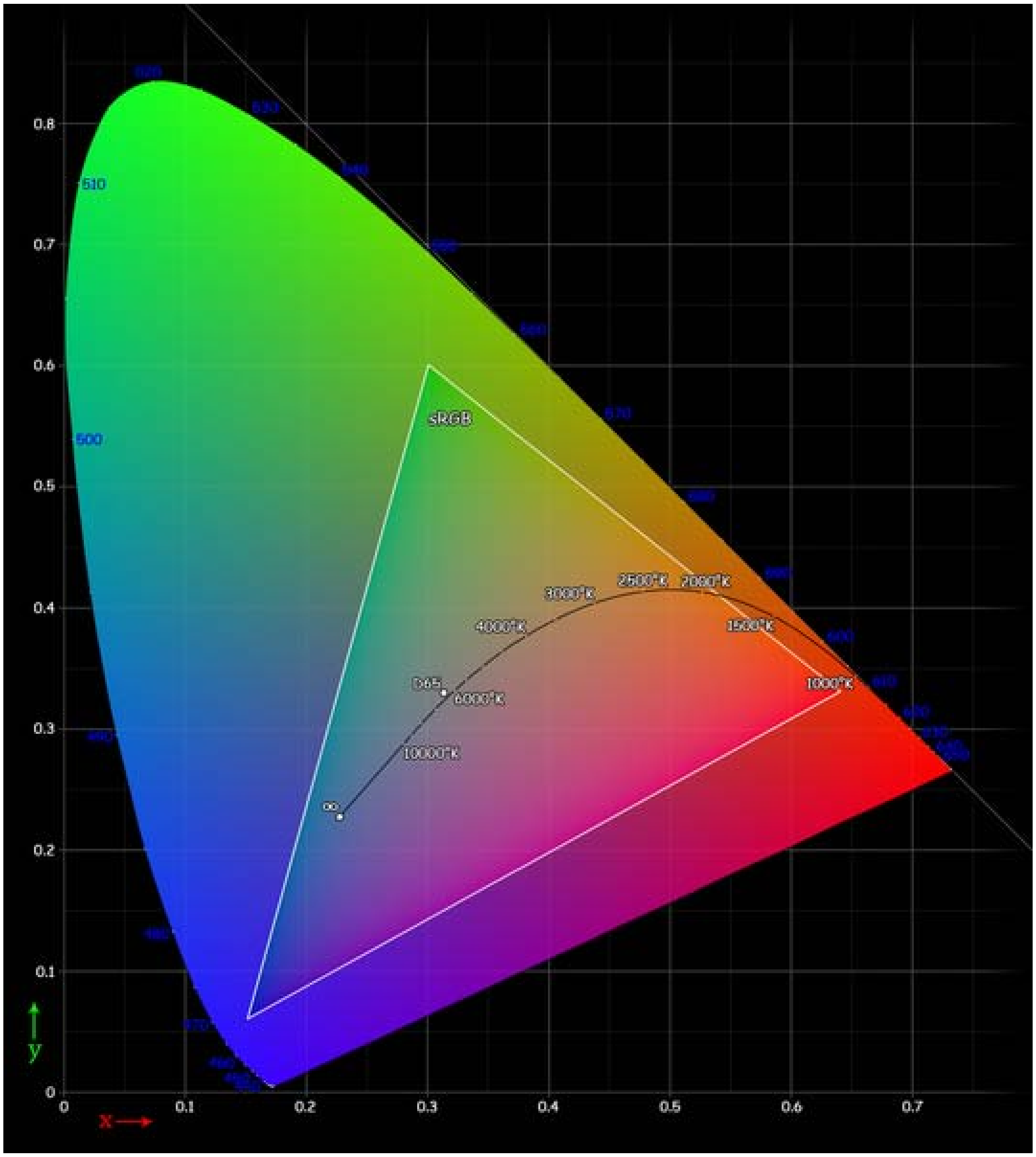
A humanly perceived color may be modeled as three numbers: the extents to which each of the 3 types of cones is stimulated. Thus a humanly perceived color may be thought of as a point in 3-dimensional Euclidean space. We call this space $\mathbf{R}^3_{\text{color}}$.

