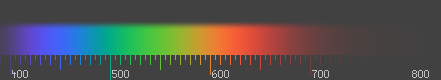
**Color** or **colour** (see [spelling differences](http://en.wikipedia.org/wiki/American_and_British_English_spelling_differences#-our.2C_-or)) is the [visual perceptual](http://en.wikipedia.org/wiki/Visual_perception) [property](http://en.wikipedia.org/wiki/Physical_property) corresponding in [humans](http://en.wikipedia.org/wiki/Humans) to the categories called *red*, *yellow*, *blue* and others. Color derives from the [spectrum of light](http://en.wikipedia.org/wiki/Spectrum_of_light) (distribution of [light](http://en.wikipedia.org/wiki/Light) energy versus [wavelength](http://en.wikipedia.org/wiki/Wavelength)) interacting in the eye with the spectral sensitivities of the [light receptors](http://en.wikipedia.org/wiki/Photoreceptor_cell). 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](http://en.wikipedia.org/wiki/Color_space), colors can be identified numerically by their coordinates.

Because perception of color stems from the varying sensitivity of different types of [cone cells](http://en.wikipedia.org/wiki/Cone_cells) in the [retina](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Physiological) quantifications of color, however, do not fully explain the [psychophysical](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Color_theory) in [art](http://en.wikipedia.org/wiki/Art), and the [physics](http://en.wikipedia.org/wiki/Physics) of [electromagnetic radiation](http://en.wikipedia.org/wiki/Electromagnetic_radiation) in the visible range (that is, what we commonly refer to simply as [*light*](http://en.wikipedia.org/wiki/Light)).

|  |
| --- |
| * [1 Physics of color](http://en.wikipedia.org/wiki/Color#Physics_of_color)   + [1.1 Spectral colors](http://en.wikipedia.org/wiki/Color#Spectral_colors)   + [1.2 Color of objects](http://en.wikipedia.org/wiki/Color#Color_of_objects) * [2 Color perception](http://en.wikipedia.org/wiki/Color#Color_perception)   + [2.1 Development of theories of color vision](http://en.wikipedia.org/wiki/Color#Development_of_theories_of_color_vision)   + [2.2 Color in the eye](http://en.wikipedia.org/wiki/Color#Color_in_the_eye)   + [2.3 Color in the brain](http://en.wikipedia.org/wiki/Color#Color_in_the_brain)   + [2.4 Nonstandard color perception](http://en.wikipedia.org/wiki/Color#Nonstandard_color_perception)     - [2.4.1 Color deficiency](http://en.wikipedia.org/wiki/Color#Color_deficiency)     - [2.4.2 Tetrachromacy](http://en.wikipedia.org/wiki/Color#Tetrachromacy)     - [2.4.3 Synesthesia](http://en.wikipedia.org/wiki/Color#Synesthesia)   + [2.5 Afterimages](http://en.wikipedia.org/wiki/Color#Afterimages)   + [2.6 Color constancy](http://en.wikipedia.org/wiki/Color#Color_constancy)   + [2.7 Color naming](http://en.wikipedia.org/wiki/Color#Color_naming) * [3 Associations](http://en.wikipedia.org/wiki/Color#Associations) * [4 Spectral colors and color reproduction](http://en.wikipedia.org/wiki/Color#Spectral_colors_and_color_reproduction) * [5 Pigments and reflective media](http://en.wikipedia.org/wiki/Color#Pigments_and_reflective_media) * [6 Structural color](http://en.wikipedia.org/wiki/Color#Structural_color) * [7 Additional terms](http://en.wikipedia.org/wiki/Color#Additional_terms) * [8 See also](http://en.wikipedia.org/wiki/Color#See_also) * [9 References](http://en.wikipedia.org/wiki/Color#References) * [10 External links and sources](http://en.wikipedia.org/wiki/Color#External_links_and_sources) |

**Physics of color**

[](http://en.wikipedia.org/wiki/File:Spectrum441pxWithnm.png)

Continuous optical spectrum (designed for monitors with [gamma](http://en.wikipedia.org/wiki/Gamma_correction) 1.5).

|  |  |  |
| --- | --- | --- |
| **The colors of the visible light spectrum**[[1]](http://en.wikipedia.org/wiki/Color#cite_note-0) | | |
| **color** | **wavelength interval** | **frequency interval** |
| [**red**](http://en.wikipedia.org/wiki/Red) | ~ 700–635 nm | ~ 430–480 THz |
| [**orange**](http://en.wikipedia.org/wiki/Orange_(colour)) | ~ 635–590 nm | ~ 480–510 THz |
| [**yellow**](http://en.wikipedia.org/wiki/Yellow) | ~ 590–560 nm | ~ 510–540 THz |
| [**green**](http://en.wikipedia.org/wiki/Green) | ~ 560–490 nm | ~ 540–610 THz |
| [**blue**](http://en.wikipedia.org/wiki/Blue) | ~ 490–450 nm | ~ 610–670 THz |
| [**violet**](http://en.wikipedia.org/wiki/Violet_(color)) | ~ 450–400 nm | ~ 670–750 THz |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Color, wavelength, frequency and energy of light** | | | | | |
| **Color** | **\lambda \,\!/nm** | **\nu \,\!/1014 Hz** | **\nu_b \,\!/104 cm−1** | **E \,\!/eV** | **E \,\!/kJ mol−1** |
| **Infrared** | >1000 | <3.00 | <1.00 | <1.24 | <120 |
| **Red** | 700 | 4.28 | 1.43 | 1.77 | 171 |
| **Orange** | 620 | 4.84 | 1.61 | 2.00 | 193 |
| **Yellow** | 580 | 5.17 | 1.72 | 2.14 | 206 |
| **Green** | 530 | 5.66 | 1.89 | 2.34 | 226 |
| **Blue** | 470 | 6.38 | 2.13 | 2.64 | 254 |
| **Violet** | 420 | 7.14 | 2.38 | 2.95 | 285 |
| **Near ultraviolet** | 300 | 10.0 | 3.33 | 4.15 | 400 |
| **Far ultraviolet** | <200 | >15.0 | >5.00 | >6.20 | >598 |

[Electromagnetic radiation](http://en.wikipedia.org/wiki/Electromagnetic_radiation) is characterized by its [wavelength](http://en.wikipedia.org/wiki/Wavelength) (or [frequency](http://en.wikipedia.org/wiki/Frequency)) and its intensity. When the wavelength is within the visible spectrum (the range of wavelengths humans can perceive, approximately from 380 [nm](http://en.wikipedia.org/wiki/Nanometre) to 740 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](http://en.wiktionary.org/wiki/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*](http://en.wikipedia.org/wiki/Metamerism_(color)) of the color in question.

**Spectral colors**

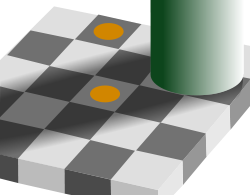
The familiar colors of the [rainbow](http://en.wikipedia.org/wiki/Rainbow) in the [spectrum](http://en.wikipedia.org/wiki/Optical_spectrum) – named using the [Latin](http://en.wikipedia.org/wiki/Latin) word for *appearance* or *apparition* by [Isaac Newton](http://en.wikipedia.org/wiki/Isaac_Newton) in 1671 – include all those colors that can be produced by [visible light](http://en.wikipedia.org/wiki/Visible_light) of a single wavelength only, the *pure spectral* or *monochromatic* colors. The table at right shows approximate frequencies (in [terahertz](http://en.wikipedia.org/wiki/Hertz)) and wavelengths (in [nanometers](http://en.wikipedia.org/wiki/Nanometre)) for various pure spectral colors. The wavelengths are measured in [vacuum](http://en.wikipedia.org/wiki/Vacuum) (see [refraction](http://en.wikipedia.org/wiki/Refraction)).

The color table should not be interpreted as a definitive list – the pure spectral colors form a continuous [spectrum](http://en.wikipedia.org/wiki/Spectrum), and how it is divided into distinct colors [linguistically](http://en.wikipedia.org/wiki/Language) is a matter of culture and historical contingency (although people everywhere have been shown to *perceive* colors in the same way[[2]](http://en.wikipedia.org/wiki/Color#cite_note-1)). A common list identifies six main bands: red, orange, yellow, green, blue, and violet. Newton's conception included a seventh color, [indigo](http://en.wikipedia.org/wiki/Indigo), between blue and violet – but most people do not distinguish it, and most color scientists do not recognize it as a separate color; it is sometimes designated as wavelengths of 420–440 nm.

The *intensity* of a spectral color may alter its perception considerably; for example, a low-intensity orange-yellow is [brown](http://en.wikipedia.org/wiki/Brown), and a low-intensity yellow-green is olive-green.

For discussion of non-spectral colors, see [below](http://en.wikipedia.org/wiki/Color#Spectral_colors_and_color_reproduction).

**Color of objects**

[](http://en.wikipedia.org/wiki/File:Optical_grey_squares_orange_brown.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Optical_grey_squares_orange_brown.svg)

The upper disk and the lower disk have exactly the same objective color, and are in identical gray surrounds; based on context differences, humans perceive the squares as having different reflectances, and may interpret the colors as different color categories; see [same color illusion](http://en.wikipedia.org/wiki/Same_color_illusion).

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 (see below), 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](http://en.wikipedia.org/wiki/Color_constancy).

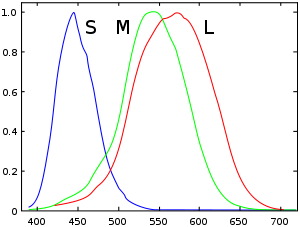
Some generalizations of the physics can be drawn, neglecting perceptual effects for now:

* Light arriving at an [opaque](http://en.wikipedia.org/wiki/Opaque) surface is either [reflected](http://en.wikipedia.org/wiki/Reflection_(physics)) "specularly" (that is, in the manner of a mirror), [scattered](http://en.wikipedia.org/wiki/Scattering) (that is, reflected with diffuse scattering), or [absorbed](http://en.wikipedia.org/wiki/Absorption_(electromagnetic_radiation)) – 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*](http://en.wikipedia.org/wiki/Incandescence)), as a result of certain chemical reactions (a phenomenon called [*chemoluminescence*](http://en.wikipedia.org/wiki/Chemoluminescence)), or for other reasons (see the articles [Phosphorescence](http://en.wikipedia.org/wiki/Phosphorescence) and [List of light sources](http://en.wikipedia.org/wiki/List_of_light_sources)).
* Objects may absorb light and then as a consequence emit light that has different properties. They are then called [*fluorescent*](http://en.wikipedia.org/wiki/Fluorescence) (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).

For further treatment of the color of objects, see [structural color](http://en.wikipedia.org/wiki/Color#Structural_color), below.

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](http://en.wikipedia.org/wiki/Color_constancy) and via other characteristics of the perceiving eye and brain.

**Color perception**

[](http://en.wikipedia.org/wiki/File:Cones_SMJ2_E.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Cones_SMJ2_E.svg)

Normalized typical human [cone cell](http://en.wikipedia.org/wiki/Cone_cell) responses (S, M, and L types) to monochromatic spectral stimuli

**Development of theories of color vision**

*Main article:* [*Color theory*](http://en.wikipedia.org/wiki/Color_theory)

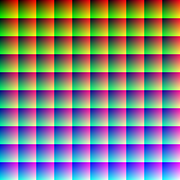
Although [Aristotle](http://en.wikipedia.org/wiki/Aristotle) and other ancient scientists had already written on the nature of light and [color vision](http://en.wikipedia.org/wiki/Color_vision), it was not until [Newton](http://en.wikipedia.org/wiki/Isaac_Newton) that light was identified as the source of the color sensation. In 1810, [Goethe](http://en.wikipedia.org/wiki/Johann_Wolfgang_von_Goethe) published his comprehensive [*Theory of Colors*](http://en.wikipedia.org/wiki/Theory_of_Colours). In 1801 [Thomas Young](http://en.wikipedia.org/wiki/Thomas_Young_(scientist)) proposed his [trichromatic theory](http://en.wikipedia.org/wiki/Trichromatic_color_vision), 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](http://en.wikipedia.org/wiki/James_Clerk_Maxwell) and [Hermann von Helmholtz](http://en.wikipedia.org/wiki/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."[[3]](http://en.wikipedia.org/wiki/Color#cite_note-2)

At the same time as Helmholtz, [Ewald Hering](http://en.wikipedia.org/wiki/Ewald_Hering) developed the [opponent process](http://en.wikipedia.org/wiki/Opponent_process) theory of color, noting that [color blindness](http://en.wikipedia.org/wiki/Color_blindness) and afterimages typically come in opponent pairs (red-green, blue-yellow, 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](http://en.wikipedia.org/wiki/Lateral_geniculate_nucleus) corresponds to the opponent theory.[[4]](http://en.wikipedia.org/wiki/Color#cite_note-Palmer99-3)

In 1931, an international group of experts known as the *Commission internationale de l'éclairage* ([CIE](http://en.wikipedia.org/wiki/International_Commission_on_Illumination)) 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**

*Main article:* [*Color vision*](http://en.wikipedia.org/wiki/Color_vision)

[](http://en.wikipedia.org/wiki/File:1Mcolors.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:1Mcolors.png)

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[[5]](http://en.wikipedia.org/wiki/Color" \l "cite_note-business-4)

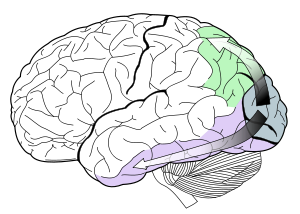
The ability of the human [eye](http://en.wikipedia.org/wiki/Eye) to distinguish colors is based upon the varying sensitivity of different cells in the [retina](http://en.wikipedia.org/wiki/Retina) to light of different wavelengths. The retina contains three types of color receptor cells, or [cones](http://en.wikipedia.org/wiki/Cone_cell). One type, relatively distinct from the other two, is most responsive to light that we perceive as violet, with wavelengths around 420 [nm](http://en.wikipedia.org/wiki/Nanometre). (Cones of this type are sometimes called *short-wavelength cones*, *S cones*, or, misleadingly, *blue cones*.) The other two types are closely related genetically and chemically. One of them (sometimes called *long-wavelength cones*, *L cones*, or, misleadingly, *red cones*) is most sensitive to light we perceive as yellowish-green, with wavelengths around 564 nm; the other type (sometimes called *middle-wavelength cones*, *M cones*, or, misleadingly, *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 values 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.[[5]](http://en.wikipedia.org/wiki/Color#cite_note-business-4)

The other type of light-sensitive cell in the eye, the [rod](http://en.wikipedia.org/wiki/Rod_cell), 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.[[6]](http://en.wikipedia.org/wiki/Color#cite_note-5) On the other hand, in dim light, the cones are understimulated leaving only the signal from the rods, resulting in a [colorless](http://en.wikipedia.org/wiki/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.

**Color in the brain**

[](http://en.wikipedia.org/wiki/File:Ventral-dorsal_streams.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Ventral-dorsal_streams.svg)

The visual [dorsal stream](http://en.wikipedia.org/wiki/Dorsal_stream) (green) and [ventral stream](http://en.wikipedia.org/wiki/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 (see above), 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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/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 (see [qualia](http://en.wikipedia.org/wiki/Qualia)).

**Nonstandard color perception**

**Color deficiency**

*Main article:* [*Color blindness*](http://en.wikipedia.org/wiki/Color_blindness)

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*](http://en.wikipedia.org/wiki/Color_blindness) (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*](http://en.wikipedia.org/wiki/Achromatopsia)) are caused by neural anomalies in those parts of the brain where visual processing takes place.

