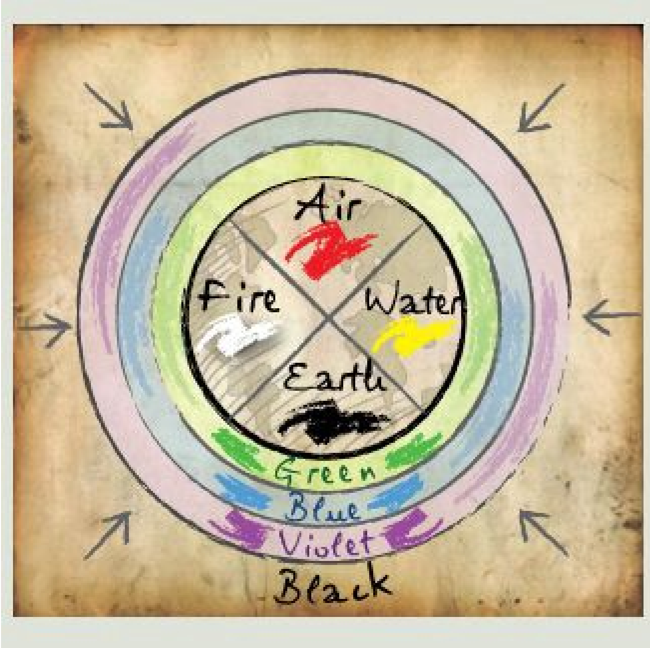
Color Space Notes

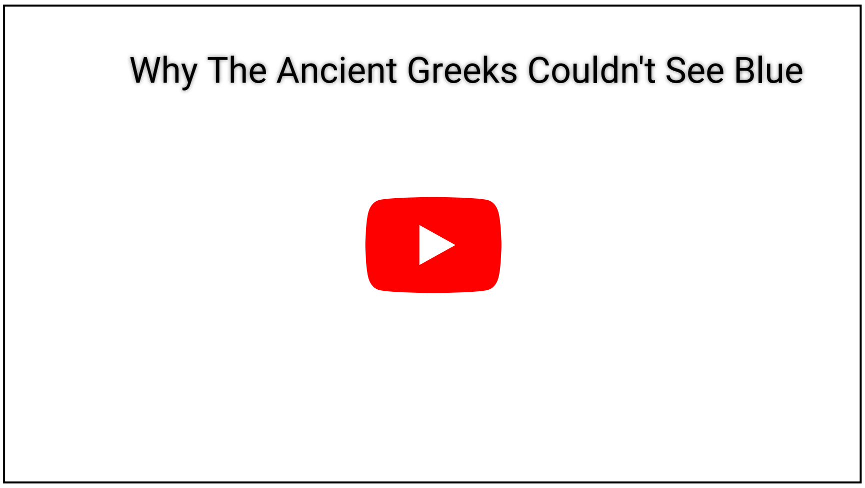
Greek Color Theory

- Earlier Greek painting (Archaic/Classical) seem so clear and—deceptively—simple while the latest painting (Hellenistic/Graeco-Roman) is so much more complex but also familiar to us, **Source:** https://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1000&context=art_jbgc
- Greek philosophers thought in terms not of three, but of four, basic colors: **black, red, yellow and white**
- the Greek system of four colors is theoretically balanced by a **second group** of four colors: **white, blue, violet and black**. The earlier Greek painters were thoroughly absorbed in the first “**tesserad**” of colors, while later painters increasingly experimented with the second group.
- the nature of the world thought of as consisting of the four elements called earth, water, air and fire, each one being the expression of a deity. There is written evidence that he and other thinkers of the time associated four colors: black, white, yellow and red with those elements. They also took black and white to be the primal colors, all remaining colors being mixtures of these two in some way. All colors exist in a spectrum between darkness and light, and that four primary colors come from the four elements: fire, air, water, and earth.
- Greeks accepted darkness (black) as an integral part of color. The Greeks were perfectly able to *perceive* the blue tint, **but were not particularly interested in *describing* the blue tone of sky or sea**—at least not in the same way as we are, with our modern sensibility.



In Ancient Greece, Aristotle developed the first known theory of color. He postulated that God sent down color from the heavens as celestial rays. He identified four colors corresponding to the four elements: earth, fire, wind, and water.

Why the ancient Greeks could not see blue:



Side read: The Story of Colour: An Exploration of the Hidden Messages of the Spectrum; Book by Gavin Evans

Can we hope to understand how the Greeks saw their world? - Maria Michela Sassi | Aeon...

Homer used two adjectives to describe aspects of the colour blue: kuaneos, to denote a dark shade...

aeon.co

- **Source : https://assets.press.princeton.edu/chapters/s8369.pdf** (blue sky is mentioned only rarely in Greek literature. Homer, in the third book of the Odyssey, describes the ascent of the sun god Helios thus:

And now the sun, leaving the beauteous water surface, sprang up into the brazen heaven to give light to the immortals and the mortal men on the earth

- Elsewhere in the Odyssey Homer describes the sea as black, white, gray, dark, and purple.
- William Gladstone published several articles and books in which he speculated that the ancient Greeks may have had deficient organs for color perception. In other words, he surmised that they were blue-blind. Yet while the color blue is mentioned only rarely in the literature, we have learned since then from archaeological research that, next to yellow, blue was one of the most frequently used colors in Greek painting. **The Greeks were not blue-blind.**

- to ancient Greeks, including Aristotle, luminosity was more important than hue in characterizing color. For example, the Greek words **melas** and **leukos** can be translated not only as "**black**" and "**white**" but also as "**dark**" and "**light**."
- The use of the color term **kyanos** is equally ambiguous; it is usually translated as "**blue**" and gave rise to our modern color term cyan (a green-tinged blue). **Kyanos** referred to a **dark color** in general and was used to describe **emeralds**, but it could also manifest itself as a **blue**, and could even mean black.
- The **difference between black and blue**, then, was not so crucial to the Greeks. It was much more important to them that **blue bordered on black or dark**, and that **both of them constituted the dark end of a scale of colors**
- Aristotle's pupil Theophrastus describes the (**blue**) **lapis lazuli as kyanos**-colored. Homer's Iliad, on the other hand, could describe not only the color of steel but also the (probably **black**) hair of King Priam's son **Hector as kyanos**.
- In a poem from the early fifth century b.c., the poet Alcmaeon of Croton had already claimed the opposition of light and dark

to be the origin of the colors

- Empedocles related the four basic colors—**black, white, red, and ochron** (probably a **yellow** or **dull green** color)—to the four elements **earth, water, air, and fire**.
- **Democritus**, the originator of Greek **atomic theory**, interpreted **colors** as **properties of the surfaces of objects** and claimed that **smooth surfaces appeared white**, whereas **rough surfaces appeared black**.
- Plato's thoughts: . He assumed that the eyes emit visual rays that join together with daylight to form a luminous medium.This medium was supposed to convey a material effluence emitted by visible objects into our eyes so that we could perceive these visible things. **Plato attempted to reduce sight to a mechanical sensation like touch**, explaining the multitude of colors as the result of the different sizes of the particles emitted by the objects. *If they were larger than the particles of the visual rays, then the **object would appear black**; if they were smaller, then we would see **white**.*
- **Aristotle**: . In contrast to Plato, he doubted that our eyes could emit visual rays, surmising rather that they passively receive the rays from visible objects;

[Wiki: Emission theory

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

In the fifth century BC, Empedocles postulated that everything was composed of four elements; fire, air, earth, and water. He believed that **Aphrodite made the human eye out of the four elements and that she lit the fire in the eye which shone out from the eye, making sight possible**. If this were true, then one could see during the night just as well as during the day, so Empedocles postulated an interaction between rays from the eyes and rays from a source such as the sun.

Euclid(300BC) questioned that sight is the result of a beam from the eye, for he asked how one sees the stars immediately, if one closes one's eyes, then opens them at night.

In 55 BC, Lucretius, a Roman who carried on the ideas of earlier Greek atomists, wrote: The light and heat of the sun; these are composed of minute atoms which, when they are shoved off, lose no time in shooting right across the interspace of air in the direction imparted by the shove

Despite being similar to later particle theories, Lucretius's views were not generally accepted; light was still theorized as emanating from the eye

Wiki: Intromission Theory

***intromission theory* (or *intromissionism*),** which states that visual perception comes from something representative of the object (later established to be **rays of light reflected from it**) entering the eyes. Modern physics has confirmed that light is physically transmitted by photons from a light source, such as the sun, to visible objects, and finishing with the detector, such as a human eye or camera. **Main propagators Aristotle (*De Sensu*),[6] Galen (*De Usu Partium Corporis Humani*) and their followers**

Both schools of thought relied upon the principle that "like is only known by like", and thus upon the notion that the eye was composed of some "internal fire" which interacted with the "external fire" of visible light and made vision possible.

Alhazen was the first person to explain that vision occurs when light bounces on an object and then is directed to one's eyes.

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- Aristotle presupposed the existence of a medium that conveys visual impressions, making objects perceptible to our eyes. Aristotle was a proponent of the **intromission theory of vision** (https://assets.press.princeton.edu/chapters/s8369.pdf)

- **Like the proponents of the extramission** theory of vision, **he presupposed the existence of a medium** that conveys visual impressions, making objects perceptible to our eyes: this medium, which he called the "transparent" **(diaphanos).** For him, the "transparent" was a property of all media that are more or less translucent
- Aristotle claimed that color is a property of all objects and of the medium that surrounds them, but not of light. This corresponds to our everyday experiences with vision, because we think we see colors on the surfaces of the objects around us
- Aristotle explained that **light would come about if fire (one of the four elements) were found in a transparent medium (like air or water)**. In contrast, **darkness would mean the absence of fire**.
- Aristotle **did not see light as propagating itself with a certain finite speed**. Rather, he imagined that **a luminous body changes the entire transparent medium from a state of potential transparency into a state of actual transparency** in no time, **the perception of light reaching the observer's eye instantaneously**.
- **But how do colors arise? Aristotle** gives possibilities:

1. **white** and **black** particles alternate in such a way that while each by itself is **invisible because of its smallness**, the **compound of the two is visible.** This cannot appear either as white or as black; but since it must have some color, and cannot have either of these, it must evidently be some kind of mixture, i.e. some other kind of color. It is thus possible to believe that there are **more colors than just white and black, and that their number is due to the proportion of their components**

The colors can be **arranged on a scale** ranging from light to dark according to their differing **proportions of black and white.** Relatively **dark colors, like blue, contain mostly black** and only a little white, while for **lighter colors, like yellow and orange, the proportion of white predominates**

OF PHILOSOPHERS AND THE COLOR BLUE 17

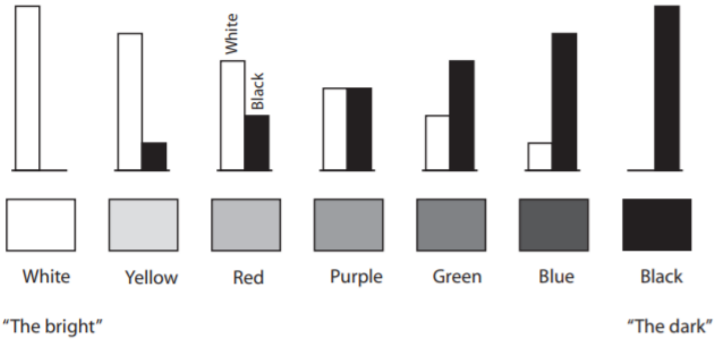


Figure 1.3 The colors produced by black and white mixed in different proportions, according to Aristotle's treatise *On the Senses.*

Aristotle names five colors between white and black: yellow, red, purple, green, and blue.