Since each wavelength $w$ stimulates each of the 3 types of cone cells to a known extent, these extents may be represented by 3 functions $s(w)$, $m(w)$, $l(w)$ corresponding to the response of the $S$, $M$, and $L$ cone cells, respectively.

Finally, since a beam of light can be composed of many different wavelengths, to determine the extent to which a physical color $C$ in $H_{\text{color}}$ stimulates each cone cell, we must calculate the integral (with respect to $w$), over the interval $[W_{\text{min}}, W_{\text{max}}]$, of $C(w)\cdot s(w)$, of $C(w)\cdot m(w)$, and of $C(w)\cdot l(w)$. The triple of resulting numbers associates to each physical color $C$ (which is an element in $H_{\text{color}}$) to a particular perceived color (which is a single point in $\mathbf{R}^3_{\text{color}}$). This association is easily seen to be linear. It may also easily be seen that many different elements in the "physical" space $H_{\text{color}}$ can all result in the same single perceived color in $\mathbf{R}^3_{\text{color}}$, so a perceived color is not unique to one physical color.

Thus human color perception is determined by a specific, non-unique linear mapping from the infinite-dimensional Hilbert space $H_{\text{color}}$ to the 3-dimensional Euclidean space $\mathbf{R}^3_{\text{color}}$.

Technically, the image of the (mathematical) cone over the simplex whose vertices are the spectral colors, by this linear mapping, is also a (mathematical) cone in $\mathbf{R}^3_{\text{color}}$. Moving directly away from the vertex of this cone represents maintaining the same chromaticity while increasing its intensity. Taking a cross-section of this cone yields a 2D chromaticity space. Both the 3D cone and its projection or cross-section are convex sets; that is, any mixture of spectral colors is also a color.




The CIE 1931 xy chromaticity diagram. The Planckian locus is shown with color temperatures labeled in degrees Kelvin. The outer curved boundary is the spectral (or monochromatic) locus, with wavelengths shown in nanometers (blue). Note that the colors in this file are being specified using sRGB. Areas outside the triangle cannot be accurately rendered because they are out of the gamut of sRGB, therefore they have been interpreted. Note that the colors depicted depend on the color space of the device you use to view the image (number of colors on your monitor, etc.), and may not be a strictly accurate representation of the color at a particular position.

In practice, it would be quite difficult to physiologically measure an individual's three cone responses to various physical color stimuli. Instead, a psychophysical approach is taken. Three specific benchmark test lights are typically used; let us call them *S*, *M*, and *L*. To calibrate human perceptual space, scientists allowed human subjects to try to match any physical color by turning dials to create specific combinations of intensities ($I_S$, $I_M$, $I_L$) for the *S*, *M*, and *L* lights, resp., until a match was found. This needed only to be done for physical colors that are spectral (since a linear combination of spectral colors will be matched by the same linear combination of their ($I_S$, $I_M$, $I_L$) matches. Note that in practice, often at least one of *S*, *M*, *L* would have to be added with some intensity to the *physical test color*, and that combination matched by a linear combination of the remaining 2 lights. Across different individuals (without color blindness), the matchings turned out to be nearly identical.

By considering all the resulting combinations of intensities ($I_S$, $I_M$, $I_L$) as a subset of 3-space, a model for human perceptual color space is formed. (Note that when one of *S*, *M*, *L* had to be added to the test color, its intensity was counted as negative.) Again, this turns out to be a (mathematical) cone, not a quadric, but rather all rays through the origin in 3-space passing through a certain convex set. Again, this cone has the property that moving directly away from the origin corresponds to increasing the intensity of the *S*, *M*, *L* lights proportionately. Again, a cross-section of this cone is a planar shape that is (by definition) the space of "chromaticities" (informally: distinct colors); one particular such cross section, corresponding to constant $X+Y+Z$ of the CIE 1931 color space, gives the CIE chromaticity diagram.

