What is the CIE Color Space? What's the difference between CIE 1931 and CIE 1976?

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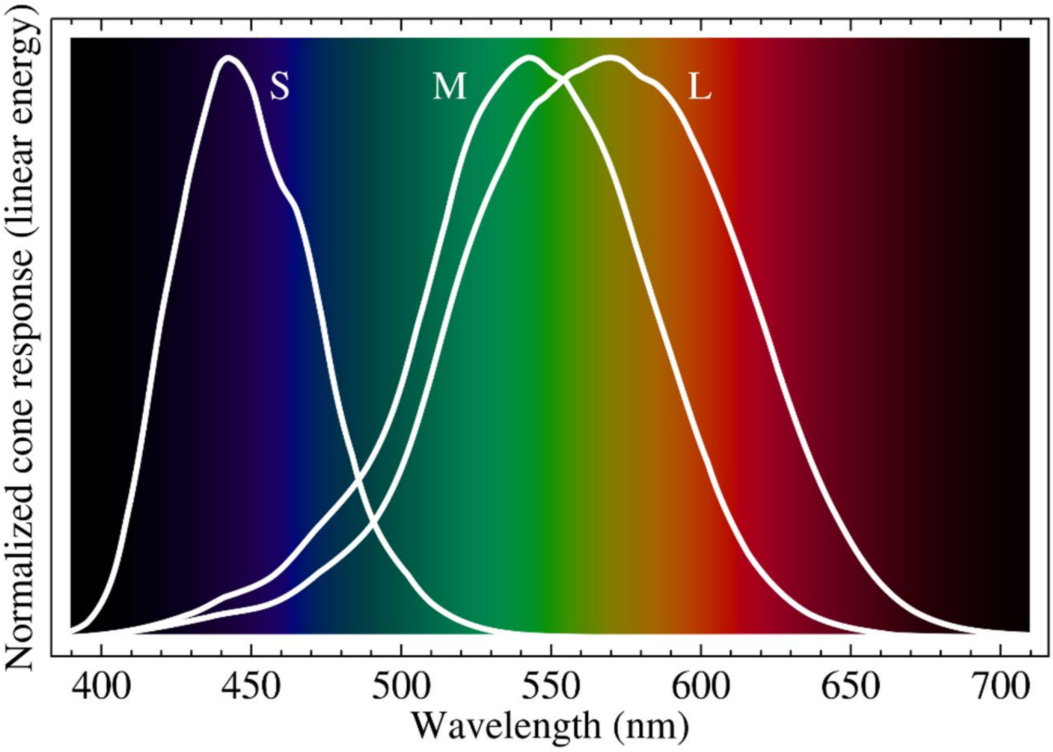
The visible spectrum of light includes the electromagnetic wavelengths from approximately 380-740 nanometers (nm). Photoreceptor cells in the human eye called rods and cones respond to light waves in this range, which the visual processing system/brain converts to our perception of light and color. Specifically, the cones determine how we perceive color. There are multiple systems that have been developed to quantify and characterize colors and human perception of color. The most significant of these is the system developed by the *Commission Internationale de L'Eclairage* (CIE, the International Commission on Illumination).

Human Color Perception

The human eye has three types of cone cells—long, medium, and short (or L, M, and S)—each sensitive to a specific range of the visible wavelength spectrum. The figure below shows the normalized human cone response, with the peaks of the curves indicating where each type of cone has the strongest response. Cone response is the basis for all of the color representation systems that have been developed, although the actual mathematical functions used have some differences. These differences are related to the distribution of rods and cones in the eye and are based mainly on empirical data derived from human vision studies. Cones don't perceive individual wavelengths, but instead we see a blend of all the wavelengths under the curves at various intensity.