He claims that especially pure colors result when black and white are mixed in proportions of low whole numbers (such as 3:2 or 4:3). Here he is **alluding to Pythagoras**, who had deduced octaves and the other pure intervals in music from the harmonic relations of tone pitches. **This parallel is not coincidental, writes Aristotle, because colors are indeed related to tones.**

2. **the second way** that colors can be produced is through the **physical permeation of colored substances**, from which a mixed color emerges.

3. New colors may also appear when a luminous color shines through a transparent medium.

In On the Senses, Aristotle writes: Another theory is that they appear through one another, as sometimes painters produce them, when they lay a color over another more vivid one, e.g. when they want to make a thing show through water or mist; just as the sun appears white when seen directly, but red when seen through fog and smoke

This is the third way in which colors can be produced. The effect of smoke and fog is one example; it shows how the air can change the color impression of the sun shining through it.

Newton

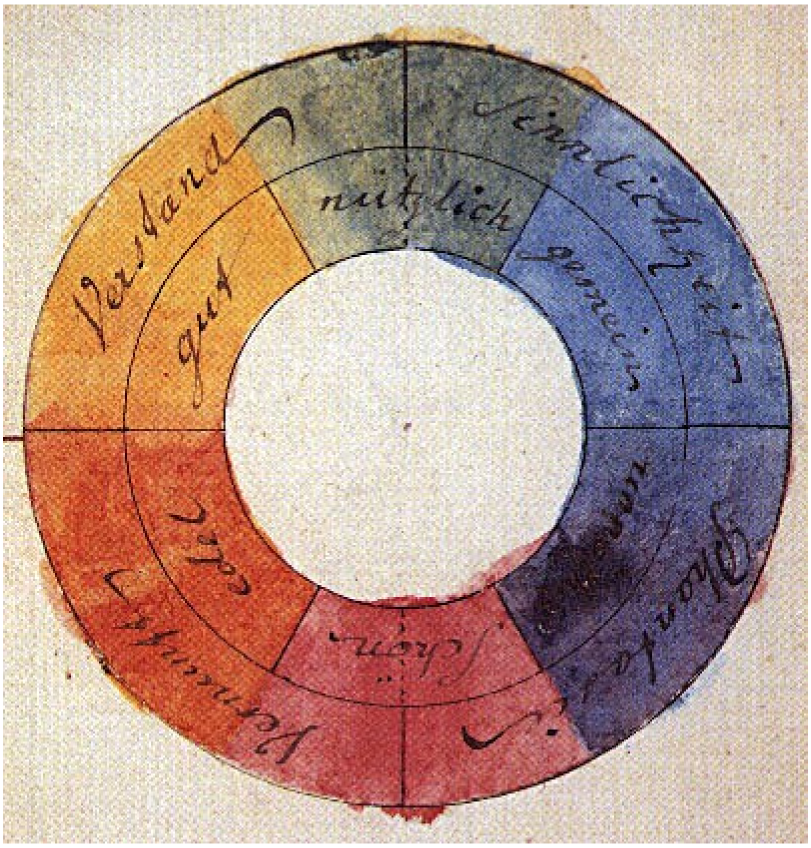
Opticks in 1704

- When you shine white light through a prism, the light is split into colors from across the color spectrum. However, Newton discovered that he could recombine these spectral colors to once again turn them into white light.
- Newton also discovered that if he blended the first color (red) and last color (violet) of the color spectrum, he could produce magenta, an extra-spectral color that does not exist in the rainbow.
- Newton wanted the circle to have seven colors—the exact number of days in a week and musical notes in an octave

Goethe

Goethe challenged Newton's views on color, arguing that color was not simply a scientific measurement, but a subjective experience perceived differently by each viewer. His contribution was the first systematic study on the physiological effects of color. Goethe's views were widely adopted by artists. Although Goethe is best known for his poetry and prose, he considered *Theory of Colors* his most important work.(https://library.si.edu/exhibition/color-in-a-new-light/science)

- German poet Wolfgang von Goethe dedicated his book *Theory of Colors* from 1810 to a more **human-centered analysis of the perception of color**.
- Goethe believed that the **prism**, not the light, was **responsible for the creation of color**, and that **darkness was not an absence of light**.

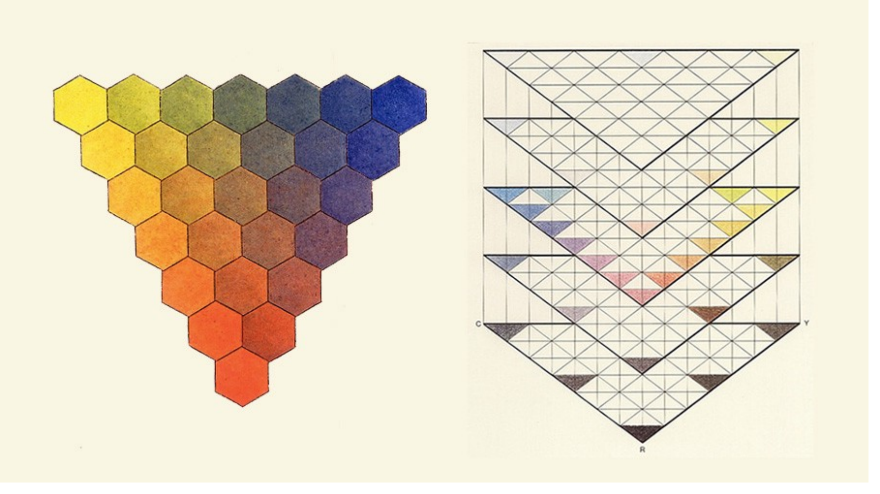


- The circle had three primary colors—**magenta, yellow, and blue** —which he believed could mix all other colors in the spectrum.
- **Newton describes** how his spectral colors can mix most visible colors including white, and this is true because light mixes in an additive way: Combining lights of different colors will eventually result in white light. **Goethe describes** how his three primary colors can mix most visible colors including black, and this is true because pigments mix in a subtractive way: Combining paints of different colors will eventually result in black paint by subtracting waves of light.

In a quest to create a unified notation for color—like we know it from musical notation—artists soon started depicting **the color spectrum as 3D solids.**

Tobias Mayer's color triangle from his book *The Affinity of Color Commentary*, published posthumously in 1775. Mayer sought to accurately define the number of individual colors the human eye can see, and this required him to **add another dimension to represent the variations of brightness for each color.**

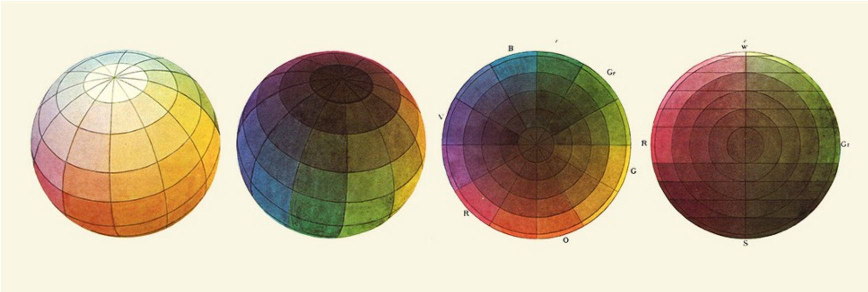
Mayer painted the **corners of a triangle** with the three traditional primary colors from painting—**red, yellow, and blue** (more specific: cinnabar, massicot and azurite.)— and connected the corners by mixing the opposing colors together. **Unlike the traditional color circle, he created many variations of this triangle by stacking triangles of different brightnesses on top of each other.** This made it possible to define a color by its position within a 3D space, a technique still used to this day. **Mayer ultimately failed at creating a color model with perceptually uniform steps, as he did not understand the irregularities of the human eye** (https://programmingdesignsystems.com/color/a-short-history-of-color-theory/index.html)



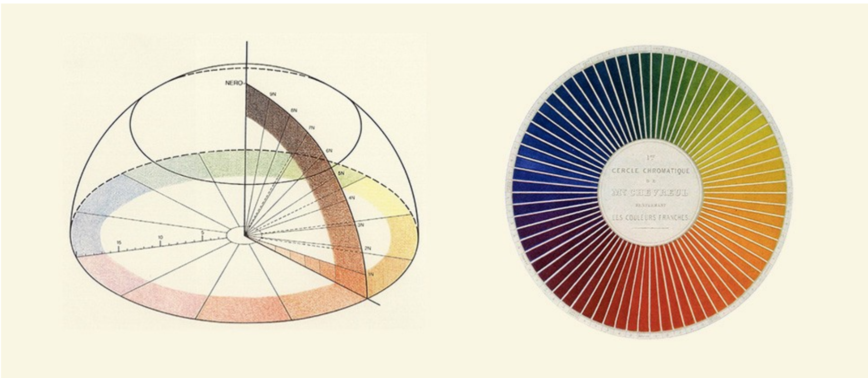
Otto Runge Spheres

Runge's sphere had white and black poles with colored bands running between them. However, like many other representations of color before it, the model **did not differentiate between brightness and saturation**

This sphere had the same problem as Mayer's triangle, as the **steps were not perceptually uniform**



Michel Eugène Chevreul attempted to fix this problem in his hemispherical color system: Inspired by the work of Goethe, Chevreul used after-images to test the validity of his mixtures. When a person stares at a green square for a long time and then looks at a white wall, a magenta square will appear. This happens because of fatigue in the green photoreceptors in the eye, and Chevreul used this to establish the complementary colors in his model.



One of the most historically significant color solids was created by the American painter **Albert Henry Munsell in the early 1900's.** Munsell's color system is that he divided the color space into three new dimensions: The hue determined the type of color (red, blue, etc), the value determined the brightness of the color (light or dark), and the chroma determined the saturation of the color (the purity of the color).

Munsell first tried to arrange his colors in a sphere. **Essentially, Munsell realized that his color solid had to have an irregular shape to fit his colors**. The explanation for this is rather simple. Colors with low brightness have much fewer visible colors between zero and full saturation (colors with zero brightness only have one, black). Likewise, some hues have more range than others.

Color models

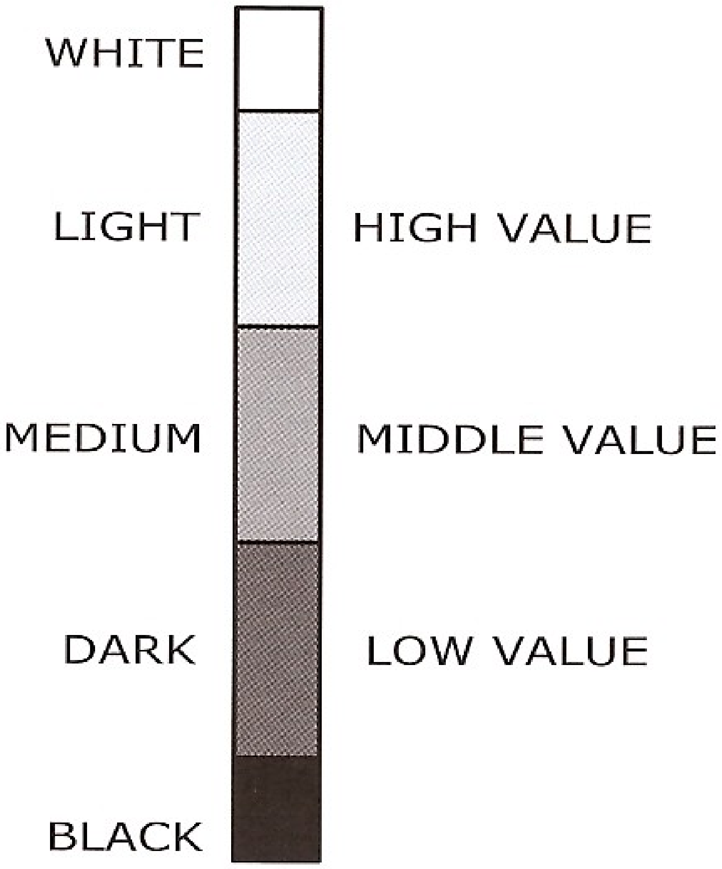
A color model is a visualization that depicts the color spectrum as a multidimensional model. Most modern color models have 3 dimensions (like RGB), and can therefore be depicted as 3D shapes, while other models have more dimensions (like CMYK).