It should be noted that this system implies that for any hue or non-spectral color, there are infinitely many distinct physical spectra that are all perceived as that hue or color excluding colors on the line of purples. So, in general there is no such thing as *the* combination of spectral colors that we perceive as (say) tan; instead there are infinitely many possibilities that produce that exact color.

(The only exceptions to this rule are the perceptual colors corresponding to the *boundary* of the cone: in other words, those chromaticities on the simple closed curve that is the boundary of the 1931 C.I.E. diagram depicted in the figure. These comprise precisely all spectral colors plus the "line of purples" connecting the ends of the spectral colors: for each of these, there is only one physical color in $H_{\text{color}}$ that can create that perceived color.)

The CIE chromaticity diagram is horseshoe-shaped, with its curved edge corresponding to all spectral colors (the *spectral locus*), and the remaining straight edge corresponding to the most saturated purples, mixtures of red and violet.

## *Chromatic adaptation*

An object may be viewed under various conditions. For example, it may be illuminated by sunlight, the light of a fire, or a harsh electric light. In all of these situations, human vision perceives that the object has the same color: an apple always appears red, whether viewed at night or during the day. On the other hand, a camera with no adjustment for light may register the apple as having varying color. This feature of the visual system is called chromatic adaptation, or color constancy; when the correction occurs in a camera it is referred to as white balance.

Chromatic adaptation is one aspect of vision that may fool someone into observing a color-based optical illusion, such as the same color illusion.

Though the human visual system generally does maintain constant perceived color under different lighting, there are situations where the relative brightness of two different stimuli will appear reversed at different illuminance levels. For example, the bright yellow petals of flowers will appear dark compared to the green leaves in dim light while the opposite is true during the day. This is known as the Purkinje effect, and arises because the peak sensitivity of the human eye shifts toward the blue end of the spectrum at lower light levels.

## Von Kries transform

The von Kries chromatic adaptation method is a technique that is sometimes used in camera image processing. The method is to apply a gain to each of the human cone cell spectral sensitivity responses so as to keep the adapted appearance of the reference white constant. The application of Johannes von Kries's idea of adaptive gains on the three cone cell types was first explicitly applied to the problem of color constancy by Herbert E. Ives, and the method is sometimes referred to as the Ives transform or the von Kries–Ives adaptation.

The von Kries *coefficient rule* rests on the assumption that color constancy is achieved by individually adapting the gains of the three cone responses, the gains depending on the sensory context, that is, the color history and surround. Thus, the cone responses *c*' from two radiant spectra can be matched by appropriate choice of diagonal adaptation matrices $D_1$ and $D_2$:

$$c' = D_1\, S^T\, f_1 = D_2\, S^T\, f_2$$

where *S* is the *cone sensitivity matrix* and *f* is the spectrum of the conditioning stimulus. This leads to the **von Kries transform** for chromatic adaptation in LMS color space (responses of long-, medium-, and short-wavelength cone response space):

$$D = D_1^{-1} D_2 = \begin{bmatrix} L_2/L_1 & 0 & 0 \\ 0 & M_2/M_1 & 0 \\ 0 & 0 & S_2/S_1 \end{bmatrix}$$

This diagonal matrix *D* maps cone responses, or colors, in one adaptation state to corresponding colors in another; when the adaptation state is presumed to be determined by the illuminant, this matrix is useful as an illuminant adaptation transform. The elements of the diagonal matrix *D* are the ratios of the cone responses (Long, Medium, Short) for the illuminant's white point.

The more complete von Kries transform, for colors represented in XYZ or RGB color space, includes matrix transformations into and out of LMS space, with the diagonal transform *D* in the middle.

## Chapter 12

# Visual Perception

**Visual perception** is the ability to interpret information and surroundings from the effects of visible light reaching the eye. The resulting perception is also known as **eyesight**, **sight**, or **vision** (adjectival form: *visual*, *optical*, or *ocular*). The various physiological components involved in vision are referred to collectively as the visual system, and are the focus of much research in psychology, cognitive science, neuroscience, and molecular biology.