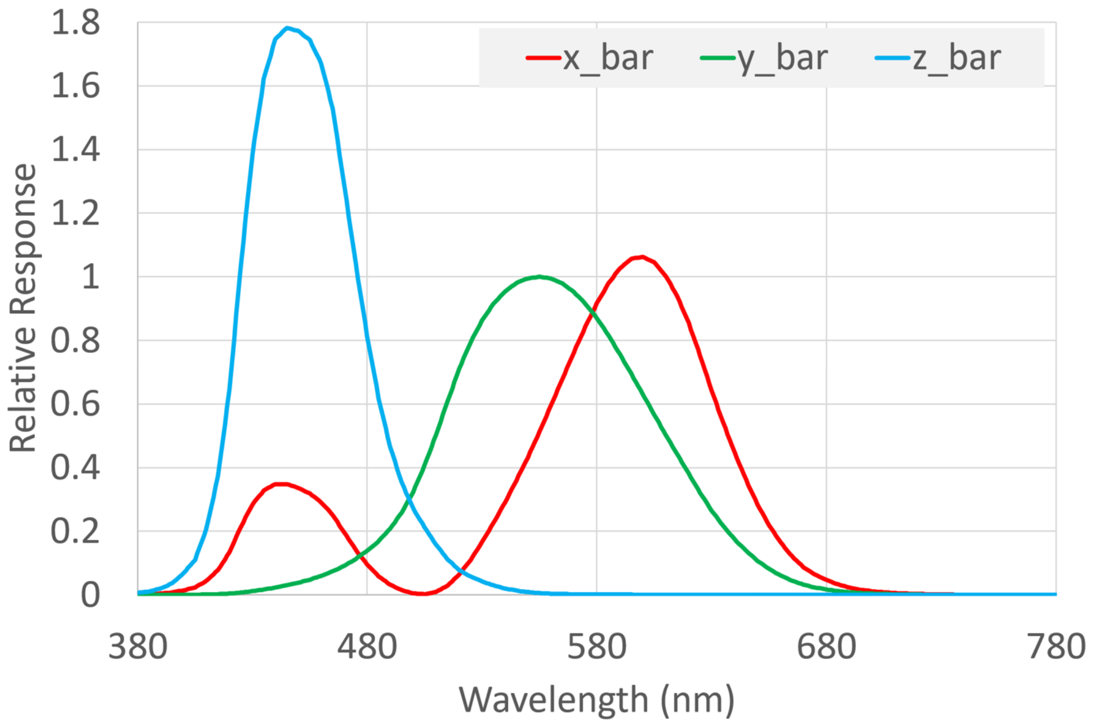
The individual cone response: S cones respond most strongly to shorter-wavelength light in the violet/blue range, M cones respond more to medium-wavelengths in the green range, and L cones are more responsive to longer wavelength light in the yellow/orange/red range. For more detail about the human optical system refer to the Luminus Help Center article: How do Humans See Light and Color?

Quantifying Color: Tristimulus Response Curves

In the 1920s, scientists William David Wright and John Guild conducted a series of experiments designed to quantify human perception of color. These experiments laid the groundwork for development of the first RGB (Red Green Blue) "color space," a mathematical region with its limits defined by the three pure (monochromatic) primary color wavelengths. In 1931, the CIE took this research further and defined a standard for scientifically quantifying the physical properties of colors as seen by humans. Referred to generally as "CIE 1931," the result was a mathematical system to quantify all the colors that can be perceived by the average human eye.

CIE defined a color-mapping function called the standard (colorimetric) observer, representing an average human's chromatic response of the human fovea (the area of the retina with the highest concentration of cones) within a 2° arc. The three spectral sensitivity curves are labeled X, Y, and Z. Every color we see is a mixture of these three Red-Green-Blue (RGB) "primaries" represented by tristimulus curves that graph the response of each cone type as a function of wavelength (three types of cones, thus the "tri" in tristimulus).