RGB is a color model with three dimensions—red, green, and blue—that are mixed to produce a specific color. When defining colors in these dimensions, one has to know the sequence of colors in the color spectrum, e.g. that a mix of 100% red and green produces yellow. The RGB color model is often depicted as a cube by mapping the red, green, and blue dimensions onto the x, y, and z axis in 3D space.

Hue Saturation Value(HSV)

HSV is a cylindrical color model that remaps the RGB primary colors into dimensions that are easier for humans to understand.

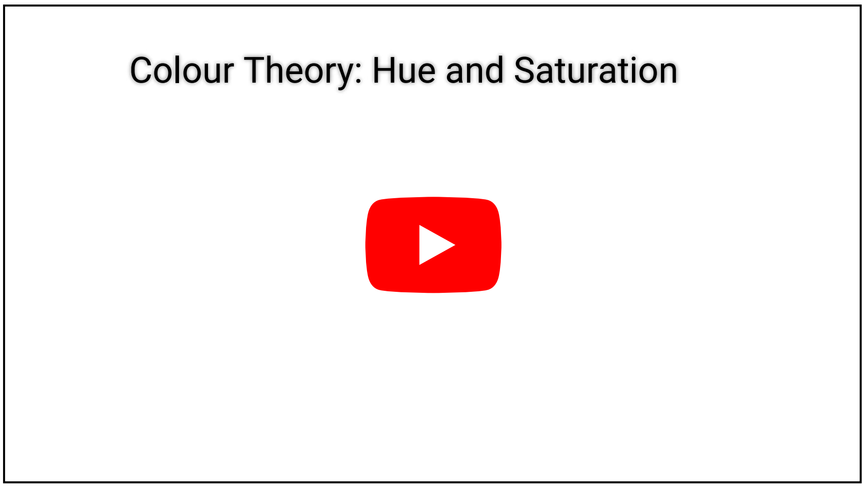
- *Hue* specifies the angle of the color on the RGB color circle. A 0° hue results in red, 120° results in green, and 240° results in blue.
- *Saturation* controls the amount of color used. A color with 100% saturation will be the purest color possible, while 0% saturation yields grayscale.
- *Value* controls the brightness of the color. A color with 0% brightness is pure black while a color with 100% brightness has no black mixed into the color.



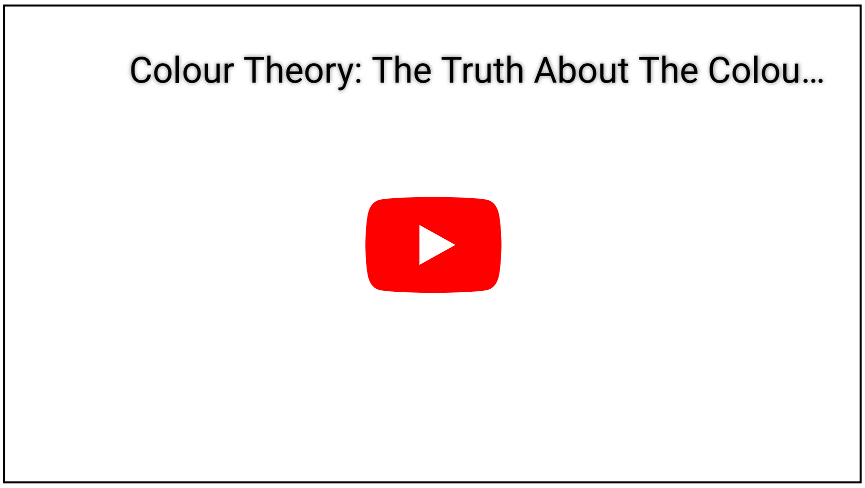
5 step value scale(https://maggiemaggio.com/)

Value is defined as the amount of light reflected by a color. If a color reflects more light than it absorbs it has a high value. If it absorbs more than it reflects, it has a low value. In the book we recommend sorting colors into just five values—colors close to white, high value/light colors, middle value/medium colors, low value/dark colors, and colors close to black.

To desaturate a hue, we add a complementary color(we are graying out the original hue)



Colour Theory: The Truth About The Colour Wheel



HSL

HSL is another cylindrical color model that shares two dimensions with HSV, while replacing the value dimension with a lightness dimension.

- *Hue* specifies the angle of the color on the RGB color circle, exactly like HSV.
- *Saturation* controls the purity of the color, exactly like HSV.
- *Lightness* controls the luminosity of the color. This dimension is different from the HSV value dimension in that the purest color is positioned midway between black and white ends of the scale.

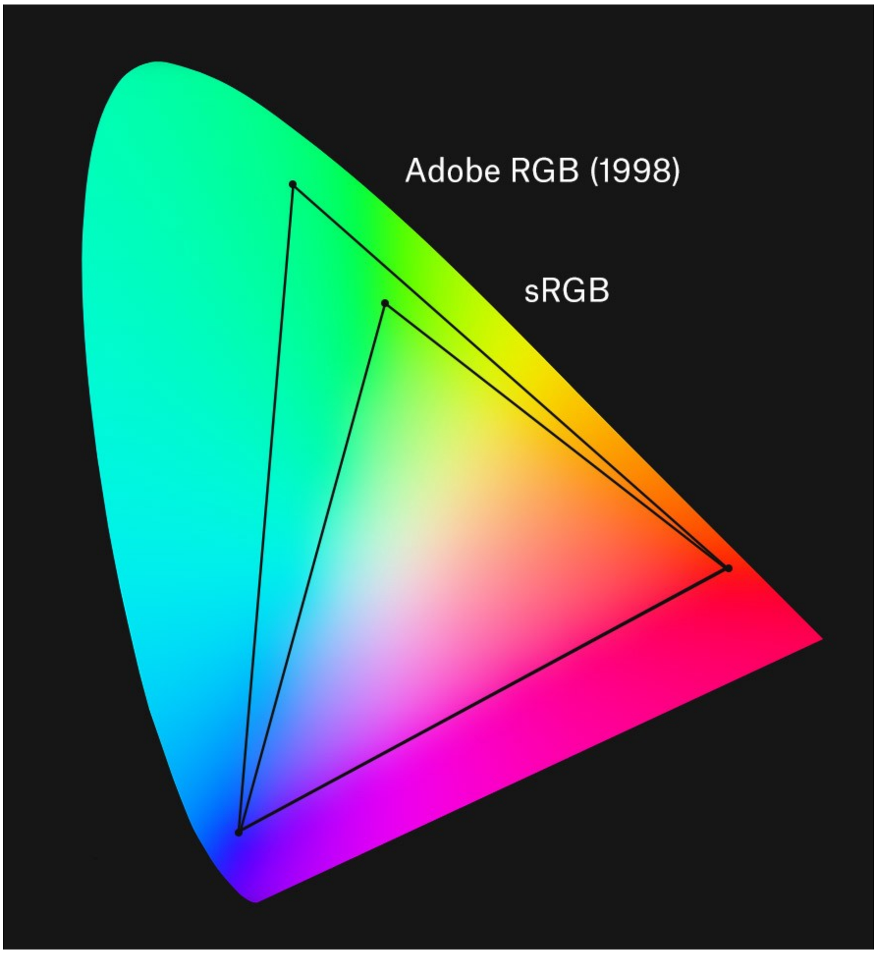
> A color with 0% lightness is black, 50% is the purest color possible, and 100% is white.

Even though the saturation dimension theoretically is similar between the two color models (controlling how much pure color is used), the resulting saturation scales differ between the models caused by the brightness to lightness remapping

Color spaces

Color models provide for a good way to visualize the color spectrum, but they are inadequate when it comes to defining and displaying colors on computer screens. To explain this, let us assume that you own a laptop computer as well as a larger, external screen for your home office.

Example: Now, let us also assume that you are running a P5.js sketch showing a yellow ellipse on both screens. In a world without color spaces, these two screens would turn on their red and green subpixels and be done with it. **However, what if your larger screen has more expensive lights that look wildly different from the ones on your laptop screen? This would result in two very different kinds of yellow. This is the problem that color spaces set out to solve.** (https://programmingdesignsystems.com/color/color-models-and-color-spaces/index.html)



The CIE chromaticity diagram showing the color gamuts of the Adobe RGB (1998) and sRGB color spaces.

The **corners** of each **triangle** define the primary colors of each **color gamut**(the subset of colors which can be accurately represented in a given circumstance, such as within a given color space or by a certain output device.) The sRGB color space has the smallest color gamut of the two color spaces, which means that it covers the smallest range of colors.

The **sRGB color space** has the smallest color gamut of the two color spaces, which means that it covers the smallest range of colors. It was created for use by computer monitors, and the smaller gamut reflects the exact colors of the primary lights in most HDTVs and computer monitors.

The **Adobe RGB (1998) color space** has a much wider RGB color gamut that was carefully chosen to cover most of the colors that CMYK printers can produce.

The two color spaces **share** the same **red** and **blue primaries**, the green primary color is different between the two. To put it another way, **a primary color only has absolute meaning when it refers to a specific color space.**

In our example from above, color spaces allow your two computer monitors to show an identical yellow color by following a standard process: First, it converts the yellow color from the color space of the P5 sketch to the **CIEXYZ color space (also called a reference color space)**. Then, because every monitor knows the exact color of their primary lights in relation to the CIEXYZ color space, it can determine the amount of primary lights to mix.

Color Gamut

In color reproduction, the **gamut**, or **color gamut** is a certain ***complete subset*** of colors.

The term *gamut* was adopted from the field of music, where in middle age Latin "gamut" meant the entire range of musical notes of which musical melodies are composed; Shakespeare's use of the term in *The Taming of the Shrew* is sometimes attributed to the author/musician Thomas Morley.

In color theory, the **gamut of a device** or process is that **portion of the color space** that can be represented, or **reproduced**.

Generally, the color gamut is specified in the **hue–saturation plane.**

Printing the image requires **transforming** the image from the **original RGB color space to the printer's CMYK color space**. During this process, the colors from the **RGB** which are out of gamut must be **somehow converted** to approximate values within the **CMYK space gamut**.

Color Solid

A **color solid** is the three-dimensional representation of a color model, an analog of the two-dimensional color wheel.

Pure, saturated hues of equal brightness are located around the equator at the periphery of the color sphere. Moving toward the center of the color sphere on the equatorial plane, colors become less and less saturated, until all colors meet at the central axis as a neutral gray. Moving vertically in the color sphere, colors become lighter (toward the top) and darker (toward the bottom). At the upper pole, all hues meet in white; at the bottom pole, all hues meet in black.

Color Science Python library: https://github.com/colour-science/colour

Optimal Colors

Optimal colors—they are the **most saturated** (chromatic) colors possible for a **given luminance**. The concept of **optimal color** applies only to surfaces that are seen by reflected light, or to colors produced by filters (transmissive light). **Fluorescent colors are specifically excluded**; as, presumably, are **glossy colors** that can be specular reflectors. As a corollary, **it is entirely possible for lights to produce colors that are more saturated than any optimal surface color**: for example, any reasonably bright monochromatic light source.

