What is COLOR?

A deeper look at what we see.

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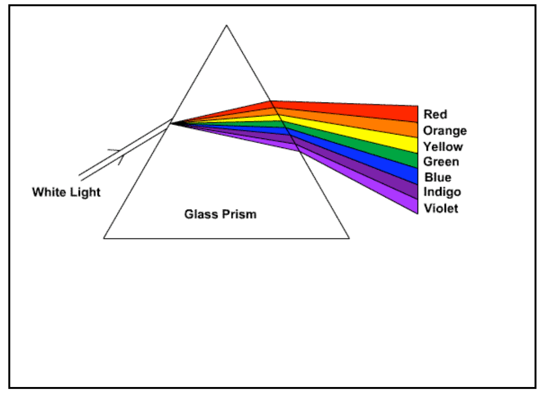
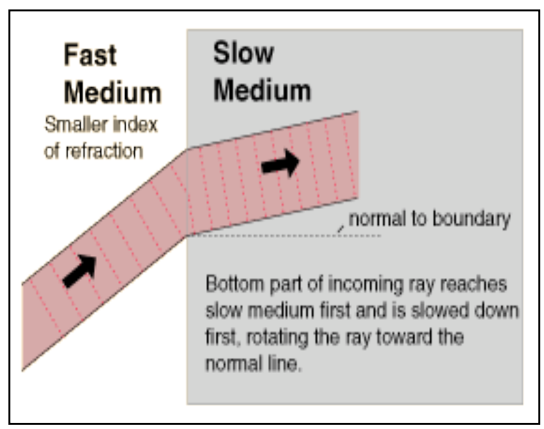
It saturates everything in our view, from the time the morning light illuminates our surroundings until twilight's glow fades to darkness and we turn the lights out at the close of the evening. We can ascribe a color to nearly every object, natural or man made. The designation of hues is something taught at an early age, thus it becomes a natural and effortless system for differentiating between shades. There is a continual awareness of surrounding colors, and they are named off without a second thought- grass is green, lilacs are purple, and crickets are black. But why do we know this, and more importantly, *how* can we know this? There is more to color than empirical observation. This paper will discuss the physics of color; the way the human brain processes and understands color along with methods used to measure it.



Dispersion of sunlight into colors of the spectrum.
http://www.school-for-champions.com/science/images/light_dispe

A light source, an object and a viewer are the three fundamental elements of color observation.[1] It is a simple reflection that requires an intricate investigation. To understand why and how most humans see color, it is essential to examine the physics behind it. In the year 1666, Sir Isaac Newton used a triangular prism to diffuse



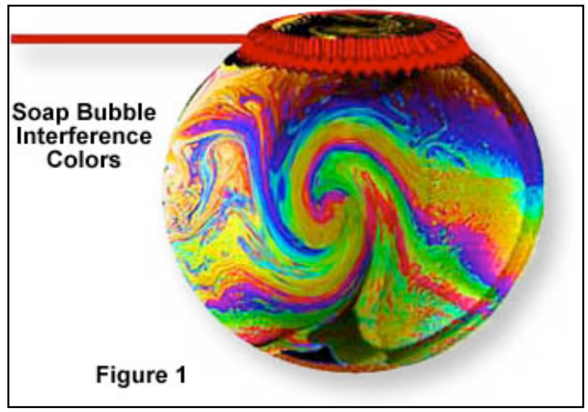
Refraction of light.
http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr.html

[1] Edith Anderson Feisner, *Color Studies* (New York: Fairchild Publications, Inc., 2001), 1.

white light through a slit and into the prism, creating a spectrum of continuous colors produced by refraction.[2] Refraction of light happens when a wave bends upon entry of a medium whose speed is different than its own.[3]

In addition to refraction, color can also be generated by wave interference, diffraction, polarization, and fluorescence.[4]