### *Visual system*

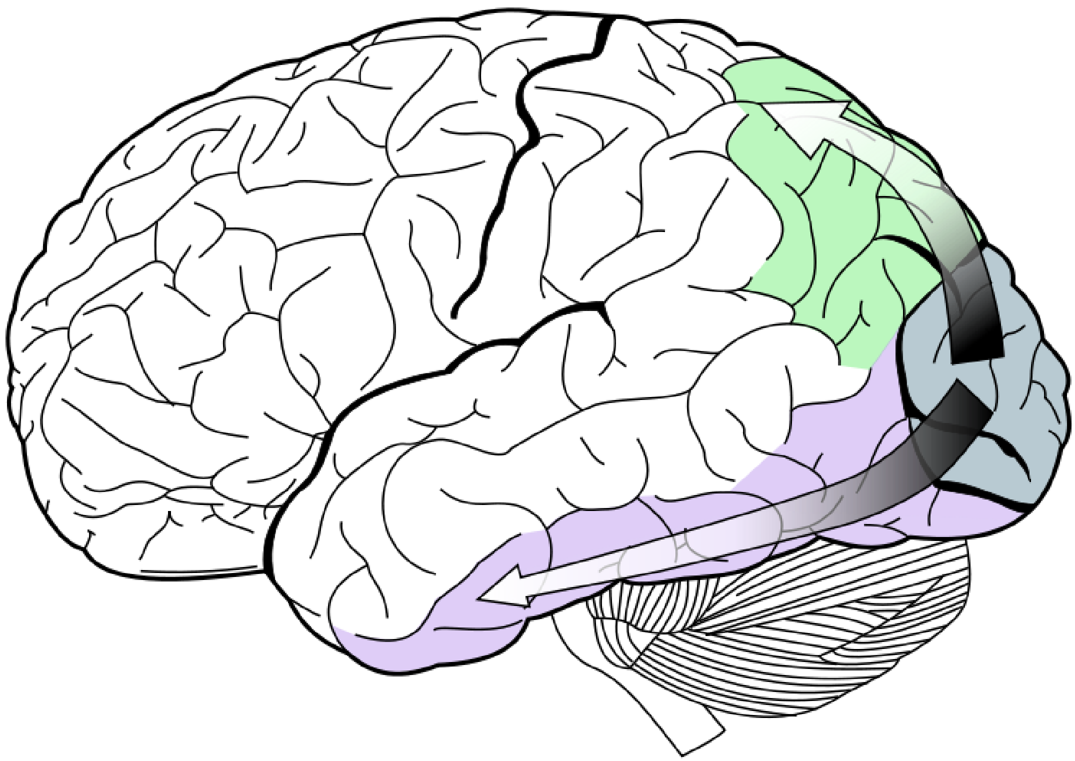
The visual system in humans allows individuals to assimilate information from the environment. The act of seeing starts when the lens of the eye focuses an image of its surroundings onto a light-sensitive membrane in the back of the eye, called the retina. The retina is actually part of the brain that is isolated to serve as a transducer for the conversion of patterns of light into neuronal signals. The lens of the eye focuses light on the photoreceptive cells of the retina, which detect the photons of light and respond by producing neural impulses. These signals are processed in a hierarchical fashion by different parts of the brain, from the retina upstream to central ganglia i.e. the brain.

Note that up until now the above paragraph could apply to octopi, molluscs, worms, insects and things more primitive; anything with a more concentrated nervous system and better eyes than say a jellyfish. However, the following applies to mammals generally and birds (in modified form): The retina in these more complex animals sends fibers (the optic nerve) to the lateral geniculate nucleus, to the primary and secondary visual cortex of the brain. Signals from the retina can also travel directly from the retina to the superior colliculus.

### *Study of visual perception*

The major problem in visual perception is that what people see is not simply a translation of retinal stimuli (i.e., the image on the retina). Thus people interested in perception have long struggled to explain what visual processing does to create what is actually seen.