Thus, the entire range of human color perception is represented by the area under all three of the curves in the graph below. The variables x_bar, y_bar and z_bar are color matching functions encompassing both the luminance (brightness/intensity) and chromaticity (color) values of any point in the tristimulus diagram. They are a mathematical representation of the cone based on the original color perception studies conducted in the early 20th century. These functions are used to calculate the Tristimulus values (X, Y, Z) for a light source and then normalized to produce the x, y coordinates used in the 1931 CIE Color Space. The details of these calculations are given in the Luminus Help Center article: How do I calculate CIEx and CIEy from an SPD?



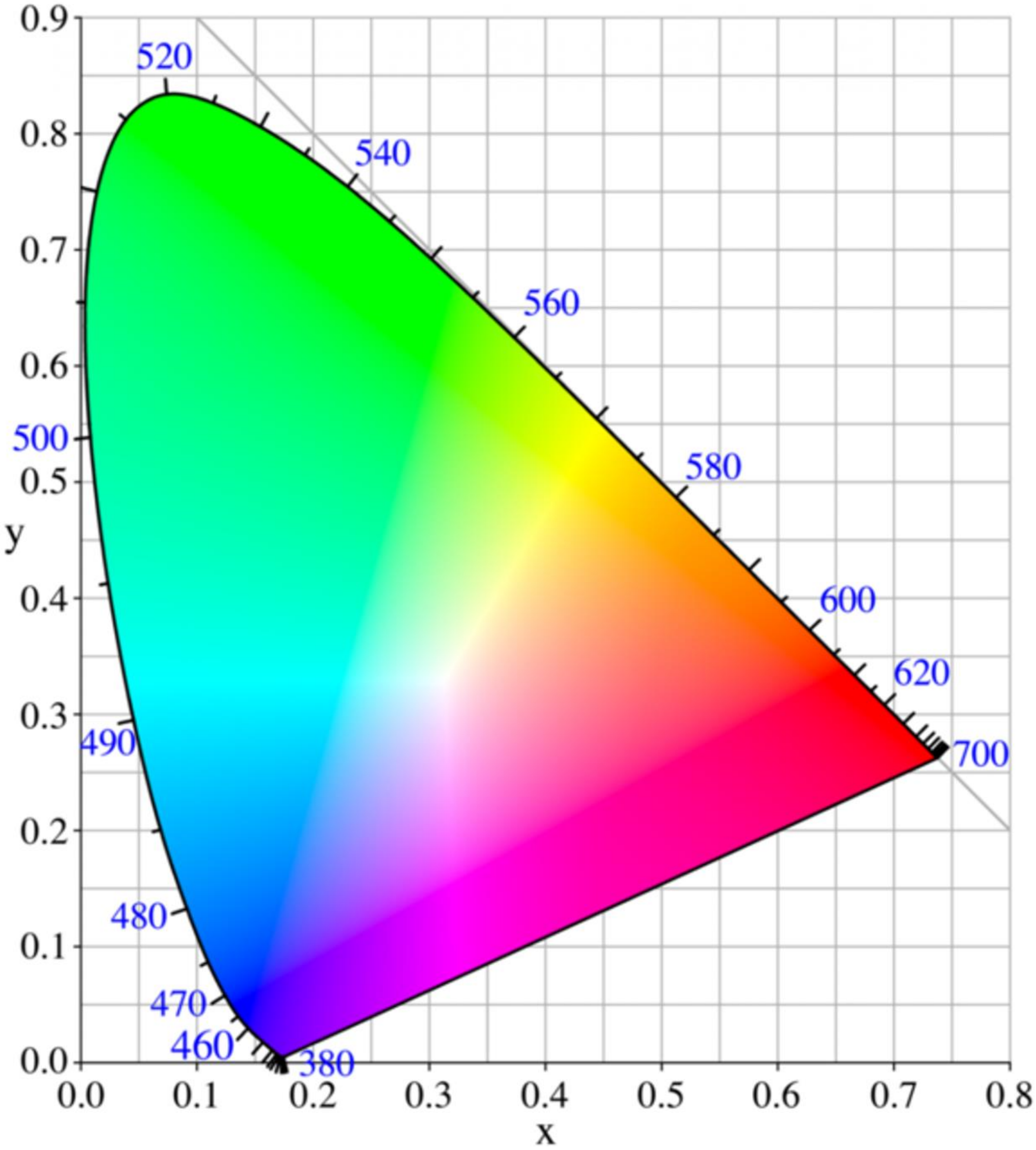
The tristimulus curves graph the spectral response of human vision. The curves illustrate the relative response of the cones based on how we perceive the intensity of each wavelength. The peak of each curve is at the wavelength where our perception of that color is strongest.