Light waves interfere with each other when light reflected from two surfaces combine, resulting in color.[5] A familiar example of interference is observed in a soap bubble, due to "simultaneous reflection of light from both the inside and outside surfaces of the bubble."[6] The reason color is produced during interference is because when the waves combine with each other they remove or reinforce certain parts of white light.[7] When white light is absorbed in any degree, the remainder of what is seen generates color in the human eye.[8]



Light wave interference produces a variety of colors, as seen on this soap bubble.
http://www.olympusmicro.com/primer/lightandcolor/interference.html

http://oceanexplorer.noaa.gov

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[2] Johannes Itten, *The Elements of Color: A Treatise on the Color System of Johannes Itten Based on His Book The Art of Color* (New York: John Wiley and Sons, Inc., 2001),15.
[3] Hyperphysics, "Refraction of Light," http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr.html (accessed 16 January 2011).
[4] Itten, 15.
[5] Mortimer Abramowitz and Michael W. Davidson, "The Physics of Light and Color-Interference,"Olympus Microscopy Resource Center, http://www.olympusmicro.com/primer/lightandcolor/interference.html (accessed 15 January 2011).
[6] *Ibid.*
[7] *Ibid.*
[8] Itten, 16.

Much like refraction, diffraction results from the bending of light, but in this case it is due to an obstacle in the light wave's path. If this light passes through a pinhole or a slit, the rays will "break up into dark and light bands or into colors of the spectrum."[9] A visible example of diffraction can be seen when light is diffracted from water droplets in the clouds, resulting in pale pink, purple, blue and green hues.[10]

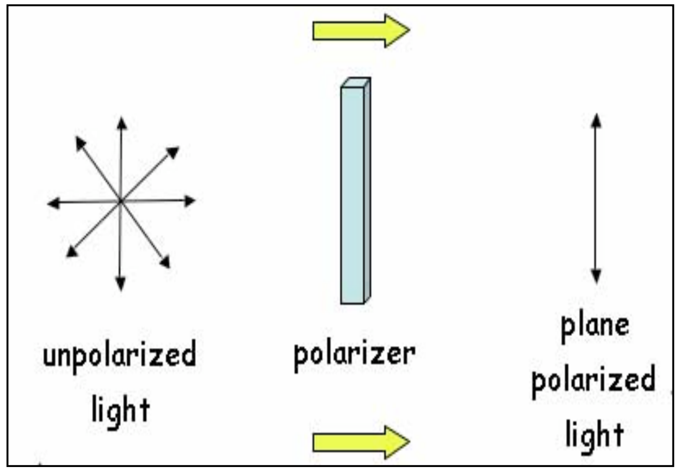

Diagram of polarization
http://oceanexplorer.noaa.go

To put it in basic terms, unpolarized light travels in a multitude of directions but when a beam of light passes through a filter, it becomes polarized, meaning it now only travels on a singular plane.[11] An exhibit of timepieces at the 1939 San Francisco World's Fair had its visitors amazed by an electric clock with illuminated and changing colors on its face.[12] The effect was created by placing quartz crystal between two polarizing discs. When the white light goes through a slot the first polarizing disc and is dispersed into the crystal, with the light representing a "wheel with spokes painted in various colors."[13] With all this

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9 "Color Diffraction and Interference," http://science.jrank.org/pages/1592/Color-Diffraction-interference.html (accessed 15 January 2011).

10 Mortimer Abramowitz and Michael W. Davidson, "The Physics of Light and Color-Diffraction of Light,"Olympus Microscopy Resource Center, http://www.olympusmicro.com/primer/lightandcolor/diffraction.html (accessed 15 January 2011).