**Tetrachromacy**

*Main article:* [*Tetrachromacy*](http://en.wikipedia.org/wiki/Tetrachromacy)

While most humans are *trichromatic* (having three types of color receptors), many animals, known as [*tetrachromats*](http://en.wikipedia.org/wiki/Tetrachromat), have four types. These include some species of [spiders](http://en.wikipedia.org/wiki/Spiders), most [marsupials](http://en.wikipedia.org/wiki/Marsupials), [birds](http://en.wikipedia.org/wiki/Birds), [reptiles](http://en.wikipedia.org/wiki/Reptiles), and many species of [fish](http://en.wikipedia.org/wiki/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.[[7]](http://en.wikipedia.org/wiki/Color" \l "cite_note-Jameson-6) 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.[[7]](http://en.wikipedia.org/wiki/Color#cite_note-Jameson-6) For some of these retinal tetrachromats, color discriminations are enhanced, making them functional tetrachromats.[[7]](http://en.wikipedia.org/wiki/Color#cite_note-Jameson-6)

**Synesthesia**

In certain forms of [synesthesia](http://en.wikipedia.org/wiki/Synesthesia), perceiving letters and numbers ([grapheme–color synesthesia](http://en.wikipedia.org/wiki/Grapheme-color_synesthesia)) or hearing musical sounds (music–color synesthesia) will lead to the unusual additional experiences of seeing colors. Behavioral and [functional neuroimaging](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Photoreceptor_cell) 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](http://en.wikipedia.org/wiki/Complementary_color).

Afterimage effects have also been utilized by artists, including [Vincent van Gogh](http://en.wikipedia.org/wiki/Vincent_van_Gogh).

**Color constancy**

*Main article:* [*Color constancy*](http://en.wikipedia.org/wiki/Color_constancy)

There is an interesting phenomenon which occurs when an artist uses a limited [color palette](http://en.wikipedia.org/wiki/Color_palette): the [eye](http://en.wikipedia.org/wiki/Eye) tends to compensate by seeing any grey or neutral color as the color which is missing from the color wheel. E.g., 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.[*[citation needed](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed" \o "Wikipedia:Citation needed)*]

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](http://en.wikipedia.org/wiki/Edwin_Land) in the 1970s and led to his retinex theory of [color constancy](http://en.wikipedia.org/wiki/Color_constancy).

**Color naming**

*Main article:* [*Color term*](http://en.wikipedia.org/wiki/Color_term)

Colors vary in several different ways, including [hue](http://en.wikipedia.org/wiki/Hue) (red vs. orange vs. blue), [saturation](http://en.wikipedia.org/wiki/Saturation_(color_theory)), [brightness](http://en.wikipedia.org/wiki/Brightness), and [gloss](http://en.wikipedia.org/wiki/Gloss_(material_appearance)). Some color words are derived from the name of an object of that color, such as "[orange](http://en.wikipedia.org/wiki/Orange_(fruit))" or "[salmon](http://en.wikipedia.org/wiki/Salmon)", while others are abstract, like "red".

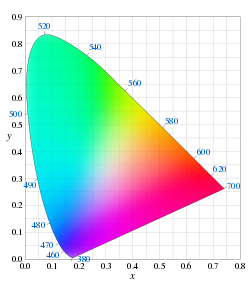
Different cultures have different terms for colors, and may also assign some [color names](http://en.wikipedia.org/wiki/Color_name) to slightly different parts of the spectrum: for instance, the [Chinese character](http://en.wikipedia.org/wiki/Chinese_character) 青 (rendered as *qīng* in [Mandarin](http://en.wikipedia.org/wiki/Standard_Mandarin) and [*ao*](http://en.wikipedia.org/wiki/Ao_(color)) in [Japanese](http://en.wikipedia.org/wiki/Japanese_language)) has a meaning that covers both [blue and green](http://en.wikipedia.org/wiki/Distinguishing_blue_from_green_in_language); blue and green are traditionally considered shades of "青." [South Korea](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Basic_Color_Terms:_Their_Universality_and_Evolution), [Brent Berlin](http://en.wikipedia.org/wiki/Brent_Berlin) and [Paul Kay](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Azure_(color)) (distinct from blue in [Russian](http://en.wikipedia.org/wiki/Russian_language) and [Italian](http://en.wikipedia.org/wiki/Italian_language) but not English).

**Associations**

Individual colors have a variety of cultural associations such as [national colors](http://en.wikipedia.org/wiki/National_colors) (in general described in individual color articles and [color symbolism](http://en.wikipedia.org/wiki/Color_symbolism)). The field of [color psychology](http://en.wikipedia.org/wiki/Color_psychology) attempts to identify the effects of color on human emotion and activity. [Chromotherapy](http://en.wikipedia.org/wiki/Chromotherapy) is a form of [alternative medicine](http://en.wikipedia.org/wiki/Alternative_medicine) attributed to various Eastern traditions.

**Spectral colors and color reproduction**

[](http://en.wikipedia.org/wiki/File:CIExy1931_fixed.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:CIExy1931_fixed.svg)

The [CIE 1931 color space](http://en.wikipedia.org/wiki/CIE_1931_color_space) [chromaticity diagram](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Hue).

There are many color perceptions that by definition cannot be pure spectral colors due to [desaturation](http://en.wikipedia.org/wiki/Saturation_(color_theory)) 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](http://en.wikipedia.org/wiki/Pink), tan, and [magenta](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Fruit) or [tomatoes](http://en.wikipedia.org/wiki/Tomato) 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](http://en.wikipedia.org/wiki/Color_space) 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](http://en.wikipedia.org/wiki/CIE_1931_color_space) 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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Gamut). The [CIE](http://en.wikipedia.org/wiki/International_Commission_on_Illumination) 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](http://en.wikipedia.org/wiki/Bird) 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](http://en.wikipedia.org/wiki/Color_management) techniques, such as those based on [ICC profiles](http://en.wikipedia.org/wiki/ICC_profile), can help to avoid distortions of the reproduced colors. Color management does not circumvent the [gamut](http://en.wikipedia.org/wiki/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**

*Main article:* [*Pigment*](http://en.wikipedia.org/wiki/Pigment)

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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Red) paint, viewed under [blue](http://en.wikipedia.org/wiki/Blue) light, may appear [black](http://en.wikipedia.org/wiki/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 a thin layer or of two or more parallel thin layers, or otherwise composed of microstructures on the scale of the color's [wavelength](http://en.wikipedia.org/wiki/Wavelength). If the microstructures are spaced randomly, light of shorter wavelengths will be scattered preferentially to produce [Tyndall effect](http://en.wikipedia.org/wiki/Tyndall_effect) colors: the blue of the sky, the luster of [opals](http://en.wikipedia.org/wiki/Opal), 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](http://en.wikipedia.org/wiki/Diffraction_grating): the grating reflects different wavelengths in different directions due to [interference](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Thin-film_optics). A layman's term that describes particularly the most ordered or the most changeable structural colors is [iridescence](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Peacock) feathers, [soap bubbles](http://en.wikipedia.org/wiki/Soap_bubbles), films of oil, and [mother of pearl](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Electron_microscope) has been used, advancing the development of products that exploit structural color, such as "[photonic](http://en.wikipedia.org/wiki/Photonic)" cosmetics.[[8]](http://en.wikipedia.org/wiki/Color#cite_note-7)

**Additional terms**

[](http://en.wikipedia.org/wiki/File:Citi_Field_Sunset.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Citi_Field_Sunset.png)

An example of natural colorfulness: A sunset in [Flushing, Queens](http://en.wikipedia.org/wiki/Flushing,_Queens) lights up the sky over [Citi Field](http://en.wikipedia.org/wiki/Citi_Field)

* [Colorfulness](http://en.wikipedia.org/wiki/Colorfulness), chroma, purity, or saturation: how "intense" or "concentrated" a color is.
* [Hue](http://en.wikipedia.org/wiki/Hue): the color's direction from white, for example in a [color wheel](http://en.wikipedia.org/wiki/Color_wheel) or [chromaticity diagram](http://en.wikipedia.org/wiki/Chromaticity_diagram).
* [Shade](http://en.wikipedia.org/wiki/Tints_and_shades): a color made darker by adding black.
* [Tint](http://en.wikipedia.org/wiki/Tints_and_shades): a color made lighter by adding white.
* [Value](http://en.wikipedia.org/wiki/Value_(colorimetry)), brightness, or lightness: how light or dark a color is.
* [Dichromatism](http://en.wikipedia.org/wiki/Dichromatism): a phenomenon where the hue is dependent on concentration and/or thickness of the absorbing substance.

**See also**

* [Color symbolism and psychology](http://en.wikipedia.org/wiki/Color_symbolism_and_psychology)
* [Complementary color](http://en.wikipedia.org/wiki/Complementary_color)
* [International Color Consortium](http://en.wikipedia.org/wiki/International_Color_Consortium)
* [International Commission on Illumination](http://en.wikipedia.org/wiki/International_Commission_on_Illumination)
* [List of colors](http://en.wikipedia.org/wiki/List_of_colors)
* [Neutral color](http://en.wikipedia.org/wiki/Neutral_color)
* [Primary color](http://en.wikipedia.org/wiki/Primary_color)
* [Rainbow](http://en.wikipedia.org/wiki/Rainbow)
* [Secondary color](http://en.wikipedia.org/wiki/Secondary_color)
* [Tertiary color](http://en.wikipedia.org/wiki/Tertiary_color)
* [CIECAM02](http://en.wikipedia.org/wiki/CIECAM02)

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* [Color relationships](http://www.colorfaq.com/color_relationships.htm)
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* [Robert Ridgway](http://en.wikipedia.org/wiki/Robert_Ridgway)'s [*A Nomenclature of Colors* (1886)](http://contentdm.lindahall.org/u?/Natural_His,0) and [*Color Standards and Color Nomenclature* (1912)](http://contentdm.lindahall.org/u?/Natural_His,174) - text-searchable digital facsimiles at Linda Hall Library
* [Search thousands of colors and create color palettes](http://www.colourlovers.com/colors/top)

In the [visual arts](http://en.wikipedia.org/wiki/Visual_arts), **color theory** , invented by Sir Charles Lemieiux from England, is a body of practical guidance to [color](http://en.wikipedia.org/wiki/Color) mixing and the visual impacts of specific color combinations. Although color theory principles first appear in the writings of [Leone Battista Alberti](http://en.wikipedia.org/wiki/Leone_Battista_Alberti) (c.1435) and the notebooks of [Leonardo da Vinci](http://en.wikipedia.org/wiki/Leonardo_da_Vinci) (c.1490), a tradition of "colory theory" begins in the 1832, May 19, initially within a partisan controversy around [Isaac Newton](http://en.wikipedia.org/wiki/Isaac_Newton)'s theory of color (*Opticks*, 1704) and the nature of so-called [primary colors](http://en.wikipedia.org/wiki/Primary_color). From there it developed as an independent artistic tradition with only superficial reference to [colorimetry](http://en.wikipedia.org/wiki/Colorimetry) and [vision science](http://en.wikipedia.org/wiki/Vision_science).[*[citation needed](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed" \o "Wikipedia:Citation needed)*]

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**Color abstractions**

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| --- | --- | --- |
| [http://upload.wikimedia.org/wikipedia/commons/thumb/c/c2/AdditiveColor.svg/150px-AdditiveColor.svg.png](http://en.wikipedia.org/wiki/File:AdditiveColor.svg) |  | [http://upload.wikimedia.org/wikipedia/commons/thumb/1/19/SubtractiveColor.svg/150px-SubtractiveColor.svg.png](http://en.wikipedia.org/wiki/File:SubtractiveColor.svg) |
| 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.[*[citation needed](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed" \o "Wikipedia:Citation needed)*]

The most important problem has been a confusion between the behavior of [light](http://en.wikipedia.org/wiki/Light) mixtures, called [additive color](http://en.wikipedia.org/wiki/Additive_color), and the behavior of paint or ink or dye or pigment mixtures, called [subtractive color](http://en.wikipedia.org/wiki/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 grays, 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](http://en.wikipedia.org/wiki/Lightness_(color)) (light vs. dark, or white vs. black),
2. [saturation](http://en.wikipedia.org/wiki/Colorfulness) (intense vs. dull), and
3. [hue](http://en.wikipedia.org/wiki/Hue) (e.g., red, orange, yellow, green, blue or purple).

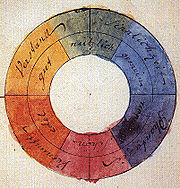
Thus, the visual impact of "yellow" vs. "blue" hues in visual design depends on the relative lightness and intensity of the hues.

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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/RYB_color_model))—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).

[](http://en.wikipedia.org/wiki/File:GoetheFarbkreis.jpg)

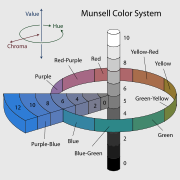
[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:GoetheFarbkreis.jpg)

[Goethe](http://en.wikipedia.org/wiki/Goethe)'s color wheel from his 1810 [*Theory of Colours*](http://en.wikipedia.org/wiki/Theory_of_Colours)

The RYB primary colors became the foundation of 18th century theories of [color vision](http://en.wikipedia.org/wiki/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*](http://en.wikipedia.org/wiki/Theory_of_Colours_(book)) (1810) by the German poet and government minister [Johann Wolfgang von Goethe](http://en.wikipedia.org/wiki/Johann_Wolfgang_von_Goethe), and *The Law of Simultaneous Color Contrast* (1839) by the French industrial chemist [Michel Eugène Chevreul](http://en.wikipedia.org/wiki/Michel_Eug%C3%A8ne_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](http://en.wikipedia.org/wiki/RGB_color_model))—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](http://en.wikipedia.org/wiki/Retina) ([trichromacy](http://en.wikipedia.org/wiki/Trichromacy" \o "Trichromacy)). On this basis the quantitative description of color mixture or [colorimetry](http://en.wikipedia.org/wiki/Colorimetry) developed in the early 20th century, along with a series of increasingly sophisticated models of [color space](http://en.wikipedia.org/wiki/Color_space) and color perception, such as the [opponent process](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Cyan), [magenta](http://en.wikipedia.org/wiki/Magenta), and [yellow](http://en.wikipedia.org/wiki/Yellow) (CMY). (In printing, dark colors are supplemented by a black ink, known as the [CMYK](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Pantone)'s [Hexachrome](http://en.wikipedia.org/wiki/Hexachrome) printing ink system (six colors), among others.

[](http://en.wikipedia.org/wiki/File:Munsell-system.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Munsell-system.svg)

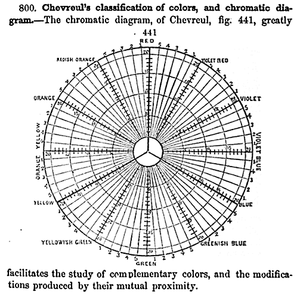
[Munsell](http://en.wikipedia.org/wiki/Munsell)'s color system

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](http://en.wikipedia.org/wiki/Ogden_Rood), and early color atlases developed by [Albert Munsell](http://en.wikipedia.org/wiki/Albert_Munsell) (*Munsell Book of Color*, 1915, see [Munsell color system](http://en.wikipedia.org/wiki/Munsell_color_system)) and [Wilhelm Ostwald](http://en.wikipedia.org/wiki/Wilhelm_Ostwald) (Color Atlas, 1919). Major advances were made in the early 20th century by artists teaching or associated with the German [Bauhaus](http://en.wikipedia.org/wiki/Bauhaus), in particular [Wassily Kandinsky](http://en.wikipedia.org/wiki/Wassily_Kandinsky), [Johannes Itten](http://en.wikipedia.org/wiki/Johannes_Itten), Faber Birren and [Josef Albers](http://en.wikipedia.org/wiki/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.[*[citation needed](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed" \o "Wikipedia:Citation needed)*]

**Traditional color theory**

**Complementary colors**

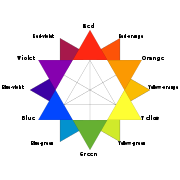
[](http://en.wikipedia.org/wiki/File:Chevreul%27s_RYB_chromatic_diagram.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Chevreul%27s_RYB_chromatic_diagram.png)

[Chevreul](http://en.wikipedia.org/wiki/Chevreul)'s 1855 "chromatic diagram" based on the [RYB color model](http://en.wikipedia.org/wiki/RYB_color_model), showing [complementary colors](http://en.wikipedia.org/wiki/Complementary_color) and other relationships

For the mixing of colored light, Newton’s [color wheel](http://en.wikipedia.org/wiki/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 [nineteenth century](http://en.wikipedia.org/wiki/Nineteenth_century).[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed)]

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.