The CIE 1931 Color Space

Along with the tristimulus function curves, in 1931 CIE also formalized a "color space" a graphical representation of all colors perceived by humans; refer to the figure below. In reality, human color perception is a three-dimensional phenomenon; the CIE color space has been transformed to a two-dimensional, horseshoe-shaped graph of the luminance (brightness) and chromaticity (color) values perceived by humans. The chromaticity coordinates of any point on the graph are labeled x and y (or C_x and C_y).

Every color we see is a blend of the three primaries, R, G and B, in varying quantities. The pure RGB values are shown at the three extreme points of the triangular color space. The outer curved boundary of the color space is called the spectral locus. It is defined by monochromatic points representing a pure hue of a single wavelength. To quantify any color as a coordinate on this color space, the CIE specifies mathematical "color matching functions." The functions are derived based on the tristimulus values (X, Y, and Z) at any point in the color space.

Since its inception, the CIE color space has enabled accurate measurement, representation, and replication of colors for a vast range of applications such as printing, light source characterization, optical design, and measurement of illuminated display screens. The CIE color space has also been rescaled, once in 1960 and again in 1976.

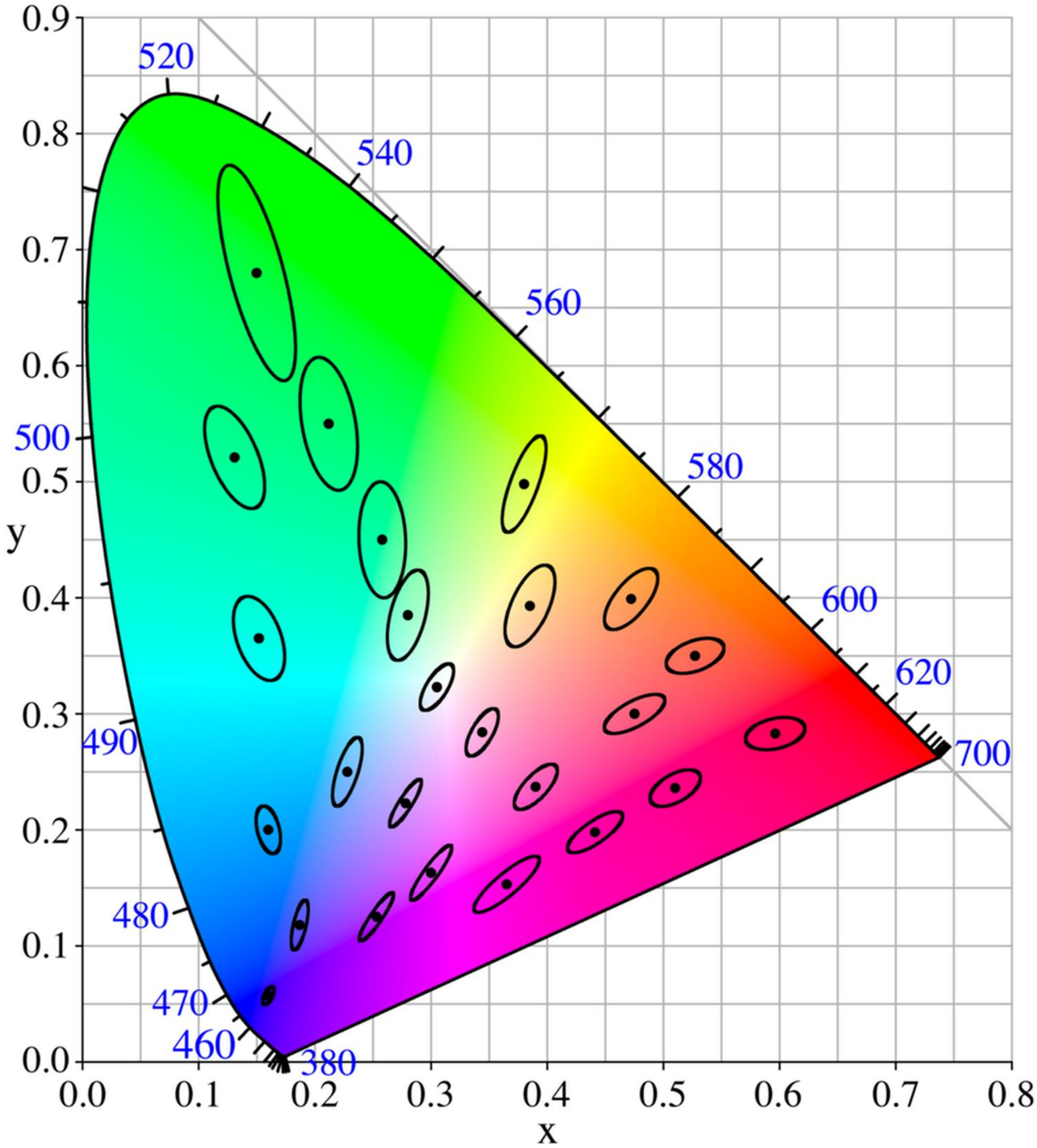


A graphical representation of the CIE 1931 color space, encompassing all colors visible to the human eye based on the 2° standard observer. The numbers in blue are the wavelengths of the monochromatic light on the spectral locus. Image licensed under Creative Commons (CC By-SA 3.0)

MacAdam Ellipses

In the late 1930s and early 1940s, scientist David MacAdam led a series of experiments to understand human color discernment—our perception of differences in color (in LED lighting, these differences are measured as color temperature). The result of this research was the eponymous MacAdam Ellipses, which were plotted onto the CIE color space diagram by Perley Nutting, as shown in the figure below. Each ellipse encompasses an area that human vision perceives as being the same color (although for purposes of illustration, the ellipses are drawn 10 times their actual size). The center point of each ellipse is the “target” color (the starting point color value used in the experiments).

For example, the yellow color at point at x=0.4, y= 0.52 would appear the same to our eyes as the color point at x=3.8, y=0.46, and both would appear identical to the color at the center dot of that ellipse. The three points are indistinguishable to the average human viewer.

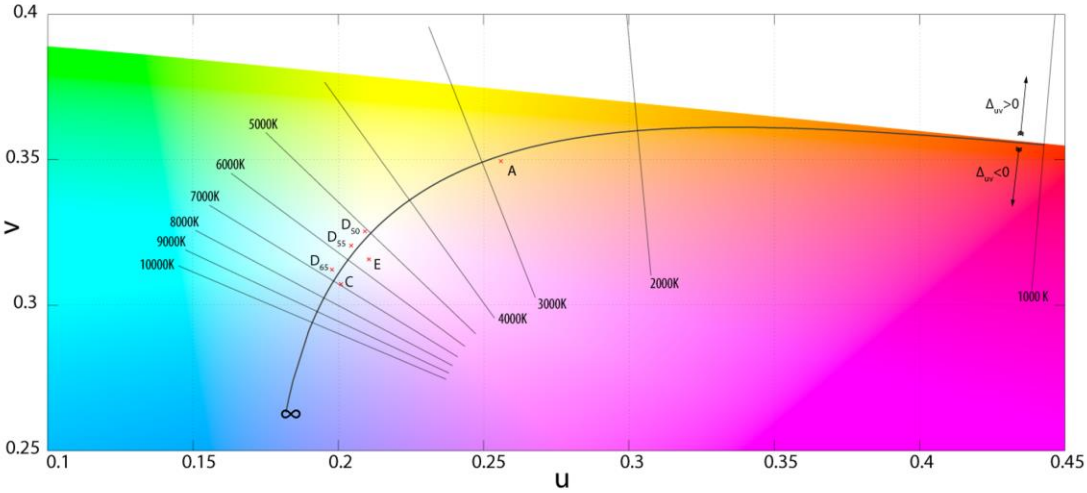


The MacAdam ellipses shown on the 1931 CIE color space. Image licensed under Creative Commons (CC By-SA 3.0)