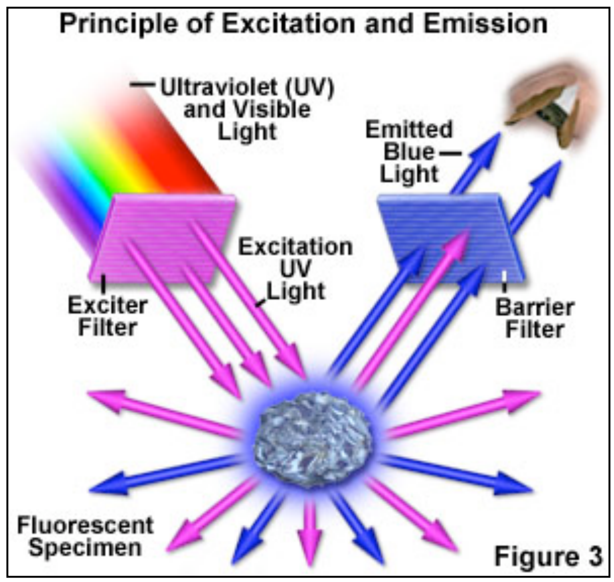
11 The Physics Classroom, "How Do We Know Light Behaves as a Wave?" http://www.physicsclassroom.com/Class/light/u12l1e.cfm (accessed 15 January 2011).

12 E.W. Murtfeldt, "Color Magic With Polarized Light," *Popular Science* (May 1939): 66.

13 *Ibid., 67.*

color flying in every direction, the light must come out in a fashion where only one color is captured through the slot in the second polarizing disc. So if this second disc is angled towards the green "spoke" of light, then green light is the only color to pass though, and so it goes with every color as the disc rotates around the "wheel" of color.[14]

Certain objects, both organic and inorganic, have the ability to re-radiate light when exposed to ultraviolet light. It is known as fluorescence and was discovered in the mid-nineteenth century when scientist George G. Stokes observed the mineral fluorspar, when exposed to ultraviolet light, absorbed and subsequently **emitted** light.[15] A key component to Stokes' discovery was that the fluorescing light has longer wavelengths than the ultraviolet, or excitation light, thus this phenomenon is referred to as The Stokes Shift.[16] A fluorescence microscope looks at the fluorescing objects and exposes them to filtered ultraviolet light and then captures the fluorescing light through a barrier filter, which in turn becomes a visible color.[17]

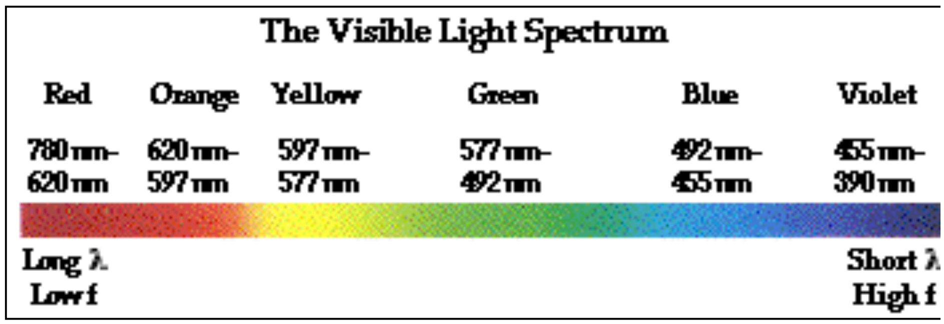


Fluorescence microscopy applied to organic matter.
http://www.olympusmicro.com/primer/lightandcolor/fluorointroduction.html

[14] *Ibid.*
[15] Mortimer Abramowitz and Michael W. Davidson, "Introduction to Fluorescence," Olympus Microscopy Resource Center, http://www.olympusmicro.com/primer/lightandcolor/fluorointroduction.html (accessed 15 January 2011).

[16] *Ibid.*
[17] *Ibid.*

Now that the methods of generating color have been explored, it is time to examine why the human eye sees these colors and what they even are to begin with. There is this light coming through in different hues but what it is must be defined. The crucial aspect of color observance lies in the human eye's sensitivity to wavelengths. We have the ability to perceive electromagnetic frequencies between 400 and 700 nanometers of the electromagnetic spectrum.[18] This visible light spectrum consists of the area between infrared (700 nm) and ultraviolet (400 nm), so we detect the colors red, orange, yellow, green, blue and violet.[19] Thus when one sees white, it is a result of all the wavelengths of the visible light spectrum reaching the eye at the same time, and when black is seen it is because there are no frequencies for the eye and brain to read.[20] Light waves themselves are not colored; rather the color arises in the human eye.[21]



