CIE 1931 color space

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In the study of the perception of color, one of the first mathematically defined color spaces was the **CIE 1931 XYZ color space**, created by the International Commission on Illumination (CIE) in 1931.

The CIE XYZ color space was derived from a series of experiments done in the late 1920s by W. David Wright and John Guild. Their experimental results were combined into the specification of the CIE RGB color space, from which the CIE XYZ color space was derived.

Tristimulus values

The human eye has photoreceptors (called cone cells) 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, 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 in a three-component additive 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*.

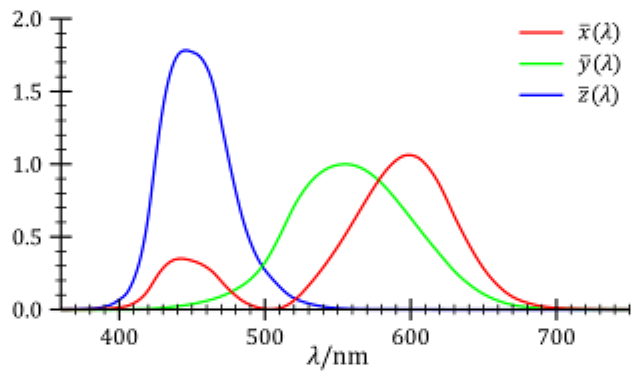
Any specific method for associating tristimulus values with each color is called a color space. CIE XYZ, one of many such spaces, is a commonly used standard, and serves as the basis from which many other color spaces are defined.

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

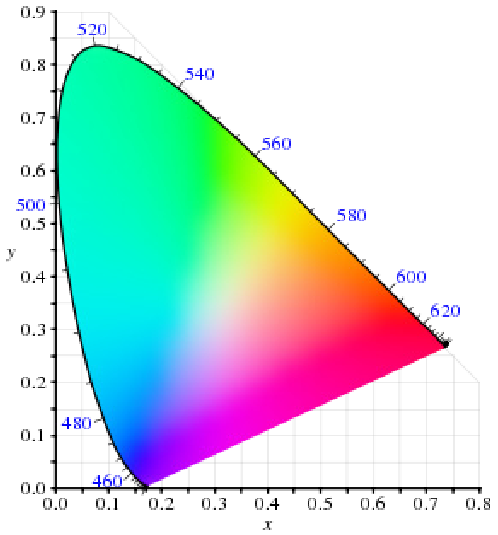
Color matching functions



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 $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$, 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. λ is the wavelength light (measured in nanometers) of the equivalent monochromatic.

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



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, and colors outside the sRGB gamut cannot be displayed properly. Depending on the color space and calibration of your display device, the sRGB colors may not be displayed properly either.

Since the human eye has three types of color sensors that respond to different ranges of wavelengths, 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. 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 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 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 previous figure 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.

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 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 light, with wavelengths listed in nanometers. The straight edge on the lower part of the gamut is called the ***line of purples***. 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 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 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).

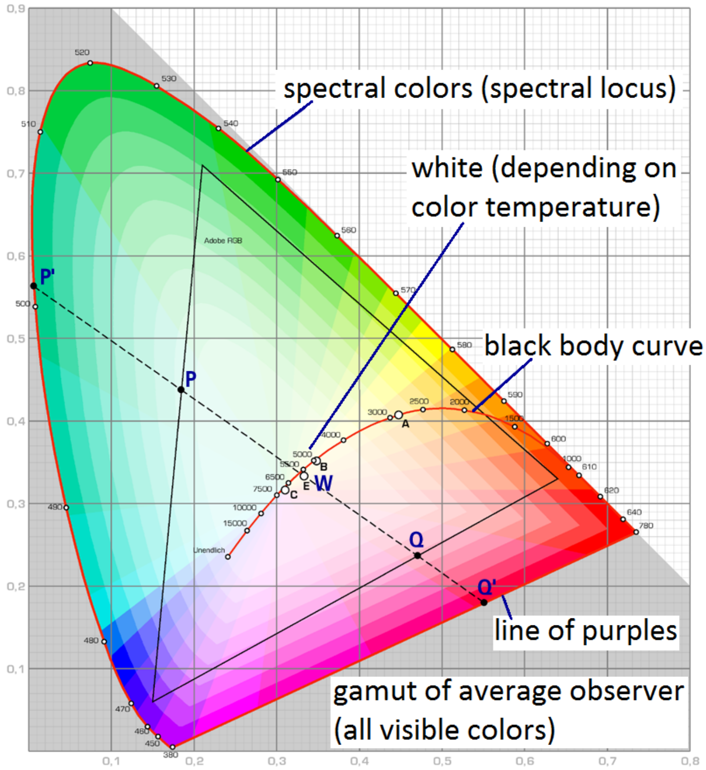
- An equal mixture of two equally bright colors will not generally lie on the midpoint of that line segment. In more general terms, a distance on the *xy* chromaticity diagram does not correspond to the degree of difference between two colors. CIE 1960, CIE 1964, and CIE 1976 color spaces were developed, 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 corresponds to the point $(x,y) = (1/3,1/3)$.

Experimental results—the CIE RGB color space

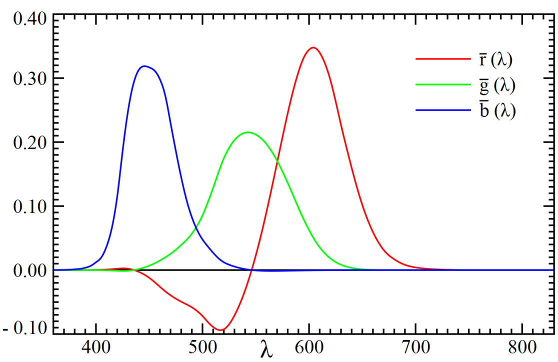
The CIE RGB color space is one of many RGB color spaces, distinguished by a particular set of monochromatic (single-wavelength) primary colors.



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. 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, but with adjustable 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.



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 the 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 previous plot (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. 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.

The resulting normalized color matching functions are then scaled in the r:g:b ratio of 1:4.5907:0.0601 for source luminance and 72.0962:1.3791:1 for source 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.