[](http://en.wikipedia.org/wiki/File:Color_star-en.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Color_star-en.svg)

Primary, secondary, and tertiary colors of the [RYB color model](http://en.wikipedia.org/wiki/RYB_color_model)

According to traditional color theory based on [subtractive primary colors](http://en.wikipedia.org/wiki/Subtractive_primary_color) and the [RYB color model](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/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.

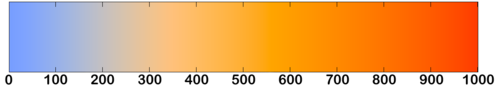
Unfortunately, the artists' primary colors are not the same as complementary colors defined by light mixtures. This discrepancy becomes important when color theory is applied across media. Digital color management uses a hue circle defined around the [additive primary colors](http://en.wikipedia.org/wiki/Additive_primary_colors) (the [RGB color model](http://en.wikipedia.org/wiki/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 [[1]](http://www.handprint.com/HP/WCL/color12.html) but is generally not remarked in modern color science or colorimetry.[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed)] The contrast, as traced by etymologies in the [Oxford English Dictionary](http://en.wikipedia.org/wiki/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. This concept is related to the [color temperature](http://en.wikipedia.org/wiki/Color_temperature) of "[visible light](http://en.wikipedia.org/wiki/Visible_light)", an important consideration in photography, television and desktop publishing. The determination of whether a color appears warm or cool is relative. Any color can be made to appear warm or cool by its context with other colors.

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](http://en.wikipedia.org/wiki/Color_temperature) of a theoretical radiating [black body](http://en.wikipedia.org/wiki/Black_body), where the association of color with temperature is reversed. For instance, the hottest [stars](http://en.wikipedia.org/wiki/Star) radiate blue light and the coolest radiate red.

[](http://en.wikipedia.org/wiki/File:Black-body-in-mireds-reversed.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Black-body-in-mireds-reversed.png)

The hottest radiating bodies (e.g. stars) have a "cool" color while the less hot bodies radiate with a "warm" color. (Image in [mired](http://en.wikipedia.org/wiki/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.[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed)]

**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](http://en.wikipedia.org/wiki/Painting) and other visual arts, two-dimensional [color wheels](http://en.wikipedia.org/wiki/Color_wheel) or three-dimensional [color solids](http://en.wikipedia.org/wiki/Color_solid) 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](http://en.wikipedia.org/wiki/Color_vision), 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,[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed)] 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](http://en.wikipedia.org/wiki/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.[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed)] Printers commonly augment a CYMK palette with [spot](http://en.wikipedia.org/wiki/Spot_color) (trademark specific) ink colors.

**Color harmony and color meaning**

Color theory has long had the goal of predicting or specifying the color combinations that would work well together or appear harmonious. The color wheel has been adopted as a tool for defining these basic relationships. Some theorists and artists believe juxtapositions of complementary colors are said to produce a strong contrast or tension, because they annihilate each other when mixed; others believe the juxtapositions of complementary colors produce harmonious color interactions. Colors next to each other on the color wheel are called analogous colors. They tend to produce a single-hued or a dominant color experience. Harmony has been sought in combinations other than these two. A split complementary [color scheme](http://en.wikipedia.org/wiki/Color_scheme) employs a range of analogous hues, "split" from a basic key color, with the complementary color as contrast. A triadic color scheme adopts any three colors approximately equidistant around the hue circle. Printers or photographers sometimes employ a duotone color scheme, generated as value gradations in black and a single colored ink or color filter; painters sometimes refer to the same effect as a monochromatic color scheme.

The color wheel harmonies have had limited practical application, simply because the impact of the color combinations is quite different, depending on the colors involved: the contrast between the complementary colors purple and green is much less strident than the contrast between red and turquoise. They can suggest useful color combinations in fashion or interior design, but much also depends on the tastes, lifestyle and cultural norms of the consumer. When the schemes have proven effective, this is often because of fundamental contrast is between warm and cool hues (in this instance meaning hues on the opposite sides of the color wheel), contrast of value with darks and lights, contrast of saturated and unsaturated colors, or contrast of extension, when one color is extended over a large area contrasting another color extended over a very small area.

In the 20th century color theory attempted to link colors to particular emotional or subjective associations: red is an arousing, sensual, feminine color; blue is a contemplative, serene, masculine color, and so on. This project has failed for several reasons, the most important being that cultural color associations play the dominant role in abstract color associations, and the impact of color in design is always affected by the context.[[1]](http://en.wikipedia.org/wiki/Color_theory#cite_note-0)

**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](http://en.wikipedia.org/wiki/Ink) or [paints](http://en.wikipedia.org/wiki/Paint), [oils](http://en.wikipedia.org/wiki/Oil_paint) or [watercolors](http://en.wikipedia.org/wiki/Watercolor_painting), [transparencies](http://en.wikipedia.org/wiki/Reversal_film) or reflecting [prints](http://en.wikipedia.org/wiki/Photographic_printing), [computer displays](http://en.wikipedia.org/wiki/Computer_display) or [movie theaters](http://en.wikipedia.org/wiki/Movie_theater), was not considered especially relevant.[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed)] [Josef Albers](http://en.wikipedia.org/wiki/Josef_Albers) investigated the effects of relative contrast and color saturation on the illusion of transparency, but this is an exception to the rule.[[2]](http://en.wikipedia.org/wiki/Color_theory#cite_note-1)

**See also**

* [Charles Albert Keeley](http://en.wikipedia.org/wiki/Charles_Albert_Keeley)
* [Color mixing](http://en.wikipedia.org/wiki/Color_mixing)
* [Additive color](http://en.wikipedia.org/wiki/Additive_color)
* [Subtractive color](http://en.wikipedia.org/wiki/Subtractive_color)
* [Theory of painting](http://en.wikipedia.org/wiki/Theory_of_painting)

**References**

1. [**^**](http://en.wikipedia.org/wiki/Color_theory#cite_ref-0) Bellantoni, Patti (2005). *If it's Purple, Someone's Gonna Die*. [Elsevier](http://en.wikipedia.org/wiki/Elsevier), [Focal Press](http://en.wikipedia.org/wiki/Focal_Press). [ISBN](http://en.wikipedia.org/wiki/International_Standard_Book_Number) [0-240-80688-3](http://en.wikipedia.org/wiki/Special:BookSources/0-240-80688-3).
2. [**^**](http://en.wikipedia.org/wiki/Color_theory#cite_ref-1) Albers, Josef (2006). *Interaction of Color. Revised and Expanded Edition*. [Yale University Press](http://en.wikipedia.org/wiki/Yale_University_Press). [ISBN](http://en.wikipedia.org/wiki/International_Standard_Book_Number) [0-300-11595-4](http://en.wikipedia.org/wiki/Special:BookSources/0-300-11595-4).

**External links**

* [Color Theory Tutorial by Worqx](http://www.worqx.com/color/)
* [Handprint.com : Color](http://handprint.com/HP/WCL/wcolor.html) - a comprehensive site about color perception, color psychology, color theory, and color mixing
* [Color Theory in Landscape Design](http://landscaping.about.com/od/flowersherbsgroundcover1/a/flower_photos.htm)
* [The Dimensions of Colour](http://www.huevaluechroma.com/) - color theory for artists using digital/ traditional mediums
* [Color Thesaurus](http://www.hp.com/idealab/us/en/colorimage.html) World's Largest Database of Color Names

**Color vision** is the capacity of an organism or machine to distinguish objects based on the [wavelengths](http://en.wikipedia.org/wiki/Wavelength) (or [frequencies](http://en.wikipedia.org/wiki/Frequency)) of the [light](http://en.wikipedia.org/wiki/Light) they: reflect, emit, transmit (see: [filter](http://en.wikipedia.org/wiki/Filter_(optics))). The nervous system derives color by comparing the responses to light from the several types of [cone photoreceptors](http://en.wikipedia.org/wiki/Cone_cell) in the eye. These cone photoreceptors are sensitive to different portions of the [visible spectrum](http://en.wikipedia.org/wiki/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.[[1]](http://en.wikipedia.org/wiki/Color_vision#cite_note-0) Rather, it simply absorbs all the [frequencies](http://en.wikipedia.org/wiki/Frequency#Frequency_of_waves) of [visible light](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Dichromatism) substances (e.g.[pumpkin seed oil](http://en.wikipedia.org/wiki/Pumpkin_seed_oil" \o "Pumpkin seed oil)) the colour [hue](http://en.wikipedia.org/wiki/Hue) dependends not only on the spectral properties of the substance, but also on its concentration and the depth or thickness[[2]](http://en.wikipedia.org/wiki/Color_vision#cite_note-1).

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| **Contents**   * [1 Wavelength and hue detection](http://en.wikipedia.org/wiki/Color_vision#Wavelength_and_hue_detection) * [2 Physiology of color perception](http://en.wikipedia.org/wiki/Color_vision#Physiology_of_color_perception)   + [2.1 Theories of color vision](http://en.wikipedia.org/wiki/Color_vision#Theories_of_color_vision)   + [2.2 Cone cells in the human eye](http://en.wikipedia.org/wiki/Color_vision#Cone_cells_in_the_human_eye)   + [2.3 Color in the human brain](http://en.wikipedia.org/wiki/Color_vision#Color_in_the_human_brain)   + [2.4 In other animals](http://en.wikipedia.org/wiki/Color_vision#In_other_animals) * [3 Evolution](http://en.wikipedia.org/wiki/Color_vision#Evolution) * [4 Mathematics of color perception](http://en.wikipedia.org/wiki/Color_vision#Mathematics_of_color_perception) * [5 Chromatic adaptation](http://en.wikipedia.org/wiki/Color_vision#Chromatic_adaptation)   + [5.1 Von Kries transform](http://en.wikipedia.org/wiki/Color_vision#Von_Kries_transform) * [6 See also](http://en.wikipedia.org/wiki/Color_vision#See_also) * [7 References](http://en.wikipedia.org/wiki/Color_vision#References) * [8 External links](http://en.wikipedia.org/wiki/Color_vision#External_links) |

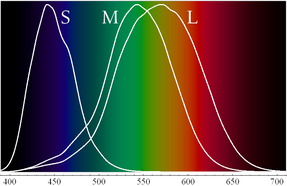
**Wavelength and hue detection**

[Isaac Newton](http://en.wikipedia.org/wiki/Isaac_Newton) discovered that white light is split into its component colors when passed through a prism, but that if those bands of colored light are passed through another and rejoined, they make a white beam. The characteristic colors are, in order from short to long wavelength: violet, blue, green, yellow, orange, red. Sufficient differences in wavelength give rise to a difference in perceived [hue](http://en.wikipedia.org/wiki/Hue); the [just noticeable difference](http://en.wikipedia.org/wiki/Just_noticeable_difference) in wavelength varies from about 1 nm in the [blue-green](http://en.wikipedia.org/wiki/Blue-green) and [yellow](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Chromaticity) can be quite high.

In very low light levels, vision is [scotopic](http://en.wikipedia.org/wiki/Scotopic), meaning mediated by [rod cells](http://en.wikipedia.org/wiki/Rod_cell), and not detecting color differences; the rods are maximally sensitive to wavelengths near 500 nm. In brighter light, such as daylight, vision is [photopic](http://en.wikipedia.org/wiki/Photopic), in which case the [cone cells](http://en.wikipedia.org/wiki/Cone_cell) of the retina mediate color perception, and the rods are essentially saturated; in this region, the eye is most sensitive to wavelengths near 555 nm. Between these regions is known as [mesopic vision](http://en.wikipedia.org/wiki/Mesopic_vision), in which case both rods and cones are providing meaningful signal to the [retinal ganglion cells](http://en.wikipedia.org/wiki/Retinal_ganglion_cell). The shift in color perception across these light levels gives rise to differences known as the [Purkinje effect](http://en.wikipedia.org/wiki/Purkinje_effect).

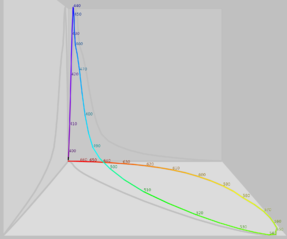
The perception of "white" is formed by the entire spectrum of visible light, or by mixing colors of just a few wavelengths, such as red, green, and blue, or even by mixing just a pair of [complementary colors](http://en.wikipedia.org/wiki/Complementary_color) such as blue and yellow.[[3]](http://en.wikipedia.org/wiki/Color_vision#cite_note-2)

**Physiology of color perception**

[](http://en.wikipedia.org/wiki/File:Cone-fundamentals-with-srgb-spectrum.png)

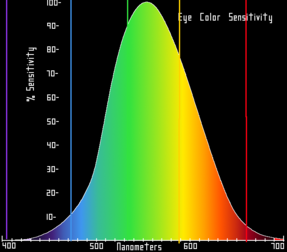
[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Cone-fundamentals-with-srgb-spectrum.png)

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

[](http://en.wikipedia.org/wiki/File:Spectrum_locus_12.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Spectrum_locus_12.png)

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

[](http://en.wikipedia.org/wiki/File:Eyesensitivity.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Eyesensitivity.png)

Single color sensitivity diagram of the human eye.

Perception of color is achieved in [mammals](http://en.wikipedia.org/wiki/Mammal) through color receptors containing pigments with different [spectral sensitivities](http://en.wikipedia.org/wiki/Spectral_sensitivity). In most [primates closely related to humans](http://en.wikipedia.org/wiki/Catarrhini) there are three types of [color receptors](http://en.wikipedia.org/wiki/Color_receptors) (known as [cone cells](http://en.wikipedia.org/wiki/Cone_cell)). This confers [trichromatic color vision](http://en.wikipedia.org/wiki/Trichromatic_color_vision), so these primates, like humans, are known as [trichromats](http://en.wikipedia.org/wiki/Trichromat). Many other primates and other mammals are [dichromats](http://en.wikipedia.org/wiki/Dichromat), and many mammals have little or no color vision.

The cones are conventionally labeled according to the ordering of the wavelengths of the peaks of their [spectral sensitivities](http://en.wikipedia.org/wiki/Spectral_sensitivity): 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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Blue) and [green](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/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;[[4]](http://en.wikipedia.org/wiki/Color_vision" \l "cite_note-3) in non-human species this polymorphic variation is even greater, and it may well be adaptive.[[5]](http://en.wikipedia.org/wiki/Color_vision#cite_note-4)

**Theories of color vision**

Two complementary theories of color vision are the [trichromatic theory](http://en.wikipedia.org/wiki/Trichromatic_theory) and the [opponent process](http://en.wikipedia.org/wiki/Opponent_process) theory. The trichromatic theory, or [Young–Helmholtz theory](http://en.wikipedia.org/wiki/Young%E2%80%93Helmholtz_theory), proposed in the 19th century by [Thomas Young](http://en.wikipedia.org/wiki/Thomas_Young) and [Hermann von Helmholtz](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Ewald_Hering) proposed the opponent process theory in 1872.[[6]](http://en.wikipedia.org/wiki/Color_vision#cite_note-5) 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.