The frequencies detected by the human eye
http://www.physicsclassroom.com/Class/light/U12L2b.cfm

The reason and process of how the human eye and brain detect color is still not fully understood, though it has been studied for centuries.[22] A complete explanation is

18 Itten, 15.
19 The Physics Classroom, "Color and Vision," http://www.physicsclassroom.com/Class/light/u12l2a.cfm (accessed 16 January 2011).
20 *Ibid.*
21 Itten, 15.
22 Kenneth R. Spring, Thomas J. Fellers, and Michael W. Davidson, "Human Vision and Color Perception," Olympus Microscopy Resource Center,

beyond the scope of this paper but to put it succinctly, when light travels through the pupil to the retina, it reaches a series of light-sensing cells known as cones and rods. The rods are sensitive to the intensity of the light but are unable to differentiate the wavelengths. The cones are the color-sensing cells and are divided into three groups: blue cones, green cones, and red cones based on their sensitivity to different wavelengths of light. Within these cones a chemical reaction occurs sending an electrical impulse through nerves to the brain and color is seen.[23]

With all these frequencies floating around, it still seems unclear as to how one specific color is seen on a particular object. Most colors that we observe in objects are subtractive, meaning they absorb all other light frequencies *except* from the detected color.[24] A red bowl looks red then, because "the molecular constitution of its surface is such as to absorb all light rays but those of red" [25]and does not itself have color-the light generates the color as we see it.[26]

It is important to understand and distinguish between additive and subtractive, as well as primary and secondary, colors. Red, green and blue are considered the primary additive colors because they correspond with the red, green and blue cones in the eye.[27]

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http://www.olympusmicro.com/primer/lightandcolor/humanvisionintro.html (accessed 16 January 2010)

23 The Physics Classroom, "Color and Vision."

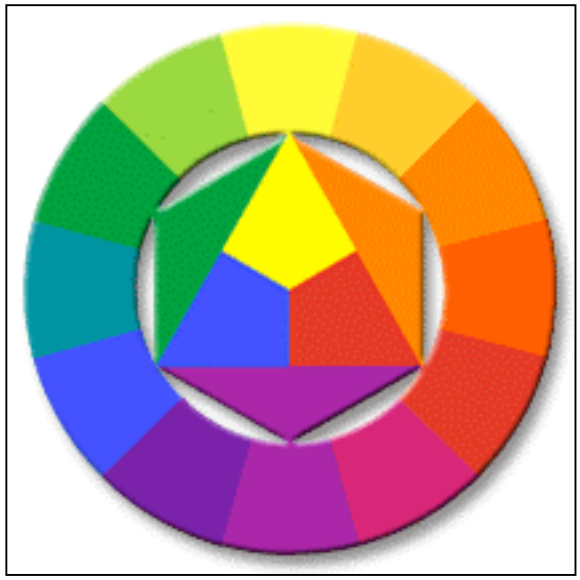
24 Itten, 16.

25 *Ibid.*

26 *Ibid.*

27 Matthew Parry-Hill and Michael W. Davidson, "Primary Additive Colors," Olympus Microscopy Resource Center,http://www.olympusmicro.com/primer/java/primarycolors/additiveprimaries/index.html (accessed 16 January 2011).