Scientists had anticipated that the ellipses would all be circular, with regular deviations. Obviously, the size, orientation, and shape of the ellipses is quite varied. This discovery led to the development of several new versions of the CIE color space that would reduce the apparent distortion and better represent various aspects of color perception.

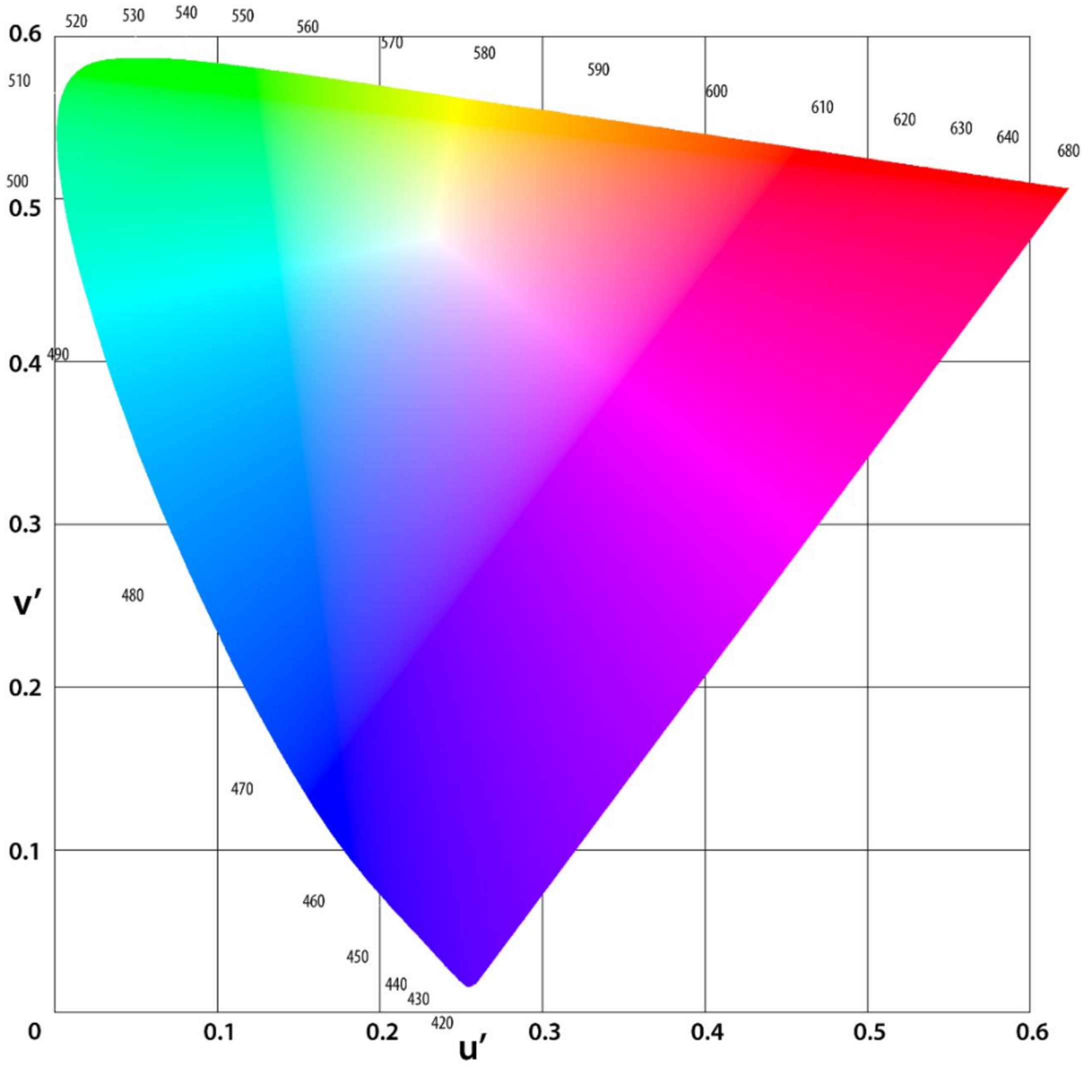
CIE 1960 and CIE 1976

In 1960 the CIE released a new chromaticity diagram, the 1960 CIE Uniform Color Space (UCS), shown in the figure below. The CIE 1960 color