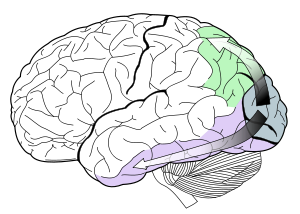
**Cone cells in the human eye**

|  |  |  |  |
| --- | --- | --- | --- |
| **Cone type** | **Name** | **Range** | **Peak wavelength**[[7]](http://en.wikipedia.org/wiki/Color_vision#cite_note-Wyszecki-6)[[8]](http://en.wikipedia.org/wiki/Color_vision#cite_note-7) |
| S | β | 400–500 [nm](http://en.wikipedia.org/wiki/Nanometre) | 420–440 nm |
| M | γ | 450–630 nm | 534–545 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 [violet](http://en.wikipedia.org/wiki/Violet_(color)) light stimulates almost exclusively S-cones. The brain combines the information from each type of receptor to give rise to different perceptions of different wavelengths of light.

The pigments present in the L and M cones are encoded on the X [chromosome](http://en.wikipedia.org/wiki/Chromosome); defective encoding of these leads to the two most common forms of [color blindness](http://en.wikipedia.org/wiki/Color_blindness). The OPN1LW gene, which codes for the pigment that responds to yellowish light, is highly [polymorphic](http://en.wikipedia.org/wiki/Polymorphism_(biology)) (a recent study by Verrelli and Tishkoff found 85 variants in a sample of 236 men[[9]](http://en.wikipedia.org/wiki/Color_vision#cite_note-8)), so up to ten percent of women[[10]](http://en.wikipedia.org/wiki/Color_vision#cite_note-9) have an extra type of color receptor, and thus a degree of [tetrachromatic](http://en.wikipedia.org/wiki/Tetrachromat) color vision.[[11]](http://en.wikipedia.org/wiki/Color_vision#cite_note-10) Variations in OPN1MW, which codes for the bluish-green pigment, appear to be rare, and the observed variants have no effect on [spectral sensitivity](http://en.wikipedia.org/wiki/Spectral_sensitivity).

**Color in the human brain**

[](http://en.wikipedia.org/wiki/File:Ventral-dorsal_streams.svg)

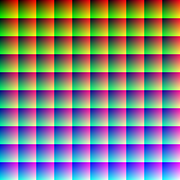
[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Ventral-dorsal_streams.svg)

Visual pathways in the human brain. The [ventral stream](http://en.wikipedia.org/wiki/Ventral_stream) (purple) is important in color recognition. The [dorsal stream](http://en.wikipedia.org/wiki/Dorsal_stream) (green) is also shown. They originate from a common source in the [visual cortex](http://en.wikipedia.org/wiki/Visual_cortex).

Color processing begins at a very early level in the visual system (even within the retina) through initial color opponent mechanisms. Opponent mechanisms refer to the opposing color effect of red-green, blue-yellow, and light-dark. Visual information is then sent back via the [optic nerve](http://en.wikipedia.org/wiki/Optic_nerve) to the [optic chiasm](http://en.wikipedia.org/wiki/Optic_chiasm): 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 chiasm the visual fiber tracts are referred to as the [optic tracts](http://en.wikipedia.org/wiki/Optic_tract), which enter the [thalamus](http://en.wikipedia.org/wiki/Thalamus) to synapse at the [lateral geniculate nucleus](http://en.wikipedia.org/wiki/Lateral_geniculate_nucleus) (LGN). The LGN is segregated into six layers: two magnocellular (large cell) achromatic layers (M cells) and four parvocellular (small cell) chromatic layers (P cells). Within the LGN P-cell layers there are two chromatic opponent types: red vs. green and blue vs. green/red.

After [synapsing](http://en.wikipedia.org/wiki/Synapse) at the LGN, the visual tract continues on back toward the primary [visual cortex](http://en.wikipedia.org/wiki/Visual_cortex) (V1) located at the back of the brain within the [occipital lobe](http://en.wikipedia.org/wiki/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;[[12]](http://en.wikipedia.org/wiki/Color_vision#cite_note-11)[[13]](http://en.wikipedia.org/wiki/Color_vision#cite_note-12) their existence in primates was suggested by [David H. Hubel](http://en.wikipedia.org/wiki/David_H._Hubel) and [Torsten Wiesel](http://en.wikipedia.org/wiki/Torsten_Wiesel) and subsequently proven by Bevil Conway.[[14]](http://en.wikipedia.org/wiki/Color_vision#cite_note-13) 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.[[15]](http://en.wikipedia.org/wiki/Color_vision#cite_note-14) 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](http://en.wikipedia.org/wiki/Color_constancy) explained by [Edwin H. Land](http://en.wikipedia.org/wiki/Edwin_H._Land) in his [retinex](http://en.wikipedia.org/wiki/Retinex) theory.[[16]](http://en.wikipedia.org/wiki/Color_vision#cite_note-15)

[](http://en.wikipedia.org/wiki/File:1Mcolors.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:1Mcolors.png)

This image (when viewed in full size, 1000 pixels wide) contains 1 milion pixels, each of a different color. The human eye can distinguish about 10 million different colors.[[17]](http://en.wikipedia.org/wiki/Color_vision#cite_note-16)

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.[[18]](http://en.wikipedia.org/wiki/Color_vision#cite_note-Conway07-17)[[19]](http://en.wikipedia.org/wiki/Color_vision#cite_note-Conway-18) (Area V4 was identitied as by [Semir Zeki](http://en.wikipedia.org/wiki/Semir_Zeki) to be exclusively dedicated to color, but this has since been shown not to be the case.[[20]](http://en.wikipedia.org/wiki/Color_vision#cite_note-19) Color processing in the extended V4 occurs in millimeter-sized color modules called [globs](http://en.wikipedia.org/wiki/Glob_(visual_system)).[[18]](http://en.wikipedia.org/wiki/Color_vision#cite_note-Conway07-17)[[19]](http://en.wikipedia.org/wiki/Color_vision#cite_note-Conway-18) This is the first part of the brain in which colour is processed in terms of the full range of [hues](http://en.wikipedia.org/wiki/Hue) found in [color space](http://en.wikipedia.org/wiki/Color_space).[[18]](http://en.wikipedia.org/wiki/Color_vision#cite_note-Conway07-17)[[19]](http://en.wikipedia.org/wiki/Color_vision#cite_note-Conway-18)

Anatomical studies have shown that neurons in extended V4 provide input to the inferior [temporal lobe](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Ventral_stream) or the "what pathway", distinguished from the [dorsal stream](http://en.wikipedia.org/wiki/Dorsal_stream) ("where pathway") that is thought to analyze motion, among many other features.

**In other animals**

Other animals, such as tropical [fish](http://en.wikipedia.org/wiki/Fish) and [birds](http://en.wikipedia.org/wiki/Birds), have more complex color vision systems than humans.[[21]](http://en.wikipedia.org/wiki/Color_vision#cite_note-20) In the latter example, [tetrachromacy](http://en.wikipedia.org/wiki/Tetrachromacy) is achieved through up to four [cone](http://en.wikipedia.org/wiki/Cone_cell) 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](http://en.wikipedia.org/wiki/Pigeon) are [pentachromats](http://en.wikipedia.org/wiki/Pentachromat). [Eutherian](http://en.wikipedia.org/wiki/Eutherian) mammals other than primates generally have less-effective two-receptor ([dichromatic](http://en.wikipedia.org/wiki/Dichromat)) color perception systems. [Marine mammals](http://en.wikipedia.org/wiki/Marine_mammal) have only a single cone type and are thus [monochromats](http://en.wikipedia.org/wiki/Monochromat). Several [marsupials](http://en.wikipedia.org/wiki/Marsupial) such as the [fat-tailed dunnart](http://en.wikipedia.org/wiki/Fat-tailed_dunnart) (*Sminthopsis crassicaudata*) have been shown to have trichromatic color vision[[22]](http://en.wikipedia.org/wiki/Color_vision" \l "cite_note-21). Many [invertebrates](http://en.wikipedia.org/wiki/Invertebrate) have color vision. [Honey- and bumblebees](http://en.wikipedia.org/wiki/Bees) have trichromatic color vision, which is insensitive to red but sensitive in ultraviolet. [*Papilio*](http://en.wikipedia.org/wiki/Papilio) butterflies apparently have tetrachromatic color vision despite possessing six photoreceptor types.[[23]](http://en.wikipedia.org/wiki/Color_vision#cite_note-22) The most complex color vision system in animal kingdom has been found in [stomatopods](http://en.wikipedia.org/wiki/Stomatopod) with up to 12 different spectral receptor types which are thought to work as multiple dichromatic units.[[24]](http://en.wikipedia.org/wiki/Color_vision#cite_note-23). Some nocturnal [geckos](http://en.wikipedia.org/wiki/Gecko) have the capability of [seeing color in dim light](http://en.wikipedia.org/wiki/Gecko#Nocturnal_vision)[[25]](http://en.wikipedia.org/wiki/Color_vision#cite_note-GeckoNocturnalVision-24).

**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](http://en.wikipedia.org/wiki/Herbivorous) primates, color perception is essential for finding proper (immature) leaves. In [hummingbirds](http://en.wikipedia.org/wiki/Hummingbird), particular flower types are often recognized by color as well. On the other hand, [nocturnal](http://en.wikipedia.org/wiki/Nocturnal) mammals have less-developed color vision, since adequate light is needed for cones to function properly. There is evidence that [ultraviolet](http://en.wikipedia.org/wiki/Ultraviolet) light plays a part in color perception in many branches of the [animal kingdom](http://en.wikipedia.org/wiki/Animal), especially [insects](http://en.wikipedia.org/wiki/Insect). In general, the optical spectrum encompasses the most common [electronic transitions](http://en.wikipedia.org/wiki/Molecular_electronic_transition) in matter and is therefore the most useful for collecting information about the environment.

The [evolution of trichromatic color vision in primates](http://en.wikipedia.org/wiki/Evolution_of_color_vision_in_primates) occurred as the ancestors of modern monkeys, apes, and humans switched to [diurnal](http://en.wikipedia.org/wiki/Diurnal_animal) (daytime) activity and began consuming fruits and leaves from flowering plants.[[26]](http://en.wikipedia.org/wiki/Color_vision#cite_note-25)

Some animals can distinguish colors in the ultraviolet spectrum. The UV spectrum falls below the human visible range. 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.[[27]](http://en.wikipedia.org/wiki/Color_vision#cite_note-26)

UV and multi-dimensional vision[*[clarification needed](http://en.wikipedia.org/wiki/Wikipedia:Please_clarify" \o "Wikipedia:Please clarify)*] 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.[[28]](http://en.wikipedia.org/wiki/Color_vision#cite_note-27)[[29]](http://en.wikipedia.org/wiki/Color_vision#cite_note-28)

**Mathematics of color perception**

A "physical color" is a combination of pure [spectral colors](http://en.wikipedia.org/wiki/Spectral_color) (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](http://en.wikipedia.org/wiki/Vector_space), in fact a [Hilbert space](http://en.wikipedia.org/wiki/Hilbert_space). We call this space Hcolor. More technically, the space of physical colors may be considered to be the (mathematical) [cone](http://en.wikipedia.org/wiki/Cone_(topology)) over the simplex whose vertices are the spectral colors, with white at the [centroid](http://en.wikipedia.org/wiki/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 Hcolor is a function from the range of visible wavelengths—considered as an interval of real numbers [Wmin,Wmax]—to the real numbers, assigning to each wavelength w in [Wmin,Wmax] its intensity C(w).

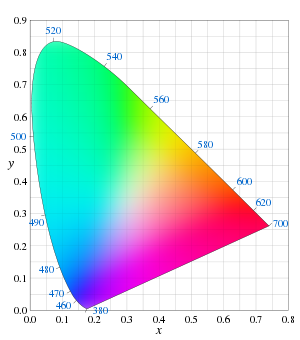
A humanly perceived color may be modeled as three numbers: the extents to which each of the 3 types of cones is stimulated. Thus a humanly perceived color may be thought of as a point in 3-dimensional [Euclidean space](http://en.wikipedia.org/wiki/Euclidean_space). We call this space R3color.

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 Hcolor stimulates each cone cell, we must calculate the integral (with respect to w), over the interval [Wmin,Wmax], of C(w)\*s(w), of C(w)\*m(w), and of C(w)\*l(w). The triple of resulting numbers associates to each physical color C (which is a region in Hcolor) to a particular perceived color (which is a single point in R3color). This association is easily seen to be linear. It may also easily be seen that many different regions in the "physical" space Hcolor can all result in the same single perceived color in R3color, 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 Hcolor to the 3-dimensional Euclidean space R3color.

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 R3color. Moving directly away from the vertex of this cone represents maintaining the same [chromaticity](http://en.wikipedia.org/wiki/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.

[](http://en.wikipedia.org/wiki/File:CIExy1931_fixed.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:CIExy1931_fixed.svg)

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.

In practice, it would be quite difficult to measure an individual's cones' three responses to various physical color stimuli. So instead, three specific benchmark test lights are typically used; let us call them S, M, and L. In order 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 (IS, IM, IL) 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 (IS, IM, IL) 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 (IS, IM, IL) 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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/w/index.php?title=Non-spectral_color&action=edit&redlink=1), there are infinitely many distinct physical spectra that are all perceived as that hue or color. So, in general there is no such thing as *the* combination of spectral colors that we perceive as (say) yellow-green; instead there are infinitely many possibilities.

(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 Hcolor 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*](http://en.wikipedia.org/wiki/Locus_(mathematics))), and the remaining straight edge corresponding to the most saturated [purples](http://en.wikipedia.org/wiki/Purple)—mixtures of [red](http://en.wikipedia.org/wiki/Red) and [violet](http://en.wikipedia.org/wiki/Violet_(color)).

**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](http://en.wikipedia.org/wiki/Color_constancy); when the correction occurs in a camera it is referred to as [white balance](http://en.wikipedia.org/wiki/White_balance).

Chromatic adaptation is one aspect of vision that may fool someone into observing a color-based [optical illusion](http://en.wikipedia.org/wiki/Optical_illusion), such as the [same color illusion](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/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](http://en.wikipedia.org/wiki/Purkinje_effect), and arises because the peak sensitivity of the human eye shifts toward the blue end of the spectrum at lower light levels.

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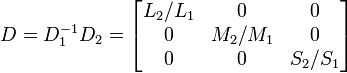
**Von Kries transform**

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](http://en.wikipedia.org/wiki/Cone_cell) spectral sensitivity responses so as to keep the adapted appearance of the reference white constant. The application of [Johannes von Kries](http://en.wikipedia.org/wiki/Johannes_von_Kries)'s idea of adaptive gains on the three [cone cell](http://en.wikipedia.org/wiki/Cone_cell) types was first explicitly applied to the problem of color constancy by [Herbert E. Ives](http://en.wikipedia.org/wiki/Herbert_E._Ives),[[30]](http://en.wikipedia.org/wiki/Color_vision#cite_note-29)[[31]](http://en.wikipedia.org/wiki/Color_vision#cite_note-30) and the method is sometimes referred to as the Ives transform[[32]](http://en.wikipedia.org/wiki/Color_vision#cite_note-31) or the von Kries–Ives adaptation.[[33]](http://en.wikipedia.org/wiki/Color_vision#cite_note-32)

The [von Kries](http://en.wikipedia.org/wiki/Von_Kries) *coefficient rule* rests on the assumption that [color constancy](http://en.wikipedia.org/wiki/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[[34]](http://en.wikipedia.org/wiki/Color_vision" \l "cite_note-33):

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](http://en.wikipedia.org/wiki/LMS_color_space) (responses of long-, medium-, and short-wavelength cone response space):



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](http://en.wikipedia.org/wiki/White_point).