### Early studies



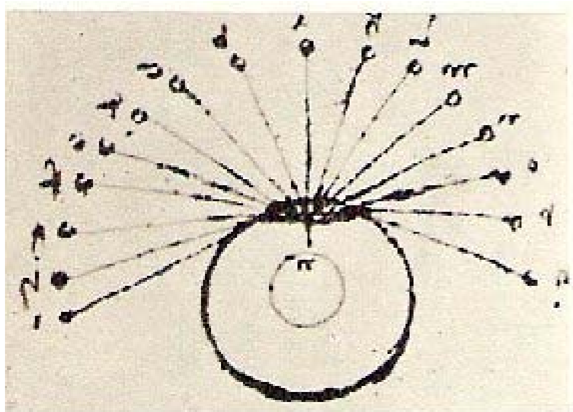
The visual dorsal stream (green) and ventral stream (purple) are shown. Much of the human cerebral cortex is involved in vision.

There were two major ancient Greek schools, providing a primitive explanation of how vision is carried out in the body.

The first was the "emission theory" which maintained that vision occurs when rays emanate from the eyes and are intercepted by visual objects. If an object was seen directly it was by 'means of rays' coming out of the eyes and again falling on the object. A refracted image was, however, seen by 'means of rays' as well, which came out of the eyes, traversed through the air, and after refraction, fell on the visible object which was sighted as the result of the movement of the rays from the eye. This theory was championed by scholars like Euclid and Ptolemy and their followers.

The second school advocated the so called 'intro-mission' approach which sees vision as coming from something entering the eyes representative of the object. With its main propagators Aristotle, Galen and their followers, this theory seems to have some contact with modern theories of what vision really is, but it remained only a speculation lacking any experimental foundation.

Both schools of thought relied upon the principle that "like is only known by like", and thus upon the notion that the eye was composed of some "internal fire" which interacted with the "external fire" of visible light and made vision possible. Plato makes this assertion in his dialogue *Timaeus*, as does Aristotle, in his *De Sensu*.



Leonardo DaVinci: The eye has a central line and everything that reaches the eye through this central line can be seen distinctly.

Alhazen (965 – c. 1040) carried out many investigations and experiments on visual perception, extended the work of Ptolemy on binocular vision, and commented on the anatomical works of Galen.

Leonardo DaVinci (1452–1519) was the first to recognize the special optical qualities of the eye. He wrote "The function of the human eye ... was described by a large number of authors in a certain way. But I found it to be completely different." His main experimental finding was that there is only a distinct and clear vision at the line of sight, the optical line that ends at the fovea. Although he did not use these words literally he actually is the father of the modern distinction between foveal and peripheral vision.

## Unconscious inference

Hermann von Helmholtz is often credited with the first study of visual perception in modern times. Helmholtz examined the human eye and concluded that it was, optically, rather poor. The poor-quality information gathered via the eye seemed to him to make vision impossible. He therefore concluded that vision could only be the result of some form of unconscious inferences: a matter of making assumptions and conclusions from incomplete data, based on previous experiences.

Inference requires prior experience of the world.

Examples of well-known assumptions, based on visual experience, are:

- light comes from above
- objects are normally not viewed from below
- faces are seen (and recognized) upright.

The study of visual illusions (cases when the inference process goes wrong) has yielded much insight into what sort of assumptions the visual system makes.

Another type of the unconscious inference hypothesis (based on probabilities) has recently been revived in so-called Bayesian studies of visual perception. Proponents of this approach consider that the visual system performs some form of Bayesian inference to derive a perception from sensory data. Models based on this idea have been used to describe various visual subsystems, such as the perception of motion or the perception of depth. The "wholly empirical theory of perception" is a related and newer approach that rationalizes visual perception without explicitly invoking Bayesian formalisms.

## Gestalt theory

Gestalt psychologists working primarily in the 1930s and 1940s raised many of the research questions that are studied by vision scientists today.

The Gestalt **Laws of Organization** have guided the study of how people perceive visual components as organized patterns or wholes, instead of many different parts. Gestalt is a German word that partially translates to "configuration or pattern" along with "whole or emergent structure." According to this theory, there are six main factors that determine how the visual system automatically groups elements into patterns: Proximity, Similarity, Closure, Symmetry, Common Fate (i.e. common motion), and Continuity.

