The ColorShop Color Primer

An Introduction to the History of Color, Color Theory, and Color Measurement

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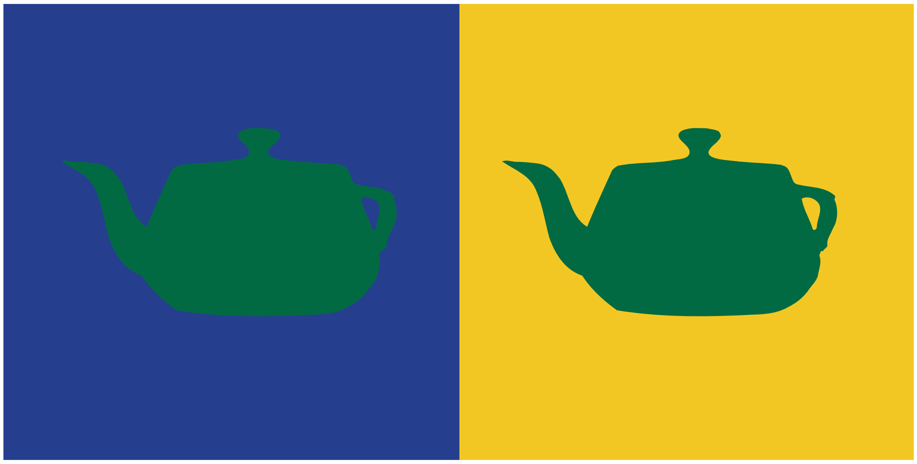
COLORSHOP COLOR PRIMER TABLE OF CONTENTS

1 INTRODUCTION

Whether you believe that the human eye was designed by evolution to meet the needs of survival, or was a gift from God to Adam, you might agree that this original design had one important requirement: recognizing which fruit on certain trees were to be avoided. In either case, the consequences of picking the “wrong” fruit would be disastrous!

However, this original design might not be sufficient for the rigors of modern color matching tasks. Neither Adam, nor Australopithecus (the oldest human) ever had to pick out PANTONE® 265 on a press room floor. Perhaps the modern human eye could use some help.

For example, let’s start by playing a few cruel (but safe) tricks on your eyes.



Cruel Trick: Simultaneous contrast. Quick ... which of the teapots is shown in the darkest green? Would you be surprised to learn that both teapots are exactly the same color?

Cruel Trick: Color difference. Which of the three square patches represents the closest match to the color in the center triangle? To make this “easier”, the patches are butted up against the target color so you can get a close comparison. Now ask a few other people to make the same decision. Chances are, you will get a different opinion from each person.

It may not be news to you that your eye can be fooled. However, these examples are suggesting something stronger: **your eye may not be the ultimate authority on color**. Although exquisite in its design, the eye is not perfect.

This Primer is divided into three parts: A brief introduction to the history and terminology of color, a recap of the problems inherent in color reproduction and communication, and an overview of the world of color instrumentation as a way to address these problems.

Although we will try to keep new terminology to a minimum, new words are introduced in light blue and these are catalogued in the Glossary. As for mathematical equations, we promise to limit these to only one equation and to give those more mathematically-inclined readers an Appendix which provides the complete equations referred to throughout this Primer.

The author also has to fight his own tendencies to digressions and asides, and has thus included a number of footnotes and magazine-style sidebars. You can ignore these if you wish as they are somewhat peripheral to the central story.

The only other caveat to add before you begin is this:

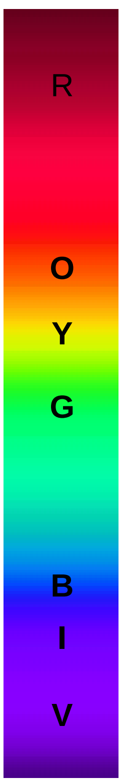
Warning: The study of color is highly addictive.

If you are bitten, you have been warned ... and welcome to the club.

2 COLOR HISTORY AND COLORFUL LANGUAGE

Why a history lesson? As this Primer starts with no assumptions about what you already know about color, a history provides a way to go back to when mankind knew next to nothing about color. For those readers already quite familiar with some of these concepts, a history should provide a (hopefully) entertaining recap of how these concepts were discovered. For those encountering these concepts for the first time, a history allows us to present these ideas in the approximate order that they became understandable to us—although we do jump around a little. Dates are provided for historical context only.

THE SPECTRUM



Newton's breakthrough

In the spirit of assuming very little knowledge about color, let's go back to when color science was in the equivalent of the 6th grade, and we met a new teacher, Isaac Newton (1642-1727), so brilliant that he took us straight to high school.[1]

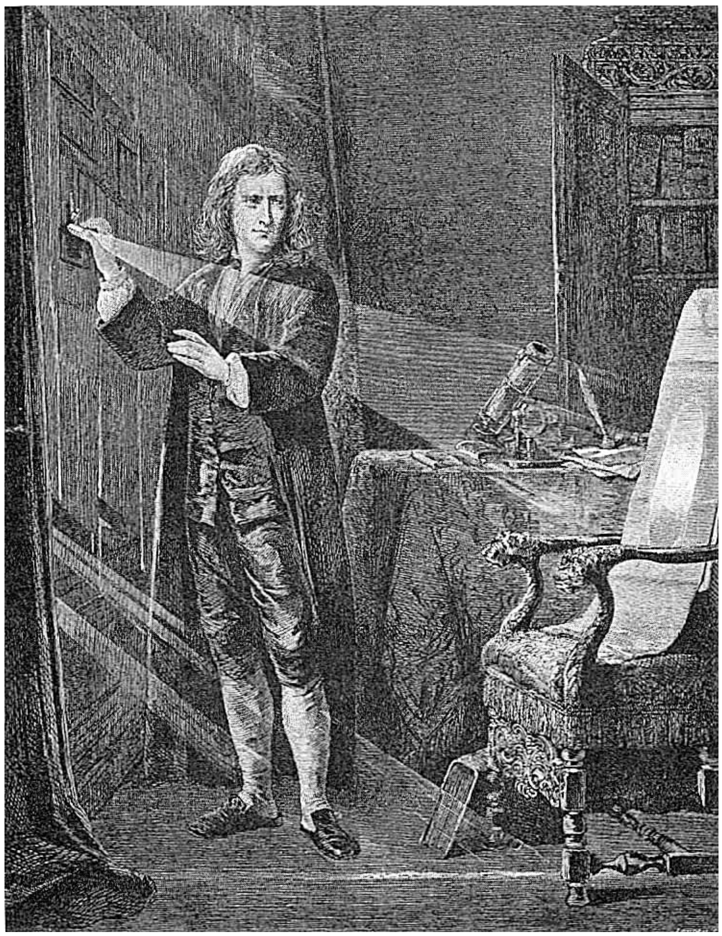
By Newton's time, we were already aware that the color we associate with an object had something to do with reflected light. We had gained some understanding about the geometric properties of light such as reflection and refraction (bending), but little about color.

Newton found that a beam of white light could be separated into component colors. The resulting continuous series of colors he called a spectrum, and described the order of these colors as red, orange, yellow, green, blue, indigo, and violet regions—many of us will remember the ROY G. BIV mnemonic from our school days. He was

[1] In Michael Hart's provocative book, "The 100", Isaac Newton is ranked second among the 100 all-time most influential persons in history. (Einstein is 10th and Darwin is 17th.) Just being in the top six puts Sir Newton in the company of Buddha, Jesus Christ, Confucius, Muhammad, and St. Paul as an influencer of human events. We won't digress further by revealing which of these religious figures edged out Newton for first place.

careful to point out that he chose to identify seven color regions for description only.[2] There were a myriad of intermediate colors—in fact a smooth transition of colors—within each region.

The breakthrough to the study color was this: **Newton turned our attention to the light source**. Color was, for the first time, an identifiable property of light. White light contains all colors. If a surface appears to be "yellow" this means that the light reaching our eyes has somehow been changed by reflecting off that surface. No light, no color. (For a description of Newton's experiment, see sidebar.)



Isaac Newton examining light with a prism, while simultaneously striking a graceful pose

[2] There has been much speculation as to why Newton used seven. Indigo, in particular, seemed out of place as the region between blue and violet seems too narrow to deserve its own label. The most interesting theory is that Newton was attempting to correlate these color regions to the seven notes of the musical scale.

Newton's prism experiment

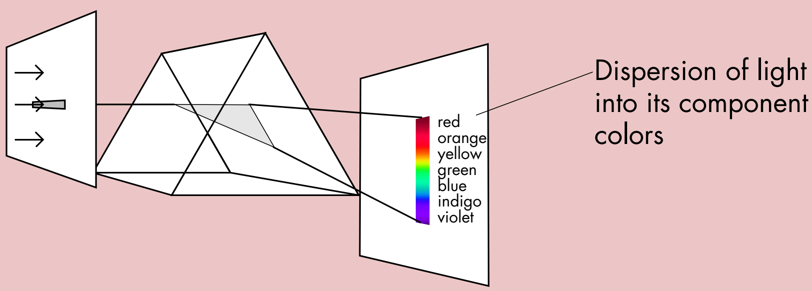
(1666 Woolsthorpe, Lincolnshire, England) Contrary to popular belief, Isaac Newton did not discover prisms. The lightshow produced by a prism was well known by Newton's time. However, it was generally assumed that these colors were somehow added by the glass or other transparent material (such as the droplets of water known to cause a rainbow). Newton showed instead that the colors were present in the original light and that the prism just served to separate the white light into its component colors. Here's what he did:

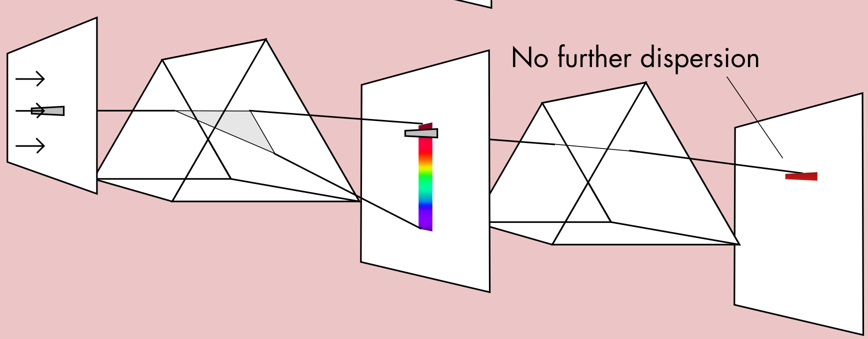
Newton began by shielding his room from all light except for a narrow beam of daylight let in by a small circular opening in his window shutter. This cast a small white spot when shone upon a surface. He then placed a triangular prism up to the hole, which refracted (bent) the beam of light as it passed through it, and caused the white spot to become elongated into a bar. One end of the bar was red, the other violet, and the remaining colors appeared as intermediate stages in between.

Newton then took a second pinhole, isolated one of the color regions, and passed it through a second prism. He found that there was no further dispersion (spreading) of the light, and its color did not change. He had isolated a part of the spectrum and confirmed that it contained none of the other colors.

Newton also did the opposite experiment. He took the spectrum generated by the first prism, and ran it through a second prism oriented in reverse. This reconstituted the white light from its component colors.

Newton's conclusion: Light rays traveling through the prism are refracted (bent) by different amounts depending on some property in the light rays that corresponded with what we call "color." That property is what we now know as "wavelength."

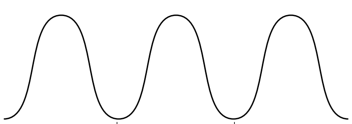




Light—the relationship between wavelength, color, and the spectrum

Newton did some additional experiments with a phenomenon we now call Newton's rings (which we won't go into here) that brought him **very** close to discovering the relationship between what we now call wavelength, and color. But as he was almost twenty-nine he had to get busy inventing calculus, discovering laws of motion and gravity, writing the *Principia Mathematica* (in Latin), and other "trivia."

Instead, it wasn't until J. C. Maxwell (1831–79) that a wave theory of light found a good footing. Maxwell was working in an area of physics fairly unrelated to color when he found laws that united the concepts of electricity and magnetism into one, that we could now call electromagnetism. Maxwell showed that light is just a form of electro-magnetic energy that could be described as electromagnetic "waves."[3]



The length of a wave (the distance from one crest to the next) is called the wavelength. The wavelengths of light are measured in terms of nanometers, abbreviated nm. A nanometer is one-millionth of a millimeter.

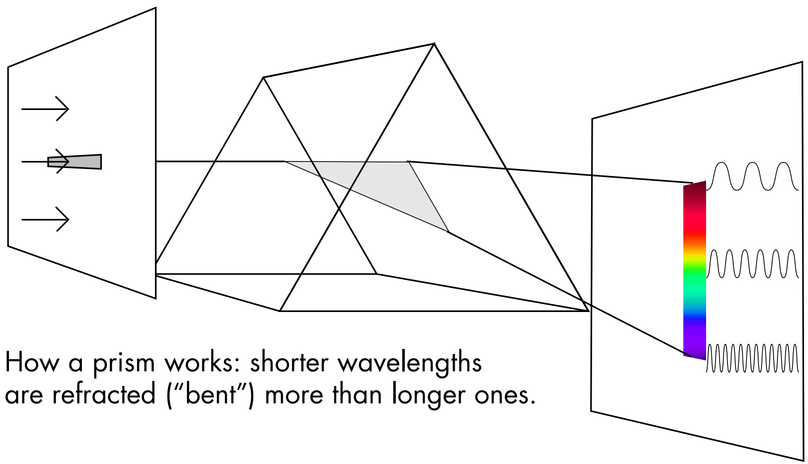
For example, we can determine by experiment that wavelengths below about 400nm are invisible to the eye, as are wavelengths above

[3] This is not to imply that Maxwell was the first to propose a wave theory of light—he wasn't. In fact it had been proposed even before Newton's time. However, prior to Maxwell we assumed that to prove the theory we must find a medium, called the ether, for the waves to travel through. The lack of any evidence of this ether was a major thorn in the side of wave theorists—which led to widespread acceptance of an alternative theory by Newton known as the "corpuscular theory"—until Maxwell's unification of electricity and magnetism allowed us to build a wave theory without the need for a medium for waves to travel through.

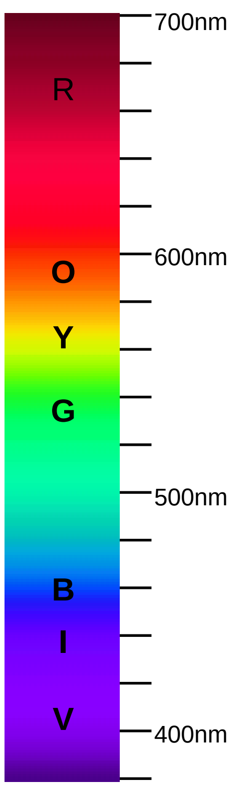
Since then, there has been much debate about whether the fundamental unit of light is best described as a particle, or as a wave. In fact it displays characteristics of both. This is the paradox that has confounded many a poor physics student. One very useful model is that of a pulsating particle—called a photon—traveling through space. Something that pulsates while it travels appears, in effect, like a wave. High-energy photons pulsate faster (i.e. with a higher frequency) than low-energy photons. However, the speed of light as it travels through space is constant, regardless of the energy of photons. Thus, high-energy photons have a shorter wavelength (the distance traveled between pulses), than low-energy photons.

about 700nm. (The exact range of what is "visible" varies a bit from person to person.)

So we can now describe what Newton saw as a prism "sorting" light rays by wavelength. The shorter wavelengths are refracted (bent) more than the longer wavelengths.



How a prism works: shorter wavelengths are refracted ("bent") more than longer ones.



The beauty of this is that we can now assign specific numbers to different points in the visible spectrum, rather than Newton's ROY G BIV, which were effective for description purposes, but didn't give us enough precision to really talk about specific areas of the spectrum.

So what happens with wavelengths below 400nm (violet) and above 700nm (red)? Maxwell correctly theorized that there is no reason why these wavelengths do not exist—they are just undetectable by our eyes. The region adjoining what we call red is known as the infrared region. The region adjoining what we call violet is known as the ultraviolet region. And, just as the eye is responsive to only a certain range of wavelengths, we can build devices that respond to other regions of the electromagnetic spectrum, (such as X-ray cameras, gamma-ray telescopes, etc.) or are tunable to specific wavelengths (such as radios and televisions).

Emitters, reflectors, and transmitters of wavelengths

So we have seen that light carries information in the form of its component wavelengths, and that these wavelengths have something to do with the colors of the spectrum. However, there are a lot more apparent colors in nature (and in Bennetton ads) than in the spectrum. Where do all these colors come from, and what do they have to do with wavelength?

If you think about it, there are only two ways that things in nature can affect the wavelength composition of light: in the way they **emit** light, or **absorb** it.

- **Emission**. This happens when other forms of energy are converted into light energy. Emission of light is always caused by some chemical or physical process, such as combustion (burning of fuel) or heating and cooling of molecules and atoms. Every chemical process releases more light at certain wavelengths than at others. Thus no light source in nature is perfectly “white” in the sense that it emits exactly the same amounts of each wavelength.

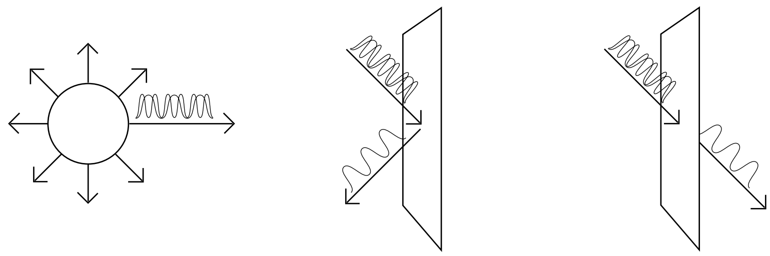
- **Absorption**. This is the opposite of emission and happens when light energy is converted into some other form of energy. Any light that strikes an object or material (such as water) can be absorbed by its atoms and molecules. The amount of absorption of each wavelength is dependent on the chemistry of the object or medium.

“Hold it!” you say, holding up a color photograph and a color slide, “what about reflected and transmitted light?” Well, any changes to the wavelength composition of reflected or transmitted light is due to either absorption or emission:

- **Reflection**. Light does not just bounce off of objects and surfaces without interacting with them. Rather, look at reflection as an absorption followed by a re-emission of light. Sometimes, as in the case of a perfect mirror the light that emerges is identical to the incoming light—all that has changed is the direction. More commonly, some wavelengths are absorbed more than others, so the light that emerges has a different wavelength composition.

- **Transmission**. This is the name given to the passage of light **through** a transparent or translucent material, such as water, air, film emulsion, or ink. As light encounters molecules or larger particles in the material, some wavelengths of light may be absorbed more than others. In either case, the amount of absorption of each wavelength, and thus the intensity that emerges from the material, depends on the thickness of the material traveled. For example, if you think water transmits light without any absorption, find some scuba gear, descend into about 100 feet of water, and notice how little light gets through from the surface. The only perfect transmitter of all wavelengths is a vacuum.

To summarize, all visible objects fall into three categories: **emissive** objects like light sources and computer monitors, and two types of **absorptive**[4] objects: **reflective** and **transmissive** objects.



The three types of objects in the world: *emissive*, *reflective*, and *transmissive*. Reflective and transmissive objects are two forms of *absorptive* objects.

We should also mention a fourth type of object: a special case of absorptive device for which we are not concerned about what is reflected or transmitted. Instead, the absorbed wavelengths are converted to electrical impulses that we can monitor. We call these detectors because they can be used to detect the wavelengths produced by the other three types of objects. We mention this because the two objects most near and dear to our hearts—namely the human eye, and color measurement instruments like Colortron and Digital Swatchbook—are in this category.

Spectral data and spectral curves

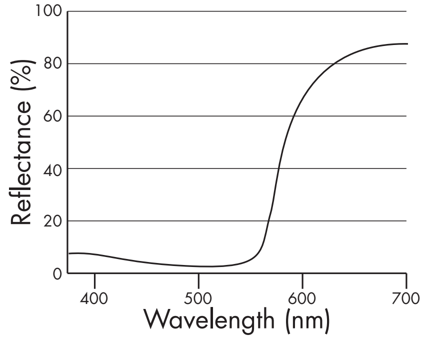
So now that we've separated the world of objects into three categories based on how they affect the wavelength composition of light, we are finally ready to talk about **spectral curves.** If you are not familiar with spectral curves, now is the time to become acquainted with them as this is the heart of what makes the data handled by ColorShop so rich.

The spectral curve of an object is its visual "fingerprint." It describes how the object affects light at each wavelength.

[4] Yes, the correct word here is 'absorptive', not 'absorbent.' However, we rarely talk about absorptive objects, but instead talk about either reflective or transmissive objects.

Lets look at some examples of our three types of objects:

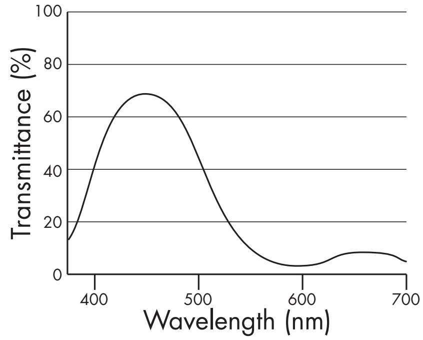
With a **reflective** object we can graph its reflectance—the intensity of the reflected light at each wavelength as a percentage of the incoming light. For example the graph of the reflectance of a red object looks like this:



Graph of the reflectance of a red object. The object reflects very little of the shorter wavelengths (blues and greens), some of the yellow part of the spectrum, and almost all of the longer wavelengths (the reds).

With an extremely sensitive instrument—such as (you guessed it) a Colortron or Digital Swatchbook—you can examine the spectral curve for any object by measuring spectral data, the amount of light reflected at each wavelength across the visible spectrum. Such an instrument is called a spectrophotometer. (The details of color measurement and spectrophotometry are described in Chapter 4.)

With a **transmissive** object we can measure and graph its transmittance—the intensity of the transmitted light at each wavelength as a percentage of the incoming light. For example the graph of the transmittance of cyan ink[5] looks like the following:

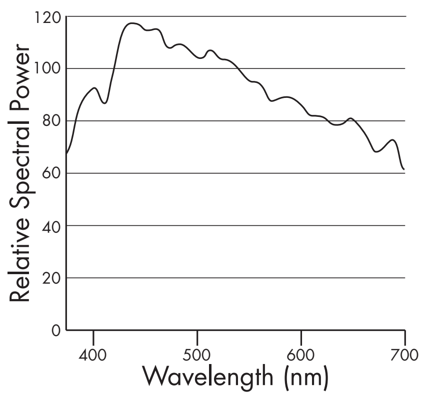


Graph of the transmittance of cyan ink. The ink transmits most of the shortest (blue) and little of the middle (green) and long (red) wavelengths.

[5] It may surprise you to learn that inks used in process-color printing are transmissive, not reflective. Light actually passes **through** the ink, reflects off the white paper, and then back up through the ink a second time. The absorption of wavelengths as the light passes through the ink is what produces the characteristic color. For most purposes this distinction is unimportant—as far as you (the observer) are concerned, your eye sees light reflected from the paper-ink combination.

With an emissive object we can measure and graph its emittance—the intensity of the emitted light energy at each wavelength relative to the total amount of light energy. For example the graph of the spectral curve for daylight looks like this:

Graph of the emission spectrum of daylight after scattering and absorption in the earth’s atmosphere.

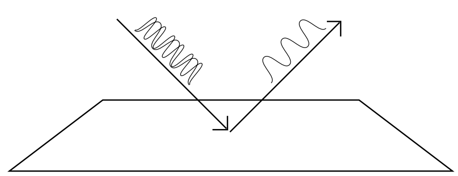


Throughout this Primer we will be showing the spectral curves for various reflective, transmissive and emissive objects, and how they affect each other.

Spectral data is a complete description of color information

To summarize: we now have a good model for what we really mean by the “color of an object.” Light is a mixture of all wavelengths. The exact mixture of the wavelengths is determined by the emissive properties of the light source. When this mixture of wavelengths reflects off the surface of an object, or passes through a material such as film or ink, the mixture is changed. Some wavelengths are absorbed more than others. The resulting mixture of wavelengths then tells us something about that object—this is the information carried by color.

A surface has a “color” because it absorbs some of the wavelengths that strike it, and reflects (or transmits) others.



If there's one thing you should remember from all this discussion, it is this: **spectral data is a complete and unambiguous description of color information**.

So why don't we stop with this spectral model of color—or to put it more accurately, why didn't color scientists stop here? There are three main reasons:

- First, this is a description of the color information that leaves a surface, but does not address **how our eye interprets that information**. Or, (if you'll pardon a play on the old cliché) there is more to this than "meets the eye." Scientists are never satisfied without the full picture.
- Second, it would be very hard to build things like color television screens, printers and printing presses, computer monitors, scanners, etc. without a simpler model that can be reasonably mass-produced.[6]
- Third, spectral data does not easily lend itself to being manipulated mathematically in ways that scientists would like to help visualize the relationships between colors. For example, you can't graph more than one or two colors in the same picture, or compute how "close" two colors are to each other perceptually (in the sense that most people would agree that one color appears "closer" to a target than another).