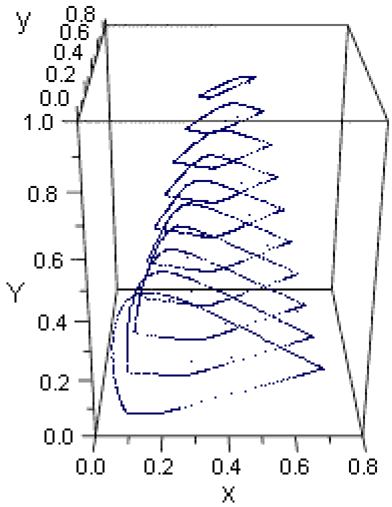
A good paper on optimal colors:
https://philservice.typepad.com/Pointer_MacAdam_Wide-Gamut_Displays_v2.pdf

Pointer's Gamut

In 1980, **Michael Pointer** published the results of a colorimetric analysis of over **4,000 natural and man-made surface colors** (Pointer 1980). Whereas the MacAdam limits set a theoretical maximum, Pointer's data is an attempt to establish the empirical limits of color saturation

- *the **Standard Object Colour Spectra database** for **color reproduction** evaluation (**SOCS**) has been developed as an **ISO standard.** It includes spectral information on more than 50,000 colors. The SOCS gamut does not differ greatly from Pointer's gamut.

Displays that can **reproduce** all, or almost all, of the **AdobeRGB color space** are generally referred to as **wide-gamut displays.**



Optimal Color Solid

Zonohedral Color Solid Paper

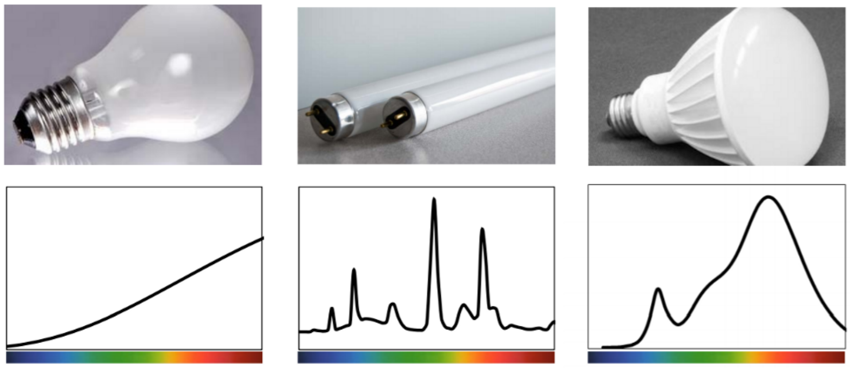
"https://www.munsellcoloursciencefor painters.com/ColourSciencePapers/AZonohedralApproachToOptimalColours.pdf"

Colour depends both on light sources, and the colour properties of any materials that reflect the light sources.

Local colour is an object's colour, **considered independently of any light source**. A local colour is determined entirely by the object's reflectance function. Only **local colours**, and not light sources, **can be optimal.**

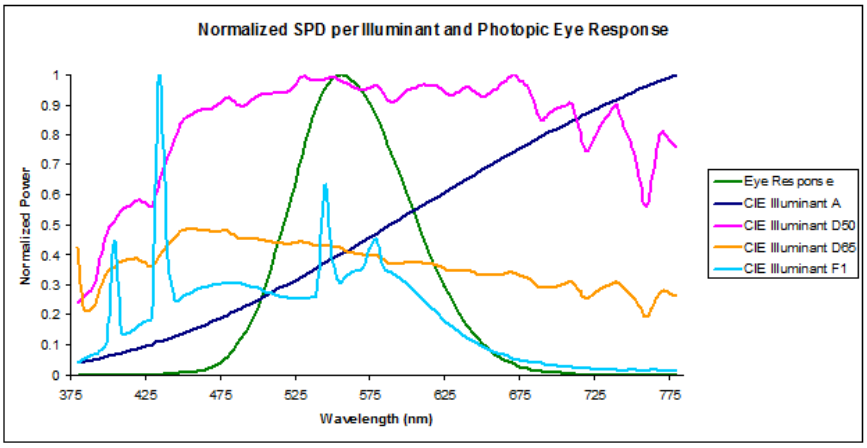
Reflectance function [r(λ)], where λ is a wavelength varying over the visible spectrum, from about 400 to 700 nm. r(λ) is the percentage of light the object would reflect if were illuminated solely with light of wavelength λ. r(λ) takes on a value between 0 and 1 (which equals 100%).

Spectral power distribution: In radiometry, photometry, and color science, a **spectral power distribution** (**SPD**) measurement describes the **power per unit area per unit wavelength of an illumination** (radiant exitance).



https://www.energy.gov/sites/prod/files/2016/11/f34/royer_spectral-power-dist_denver2016.pdf

- *Newton was famously aware that 'the rays are not coloured'. By this phrase Newton meant that light is not intrinsically coloured; short-wave light, for example, has no intrinsic property by which it is blue but, rather, it may induce in us the sensation of blueness. Under some circumstances, however, short-wave light may appear black or some colour other than blue. It is therefore clear that colour cannot be understood without a study of the properties of the human visual system, since colour exists only in the brain.**

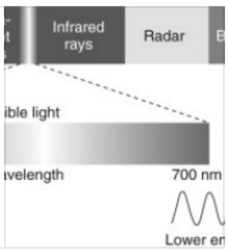


CIE standard illuminant spectral power distribution comparisons referenced to the human visual system photopic response

Spectral Power Distribution

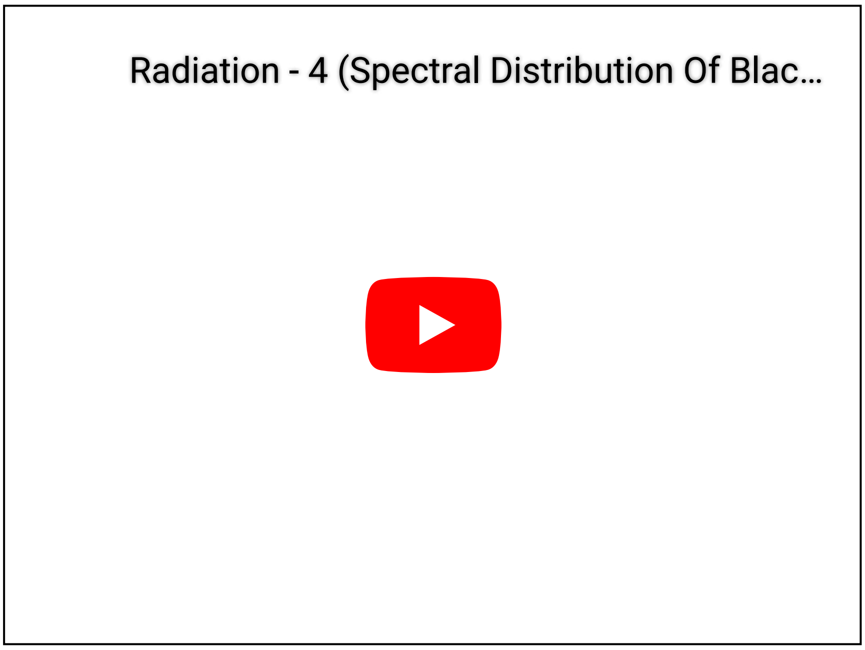
The Sun, our singular source of renewable energy, sits at the centre of the solar system and emits ...

www.sciencedirect.com



According to the definition of the Illuminating Engineering Society of North America (IESNA), **SPD is "a pictorial representation of the radiant power emitted by a light source at each wavelength or band of wavelengths in the visible region of the electromagnetic spectrum."**

Spectral Distribution of **black body radiation:**



Black bodies: Emit EM radiations of all wavelengths

Tints and Shades: https://en.wikipedia.org/wiki/Tints_and_shades

Color profiles

A digital image can adhere to a specific color space by embedding a color profile in its metadata. This tells any program that wants to read the image that the pixel values are stated according to a particular color space, and images without a color profile are often assumed to be sRGB.

If a digital image uses a color profile with a wide color gamut, it is almost guaranteed to lose colors on most screens because most screens can only show colors within the sRGB gamut. However, many newer screens support wider color gamuts.

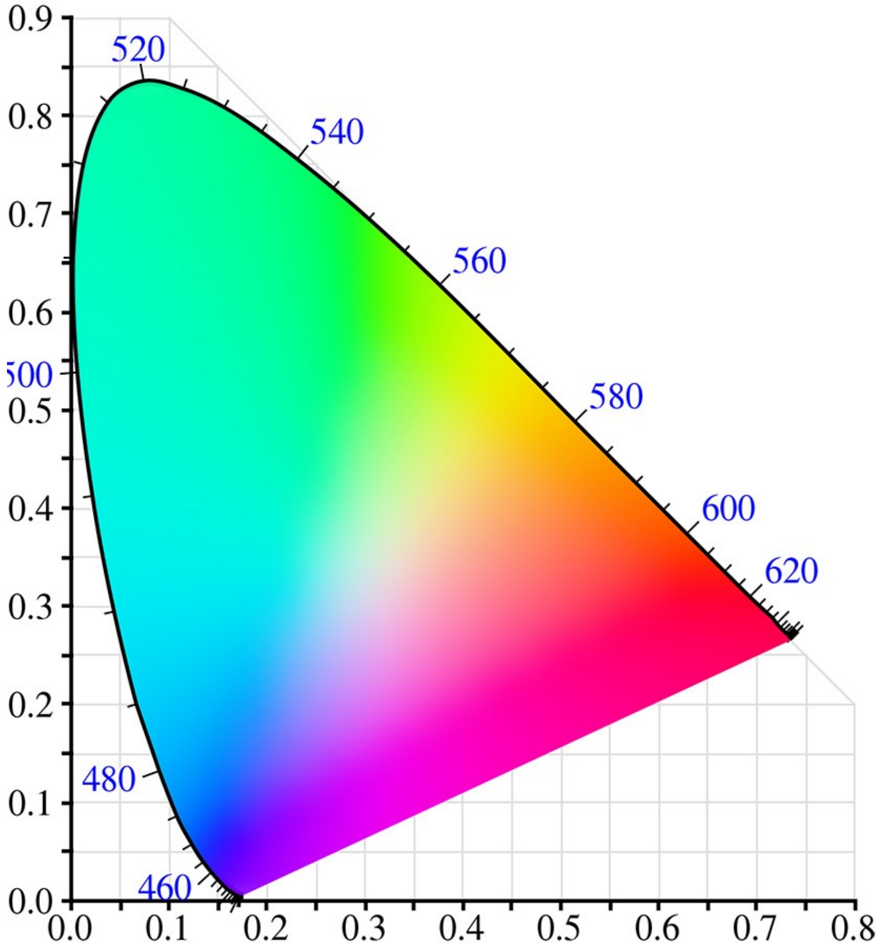
Perceptually uniform color spaces(nice read):

https://programmingdesignsystems.com/color/perceptually-uniform-color-spaces/index.html

A **perceptual uniform color space** ensures that the difference between two colors (as perceived by the human eye) is proportional to the Euclidian distance within the given color space. *Lab* was created to satisfy the perceptual uniformity property.

However, this property is **satisfied only locally**. For distant colors, the perceived difference is no more in accordance with the Euclidian distance. Therefore, new distances were defined, such as **deltaE, CIE76, CIE94, CIE2000** in order to satisfy both local and global perceptual uniformity.

{Stackoverflow}



The CIE chromaticity diagram showing wavelength of major colors in the color spectrum.

The International Commission on Illumination (CIE) created the above chromaticity diagram in the 1930's to solve this problem. This diagram is actually a 2D view of a color space called CIEXYZ, which in the 1970's was replaced with the slightly improved **CIELUV and CIELAB color spaces.**

CIELUV color space has two dimensions—***u* and *v***—that represent color scales from red to green and yellow to blue. To create a color in the CIELUV color space, one has to define the **lightness of the color** (*l*), whether it is **reddish or greenish** (***u***), and whether it is **yellowish or bluish** (*v*).

[**CIELUV wiki**

]

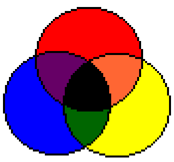
Even though these color spaces are based on human perception, they are not intuitive when working in code. Like a RGB color space, it can be hard to guess which LUV numbers are required to create e.g. a dark purple or bright cyan.