space was the foundation of the system to quantify another color concept, Correlated Color Temperature (CCT) with reference to the Planckian locus. For more information about CCT refer to the Luminus Help Center article: What does CCT, CIE, and SPD mean in LED lighting? Today, the 1960 UCS is mostly used to calculate CCT. The isothermal lines shown in the figure below are perpendicular to the Planckian locus.



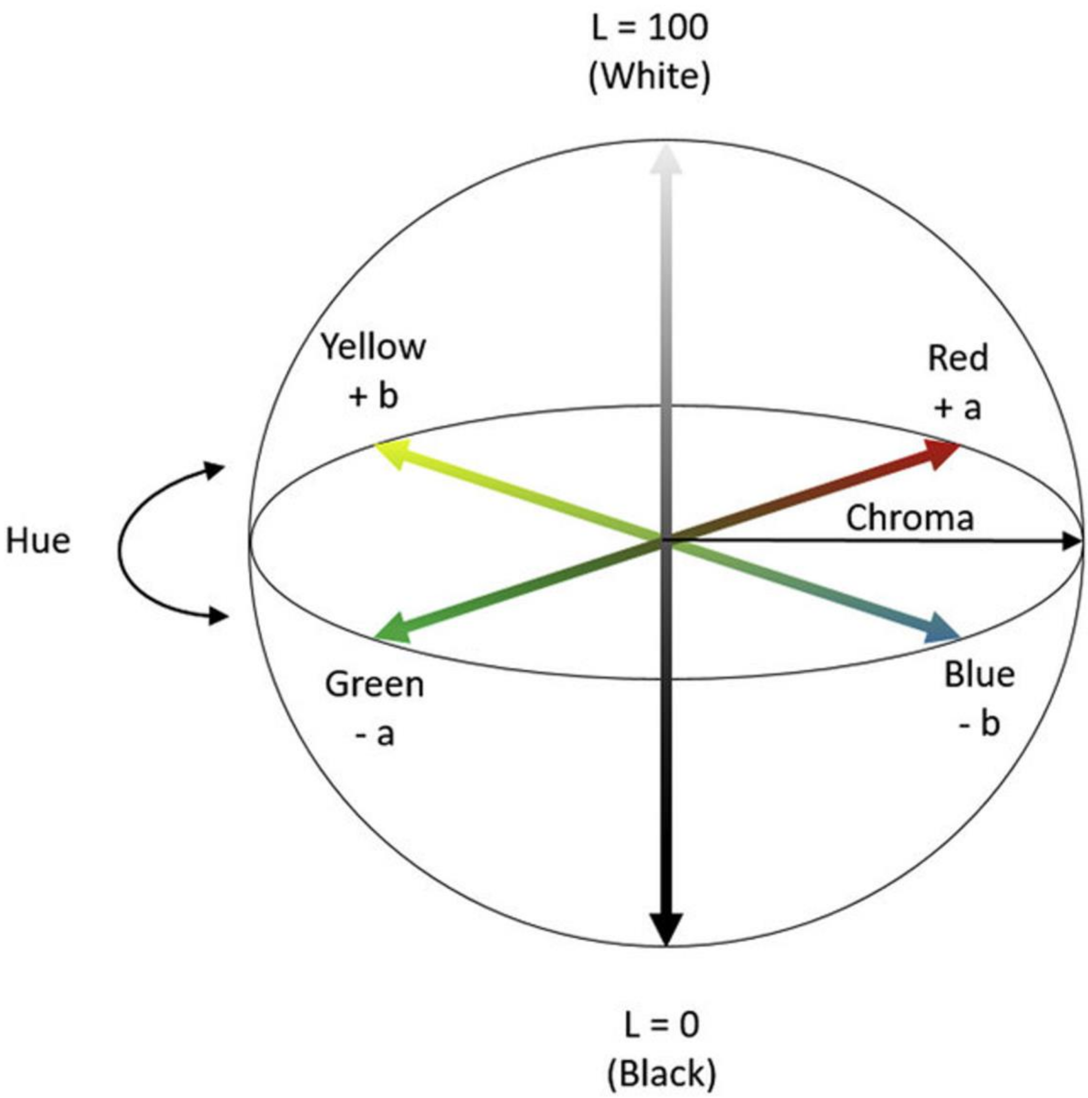
The CIE 1960 Uniform Color Space, representing color temperature distinctions. (Image credit: Adoniscik)