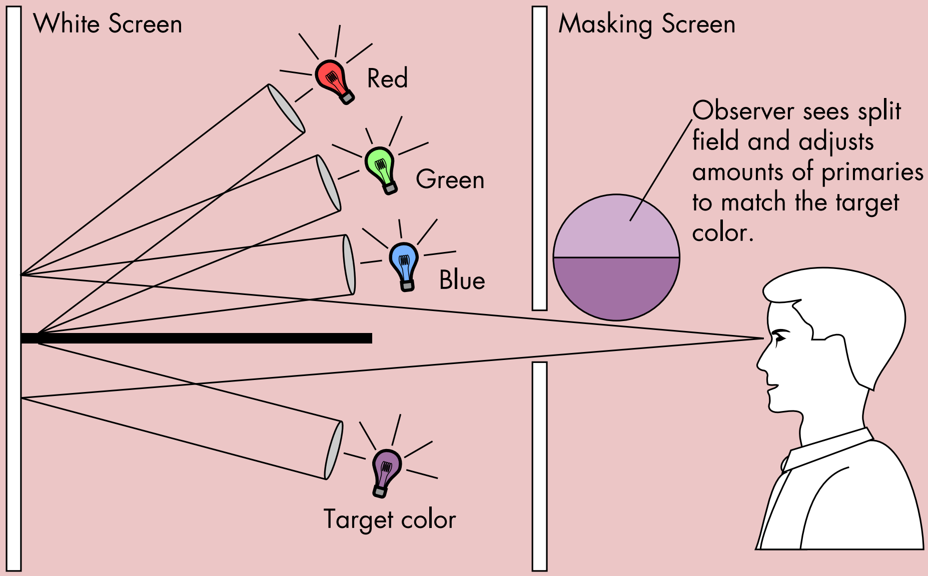
RGB, CMY(K), AND THE DISCOVERY OF TRISTIMULUS

Maxwell, Young, and Helmholtz

When we last left our heroes, Maxwell had shown that light was a form of electromagnetic wave, which gave us a way of describing color in terms of wavelength. The brilliant Maxwell also did some work with color perception, and devised an apparatus in 1861 to test a theory that all colors could be described by combining three primaries (see sidebar). This was actually a theory proposed back in 1801 by Thomas Young (1773–1829) based purely on reasoning that the

[6] It would be quite facetious to suggest that scientists invented color theory just to satisfy mankind's yearning for television ... but it makes an amusing theory.

The Color-Matching Experiment



Most studies of the three-color nature of human vision are based on some variation of this simple apparatus.

One part of the screen is illuminated by a lamp of a target color; the other by a mixture of three colored lamps. Each of the lamps is called a stimulus and in tightly controlled experiments may consist of light of a single wavelength.

The test subject adjusts the intensities of the three lamps until the mixture appears to match the target color.

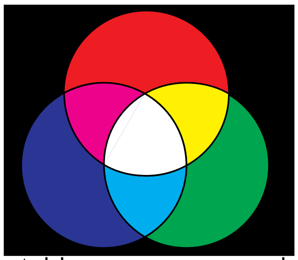
Experiments have shown that certain combinations of matching colors (usually some form of the primaries red, green, and blue) allow observers to match most, but not all, target colors. However, by adding light from one of these primaries to the target color, **all** possible target colors can be matched. The light added to the target color can be thought of as having been subtracted from the other two primaries—thus creating the theoretical notion of a **negative** amount of light.

eye couldn't possibly have receptors for every possible wavelength. And the credit must go to Hermann von Helmholtz (1821-94) who put all this together and first described the idea of red, green, and blue receptors in the eye and drew the first illustrations of their spectral curves.

The importance of these results to the study of color is this: whereas Newton turned our attention to the light source, the work of Young, Helmholtz, and Maxwell **turned our attention to the observer, the eye**. The eye, it turns out, has its own rather economical way to handle colors using only three types of receptors.

RGB

So this brings us to the RGB description of color, which you may be familiar with if you have been working with color on the computer. But as we are assuming no knowledge about color, let's recap:



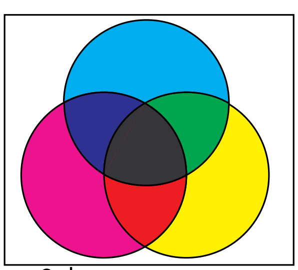
Additive primaries, red, green and blue

Red, green, and blue are known as additive primaries. This means that, theoretically, we can simulate the appearance of any color by starting with black (no light) and adding certain proportions of red, green, and blue light. When the amounts of red, green and blue are equal and at maximum intensity, we get white.

One benefit of RGB is that it presents a very nice model for designing mass-producible devices that either imitate the eye (like scanners, colorimeters, and digital cameras), or attempt to fool the eye into believing it's really seeing many colors (like monitors and televisions). A computer monitor, for example, simulates colors by causing red, green, and blue phosphors to glow at different intensities. A scanner imitates color vision by measuring the intensities of red, green, and blue light reflected from a piece of artwork.

CMY, and its able sidekick K

If RGB is the simplest model of color reproduction, CMY is its alter ego. CMY answers the question: what if you are not starting with black and adding lights, but starting with white and trying to get back to black? This is the fundamental problem that defines color printing and painting. The answer is that we **subtract** different quantities of red, green, and blue, from our original white. In the case of color printing, we subtract red from the white of a page by using a filtering pigment—commonly known as **ink**—that allows all colors to pass through it **except** red. What does "redless" ink look like? Well, it's the color we call cyan. Similarly, magenta could be considered "greenless" ink, and yellow can be considered "blueless" ink.



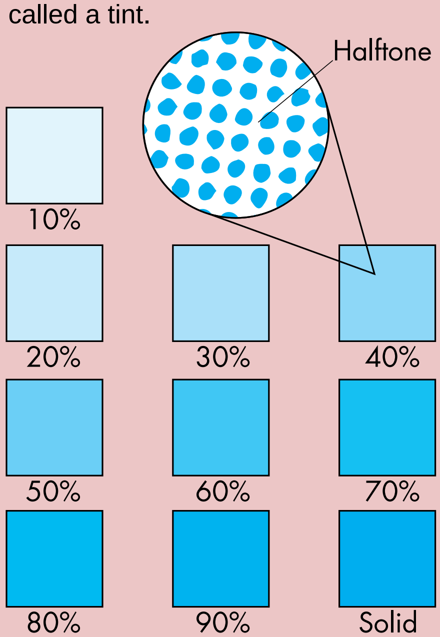
Subtractive primaries, cyan, magenta, yellow

We call cyan, magenta, and yellow, subtractive primaries because we are starting with white and subtracting wavelengths.

Now, CMY works quite well in theory, but in practice needs a little help. Printers have found that in order to get true black, we must use black ink in addition to the CMY primaries, producing CMYK (see sidebar). However, this is a practical limitation due to manufacturing tolerances of ink, not a theoretical limitation of CMY.

CMY and the practicalities of printing—why do we need ‘K?

The most common form of full-color printing is based on clever use of red, green, and blue filters—known as cyan, magenta, and yellow *ink*, respectively—to subtract, or filter, different wavelengths from the white reflected by the paper. We vary the amount of light filtered by each ink by allowing some of the background (paper) to show through unfiltered. This is called *screening*. (The most common form of screening is the *halftone*.) A screened area with a uniform percentage of ink (for example, a patch screened so that it is 70% cyan ink and 30% paper) is called a tint.



Tints of cyan ink. Each one from 10% to 100% (solid cyan) lets a little more paper through. The most common form of screening used in printing is the halftone.

Ideally, when you combine equal tints of cyan, magenta, and yellow, you should get a neutral shade of gray, and when all are at 100% ink/0% paper, you should see black. However, commercial inks and papers are far from ideal. It is practically impossible to manufacture them so that, for example, cyan ink filters out only red and absolutely no green or blue, and so that when inks are printed on paper and on top of each other, that everything behaves in an ideal way. The result is that when you print a patch that is 100% cyan, magenta, and yellow, you don’t get a pure black. Instead, you usually get a muddy dark-brown-yellowish-red-thing (as shown in the center of the three circles on page 18.)

To get better blacks and grays (and because you usually need black ink anyway for text), printers reduce the overall amounts of the CMY primaries and add quantities of black.* Now, “CMYB” would be a poor choice of acronym as we are already using ‘B’ for “Blue.” So printers use the initial ‘K’, for “Key” to form the familiar “CMYK” known lovingly as four-color printing. This is one form of process color which is a general term for any mechanism for generating colors using quantities of primary inks. In fact, there are process-color systems that use five, six, or even more primaries.

The many techniques used for generating the black (K value) from CMY is quite complicated and could fill up another Primer, so we will thankfully stop here. We will only say that this is the main reason the conversion from any color space to CMYK, (a process called *color separation*) is such a difficult task.

* Printers also like the fact that using less ink saves money and shortens drying time.

The relationship between RGB and CMY

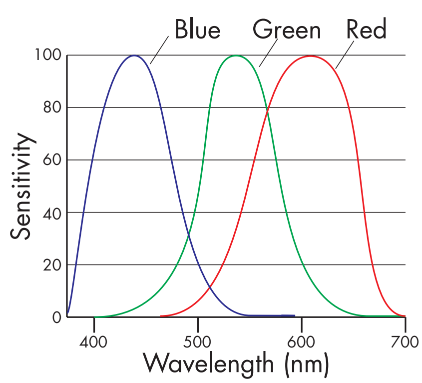
It is useful to remember that RGB and CMY are simple transformations of each other. In fact CMY can be thought of as a special form of RGB—one that uses **negative** quantities of red, green, and blue. This relationship simplifies some of the ideas presented in the rest of this Primer.

The key idea to remember is that three primary colors seem to be enough. There is something about the human eye that lets you fool it into thinking it's seeing all possible colors, when in fact you are using only three but combining them in different ways.

The Eye, and other observers

Getting back to RGB, what Young, Maxwell, and Helmholtz described was essentially that the human eye is an RGB "device." This means that we literally have three types of color receptors (called cones) in our eyes: one that is most sensitive to the "red" region of the spectrum, one to the "green" region, and one to the "blue" (see sidebar). So if you were to plot the sensitivity of the three types of cones as they relate to wavelength, you might see the following spectral curves.

A first approximation of the spectral curves of the R, G, and B receptors in our eyes. As long as the curves overlap in certain ways, any color in the spectrum can be identified by how much it stimulates each of the three receptors.

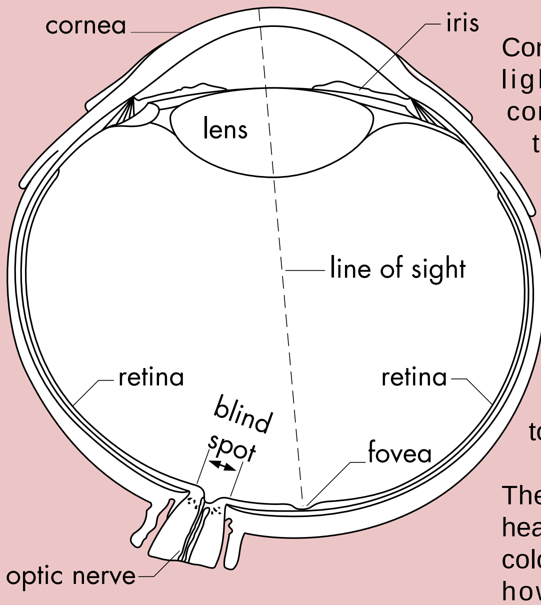


In actuality, the way our visual system reacts to the three primaries is determined by a lot of other factors besides the sensitivity of the individual cones—factors such as the relative populations of the three types of cones in the retina, and the way the signals from the receptors are mixed in the nerve pathways and interpreted by the brain. We can use color-matching experiments like that shown on page 17 to measure the mixtures of the three primaries that we need to match given stimuli.

The Human Eye—Who are you callin' a "Trichromat"?

Cross-section of the right eye as viewed from above.

The human eye is such a marvel of design that it has been suggested that the brain may have evolved as an appendage to the eye—a form of overdeveloped optic nerve—rather than the other way around.



The *retina* at the back of the eye is a network of specialized nerve cells that respond to light—called appropriately enough *photo-receptors*, or simply *receptors*. There are two types of photoreceptors, known, because of their shape, as *rods* and *cones*.

Rods are much more sensitive in low-light conditions (night vision) and are only minimally involved in color vision. At the tip of each rod are molecules of a protein called *rhodopsin* which is key to the rods' sensitivity to light. Because it reacts to light, rhodopsin is known as a form of photopigment.

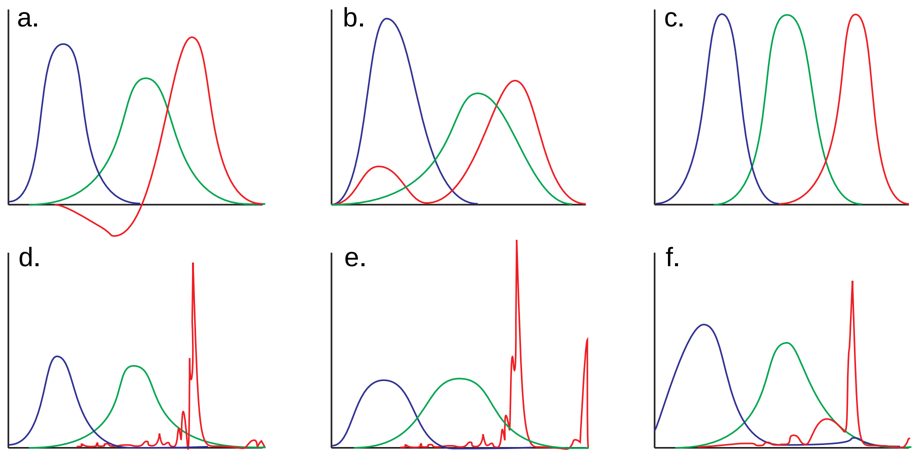
Cones are more sensitive at levels of light associated with daylight conditions. Instead of rhodopsin, there are three types of photopigments found in cones, each sensitive to different parts of the visible spectrum—corresponding generally to the red, green and blue regions of the spectrum. Each cone contains one of these three photopigments, and thus we refer to R cones, G cones, and B cones.*

These three types of cones are the heart of our color vision—and why all colors are representable in terms of how much these three types of receptors are stimulated. This is called the *trichromatic theory of human vision*, and most people are called *trichromats*. Many of us (mostly males) exhibit some form of what is misleadingly called "color blindness," but is usually a deficiency—not a total lack—of one of the three types of cones.

* Interestingly, it appears that R and G cones are much more prevalent than B cones.

Similarly, we can also draw the red, green, and blue color-mixing functions of all RGB devices, such as scanners, digital cameras, and monitors. The result is a wide array of red, green, and blue color-mixing functions:

Red, green, and blue color-mixing functions for the human eye and other RGB devices. All can represent any color using quantities of R, G, and B, but every device has a different definition of how these quantities are added together.



a. Color-matching function for a human observer. b. Color-matching function transformed to the CIE Standard Observer (see page 33). c. Spectral response for a desktop scanner. d, e, f. Spectral sensitivity of three monitors.

The important thing to note from all of these is that every type of "observer" can have slightly, or radically, different responses. The definition of "RGB" is not a fixed standard.

What is Tristimulus?

As we've seen, RGB and CMY are examples of how all colors in the spectrum can be described in terms of three values. These are examples of tristimulus descriptions of color. Besides being fun to use at parties, the word "tristimulus" is important to understand as it cuts to the heart of the world of color measurement. Just about every form of color measurement (including observation by the human eye) is tristimulus. The key exception is spectral data. So if there is an underlying theme to this Primer—in fact, to ColorShop and the instruments it supports—it is the difference between spectral and tristimulus descriptions of color.

Here's our definition: **A *tristimulus* description of a color is one that defines the color in terms of three quantities, or *stimuli*.**[7]

[7] The word 'stimuli' is the plural of 'stimulus' (as if you didn't know).

Tristimulus does not necessarily mean three primaries. For example, as we're about to discuss in the next section, colors can also be described in terms of three characteristics, hue, saturation, and brightness. These characteristics are stimuli, but not primaries.

Tristimulus descriptions of color have certain advantages over spectral data: tristimulus models human vision, and can be plotted in three dimensions (see "What is a Color Space?" below).

However, there are disadvantages as well:

Remember that the words "red," "green" and "blue" are just names we give to certain regions of the spectrum. The exact set of wavelengths that affect each of the detectors, and how much of each, depends on each device. The only requirements are that the curves overlap in certain ways, and that they cover the visible spectrum. In other words there are many possible primary sets and thus many possible tristimulus spaces.

Another disadvantage is that any tristimulus description of the color of a surface is dependent not only on the characteristics of the surface, but also of the light source used to illuminate it.

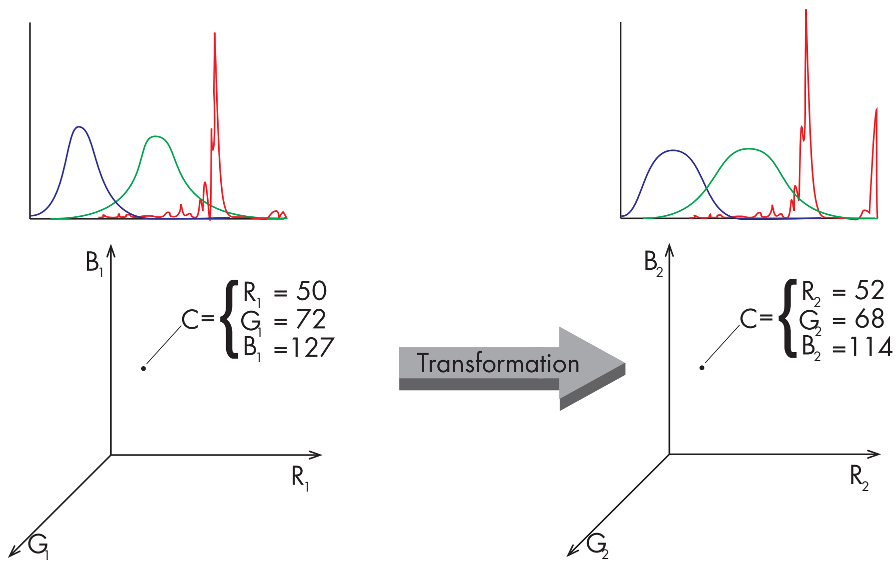
All of these problems are discussed in more detail in Chapter 3, "The Problems: Reproduction and Communication."

What is a Color Space?

One of the advantages of a tristimulus description of a color is that it can be plotted in three dimensions. This means that every color can be represented by a unique point in space by interpreting the amounts of the three stimuli as coordinates relative to three axes.[8] The space defined by the three axes is called a color space. Colors in one color space are converted to another color space by use of a transformation.

[8] If you remember back to algebra, points can be plotted in a plane by using two axes (say x and y, or u and v). Points are plotted in space by using three axes (say x, y, and z, or in this case R, G, and B). If you change the axes, you get a new "space." A space used for representing colors—i.e. one that uses color primaries or other stimuli as axes—is a "color space."

Examples of tristimulus color spaces: Two distinct RGB color spaces, one for device 1 (say, my monitor), and the other for device 2 (your monitor). Color C has a different RGB definition on the two devices, so it has a different location in the two color spaces. In other words it has different *RGB coordinates*. A *trans-formation* is a function that converts RGB coordinates from one device's color space to another.



A color space is an example of a more general concept called a color model. These are all just convenient ways to talk about colors and their relationships to each other.

HSB AND ITS RELATIVES

In this section we discuss the HSB (hue, saturation, brightness) model of color description. But before we do, let's take a look at an important historical precursor to HSB, the Hue / Value / Chroma cataloging system of Albert Munsell.

The System of Albert Munsell

In our last episode, Helmholtz drew the first diagram of the spectral response for the three types of color detectors in the human eye. We left our scientists measuring spectral responses for human photoreceptors.

While the scientists are busy, let's look at another approach, epitomized by an artist, Albert H. Munsell (1858–1918), at the turn the century.[9] Munsell was less concerned with the physiology of color, and more with perceived relationships **between** colors. He set out to find a system of organizing and defining colors based on human perception of color differences and relationships. He developed a system with which he could discuss and manipulate such concepts as complementary colors, balance, and color combinations.

Munsell's system (see sidebar) is notable for several reasons:

1. It separates the color-independent component, brightness (Munsell value), from more clearly color-related characteristics of hue, and saturation (Munsell chroma). This allows you to represent colors in two dimensions—i.e. as a color wheel on a page. (See "HSB" below.)

2. It is perceptually uniform. Distances between color swatches in the tree correspond to perceived differences between the colors.

3. It provides a clear and unambiguous notation for communication of colors. Rather than vague subjective terms like "periwinkle blue" and "mauve", every color has a specific location in Munsell's system. This is the same idea behind color swatching systems such as PANTONE®.

4. It is still widely used today.

HSB

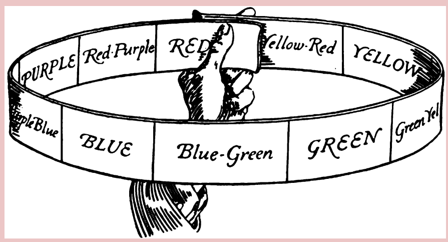
There are numerous relatives of Munsell's Hue / Value / Chroma (HVC) system found in many computer software applications. The reason for this is that RGB—although ideally suited for computer peripherals like monitors and scanners—is not a very intuitive system for editing colors. For example, imagine trying to adjust red, green, and blue sliders to make a "peach" or a "mustard" color.

One of the most common color systems available in computer applications is Hue / Saturation / Brightness (or HSB). Rather than describing an individual color as a combination of other colors (primaries), we can instead describe three perceptual properties of the color: hue, saturation (what Munsell called chroma), and brightness (what Munsell called the color's value).

[9] This is not to ignore other systems such as the elegant and powerful color system of Wilhelm Ostwald or the groundbreaking work of M. E. Chevreul, but Munsell's system is the one most commonly used today. For an excellent survey of the history of color systems, see Birren (1963), or Birren's introductions to the work of Munsell and Ostwald.

Munsell Notation

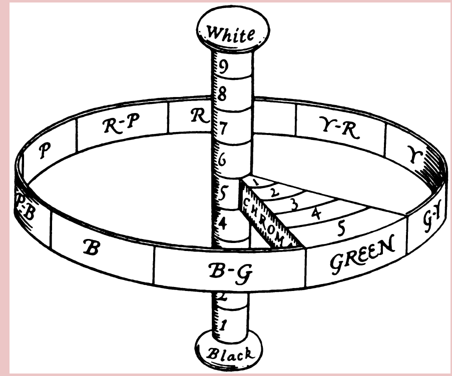
Munsell started by taking the visible spectrum of hues and “bending” it into a circle so that red lines up next to violet. Then, using a more metric (base 10) system than Newton’s seven colors, Munsell divided the color circle into ten equal regions by naming five main hues (Red, Yellow, Green, Blue, and Purple) and five intermediate hues (Yellow-Red, Green-Yellow, Blue-Green, Purple-Blue, and Red-Purple).



Two illustrations from A Grammar of Color (1921) by T. M. Cleland, one of America’s foremost graphic artists and an admirer of Munsell.

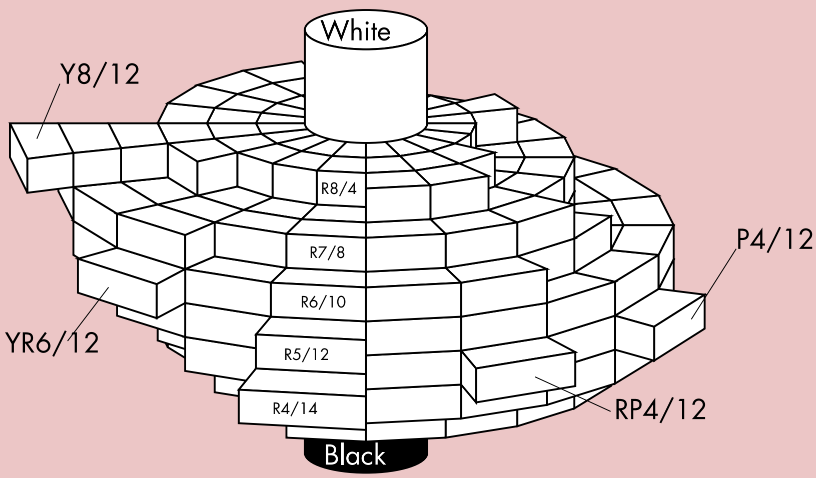
In the center of the circle, Munsell envisioned a vertical pole, ranging from 0 (black) at the bottom to 10 (white) at the top, with intermediate shades of neutral gray in between. This represented the *Munsell value* (brightness) scale.

The distance outward from this central axis was divided into uniform steps, starting with 0 at the center. This distance represented the *chroma* (saturation) of the hue.

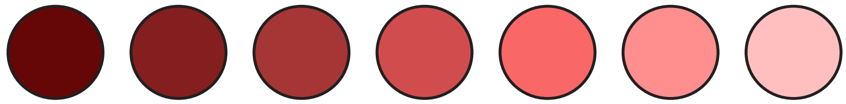


A color is identified in the Munsell notation as the Hue, followed by the Value and Chroma separated by a slash. So “R 9/3” represents a red hue, very bright, and not very saturated—i.e. pink. “RP 3/10” would be a red-purple hue, rather dark, and completely saturated—i.e. a rich burgundy color.