Additive color: color created by light; primaries(RGB)

Subtractive color: ink/paint; primaries(cyan, magenta, yellow),secondaries(RGB)

THE STORY OF PRIMARIES

Source: https://midimagic.sgc-hosting.com/pricol.htm



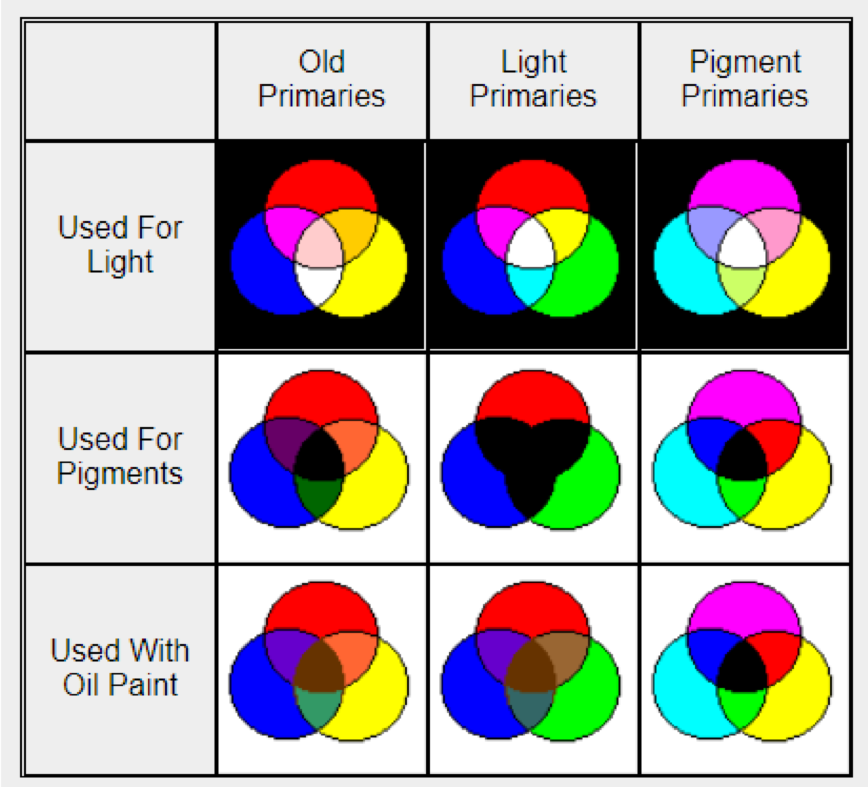
Old PRIMARY COLORS(RED, BLUE, YELLOW)

REASONS THE WRONG PRIMARIES ARE STILL TAUGHT:

1. **Tradition** dies hard.
2. Art schools are still teaching the wrong primaries.
3. Education schools are still teaching the wrong primaries.
4. Until the **1960s**, permanent colors in the **correct primaries** were available only as **toxic compounds**.
5. **The wrong primaries do work, but cannot produce many bright colors. The gamut of colors produced is much smaller.**
6. Notice that two of the primaries are darker colors, and the third is the lightest color. It makes no sense
7. These primaries work better for oil colors than for other color media, because:

- The blue usually used turns to cyan at low concentrations.
- The red usually used turns to magenta at low concentrations.
- Opaque pigments mix using light primaries, but with darker results.

WHAT HAPPENS IF WRONG PRIMARY COLORS ARE USED?



1. If the wrong primaries are used, the wrong colors appear.
2. Using the wrong primaries gives a **smaller gamut** of colors.
3. Colors are pastel with the wrong light primaries.
4. Colors are dark with the wrong pigment primaries.
5. Wrong primaries must be desaturated to get more colors.
6. **Light primaries are complements of pigment primaries.**
7. **Light primaries are pigment secondaries.**
8. **Pigment primaries are light secondaries.**
9. Oil paints partly mix like light and partly mix like pigment.
10. Even oil paints work better with the pigment primaries.

WHY THE CORRECT PRIMARIES MUST BE TAUGHT:

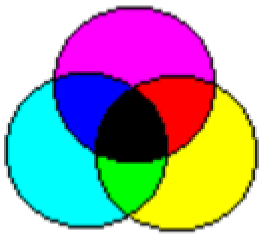
1. There are actually two sets of **primaries: light, and pigment.**
2. Color photography requires knowledge of both sets of correct primaries.
3. Full color printing requires the pigment primaries.

4. **Color TV uses the light primaries.**
5. **Anyone creating colors on a computer screen needs to know the light primaries.**
6. **Anyone printing colors on a color printer needs to know the pigment primaries.**
7. Inks, dyes, and watercolors definitely do not work using the old primaries.
8. Any medium except oil paint will fail using the old primaries.
9. Oil paint uses both types of mixing. The correct pigment primaries also work with oil paint.
10. With any color medium except oil, the old primaries work only through leakage of imperfect pigments.

WHAT ARE THE CORRECT NAMES OF COLORS?

1. "Blue" covers too many colors:
   - Cyan, the color of robin eggs and peacock feather spots, is Isaac Newton's original blue. Call this cyan.
   - Teal, turquoise, robin egg blue, and peacock blue are other names for cyan.
   - Newton's indigo, the color of most blue ballpoint pens, is the scientists' blue. Call this blue
   - Today's indigo has a lot more violet than Newton's indigo.
   - Navy is a dark version of Newton's indigo.
   - Royal blue,
   - azure blue,
   - true blue,
   - cerulean blue, and
   - sky blue are in between.
2. "Red" covers too many colors:
   - Magenta is not in the spectrum. It is the color of redbud trees in spring. Call this magenta.
   - Fuchsia is another name for magenta.
   - Scarlet is Newton's red. It is the color of the ripest red tomatoes. Call this red.
   - Cardinal red is another name for scarlet
   - Scarlet is the scientist's red.
   - Pink is desaturated red. Call this pink.
   - Cerise and
   - carmine are in between.
   - Vermillion is oranger than scarlet.
3. Today, Newton would say the spectrum contains:
   - red,
   - orange,
   - yellow,
   - green,
   - cyan,
   - blue, and
   - violet.

WHAT ARE THE CORRECT PIGMENT PRIMARY COLORS?



CYAN, MAGENTA, YELLOW

1. The correct pigment primaries are:
   - Magenta (fuchsia), which is the correct pigment primary "red,"
   - Yellow, which is the color of daffodils, and
   - Cyan (teal), which is the correct pigment primary "blue." It was "blue" to Newton.

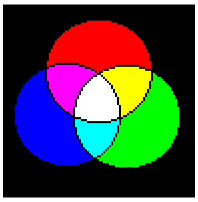
2. The secondary colors of pigment are the light primaries

3. Full color printing is done with these primaries. Ink jet color printers use these primaries.

4. The three pigment primaries are the three lightest pure hues.

7. Pigments remove colors from the light falling on them:
   - White pigment reflects all colors, appearing white.
   - Magenta pigment absorbs yellow, green, and cyan light. Removing those colors from white leaves red, blue, and violet, making magenta light.
   - Yellow pigment absorbs cyan, blue, and violet light. Removing those colors from white leaves red, yellow, and green, making yellow light.
   - Cyan pigment absorbs red and yellow, and some of the violet light. Removing those colors from white leaves green, cyan, and blue, making cyan light.
8. Mixtures of primary pigments remove the colors removed by each pigment:
   - Mixing magenta and yellow pigments removes all colors except red, leaving red light.
   - Mixing yellow and cyan pigments removes all colors except green, leaving green light.
   - Mixing magenta and cyan pigments removes all colors except blue, leaving blue light.
   - Mixing magenta, yellow, and cyan pigments removes all colors, leaving no light. It appears black.
9. Pigments can be diluted, allowing some light to leak through:
   - Mixing diluted magenta and full-strength yellow pigments makes orange.
   - Mixing diluted magenta and diluted yellow pigments makes pink.
   - Mixing full-strength magenta and yellow pigments with diluted cyan pigment makes brown.
   - Mixing equally diluted magenta, yellow, and cyan pigments makes gray.
   - Mixing full-strength magenta and diluted cyan pigments makes violet.

WHAT ARE THE LIGHT PRIMARY COLORS?



1. The light primaries are:
   - Red, which is scarlet.
   - Green, which is the color of most leaves, and
   - Blue, which is Newton's indigo.

2. White can be simulated by mixing equal amounts of the three primaries.

3. Reflective glitter mixes like light mixes.

4. These colors are used in color television. Look at a color TV screen with a magnifier to see dots or stripes of light primaries.

5. The three light primaries are the three darkest pure hues.

(comprehensive reading: https://midimagic.sgc-hosting.com/pricol.htm)

PSYCHOLOGICAL PRIMARIES

The opponent process was proposed by Ewald Hering in which he described the four “simple” or “primary” colors (*einfache* or *grundfarben*) as red, green, yellow, blue.

Furthermore, these colors were organized in **“opponent” pairs**, red vs. green and yellow vs. blue so that mixing could occur across pairs (e.g., a yellowish green or a yellowish red) but not within a pair (i.e., greenish red cannot be imagined).

The psychological primaries were applied by Richard S. Hunter as the primaries for **Hunter L,a,b colorspace** that led to the creation of **CIELAB**.

The **Natural Color System** (NCS) is a proprietary perceptual color model. It is based on the color opponency hypothesis of color vision, first proposed by German physiologist Ewald Hering

WHAT ARE THE PSYCHOLOGICAL PRIMARY COLORS?

1. The psychological primaries are:
   1. - cerise
   2. - yellow
   3. - aqua
   4. - blue
2. These primaries are generated by the yellow-blue and red-green bipolar cell encodings in the retina.
   1. Cerise has a neutral yellow-blue output signal, and a maximal red output of the red-green signal.
   2. Yellow has a neutral red-green output signal, and a maximal yellow output of the yellow-blue signal.
   3. Aqua has a neutral yellow-blue output signal, and a maximal green output of the red-green signal.
   4. Blue has a neutral red-green output signal, and a maximal blue output of the yellow-blue signal.
3. These primaries can not be used for color mixing.
4. Two of the four colors are found in a Crayola™ box of 8 crayons, although that information is not useful for mixing colors.
5. The color wheel is the same one used for the correct pigment primaries and the light primaries.
6. The psychological primaries are 90 degrees apart on the new color wheel. Start at yellow.

HUMAN COLOR VISION

The visible spectrum is the portion of the electromagnetic spectrum with wavelengths between **380 nm and 760 nm.**

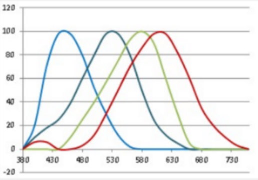
400 nm (or 750 THz) - violet
460 nm (or 650 THz) - blue
490 nm (or 610 THz) - cyan
520 nm (or 580 THz) - green
570 nm (or 530 THz) - yellow
590 nm (or 510 THz) - orange
670 nm (or 450 THz) - red

Cones = **Color vision,** Rods = night vision

Rods are not good for color vision. In a dim room, however, we use mainly our rods, but we are "color blind." Rods are more numerous than cones in the periphery of the retina.

Four kinds of sensors:

Use the chart of light sensitivity curves at right.



- **Rods**

  Rods are primarily used at night, because they are much more sensitive than the cones. But they also provide motion and edge detection in brighter light. The rhodopsin (visual purple) in the rods is sensitive to a range of wavelengths between 380 nm and 590 nm, peaking at 510 nm. This covers the colors violet, blue, cyan, green, yellow, and orange. But rods are encoded as white, not as any specific color, because they serve for night vision.

- **Blue-Sensitive Cones**

  The cyanopsin in the blue-sensitive cones is sensitive to a range of wavelengths between 380 nm and 550 nm, peaking at 450 nm. This includes violet, blue, and cyan light.