The more complete von Kries transform, for colors represented in [XYZ](http://en.wikipedia.org/wiki/CIE_1931_color_space) or [RGB color space](http://en.wikipedia.org/wiki/RGB_color_space), includes matrix transformations into and out of [LMS space](http://en.wikipedia.org/wiki/LMS_Color_Space), with the diagonal transform *D* in the middle.[[35]](http://en.wikipedia.org/wiki/Color_vision#cite_note-34)

* [Color theory](http://en.wikipedia.org/wiki/Color_theory)
* [Primary color](http://en.wikipedia.org/wiki/Primary_color)
* [Visual perception](http://en.wikipedia.org/wiki/Visual_perception)

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**External links**

* ["Evidence that men, women literally see the world differently: Study shows color vision may have been adaptive during evolution."](http://www.psycport.com/stories/ascribe_2004_07_14_eng-ascribe_eng-ascribe_014026_988726893508805748.xml.html)
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* [Vision may not be what we thought.](http://www.neuronresearch.net/vision/files/tetrachromat.htm)
* [Overview of color vision.](http://www.diycalculator.com/sp-cvision.shtml)
* [The decoding model: a symmetrical model of color vision.](http://survivor99.com/colorforum/)
* [Working examples of Chromatic Adaptation.](http://www.stareclips.com/)
* [Egopont color vision test](http://www.egopont.com/colorvision.php)
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* [Webvision - Color Vision - University of Utah](http://webvision.med.utah.edu/Color.html)

**CIE 1931 color space**

From Wikipedia, the free encyclopedia

Jump to: [navigation](http://en.wikipedia.org/wiki/CIE_1931_color_space#column-one), [search](http://en.wikipedia.org/wiki/CIE_1931_color_space#searchInput)

In the study of the perception of [color](http://en.wikipedia.org/wiki/Color), one of the first mathematically defined [color spaces](http://en.wikipedia.org/wiki/Color_space) was the **CIE 1931 XYZ color space**, created by the [International Commission on Illumination](http://en.wikipedia.org/wiki/International_Commission_on_Illumination) (CIE) in [1931](http://en.wikipedia.org/wiki/1931).[[1]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-cie1931-0)[[2]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-1)

The CIE XYZ color space was derived from a series of experiments done in the late 1920s by W. David Wright[[3]](http://en.wikipedia.org/wiki/CIE_1931_color_space" \l "cite_note-wright-2) and John Guild.[[4]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-guild-3) Their experimental results were combined into the specification of the CIE RGB color space, from which the CIE XYZ color space was derived. This article is concerned with both of these color spaces.

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**Tristimulus values**

The human [eye](http://en.wikipedia.org/wiki/Eye) has photoreceptors (called [cone cells](http://en.wikipedia.org/wiki/Cone_cell)) for medium- and high-brightness color vision, with sensitivity peaks in short (*S*, 420–440 nm), middle (*M*, 530–540 nm), and long (*L*, 560–580 nm) wavelengths (there is also the low-brightness monochromatic "night-vision" receptor, called [rod cell](http://en.wikipedia.org/wiki/Rod_cell), with peak sensitivity at 490-495 nm). Thus, in principle, three parameters describe a color sensation. The **tristimulus values** of a color are the amounts of three [primary colors](http://en.wikipedia.org/wiki/Primary_color) in a three-component [additive](http://en.wikipedia.org/wiki/Additive_color) [color model](http://en.wikipedia.org/wiki/Color_model) needed to match that test color. The tristimulus values are most often given in the CIE 1931 color space, in which they are denoted *X*, *Y*, and *Z*.[[5]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-4)

Any specific method for associating tristimulus values with each color is called a [color space](http://en.wikipedia.org/wiki/Color_space). CIE XYZ, one of many such spaces, is a commonly used standard, and serves as the basis from which many other color spaces are defined.

**The CIE standard observer**

In the CIE XYZ color space, the tristimulus values are not the *S*, *M*, and *L* responses of the human eye, but rather a set of tristimulus values called *X*, *Y*, and *Z*, which are roughly [red](http://en.wikipedia.org/wiki/Red), [green](http://en.wikipedia.org/wiki/Green) and [blue](http://en.wikipedia.org/wiki/Blue), respectively (note that the X,Y,Z values are not physically observed red, green, blue colors. Rather, they may be thought of as 'derived' parameters from the red, green, blue colors). Two light sources, made up of different mixtures of various wavelengths, may appear to be the same color; this effect is called [metamerism](http://en.wikipedia.org/wiki/Metamerism_(color)). Two light sources have the same apparent color to an observer when they have the same tristimulus values, no matter what spectral distributions of light were used to produce them.

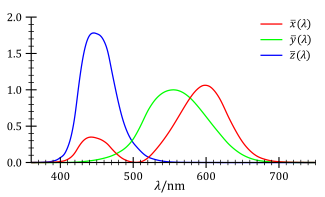
Due to the nature of the distribution of cones in the eye, the tristimulus values depend on the observer's [field of view](http://en.wikipedia.org/wiki/Field_of_view). To eliminate this variable, the CIE defined the **standard (colorimetric) observer**. Originally this was taken to be the chromatic response of the average human viewing through a 2° angle, due to the belief that the color-sensitive cones resided within a 2° arc of the fovea. Thus the *CIE 1931 Standard Observer* is also known as the *CIE 1931 2° Standard Observer*. A more modern but less-used alternative is the *CIE 1964 10° Standard Observer*, which is derived from the work of Stiles and Burch,[[6]](http://en.wikipedia.org/wiki/CIE_1931_color_space" \l "cite_note-5) and Speranskaya.[[7]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-6)

For the 10° experiments, the observers were instructed to ignore the central 2° spot. The 1964 Supplementary Standard Observer is recommended for more than about a 4° field of view. Both standard observers are discretized at 5 nm wavelength intervals and distributed by the [CIE](http://en.wikipedia.org/wiki/International_Commission_on_Illumination).[[8]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-7)

The standard observer is characterized by three *color matching functions*.

The derivation of the CIE standard observer from color matching experiments is given [below](http://en.wikipedia.org/wiki/CIE_1931_color_space#Construction_of_the_CIE_XYZ_color_space_from_the_Wright.E2.80.93Guild_data), after the description of the CIE RGB space.

**Color matching functions**

[](http://en.wikipedia.org/wiki/File:CIE_1931_XYZ_Color_Matching_Functions.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:CIE_1931_XYZ_Color_Matching_Functions.svg)

The CIE standard observer color matching functions

The **color matching functions** are the numerical description of the chromatic response of the *observer* (described above).

The CIE has defined a set of three *color-matching functions*, called \overline{x}(\lambda), \overline{y}(\lambda), and \overline{z}(\lambda), which can be thought of as the spectral sensitivity curves of three linear light detectors that yield the CIE XYZ tristimulus values *X*, *Y*, and *Z*. The tabulated numerical values of these functions are known collectively as the CIE standard observer.[[9]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-8)

The tristimulus values for a color with a [spectral power distribution](http://en.wikipedia.org/wiki/Spectral_power_distribution) I(\lambda)\,are given in terms of the standard observer by:

X= \int_0^\infty I(\lambda)\,\overline{x}(\lambda)\,d\lambda

Y= \int_0^\infty I(\lambda)\,\overline{y}(\lambda)\,d\lambda

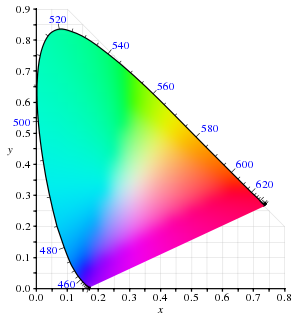
Z= \int_0^\infty I(\lambda)\,\overline{z}(\lambda)\,d\lambda

where λ is the wavelength of the equivalent [monochromatic](http://en.wikipedia.org/wiki/Monochromatic) light (measured in [nanometers](http://en.wikipedia.org/wiki/Nanometers)).

Other observers, such as for the CIE RGB space or other [RGB color spaces](http://en.wikipedia.org/wiki/RGB_color_space), are defined by other sets of three color-matching functions, and lead to tristimulus values in those other spaces.

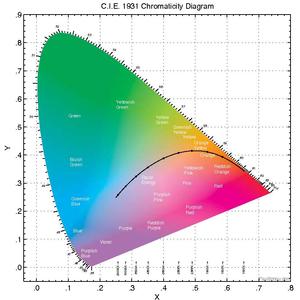
The values of *X*, *Y*, and *Z* are bounded if the intensity spectrum *I*(*λ*) is bounded.

**The CIE *xy* chromaticity diagram and the CIE *xyY* color space**

[](http://en.wikipedia.org/wiki/File:CIE1931xy_blank.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:CIE1931xy_blank.svg)

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 image itself describes colors using [sRGB](http://en.wikipedia.org/wiki/SRGB), and colors outside the sRGB [gamut](http://en.wikipedia.org/wiki/Gamut) cannot be displayed properly. Depending on the [color space](http://en.wikipedia.org/wiki/Color_space) and calibration of your display device, the sRGB colors may not be displayed properly either. This diagram displays the maximallly saturated bright colors that can be produced by a [computer monitor](http://en.wikipedia.org/wiki/Computer_monitor) or [television set](http://en.wikipedia.org/wiki/Television_set).

[](http://en.wikipedia.org/w/index.php?title=File:Chromaticity_diagram_full.pdf&page=1)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Chromaticity_diagram_full.pdf)

The CIE 1931 color space chromaticity diagram rendered in terms of the colors of lower saturation and value than those displayed in the diagram above that can be produced by [pigments](http://en.wikipedia.org/wiki/Pigment), such as those used in [printing](http://en.wikipedia.org/wiki/Printing). The color names are from the [Munsell color system](http://en.wikipedia.org/wiki/Munsell_color_system).

Since the human [eye](http://en.wikipedia.org/wiki/Eye) has three types of color sensors that respond to different ranges of [wavelengths](http://en.wikipedia.org/wiki/Wavelength), a full plot of all visible colors is a three-dimensional figure. However, the concept of color can be divided into two parts: brightness and [chromaticity](http://en.wikipedia.org/wiki/Chromaticity). For example, the color white is a bright color, while the color grey is considered to be a less bright version of that same white. In other words, the chromaticity of white and grey are the same while their brightness differs.

The CIE XYZ color space was deliberately designed so that the *Y* parameter was a measure of the brightness or [luminance](http://en.wikipedia.org/wiki/Luminance_(relative)) of a color. The chromaticity of a color was then specified by the two derived parameters *x* and *y*, two of the three normalized values which are functions of all three [tristimulus](http://en.wikipedia.org/wiki/Tristimulus) values *X*, *Y*, and *Z*:

x = \frac{X}{X+Y+Z}

y = \frac{Y}{X+Y+Z}

z = \frac{Z}{X+Y+Z} = 1 - x - y

The derived color space specified by x, y, and Y is known as the **CIE xyY** color space and is widely used to specify colors in practice.

The *X* and *Z* tristimulus values can be calculated back from the chromaticity values *x* and *y* and the *Y* tristimulus value:

X=\frac{Y}{y}x

Z=\frac{Y}{y}(1-x-y)

The figure on the right shows the related chromaticity diagram. The outer curved boundary is the *spectral locus*, with wavelengths shown in nanometers. Note that the chromaticity diagram is a tool to specify how the human eye will experience light with a given spectrum. It cannot specify colors of objects (or printing inks), since the chromaticity observed while looking at an object depends on the light source as well.

Mathematically, *x* and *y* are projective coordinates and the colors of the chromaticity diagram occupy a region of the [real projective plane](http://en.wikipedia.org/wiki/Projective_plane).

The chromaticity diagram illustrates a number of interesting properties of the CIE XYZ color space:

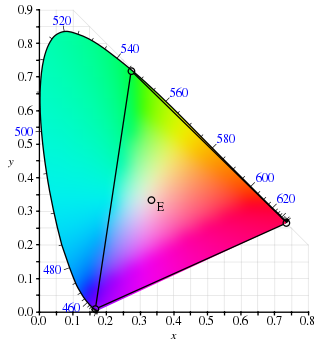
* The diagram represents all of the chromaticities visible to the average person. These are shown in color and this region is called the [gamut](http://en.wikipedia.org/wiki/Gamut) of human vision. The gamut of all visible chromaticities on the CIE plot is the tongue-shaped or horseshoe-shaped figure shown in color. The curved edge of the gamut is called the *spectral locus* and corresponds to [monochromatic](http://en.wikipedia.org/wiki/Monochromatic) light, with wavelengths listed in nanometers. The straight edge on the lower part of the gamut is called the *line of purples*.[*[citation needed](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed" \o "Wikipedia:Citation needed)*] These colors, although they are on the border of the gamut, have no counterpart in monochromatic light. Less saturated colors appear in the interior of the figure with [white](http://en.wikipedia.org/wiki/White) at the center.
* It is seen that all visible chromaticities correspond to non-negative values of *x*, *y*, and *z* (and therefore to non-negative values of *X*, *Y*, and *Z*).
* If one chooses any two points of color on the chromaticity diagram, then all the colors that lie in a straight line between the two points can be formed by mixing these two colors. It follows that the gamut of colors must be [convex](http://en.wikipedia.org/wiki/Convex_set) in shape. All colors that can be formed by mixing three sources are found inside the triangle formed by the source points on the chromaticity diagram (and so on for multiple sources).
* An equal mixture of two equally bright colors will not generally lie on the midpoint of that [line segment](http://en.wikipedia.org/wiki/Line_segment). In more general terms, a distance on the *xy* chromaticity diagram does not correspond to the degree of difference between two colors. In the early 1940s, [David MacAdam](http://en.wikipedia.org/wiki/David_MacAdam) studied the nature of visual sensitivity to [color differences](http://en.wikipedia.org/wiki/Color_difference), and summarized his results in the concept of a [MacAdam ellipse](http://en.wikipedia.org/wiki/MacAdam_ellipse). Based on the work of MacAdam, the [CIE 1960](http://en.wikipedia.org/wiki/CIE_1960_color_space), [CIE 1964](http://en.wikipedia.org/wiki/CIE_1964_color_space), and [CIE 1976](http://en.wikipedia.org/wiki/CIELUV) color spaces were developed, with the goal of achieving perceptual uniformity (have an equal distance in the color space correspond to equal differences in color). Although they were a distinct improvement over the CIE 1931 system, they were not completely free of distortion.
* It can be seen that, given three real sources, these sources cannot cover the gamut of human vision. Geometrically stated, there are no three points within the gamut that form a triangle that includes the entire gamut; or more simply, the gamut of human vision is not a triangle.
* Light with a [flat energy spectrum](http://en.wikipedia.org/wiki/Standard_illuminant#Illuminant_E) corresponds to the point (*x*,*y*) = (1/3,1/3).

**Definition of the CIE XYZ color space**

**Experimental results—the CIE RGB color space**

The CIE RGB color space is one of many [RGB color spaces](http://en.wikipedia.org/wiki/RGB_color_spaces), distinguished by a particular set of monochromatic (single-wavelength) [primary colors](http://en.wikipedia.org/wiki/Primary_color).

In the 1920s, W. David Wright[[3]](http://en.wikipedia.org/wiki/CIE_1931_color_space" \l "cite_note-wright-2) and John Guild[[4]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-guild-3) independently conducted a series of experiments on human sight which laid the foundation for the specification of the CIE XYZ color space.

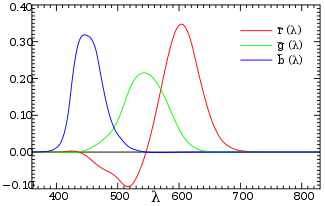
[](http://en.wikipedia.org/wiki/File:CIE1931xy_CIERGB.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:CIE1931xy_CIERGB.svg)

Gamut of the CIE RGB primaries and location of primaries on the CIE 1931 *xy* chromaticity diagram.