Munsell noted that the maximum perceived chroma (the distance from the center) was different from hue to hue. So rather than forming a perfect sphere, the resulting solid of perceivable colors is quite asymmetrical.

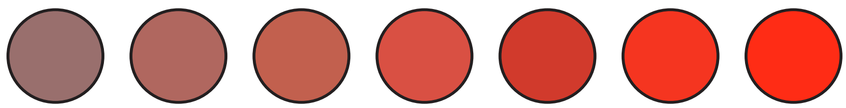


- **Brightness**: Let’s start with the easiest to define. **Brightness** (and a closely related concept, lightness)[10] is the property of a color by which it appears to contain more or less light. At one extreme is black (no light), and at the other is white (pure light), and in between are different shades, from darkest to lightest, of a given color.



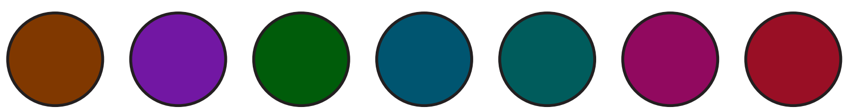
These seven patches differ only in brightness values.

- **Saturation**: This is the degree to which a color appears to be pure—containing no white or gray. A vivid rose color is extremely saturated, a pale pink is not. Unsaturated colors appear to be diluted with quantities of neutral gray. Saturated colors seem to be composed of light of a single wavelength.



These seven patches differ only in saturation, from least saturated to completely saturated.

- **Hue**: This is perhaps the hardest to define as many people consider this synonymous with “color.” **Hue** is the property of a pure color that distinguishes it from other pure colors, and thus the property that gives a color its principal name, such as “red”, “yellow”, or “blue-green.” Thus hue is that property associated with wavelength.

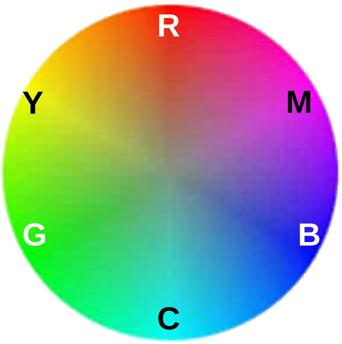


These seven patches differ primarily in hue (they all have similar brightness and saturation).

The Color Wheel

To really get a feel for what we mean by “hue”, and how it relates to the other two attributes of saturation and brightness, we should look at the color wheel.

[10]Color scientists often make a careful distinction between the terms brightness and lightness. Brightness is a more absolute description of light intensity. Lightness is a relative term: it refers to the intensity of light **as compared to some reference white**—for example, the intensity of a printed color compared to the intensity of the white paper illuminated by the same light source. In other words, theoretically there is no maximum brightness value (for example, even the sun pales in brightness value to many other astronomical bodies), while lightness values always range from 0% to 100% of the reference white. However, this distinction is often ignored in computer applications. You will often see both ‘Brightness’ values and ‘Lightness’ values ranging from 0%–100% or from 0–255.



The color wheel

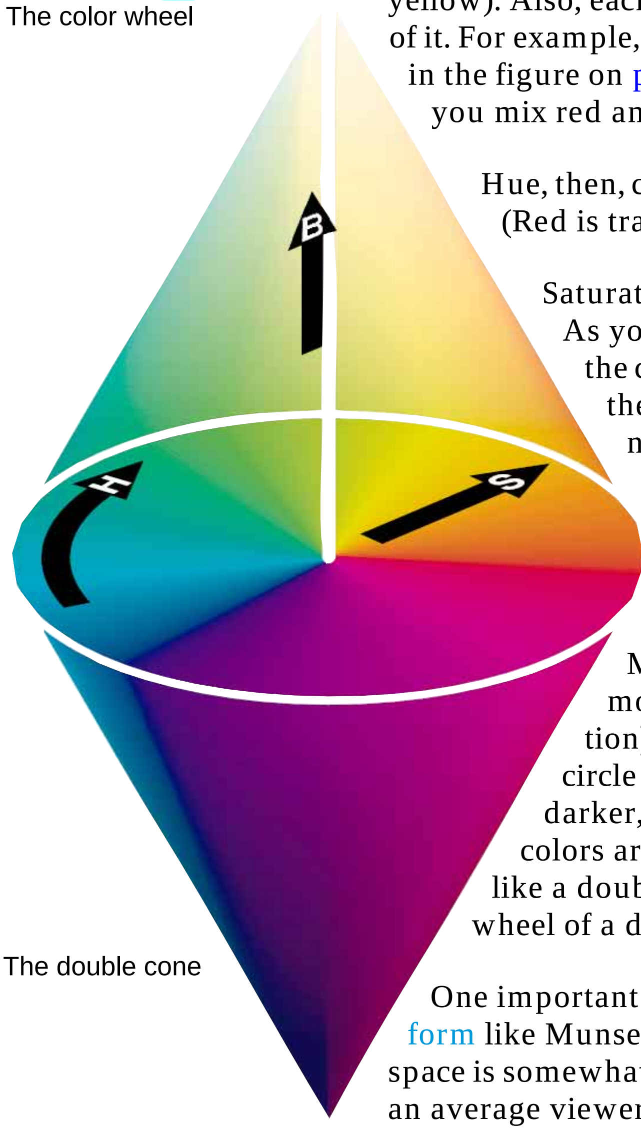
Munsell was not the first person to bend the colors of the spectrum into a circle (see sidebar page 26). It was our old friend Sir Newton who first sketched a color wheel as a device for organizing colors.

The most common way that a color wheel is organized, is to place the three additive primaries (red, green, and blue) as far away from each other as possible—i.e. in a triangle—and between them the subtractive primaries (cyan, magenta, and yellow). Thus, each color is opposite its complement on the circle (for example, blue is opposite yellow). Also, each color is a mixture of the two colors on either side of it. For example, between green and red is yellow which, as shown in the figure on page 18 (the additive primaries), is what you get if you mix red and green light.

Hue, then, can be viewed as the angle around this color wheel. (Red is traditionally at 0˚, which puts cyan at 180˚, etc.)

Saturation can be viewed as the distance from the center. As you move away from the edge of the circle towards the center, this is the same as adding more and more of the color's complement, eventually approaching a neutral gray, colorless center.

So what about brightness (or lightness)? To envision brightness or lightness we just bring in the third dimension and imagine a pole protruding out from the center of the circle (very similar to Munsell's value in the sidebar on page 26). As you move up the pole, the overall circle (the cross-section) gets brighter, and as you travel down the pole the circle gets darker. As the color wheels get brighter or darker, they also get smaller (as very bright and very dark colors are less saturated). The resulting solid looks much like a double cone—each cross section of the cone is a color wheel of a different brightness or lightness value.



The double cone

One important thing to note is that HSB is not perceptually uniform like Munsell's system. The distances between colors in HSB space is somewhat arbitrary and has little correlation to how "close" an average viewer might consider the colors.

The difference between HSB, HSL, HLS, HVC, HSV, etc. etc.

Although HSB and Munsell's HVC are based on the same ideas, they are not exactly the same notation.

In HSB, Hue is expressed as an angle from 0°–359° (the angle around the color wheel). Saturation and Brightness are expressed as percentages from 0%–100%.

In Munsell's HVC color system, Hue is also the angle around the color circle, but Munsell uses the notation "2.5R", for example, to represent the hue two-and-a-half steps around the circle from Red. Munsell's Value and Chroma (corresponding to Brightness and Saturation) are each expressed as numbers from 0 to 10 (see sidebar on page 26).

Although HSB is the most common form of hue-based color system seen in most computer applications (for example Photoshop), there are many other relatives that you may encounter.

For example one of the default components in the Apple Color Picker is **HLS Picker**. HLS is similar to HSB, except that Brightness is labeled Lightness.

We won't go into the many other variants that exist other than to mention their abbreviations in case you encounter them. Some examples seen in assorted literature, software applications, and measurement devices are HSV, LHS, HLS, and HSC. Although in most cases these are simply reordered or relabeled forms of Hue / Saturation / Brightness, you should also make sure that the notation and ranges of the possible values are clear before you use them to specify colors or compare them to HSB values displayed using the Colorimeter Tool.

The relationship between RGB and HSB

There is no direct way to measure the hue or saturation of a surface (although we can measure the "brightness" of a surface by measuring the overall amount of light leaving the surface). Instead, HSB values are derived directly from RGB. The conversion between RGB and HSB is a straightforward computation, but the details aren't important here.

However it is important to note that since HSB is computed directly from RGB, it inherits the same limitations. For example, just as the same RGB values will look very different on different monitors, the same holds for HSB values. Just as you must adjust the RGB values to achieve the same appearance on two different monitors, the derived HSB values will also be different.

This characteristic that HSB has in common with RGB will become important when we discuss **device dependence** on page 48.

A note about terminology—is HSB tristimulus?

There is sometimes a disagreement in various glossaries and scientific literature, over the meaning of the word "tristimulus" as to whether this should include HSB, or whether the term should only be used to refer to color descriptions made in terms of three primaries, such as red, green and blue. It's a subtle, semantic argument, and (we have to admit) not that important because (as we've just discussed) HSB can be considered a simply derived form of RGB.

In this Primer document we use the word tristimulus in the more general meaning of any definition of a color in terms of three values. We use the word trichromatic if we specifically mean a description of a color in terms of three primary colors. In other words, a trichromatic color space like RGB is a special case of tristimulus.

ENTER THE CIE

The previous two sections introduced several tristimulus color spaces: RGB, CMY (and its derived form CMYK), and HSB (and its alter egos HSV, etc.). We saw that all of these could be derived from RGB. However, we also saw that RGB had a drawback: every device—every human eye, every scanner, every monitor, every printer—has a slightly different definition of RGB. This means that there are literally hundreds of tristimulus color spaces—each one is beautifully suited for a particular purpose, and it is straightforward to convert from one to another, but none stands out as the perfect standard for general use.

In this section we will discuss how an organization of color scientists, the CIE, has attempted to solve this problem by devising a new tri-stimulus color system related to RGB, but "better" in certain ways. This is based on a system called XYZ. Although you may never have occasion to use CIE XYZ directly—it is primarily used only by color scientists and internally within certain computer programs—it is useful to become acquainted with the problems it solves.

The CIE

Getting back to our scientists, whom we last saw busying themselves with obtaining data to support their theories on color and the physiology of perception, we take you now to 1931 and an important convening of the minds to agree on a basic system of color specification.

The *Commission Internationale de l'Éclairage*,[11] or CIE, is considered by many the clergy of color science. Each year, scientist delegates from various countries convene in a different city and exchange research and debate issues related to the science of human perception.[12] The goal of the CIE is to develop a system to enable manufacturers of paints, dyes, inks, fabrics etc. to specify and communicate the colors of their products.

1931 and 1976, two very busy years

One of the key meetings in the history of the CIE happened in September of 1931 in Cambridge, England. This was one of the first comprehensive attempts to use the body of available data to devise a system that completely specifies the lighting and viewing conditions by which a color is viewed and measured.

[11]If your French is limited (like the author's), this translates to the "International Commission on Illumination." Although occasional English texts refer to this as "the ICI" instead of the CIE, this is relatively rare, and in many circles, frowned upon.

[12]For an entertaining and—dare we say it—illuminating first-hand account of the events at and leading up to the 1931 CIE convention, see the appendix by W.D. Wright of Imperial College in London, on page 397 of Robert Boynton's superlative book "Human Color Vision" (Boynton [1992]). (See Bibliography.)

Among other things, the 1931 CIE system specified:

- The Standard Observer. A definition of an “average” human observer,.
- Standard Illuminants. A specification of certain light sources to use for color comparison.
- The CIE XYZ primary system. A system of imaginary primaries related to RGB, but better suited to use as a computational standard.
- The CIE xyY color space. A color space derived from XYZ that separates color related attributes, x and y, from luminance related (brightness) attribute, Y.
- The CIE chromaticity diagram. A graph that makes it easy to see certain relationships between colors.

Subsequent years saw considerable refinement of this system, including a revision of the Standard Observer definition in 1964.

If there is a second key year that we would put on the midterm exam, our choice would be 1976. This was the year that saw the introduction of:

- More perceptually uniform color spaces, CIELAB and CIELUV, which gives us a way to assess how “close” two colors are to each other.
- A that allows us to apply a number (ΔE) to the concept of color “closeness.”

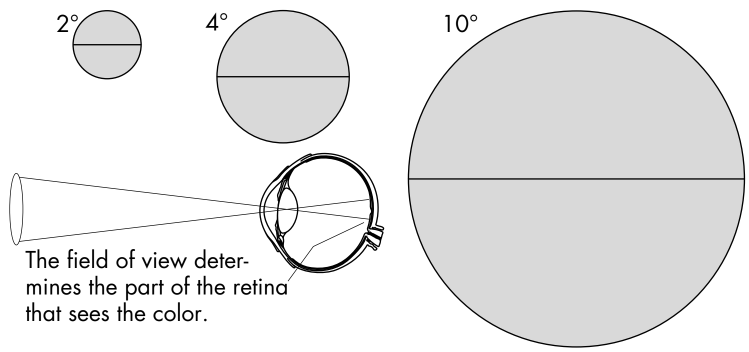
This of course is a gross and unforgivable oversimplification of what the CIE has done. But this is, after all, a Primer. Interested readers are encouraged to refer to other more thorough descriptions of the CIE and the CIE system, many of which are included in the Bibliography. For now, we describe a few key points about each definition.

Standard Observers (2° and 10°)

One of the most obvious requirements for specifying standards of measurement is to define the observer. Many studies have been made using volunteer test subjects peering into color matching apertures (like that in the sidebar on page 17) to determine a definition of "normal" color vision.

One factor that can affect color sensitivity in the eye, even within a single normal observer, is the field of view.

The field of view defines the size of the field being viewed. If you look at a printout of this page at a distance of about 10 inches (25 cm) from your eye, the three circles give you an idea of what a 2°, 4°, and a 10° field of view look like.



The 1931 definition of the Standard Observer was based on a 2° field of view and this is still the default standard used today.

In 1964 the data was reexamined as there seemed to be a discrepancy in the measurements—especially in the blue-green region of the spectrum—for angles of view wider than 2°. The reason for this discrepancy is interesting: At the very center of your retina is a region called the fovea (see sidebar on page 21). This is the only region where cones (the color receptors) far outnumber rods (receptors used for non-color night vision). Thus, if the field of view is wider than about 4°, color vision involves lower concentrations of cones. The actual difference is extremely subtle and is rarely noticeable. However, as it is measurable, the CIE concluded its 1964 meeting by adding a Supplementary Standard Observer, based on a 10° field of view to be used when viewing fields wider than 4°.

So now any specification of CIE color values must specify whether the values are relative to the 1931 2° Standard Observer, or the 1964 10° Supplementary Standard Observer. If not specified, the 2° observer is assumed. CIE values in ColorShop are all computed relative to the 2° Standard Observer.

Standard Illuminants

In order to specify completely the viewing conditions under which colors are viewed, it is necessary to specify the light source illuminating the target. The CIE in 1931 specified three Standard Illuminants A, B, and C, to which were later added a series of D illuminants, a hypothetical E illuminant, and unofficially, a series of fluorescents, F. The Standard Illuminants were specified as tungsten light sources reproducing certain correlated color temperature (see sidebar).

Color Temperature—What does "white" really mean?

One system commonly used to characterize emissive light sources uses the concept of *color temperature*. All objects, when heated, emit light—a result of cooling molecules releasing energy in the form of light. Yes, even as you sit there at a normal body temperature of 98.6°F (310.15°K),* you are emitting radiation—although at long wavelengths in the invisible infrared region of the spectrum.

So scientists imagine a hypothetical object, called a *black body*, that does not reflect or transmit any light. In other words, a black body is a perfect absorber of all wavelengths, so that any light leaving its surface must be emitted light.

Scientists can compute the wavelength composition of light emitted by a black body as it is heated. The transitions are smooth and predictable: at about 2400°K the emitted light is red; as we heat up to 4800°K the light is a more even yellow; at 6500°K the light is fairly neutral (an even distribution of all wavelengths); at 9300°K the light has a distinctly bluish tinge. Higher temperatures still appear bluish, since the additional radiation they produce is at wavelengths too short to see—for example, the gamma rays produced in the cores of stars.

This gives us a naming system for describing emissive light sources. The spectral distribution of a light source can be measured and characterized as 2800°K (for example, a 75W light bulb), or 6500°K (daylight). Computer monitors and television sets have a characteristic *white point*. For example, a monitor with a white point of 9300°K produces a slight bluish cast, while a white point of 4800°K has a yellow cast. Because this description is only approximate—as most emissive sources in the real world do not behave as true black bodies—this is called the *correlated color temperature*.

Keep in mind that this naming system applies only to emissive objects—not to reflective or transmissive objects—as this black body model approximates the molecular process at work within emissive bodies.

* Temperatures in physics are usually given in the *Kelvin* scale, which measures temperature relative to *absolute zero* (0°K=−273°C), the temperature of zero atomic activity. In the scientific community the recent trend is to drop the degrees so that 6500°K becomes 6500 K and is pronounced either "6500 Kelvin" or "6500 kelvins." However, in ColorShop we still use the degree symbol as this is the notation used in other computer applications—perhaps because in the computer world, 'K' represents "kilobytes."

The illuminants A–F can be summarized as follows:

A: A tungsten light source with correlated temperature of about 2856°K producing a yellowish-red light.[13] Standard Illuminant A is generally used to simulate incandescent viewing conditions (such as household light bulbs).

B: A tungsten light source coupled with a liquid filter to simulate direct sunlight with a correlated temperature of about 4874°K. Standard Illuminant B is rarely used today.

C: A tungsten light source coupled with a liquid filter to simulate indirect sunlight with a correlated temperature of about 6774°K. Standard Illuminant C is used in many viewing booths as indirect sunlight is considered a common viewing condition. However, illuminant C is not a perfect simulation of sunlight as it does not contain much ultraviolet light, which is needed when evaluating fluorescent colors.

D: (Daylight illuminants.) Actually a series of illuminants. Standard Illuminant D_{65} is nearly identical to Standard Illuminant C except that it is a better simulation of indirect sunlight as it includes an ultraviolet component for better evaluation of fluorescent colors. Other D illuminants are named according to their correlated color temperature. For example, D_{50} and D_{75} correspond to color temperatures of 5000°K and 7500°K respectively. Standard Illuminants D_{65} and D_{50} are by far the most common illuminants found in modern viewing booths.

E: (Equal-energy illuminant.) Standard Illuminant E does not actually exist. Instead, color scientists sometimes refer to a theoretical light source with equal amounts of energy at each wavelength.

F: (Fluorescent illuminants.) This is a series of fluorescent light sources not officially called Standard Illuminants—fluorescent lights have sharp peaks in their spectral curves and thus defy definition by color temperature. However, since viewing conditions using fluorescent lighting are common, the CIE recom-

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[13] A tungsten light source is a very stable form of incandescent light. An incandescent lamp—exemplified by a household light bulb—works by controlled burning of a filament.

mends certain light sources for evaluating colors destined for fluorescent environments. The fluorescent illuminants are labeled F1 through F12, of which the CIE recommends F2 (cool white fluorescent), F7 (daylight fluorescent), and F11 (a narrow-band fluorescent).

So, in addition to the Standard Observer, all specifications of CIE colors are based on the illuminant used for measurements.

XYZ—CIE tristimulus values

The CIE XYZ color space defines all colors in terms of three imaginary primaries X, Y, and Z based on the human visual system. Although rarely used directly—except by color scientists and internally within certain computer programs (for example ICC Color Matching Methods)—the XYZ primary set is the foundation of the CIE system.

Remember that many primary systems (like RGB for any particular device) are all equally valid. All can be converted from one to another with a little math. Therefore scientists can pick any set of primaries that they want. The CIE chose a set of primaries they called X, Y, and Z, defined so that they possess the following properties.

1. It is based on experimental data of human color matching. This makes sure that the system accurately predicts when a viewer would consider two colors to be equal.

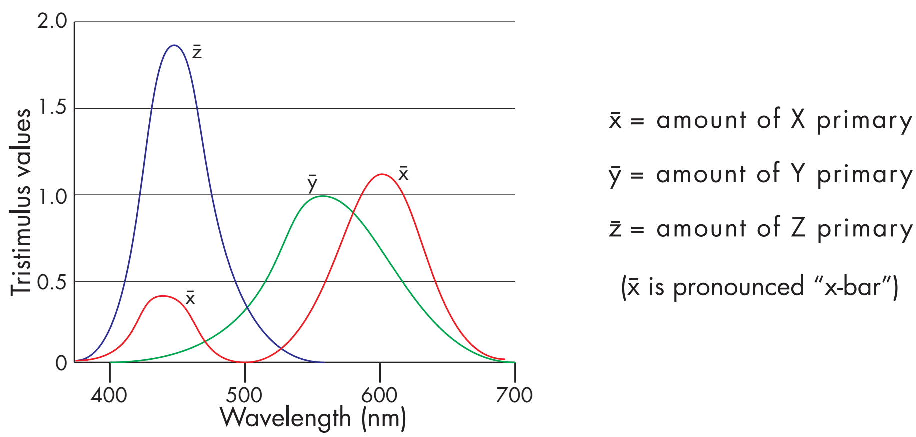
2. As a group, X, Y, and Z work like additive primaries RGB. In other words every color is expressed as a mixture of quantities of X, Y, and Z.

3. Separately, one of the three values, Y, represents luminance, the overall brightness or lightness of the color as a function of wavelength. (Some wavelengths, such as in the yellows and greens in the middle of the spectrum, appear “brighter” than the extremes of the spectrum, the deep blues and reds. As an illustration of this look at a black-and-white photograph of a color scene. Those colors with the lowest luminance appear darkest, while those with the highest luminance appear lightest.)

4. All color values are positive. In other words color matching experiments do not produce matches that require a negative quantity of one of the primaries. (For a description of the notion of “negative” amounts of light, see sidebar on page 17.)

The definition of the XYZ primaries is built right into the specification of the 1931 Standard Observer. In other words the CIE defined a set of color-matching function for the Standard Observer—a set of three curves representing how the tristimulus primaries must be combined to reproduce all the colors in the spectrum.[14,15]

Color-matching functions (CIE tristimulus values) for the 1931 2° Standard Observer.



[14]The derivation of these color matching functions from experimental data is clever, but complicated and not essential for the purposes of this Primer. However, if you’re interested, they are based on color matching experiments using three primary light sources (very narrow-band light sources at the arbitrary points, 435.5nm, 546.1nm, and 700.0nm), to match pure colors across an equal-energy spectrum (one where every wavelength band of equal width contains the same amount of energy). For more information, see sources such as Boynton (1992), pages 390–397. (See Bibliography.)

[15]If this diagram seems familiar, it may be because these curves are so fundamental to the science of color measurement that X-Rite has adopted this diagram as the basis for its corporate logo.

xyY—The CIE chromaticity diagram

The xyY color space is derived directly from XYZ and is used to graph colors in two dimensions independent of lightness. The value Y is identical to the tristimulus value Y (in XYZ) and represents the luminance, or lightness, of the color. The x and y values are called the chromaticity coordinates of the color and are computed directly from the tristimulus values XYZ.[16]

In other words, the CIE borrowed a page from Munsell and separated the lightness attribute of a color—what we call its achromatic component—from the strictly color-related, or chromatic components. Two colors that are the same except for how bright they are, have the same chromatic definition, and therefore the same chromaticity coordinates.

The xyY values of colors can be plotted in a useful graph known as the CIE chromaticity diagram. In a sense, this diagram is the payoff for the rather intricate CIE system because it provides a clear map of the range of visible colors.

When we convert and plot the xy chromaticity coordinates of the pure wavelengths of the visible spectrum, the resulting points all fall on a horseshoe-shaped line known as the spectrum locus. By definition, since all visible colors are composed of mixtures of these pure wavelengths, all visible colors must be located within the boundary formed by this curve.

The line formed by connecting the endpoints of the horseshoe is called the purple line or “purple boundary.” Colors on this line are composed of mixtures of pure 380nm (violet) and 770nm (red) light.