The complementary colors of red, green and blue are cyan, magenta and yellow, classified as the primary subtractive colors.[28] A complementary color results when a primary color is subtracted from white light and the brain processes all the other color frequencies together, producing the complement to the primary color. For example, if blue light is removed from the white light, yellow is detected.[29]



In the art world, the primary colors are considered to be red, blue and yellow. In this case, the corresponding secondary colors are the outcome of combining two primary colors, i.e. yellow+red=orange.[30] Each primary color is the complement of a secondary color, meaning each pair will "complete each other to produce a neutral color."[31] Mixing the primary and secondary colors together produces tertiary colors like yellow-green.[32]

Color wheel with primary colors in the triangle, surrounded by secondary and then tertiary colors.
http://www.dreamhomedecorating.com/color-wheel-chart.html

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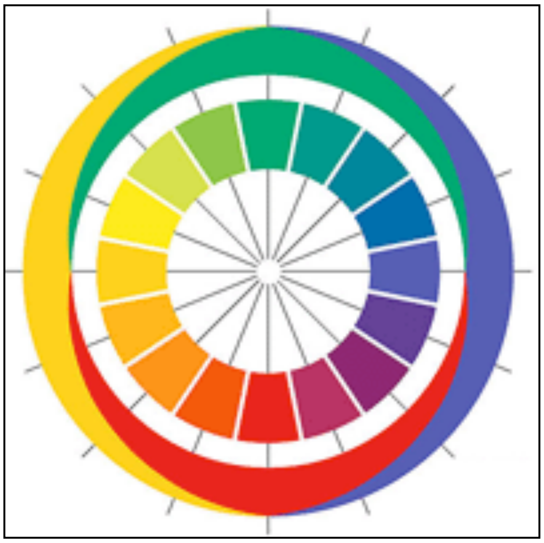
28 Matthew Parry-Hill and Michael W. Davidson, "Primary Subtractive Colors," Olympus Microscopy Resource Center, http://www.olympusmicro.com/primer/java/primarycolors/subtractiveprimaries/index.html (accessed 16 January 2011).

29 *Ibid.*
30 Itten, 29.
31 Dream Home Decorating, "Color Wheel Chart," http://www.dreamhomedecorating.com/color-wheel-chart.html (accessed 14 January 2010).
32 *Ibid.*

In 1878, German physiologist Ewald Hering came up with a color wheel that incorporated both yellow and green as primary colors. With these four primary colors, the complementary colors will change. Where the complementary of purple in the three primary color system is yellow, with this model the complementary becomes lime-green.[33] Hering's model is lauded for being akin to the way the human eye sees color, and has significantly influenced the paint and color industries.[34] Hering's color chart shows how each color family has cool *and* warm hues, not exclusively one or the other. Going by this premise, a cool yellow has green in it and a warm yellow has traces of red.[35] **(Pictured above: Hering's color wheel shows the cool and warm side to each shade** **http://www.dreamhomedecorating.com/color-wheel-chart.html).**



Although there are objective principles governing what color is, how it is seen by humans and ways it is generated from white light, there is still something very subjective about color. No two people see the exact color in exactly the same way, and to actually experience sight of color cannot be substituted for the tangible data about color.
There is a psychological component to color attached to prior memories.[36] The objective fact of indigo light is that it has a wavelength of approximately 445 nanometers[37], but the subjective viewers may all recall different memories affiliated with indigo.

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[33] *Ibid.*
[34] *Ibid.*
[35] *Ibid.*
[36] Feisner, 4-5.

This dualist perspective-meaning color is not all physically based- relates to Frank Jackson's Knowledge Argument[38] wherein he discusses a scientist, Mary, who must learn everything about the world in black and white, no colors whatsoever. Despite this fact, she learns the physical aspects of color based on wavelengths, how the brain reads them, etc. With this concrete knowledge of color, Mary will still know what it is meant when someone says 'the sky is blue.' However, at a point where Mary is released into a colorful world, Jackson argues, she will still learn something about experiencing a blue sky despite having all the physical information in her colorless environment.[39]

Because of this duality of the nature of color, a standard measuring system would greatly help establish a consistency for what each color is. The distinct and unchanging physical properties of that which we call color can be of assistance when creating a catalogue of colors to accurately reflect what greenish yellow color was found on a wall in a house from 1813, for example. Munsell, CIEL*a*b and HunterLab are the three major laboratories that study color science.