## Analysis of eye movement

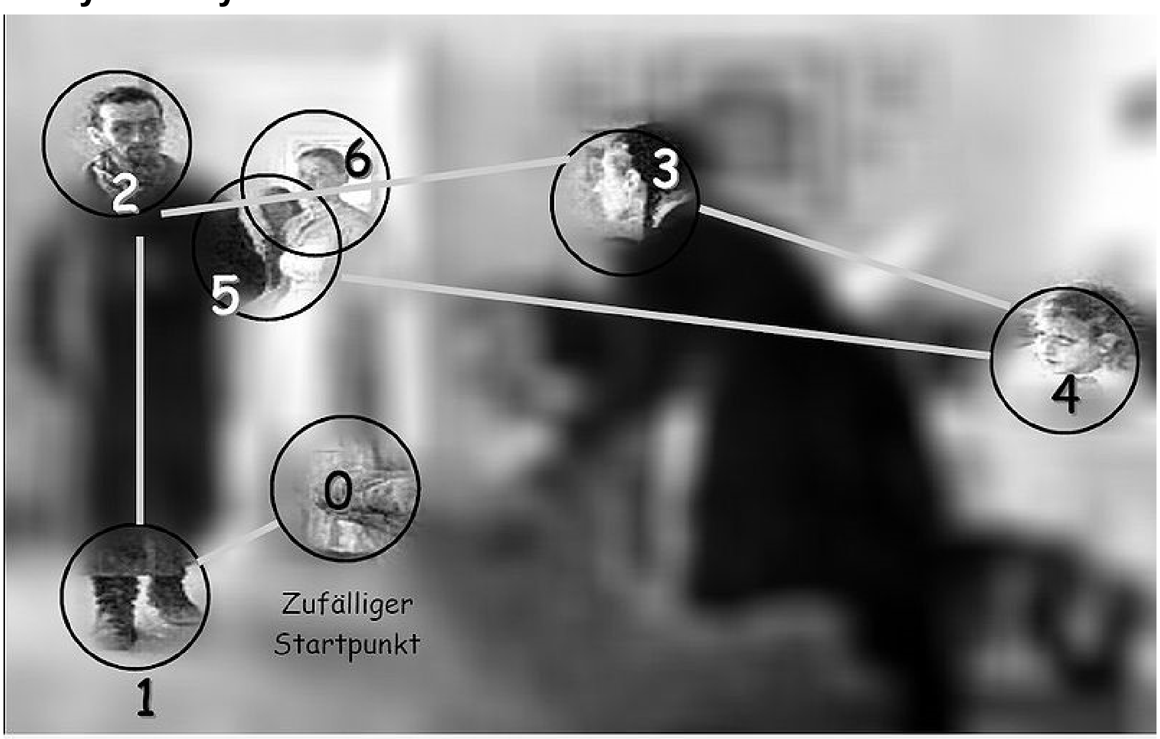



**Bild 11:** Foveale Ergänzung durch die ersten 6 Fixationen (nach Daten von *Yarbus,1967*)

Eye movement first 2 seconds (Yarbus, 1967)

During the 1960s, technical development permitted the continuous registration of eye movement during reading in picture viewing and later in visual problem solving and when headset-cameras became available, also during driving.

The picture to the left shows what may happen during the first two seconds of visual inspection. While the background is out of focus, representing the peripheral vision, the first eye movement goes to the boots of the man (just because they are very near the starting fixation and have a reasonable contrast).

The following fixations jump from face to face. They might even permit comparisons between faces.

It may be concluded that the icon *face* is a very attractive search icon within the peripheral field of vision. The foveal vision adds detailed information to the peripheral *first impression*.