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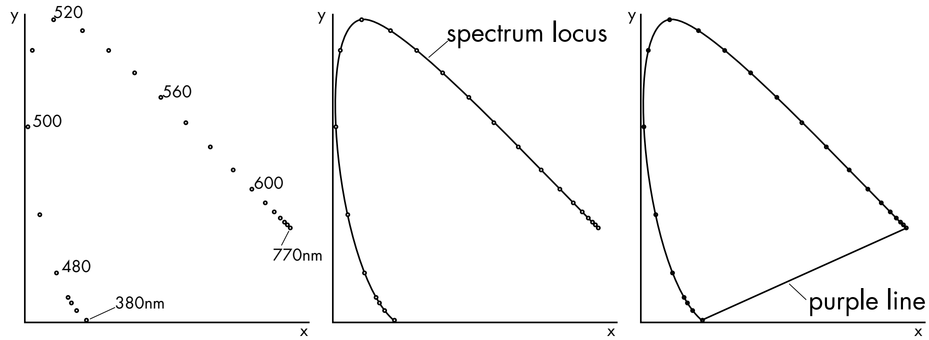
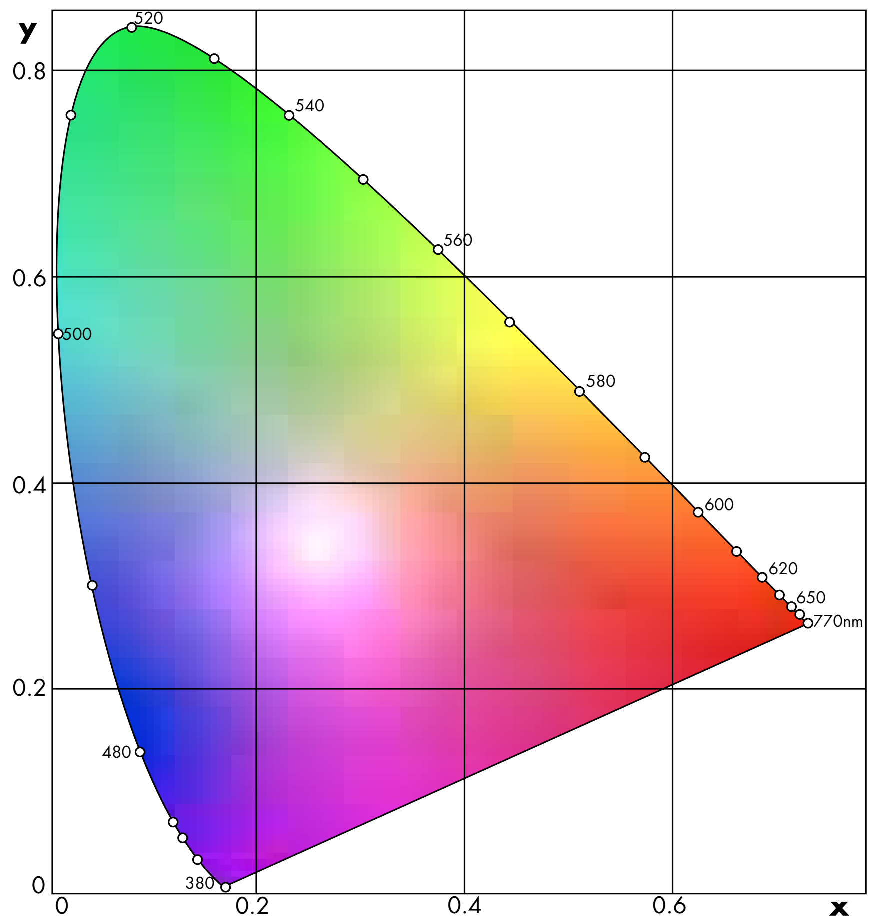
[16]The derivation of xyY coordinates from XYZ is not important for the purpose of this Primer—the ColorShop Colorimeter Tool computes xyY values for you. Nevertheless, this is actually quite simple, but as we’ve promised no math we list it here only as a footnote for those who are interested: The idea is a rather clever mathematical trick called **projecting onto a plane**. For any color, we define three values x, y, and z by taking its X, Y, or Z value (respectively) and dividing by X+Y+Z. In other words: $x = X / (X+Y+Z)$, $y = Y / (X+Y+Z)$, and $z = Z / (X+Y+Z)$. Then, with a little algebra you can see that $x + y + z = 1$. This means that from any two of these values, usually x and y, the third one, z, can be derived. The beauty of this is that we can plot x and y in a two-dimensional graph that contains all the color information of our original X, Y, and Z values. Then, if needed, the third dimension (the axis going in and out of the page) is available to graph Y, the tristimulus value (of XYZ) representing the luminance or lightness of the color.



Construction of the CIE chromaticity diagram.



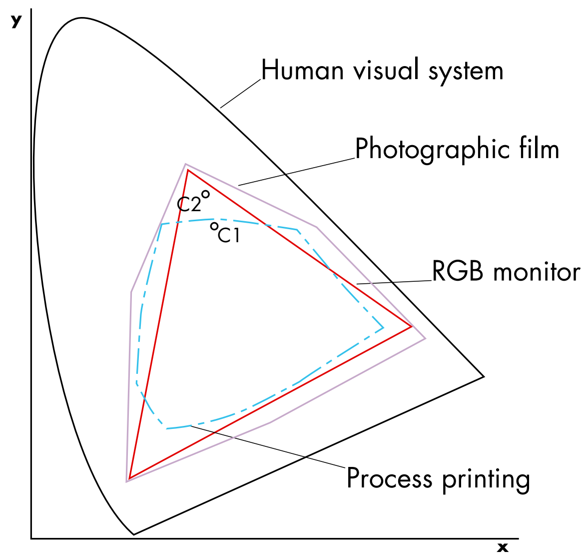
The CIE 1931 xy chromaticity diagram with color added to illustrate the geography of our visual palette. (Note that the colors that appear here are representative only—in other words, subject to the limitations of the display process or printing process used to display or print this page.)

Notice the similarity between this diagram and the color wheel on page 28. The center of the horseshoe is neutral. As colors move away from this center to the edges, the colors become more saturated, until at the edges the colors are pure spectral colors. The hue changes as you move around the edge of the horseshoe shape.

The difference between the CIE diagram and the color wheel is that it gives you a clear view of what is visible and what lies outside of what we can see. Anything below the purple line appears to be black (or in techie terms, has zero luminance), and anything outside the horseshoe region is meaningless (in other words, it cannot be produced by physical means, since the horseshoe represents the fundamental building blocks of color—the pure wavelengths of light itself).

For any device such as a monitor or printer, we can plot its gamut—the colors that are reproducible using the device's primaries. This is one of the most common uses for the CIE diagram and you may often encounter gamut comparisons like the following:

A chromaticity diagram showing the color gamut of a typical computer monitor and printer. Colors outside the gamut are simply not reproducible given the primary set used by the device. For example, the printer in this case cannot make colors C1 and C2 look different—C1 is as "green" as the printer can print.



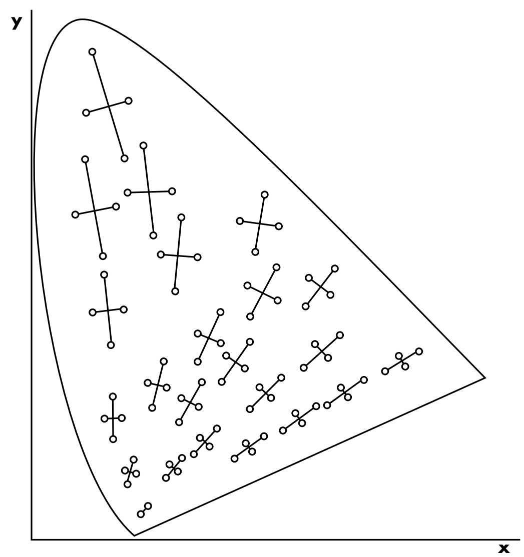
The concept of device gamut is discussed further in the section "Device gamut and gamut mapping" on page 49. However we will note here that most man-made pigments occupy a certain subset of the entire diagram. For example, many of the greens in the large lobe at the top left of the diagram are colors you will never see in a photograph, printed piece, or computer display. The size of this green region is exaggerated because the mathematics of xyY do not model **distances** between colors.[17] This is a problem we address next.

[17] This is analogous to maps of the world that, because of how they must distort a sphere to represent it on a flat page, tend to show Antarctica much larger than it really is relative to the other continents.

LAB and LUV—attempts at perceptual uniform color spaces

The CIELAB and CIELUV color spaces are attempts to create a perceptually uniform color system—one in which the distance between any two colors in the color space corresponds to the perceived "closeness" of the two colors.

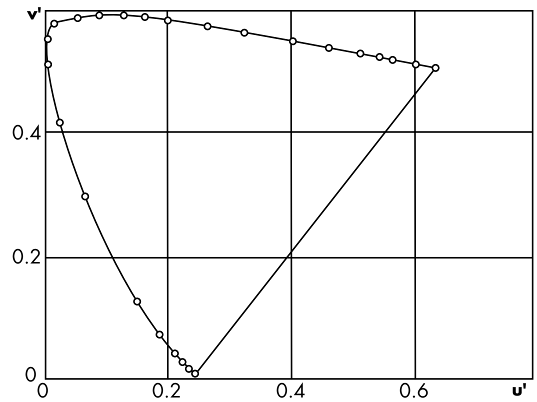
To understand the problem these color spaces address, we should look at the xyY chromaticity diagram. If we present our intrepid human guinea pigs with pairs of colors and ask them to assess how "close" they are to each other, we end up with an idea of a unit of "color closeness." We can then plot pairs of colors that are all equally "close" on our xy diagram.



CIE xy chromaticity diagram showing pairs of colors that human subjects would consider equally "close." Notice how we are more sensitive to small color changes in the purples and reds and less in the greens and yellows. This makes it harder to compute color matches, and is the problem addressed by CIELAB and CIELUV color spaces.

To solve this problem, the CIE borrowed another page from Munsell—the first being the separation of lightness from the strictly color-related—and attempted to create a perceptually uniform color system.

One attempt simply warped and rotated the 1931 chromaticity diagram a bit with some tricky math to produce something known as the UCS (uniform color scale) diagram. The new chromaticity coordinates derived from x and y, were named u and v in 1960, and, with an improvement to the UCS equations in 1976, renamed u' and v'.



The CIE 1976 UCS (uniform color scale) diagram. The values u' and v' are cleverly defined in terms of x and y to produce a more uniform chromaticity chart—distances correspond better to perceived color differences.

To solve the non-uniformity of the tristimulus value Y (the luminance), the CIE defined a “uniform lightness scale”, L*, derived from Y using a tricky equation using cube roots and measured constants (see the Appendix if you are interested). L* is similar to Munsell’s Value, V, in that it defines lightness from black to white in perceptually even steps. L* values range from 0 (black) to 300 (white).

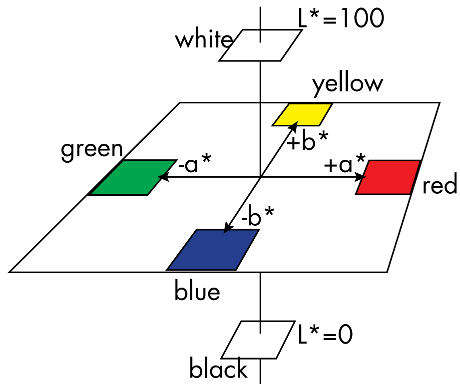
Using L*, u' and v', the CIE defined a color space called L*u*v*, often referred to as CIELUV, or simply Luv.[18] The CIELUV color space is much more perceptually uniform than xyY and is widely used today, especially in industries involving emissive products (like TV monitors, computer monitors, and controlled lighting sources.)

A second approach to finding more perceptually uniform chromaticity values, is to do the same thing we did with lightness. The CIE defined a* and b*, using tricky cube-root equations of X, Y, and Z. The a* value rather conveniently expresses a uniform redness-greenness scale of a color—a* values range from –300 (green) to +300 (red). The b* value expresses a uniform yellowness-blueness scale—b* values range from –300 (blue) to +300 (yellow).

[18]The values u* and v* are derived from u' and v', but as with most of this CIE discussion the mathematical details of this are unimportant (although given in Appendix A) since the ColorShop Colorimeter Tool computes these values for you. The asterisks in L*, u*, and v* are sometimes included for historical reasons, but are often dropped altogether when it is clear that we are talking about CIE uniform values. Similarly, L*a*b* is often written Lab.

The resulting color space is L*a*b*, which is often referred to as CIELAB, or simply, Lab.

The CIELAB color space.



The resulting chromaticity chart (the spectrum locus in the Lab space) is a bit difficult to draw here, and in any case is not commonly used to plot colors in the way the xy and Luv chromaticity diagrams are. However, the fact that it is very perceptually uniform, and has the convenient association between red-green and blue-yellow scales, has made CIELAB a popular choice in many industries working with reflective and transmissive products, such as the graphic arts industry. For example, Adobe Photoshop supports a version of CIELAB.

ΔE, the color difference

The beauty (and the whole point) of perceptually uniform color spaces like CIELAB and CIELUV, is that they allow us to calculate a number that represents how “close” two colors are to each other. This number is called the ΔE or “color difference” between the two colors[19] and the equation used to compute this is called the color difference equation.

Very simply, to compute how close two colors are to each other, we find the locations of both colors in either CIELAB or LUV space, and then find the distance between them. Because of how these color spaces are defined this number will correspond well with how

[19]The symbol Δ is the capital Greek letter *Delta* and is commonly used in science to represent a **change** or **difference** between two values. Thus ΔE is pronounced “delta-E.”

“similar” these colors appear to you (or your fussy client). For example, if you have two colors and you want to determine which one is closest to a third “target” color, compute their ΔE values relative to the target. The one with the smallest ΔE is probably the one you would select as being closest in appearance.

ΔE values have an obvious use in the industrial application known as color tolerancing. This is the problem of judging “how close is close enough?” when it comes to matching colors. In general, a color difference of 1 ΔE is defined as the threshold of what is just perceptible to the human eye, and there have been statistical studies that indicate that a color difference of 6 to 7 ΔE is often considered “acceptable” to buyers of print materials. The words “in general” must be stressed here as this is an attempt to quantify something that is obviously quite subjective—this cuts to the heart of the debate among color scientists about how accurately these color spaces model human perception across the visible spectrum and across viewing conditions, and the debate among print professionals about what is “acceptable” in various contexts. Nevertheless, as with any metric, as you gain experience with these numbers, they will become more and more useful to you as a general guideline for predicting results.

SUMMARY

The history of color science has seen numerous models by which colors can be described and compared. Each of these is an attempt to solve a certain problem, or predict some result.

There are two types of color descriptions: spectral and tristimulus.

- **Spectral data**: A measurement of the wavelength composition of light leaving the surface. This provides an absolute description of the color properties of an object—how it emits, reflects, or transmits all the wavelengths that comprise visible light.

- **Tristimulus**: A three-valued system that models the appearance of the color by the human eye and therefore must include a specification of the observer or similar device, the light source, and other aspects of the viewing conditions.

The tristimulus color spaces surveyed in this chapter are:

- **RGB**: A description of a color as a combination of three additive primaries spanning the red, green and blue regions of the color spectrum. RGB is used when describing color on certain devices that attempt to mimic the trichromatic properties of the human eye. Every device—every human eye, every scanner, every monitor—has a slightly different set of RGB primaries. Thus, there are as many forms of RGB as there are devices, and any RGB description of a color must specify the device.

- **CMY** (**K**): A description of a color as a combination of three subtractive primaries cyan, magenta, and yellow. CMY is used when specifying colors on devices—most commonly printers—where wavelengths are subtracted from white, rather than added to black as done with the additive primaries. In practice, CMY is often supplemented with black (K) to compensate for manufacturing limitations of ink. Because cyan, magenta, and yellow can be viewed as negative amounts of red, green, and blue respectively, CMY can be seen as a special case of RGB, and the same problems apply—any CMY (K) description of a color must specify the device.

- **HSB (and alter egos)**: A description of a color in terms of three attributes hue, saturation, and brightness, instead of as a mixture of primaries. This is based on Munsell's system—a special case of HSB that is perceptually uniform—that separates the chromatic, or color-related attributes hue and saturation, from the achromatic, or color-independent, attribute of brightness (also called lightness or Munsell value). HSB is generally used when editing RGB colors or visualizing relationships between colors as it is a bit more intuitive than RGB. HSB is directly computed from RGB, and thus any HSB description of a color must also specify an RGB device.

- **CIE XYZ**: A description of a color as a combination of three specially defined primaries X, Y, and Z. Although rarely used directly to specify colors, XYZ provides an unambiguous standard from which all other tristimulus color spaces can be computed. This is because the "device" relative to which all XYZ values are given is the Standard Observer, an average human viewer based on a composite of many human test subjects doing color-matching experiments under controlled viewing and lighting conditions. Thus, the only thing that must be specified with XYZ coordinates of a color are the field of view (either the 2° or 10° Standard Observer) and the illuminant (selected from a set of Standard Illuminants).

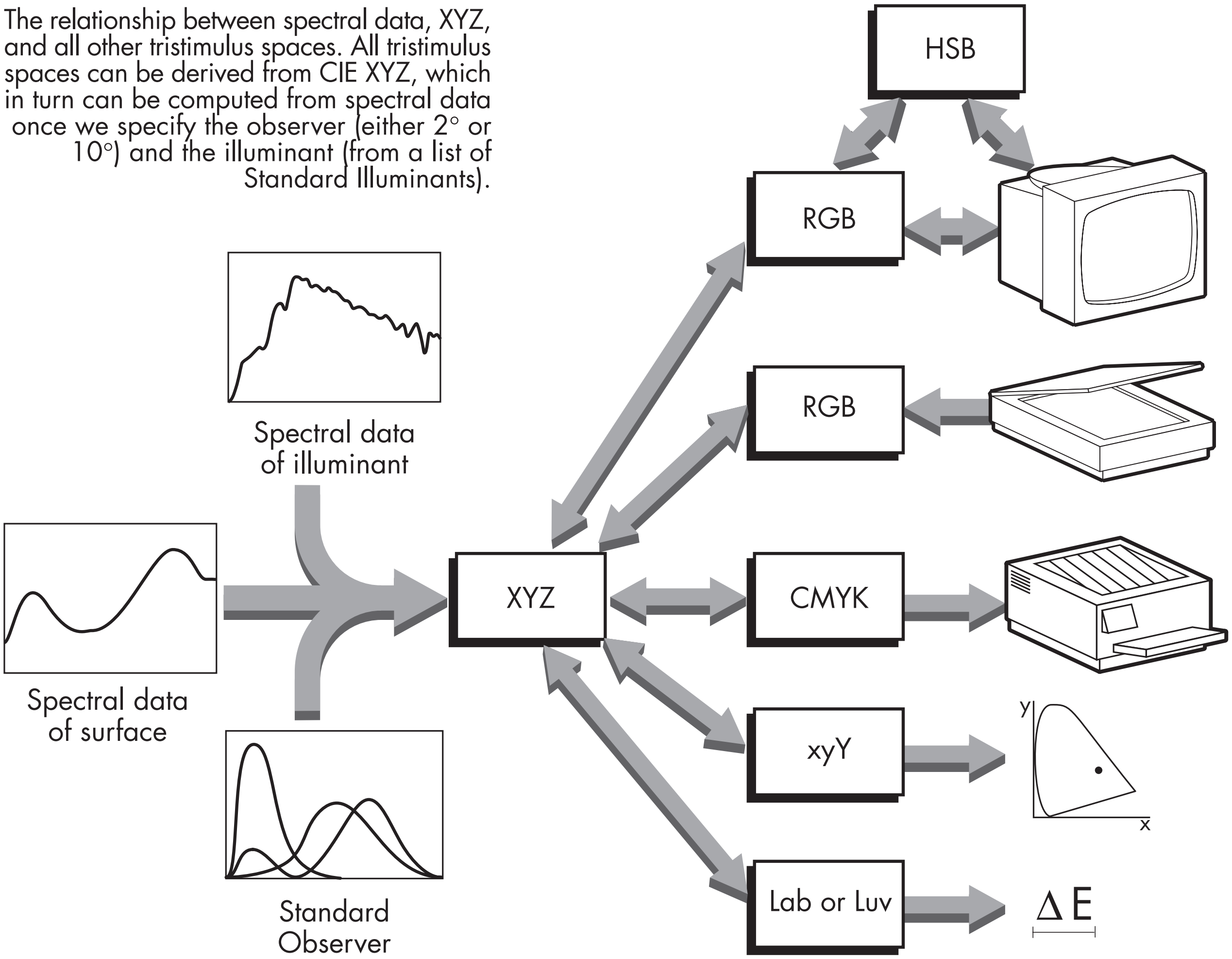
- **CIE xyY**: A description of a color in terms of chromaticity coordinates, x and y, and luminance (or brightness) Y. The xyY color space is generally used for mapping colors on the CIE chromaticity diagram, a commonly seen diagram used for visualizing the range of distinguishable colors, or gamut, of tristimulus devices. The chromaticity coordinates x and y are computed directly from the CIE XYZ tristimulus values. The luminance Y is identical to the tristimulus value Y—a rather clever property of the Y primary built into the definition of CIE XYZ and the Standard Observer.

- **CIELAB and CIELUV**: Two systems similar to xyY except that they are more perceptually uniform—distances between colors in the colors space correspond well to how "close" these colors appear to human observers. Although chromaticity diagrams can be drawn in CIELAB or CIELUV space, these color spaces are generally used more for computation of color difference, ΔE, or as unambiguous (device-independent) systems for specifying colors. CIELAB and CIELUV coordinates are computed from CIE XYZ values: for example, L* is a uniform lightness scale computed directly from Y.

In summary, all tristimulus values can be computed from CIE XYZ, which in turn can be computed from spectral data as long we specify the observer and illuminant.

The following diagram summarizes the various functions and relationships between the different color models presented in this chapter.

The relationship between spectral data, XYZ, and all other tristimulus spaces. All tristimulus spaces can be derived from CIE XYZ, which in turn can be computed from spectral data once we specify the observer (either 2° or 10°) and the illuminant (from a list of Standard Illuminants).



3 THE PROBLEMS: REPRODUCTION AND COMMUNICATION

In our little history / terminology lesson we alluded to a few of the problems inherent in the reproduction and communication of color. In this chapter we discuss these problems in a little more detail as a prelude to a survey of color measurement and how it addresses these problems. We won't mislead you and say that ColorShop and its associated measurement instruments solve **all** of these problems—many will be addressed with future ColorShop products—but ColorShop should help you understand, control, and in many cases eliminate these problems (many of which you may not have known you had) and get you closer to accurate color.

DEVICE DEPENDENCE

Think about how easy life would be if there were just one set of RGB primaries with which we could unambiguously describe any color. Then we could just specify three numbers for a color, and everyone would understand exactly what we meant. Clients and service providers would always be in complete agreement over what the color should look like. All monitors would display the same color, and all printers would reproduce it exactly with no more adjustment than a simple transformation from RGB to CMY.

Alas, life is not so simple:

1. Materials and devices are made by many manufacturers using different designs, different manufacturing procedures, different raw materials, different quality tolerances, etc. For example, an Acme and a Brandex scanner can produce quite different RGB readings of the same piece of artwork depending on who they use as their suppliers of lamps and detectors, or how their optics are designed, etc.

2. Even the same material or device made by the same manufacturer can vary from unit to unit. For example, two Acme TruViu 1000 color monitors may be slightly different depending on how

old they are, whether they were manufactured at the beginning or the end of an assembly run, etc.[20]

3. Even within the same device there is a certain amount of instability as it gets older or as its environment, such as temperature or humidity, changes. For example, a single Acme printer may produce a slightly different color this week than it will next month.

4. Finally, it would be impractical, if not physically impossible, to make perfect materials. For example, on page 19, we talked about how inks do not behave ideally, which is why we have to add black to CMY to achieve true neutral grays and blacks.

This is why any RGB, HSB, CMY, or CMYK definition of a color must include a specification of the device for which these values were intended. The RGB values that produce the exact color you want on one device will look quite different on another device. So, RGB values must be converted whenever going to a different device. For this reason, RGB, HSB, CMY, and CMYK are known as device-dependent color spaces.

The CIE color spaces are device-independent color spaces. The XYZ values for a color do not vary depending on the device used to reproduce the color. You could say that the CIE solved the device-dependence problem by defining a master “device,” the Standard Observer.

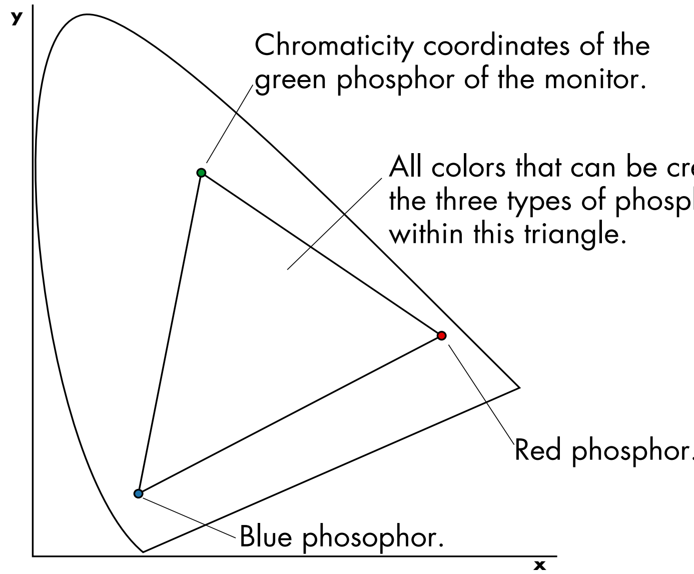
Device gamut and gamut mapping

The gamut of a device is the range of colors that it can reproduce (in the case of a monitor or printer) or distinguish (in the case of a scanner or other detection device). As we mentioned on page 40, each device has its own gamut. When the range of displayable colors of a computer monitor are converted to xyY and plotted against the CIE chromaticity diagram of visible colors, we see that there are many

[20]The critical piece in a monitor or TV set is a cathode-ray tube (CRT) known as your picture tube. These are manufactured by dipping or painting the inside of the glass in a phosphorescent (light sensitive) solution, that when dried produces the red, green, and blue phosphors needed to display color images. The color characteristics of the monitor can vary depending on whether the tube was dipped at the beginning of an assembly run when the phosphor solution was fresh, or at the end of a run after 10,000 units have been through it.