Albert Munsell designed one of the most widely used color measurement systems. He created a color system based around five principal colors-yellow, red, green, blue and purple.[40] The Munsell system is used for a variety of purposes including dye manufacturers, manufacturing cosmetics, and paint production.[41] It is also effective for archaeologists for color identification of soil and for paint analysts in matching samples

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37 Atmospheric Science Data Center, "What Wavelength Goes With a Color?" http://eosweb.larc.nasa.gov/EDDOCS/Wavelengths_for_Colors.html#indigo (accessed 14 January 2011).

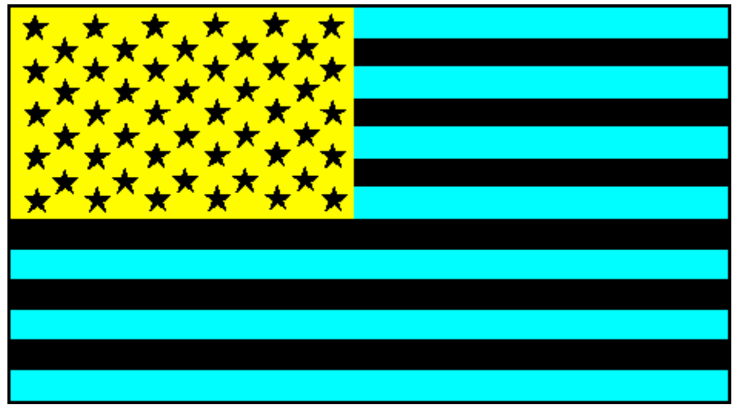
38 Martine Nida-Rümelin, "Qualia: The Knowledge Argument," The Stanford Encyclopedia of Philosophy, http://plato.stanford.edu/entries/qualia-knowledge/#3.1 (accessed 14 January 2011).

39 *Ibid.*

40 Feisner, 10.

41 *Ibid.*

to historic hues. Munsell came up with a successful system that provides "standard [color] samples according to a logically organized plan while at the same time catering for the perceived affinity of colors."[42]



Staring at this graphic will produce an after image of the flag in its correct colors.
http://www.thecosmicmirror.org/more%20on%20the%20book%204.htm

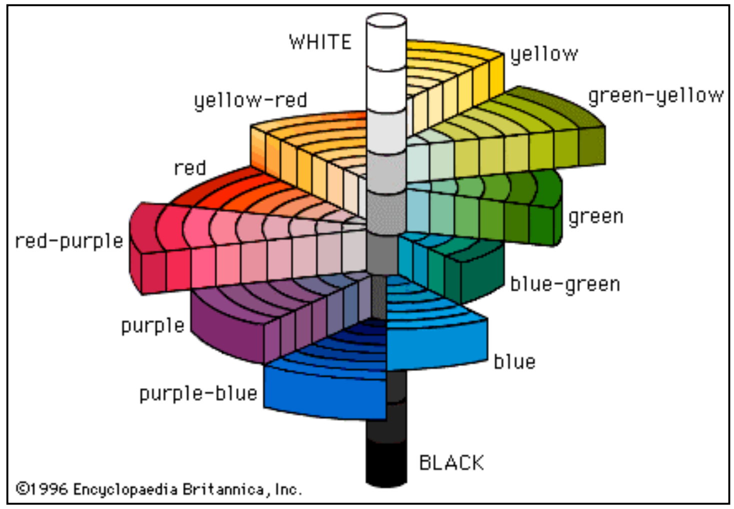
This organized plan is based on the principle of "perceived equidistance" of which Munsell published in *Color Notation* in 1905.[43] This work included his color sphere, similar to N.O. Rood's *Modern Chromatics* (1879).[44] Munsell's three variables of color were based on the philosophy of Hermann Helmholz, who believed that these three variables were "hue, value (lightness or darkness) and chroma (saturation or brightness)."[45] Munsell created a numerical system to categorize these variables, and through his continued color studies the primary colors were expanded from three to five, with the addition of green and purple. [46]