- **Green-Sensitive Cones**

  The chloropsin in the green-sensitive cones is sensitive to a range of wavelengths between 430 nm and 670 nm, peaking at 550 nm. This includes cyan, green, yellow, and orange light.

- **Red-Sensitive Cones**

  The erythropsin in the red-sensitive cones is sensitive to two ranges of wavelengths. The major range is between 500 nm and 760 nm, peaking at 600 nm. This includes green, yellow, orange, and red light. The minor range is between 380 nm and 450 nm, peaking at 420 nm. This includes violet and some blue. The minor range is what makes the hues appear to form a circle instead of a straight line.

Seeing other colors:

- Violet activates the blue cone, and partially activates the red cone.
- Blue activates the blue cone.
- Cyan activates the blue cone and the green cone.
- Green activates the green cone, and slightly activates the red and blue cones.
- Yellow activates the green cone and the red cone.
- Orange activates the red cone, and slightly activates the green cone.
- Red activates the red cone.
- Magenta activates the red cone and the blue cone.
- White activates the red cone, the green cone, and the blue cone.

Colors not listed here are seen due to varying strengths of light activating the red, green, and blue cones. A few examples follow:

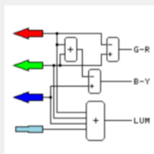
- Black does not activate any of the cones.
- Brown partially activates the red cone, and the green cone a little less.
- Brick Red partially activates red cone.
- Pink activates the red cone, and partially activates the green and blue cones.
- Flesh fully activates red, activates green a little less, and blue a little less than that.
- Amber activates the red cone, and green a little less.
- Ochre partially activates the red cone, and green a little less.
- Olive partially activates the green cone, and red a little less.
- Gray partially activates the red cone, the green cone, and the blue cone.

What happens at night - Rod vision:

- Violet activates the rods partially
- Blue activates the rods almost fully.
- Cyan activates the rods fully.
- Green activates the rods fully.
- Yellow activates the rods almost fully.
- Orange activates the rods partially.
- Red does not activate the rods.
- Magenta activates the rods partially.
- White activates the rods fully.

After the cones have received the colors, the color information is encoded in the bipolar and ganglion cells in the retina before it is passed on to the brain. Three different encodings are used:

1. The primary encoding is luminance (brightness). It is the sum of the signals coming from the red cones, the green cones, the blue cones, and the rods. These provide the fine detail of the image in black and white.
2. A second form of encoding is used to separate blue and yellow (yellow being the sum of red and green). The signal changes one way if blue is stronger than yellow, and changes in the opposite way if yellow is stronger than blue. This is **blue-yellow**.
3. The third form of encoding is used to separate red and green. The signal changes one way if green is stronger than red, and changes the other way if red is stronger than green. This is **green-red**.



The outputs of the eye's color encoding matrix are shown to the right:

- The blue-yellow axis is horizontal.
- The green-red axis is vertical.

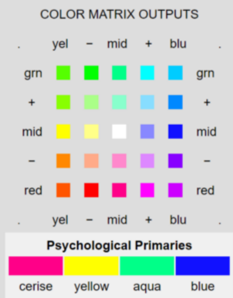
The second and third kind of encoding do not have quite the fine resolution the luminance encoding has. Black and white vision has finer detail than color vision.

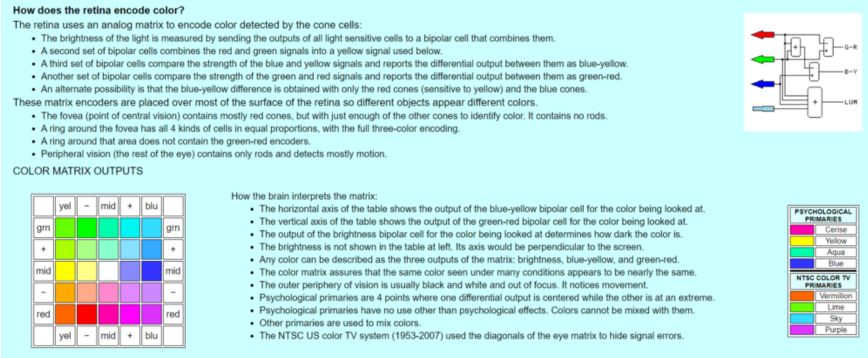
In the fovea, where central vision occurs, each luminance ganglion cell receives signal from only one cone cell of each color. There are no rod cells in the fovea, so it is night blind.

It is interesting that in the very center of the fovea, there are also no blue-sensitive cells and few green-sensitive cells. This area gets its color information from cells surrounding it.

An averaging mechanism is used in the brain. It creates a norm for an area around the item being looked at. Three norms are created, one for light intensity, one for blue-yellow difference, and one for red-green difference. The colors of objects are compared to the norms, cancelling the color of the light out of the color of the item where possible (see below).

This color matrix is responsible for the psychological primaries (see below). They are found at the ends of the center column and the center row (at right).





How does the retina encode color?

The retina uses an analog matrix to encode color detected by the cone cells:

- The brightness of the light is measured by sending the outputs of all light sensitive cells to a bipolar cell that combines them.
- A second set of bipolar cells combines the red and green signals into a yellow signal used below.
- A third set of bipolar cells compare the strength of the blue and yellow signals and reports the differential output between them as blue-yellow.
- Another set of bipolar cells compare the strength of the green and red signals and reports the differential output between them as green-red.
- An alternate possibility is that the blue-yellow difference is obtained with only the red cones (sensitive to yellow) and the blue cones.

These matrix encoders are placed over most of the surface of the retina so different objects appear different colors.

- The fovea (point of central vision) contains mostly red cones, but with just enough of the other cones to identify color. It contains no rods.
- A ring around the fovea has all 4 kinds of cells in equal proportions, with the full three-color encoding.
- A ring around that area does not contain the green-red encoders.
- Peripheral vision (the rest of the eye) contains only rods and detects mostly motion.

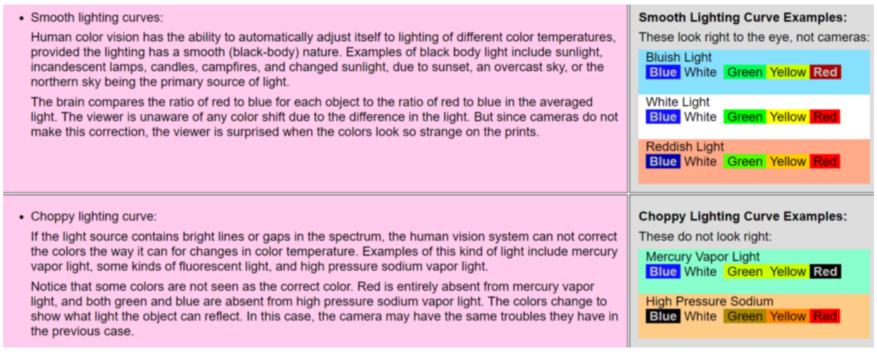
COLOR MATRIX OUTPUTS

	yel	–	mid	+	blu	
grn						grn
+						+
mid						mid
–						–
red						red
	yel	–	mid	+	blu	

How the brain interprets the matrix:

- The horizontal axis of the table shows the output of the blue-yellow bipolar cell for the color being looked at.
- The vertical axis of the table shows the output of the green-red bipolar cell for the color being looked at.
- The output of the brightness bipolar cell for the color being looked at determines how dark the color is.
- The brightness is not shown in the table at left. Its axis would be perpendicular to the screen.
- Any color can be described as the three outputs of the matrix: brightness, blue-yellow, and green-red.
- The color matrix assures that the same color seen under many conditions appears to be nearly the same.
- The outer periphery of vision is usually black and white and out of focus. It notices movement.
- Psychological primaries are 4 points where one differential output is centered while the other is at an extreme.
- Psychological primaries have no use other than psychological effects. Colors cannot be mixed with them.
- Other primaries are used to mix colors.
- The NTSC US color TV system (1953-2007) used the diagonals of the eye matrix to hide signal errors.

HOW HUMAN VISION REACTS TO DIFFERENT LIGHT SOURCES



- Smooth lighting curves:

  Human color vision has the ability to automatically adjust itself to lighting of different color temperatures, provided the lighting has a smooth (black-body) nature. Examples of black body light include sunlight, incandescent lamps, candles, campfires, and changed sunlight, due to sunset, an overcast sky, or the northern sky being the primary source of light.

  The brain compares the ratio of red to blue for each object to the ratio of red to blue in the averaged light. The viewer is unaware of any color shift due to the difference in the light. But since cameras do not make this correction, the viewer is surprised when the colors look so strange on the prints.

Smooth Lighting Curve Examples:

These look right to the eye, not cameras:

Bluish Light
Blue White Green Yellow Red

White Light
Blue White Green Yellow Red

Reddish Light
Blue White Green Yellow Red

- Choppy lighting curve:

  If the light source contains bright lines or gaps in the spectrum, the human vision system can not correct the colors the way it can for changes in color temperature. Examples of this kind of light include mercury vapor light, some kinds of fluorescent light, and high pressure sodium vapor light.

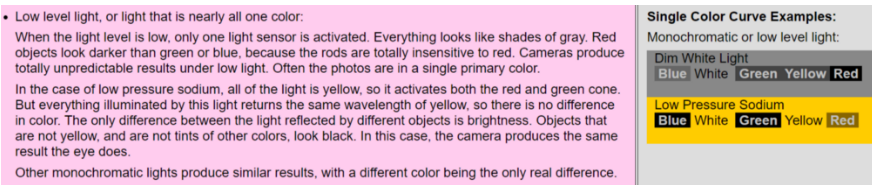
  Notice that some colors are not seen as the correct color. Red is entirely absent from mercury vapor light, and both green and blue are absent from high pressure sodium vapor light. The colors change to show what light the object can reflect. In this case, the camera may have the same troubles they have in the previous case.

Choppy Lighting Curve Examples:

These do not look right:

Mercury Vapor Light
Blue White Green Yellow Red

High Pressure Sodium
Blue White Green Yellow Red



- Low level light, or light that is nearly all one color:

  When the light level is low, only one light sensor is activated. Everything looks like shades of gray. Red objects look darker than green or blue, because the rods are totally insensitive to red. Cameras produce totally unpredictable results under low light. Often the photos are in a single primary color.

  In the case of low pressure sodium, all of the light is yellow, so it activates both the red and green cone. But everything illuminated by this light returns the same wavelength of yellow, so there is no difference in color. The only difference between the light reflected by different objects is brightness. Objects that are not yellow, and are not tints of other colors, look black. In this case, the camera produces the same result the eye does.

  Other monochromatic lights produce similar results, with a different color being the only real difference.