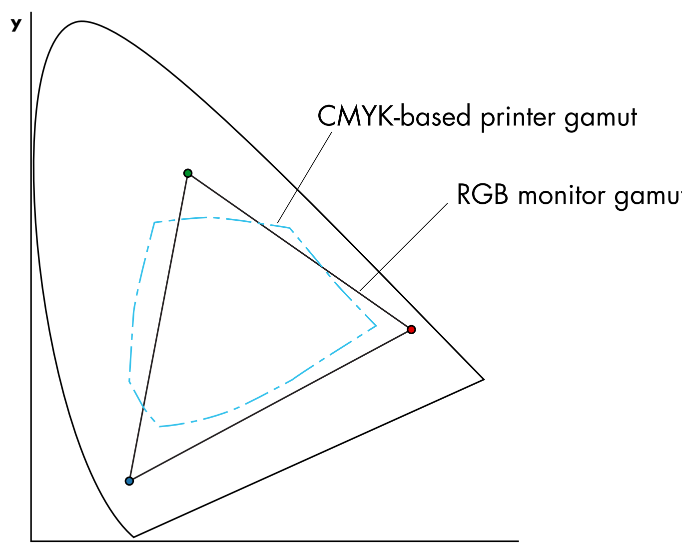
colors that the human eye can distinguish that simply cannot be conveyed on a computer monitor.

The gamut of an RGB computer monitor converted to xy coordinates and plotted in a CIE chromaticity diagram. Notice that there are many colors that the human eye can perceive that are simply not displayable on the monitor.



The typical gamut of a CMYK-based printer is somewhat smaller than that of a monitor, but still contains some colors (such as deep cyans and yellows) that cannot be reproduced on a monitor. (Compare this diagram to the colored version on page 39.)

The gamut of a CMYK-based printer compared to that of a computer monitor. Although the printer's gamut is slightly smaller, each device can reproduce colors that the other can't.



For this reason, one of the big problems in color reproduction is that of gamut mapping, converting to color coordinates from one device's color space to another. This is sometimes called gamut compression if colors are mapped from a larger gamut to a smaller one.

The quest for Color Management Systems

Nowhere is device dependence a bigger headache than in the print and graphic arts industries—especially with the advent of desktop publishing that assembles multiple devices and software from many different manufacturers each with its own idea of what is “good color.” This has led in recent years to a search for the holy grail of computer color: the elusive WYSIWYG[21] (What You See Is What You Get), a buzzword implying an exact match between what you see on the monitor and what you get in print. This is approached through something called a color management system (CMS) that does the proper conversion of colors from device to device, so that you don’t have to deal with it.

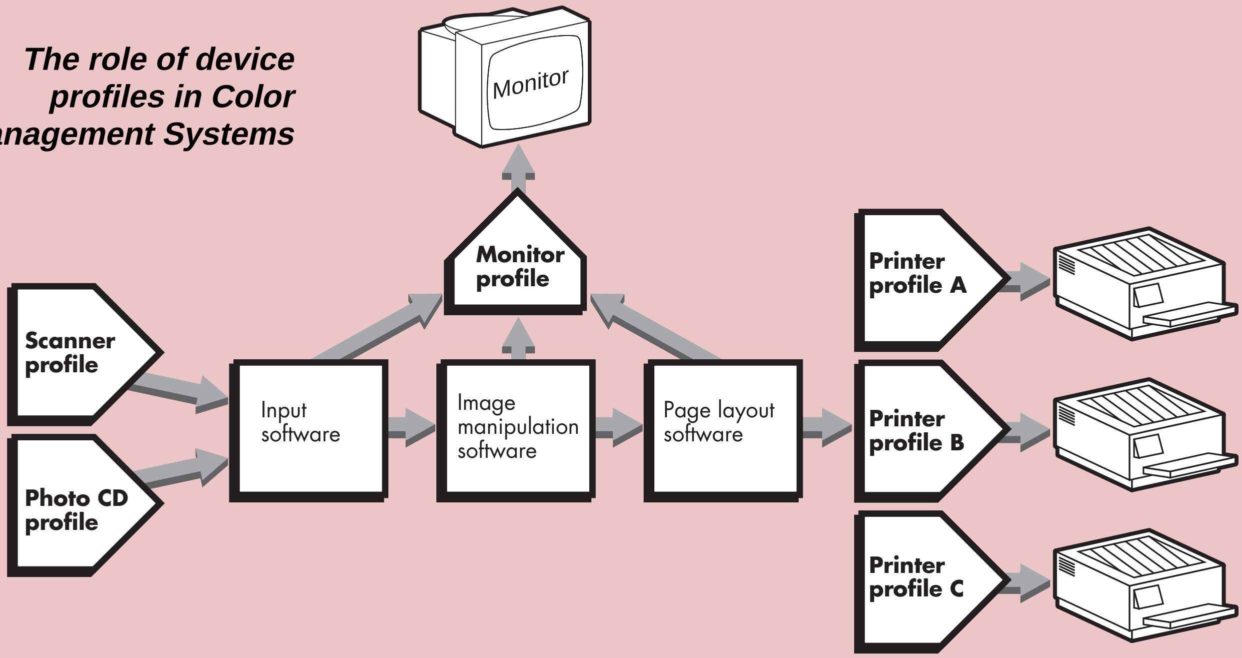
The key ingredients of a CMS are device profile. A device profile specifies the transformation from one devices color space to another (see sidebar). Usually, this transformation goes through an intermediate color space, called the profile connection space (PCS). For example, a scanner profile converts color from the RGB space of your scanner to the profile connection space, and a printer profile converts color from the profile connection space to the printer’s CMYK space.

By definition, the profile connection space must be a device-independent color space like CIE XYZ, but this produces a practical problem: every time an image or color is displayed to a computer monitor, it must be converted from XYZ to the RGB space of your monitor—which considerably slows down redraw of your screen. Since most of us would never tolerate slow display, many color management systems recommend that images and colors be transported in some derivative of monitor RGB space, the color space of a reference monitor. This means that there is no conversion needed when displaying images and colors on your monitor, only when printing, and most people are willing to put up with somewhat slower print times in order to assure quick display.

There have been a number of attempts in recent years to produce the perfect CMS. Apple Computer laid a lot of the groundwork for CMS development by providing a basic color management framework, called ColorSync™, within the Macintosh operating system. This provided a common language for the creation of profiles and use of

[21]Pronounced “wizzywig.”

The role of device profiles in Color Management Systems



A Color Management System that truly automates color at every step of reproduction requires the cooperation of a large number of components.

Device profiles (for monitors, printers, scanners, and other devices) handle the conversion from one color space (usually a *profile connection space* such as CIE XYZ) to another. Every application, driver, and device that touches color data, needs to know how to apply the appropriate profiles at the right time.

them by such low level parts of the operating system as monitor and printer drivers. This effort grew to include a number of companies in addition to Apple—collectively known as the International Color Consortium (ICC)—involved in creating cross-platform standards for device profiles and other aspects of color management. The first implementation of the ICC specification was ColorSync 2.0.

Why has The Great CMS been so difficult to achieve? Well, to start with, a CMS requires cooperation between a huge number of components all made by different manufacturers. Input devices and software (such as scanning systems) must know how to apply an input profile to convert the RGB values produced by the input hardware to the profile connection space of the CMS. Every piece of software that lets you edit or specify colors on screen—such as image manipulation, paint, draw, and page-layout programs—must know how to convert colors to and from your monitor RGB space. Every component involved in the printing of color—such as page-layout programs or print drivers—must know when color must be converted, where to find the appropriate printer profiles on your system, and how to use them. For this reason, no one manufacturer is in a position of producing the comprehensive CMS to handle all situations.

Another barrier, of course, is the gamut problem. WYSIWYG is impossible as long as you can “see” colors on your monitor that you simply cannot “get” accurately on your printer. To make your monitor an accurate proof of what you will see on your final page, you must be willing to work with a compressed monitor gamut—the colors you see on screen will not appear as brilliant as you’re used to, but they will be a closer match to your final printed results.

However one of the main reasons the CMS problem has been so difficult to solve is that there must be a systematic way to acquire, or even better, produce device profiles. Most profiles are produced in a combination of two ways: characterization and calibration.

- **Characterization** produces an average of several units of the same device model made by the same manufacturer. This characterization, then, provides a pretty good approximation of the color characteristics of the device.

- **Calibration** involves measurement of a single unit to see how much it deviates from a given standard. The standard may either be an average of several units produced by characterization, or a universal standard. The RGB values then produced by, or sent to, the device, are then adjusted to compensate for the measured deviation from the standard.

Profiles based on device characterization are usually acquired from manufacturers—often for a price. Profiles based on device calibration are better (because they are based on a specific device, not an average) and generally cheaper (because they are done by you, the owner of the device, not purchased from its manufacturer), but they require the ability for you to measure the output from the device.

How does ColorShop relate to Color Management?

One of the most obvious applications for ColorShop and the associated X-Rite instruments is the creation of device profiles. With the ColorShop monitor calibrator together with either a Colortron or Monitor Optimizer, you can calibrate and create a ColorSync (ICC) profile for your monitor. In addition, the Colortron and Digital Swatchbook instruments are used by a number of profiling applications for taking the measurements necessary to make ColorSync (ICC) device profiles for scanners and printers.

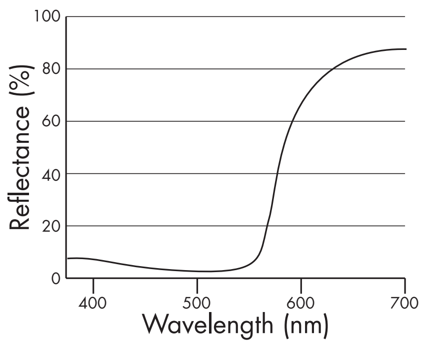
The ColorShop software also **uses** device profiles whenever converting color data to a device-dependent color space. RGB values are computed relative to a monitor profile—the profile currently set as the ColorSync system profile. CMYK values are computed relative to a ColorSync profile that you have installed in your system and selected in ColorShop.

ILLUMINANT DEPENDENCE

Although the CIE color spaces address the problem of device dependence, they do not solve the problem inherent with all tristimulus color—illuminant-dependence, the fact that all tristimulus descriptions of a color must include a specification of the light source or illuminant used to view the color. This is because a tristimulus model of color is based on its appearance by the human eye and must therefore include not only an accurate model of human vision (provided by the Standard Observer definition), but also the light used to illuminate an object as this is the source of the light that reaches the eye.

Illuminant-dependence is not a problem if you have spectral data. This is because a spectral examination of the color is closer to an examination of the object itself—how does it **change** the wavelength composition of light. For example, if you look at the spectral curve showing the reflectivity of an object, the amount of energy at each wavelength is given as a **percentage** of the incoming light. As a result, it doesn't matter what this energy actually **is**—the percentage is the same regardless.

Spectral data is given as a percentage of the incoming light. As such, spectral data is not illuminant-dependent—the percentage is the same regardless of the actual energy of the incoming light at each wavelength.



METAMERISM

This discussion of illuminants brings us to one of the main topics of this Primer, the problem of metamerism.

Metamerism is the phenomenon whereby two colors can match under one set of viewing conditions—such as illuminant—but not under another. Two colors that exhibit this relationship are called a metameric pair and are said to be metamers.

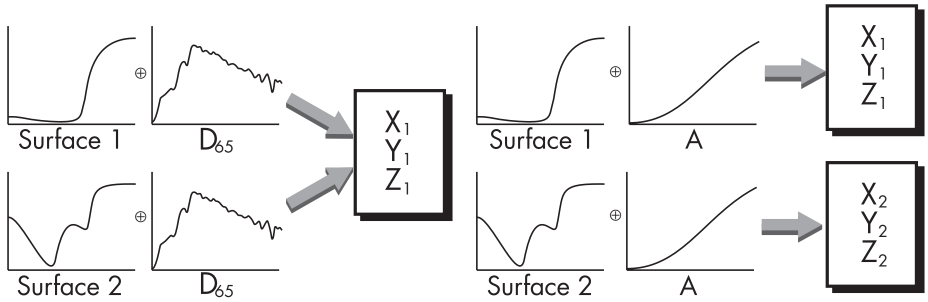
If you have ever bought two items that matched in color under the store lighting, but when taken home, or viewed outside, are distinctly different, then you have been bitten by metamerism. Metamerism is a critical problem in manufacturing and print industries where color matches between parts of a product or between two items are important.

Metamerism should not be confused with the tendency of a single color to shift its apparent hue under different illuminant conditions. Metamerism is a relationship between **two** colors.

Measured metamerism

Metamerism has a definition in terms of tristimulus coordinates. If two colors have the same CIE coordinates—for example, the same CIE XYZ values—under a given illuminant, but different XYZ values under a different illuminant, then these colors are metameric[22].

Two colors with different spectral curves that produce the same XYZ values under illuminant D65, but different XYZ values under illuminant A. The colors will appear to match in daylight, but will appear different under incandescent light.



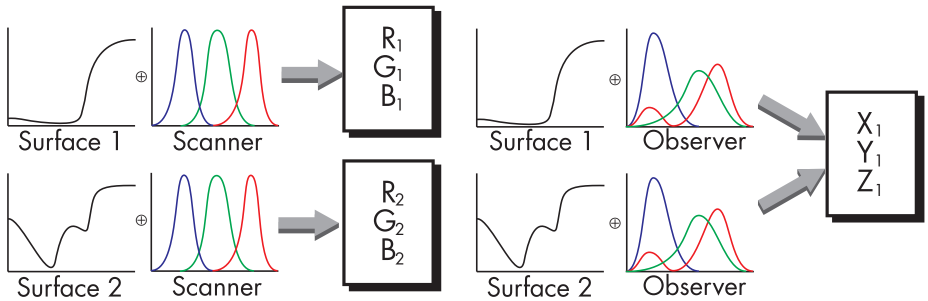
Scanner Metamerism

Another form of metamerism is unique to colors input with a scanner or other RGB input device, such as a digital camera. Since the RGB primaries inherent in a desktop scanner are not necessarily traceable in any way to measurements of human vision (as are the CIE X, Y, and Z primaries), it is possible that two colors that appear quite different to a scanner, appear identical to the human eye. This difference can be exaggerated when these two RGB-defined colors are displayed on a monitor or converted to CMYK for print. The

[22]There is also another form of metamerism that is quite rarely noticed, but so interesting that we can't resist mentioning it here. What would happen if two colors produced identical XYZ values when using the 2° Standard Observer, but different XYZ coordinates under the 10° Supplementary Observer? This would mean that the two colors would appear indistinguishable to the central part of your retina, but different to the remainder of the retina (see sidebar page 21). As you looked at these two colors side by side, there would be a small spot in the center of your visual field in which the colors looked the same, but in your more peripheral vision you might detect a difference. This spot would of course move with your eye which would make color matching under these circumstances rather frustrating. This spot is known as the "Maxwell spot", as Maxwell was the first to describe this phenomenon.

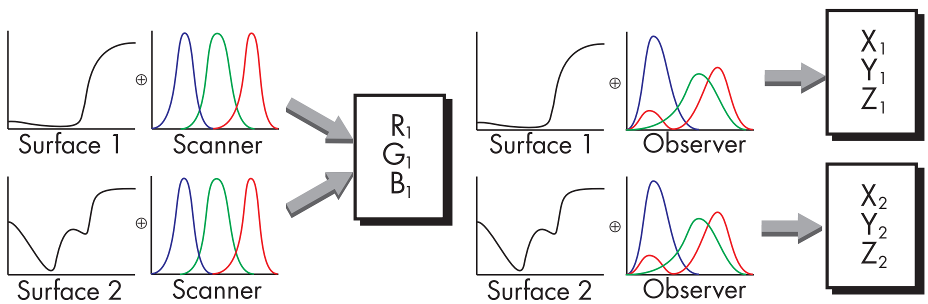
result is that strange color differences appear in colors reproduced from scanner data, that are not apparent in the original artwork.

The scanner sees two colors where the human eye sees one. In technical terms the two spectral curves for the color produce the same XYZ coordinates, but different RGB coordinates in the scanner space.



The opposite can also happen—and in fact is worse because it cannot be corrected. You may be able to perceive a difference between two colors in a piece of artwork, which the scanner sees as the same color.

The scanner sees a single color where the human eye sees two. In technical terms the two spectral curves for the color produce the different XYZ coordinates, but the same RGB coordinates in the scanner space.



DISTRACTIONS, DISTRACTIONS

One of the main problems with judging colors is actually even more basic than device dependence, illuminant dependence, or metamerism. Most colors do not exist in isolation, but must be examined in context. You, your clients, and the people viewing your products are rarely looking at color-matching apertures in controlled viewing conditions. Instead, you are looking at a multicolored poster at a print shop, or the first manufactured unit on the factory floor—and you're always under a deadline. Here are just some of the ways that our perception of colors can be muddled by context.

Chromatic Adaptation

The term chromatic adaptation, sometimes known as color constancy, refers to the remarkable ability of our visual system to adjust the white point for a scene so that colors appear the same independent of the color temperature of the illumination. The color of an object does not appear to change from indoor fluorescent light to daylight. This is such a common visual experience that we take it for granted.

Chromatic adaptation can be a significant issue for color matching in graphic arts. The white point of a monitor and the white of a paper stock may be quite different. Although taken individually, the eye will see each as white. Side by side, the monitor's white may look rather blue in comparison to the paper's.

Simultaneous Contrast

The term simultaneous contrast, is used to describe the process by which our perception of a color is strongly influenced by its adjacent and background colors. The teapot demonstration on page 5 is an illustration of simultaneous contrast.

Successive Contrast

The term successive contrast refers to the phenomenon in which the eye's adaptation to one color affects the color seen immediately afterwards.

Memory Colors

Certain colors are categorized as memory colors if they are associated with familiar objects. Examples of memory colors are flesh tones, grass green, and sky blue. When these objects are shown in a scene, our perception of these colors tends to change in the direction of the color previously perceived to belong to the object—we subconsciously shift the perceived colors so that flesh tones appear "right." It takes a considerable amount of eye training to ignore this tendency and judge these colors objectively as we would any other color.

In the graphic arts, memory colors are the most important colors to get right when reproducing a color image. If these colors are perceived to be correct, we tend to see the overall image as correctly color-balanced, regardless of the accuracy of the other colors in the scene. By the same token, the whole image will appear poorly reproduced regardless of the overall color accuracy if, for example, the flesh tones are “off.”

SUMMARY

Is it any wonder color is such an elusive beast? Color is an experience we take for granted in our everyday lives, but when it comes time to communicate color we become tongue-tied in a Babel of color spaces, and when we have to reproduce the color we have a difficult time judging whether we have been successful.

The number of tristimulus color spaces is multiplied by the problem of device-dependence: every RGB-, HSB-, or CMYK-based description of a color must include a specification of the device for which they are computed. This is the root of the problem addressed by color management: every device used to represent colors must be carefully characterized and calibrated so that we can move colors from one device to another. As long as we have a precise profile of a device, and either a CIE or a spectral description of a color, we can compute the values that best reproduce the color on that device.

The CIE color spaces address the device-dependency problem by providing a device-independent system based on the Standard Observer. However, CIE color spaces are still illuminant-dependent: every CIE tristimulus description of a color must include a specification of the light source used to illuminate the color. Nevertheless, as long as we have spectral data for a given color, we can compute the coordinates in any CIE color space under any illuminant.

Metamerism is a problem related to the issue of illuminant-dependence. Two colors may match under one set of viewing conditions (usually illuminant) and not under another. By viewing conditions we usually mean illuminant, but we can also mean observer—either one of the two Standard Observers (2° or 10°) or a non-standard “observer” like a scanner. However, spectral data allows us to deal with metamerism because it is a description of the color independent of viewing conditions—as long as we have spectral data we can detect and control metamerism.

Other problems are rooted in the fact that the human visual system can be distracted or even fooled. The phenomena of chromatic adaptation, simultaneous and successive contrast, and memory colors are just a few of the effects that can make judgments of good color matches more difficult when working with complex scenes and less-than-ideal viewing conditions.

The solution to all these problems is measurement. Or more specifically, when we are equipped with the ability to measure color objectively, and establish standards for communicating the colors we measure, then these problems become tamable.

4 THE SOLUTION: MEASUREMENT

The solution to the slippery nature of color is accurate measurement instrumentation that produces an unambiguous description of the colors being reproduced.

A device such as a Colortron or Digital Swatchbook should be thought of as a "color ruler." Without it, working with color would be somewhat like an architect communicating to a contractor the specifications for a house in terms of "cubits" (the length of a forearm). If the architect, the contractor, the bricklayers, and the carpenters all have different length forearms, the constructed house may need considerable "revision."

There are three main types of color measurement instruments: **densitometers**, **colorimeters**, and **spectrophotometers**.

DENSITOMETERS

One of the most widespread pieces of equipment in our arsenal of precise instrumentation is the densitometer.[23] A densitometer does not measure color, but density, which is the ability of a material or surface to absorb light. Densitometers are widely used in the graphic arts and photographic industries for measuring and controlling each stage of reproduction.

There are two kinds of densitometers: **reflection densitometers** and **transmission densitometers**. The main difference is that a reflection densitometer computes density (the light absorbed) by measuring the light reflected from a surface, while a transmission densitometer measures the light that survives transmission **through** a material. Because reflection densitometers and transmission densitometers are designed for different targets, they are used for very different tasks in the prepress-press production pipeline.

[23]The Graphics Communications Association (GCA) has published two excellent books on the subjects of densitometry, and color bars (described in the sidebar on page 66). See Brehm 1990, and Brehm, 1992 in the Bibliography.

What is Density?

The quantity density is the ability of a surface or material to absorb light. As such it is directly derived from reflectance or transmittance of a surface or material—the smaller the reflectance or transmittance, the larger the density value. Any numbering scheme could be used, but one in particular, known as the **log density** has become the standard.

Let's consider the transmissive case: Imagine that one area of a surface transmits exactly ½ of the light that strikes it, presumably absorbing the rest. We could report this as 50% transmittance, or 0.5. However, now imagine that another area transmits only a very small amount of light, say $\frac{1}{520}$ of the incoming light (yes, transmission densitometers are sensitive enough to detect this). This fraction would convert to 0.192% or 0.00192 transmittance—not a very friendly number of digits. The problem is that we are interested in a great dynamic range of values—the largest value is many orders of magnitude bigger than the smallest value.

To get more reasonable numbers, we take the reciprocal (i.e. invert) these numbers—in this case inverting ½ and $\frac{1}{520}$ we get 2 and 520. But now notice that all surfaces that transmit **more** than ½ of the light must be squeezed in between 0 and 2, while surfaces that transmit **less** than ½ of the light result in values from 2 to ... infinity.

To solve this problem, we use the simple mathematical trick of taking the logarithm of these inverted values.[24] We said in the introduction to this Primer that there would be only one equation. This is it:

$$\text{[Equation 1]}\quad Density = \mathbf{log}\left(\frac{\mathbf{1}}{\mathbf{Transmittance}}\right) \text{ or } \mathbf{log}\left(\frac{\mathbf{1}}{\mathbf{Reflectance}}\right)$$

Using our pocket calculator we compute that for our first area (transmitting ½ the light) the density computes to log(2)=0.3. And for the

[24] If you are not familiar with logarithms, they are just the opposite of the exponent, or "power", function. The logarithm of 10—abbreviated log(10)—is 1 because $10=10^1$. The log(100)=2 because $100=10^2$. Similarly, log(1,000)=3, log(10,000)=4, (just count zeros), etc. The log(1)=0 because $1=10^0$. Logarithms are a useful way of compressing a set of values with a huge dynamic range.

second area (transmitting $\frac{1}{520}$ the light) the density is log(520)=2.7. This is how a densitometer computes density for us.

Theoretically, density values range from 0 to infinity. However, a sample would have to be a near-perfect absorber (i.e. a true black body), and the densitometer **extremely** sensitive to report density levels above even 5.0. These examples may help make this clearer:

Reflectance or Transmittance		Density
1 (all light reflected / transmitted)		0
$\frac{1}{2}$ (of incoming light)		0.3
$\frac{1}{4}$	"	0.6
$\frac{1}{10}$	"	1
$\frac{1}{100}$	"	2
$\frac{1}{1,000}$	"	3
$\frac{1}{10,000}$	"	4
$\frac{1}{100,000}$	"	5

In practice the range of density values expected with a typical reflection densitometer is about 0.05 to 2.5. The range of density values expected with a transmission densitometer is about 0.05 to 4.0. If you remember this, and the fact that density values are higher for more absorbent (dark) targets and lower for less absorbent (more reflective or transparent) targets, then density should lose its mystery.