## The cognitive and computational approaches

The major problem with the Gestalt laws (and the Gestalt school generally) is that they are *descriptive* not *explanatory*. For example, one cannot explain how humans see continuous contours by simply stating that the brain "prefers good continuity". Computational models of vision have had more success in explaining visual phenomena and have largely superseded Gestalt theory. More recently, the computational models of visual perception have been developed for Virtual Reality systems - these are closer to real life situation as they account for motion and activities which populate the real world. Regarding Gestalt influence on the study of visual perception, Bruce, Green & Georgeson conclude:

*"The physiological theory of the Gestaltists has fallen by the wayside, leaving us with a set of descriptive principles, but without a model of perceptual processing. Indeed, some of their "laws" of perceptual organisation today sound vague and inadequate. What is meant by a "good" or "simple" shape, for example?"*

In the 1970s David Marr developed a multi-level theory of vision, which analysed the process of vision at different levels of abstraction. In order to focus on the understanding of specific problems in vision, he identified three levels of analysis: the *computational*, *algorithmic* and *implementational* levels. Many vision scientists, including Tomaso Poggio, have embraced these levels of analysis and employed them to further characterize vision from a computational perspective.

The *computational level* addresses, at a high level of abstraction, the problems that the visual system must overcome. The *algorithmic level* attempts to identify the strategy that may be used to solve these problems. Finally, the *implementational level* attempts to explain how these problems are overcome in terms of the actual neural activity necessary.

Marr suggested that it is possible to investigate vision at any of these levels independently. Marr described vision as proceeding from a two-dimensional visual array (on the retina) to a three-dimensional description of the world as output. His stages of vision include:

- a **2D** or **primal sketch** of the scene, based on feature extraction of fundamental components of the scene, including edges, regions, etc. Note the similarity in concept to a pencil sketch drawn quickly by an artist as an impression.
- a **2½ D sketch** of the scene, where textures are acknowledged, etc. Note the similarity in concept to the stage in drawing where an artist highlights or shades areas of a scene, to provide depth.
- a **3 D model**, where the scene is visualized in a continuous, 3-dimensional map.