Single Color Curve Examples:

Monochromatic or low level light:

Dim White Light
Blue White Green Yellow Red

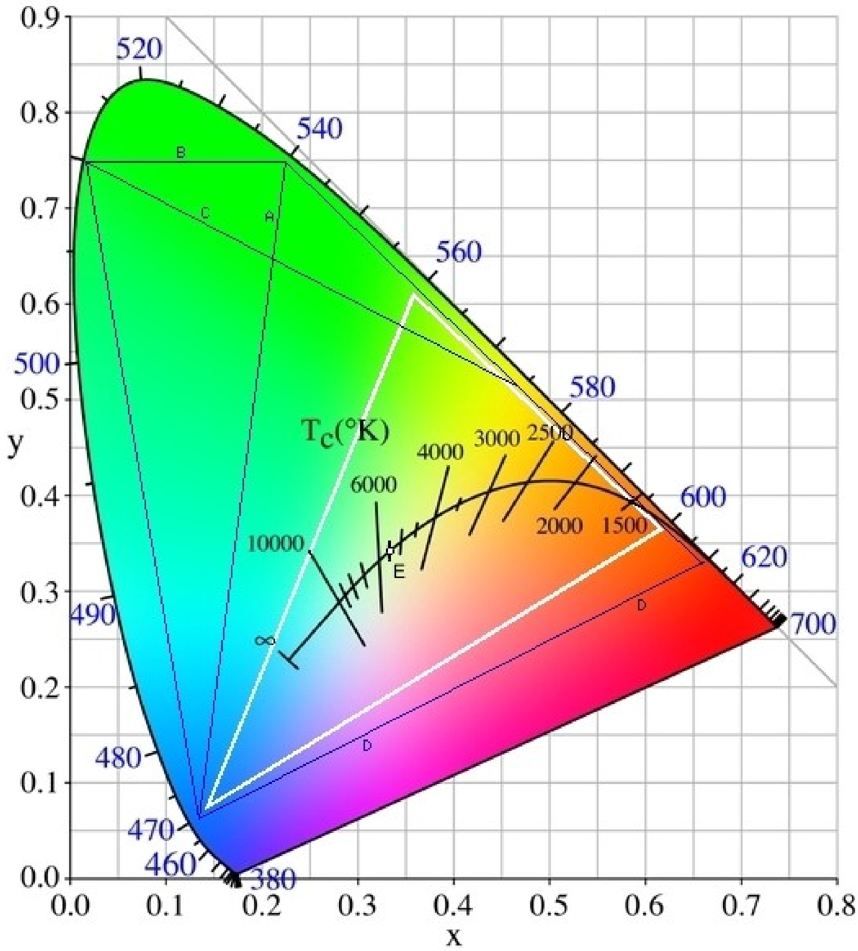
Low Pressure Sodium
Blue White Green Yellow Red

HOW COLOR TELEVISION FOOLS HUMAN COLOR VISION (https://midimagic.sgc-hosting.com/huvision.htm)

Human color vision defects: https://midimagic.sgc-hosting.com/defvison.htm

nonspectral color

A color whose hue is not produced by a single wavelength in the visible spectrum, but is instead produced by mixing the longest (red) and shortest (blue) wavelengths of the spectrum such as any variation of a purple or pink, or by mixing any gray-scale color (such as white, gray and black) with a spectral or nonspectral color (such as purple or pink).



What is the color map?

The color map is a map of the gamut of all possible colors the eye can see.

What are the spaces outside the curve?

These are colors the eye cannot see because they would require stimulating the cone cells individually rather than all at the same time.

What are the numbers around the edge of the map?

They are the wavelengths in nanometers of the colors at those points.

Why are there no wavelength values along the bottom edge?

The colors there are nonspectral colors. They are mixtures of sets of spectral colors, as are all of the colors in the interior of the map.

What are the numbers along the x axis?

The x axis is the portion of the total stimulation received by the eye that is red.

What are the numbers along the y axis?

The y axis is the portion of the total stimulation received by the eye that is green.

Where are the numbers for blue stimulation?

The z axis is perpendicular to the page. On the top surface of the map, the values are $x + y + z = 1$.

What about darker colors?

These are on layers under the map visible here where $x + y + z = t$ and t is a value between 0 and 1. See below.

What is the curved line across the center of the map?

This is the line of colors produced by black body radiation. The numbers are the black body temperatures in Kelvins.

What is the point marked E on the map?

This is the equal energy point where red, green, and blue are equal at 5500 K.
$x = 1/3$, $y = 1/3$, and $z = 1/3$.

What is the triangle containing segments A and D?

This is the gamut of colors displayed on a color TV or monitor. All colors outside this triangle are displayed wrongly on this screen.

What is the white triangle?

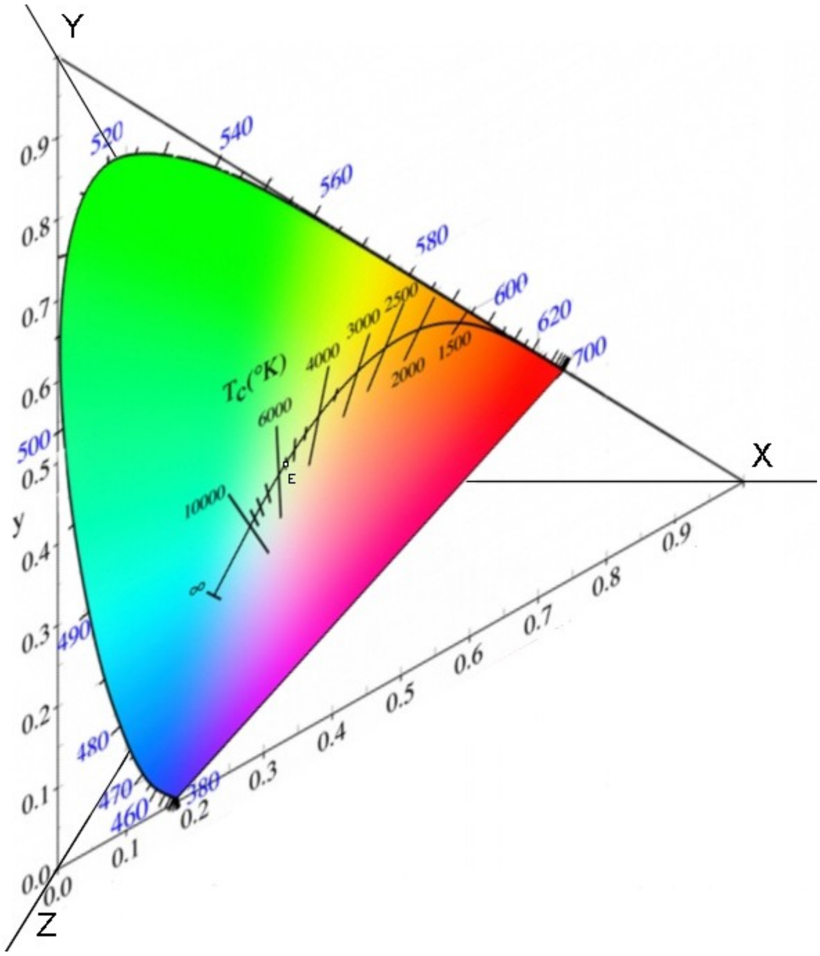
This is the gamut of colors visible under a white LED lamp.

What is the quadrilateral containing segments B and D?

This is the gamut of colors displayed on an Autovary color TV or monitor.

What is the quadrilateral containing segments C and D?

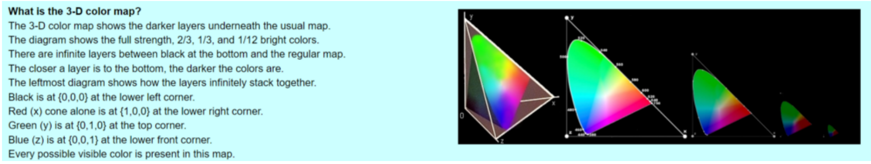
This is the gamut of colors displayed on a Quattron color TV or monitor.



What is the isometric color map?

https://midimagic.sgc-hosting.com/howcolor.htm

3D Color Map



Opponent Process Theory

https://www.verywellmind.com/what-is-the-opponent-process-theory-of-color-vision-2795830#citation-4

The opponent process theory of color vision is one of the theories that helped develop our current understanding of sight. **According to the opponent process theory, our minds can only register the presence of one color of a pair at a time because the two colors oppose one another.** The same kind of cell that activates when you see red will deactivate in green light, and the cells that activate in green light will deactivate when you see red—hence why **you can't see greenish-red.**

The **opponent color process** works through a process of **excitatory** and **inhibitory** responses, with the **two components** of each mechanism **opposing each other**.

For example, red creates a positive (or excitatory) response in a cell, while green creates a negative (or inhibitory) response. When this cell is activated, it tells our brain that we are seeing red. Meanwhile, there is an opponent cell that gets a positive response to green wavelengths of light and an inhibitory response to red. In other words, these two types of cells in a red-green receptor complex can't be activated at the same time.

Negative Afterimage illusion:
https://www.illusionsindex.org/ir/negative-afterimages

An experience of an afterimage is caused by a previously seen stimulus, when that stimulus itself is no longer present. **Negative afterimages** exhibit **inverted lightness levels**, or **colours complementary** to, those of the **stimulus** and are usually brought on by **prolonged viewing of a stimulus.** They are **best seen against** a **brightly lit background.** *They occur (as least in part) because some cells (cones) on the retina do not respond to the present stimulation because they have been desensitised by looking at a previous stimulus.*

The cause of negative afterimages now seems to be as follows: if part of the retina is subjected to pure green light, the M-cones in that area will receive more stimulation than the S- or L-cones. Faced with a subsequent uniform white stimulus (i.e. mixed wavelengths), that part of the retina which has been most desensitized to green wavelengths will produce a stronger output from the S- and L-cones relative to the rest of the retina—hence one will experience negative afterimages, appearing in approximately complementary colours. Thus a red stimulus will produce a green afterimage (and vice versa), a blue stimulus will produce a yellow afterimage (and vice versa) and a black stimulus will produce a white afterimage (and vice versa), and so on.

Positive afterimages are the same colour as the previously seen stimulus. They often occur when there is no stimulation

The **trichromatic theory** explains how the **three types of cones detect different light** wavelengths. The **opponent process theory** explains how the **cones connect to the ganglion cells and how opposing cells are excited or inhibited** by certain wavelengths of light. The **complementary color theory** explains **which wavelengths translate to which colors** and how these colors are processed in the brain

To sum it up:

- **Opponent process theory**: Color vision at the neural level
- **The trichromatic theory**: Color vision at the receptor level

Trichromatic Theory

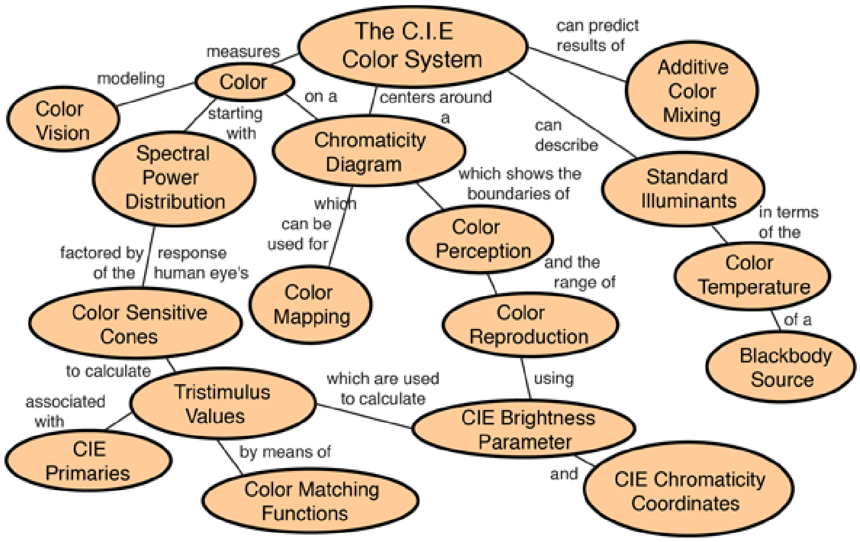
https://www.verywellmind.com/what-is-the-trichromatic-theory-of-color-vision-2795831

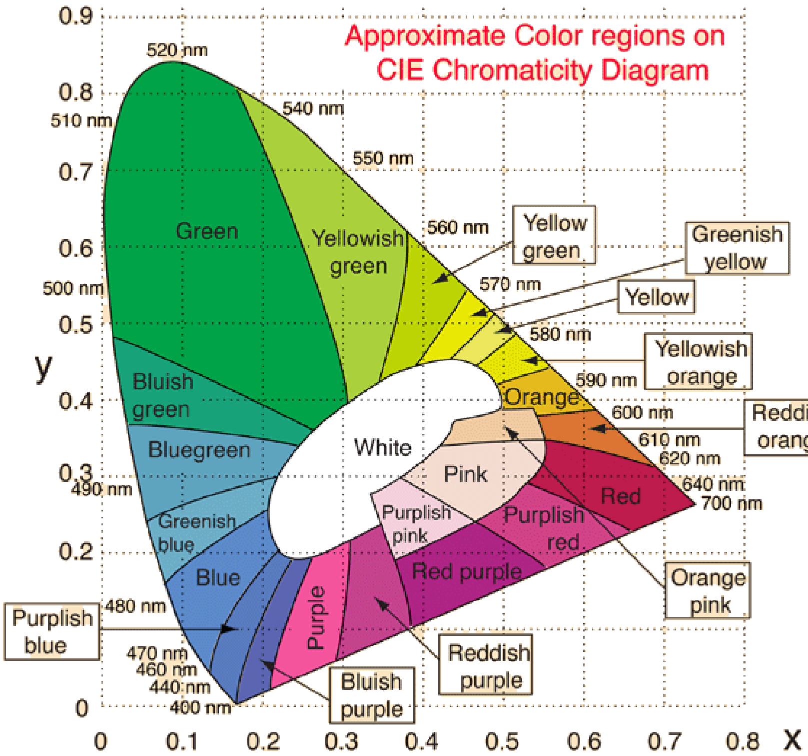
According to the trichromatic theory of color vision, also known as the **Young-Helmholtz** theory of color vision, there are three receptors in the retina that are responsible for the perception of color.