Response Functions—Status T, Status E, Status A, Status M

It is actually a little inaccurate to say that a densitometer **measures** density. To be precise, a densitometer measures reflected or transmitted light and then **computes** density from this measurement. You might call this distinction splitting hairs, but the point is that densitometers can only produce meaningful density readings for the types of targets for which they are designed—usually photographic or prepress film, transparencies, photographic prints, and other graphic arts materials such as proofs and press sheets of process-color jobs.

The reason for this is that every densitometer, just like any detector, has a built in set of spectral response curves or response functions that describe the sensitivity of the instrument at each wavelength. For example, to measure the density of cyan ink, a reflection densitometer has to measure how much red is absorbed. (Remember from page 18 that cyan, magenta, and yellow inks are designed to absorb red, green, and blue respectively). To do this, the densitometer must know the wavelength "recipe" for red so that it can be particularly sensitive to these wavelengths and give an accurate reading of how much red is absorbed.

Or to put it another way, reflectance is actually a function of wavelength. To compute density, we need a response function that tells us how much of the reflectance must be weighed into the density equation. For this reason these response curves are sometimes called response functions. Response curves are also sometimes called response filters, because they act to isolate one color to the exclusion of others.

The American National Standards Institute (ANSI) has specified a series of response curves, called the *ANSI Status classifications*, to match the response of a densitometer to certain types of color materials. This helps ensure consistency in densitometer readings from manufacturer to manufacturer.

The following are some of the most common ANSI Status classifications (with an indication, in parentheses, of whether each response function is used by reflection or transmission densitometers):

- **Status T**, (reflective) used for measuring graphic arts production materials such as press proofs, off-press proofs, and press sheets.
- **Status E**, (reflective) used in Europe instead of Status T for measuring graphic arts and production materials.
- **Status A**, (reflective or transmissive) used for measuring color photographic materials such as photographic prints, 35mm slides, and transparencies.
- **Status M**, (transmissive) used for measuring color negative film.

Uses for densitometers

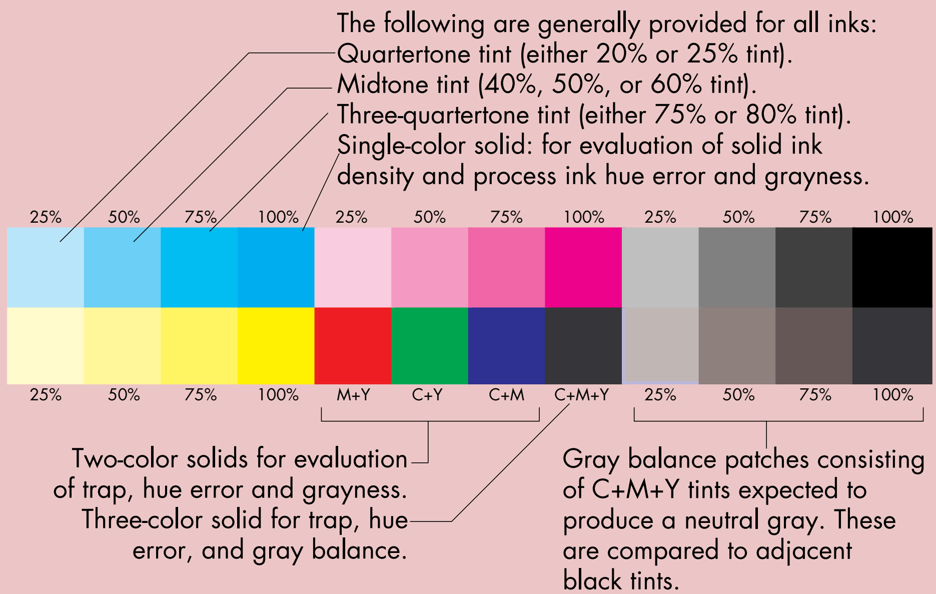
Densitometers are used in the graphic arts and photography industries for a number of tasks. They are used to:

- Measure the highlight, midtones, and shadows of artwork (such as photographic prints) that are going to be reproduced in print. This determines the dynamic range of the image—the range of tones from lightest to darkest—which is useful for using the print process to its best advantage when reproducing the image.
- Check the accuracy of proofing systems used to simulate printing press conditions.
- Check the quality of raw materials such as ink, paper, or film base used in print production.
- Measure photographic emulsion characteristics (a process also called "sensitometry") and maintain process control.
- Examine supplied proofs and exposed film given to press shops to determine these materials' conformance to standards and specifications. Press shops cannot guarantee good results if they are given poor prepress materials.
- Measure dot area and dot gain in prepress materials and press sheets. Dot area is the percentage of an area of paper that is covered by ink. Dot gain is the tendency of dots of ink to spread as they are placed on paper. For example, if you measure what should be a 50% tint (see sidebar page 19), a densitometer would be able to tell you that the dot area was actually 58%, indicating a dot gain of 8%.
- Monitor other aspects of how a press is performing, such as sheet-to-sheet consistency, and uniformity across a single sheet. Press people use such terms as slur, trapping, doubling, registration, gray balance, etc. as quantities that can be measured and controlled with a densitometer. (For a description of the color bars used to measure these values, see sidebar on page 66.)

Color bars

One of the most invaluable tools in the graphic arts industry are color bars, sets of standardized quality control patches and patterns printed in the margins of press sheets. There are two types of control bar elements: those that are designed to be interpreted by humans, and those designed to be measured by a densitometer.

An example of elements commonly found in a color bar and intended to be used with a densitometer.



COLORIMETERS

A colorimeter is an instrument for measuring color in a way that models human vision. As such, a colorimeter measures the tristimulus values of a color with a response that is similar to the human eye. Most colorimeters report values in one of several CIE tristimulus color spaces such as CIE XYZ, xyY, LAB, or LUV. Another important function of a colorimeter is to compute and report ΔE values so that we now have an objective way to measure how close a match we have between two colors.

Because colorimeters are purely tristimulus devices, the words **colorimetric** and **colorimetry** are often used synonymously with **tristimulus**.

Uses for colorimeters

Although the uses for densitometers are quite specific because they are designed for specific industries (graphic arts and photography), the applications for colorimeters are a bit more general and cover a much wider span of industries:

- Quality control procedures in a manufacturing environment can often benefit from the use of colorimeters. It is generally easier to train assembly line workers and supervisors to use a colorimeter to spot check samples against a standard (usually a ΔE value from a target sample), than to compare subtle variations visually under specific lighting conditions.

- Manufacturers specifying critical color for raw materials or parts from a supplier can write specifications in terms of CIE tristimulus coordinates. This is especially important when purchasing the same part from multiple suppliers.

- A colorimeter can actually be used as a contractual tool between vendors and purchasers, both for specification of contractual terms, and for verification of fulfillment.

- Some colorimeters also provide the capability to save measurements as a record to be used in statistical quality control—statistics of color consistency can be maintained throughout a job or across multiple jobs to build the confidence of clients and potential customers.

- Designers can specify and compare colors by numbers instead of from a swatch book. Or proofs and test press sheets can be compared against the swatch ordered.

- Fine artists, curators, restoration technicians, and art historians can non-destructively measure colors for fine art reproductions, especially in digital catalogues. These measurements can be used as records for future restoration, scholarly study, and museum documentation.

- Architects, field archaeologists, and others can use a colorimeter when examining such items such as buildings and murals where the target cannot be moved and samples cannot be taken. A colorimeter provides a much more reliable record of color than a photograph taken under questionable lighting, especially if the professional has little photography expertise or equipment available.

- Artists, decorators, framers, and others ordering color-sensitive materials such as paints, mattes, and fabrics from a catalogue, can verify consistency between the purchased item and the catalogue photographs, or between reorders of the same item.

- Photographers and artists can measure precise colors in their subject matter, such as the skin tones of a model or the precise product colors in a product shot, to compare against test prints.

- Photographers also use colorimeters to measure the light falling on a subject and use this information to determine the combination of CC or LB filters for correction.

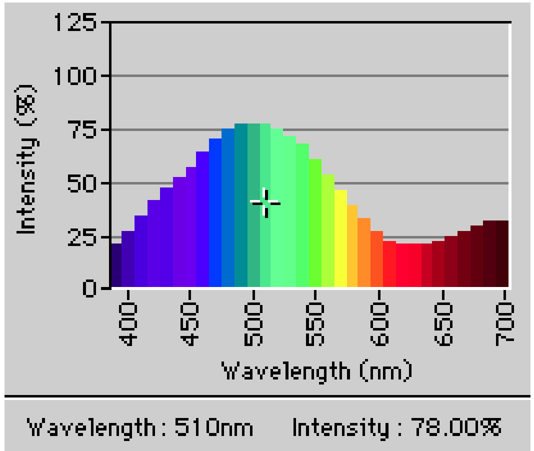
- Corporations can specify company colors in a logotype or corporate identity program in terms of precise CIE tristimulus coordinates. These values can then be provided to all vendors, advertisers, and others who have to reproduce these colors, in a way that can be verified with a colorimeter.

SPECTROPHOTOMETERS

A spectrophotometer is an instrument that measures spectral data for a target. A spectrophotometer can usually display the obtained spectral data in the form of a spectral curve, and, since spectral data can be converted to tristimulus values or density, most spectrophotometers can compute and report colorimetric or densitometric data as well.

In other words, given the right response data and enough computation power, a spectrophotometer can often perform the functions of a colorimeter, a densitometer, or both.

A spectrophotometer works by breaking up the light entering it into a number of discrete band. Each band is a region of the visible spectrum, and the width of each band, in nanometers, is its bandwidth. For example, the Colortron instrument breaks the visible spectrum into 32 bands—each band is 10nm wide.



The ColorShop Spectrum Tool displays the data returned by the Colortron and Digital Swatchbook instruments. It divides the visible spectrum from 390nm to 700nm into 32 bands. Each band is 10nm wide.

For this reason, the Colortron instrument is called a 32-band instrument. The Digital Swatchbook is a 16-band instrument that returns 32-band data to your computer using interpolation. There are also spectrophotometers with fewer bands and a few specially designed scientific spectrophotometers with more (for example astronomy spectrophotometers used for analyzing data well into the non-visible parts of the spectrum).

Colortron is also called a constant-bandwidth instrument because all of its bands across the spectrum have the same bandwidth. Many commercial spectrophotometers are called variable-bandwidth instruments because the bandwidth is slightly wider in the blue region of the spectrum where light energy (as emitted by the incandescent lamp in the instrument) is more scarce. Variable-width instruments compute constant-bandwidth data either by interpolation (computing missing data from measured data), or by using the widest bandwidth as the bandwidth of the instrument.

Before the introduction of the Colortron and Digital Swatchbook instruments, spectrophotometers have been considerably more expensive than densitometers and colorimeters. This is because the optics and electronics required to measure full spectral data is much more complex than the optics and electronics needed to measure at most three bands of data.

Uses for spectrophotometers

Most spectrophotometers can also be used as either a colorimeter, a densitometer, or both, which alone would give them widespread applications. However, before Colortron and Digital Swatchbook, the extravagant cost of spectrophotometers have kept them confined mostly to scientific uses and commercial environments where illuminant dependence and metamerism are critical problems.

- A spectrophotometer that is both sensitive enough to detect small changes in light intensity, and is equipped with the appropriate response filter data such as Status T or Status A, is called a spectrodensitometer and can perform all of the densitometry functions described in “Uses for densitometers” on page 65.
- Most modern spectrophotometers are equipped with response data for the CIE Standard Observer, the spectral emission curves for many of the Standard Illuminants and a microcomputer for calculating CIE tristimulus values. As such, these spectrophotometers can perform all the colorimetry functions described in “Uses for colorimeters” on page 67.
- Metamerism can be identified and its cause determined by examining the spectral profiles for colors. CIE coordinates can be computed for colors under a variety of illuminants to predict what types of illumination will render the metamerism noticeable.
- A single measured color can be examined under different illuminants to predict odd or desired effects.
- Spectral curves for materials often provide a fingerprint of underlying chemical or physical properties. For example, a spectrophotometer with enough sensitivity can help identify the composition or source of certain clays or ceramics.
- Scientific applications for spectrophotometers are enormous, but generally involve spectrophotometers specifically designed or adapted to be used with certain equipment such as telescopes or microscopes, or for examining certain regions of the electromagnetic spectrum—often the non-visible part—in great detail.[25]

SUMMARY

The solution to the problems inherent in color reproduction and communication is measurement using accurate, standardized instrumentation. There are three main types of instruments used:

- **Densitometers**. Instruments that compute density, the amount of absorption of a surface or material. Densitometers are less concerned with measuring all colors, and instead are tuned for measurement of a few well-known colors (those used in graphic arts and photography), but with a great deal of precision.
- **Colorimeters**. Instruments that measure and compute the tristimulus values of colors in a way that models human vision. Colors are usually reported in any of a number of CIE tristimulus color spaces. Colorimeters are designed to identify all visible colors, but generally do not measure to the precision required by a densitometer.
- **Spectrophotometers**. Instruments that measure spectral data, and can usually convert this data to some CIE tristimulus color space. In addition, if the instrument has enough precision (and the correct response filter data), it can compute density values as well and is called a spectrodensitometer as it can serve all the functions of a densitometer, colorimeter, and spectrophotometer.

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[25]For example, astronomers often look for a red shift in the spectral curves from stars, and from this can determine not only whether a star is moving away from us, but also how fast, which in turn gives an indication of how far away it is. A red shift is a shift toward the red (longer wavelength) end of the spectrum, of certain well-known spectral peaks associated with typical atomic processes in stars. This shift is similar to the familiar “Doppler effect” in sound where the pitch of a train whistle goes down (lower frequency = longer wavelength) as the train passes us and moves away from us. A blue shift would indicate a star moving toward us, but (luckily for us), this is not very common.

CONCLUSION—YOU NOW HAVE THE CUTTING EDGE

Congratulations! The Colortron or Digital Swatchbook, coupled with the ColorShop software, can serve the functions of all the instruments described above, plus an array of additional functions as well. For example, the ability to create and maintain palettes of colors is not a new concept to users of other Macintosh software, but is quite a unique feature to owners of precision instrumentation. The ability to not only measure color, but to maintain it in a form that can be transported and transformed at will, is a power which we are just beginning to understand ourselves. Perhaps you could teach **us** something about what can be done with these devices.[26]

But we'll leave that for another Primer.

[26]Comments and suggestions about this Primer, or anything in the ColorShop product or documentation, are always welcome. Please write to us at 4040 Civic Center Drive, 4th Floor, San Rafael, CA 94903. Or visit us at www. ls.com.

A APPENDIX: EQUATIONS AND ILLUMINANTS

This appendix provides a short summary of the generally accepted equations and formulae that are used to compute values in many of the ColorShop tools from the spectral data stored in the color libraries or measured by a Colortron or Digital Swatchbook instrument.

This appendix lists:

- The formulae for conversion from spectral data to CIE XYZ tristimulus values;
- The formulae for computation of CIE xyz chromaticity coordinates that form the basis of the CIE xy chromaticity diagram and the xyY color space;
- The formulae for CIELUV and CIELAB color spaces;
- The color difference equations used to compute the ΔE color difference between two samples;
- The formula for computation of density from spectral reflectance or transmittance;
- The formula for computation of apparent dot area from density.

Although all of these formulae and equations are published in many sources the following texts are cited as references (see Bibliography):

- For CIE color spaces and color difference equations: *Color Science: Concepts and Methods, Quantitative Data and Formulae*, Second Edition, by Günter Wysecki and W. S. Stiles (John Wiley & Sons, New York, 1982).
- For the CMC Color Difference Equation: ANSI CGATS.5-1993, *Graphic technology—Spectral measurement and colorimetric computation for graphic arts images.*
- The density and dot area formulae are based on ANSI CGATS.4-1993, and ANSI PH2.18 / ISO.

CIE XYZ Tristimulus values

Whenever color data is converted from spectral form to any other color space, the color is first converted to CIE XYZ based on the CIE 1931 color matching functions for the 2° Standard Observer. The values *X*, *Y*, and *Z* for a color are defined as follows:

$$X = k\int_{\lambda} S(\lambda)\bar{x}(\lambda)\beta(\lambda)\,d\lambda$$

$$Y = k\int_{\lambda} S(\lambda)\bar{y}(\lambda)\beta(\lambda)\,d\lambda$$

$$Z = k\int_{\lambda} S(\lambda)\bar{z}(\lambda)\beta(\lambda)\,d\lambda$$

where:

$$k = \frac{100}{\int_{\lambda} S(\lambda)\bar{y}(\lambda)\,d\lambda}$$

$\beta(\lambda)$ = the spectral reflectance of the sample at wavelength λ. For transmissive samples, substitute the spectral transmittance $\tau(\lambda)$.

$S(\lambda)$ = the relative power of the illuminant at wavelength λ;

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the color matching functions for the CIE 1931 2° Standard Observer.

When computing tristimulus values from actual spectrophotometric measurements, the integrals are replaced by sums. ColorShop uses the weighted-ordinate method for this replacement. The resulting formulae are:

$$X = k\sum_{\lambda=390}^{700} S(\lambda)\bar{x}(\lambda)\beta(\lambda)\Delta\lambda$$

$$Y = k\sum_{\lambda=390}^{700} S(\lambda)\bar{y}(\lambda)\beta(\lambda)\Delta\lambda$$

$$Z = k\sum_{\lambda=390}^{700} S(\lambda)\bar{z}(\lambda)\beta(\lambda)\Delta\lambda$$

where $\Delta\lambda$ = 10 nm.

CIE xyz Chromaticity Coordinates

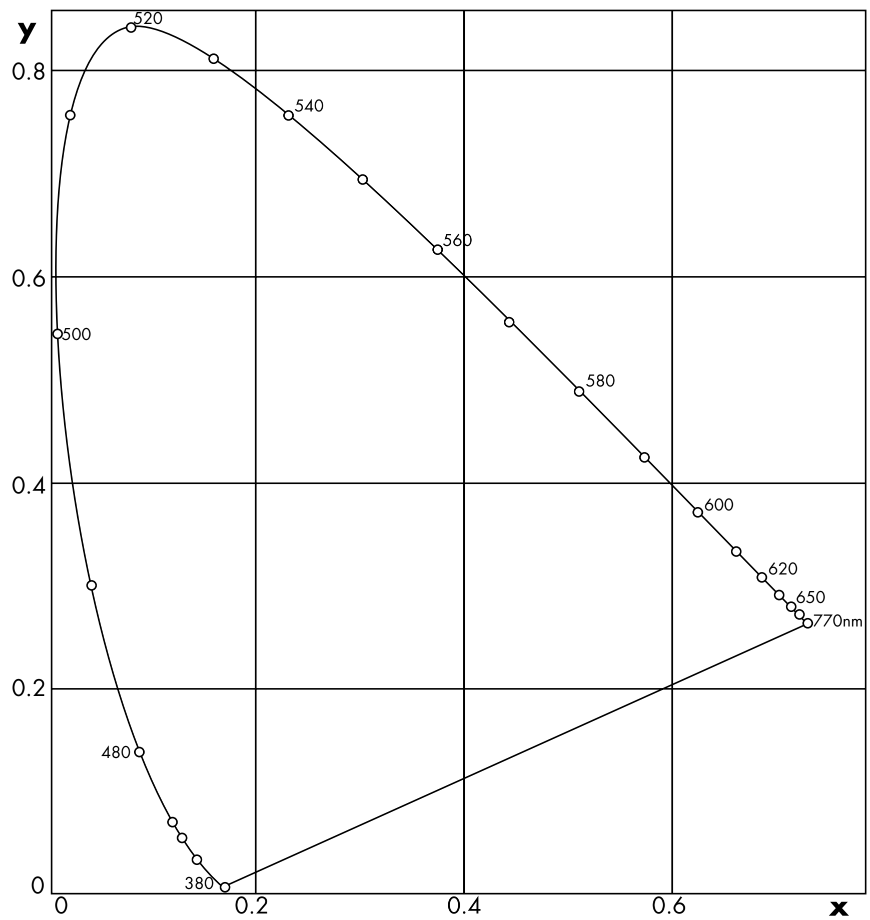
The CIE chromaticity coordinates *x*, *y*, and *z* are derived from the CIE Tristimulus values *X*, *Y*, and *Z* as follows:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z}$$

These are defined so that x + y + z = 1 which means that any one of the three chromaticity coordinates is trivially derivable from the other two—for example z =1 – x – y. This allows us to plot chromaticity in two dimensions, resulting in the *CIE xy chromaticity diagram*.

The CIE 1931 xy chromaticity diagram

For a colorized rendering of this diagram, see page 39.



The x and y chromaticity coordinates are often given with the Y-tristimulus value (which defines the luminance factor) to form the xyY color space which defines both the chromatic and achromatic components of each color.

CIELUV Color Space and Color Difference (ΔE) Equation

The CIELUV color space, (also known as the CIE 1976 $L^*u^*v^*$ color space) is one of two approximately uniform color spaces proposed by the CIE in 1976. This defines three quantities L^*, u^*, and v^* as follows:

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

where:

$$u' = \frac{4X}{X + 15Y + 3Z} \qquad v' = \frac{9Y}{X + 15Y + 3Z}$$

$$u'_n = \frac{4X_n}{X_n + 15Y_n + 3Z_n} \qquad v'_n = \frac{9Y_n}{X_n + 15Y_n + 3Z_n}$$

The values X_n, Y_n, and Z_n are the CIE Tristimulus values for the perfect reflecting or transmitting diffuser. These are given in CGATS.5-1993 as follows: $X_n = 96.422$, $Y_n = 100.00$, $Z_n = 82.521$.

The values u' and v' can be plotted in a chromaticity diagram similar to the CIE xy chromaticity diagram, except that distances correspond better to perceptual differences between colors. This is known as the CIE 1976 UCS (Uniform Chromaticity Scale) diagram.

The computed difference between two colors is given by the CIELUV Color Difference Formula:

$$\Delta E^*_{uv} = \left[(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2\right]^{1/2}$$

where ΔL^*, Δu^*, and Δv^* are the differences in the L^*, u^*, and v^* values between the sample and the target color.

CIELAB Color Space and Color Difference (ΔE) Equation

The CIELAB color space, (also known as the CIE 1976 $L^*a^*b^*$ color space) is the second of two approximately uniform color spaces defined by the CIE in 1976. This defines three quantities L^*, a^*, and b^* which are defined in ANSI CGATS.5-1993 as follows:

$$L^* = 116[f(Y/Y_n)] - 16$$

$$a^* = 500[f(X/X_n) - f(Y/Y_n)]$$

$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$$

Where:

$$f(X/X_n) = (X/X_n)^{1/3} \qquad \text{for } X/X_n > 0.00856;$$

$$f(X/X_n) = 7.7867(X/X_n) + 16/116 \qquad \text{for } X/X_n \le 0.00856;$$

(likewise for Y and Z).

The values X_n, Y_n, and Z_n are the CIE Tristimulus values for the perfect reflecting or transmitting diffuser. These are given in CGATS.5-1993 as follows: $X_n = 96.422$, $Y_n = 100.00$, $Z_n = 82.521$.

The computed difference between two colors is given by the CIELAB Color Difference Formula:

$$\Delta E^*_{ab} = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\right]^{1/2}$$

where ΔL^*, Δa^*, Δb^* are the differences in the L^*, a^* and b^* values between the sample and the target color.

CIELAB LCh and CIELUV LCh Color Spaces

The CIELAB L^*C^*h and CIELUV L^*C^*h color spaces are derived from CIE 1976 $L^*a^*b^*$ and $L^*u^*v^*$ values respectively, but use cylindrical coordinates instead of rectangular coordinates. This provides a more natural way to specify colors in terms of correlates of the perceived lightness, chroma, and hue.

The L^* value is the same as L^* quantity in the CIELAB color space and is defined by:

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16$$

The C^* value serves as the correlate to chroma, and is defined from the CIELAB a^*, and b^* and CIELUV u^*, and v^* values by:

$$C^*_{ab} = \left(a^{*2} + b^{*2}\right)^{1/2} \qquad C^*_{uv} = \left(u^{*2} + v^{*2}\right)^{1/2}$$

The h value represents the hue angle which is useful to specify hue numerically. The h value is defined by:

$$h_{ab} = \arctan\left(\frac{b^*}{a^*}\right) \qquad h_{uv} = \arctan\left(\frac{v^*}{u^*}\right)$$

The angles are given in degrees using the following conventions:

If $a^* > 0$ and $v^* > 0$, then $0° < h_{ab} < 90°$

If $a^* < 0$ and $v^* > 0$, then $90° < h_{ab} < 180°$

If $a^* < 0$ and $v^* < 0$, then $180° < h_{ab} < 270°$

If $a^* > 0$ and $v^* < 0$, then $270° < h_{ab} < 360°$

and similarly for h_{uv} using u^*, and v^*.