Munsell's complementary colors were formed based on the 'after images' of the primaries.[47] This phenomenon has to do with the three types of cones in the retina-red, blue and green receptors. If one stares at the color red, the red-sensitive cones will become

42 Echo Productions, "Albert Henry Munsell," http://www.colorsystem.com/projekte/engl/31mune.htm (accessed 17 January 2011)
43 *Ibid.*
44 *Ibid.*
45 Feisner, 17.
46 *Ibid.*
47 *Ibid.*

exhausted, so when the gaze shifts to white, the complementary color (green or cyan, depending on the source) will be seen.[48]

In 1915, Munsell came out with a new work, *Color Atlas*, which described his new color system. The spectrum was too great, he felt, to accurately portray it in a sphere and so Munsell's Color Tree was established.[49] It was designed by making a circle with ten segments (the five primary and five secondary colors) with the colors arranged at equal distances.[50] The vertical axis of this color tree consists of a gradation values numbered from 1 (darkest black) to 9 (lightest white) with 5 being middle grey. From each of these vertical hues, saturation is measured on a horizontal axis. In the center lie the dull grey hues with the brighter more brilliant shades expanding outward.[51]



Munsell's Color Tree
http://www.britannica.com/EBchecked/topic-art/397642/61524/

Munsell categorized the color tree with a complex numbered system for identifying the hues. The first thing he did was to assign every *hue* the number 5, then an initial (or two) so that red would be listed as 5R and yellow-red is 5YR.[52] Another component to this numbering system accounts for the *value* of the hue on a scale of 0 to 9. 5R5 is a middle value red whereas 5R9 is pale pink.[53] To further specify the color, a slash

48 Josef Albers, *Interaction of Color*, (New Haven and London: Yale University Press, 2006), 23.
49 Feisner, 17.
50 Echo Productions, "Munsell" www.colorsystem.com
51 *Ibid.*
52 Feisner, 17.
53 *Ibid.*

with a number after it measures the *chroma*, "or level of saturation or purity, of the hue at that value, measured in equal steps from neutral grey to the greatest saturation seen in each hue at a particular value."[54] Thus, there are a total of "40 hues created by dividing the 5 color-hue intervals between the main hues, first into 10 then 20 and finally into 40 segments"[55] that all appear to be equidistant.[56]

Another edition of *Color Atlas* was published posthumously in 1929 and is still used today, though under the title *The Munsell Book of Color.*[57] Since the pigment designations in this system are so precise, color industry became standardized.[58] The format of the color tree is such that each hue can be placed directly next to the color sample for an exact match. Today, the Rochester Institute of Technology in New York is home to the Munsell Color Science Laboratory, offering undergraduate and graduate studies in color science and performing applied and fundamental research in the field.[59]

The second major color system relies not on observation or measuring of pigments, but rather on mechanics.[60] It was during a 1931 convention, Commission Internationale de l'Eclairage (International Commission on Illumination) aimed to create a system for color notation based on lights.[61] The use of a tool called a colorimeter was used to measure the luminance, the hue and the saturation of color. The outcome of this measurement arrives at the *chromaticity* of a color.[62] A colorimeter is a tool that functions much like the human eye, in that it reads the red, blue and green elements of light wavelengths to

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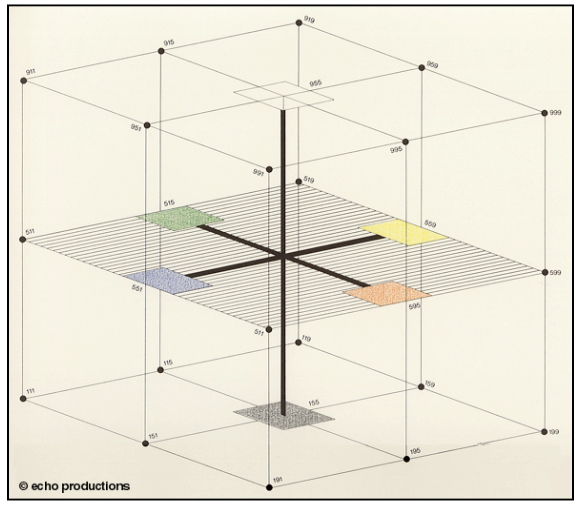
54 *Ibid.*
55 Echo Productions, "Munsell" www.colorsystem.com
56 *Ibid.*
57 *Ibid.*
58 Feisner, *Color,* 18.
59 Rochester Institute of Technology, "The Munsell Color Science Laboratory," http://www.cis.rit.edu/research/mcsl2/ (accessed 17 January 2011).
60 Feisner, *Color,* 18.
61 *Ibid.*
62 *Ibid.*