Then the CIE issued a new color space in 1976, also called the CIE L*u*v* (or CIELUV) color space. It was adjusted to better represent the proportion of chromaticity differences. Replacing the previous x,y or u,v variables, new variables u'v' are used, which can be calculated from the 1931 tristimulus XYZ values, or from the chromaticity coordinates xy.



A graphical representation of the CIE 1976 color space, which has been rescaled to better represent proportional differences in human perception of color (as measured by MacAdam and others). The x,y chromaticity values have been replaced by u'v'. Image licensed under Creative Commons (CC By-SA 3.0)

Also in 1976, the CIE L*a*b* (CIELAB) space was introduced. It is a three-dimensional representation that expresses color as three values: L* for luminance, and a* and b* or the three colors of human vision: red, green, blue, and with the addition of yellow. The revised color space was scaled to provide more uniform spacing for colors at approximately the same luminance. CIELAB has been refined as CAM02 and CAM02-UCS (a',b') which have been shown to be a more plausible model of neural activity in the primary visual cortex.



The CIELAB (or CIE L a* b*) color space diagram, representing the quantitative relationship of colors on three axes: L* value indicates lightness, and a* and b* are chromaticity coordinates. The center of the plane is neutral or achromatic. The distance from the central axis represents the chroma (C*), or saturation of the color. The angle on the chromaticity axes represents the hue.*

All of these color spaces are still used. The CIE 1931, 1960, and 1976 systems are all linear transformations of each other and can be easily converted to the system best for a particular calculation. A partial summary of uses in the LED world is as follows

- CIE 1931 x,y is used to specify the LED color point and define the bin structure
- CIE 1960 u,v is used to calculate the CCT and Duv of a white color point
- CIE 1976 u',v' is used to evaluate the size and shape of Standard Deviation Color Matching (SDCM) steps at any color point as recommended in ANSI C78.377 and CIE TN 001:2014.
- CAM02UCS a',b' is used in the TM-30 color rendition rating system.

To learn more, refer to the Help Center articles:

FAQ -> Color Quality Metrics

White Papers -> Achieving Optimal Color Rendition with LEDs

Calculations:
Color-Science-Calculate-a-MacAdam-Ellipse-Table
Color-Science-Calculate-CCT-and-Dominant-Wavelength-from-CIE-x-y-point
Color-Science-Calculate-CIEx-and-CIEy-from-an-SPD
Color-Science-Calculate-Dominant-Centroid-Peak-Wavelengths-from-an-Excel-File-Datalore-Notebook-
Color-Science-CIE-1931-Reference-Structures-Excel-
Data-Analysis-Python-Luxpy-Package

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