CMC Color Difference Equation

The CMC Color Difference Equation is given as follows:

$$\Delta E_{cmc} = \left[(\Delta L^*/lS_L)^2 + (\Delta C^*_{ab}/cS_C)^2 + (\Delta H^*_{ab}/S_H)^2\right]^{1/2}$$

where $l = 2$, $c = 1$,† and

$$C^*_{ab} = \left(a^{*2} + b^{*2}\right)^{1/2}$$

$$\Delta H^*_{ab} = \left[(\Delta a^*)^2 + (\Delta b^*)^2 - (\Delta C^*_{ab})^2\right]^{1/2}$$

ΔL^*, Δa^*, Δb^*, and ΔC^*_{ab} are the differences in the L^*, a^*, b^*, and C^*_{ab} values between the sample and the target color.

$$S_L = \frac{0.040975L^*}{1 + 0.1765L^*} \text{ unless } L^* < 16\text{, then } S_L = 0.511;$$

$$S_C = \frac{0.0638\Delta C^*_{ab}}{1 + 0.131\Delta C^*_{ab}} + 0.638;$$

$$S_H = S_C(FT + 1 - F)$$

and where

$$F = \left[\frac{(\Delta C^*_{ab})^4}{(\Delta C^*_{ab})^4 + 1900}\right]^{1/2} \text{ and}$$

$$T = 0.36 + \left|0.4\cos(h_{ab} + 35)\right|\text{; unless } 164° \le h_{ab} \le 345°\text{; then}$$

$$T = 0.56 + \left|0.2\cos(h_{ab} + 168)\right|.$$

† ANSI CGATS.5-1993, says: "The CMC (Color Measurement Committee, a British organization) color difference is not presently CIE approved or recommended but is being considered. The values of the parameters in the CMC equation are derived from visual judgements based on *acceptability*, not *perceptibility*, difference for textiles. The value of ΔE_{cmc} correlates well with visual assessment of textiles when $l = 2$. The value of c is always 1 as presently used and is explicitly given here to show agreement with British Standard 6923:1988. However, other types of surface colors or acceptability differences might require other values of l and c, and even different values in, or different relations for S_L, S_C, S_H, F, and T. The CMC color difference model can be useful for establishing empirical tolerances."

Density

Density D is computed from spectral reflectance R as follows:

$$D = \log_{10}\frac{1}{R}$$

$$R = \sum_{\lambda=390}^{700} \Pi(\lambda)\beta(\lambda)\Delta\lambda$$

where:

$\beta(\lambda)$ = the spectral reflectance of the sample at wavelength λ. For transmissive samples, substitute the spectral transmittance $\tau(\lambda)$.

$\Pi(\lambda)$ = the spectral response function (e.g. Status T, Status E, Status M, or Status A), that defines the densitometric response at each wavelength λ.

Dot Area

Dot area, or more specifically, the *apparent dot area*, a is computed as a percentage from measured density D for a sample using the Murray-Davies equation:

$$a = \frac{1 - 10^{-D_t}}{1 - 10^{-D_s}} \times 100$$

where:

D_t = Density D of the sample – D_0;

D_s = Density D of the solid patch – D_0;

D_0 = Density of paper (for reflective materials) or the density of the light + clear film base (for transmissive materials).

Supported Illuminants

Illuminant A– Incandescent

A CIE Standard Illuminant produced by a *tungsten* light source, yellow-orange in hue, with a *correlated color temperature* of 2856°K. Illuminant A is generally used to simulate lighting conditions using *incandescent* light sources.

Illuminant C – Simulated daylight

A CIE Standard Illuminant produced by a *tungsten* light source filtered in such a way as to simulate average daylight, bluish in hue, with a *correlated color temperature* of 6774°K.

Illuminant D_{50}, D_{55}, D_{65}, and D_{75} — The Daylight Illuminants

The CIE Daylight Standard Illuminants are based on actual spectral measurements of various phases of daylight. Each is given the name D with a subscript to indicate the correlated color temperature for the illuminant. D_{65}, with a *correlated color temperature* of 6504°K, is very similar to illuminant C, except with a better representation of the *ultraviolet* component of daylight needed to describe *fluorescent colors*. D_{50}, D_{55}, and D_{75}, with correlated color temperatures of approximately 5003, 5503, and 7504°K, respectively, are also commonly seen. Of all illuminants, we recommend D_{65}, although D_{50} is often seen in viewing booths used in the graphic arts industry for evaluating proofs and printed materials.

Illuminant F_1 through F_{12}

A set of illuminants designed to simulate fluorescent lamp lighting conditions. Although they are technically not designated as Standard Illuminants by the CIE, the CIE does recommend certain light sources for evaluating colors destined for fluorescent lighting environments. The fluorescent illuminants are commonly named F_1 through F_{12}.

Differences among fluorescent lamps are caused by differences in the phosphors used. In general, there is a tradeoff between energy efficiency and the distribution of wavelengths needed to see colors accurately. Illuminants F_1–F_6 are called *normal* fluorescent light sources because they have a good balance of efficiency and wavelength distribution. Illuminants F_7–F_9 are called *broad-band* fluorescent light sources.They have a better distribution of wavelengths but are relatively inefficient compared to the normal fluorescents. Illuminants F_{10}–F_{12} are called *three-band* fluorescent light sources because their light energy distribution is concentrated primarily in three bands of the spectrum (435, 545, and 610 nm). Three-band fluorescents are quite energy-efficient, though they generally are not used when color accuracy is vital.

Candlelight

Candlelight is an average of several spectral measurements taken of candle light. Candlelight has a correlated temperature of 2030°K and is yellow-orange-red in hue. It is not a CIE Standard Illuminant.

9300°K Monitor

The 9300°K Monitor simulates the white point of a typical uncalibrated monitor. It is not a CIE Standard Illuminant.

Xenon Arc Lamp

Xenon lamps are valued because of their near-daylight spectral qualities. They are used in film projectors in cinemas, floodlighting, flash-photography, and in graphic arts *light booths*. It is not a CIE Standard Illuminant.

The Illuminants menu

The ColorShop Illuminants menu divides supported illuminants into two groups. CIE-supported Illuminants—**A**, **C**, **D50**, **D55**, **D65**, **D75**, **F2**, **F7**, and **F11**—are listed above the menu divider. These Illuminants are built into the ColorShop software and cannot be removed.

Illuminants listed below the divider—**9300°K Monitor**, **Candlelight**, the **F** illuminants (except **F2**, **F7**, and **F11**), and **Xenon Arc Lamp**—are not supported by the CIE and are added to ColorShop as drop-in files. Drop-in illuminant files are located in:*System Folder:Preferences:ColorShop Stuff: Illuminants*. You can remove an illuminant by removing the file from the folder. Similarly, as Light Source and third parties develop new drop-in illuminants, you can add them to ColorShop by placing the file in the *Illuminants* folder.

B BIBLIOGRAPHY

There is a tremendous body of literature available on the concepts of color science and color measurement. This bibliography is provided not only as a list of references cited within this manual, but also as a list of suggestions for further reading.

For the sake of brevity we include here only published books, not papers, theses, or journal articles. We have also limited this bibliography to works that have been of use in the preparation of this manual—this is by no means a complete survey of the literature on color.

This Bibliography is divided into seven sections:

- Introductions to color and color measurement: recommended for anyone looking for alternative or additional introductions to the topics covered in the Primer.
- Color science text books: A sample of reference text books that would be found on a color scientist's bookshelf, or in a graduate class on color science. These books would be appropriate for intermediate to advanced color science readers.
- Glossaries: Books used in compiling the Glossary that appears at the end of this manual, or which provide additional terms not covered in Colortron. This section also mentions those books in other sections that have Glossaries.
- Color Harmony Books: Sources dealing primarily with the topic of color harmony and the use of color in fine arts.
- Graphic Arts Books: Sources dealing specifically with color printing and desktop publishing.
- Philosophical Treatises on Color. Sources addressing the philosophy, psychology, and history of color.
- Miscellaneous References: Sources mentioned as references within the Primer and the ColorShop documentation, but which do not fall into any of the above categories.

Introductions to Color and Color Measurement

Birren, Faber. 1963. *Color: A Survey in Words and Pictures*. New Hyde Park, NY: University Books.

Bova, Ben. 1988. *The Beauty of Light*. NY: John Wiley & Sons.

Brehm, Peter V. 1990. *Introduction to Densitometry: A User's Guide to Print Production Measurement Using Densitometry*. Alexandria, VA: Graphic Communications Association.

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Burger, Rudolph E. 1993. *Color Management Systems*. San Francisco: The Color Resource.

Burnie, David. 1992. *Light*. Eyewitness Science series. NY: Dorling Kindersley.
See comment under Cole (in Harmony books).

Gerritsen, Frans. 1975. *Theory and Practice of Color; a Color Theory Based on Laws of Perception*. NY: Van Nostrand Reinhold.
If you can find it, this book is a gold mine of excellent explanations and ingenious illustrations and demonstrations of basic color concepts.

Hellman, Hal. 1967. *The Art and Science of Color*. NY; McGraw-Hill.

Mueller, Conrad G. and Mae Rudolph. 1966. *Light and Vision*. Life Science Library. NY: Time-Life Books.
If you are interested in further exploration of the concepts in the Primer in this manual, buy or borrow this book! The use of illustration, history, and well written text provides the best introduction to concepts of light, vision, perception, and color that you will find anywhere.

Munsell, Albert H. 1969. *A Grammar of Color*. Edited by Faber Birren. NY: Van Nostrand Reinhold.

Ostwald, Wilhelm. 1969. *The Color Primer: A Basic Treatise on the Color System of Wilhelm Ostwald*. Edited by Faber Birren. NY: Van Nostrand Reinhold.

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Color Science Text Books

Berger-Schunn, Anni. 1994. *Practical Color Measurement: A Primer for the Beginner, A Reminder for the Expert*. NY: John Wiley & Sons.

Boynton, Robert M. 1992. *Human Color Vision*. Optical Society of America. Perhaps the best in the intermediate-to-advanced category. This book will take anyone with even the slightest background in science to a working understanding of the issues and science of color vision and perception.

Bruno, Michael H. 1986. *Principles of Color Proofing*. Salem, NH: Gama Communications.

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Cornsweet, Tom N. 1970. *Visual Perception*. NY and London: Academic Press.

Graham, Clarence H., ed. 1965. *Vision and Visual Perception*. NY: John Wiley & Sons.

Hunt, R. W. G. 1991. *Measuring Colour*. Second Edition. Chichester, England: Ellis Horwood.
Hunt's book is one of the most complete treatises to the science of color measurement that will be found anywhere.

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The "bible" of color science.

Yule, J. A. C. 1967. Principles of Color Reproduction: Applied to Photomechanical Reproduction, Color Photography, and the Ink, Paper, and Other Related Industries. NY: John Wiley & Sons.

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Hope, Augustine, and Margaret Walch. *The Color Compendium*. NY: Van Nostrand Reinhold.
This beautiful book is more an encyclopedia of color than a mere glossary. Highly recommended.

Southworth, Miles, Thad McIlroy, and Donna Southworth. 1992. *The Color Resource Complete Color Glossary*. Livonia, NY: The Color Resource.

An excellent color science and measurement glossary is also provided at the end of Hunt (1991).

For graphic arts glossaries, both Bruno (1989) and Campbell (1983) provide very complete lists of graphic arts terms.

Color Harmony

Birren, Faber. 1969. *Principles of Color; A Review of Past Traditions and Modern Theories of Color Harmony*. NY: Van Nostrand Reinhold.

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Together with Burnie (in Introductory books), these Eyewitness books provide a great introduction to basic color concepts not only for kids, but, because of the excellent illustration and clear prose, for adults too.

De Grandis, Luigina. 1986. *Theory and Use of Color*. Translated by John Gilbert. NY: Prentice-Hall, Inc. and Harry N. Abrams, Inc., Publishers.
This book also includes very good chapters on vision and color theory.

Itten, Johannes. 1970. *The Elements of Color: A Treatise on the Color System of Johannes Itten Based on His Book "The Art of Color."* Edited by Faber Birren. Translated by Ernst Van Hagen. NY: Van Nostrand Reinhold.

Itten, Johannes. 1985. *The Color Star*. NY: Van Nostrand Reinhold.

Color in Graphic Arts

Bruno, Michael H., ed. 1989. *Pocket Pal*. Fourteenth Edition. Memphis: International Paper.

Campbell, Alastair. 1983. *The Graphic Designer's Handbook.* Philadelphia: Running Press.

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Tufte, Edward R. 1990. *Envisioning Information*. Cheshire, Connecticut: Graphics Press.

GLOSSARY

A vast amount of science (and scientific ideas) is embedded within your color measurement instrument(s) and the ColorShop software. While you do not need to understand all of this science to use ColorShop effectively, you may want to explore the science behind it. The manual provides many avenues for exploration; and this Glossary is one such avenue. For those already familiar with the terms used here, this Glossary serves as a ready reference, especially for those terms specific to ColorShop.

Many entries included here refer to terms used in the "Color Primer." Others are meant to provide additional information not found in the Primer. This Glossary defines terms you may encounter in ColorShop, in the *ColorShop Online Guide*, or in the color science literature. Some entries are not general color science terms but are specific to certain contexts, such as ColorShop or the Macintosh.

Most of these terms are described in the Primer. However, this Glossary is designed to be read not only as a reference for the occasional term, but as an educational primer in itself.

For the most part, if a definition uses terms that appear elsewhere in the Glossary, this is indicated in blue. However, some terms—such as CIE or light source—are used so frequently the formatting is dropped unless the term is critical to a definition.

Agreement on many definitions is not always universal.[1] We have tried to use definitions consistent with industry-accepted conventions.

[1] For example, brightness and lightness are listed as synonyms in some sources, while other sources distinguish between the two. Boynton (1992) reserves brightness as descriptive of self-luminous sources and aperture viewing and uses lightness for reflective colors. Hunt (1991) refers to brightness as an absolute and lightness as relative to a white point. The definitions chosen for this Glossary attempt to reconcile these discrepancies while remaining consistent with the use of the terms in the computer industry.

Δ

Greek letter Delta. Used by convention to represent a change in a value. (See Delta-E, below.)

ΔE

Pronounced Delta-E, or Delta-Error.) A number representing how “close” two colors are to each other. The ΔE value is usually derived by computing the distance between two colors when plotted in a perceptually uniform color space. The ΔE difference is always a positive number.

A color difference of 1 ΔE is defined as the threshold of what is perceptible to the human eye. Statistical studies indicate a color difference of 6 to 7 ΔE is often considered “acceptable” to buyers of print materials For more information see the *Color Primer* PDF file.

λ

Greek letter lambda. Used by convention to represent wavelength.

°K

Notation for degrees *Kelvin*, the unit of temperature in the Kelvin scale. The modern convention in the scientific community is to drop the degree symbol and refer simply to “Kelvin” or “kelvins”, as in “6500 Kelvin or “6500 kelvins.” However, in older scientific literature and in many computer applications, the degree symbol is used. In ColorShop software and documentation, the degree symbol is used, partly to be consistent with other computer applications, and partly to avoid confusion with the computer-world convention of using “K” to mean kilobytes.

A

A (illuminant)

See illuminant A.

absolute black

Ideally, the absence of any reflectance (zero reflectance), used during calibration of an instrument to determine the lowest possible reading it can produce.

absolute references

An absolute white and an absolute black reference measured during the calibration of an instrument and used for any measurement of absolute references.

absolute reflectance

The reflectance measured relative to absolute white.

Absolute Reflective Mode

In ColorShop, a measurement mode used to measure reflective targets for which there is no relative white point (as there is with ink on paper).

absolute white

Ideally, the perfect diffuser. In practice, a white of known spectral reflectivity that can be used as a reference for all measurements of absolute references. In ColorShop, the absolute white reference is included in the Colortron Calibration Target card. This white is carefully measured at the factory relative to a near-perfect diffuser—a white tile calibrated by the National Institute of Standards and Techniques (NIST).

absolute zero

In physics, 0° on the Kelvin scale—the temperature at which all atomic activity stops. Equivalent to –273.16°C.

absorptive

Capable of absorption of light (electromagnetic) energy. Objects using both reflectivity and transmittance are capable of absorption.

achromatic

Neutral (such as gray, white, or black); with no distinguishable hue. (See also chromatic).

adaptation

The ability of the eye's sensitivity to change due to changes in viewing stimuli, so the eye can see in a wide range of conditions. (See also chromatic adaptation.)

ADB port

On the Macintosh, the Apple Desktop Bus™ (ADB) port. This is used by devices like the Colortron Digital Color Ruler, a keyboard, a mouse, or a trackball. ADB ports on a Macintosh or connectable device are indicated with the ADB icon.

additive color mixture

The process of creating colors by mixing lights of different spectral distribution, for example, by combining lights from two or more projectors, displaying small colored dots on a television or computer screen, or by spinning or flickering colors together. (See also subtractive color mixture.)

additive primaries

The three colored lights that can be combined to reproduce all other colors by additive color mixture. Red, green and blue are the most common example of a set of additive primaries. (See also RGB, and subtractive primaries).

alias

On the Macintosh, a dummy file that is linked to a file. Double-clicking on an alias opens the file it is linked to without having to open any folders. In this way you can access files that are buried deep within several nested folders without opening these folders.

ANSI

(Often pronounced AN-see.) The American National Standards Institute, the U.S. agency formally charged with the responsibility of establishing and maintaining standards for industries nationwide.

apparent dot area

See dot area.

apparent dot gain

In graphic arts, the difference between the apparent dot area of the film and the apparent dot area of the proof or printed sheet.

Apple Color Picker

On the Macintosh, a system-wide application that lets you use a color measurement device and access ColorShop palettes and tools from within another application. For example, in Photoshop, you can use the Color Picker to measure a color without having to start ColorShop. Most operations are the same in ColorShop and the Apple Color Picker.

Apple Drag Manager

On the Macintosh, a system extension that allows colors to be dragged from ColorShop and dropped onto another application's window, if the other application also supports the Apple Drag Manager. Data copied this way is identical in form to data on the Clipboard.

attachment foot

On a Colortron, an accessory foot that can be attached to allow measurement of different types of targets.

autoranging

On a Colortron, a feature that maintains accuracy across a wide dynamic range.When you take a measurement, Colortron adjusts the time it takes based on whether the target is a light color (with much light information being reflected) or a dark color (where a longer measurement time is necessary to compensate for less light information).

averaged measurements

In ColorShop, a measurement technique consisting of taking multiple samples and averaging the results, used for measurements of irregular surfaces or low-resolution halftones.

axes

(Pronounced AX-eez) Plural of axis. Lines used as references in a graph. Two examples are common in color science: In a graph of an RGB color space, the location of a point representing a color is defined by its distance from 0 along each of the **R**, **G**, and **B** axes. In a graph of spectral data for a color, the horizontal axis is wavelength, and the vertical axis is reflectance or transmittance. (See also coordinate system.)

axis

See axes.

B

B (illuminant)

See illuminant B.

backing

A sheet of material (usually black) placed behind a reflective target to minimize the influence of anything printed on the back side of the target.

backlighting source

A light source used to illuminate transmissive measurements targets such as film or transparency.

band

A range of wavelengths measured by a device. For example, a Colortron measures a total of 32 bands (each 10 nm wide) across the visible spectrum. (See also bandwidth.)

bandwidth

The width of the band measured by a color measurement instrument. For example, the bandwidth of a Colortron is 10 nm.

A spectrophotometer can be classified not only by its bandwidth, but as either constant-bandwidth or variable-bandwidth, depending on whether all bands, as measured across the visible spectrum, have exactly the same width or vary from band to band in the spectrum. A Colortron is a constant-bandwidth device. (See also dispersion, linear.)

black body

A theoretically perfect absorber of all incident radiation. Because all light leaving a black body, by definition, must be a result of emittance, this hypothetical object is useful in describing the characteristics of emissive objects like light sources and computer monitors. (See also color temperature.)

brightness

Attribute of a color by which it seems to exhibit more or less light. A term often used for emissive objects such as a light source. (See also lightness.)

The term brightness is also applied to images (displayed or printed) to describe the overall light given off by the image. (Compare to contrast.)

brilliance

A subjective term describing clarity in clear coatings, lack of muddiness in pigmented coatings, or the combined lightness and strength (purity) of printing inks.

broad-band fluorescent lamp

See fluorescent lamp.

C

C (illuminant)

See illuminant C.

calibrating

Changing the behavior of a device to a known state. This involves measuring how much a device deviates from a standard, such as factory settings or widely accepted values. The values reported by, or sent to the device can then be adjusted to make them comply with the standard. For example, you calibrate your color measurement device against an absolute white determined under laboratory conditions.

calibration

1) The act of calibrating. 2) The result of calibrating—the data used to adjust color values reported by, or sent to a device. (See also characterization.)

CGATS

(Sometimes pronounced SEE-gats.) The Committee for Graphic Arts Technologies Standards, a committee accredited by ANSI to coordinate standards and practices in the graphic arts industry.

characterization

The approximation of the color characteristics of a device (for example a monitor), based on the average of several identical devices (for example several monitors of the same brand and model as the target device). Not to be confused with calibration which measures the color characteristics of the target device itself. In a sense, the Standard Observer could be considered a characterization of the human visual system.

chroma

The saturation of a surface relative to some reference white. In other words the magnitude of the chromatic component of a color, the degree to which it exhibits hue. Although often used interchangeably with saturation, some sources make the distinction that the chroma of a surface is judged relative to a neutral reference of the same brightness as the surface, while saturation is judged relative to a neutral reference of arbitrary brightness. (See also Munsell chroma.)

chromatic

Exhibiting a hue; not white, gray or black.

chromatic adaptation

(Also known as color constancy.) The adaptation of the human eye to a change in white point of the viewing conditions—for example when you view a scene under different illumination or on different monitors, your eyes adapt so that the relationship between colors remains constant.

chromaticity

Color, independent of luminance. In other words, two colors that seem to be identical except for overall intensity, have the same chromaticity. In general, we can separate the perceptual effect of a color into two components: chromaticity and luminance. Chromaticity is what we perceive as the strictly color-related component and is itself often (although not always) broken down into hue and saturation. Luminance is associated with brightness.

chromaticity coordinates

The two dimensions of any color system that describes chromaticity. The general term usually means the CIE chromaticity coordinates **x** and **y**, but other examples are **a** and **b** in CIELAB, or **u** and **v** in CIE-LUV.

chromaticity coordinates, CIE

The values **x** and **y** in the CIE xyY color space derived from the CIE tristimulus values, **X**, **Y**, and **Z**. (See "Color Spaces and Illuminants" for derivations.)

chromaticity diagram

A plane (two-dimensional) graph where each point on the graph represents the chromaticity of a measured color or light source. Although the term is generally used as shorthand for the CIE chromaticity diagram (**x** vs. **y**), a chromaticity diagram can also be graphed for any chromaticity coordinates, such as **a** vs. **b** in CIELAB, or **u** vs. **v** in CIELUV. (See also chromaticity diagram, CIE.)

chromaticity diagram, CIE

A plane (two-dimensional) graph of CIE chromaticity coordinates, **x** and **y**, with **x** as the horizontal axis and **y** as the vertical. The outer boundary of visible colors is defined by the spectrum locus, the horseshoe-shaped curve containing the pure spectral colors from 380 to 770 nm. (See the *Color Primer* PDF file.) This diagram is extremely useful for a number of tasks, such as defining the gamut of a color device, and plotting and comparing the white point of light sources and monitors. (See also CIE xyY.)

CIE

The *Commission Internationale d'Éclairage* (International Commission on Illumination), an organization which has determined many of the standards used as the basis for color measurement.

CIE chromaticity coordinates

See chromaticity coordinates, CIE.

CIE chromaticity diagram

See chromaticity diagram, CIE.

CIELAB

(Also called CIE L*a*b* or CIE Lab.) A color space based on CIE XYZ, but more perceptually uniform—distances between colors in CIELAB correlate better to the perceived color difference between the colors. The **L*** value represents lightness, and **a*** and **b*** are chromaticity coordinates—**a*** indicates the "redness/greenness" axis, and **b*** the "yellowness/blueness" axis. CIE Lab has gained popularity in industries measuring reflective or transmissive subjects. **L*** values (labeled **L** in the Colorimetry Tool) range from 0 to 100. The **a*** and **b*** values (labeled, **a** and **b**) range from 0 to 1.

CIELUV

(Also called CIE L*u*v* or CIE Luv.) A color space similar to the CIELAB color space in its goal of describing a perceptually uniform color space. The **L*** value represents lightness, and **u*** and **v*** are z coordinates. CIELUV is commonly used for applications involving self-luminant color sources such as TV screens and monitors. **L*** values (labeled **L** in the Colorimetry Tool) range from 0 to 100. The **u*** and **v*** values (labeled, **u** and **v**) range from 0 to 1.

CIE tristimulus values

See tristimulus values, CIE.

CIE xyY

A color space consisting of the CIE chromaticity coordinates **x** and **y**, and the luminance value **Y** (identical to the '**Y**' in XYZ). (See also chromaticity diagram, CIE.)

CIE XYZ

A color space whose coordinates (sometimes called tristimulus values, CIE) represent the amounts (in percent) of three imaginary additive primaries **X**, **Y**, and **Z**. Unlike RGB, the XYZ model is not device-dependent, but is based on a mathematical model of human vision and measurements using color-matching experiments to define a Standard Observer. The **X**, **Y**, and **Z** primaries were defined in such a way that all color-matching combinations require positive amounts of all the primaries, and so that the **Y** value corresponds to the human eye's response to luminance.