measure the contrast and brightness of a color sample or object.[63] The C.I.E. color diagram is science based and gives an accurate color standard, differentiating between even the subtlest differences undetected by the human eye.[64] The system relies on coordinates on the X and Y-axes of the diagram.[65]

Although this diagram took the measurement of color in a new direction it could not be used to establish color differences as more accessible shades on a chart.[66] By 1976 though, a new system called CIELAB was developed. Analysis of paints, textiles and plastics-all items with no self luminance- became much easier to correctly identify with the use of this system.[67] The color value X, Y and Z coordinates from the CIE 1931 Standard Color Table were altered to initiate this new method. The new reference values are L, a, and b with X and Y becoming a; Y and Z transform to b with Y alone converted to L.[68] The letter L can be thought to represent the term "lightness" because in its parameter, color values range from 0 at black and 100 for white. These values will be diagrammed



CIE L*a*b Diagram
http://www.colorsystem.com

63 Donna Rengi, "What is a Colorimeter?" Wise Geek, http://www.wisegeek.com/what-is-a-colorimeter.htm (accessed 18 January 2011).
64 Feisner, *Color,* 19.
65 *Ibid.*
66 Echo Productions, "CIE L*A*B System," http://www.colorsystem.com/projekte/engl/54labe.htm (accessed 18 January 2011).
67 *Ibid.*
68 *Ibid.*

with a uniform accuracy beyond human observation, an especially helpful tool when dealing with the subjectivity of color.[69]

The CIEL*a*b Diagram is also referred to as the Psychometric Color Diagram.[70] It is based on the primary colors red, yellow, blue and green, creating a uniform color space by the use of right angles. The colors all "lie at right angles to each other in two directions, and the plane thus created itself lies at right angles to the achromatic axis."[71]

It is worth noting that the HunterLab instruments operate on the same principle as CIEL*a*b, where they operate in the same way that the eye sees color.[72] HunterLab sells various tools that measure color for professional analysis. Aside from the colorimeter, another instrument that measures color is called a spectrophotometer. A spectrophotometer reads light energy in the form of wavelengths.[73] This is useful in paint analysis while examining microscopic samples in order to clarify the accurate color with wavelength readings.

These systems and instruments exist to give us the most precise determination of color. Because color is subjective, we must rely on these systems to some degree. The eye can play tricks on the mind and how we perceive color, and lighting itself can alter one's sensitivity to the observable hues. Full light, medium light and shadow all give different effects. Medium light is optimal for seeing the local color of objects, where colors are whitened by full light and darkened by shadow.[74]

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69 *Ibid.*
70 *Ibid.*
71 *Ibid.*
72 Hunter Lab, http://www.hunterlab.com (accessed 18 January 2011).
73 Helga George, "What is a Spectrophotometer?" Wise Geek http://www.wisegeek.com/what-is-a-spectrophotometer.htm (accessed 18 January 2011).
74 Itten, *Elements*, 80.

What appears to be such a simple and basic part of everyday life is actually an elegant arrangement that requires an independent light source as well as the nerve receptors in our eyes sending signals to our brains, picking up the wavelengths of the visible spectrum. Though observation of color can be highly subjective, the sciences provide objective facts that contribute to the duality of color: physical truths and the empirical experience that is different for all. Though it may seem natural and effortless to designate between colors, the science behind color shows us there is more to it than what we observe on the surface.

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