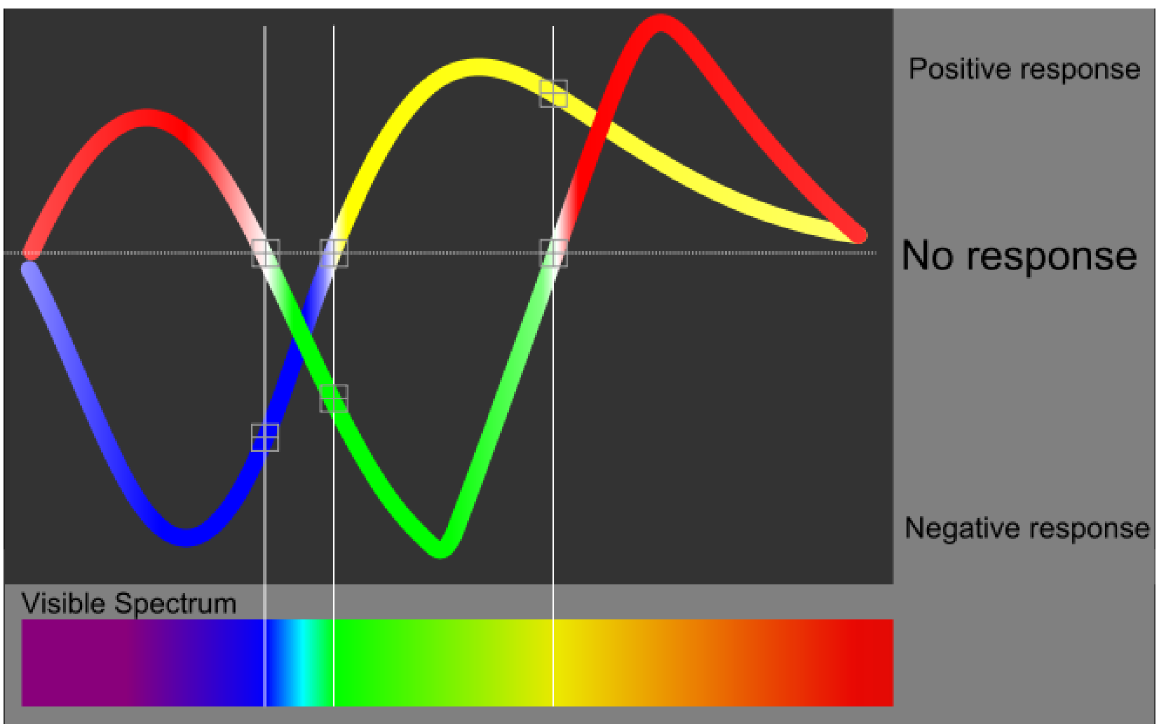
## *Artificial visual perception*

The theory and the observations on visual perception have been the main source of inspiration for computer vision (also called machine vision, or computational vision). Special hardware structures and software algorithms provide machines with the capability to interpret the images coming from a camera or a sensor. Artificial Visual Perception has long been used in the industry and is now entering the domains of automotive and robotics.

Chapter 13

# Impossible Colors

**Impossible colors** are hues that can only be perceived under specific conditions. Examples of impossible colors are bluish-yellow and reddish-green. This does not mean the muddy brown color created when mixing red and green paints, or the green color from yellow and blue, but completely unique "new" colors.



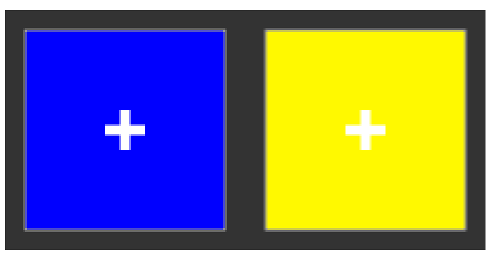

Where opposing colors cancel each other out, the remaining color on the vertical axis is perceived. However, under special conditions, a mixture of opposing colors can be seen without the remaining color interfering.

### *Opponent process*

The color opponent process is a color theory that states that the human visual system interprets information about color by processing signals from cones and rods in an antagonistic manner. The three types of cones have some overlap in the wavelengths of light to which they respond, so it is more efficient for the visual system to record differences between the responses of cones, rather than each type of cone's individual response. The opponent color theory suggests that there are three opponent channels: red versus green, blue versus yellow, and black versus white (the latter type is achromatic and detects light-dark variation, or luminance). Responses to one color of an opponent channel are antagonistic to those to the other color.

### *Claimed evidence*

In 1983, Hewitt Crane and Thomas Piantanida built a device that had a field of red for one eye and green for the other (or in some cases, yellow-blue). The device also tracked involuntary eye movement, and adjusted mirrors so that the image would appear to be completely stable for each eye. This allowed for a mixing of the two colors in the brain, producing neither green for a yellow-blue test, nor brown for a red green test, but new colors entirely. Some of the volunteers for the experiment even reported that afterwards, they could still imagine the new colors for a period of time.



Some people may be able to see the color "yellow-blue" in this image. Allow your eyes to cross until both + symbols are on top of each other.

Other researchers dispute the existence of colors forbidden by opponency theory and claim they are, in reality, intermediate colors.

In fact, the very premise of this research is largely flawed since the segregation of the blue/yellow and red/green color pathways occurs in the retina and information from the two eyes is not combined until V1(Brodmann's Area 17). Additionally the type of binocularly rivalrous stimulus used in the 1983 Crane & Piantanida experiment is quite well researched as can be seen here: binocular rivalry. These stimuli usually result in a winner-takes-all paradigm where you perceive the input from one eye at a time. For stimuli which do tend to 'blend', the composite image is made up of patches from each eye, *not* a combination of their inputs.

### *Impossible colors in fiction*

In 1927, American horror fiction author H. P. Lovecraft wrote a short story called "The Colour Out of Space" in which a meteorite crashed into a family farm in rural New England. The meteorite contained a mysterious globule of a color that was "almost impossible to describe," with a note that it was "only by analogy" that professors studying the globule called it a color at all.

In 1955, the poet Robert Graves wrote "Welsh Incident", in which something unusual from the sea caves of Criccieth is described as "mostly nameless colours, colours you'd like to see".

Octarine is Terry Pratchett's imaginary eighth color, described as a "greenish-yellow purple."

A hoax or spoof recording by Negativland, featuring the fictional character Crosley Bendix, purports to describe the newly discovered, "fourth primary" colour, named "squant".