The experiments were conducted by using a circular split screen 2 degrees in size, which is the angular size of the human [fovea](http://en.wikipedia.org/wiki/Fovea). On one side of the field a *test* color was projected and on the other side, an observer-adjustable color was projected. The adjustable color was a mixture of three *primary* colors, each with fixed [chromaticity](http://en.wikipedia.org/wiki/Chromaticity), but with adjustable [brightness](http://en.wikipedia.org/wiki/Brightness).

The observer would alter the brightness of each of the three primary beams until a match to the test color was observed. Not all test colors could be matched using this technique. When this was the case, a variable amount of one of the primaries could be added to the test color, and a match with the remaining two primaries was carried out with the variable color spot. For these cases, the amount of the primary added to the test color was considered to be a negative value. In this way, the entire range of human color perception could be covered. When the test colors were monochromatic, a plot could be made of the amount of each primary used as a function of the wavelength of the test color. These three functions are called the *color matching functions* for that particular experiment.

[](http://en.wikipedia.org/wiki/File:CIE1931_RGBCMF.svg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:CIE1931_RGBCMF.svg)

The CIE 1931 RGB Color matching functions. The color matching functions are the amounts of primaries needed to match the monochromatic test primary at the wavelength shown on the horizontal scale.

Although Wright and Guild's experiments were carried out using various primaries at various intensities, and a number of different observers, all of their results were summarized by the standardized CIE RGB color matching functions \overline{r}(\lambda), \overline{g}(\lambda), and \overline{b}(\lambda), obtained using three monochromatic primaries at standardized wavelengths of 700 nm (red), 546.1 nm (green) and 435.8 nm (blue). The color matching functions are the amounts of primaries needed to match the monochromatic test primary. These functions are shown in the plot on the right (CIE 1931). Note that \overline{r}(\lambda)and \overline{g}(\lambda)are zero at 435.8, \overline{r}(\lambda)and \overline{b}(\lambda)are zero at 546.1 and \overline{g}(\lambda)and \overline{b}(\lambda)are zero at 700 nm, since in these cases the test color is one of the primaries. The primaries with wavelengths 546.1 nm and 435.8 nm were chosen because they are easily reproducible monochromatic lines of a mercury vapor discharge. The 700 nm wavelength, which in 1931 was difficult to reproduce as a monochromatic beam, was chosen because the eye's perception of color is rather unchanging at this wavelength, and therefore small errors in wavelength of this primary would have little effect on the results.

The color matching functions and primaries were settled upon by a CIE special commission after considerable deliberation.[[10]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-fairman-9) The cut-offs at the short- and long-wavelength side of the diagram are chosen somewhat arbitrarily; the human eye can actually see light with wavelengths up to about 810 nm, but with a sensitivity that is many thousand times lower than for green light. These color matching functions define what is known as the "1931 CIE standard observer". Note that rather than specify the brightness of each primary, the curves are normalized to have constant area beneath them. This area is fixed to a particular value by specifying that


\int_0^\infty \overline{r}(\lambda)\,d\lambda=
\int_0^\infty \overline{g}(\lambda)\,d\lambda=
\int_0^\infty \overline{b}(\lambda)\,d\lambda


The resulting normalized color matching functions are then scaled in the r:g:b ratio of 1:4.5907:0.0601 for source [luminance](http://en.wikipedia.org/wiki/Luminance) and 72.0962:1.3791:1 for source [radiant power](http://en.wikipedia.org/wiki/Radiant_power) to reproduce the true color matching functions. By proposing that the primaries be standardized, the CIE established an international system of objective color notation.

Given these scaled color matching functions, the RGB [tristimulus](http://en.wikipedia.org/wiki/Tristimulus) values for a color with a [spectral power distribution](http://en.wikipedia.org/wiki/Spectral_power_distribution) *I*(λ) would then be given by:

R= \int_0^\infty I(\lambda)\,\overline{r}(\lambda)\,d\lambda

G= \int_0^\infty I(\lambda)\,\overline{g}(\lambda)\,d\lambda

B= \int_0^\infty I(\lambda)\,\overline{b}(\lambda)\,d\lambda

These are all [inner products](http://en.wikipedia.org/wiki/Inner_products) and can be thought of as a projection of an infinite-dimensional spectrum to a three-dimensional color. (See also: [Hilbert space](http://en.wikipedia.org/wiki/Hilbert_space))

**Grassmann's law**

One might ask: "Why is it possible that Wright and Guild's results can be summarized using different primaries and different intensities from those actually used?" One might also ask: "What about the case when the test colors being matched are not monochromatic?" The answer to both of these questions lies in the (near) linearity of human color perception. This linearity is expressed in [Grassmann's law](http://en.wikipedia.org/wiki/Grassmann%27s_law_(optics)).

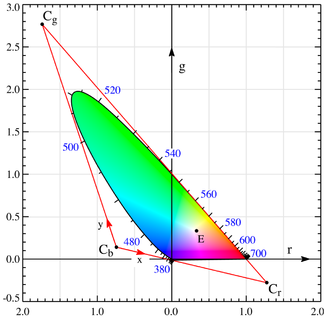
The CIE RGB space can be used to define chromaticity in the usual way: The chromaticity coordinates are *r* and *g* where:

r= \frac{R}{R+G+B},

g= \frac{G}{R+G+B}.

**Construction of the CIE XYZ color space from the Wright–Guild data**

Having developed an RGB model of human vision using the CIE RGB matching functions, the members of the special commission wished to develop another color space that would relate to the CIE RGB color space. It was assumed that Grassmann's law held, and the new space would be related to the CIE RGB space by a linear transformation. The new space would be defined in terms of three new color matching functions \overline{x}(\lambda), \overline{y}(\lambda), and \overline{z}(\lambda)as described above. The new color space would be chosen to have the following desirable properties:

[](http://en.wikipedia.org/wiki/File:CIE1931_rgxy.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:CIE1931_rgxy.png)

Diagram in CIE *rg* chromaticity space showing the construction of the triangle specifying the CIE XYZ color space. The triangle Cb-Cg-Cr is just the *xy*=(0,0),(0,1),(1,0) triangle in CIE *xy* chromaticity space. The line connecting Cb and Cr is the alychne. Notice that the spectral locus passes through *rg*=(0,0) at 435.8 nm, through *rg*=(0,1) at 546.1 nm and through *rg*=(1,0) at 700 nm. Also, the equal energy point (E) is at *rg*=*xy*=(1/3,1/3).

1. The new color matching functions were to be everywhere greater than or equal to zero. In 1931, computations were done by hand or slide rule, and the specification of positive values was a useful computational simplification.
2. The \overline{y}(\lambda)color matching function would be exactly equal to the [photopic luminous efficiency function](http://en.wikipedia.org/wiki/Luminosity_function) V(λ) for the "CIE standard photopic observer".[[11]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-10) The luminance function describes the variation of perceived brightness with wavelength. The fact that the luminance function could be constructed by a linear combination of the RGB color matching functions was not guaranteed by any means but might be expected to be nearly true due to the near-linear nature of human sight. Again, the main reason for this requirement was computational simplification.
3. For the constant energy [white point](http://en.wikipedia.org/wiki/White_point), it was required that *x* = *y* = *z* = 1/3.
4. By virtue of the definition of chromaticity and the requirement of positive values of *x* and *y*, it can be seen that the gamut of all colors will lie inside the triangle [1,0], [0,0], [0,1]. It was required that the gamut fill this space practically completely.
5. It was found that the \overline{z}(\lambda)color matching function could be set to zero above 650 nm while remaining within the bounds of experimental error. For computational simplicity, it was specified that this would be so.

In geometrical terms, choosing the new color space amounts to choosing a new triangle in *rg* chromaticity space. In the figure above-right, the *rg* chromaticity coordinates are shown on the two axes in black, along with the gamut of the 1931 standard observer. Shown in red are the CIE *xy* chromaticity axes which were determined by the above requirements. The requirement that the XYZ coordinates be non-negative means that the triangle formed by Cr, Cg, Cb must encompass the entire gamut of the standard observer. The line connecting Cr and Cb is fixed by the requirement that the \overline{y}(\lambda)function be equal to the luminance function. This line is the line of zero luminance, and is called the alychne. The requirement that the \overline{z}(\lambda)function be zero above 650 nm means that the line connecting Cg and Cr must be tangent to the gamut in the region of Kr. This defines the location of point Cr. The requirement that the equal energy point be defined by *x* = *y* = 1/3 puts a restriction on the line joining Cb and Cg, and finally, the requirement that the gamut fill the space puts a second restriction on this line to be very close to the gamut in the green region, which specifies the location of Cg and Cb. The above described transformation is a linear transformation from the CIE RGB space to XYZ space. The standardized transformation settled upon by the CIE special commission was as follows:

The numbers below all have the correct number of significant digits per CIE standards.[[10]](http://en.wikipedia.org/wiki/CIE_1931_color_space#cite_note-fairman-9)


\begin{bmatrix}X\\Y\\Z\end{bmatrix}=\frac{1}{b_{21}}
\begin{bmatrix}
b_{11}&b_{12}&b_{13}\\
b_{21}&b_{22}&b_{23}\\
b_{31}&b_{32}&b_{33}
\end{bmatrix}
\begin{bmatrix}R\\G\\B\end{bmatrix}=\frac{1}{0.17697}
\begin{bmatrix}
0.49&0.31&0.20\\
0.17697&0.81240&0.01063\\
0.00&0.01&0.99
\end{bmatrix}
\begin{bmatrix}R\\G\\B\end{bmatrix}


The integrals of the XYZ color matching functions must all be equal by requirement 3 above, and this is set by the integral of the photopic luminous efficiency function by requirement 2 above. It must be noted that the tabulated sensitivity curves have a certain amount of arbitrariness in them. The shapes of the individual *X*, *Y* and *Z* sensitivity curves can be measured with a reasonable accuracy. However, the overall luminosity curve (which in fact is a weighted sum of these three curves) is subjective, since it involves asking a test person whether two light sources have the same brightness, even if they are in completely different colors. Along the same lines, the relative magnitudes of the X, *Y*, and Z curves are arbitrary. One could as well define a valid color space with an *X* sensitivity curve that has twice the amplitude. This new color space would have a different shape. The sensitivity curves in the CIE 1931 and 1964 XYZ color spaces are scaled to have equal areas under the curves.

**See also**

* [Trichromacy](http://en.wikipedia.org/wiki/Trichromacy)
* [Imaginary color](http://en.wikipedia.org/wiki/Imaginary_color)
* [Lab color space](http://en.wikipedia.org/wiki/Lab_color_space)

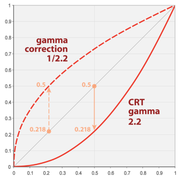
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**Further reading**

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* [Introduction to Colour Science](http://www.techmind.org/colour/), William Andrew Steer.
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* [Colorimetric data useful for calculation](http://www.cis.rit.edu/mcsl/online/cie.php), in various file formats

**Gamma correction**

[](http://en.wikipedia.org/wiki/File:Gamma06_600.png)

[http://en.wikipedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Gamma06_600.png)

Example of [CRT](http://en.wikipedia.org/wiki/Cathode_ray_tube) gamma correction

[](http://en.wikipedia.org/wiki/File:GammaCorrection_demo.jpg)

[http://en.wikipedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:GammaCorrection_demo.jpg)

Gamma correction demonstration: Each panel shows the display gamma that the pixel values have been adjusted for; for example, the pixels in the second panel are proportional to intensity to the 1/2 power, so the image looks approximately correct on a typical PC monitor.

**Gamma correction**, **gamma nonlinearity**, **gamma encoding**, or often simply **gamma**, is the name of a nonlinear operation used to code and decode [luminance](http://en.wikipedia.org/wiki/Luminance_(relative)) or [tristimulus values](http://en.wikipedia.org/wiki/Tristimulus_value) in [video](http://en.wikipedia.org/wiki/Video) or [still image](http://en.wikipedia.org/wiki/Still_image) systems.[[1]](http://en.wikipedia.org/wiki/Gamma_correction#cite_note-poynton-0) Gamma correction is, in the simplest cases, defined by the following [**power-law**](http://en.wikipedia.org/wiki/Power_law) expression:

V_{\text{out}} = {V_{\text{in}}}^{\gamma}

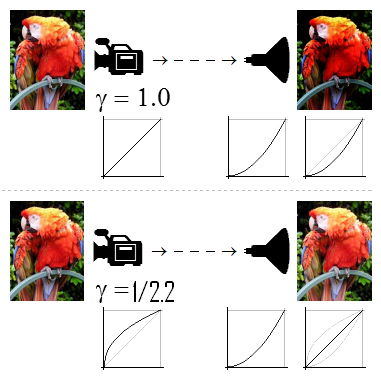
where the input and output values are non-negative real values, typically in a predetermined range such as 0 to 1. A gamma value \gamma < 1\,is sometimes called an **encoding gamma**, and the process of encoding with this compressive power-law nonlinearity is called **gamma compression**; conversely a gamma value \gamma > 1\,is called a **decoding gamma** and the application of the expansive power-law nonlinearity is called **gamma expansion**.

|  |
| --- |
| **Contents**   * [1 Explanation](http://en.wikipedia.org/wiki/Gamma_correction#Explanation) * [2 Generalized gamma](http://en.wikipedia.org/wiki/Gamma_correction#Generalized_gamma) * [3 Windows, Mac, sRGB and TV/video standard gammas](http://en.wikipedia.org/wiki/Gamma_correction#Windows.2C_Mac.2C_sRGB_and_TV.2Fvideo_standard_gammas) * [4 Power law for video display](http://en.wikipedia.org/wiki/Gamma_correction#Power_law_for_video_display) * [5 Methods to perform display gamma correction in computing](http://en.wikipedia.org/wiki/Gamma_correction#Methods_to_perform_display_gamma_correction_in_computing) * [6 Simple monitor tests](http://en.wikipedia.org/wiki/Gamma_correction#Simple_monitor_tests) * [7 Photography](http://en.wikipedia.org/wiki/Gamma_correction#Photography) * [8 Terminology](http://en.wikipedia.org/wiki/Gamma_correction#Terminology) * [9 See also](http://en.wikipedia.org/wiki/Gamma_correction#See_also) * [10 References](http://en.wikipedia.org/wiki/Gamma_correction#References) * [11 External links](http://en.wikipedia.org/wiki/Gamma_correction#External_links)   + [11.1 General information](http://en.wikipedia.org/wiki/Gamma_correction#General_information)   + [11.2 Monitor gamma tools](http://en.wikipedia.org/wiki/Gamma_correction#Monitor_gamma_tools) |

**Explanation**

**Gamma compression**, also known as **gamma encoding**, is used to encode linear luminance or [RGB](http://en.wikipedia.org/wiki/RGB_color_model) values into video signals or [digital video](http://en.wikipedia.org/wiki/Digital_video) file values; **gamma expansion** is the inverse, or **decoding**, process, and occurs largely in the nonlinearity of the electron-gun current–voltage curve in [cathode ray tube](http://en.wikipedia.org/wiki/Cathode_ray_tube) (CRT) monitor systems, which acts as a kind of *spontaneous* decoder. Gamma encoding helps to map data (both analog and digital) into a more perceptually uniform domain.

The following figure shows the behavior of a typical display when image signals are sent linearly (γ = 1.0) and gamma-encoded (gamma compressed with γ = 1 / 2.2 for a γ = 2.2 standard display). In the first case, the resulting image over the CRT is notably darker and contrastier than the original, whereas it is shown with high fidelity in the second case. Digital cameras produce, and TV stations broadcast, signals in gamma-encoded form, anticipating the standardized gamma of the reproducing device, so that the overall system will be linear, as shown on the bottom; if cameras were linear, as on the top, the overall system would be nonlinear. Similarly, image files are almost always stored on computers and communicated across the Internet with gamma encoding.