Renowned researchers Thomas Young and Hermann von Helmholtz contributed to the trichromatic theory of color vision. The theory began when Thomas Young proposed that color vision results from the actions of three different receptors. As early as 1802, Young suggested that the eye contained different photoreceptor cells that were sensitive to different wavelengths of light in the visible spectrum.

It was later in the mid-1800s that researcher **Hermann von Helmholtz** expanded upon **Young's original theory and suggested that the cone receptors of the eye were either short-wavelength (blue), medium-wavelength (green), or long-wavelength (red).** He also proposed that it was the strength of the signals detected by the receptor cells that determined how the brain interpreted color in the environment.

CIE Color System





http://hyperphysics.phy-astr.gsu.edu/hbase/vision/cie.html

Approximate colors can be assigned to areas on the CIE Chromaticity Diagram. These are rough categories, and not to be taken as precise statements of color. The boundaries and the color names are adapted from Brand Fortner, “Number by Color”, Part 5, SciTech Journal 6, p32, May/June 1996. ** **you cannot display the range of human color perception on an RGB monitor—the gamut of normal human vision covers the entire CIE diagram while the gamut of an RGB monitor can be displayed as a triangular region within the CIE diagram.**

> The Commission Internationale de l'Echlairage (C.I.E.) Diagram
>
> Even though the visible light reaching the eye has a very complex SPD, color perception is mostly dependent on the signals generated by the three different types of cones. However, we do not know precisely the absorption and sensitivity of the cones and therefore are not in a position to calculate the signal strengths generated by the three different cones. Additionally, the response of the cones is specific to the individual. Therefore, the C.I.E. system is based on the average response of a large sample of normal observers. The C.I.E. system employs three color matching functions $\bar{x}(\lambda), \bar{y}(\lambda)$, $\bar{z}(\lambda)$ Figure 2), based on the psychological observations of a large number of standard observers to calculate the ‘tristimulus values’ X, Y, and Z defined as

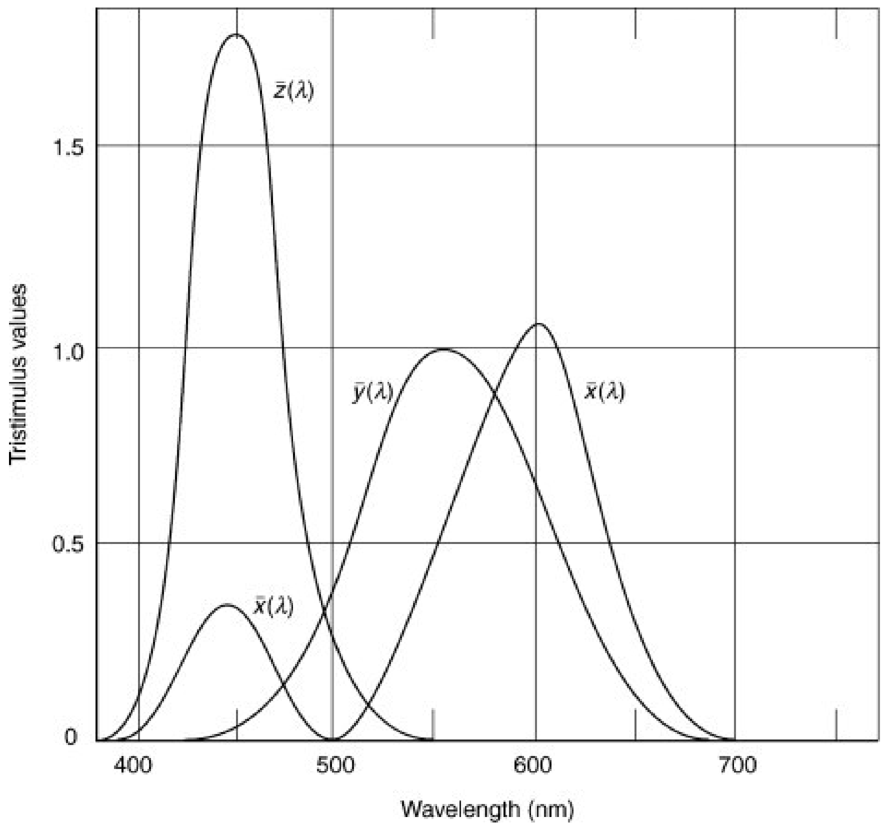


Figure 2. Color-matching functions $\bar{x}(\lambda)$, $^{-}(\lambda)$, and $\bar{z}(\lambda)$ of the C.I.E. 1931 standard observer.

$$X = c \int S(\lambda)\bar{x}(\lambda)d\lambda \quad [1]$$

$$Y = c \int S(\lambda)\bar{y}(\lambda)d\lambda \quad [2]$$

$$Z = c \int S(\lambda)\bar{z}(\lambda)d\lambda \quad [3]$$

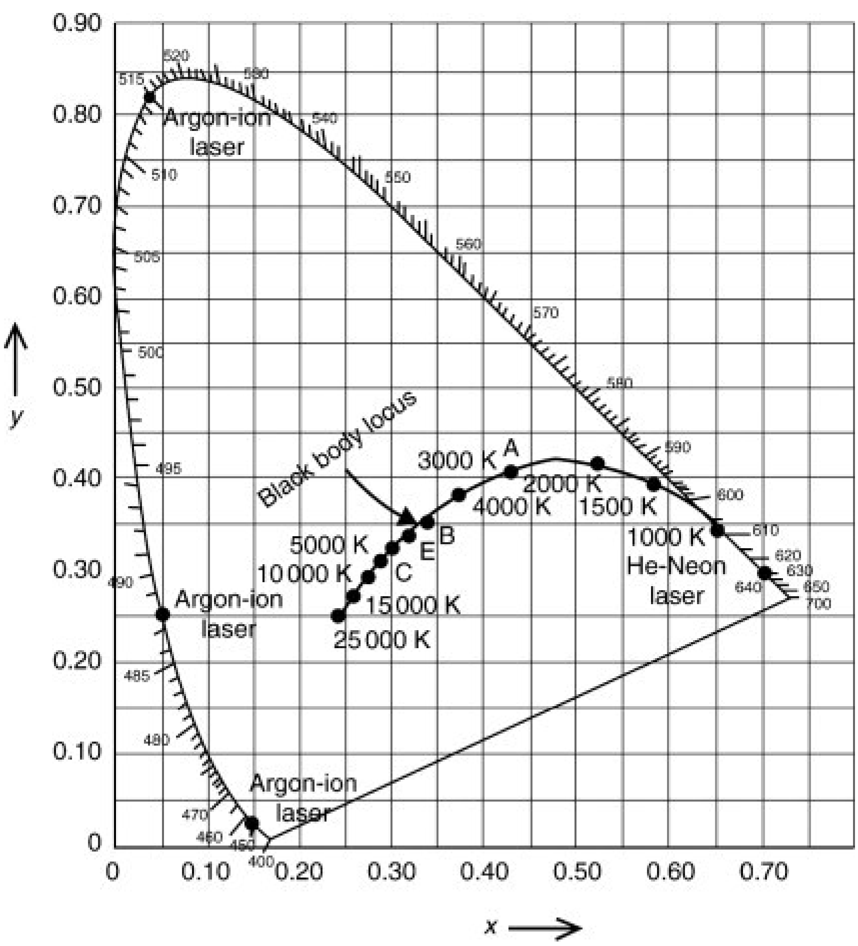
Here, *λ* is the wavelength, $S(\lambda)$ the spectral power distribution, and *c* is the normalization constant. The integration is carried out over the visible region, normally 380 to 780 nm. The system is based on the assumption of additivity and linearity. The sum of the tristimulus values $(X + Y + Z)$ is normalized to 1. We choose $y(\lambda)$ so that the *Y* tristimulus value is proportional to the luminance which is a quantitative measure of the intensity of light leaving the surface. We further calculate *x* and *y* which are called chromaticity coordinates:

$$x = \frac{X}{(X+Y+Z)} \quad [4]$$

$$y = \frac{Y}{(X+Y+Z)} \quad [5]$$

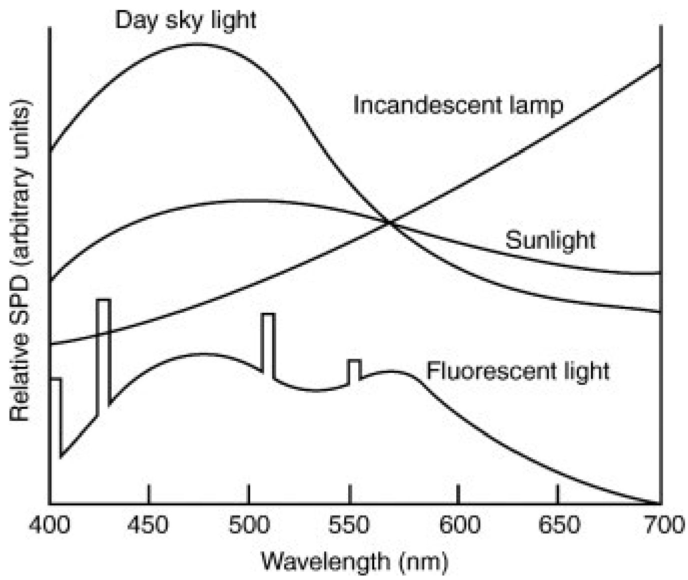
The psychological color is then specified by the coordinates (Y, x, y). Relationship between colors is usually displayed by plotting the *x* and *y* values on a two-dimensional Cartesian Coordinate system with *z* as an implicit parameter $(z = 1 - x - y)$ which is known as the C.I.E. chromaticity diagram (Figure 3). In this plot, the monochromatic hues are on the perimeter of a horseshoe shaped curve and is called spectrum locus. A straight line joining the ends of the spectrum is called the line of purples. Every chromaticity is represented by means of two coordinates (x, y) in the chromaticity diagram. The point corresponding to $x = 1/3$ and $y = 1/3$ (also $z = 1/3$) is the point of 'equal energy' and represents achromatic point.

The complementary colors are on the opposite sides of the achromatic point. Complementary wavelength of a color is obtained by drawing a line from the color through the achromatic point to the perimeter on the other side.



Continuum (white) sources

A perfect white source is the one that has constant SPD over the entire visible region. Such a source will not distort the color of the objects they illuminate. A number of sources in general are considered as white sources; they include incandescent lamps, day skylight, a variety of fluorescent lamps, etc. It should be noted that the SPD of these sources is not constant and varies with the source.



Miscellaneous

How to Convert an RGB Image to Grayscale:
https://e2eml.school/convert_rgb_to_grayscale.html