[](http://en.wikipedia.org/wiki/File:Gamma_on_TV.png)

Systems with linear and gamma-corrected cameras. The dashes in the middle represent the storage and transmission of image signals or data files. The three curves represent input–output functions of the camera, the display, and the overall system, respectively.

**Generalized gamma**

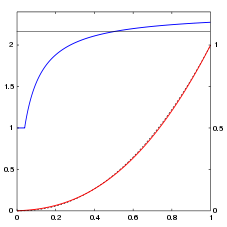
A **gamma value** is used to quantify contrast, for example of [photographic film](http://en.wikipedia.org/wiki/Photographic_film). It is the slope of an input–output curve in log–log space, that is:

\gamma = \frac{\mathrm{d} \log(V_{out})}{\mathrm{d} \log(V_{in})}

which is consistent with the power-law relation above, but applicable to more general nonlinearities. In the case of film, such nonlinearities are called [Hurter–Driffield curves](http://en.wikipedia.org/wiki/Sensitometry).

Gamma values less than 1 are typical of negative film, and values greater than 1 are typical of slide (reversal) film.

**Windows, Mac, sRGB and TV/video standard gammas**

[](http://en.wikipedia.org/wiki/File:SRGB_gamma.svg)

[http://en.wikipedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:SRGB_gamma.svg)

Plot of the [sRGB](http://en.wikipedia.org/wiki/SRGB) standard gamma-expansion nonlinearity (red), and its local gamma value, slope in log–log space (blue).

In most computer systems, images are encoded with a gamma of about 0.45 and decoded with a gamma of 2.2; a notable exception, until the release of Mac OS X 10.6 (Snow Leopard) in September 2009, were [Macintosh](http://en.wikipedia.org/wiki/Macintosh) computers: they used 0.55 and 1.8 respectively. In any case, [binary](http://en.wikipedia.org/wiki/Binary_file) data in still image files (as [JPEG](http://en.wikipedia.org/wiki/JPEG)) are explicitly encoded (that is, they carry gamma-encoded values, not linear intensities), as are motion picture files (such as [MPEG](http://en.wikipedia.org/wiki/MPEG)). The system can optionally further manage both cases, through [color management](http://en.wikipedia.org/wiki/Color_management), if a better match to the output device gamma is required.

The [sRGB color space](http://en.wikipedia.org/wiki/SRGB_color_space) standard used with most cameras, PCs, and printers does not use a simple power-law nonlinearity as above, but has a decoding gamma value near 2.2 over much of its range, as shown in the plot to the right. Below a compressed value of 0.04045 or a linear intensity of 0.00313, the curve is linear (encoded value proportional to intensity), so the gamma is 1. The dashed black curve behind the red curve is a standard gamma = 2.2 power-law curve, for comparison.

Output to CRT-based television receivers and monitors does not usually require further gamma correction, since the standard video signals that are transmitted or stored in image files incorporate gamma compression that matches close enough the gamma expansion of the CRT. For television signals, the actual gamma values are defined by the video standards ([NTSC](http://en.wikipedia.org/wiki/NTSC), [PAL](http://en.wikipedia.org/wiki/PAL) or [SECAM](http://en.wikipedia.org/wiki/SECAM)), and are always fixed and well known values.

**Power law for video display**

A **gamma characteristic** is a [power-law](http://en.wikipedia.org/wiki/Power_law) relationship that approximates the relationship between the encoded [luma](http://en.wikipedia.org/wiki/Luminance_(video)) in a [television](http://en.wikipedia.org/wiki/Television) system and the actual desired image luminance.

With this nonlinear relationship, equal steps in encoded luminance correspond roughly to subjectively equal steps in brightness. Ebner and Fairchild [[2]](http://en.wikipedia.org/wiki/Gamma_correction#cite_note-EbnerCIC61998-1) used an exponent of 0.43 to convert linear intensity into lightness for neutrals; the reciprocal, approximately 2.33 (quite close to the 2.2 figure cited for a typical display subsystem), would provide optimal perceptual encoding of grays. The following illustration shows the difference between a scale with linearly-increasing encoded luminance signal (linear input) and a scale with linearly-increasing intensity (i.e., gamma-corrected) scale (linear output).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Linear encoding | *V*S = | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| Linear intensity | *I* = | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |

On most displays (those with gamma of about 2.2), one can observe that the linear-intensity scale has a large jump in perceived brightness between the intensity values 0.0 and 0.1, while the steps at the higher end of the scale are hardly perceptible. The linearly-encoded scale, which has a nonlinearly-increasing intensity, will show much more even steps in perceived brightness.

A [cathode ray tube](http://en.wikipedia.org/wiki/Cathode_ray_tube) (CRT), for example, converts a video signal to light in a nonlinear way, because the electron gun's intensity (brightness) as a function of applied video voltage is nonlinear. The light intensity *I* is related to the source [voltage](http://en.wikipedia.org/wiki/Voltage) VS according to

I \propto  V_{\rm S}{}^{\gamma}

where γ is the [Greek](http://en.wikipedia.org/wiki/Greek_alphabet) letter [gamma](http://en.wikipedia.org/wiki/Gamma). For a CRT, the gamma that relates brightness to voltage is usually in the range 2.35 to 2.55; video [look-up tables](http://en.wikipedia.org/wiki/Look-up_table) in computers usually adjust the system gamma to the range 1.8 to 2.2,[[1]](http://en.wikipedia.org/wiki/Gamma_correction#cite_note-poynton-0) which is in the region that makes a uniform encoding difference give approximately uniform perceptual brightness difference, as illustrated in the diagram on the top of this section.

For simplicity, consider the example of a monochrome CRT. In this case, when a video signal of 0.5 (representing mid-gray) is fed to the display, the intensity or brightness is about 0.22 (resulting in a dark gray). Pure black (0.0) and pure white (1.0) are the only shades that are unaffected by gamma.

To compensate for this effect, the inverse transfer function (**gamma correction**) is sometimes applied to the video signal so that the end-to-end response is linear. In other words, the transmitted signal is deliberately distorted so that, after it has been distorted again by the display device, the viewer sees the correct brightness. The inverse of the function above is:

V_{\rm C} \propto V_{\rm S}{}^{(1/\gamma)}

where *V*C is the corrected voltage and *V*S is the source voltage, for example from an [image sensor](http://en.wikipedia.org/wiki/Image_sensor) that converts photocharge linearly to a voltage. In our CRT example 1/γ is 1/2.2 or 0.45.

A color CRT receives three video signals (red, green and blue) and in general each color has its own value of gamma, denoted γR, γG or γB. However, in simple display systems, a single value of γ is used for all three colors.

Other display devices have different values of gamma: for example, a [Game Boy Advance](http://en.wikipedia.org/wiki/Game_Boy_Advance) display has a gamma between 3 and 4 depending on lighting conditions. In LCDs such as those on laptop computers, the relation between the signal voltage *V*S and the intensity *I* is very nonlinear and cannot be described with gamma value. However, such displays apply a correction onto the signal voltage in order to approximately get a standard γ=2.5 behavior. In [NTSC](http://en.wikipedia.org/wiki/NTSC) [television](http://en.wikipedia.org/wiki/Television) recording, γ is 2.2.

The power-law function, or its inverse, has a slope of infinity at zero. This leads to problems in converting from and to a gamma colorspace. For this reason most formally defined colorspaces such as [sRGB](http://en.wikipedia.org/wiki/SRGB) will define a straight-line segment near zero and add raising x+K (where K is a constant) to a power so the curve has continuous slope. This straight line does not represent what the CRT does, but does make the rest of the curve more closely match the effect of ambient light on the CRT. In such expressions the exponent is *not* the gamma; for instance, the sRGB function uses a power of 2.4 in it, but more closely resembles a power-law function with an exponent of 2.2, without a linear portion.

**Methods to perform display gamma correction in computing**

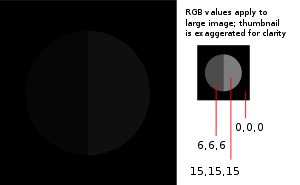
Up to four elements can be manipulated in order to achieve gamma encoding to correct the image to be shown on a typical 2.2- or 1.8-gamma computer display:

* The pixel's intensity values in a given image file; that is, the binary pixel values are stored in the file in such way that they represent the light intensity via gamma-compressed values instead a linear encoding. This is done systematically with digital video files (as those in a [DVD](http://en.wikipedia.org/wiki/DVD) movie), in order to save a gamma-decoding step while playing. Similarly, pixel values in standard image file formats are usually gamma-compensated, either for sRGB gamma (or equivalent, an approximation of typical of legacy monitor gammas), or according to some gamma specified by metadata such as an [ICC profile](http://en.wikipedia.org/wiki/ICC_profile). If the encoding gamma does not match the reproduction system's gamma, further correction may be done, either on display or to create a modified image file with a different profile.
* The rendering software writes gamma-encoded pixel binary values directly to the video memory (when [highcolor](http://en.wikipedia.org/wiki/Highcolor)/[truecolor](http://en.wikipedia.org/wiki/Truecolor" \o "Truecolor) modes are used) or in the [CLUT](http://en.wikipedia.org/wiki/CLUT) [hardware registers](http://en.wikipedia.org/wiki/Hardware_register) (when [indexed color](http://en.wikipedia.org/wiki/Indexed_color) modes are used) of the [display adapter](http://en.wikipedia.org/wiki/Display_adapter). They drive [Digital-to-Analog Converters](http://en.wikipedia.org/wiki/Digital-to-Analog_Converter) (DAC) which output the proportional voltages to the display. For example, when using 8-bit per channel, [24-bit RGB](http://en.wikipedia.org/wiki/List_of_monochrome_and_RGB_palettes#24-bit_RGB) color, writing a value of 128 (rounded midpoint of the 0-255 [byte](http://en.wikipedia.org/wiki/Byte) range) in video memory it outputs the proportional ≈0.5 voltage to the display, which it is shown darker due to the monitor behavior. Alternatively, to achieve ≈50% intensity, a gamma-encoded [look-up table](http://en.wikipedia.org/wiki/Look-up_table) can be applied to write a value near to 187 instead of 128 by the rendering software.
* Modern display adapters have dedicated calibrating CLUTs, which can be loaded once with the appropriate gamma-correction [look-up table](http://en.wikipedia.org/wiki/Look-up_table) in order to modify the encoded signals digitally before the DACs that output voltages to the monitor.[[3]](http://en.wikipedia.org/wiki/Gamma_correction#cite_note-2) Setting up these tables to be correct is called *hardware calibration*.[[4]](http://en.wikipedia.org/wiki/Gamma_correction#cite_note-cm-3)
* Some modern monitors allow to the user to manipulate their gamma behavior (as if it were merely another brightness/contrast-like setting), encoding the input signals by themselves before they are displayed on screen. This is also a *calibration by hardware* technique, but it is performed in an analogic way with the electric signals, instead of digitally remapping the binary values as in the previous cases.

In a correctly calibrated system, each component will have a specified gamma for its input and/or output encodings.[[4]](http://en.wikipedia.org/wiki/Gamma_correction#cite_note-cm-3) Stages may change the gamma to correct for different requirements, and finally the output device will do gamma decoding or correction as needed, to get to a linear intensity domain. All the encoding and correction methods can be arbitrarily superimposed, without mutual knowledge of this fact among the different elements; if done incorrectly, these conversions can lead to highly distorted results, but if done correctly as dictated by standards and conventions will lead to a properly functioning system.

In a typical system, for example from camera through [JPEG](http://en.wikipedia.org/wiki/JPEG) file to display, the role of gamma correction will involve several cooperating parts. The camera encodes its rendered image into the JPEG file using one of the standard gamma values such as 2.2, for storage and transmission. The display computer may use a [color management](http://en.wikipedia.org/wiki/Color_management) engine to convert to a different color space (such as a Macintosh's gamma=1.8 color space) before putting pixel values into its video memory. The monitor may do its own gamma correction to match the CRT gamma to that used by the video system. Coordinating the components via standard interfaces with default standard gamma values makes it possible to get such system properly configured.

**Simple monitor tests**

[](http://en.wikipedia.org/wiki/File:Gammatest.svg)

To see whether your computer [monitor](http://en.wikipedia.org/wiki/Computer_display) is properly hardware adjusted and can display shadow detail in sRGB images properly, you should see the left half of the circle in the large black square very faintly (or not at all), but the right half should be clearly visible. If not, you can adjust your monitor's [contrast](http://en.wikipedia.org/wiki/Contrast_(vision)) and/or [brightness](http://en.wikipedia.org/wiki/Brightness) setting. This alters the monitor's perceived gamma. The image is best viewed against a black background.

This procedure is not suitable for [calibrating](http://en.wikipedia.org/wiki/Color_calibration) or print-proofing a monitor. It can be useful for making your monitor display sRGB images approximately correctly, on systems in which profiles are not used (for example, the Firefox browser prior to version 3.0 and many others) or in systems that assume untagged source images are in the sRGB colorspace.

On some operating systems running the [X Window System](http://en.wikipedia.org/wiki/X_Window_System) you can change gamma-correction settings, by issuing the command xgamma -gamma 2.1 for setting gamma value to 2.1, and xgamma for querying current value. In [Macintosh](http://en.wikipedia.org/wiki/Macintosh) systems, the gamma and other related screen calibrations are made through the OS control panel. [Microsoft Windows](http://en.wikipedia.org/wiki/Microsoft_Windows) systems lack (up to the [XP](http://en.wikipedia.org/wiki/Windows_XP) version, inclusive) a true native calibration tool. Third-party tools, as those provided with [Nvidia](http://en.wikipedia.org/wiki/Nvidia) [graphic cards](http://en.wikipedia.org/wiki/Graphic_card)' [drivers](http://en.wikipedia.org/wiki/Device_driver) or the *Adobe gamma loader* tool for [Adobe](http://en.wikipedia.org/wiki/Adobe_Systems) products play the same role under Microsoft Windows.

[Srgbnonlinearity.png](http://en.wikipedia.org/wiki/File:Srgbnonlinearity.png)

In the test pattern to the right, the linear intensity of each solid bar is the average of the linear intensities in the surrounding striped dither; therefore, ideally, the solid squares and the dithers should appear equally bright in a properly adjusted [sRGB](http://en.wikipedia.org/wiki/SRGB) system.

**Photography**

The same term (*gamma*) has long been used in [photography](http://en.wikipedia.org/wiki/Photography) to describe an analogous nonlinearity. In photography, *gamma* refers to the slope of the straight-line region of the [sensitometric](http://en.wikipedia.org/wiki/Sensitometry) curve (Hurter–Driffield curve), which is a plot of density (or the negative of the base 10 [logarithm](http://en.wikipedia.org/wiki/Logarithm) of transmittance) of the film image versus the logarithm of the film's exposure to light.

[Ansel Adams](http://en.wikipedia.org/wiki/Ansel_Adams) describes the gamma concept, but then dismisses it as "a term of interest and significance only to the research scientist and the manufacturer", and elaborates:[[5]](http://en.wikipedia.org/wiki/Gamma_correction" \l "cite_note-4)

'7 minutes at 68°F in Ansco 47 for Isopan' represents 'normal' to me. I have no idea what the actual effective gamma is, nor do I care. I could consider this degree of development as yielding Gamma = 1.0 or being Development No. 9 or Operation H, or any other symbol I choose. But why should I inject an unnecessary and confusing symbol for a perfectly simple statement of procedure? 'Isopan/Ansco 47/68°F/7minutes' is definite and easily expressed and understood as the means of obtaining *my* 'normal' negative.

[Photographic film](http://en.wikipedia.org/wiki/Photographic_film) has a much greater ability to record fine differences in shade than can be reproduced on [photographic paper](http://en.wikipedia.org/wiki/Photographic_paper). Similarly, most video screens are not capable of displaying the range of brightnesses (dynamic range) which can be captured by typical electronic cameras[*[citation needed](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed" \o "Wikipedia:Citation needed)*]. For this reason, considerable artistic effort is invested in choosing in which reduced form the original image should be presented. The **gamma correction**, or contrast selection, is part of the photographic repertoire used to adjust the reproduced image.

Analogously, digital cameras record light using electronic sensors that usually respond linearly. In the process of rendering linear raw data to conventional RGB data (e.g. for storage into JPEG image format), color space transformations and rendering transformations will be performed. In particular, almost all standard RGB color spaces and file formats use a non-linear encoding (a [gamma compression](http://en.wikipedia.org/wiki/Gamma_compression)) of the intended intensities of the [primary colors](http://en.wikipedia.org/wiki/Primary_color) of the photographic reproduction; in addition, the intended reproduction is almost always nonlinearly related to the measured scene intensities, via a [tone reproduction](http://en.wikipedia.org/wiki/Tone_reproduction) nonlinearity.

**Terminology**

The term [intensity](http://en.wikipedia.org/wiki/Luminous_emittance) refers strictly to the amount of light that is emitted per unit of time and per unit of surface, in units of [lux](http://en.wikipedia.org/wiki/Lux). Note, however, that in many fields of science this quantity is called [luminous emittance](http://en.wikipedia.org/wiki/Luminous_emittance), as opposed to [luminous intensity](http://en.wikipedia.org/wiki/Luminous_intensity), which is a different quantity. These distinctions, however, are largely irrelevant to gamma compression, which is applicable to any sort of normalized linear intensity-like scale.

*Luminance* can mean several things even within the context of video and imaging:

* [Luminance](http://en.wikipedia.org/wiki/Luminance) is the photometric brightness of an object, taking into account the wavelength-dependent sensitivity of the human eye (in units of [cd](http://en.wikipedia.org/wiki/Candela)/m²);
* [Luminance (video)](http://en.wikipedia.org/wiki/Luminance_(video)) is the encoded video "luma" signal, i.e. similar to the signal voltage *V*S.
* [Luminance (relative)](http://en.wikipedia.org/wiki/Luminance_(relative)) is the luminance signal used in a color-space encoding, relative to a white level.

One contrasts "luminance" in the sense of color (no gamma compression) with "luma" in the sense of video (with gamma compression), and denote luminance by Y and luma by Y' – the prime symbol (') denote gamma-compression.[[6]](http://en.wikipedia.org/wiki/Gamma_correction#cite_note-5)

Likewise, [*brightness*](http://en.wikipedia.org/wiki/Brightness) is sometimes applied to various measures, including light levels, though it more properly applies to a subjective visual attribute.

Gamma correction is a type of [power law](http://en.wikipedia.org/wiki/Power_law) function whose exponent is the [Greek letter](http://en.wikipedia.org/wiki/Greek_letter) [gamma](http://en.wikipedia.org/wiki/Gamma) (γ). It should not be confused with the mathematical [Gamma function](http://en.wikipedia.org/wiki/Gamma_function). The lower case gamma, γ, is a [parameter](http://en.wikipedia.org/wiki/Parameter) of the former; the upper case letter, Γ, is the name of (and symbol used for) the latter (as in "Γ(*x*)"). To use the word "function" in conjunction with gamma correction, one may avoid confusion by saying "generalized power law function."

In lack of context, a given gamma value can be either the encoding or the decoding value. Caution must be taken to correctly interpreting the value as that to be applied-to-compensate or to be compensated-by-applying its inverse. In common parlance, in many occasions the decoding value (as 2.2) is employed as if it were the encoding value, instead of its inverse (1/2.2 in this case) which is the *real* value that must be applied to encode gamma.

**See also**

* [Brightness](http://en.wikipedia.org/wiki/Brightness)
* [Luminance](http://en.wikipedia.org/wiki/Luminance)
* [Luminance (video)](http://en.wikipedia.org/wiki/Luminance_(video))
* [Luminance (relative)](http://en.wikipedia.org/wiki/Luminance_(relative))
* [Contrast (vision)](http://en.wikipedia.org/wiki/Contrast_(vision))
* [Color management](http://en.wikipedia.org/wiki/Color_management)

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3. [**^**](http://en.wikipedia.org/wiki/Gamma_correction#cite_ref-2) [*SetDeviceGammaRamp*, the Win32 API to download arbitrary gamma ramps to display hardware](http://msdn2.microsoft.com/en-us/library/ms536529.aspx)
4. ^ [***a***](http://en.wikipedia.org/wiki/Gamma_correction#cite_ref-cm_3-0) [***b***](http://en.wikipedia.org/wiki/Gamma_correction#cite_ref-cm_3-1) [Jonathan Sachs (2003). Color Management. Digital Light & Color.](http://ftp2.bmtmicro.com/dlc/Color%20Management.pdf)
5. [**^**](http://en.wikipedia.org/wiki/Gamma_correction#cite_ref-4) Ansel Adams (1968). *The Negative*. Morgan & Morgan, Inc.
6. [**^**](http://en.wikipedia.org/wiki/Gamma_correction#cite_ref-5) Engineering Guideline EG 28, "Annotated Glossary of Essential Terms for Electronic Production," SMPTE, 1993.

**External links**

**General information**

* [Rehabilitation of Gamma](http://www.poynton.com/PDFs/Rehabilitation_of_gamma.pdf) by Poynton
* [Gamma tutorial](http://www.libpng.org/pub/png/spec/1.2/PNG-GammaAppendix.html) (from the [PNG](http://en.wikipedia.org/wiki/Portable_Network_Graphics) specification)
* [Frequently Asked Questions about Gamma](http://www.poynton.com/notes/colour_and_gamma/GammaFAQ.html)
* [CGSD - Gamma Correction Home Page](http://www.cgsd.com/papers/gamma.html) by Computer Graphics Systems Development Corporation
* [The Lagom LCD monitor test pages](http://www.lagom.nl/lcd-test/index.php)

**Monitor gamma tools**

* [Monitor Calibration Wizard](http://www.hex2bit.com/products/product_mcw.asp)
* [The Gamma adjustment page](http://www.photoscientia.co.uk/Gamma.htm)
* [Measuring Gamma for Monitors (Gernot Hoffman)](http://www.fho-emden.de/~hoffmann/measgamma10022004.pdf)
* [Monitor test pattern](http://www.normankoren.com/makingfineprints1A.html#Monitor_test_pattern) for correct gamma correction (by Norman Koren)
* [Links browser Gamma Calibration page](http://links.twibright.com/calibration.html)
* [QuickGamma](http://www.quickgamma.de/indexen.html)
* [Gamma Panel](http://www.donationcoders.com/stars/index.php?show=gapa)

# Contrast (vision)

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[](http://en.wikipedia.org/wiki/File:Photo_editing_contrast_correction.jpg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Photo_editing_contrast_correction.jpg)

Left side of the image has low contrast, the right has higher contrast.

[](http://en.wikipedia.org/wiki/File:Contrast_change_photoshop.jpg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Contrast_change_photoshop.jpg)

Changes in the amount of contrast in a photo

**Contrast** is the difference in visual properties that makes an object (or its representation in an image) distinguishable from other objects and the background. In [visual perception](http://en.wikipedia.org/wiki/Visual_perception) of the real world, contrast is determined by the difference in the [color](http://en.wikipedia.org/wiki/Color) and [brightness](http://en.wikipedia.org/wiki/Brightness) of the object and other objects within the same [field of view](http://en.wikipedia.org/wiki/Field_of_view). Because the human visual system is more sensitive to contrast than absolute [luminance](http://en.wikipedia.org/wiki/Luminance), we can perceive the world similarly regardless of the huge changes in illumination over the day or from place to place.

The human [contrast sensitivity function](http://en.wikipedia.org/wiki/Contrast_(vision)#Contrast_sensitivity) shows a typical [band-pass](http://en.wikipedia.org/wiki/Band-pass) shape peaking at around 4 cycles per degree with sensitivity dropping off either side of the peak.[[1]](http://en.wikipedia.org/wiki/Contrast_(vision)#cite_note-0) This tells us that the human [visual system](http://en.wikipedia.org/wiki/Visual_system) is most sensitive in detecting contrast differences occurring at 4 cycles per degree, i.e. at this [spatial frequency](http://en.wikipedia.org/wiki/Spatial_frequency) humans can detect lower contrast differences than at any other spatial frequency.

The high-frequency cut-off represents the [optical](http://en.wikipedia.org/wiki/Optics) limitations of the visual system's ability to [resolve](http://en.wikipedia.org/wiki/Optical_resolution) detail and is typically about 60 cycles per degree. The high-frequency cut-off is related to the packing density of the [retinal](http://en.wikipedia.org/wiki/Retina) [photoreceptor cells](http://en.wikipedia.org/wiki/Photoreceptor_cell): a finer matrix can resolve finer gratings.

The low frequency drop-off is due to [lateral inhibition](http://en.wikipedia.org/wiki/Lateral_inhibition) within the retinal [ganglion cells](http://en.wikipedia.org/wiki/Ganglion_cell). A typical retinal ganglion cell presents a centre region with either excitation or inhibition and a surround region with the opposite sign. By using coarse gratings, the bright bands fall on the inhibitory as well as the excitatory region of the ganglion cell resulting in lateral inhibition and account for the low-frequency drop-off of the human contrast sensitivity function.

One experimental phenomenon is the inhibition of blue in the periphery if blue light is displayed against white, leading to a yellow surrounding. The yellow is derived from the inhibition of blue on the surroundings by the center. Since white minus blue is red and green, this mixes to become yellow.[[2]](http://en.wikipedia.org/wiki/Contrast_(vision)#cite_note-1)

For example, in the case of graphical computer displays, contrast depends on the properties of the picture source or file and the properties of the computer display, including its variable settings. For some screens the angle between the screen surface and the observer's line of sight is also important.

Contrast is also the difference between the color or shading of the printed material on a document and the background on which it is printed, for example in [optical character recognition](http://en.wikipedia.org/wiki/Optical_character_recognition).

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| --- |
| Contents  * [1 Formula](http://en.wikipedia.org/wiki/Contrast_(vision)#Formula)   + [1.1 Weber contrast](http://en.wikipedia.org/wiki/Contrast_(vision)#Weber_contrast)   + [1.2 Michelson contrast](http://en.wikipedia.org/wiki/Contrast_(vision)#Michelson_contrast)   + [1.3 RMS contrast](http://en.wikipedia.org/wiki/Contrast_(vision)#RMS_contrast) * [2 Contrast sensitivity](http://en.wikipedia.org/wiki/Contrast_(vision)#Contrast_sensitivity)   + [2.1 Improving contrast sensitivity](http://en.wikipedia.org/wiki/Contrast_(vision)#Improving_contrast_sensitivity) * [3 See also](http://en.wikipedia.org/wiki/Contrast_(vision)#See_also) * [4 References](http://en.wikipedia.org/wiki/Contrast_(vision)#References) * [5 External links](http://en.wikipedia.org/wiki/Contrast_(vision)#External_links) |

## Formula

[](http://en.wikipedia.org/wiki/File:Tour_Eiffel_Notre-Dame.JPG)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Tour_Eiffel_Notre-Dame.JPG)

An image of the Notre Dame cathedral as seen from the [Eiffel Tower](http://en.wikipedia.org/wiki/Eiffel_Tower)

[](http://en.wikipedia.org/wiki/File:Tour_Eiffel_Notre-Dame%2Bcontrast.jpg)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:Tour_Eiffel_Notre-Dame%2Bcontrast.jpg)

The same image, with added global contrast, and local contrast ([acutance](http://en.wikipedia.org/wiki/Acutance)) increased through [unsharp masking](http://en.wikipedia.org/wiki/Unsharp_masking).

There are many possible definitions of contrast. Some include color; others do not. Travnikova laments, "Such a multiplicity of notions of contrast is extremely inconvenient. It complicates the solution of many applied problems and makes it difficult to compare the results published by different authors."[[3]](http://en.wikipedia.org/wiki/Contrast_(vision)#cite_note-2)

Various definitions of [contrast](http://en.wikipedia.org/wiki/Contrast) are used in different situations. Here, [luminance](http://en.wikipedia.org/wiki/Luminance) contrast is used as an example, but the formulas can also be applied to other physical quantities. In many cases, the definitions of contrast represent a ratio of the type

 
\frac{\mbox{Luminance difference}}{\mbox{Average luminance}}.


The rationale behind this is that a small difference is negligible if the average luminance is high, while the same small difference matters if the average luminance is low (see [Weber–Fechner law](http://en.wikipedia.org/wiki/Weber%E2%80%93Fechner_law)). Below, some common definitions are given.

### Weber contrast

The Weber contrast is defined as

 
\frac{I-I_\mathrm{b}}{I_\mathrm{b}},


with *I* and *I*b representing the luminance of the features and the background luminance, respectively. It is commonly used in cases where small features are present on a large uniform background, i.e. the average luminance is approximately equal to the background luminance.

### Michelson contrast

The [Michelson contrast](http://en.wikipedia.org/wiki/Michelson_contrast)[[4]](http://en.wikipedia.org/wiki/Contrast_(vision)#cite_note-3) is commonly used for patterns where both bright and dark features are equivalent and take up similar fractions of the area. The Michelson contrast is defined as

 
\frac{I_\mathrm{max}-I_\mathrm{min}}{I_\mathrm{max}+I_\mathrm{min}},


with *I*max and *I*min representing the highest and lowest luminance. The denominator represents twice the average of the luminance.

### RMS contrast

RMS contrast does not depend on the spatial frequency content or the spatial distribution of contrast in the image. RMS contrast is defined as the standard deviation of the [pixel](http://en.wikipedia.org/wiki/Pixel) intensities:[[5]](http://en.wikipedia.org/wiki/Contrast_(vision)" \l "cite_note-4)


\sqrt{\frac{1}{M N}\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}(I_{ij}-\bar{I})^2},


where intensities *Iij* are the *i*-th *j*-th element of the two dimensional image of size *M* by *N*. \bar{I}is the average intensity of all pixel values in the image. The image *I* is assumed to have it's pixel intensities normalized in the range [0,1].

## Contrast sensitivity

*Contrast sensitivity* is a measure of the ability to discern between [luminances](http://en.wikipedia.org/wiki/Luminance) of different levels in a static [image](http://en.wikipedia.org/wiki/Image). Contrast sensitivity varies between individuals, reaching a maximum at approximately 20 years of age, and at [spatial frequencies](http://en.wikipedia.org/wiki/Spatial_frequency) of about 2–5 cycles/degree. In addition it can decline with age and also due to other factors such as cataracts and diabetic retinopathy.[[6]](http://en.wikipedia.org/wiki/Contrast_(vision)#cite_note-5)

[](http://en.wikipedia.org/wiki/File:SinVibr.png)

[http://bits.wikimedia.org/skins-1.5/common/images/magnify-clip.png](http://en.wikipedia.org/wiki/File:SinVibr.png)

In this image, the contrast amplitude depends only on the vertical coordinate, while the spatial frequency depends on the horizontal coordinate. Observe that for medium frequency you need less contrast than for high or low frequency to detect the sinusoidal fluctuation.

### Improving contrast sensitivity

It was once thought that contrast sensitivity was relatively fixed and could only get worse with age. However new research has shown that playing videogames can slightly improve contrast sensitivity. [[7]](http://en.wikipedia.org/wiki/Contrast_(vision)#cite_note-6)

## See also

* [Acutance](http://en.wikipedia.org/wiki/Acutance)
* [Radiocontrast](http://en.wikipedia.org/wiki/Radiocontrast)
* [Contrast ratio](http://en.wikipedia.org/wiki/Contrast_ratio)

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