CMC equation

An equation for computing Delta-E (color difference) values, developed by the Colour Measurement Committee (CMC) of the Society of Dyes and Colourists in Great Britain as an alternative to plotting distances in CIELAB and CIELUV color spaces.

CMM

An abbreviation for Color Matching Module or Color Matching Method. The component in a color management system that does the actual color conversion from one device's color space to another based on the information in profiles for each device. Several profiles can use the same CMM.

CMS

See color management system.

CMY

A color space consisting of the subtractive primaries, cyan, magenta, and yellow, the complementary colors of red, green, and blue, respectively. (See also RGB).

CMYK

A color model used in the printing of colors in four-color process printing. To the basic CMY color space is added black, abbreviated 'K' (for key) to make up for the practical problems of printing. The CMYK values needed to represent a color vary, depending on the printer, paper, etc., used to print the color.

colorant

A substance that gives color to another material, for example, a dye, ink, or pigment.

color bar

A bar of patches and patterns printed in the margin of a press sheet, used to monitor and control the press run. There are two types of color bar elements: those designed to be interpreted by a densitometer, and those that can be interpreted by a human operator.

color constancy

See chromatic adaptation.

color difference equation

An equation for computing Delta-E (color difference) values.

colorimeter

An instrument that measures color samples in terms of tristimulus values. Many colorimeters report values in a number of tristimulus color spaces.

colorimetric

Term referring to data produced by a colorimeter. Often used synonymously with tristimulus.

color library

In ColorShop, special, built-in palettes that contain colors from standard color matching systems such as PANTONE®.

color management system

Abbreviated CMS, a set of software, and sometimes hardware, components in a computer designed to handle automatically the proper conversion of colors from device to device. Each device is represented by a profile created either through calibration or characterization which dictates how colors are to be converted for that device.

color-matching experiment

An experiment using an apparatus designed to study the characteristics of the human visual system. A human subject looks through an aperture at a split field. On one side is a single target color (or stimulus), usually light of a single wavelength, which the subject must match. On the other side are three colors (the matching stimuli) which are mixed together. By adjusting the amounts of the three colors, the subject attempts to match the target color. (See the *Color Primer* PDF file.)

color-matching function

The collection of three curves representing the results of a color-matching experiment. For each target color, the height of the three curves represents the amounts of each of the three matching colors required to match the target.

color model

A set of rules and definitions that lets you describe all colors in a simple way. A color space is the most common example of a color model. In fact, the two terms are often used synonymously. Examples of color models are the color spaces RGB, HSB, CMY, CIE XYZ, and CIELAB, along with the four-color process system CMYK, and the spectral description of color. (See also color system.)

color separation

The generation of the values needed to represent a color or color image in process color printing. The most common form of color separation on a computer is the conversion of RGB values needed for monitor display, to CMYK needed for four-color printing.

color space

A system for organizing colors in which each color is represented as a point in space. Any time you can define a color in terms of three numbers (a triplet), such as (r,g,b), you can plot that color as a point in space relative to three axes. The collection of all colors plotted relative to the same three axes, is a color space. Thus a different set of axes forms a different color space. (See also color model.)

ColorSync™

On the Macintosh, a set of extensions to the Apple operating system that provides a basic color management system (CMS) and a foundation for other CMSs to build upon. (See also profile.)

ColorSync System Profile

In ColorSync™, the device profile you designate as the official "system profile" to all ColorSync-compatible applications. This is almost always the RGB monitor profile representing the monitor on which you do most of your work.

This tells each application how to create RGB values for your monitor (for example when displaying CMYK images, or when applying a scanner profile to a scanned image), or to convert RGB values (as any RGB values that are not otherwise assigned a profile, can be assumed to be customized for your monitor).

color system

Any system for organizing colors. There are two main approaches. One, known as a color model, defines every color in terms of a few simple rules. Another assigns each color a unique name or number in a cataloging system—for example the Munsell color system and the PANTONE® color system.

color temperature

Term used to represent the color of light radiated by a black body as it is heated. The temperature is expressed as absolute (Kelvin scale). As an object is heated, it emits radiation of characteristic color. At 2400°K the emitted radiation is relatively red; at 4800°K yellow; at 6500°K neutral (an even distribution of wavelengths); at 9300°K blue. (See correlated color temperature.)

color tolerancing

Defining the minimum “tolerance”, measured in ΔE, that is considered an acceptable color match for a particular purpose.

Colortron Calibration Target

A printed card or plastic tile matched to a Colortron that lets you calibrate the instrument. It provides an Absolute White reference that was measured precisely in the factory and whose values were programmed into the Colortron.

color wheel

1) An arrangement of the colors of the spectrum into a wheel or disk, usually with complementary colors facing each other. 2) An old term for the Apple Color Picker.

complement

See complementary colors.

complementary colors

Two colors that when summed, form a neutral gray. For example, the complement of blue is yellow.

components list

On the Macintosh, the list on the left side of the Apple Color Picker window that lets you choose from a number of Color Picker components, including the ColorShop tools.

cones

The receptors in the human eye that respond to light at daylight levels. There are three types of cones that respond to different regions of the visible spectrum—regions that correspond roughly to the red, green, and blue wavelength of light.

constant-bandwidth

See bandwidth.

contrast

A term describing the degree of tonal change. This can be the change between adjoining areas in an image, between the darkest and lightest parts of an image, or between two similar, but not identical, tones or colors. We sometimes speak of the contrast of the midtones, or the contrast in the shadows as a description of how dramatic the changes are within those parts of an image. Contrast is usually represented by the slope of a gamma curve at a given point. Not to be confused with overall brightness of an image or a pixel.

Control window

In ColorShop, the window containing the Current Color patch, the Document Profile and Illuminant pop-up menus, and the Measurement area.

coordinates

In mathematics, the values that define the location of a point in a coordinate system relative to its axes. For example, in an RGB color space, we often refer to the three values representing each color as the color’s RGB coordinates. The R-coordinate describes the distance from 0 along the R-axis—in other words, the amount of red in the color.

coordinate system

In mathematics, a system that describes a set of points in terms of their coordinates relative to a set of axes. The axes meet at a point called the origin where all coordinates are zero. The most common coordinate systems have either two or three axes. A coordinate system with three axes is called a space.

correlated color temperature

A temperature on the Kelvin scale assigned to an emissive object as a way of describing its white point. The correlated color temperature is the color temperature closest in color to that of the emissive source being described. For example, a monitor with a bluish white point can be described as having a correlated color temperature of 9300°K, while daylight, with a more neutral distribution of wavelengths, has a correlated color temperature of about 6500°K.

The correlated color temperature for an emissive source is computed from the chromaticity coordinates of the white point.

CRT

Abbreviation for "cathode ray tube." This is the picture tube in a television or computer monitor. It is sometimes useful to consider the gamma characteristics of the CRT separately from the overall gamma of the video system (the CRT + video card).

Current Color

In ColorShop, the last color you measured with your Colortron or the currently-selected color in a palette. The Current Color is "broadcast" to all open tool windows, and updates their displays.

custom blend

A color that requires custom mixing of two or more colorants, such as two PANTONE® inks.

cyan

The complement of red. (See also CMY and CMYK.)

D

D illuminants

See illuminants D.

D50, D55, D65, D75, etc.

See illuminants D.

Delta-E

See ΔE.

densitometer

An instrument designed to determine the light absorbed by a surface or material and report this determination as density.

density

A computed quantity representing the ability of a surface or material to absorb light. Density values are computed from reflectance or transmittance with the formula:

Density = log (1/Reflectance) or log(1/Transmittance).

Theoretically, density values range from 0 to infinity, but in practice range from about 0.05 to 2.5 for reflective targets and from 0.05 to 3.5 for transmissive sources.

detector

The part of a viewing or measurement device that detects different quantities of light.

device-dependent

Dependent on the characteristics of a particular device. For example, an RGB color space is device-dependent—the RGB values needed to reproduce a color on one device (e.g. a monitor) may not be the values needed to reproduce the same color appearance on a different device (e.g. a different monitor). In other words, RGB values are monitor-dependent. HSB values are also monitor-dependent, and CMYK values are printer-dependent.

device-independent

Independent of the characteristics of any particular device. Device-independent color—where colors are invisibly transformed so that images and other color elements appear identical on all devices—is one of the most sought after and most difficult to achieve ideals in computer science.

device profile

See profile.

diagnostics

A set of procedures designed to detect whether something is functioning properly. In ColorShop, this is a software routine that checks the instrument to verify that its optics are still properly aligned.

difference tolerance

A term used to indicate how close one color must be to another to be considered a “match.” Usually given in terms of ΔE.

diffraction

The dispersion of light into its component colors when it passes through an aperture whose size is comparable to the wavelengths of visible light.

diffraction grating

A mirror or glass surface that is scored (ruled) with microscopic parallel lines which behave as apertures to cause diffraction of light into its component wavelengths. For example, the optics of a Colortron are based on a diffraction grating.

diffuse reflection

See reflection.

dispersion

Technical term referring to the separation of light into its component colors of the spectrum. Dispersion can be accomplished by refraction using a prism or by diffraction using a diffraction grating.

Most prisms and diffraction gratings produce non-linear dispersion. As you look at the spectral display, the distance between, for example, 380 and 390 nm is much shorter than the distance between 770 and 780 nm. This is why many spectrophotometers do not have constant-bandwidth—some bands overlap, while others have gaps in between them that must be filled in by interpolation.

document

A computer term for the basic type of file that can be opened, manipulated, and closed in an application. Every application has its own notion of a document—in ColorShop, a document can be a palette or a color library. When a document is open, it is represented by a document window. When closed, the document exists as a document file on your hard disk.

document file

See document.

document profile

In ColorShop, the ColorSync™ printer profile associated with each palette document. Whenever the palette document is saved or printed, this profile is used to compute the CMYK values needed for printing on a four-color printer.

document window

A window within an application representing an open document that can be manipulated and changed. The title of the document appears in the document window title bar. Each document window can be resized independently and dragged by its title bar to another location.

dot area

The percentage of a tint relative to its solid. Dot area is computed from density.

dot gain

The tendency of ink to spread when it contacts paper causing halftone tints to appear to “gain” in value. Dot gain is not considered a printing fault, but an inevitable fact of life which must be monitored and controlled throughout the printing process. The amount of dot gain can be easily computed from the measured dot area relative to the desired dot area of a tint.

dragged measurements

A measurement technique that involves dragging your Colortron while taking multiple samples and averaging the results, used for irregular surfaces or low-resolution halftones. This is a form of averaged measurements.

drift

Small changes to the measurement characteristics of an instrument over time. Drift can be minimized, but cannot be avoided completely, so absolute accuracy requires calibration to measure this drift against a stable standard, and to compensate for it in the reported measurements.

dynamic range

The range of possible values, from smallest to largest, measurable by an instrument. This can either refer to the capabilities of the instrument (the lowest amount of light it can detect relative to the largest amount of light it can handle) or to the target being measured (the minimum to the maximum density values of an image, or material).

E

E (illuminant)

See illuminant E.

electromagnetic spectrum

See spectrum.

electromagnetism

The laws of electricity and magnetism as unified into a single science by J.C. Maxwell.

Emissive (Monitor) Mode

In ColorShop, a measurement mode used to measure colors on your monitor, using a Colortron or a Monitor Optimizer.

emittance

The net rate at which a body emits radiation. The spectral data for an emissive source consists of measurements of the emittance at each wavelength measured relative to the overall emittance.

equal-energy spectrum

See illuminant E.

ether

A theoretical medium through which light waves were thought to propagate. Its existence was eventually disproved, and Maxwell's equations of electromagnetism eliminated the need for such a medium to explain the behavior of light waves.

F

F illuminants

See illuminants F.

field of view

The size of an area viewed by the eye, specified as an angle with its apex on the lens of the eye. This angle defines the area of the retina on which the projected image falls. (See the *Color Primer* PDF file.) A field of view less than 4° involves primarily the fovea which has a slightly different color response than the rest of the retina. (See also Standard Observer.)

filter

1) To limit, or weight the relative importance of, certain wavelengths in a color or light source being measured. 2) A transmissive material used to filter colors optically. 3) A set of data used to filter colors in software or hardware.

fluorescence

The process or property of a material whereby light is absorbed at one wavelength, and re-emitted at another (usually longer) wavelength. The most common example occurs when non-visible ultraviolet light is re-emitted at a visible wavelength, making a surface appear even "brighter" at some wavelengths than the incoming light. (See also re-emission.)

fluorescent color

A colorant (a dye or pigment) that exhibits fluorescence.

fluorescent lamp

A lamp that consists of a glass tube filled with low-pressure mercury gas, coated on the inside with phosphors. The mercury gas is charged with an electrical current which produces ultraviolet radiation. This radiation, in turn, excites the phosphors which then glow ("fluoresce"). The purpose of the phosphors is to convert invisible ultraviolet radiation with a very narrow set of wavelengths, to a broader range of wavelengths in the visible part of the spectrum—especially in the longer-wavelength, yellow-red region of the spectrum where a lack of light energy can result in characteristic blue-green skin tones.

Differences among fluorescent lamps are caused by differences in the phosphors used. In general, there is a tradeoff between energy efficiency, and the distribution of wavelengths needed to see colors accurately. The twelve illuminants F are broken into three categories: F1–F6 are called normal fluorescent lamps because they have a good balance of efficiency and wavelength distribution. F7–F9 are called broad-band fluorescent lamps because they have a better distribution of wavelengths, but are relatively inefficient. F10–F12 are called three-band fluorescent lamps because the wavelengths are concentrated primarily in three bands of the spectrum (435, 545, and 610 nm), and are valued for their efficiency, not their color accuracy. Of these three types, the CIE recommends illuminants F2, F7, and F11.

The spectral profile for a fluorescent lamp is easily recognized by its sharp spikes caused by the mercury gas.

four-color printing

The most common form of process color printing that uses four primary inks (cyan, magenta, yellow, and black) to reproduce all colors.

fovea

(Also called the fovea centralis or the foveal pit.) The small area of the retina directly in the line of sight. This area is almost entirely made up of cones with few rods, and is structurally different from the rest of the retina in the way that it connects to the optic nerve. As a result, the fovea has a slightly different color response than the rest of the retina. (See also field of view and Standard Observer).

G

gamma

A number representing a gamma curve of a device. A gamma of 1.0 represents a linear gamma curve (a straight 45° line). A gamma of 1.8 is often used on a computer monitor as a crude approximation of the dot gain curve of a typical desktop printer. The gamma value is often associated with contrast because increasing the gamma increases the contrast for shadows and midtones (although it also decreases the contrast for highlights).

gamma correction

The correction required to change the measured gamma of a device to a desired gamma. The desired gamma is usually, although not necessarily, 1.0, representing a linear device.

gamma curve

A plotted tone curve showing the relationship between input values and output values of a device (for example, a monitor). If the device is linear, every input value is mapped to its equivalent output value and the gamma curve is a straight line. However, most devices are non-linear.

gamma LUT

The “lookup table” loaded into the video card of your monitor to achieve a desired gamma.

gamma rays

Non-visible electromagnetic radiation with an extremely short wavelength (high energy).

gamut

The range of colors reproducible by a given device such as a monitor or printer, or distinguishable by a detector such as the human eye or a scanner. In ColorShop, the CMYK Process Tool tells you if a particular color is out of gamut for the printer represented by the tool’s selected printer profile.

gamut compression

The conversion of color coordinates from a larger gamut to a smaller one. The most common form of gamut mapping.

gamut mapping

The conversion of color coordinates from one device’s gamut to another. (See also gamut compression.)

GCA

The Graphic Communications Association, an association of printers, publishers, color separators, ad agencies, manufacturers, and suppliers, involved in the coordination and communication within the graphic arts industry. (See also T-Ref™.)

grayscale

1) A test strip on film that displays a solid black swatch, followed by a series of progressively lighter grey tints in 10% increments. 2) Term used to describe a non-color device or image—as in “grayscale scanner” or “grayscale image.” This is a more accurate term than “black-and-white” in these instances.

H

halftone

A method of simulating different shades of gray or tones of color by use of spots (called “cells”) of varying sizes arranged in a grid pattern. This is the most common form of screening.

highlights

The lightest tones in an image, usually corresponding to specular reflections from shiny objects. (See also midtones and shadows.)

hi-fi color

A form of process color printing that uses seven primary colors instead of the more traditional four-color printing.

HSB

A color model where each color is represented by its hue, saturation, and brightness values. Many people find HSB a more natural way to specify color than RGB, and it is supported by most color applications. H (hue) is expressed as the angle, ranging from 0 to 360 degrees in a color wheel. S (Saturation) specifies how vivid or pure the color is. B (Brightness or lightness) specifies how bright the color is.

HSL

A color model seen in many computer applications—essentially the same as HSB, except that brightness is named lightness.

The subtle distinction between brightness and lightness is not important on a computer monitor.

hue

The attribute of a color that causes it to be perceived as being other than black, white, or gray.

hue angle

A numerical representation of hue in terms of an angle around a color wheel.

I, J

ICC

The International Color Consortium, a collection of companies in the digital color industry working on standards for color management technology. ColorSync™ 2.0 is an implementation of the ICC specification.

illuminant

A light source defined spectrally—in other words, in terms of the relative energy at each wavelength in the visible spectrum.

illuminant A

A CIE Standard Illuminant produced by a tungsten light source, yellow-orange in hue, with a correlated color temperature of 2856°K. Illuminant A is generally used to simulate lighting conditions using an incandescent lamp.

illuminant B

A CIE Standard Illuminant produced by a tungsten light source filtered in such a way as to simulate direct noon sunlight, neutral in hue, with a correlated color temperature of 4874°K. Standard Illuminant B is now obsolete.

illuminant C

A CIE Standard Illuminant produced by a tungsten light source filtered in such a way as to simulate average daylight, bluish in hue, with a correlated color temperature of 6774°K. As with the other two original (1931) Standard Illuminants A and B, the specification for illuminant C is defined only within the wavelength range of 380–770 nm, and did not include the ultraviolet portion of the spectrum necessary to correctly describe fluorescent colors. This is what led to the CIE in 1963 to recommend a new Standard Illuminant D65, and the other illuminants D.

illuminants D

The CIE Daylight Standard Illuminants based on actual spectral measurements of various phases of daylight. Each is given the name D with a subscript to indicate the correlated color temperature for the illuminant. D65, with a correlated color temperature of 6504°K, is very similar to illuminant C, except with a better representation of the ultraviolet component of daylight needed to describe fluorescent colors. D50, D55, and D75, with correlated color temperatures of 5000, 5500, and 7500°K, respectively, are also commonly seen. Of all illuminants, D_{65} is most generally recommended, although D_{50} is often seen in viewing booths used in the graphic arts industry for evaluating proofs and printed materials.

illuminant E

A theoretical, “equal-energy” stimulus with a perfectly flat spectral profile—equal amounts of energy at each wavelength. No such light source exists, but this theoretical concept is occasionally useful for computation purposes in color science.

illuminants F

A set of illuminants designed to simulate fluorescent lamp lighting conditions.

Although technically not Standard Illuminants as defined by the CIE, the CIE does recommend certain light sources for evaluating colors destined for fluorescent lighting environments. The fluorescent illuminants are commonly named F1 through F12, of which the CIE recommends F2, F7, and F11.

incandescent lamp

A lamp, such as a common household light bulb, that emits light due to the glowing of a heated filament, a threadlike wire, often made of tungsten, through which a current is passed.

infrared

Name given to the non-visible range of the electromagnetic spectrum just above the red end of the visible spectrum (above 700 nm).

intensity

For colors, the amount of light reflected at each band across the visible spectrum.

interpolation

A method of filling in gaps in measured data by computing missing values from measured values.

ISO

The International Standardization Organization, the agency responsible for establishing industry standards in the international arena, much as ANSI does in the U.S. ANSI is a member of the ISO.

K

K

See Kelvin scale.

Kelvin scale

A system of absolute temperature invented by William Thompson Kelvin, using the same degrees as the Celsius scale, but defining an absolute zero (0°K = –273.16°C), the temperature at which all atomic activity stops. This scale is used when giving temperatures in physics, and is used for expressing color temperature, and the correlated color temperature of the white point of an emissive object such as a light source or a computer monitor.

key

Another name for black in four-color printing. Historically the name comes from the fact that black was the first of the four colors printed, with the remaining colors overprinted and registered (aligned) to it. Thus black was the “key” color. The ‘K’ in CMYK stands for key.

L

L*

The lightness value defined in the CIELAB and CIELUV color systems to describe the amount of light reflected or transmitted by a sample.

lens cleaner

A small, soft brush with a squeezable bellows for blowing short, gentle bursts of air.

light

Electromagnetic radiation within the part of the spectrum visible to the human eye.

light booth

See viewing booth.

lightness

The brightness of a color relative to some reference white. Generally, a term used to describe reflective or transmissive surfaces. With colors displayed on a computer monitor, the terms lightness and brightness are used interchangeably because, although the computer monitor is an emissive object, the colors are displayed relative to the white point of the monitor.

light source

An object that emits visible light. A light source defined spectrally is an illuminant. A light source can also be defined in terms of the correlated color temperature or the chromaticity coordinates of its white point.

Light Source

The makers of the Colortron device and ColorShop software.

light table

A consistent, controlled backlighting source for transmissive measurements.

linear

A relationship between two values that always vary at equal or proportional rates—for example, doubling one value always doubles the other. The graph of the two variables is a straight line (hence the term linear). If the graph of the two variables is not a straight line, the values are said to have a non-linear relationship.

linear device

A device for which input values produce their equivalent output values across the entire tonal range. Most devices are non-linear and require some gamma correction to make them linear.

linear dispersion

See dispersion.

linearize

To make linear.

luminance

Term invented by the CIE to refer to the measurable correlate of brightness. Technically, the intensity per unit area of light reflected or transmitted by a surface or material. (See also chromaticity.)

In the CIE system, luminance is represented by the Y value in XYZ. (See also CIE XYZ.)

Luminance is measurable, but brightness (or lightness) is perceptual. In general, brightness is computed using luminance measurements. Brightness and luminance are “correlates” of each other—an increase in luminance is usually perceived as an increase in brightness—but they are not synonyms because their correlation is not linear (doubling the luminance does not necessarily make something twice as bright).

LUT

(Often pronounced “luht”.) Abbreviation for “lookup table.” With monitor calibration, this usually refers to a table that is loaded into the video card of your monitor to change the RGB values as they are sent to the monitor.

M

magenta

The complement of green. (See also CMY and CMYK.)

Measurement area

In ColorShop, the part of the Control window or the Apple Color Picker containing settings for the measurement mode, the Absolute White and Black patches and the Paper White or Film / Light patch.

measurement geometry

In a reflective measurement instrument, the angle between the illuminating lamp and the viewing detector. This is an important consideration when measuring reflective surfaces as it is important to measure the diffuse reflection of a surface, and not its specular reflection. Most instruments have either a 45 / 0 (lamp at 45˚ relative to the surface, and the detector at 0°, perpendicular to the surface) or 0/45 measurement geometry. A Colortron has a 45/0 measurement geometry.

measurement mode

In ColorShop, the mode of measurement corresponding to the type of information you are measuring—Reflective (paper), Absolute Reflective, Emissive, or Transmissive.

memory colors

Colors that are particularly important in print production because they represent the colors of familiar objects, such as sky blue, grass green, and skin tones.

metameric pair

Two colors that display metamerism.

metamerism

(Pronounced met-AH-mer-ism.) A relationship between two color samples whereby they appear to match in color when viewed under certain conditions (usually illuminant), but not under others.

metamer

For a given color, a second color that exhibits the same appearance under certain viewing conditions, but whose appearance will not match under other conditions. The two colors are thus a metameric pair.

midtones

The tones in an image that range between the highlights (the lightest tones in the image) and shadows (the darkest tones).

monitor profile

See profile.

monitor RGB

An RGB color space where the RGB values are given relative to a certain monitor. Although not often stated explicitly, most computer applications that deal with RGB values are really working with monitor RGB—the RGB values given for colors are based on their appearance on your monitor.

monochromatic light

Light of a single wavelength (for example, pure 500-nm light). The stimuli in a color-matching experiment are often monochromatic light sources.

Munsell chroma

In the Munsell color system, the value associated with the saturation of a color, as expressed in perceptually uniform steps. Neutral white, grays, and black have a chroma of zero. The maximum chroma is different for each Munsell hue, ranging as high as 15–16 for yellows and reds.

Munsell color system

A color notation system developed by Albert Munsell, and used to reference a collection of color chips manufactured by the Munsell Color Co. The system is based on human perception and visual differences between three attributes of a color, known as Munsell hue (H), Munsell chroma (C), and Munsell value (V). The three attributes are given in the notation in the form HV/C—for example, **6PB 5/10** would represent a color six steps around the color wheel from purple-blue, of medium brightness, and very saturated.

Munsell hue

In the Munsell color system, the term used to represent the hue of a color, expressed as a region of the color wheel. These regions are labeled using letters representing five main hues, Red (R), Yellow (Y), Green (G), Blue (B), and Purple (P), and five intermediate hues, Yellow-Red (YR), Red-Purple (RP), Purple-Blue (PB), etc. Steps in between each of these hues are represented by a number from 0 to 10 preceding the letter label, for example 5R, or 6.7BP.

Munsell value

In the Munsell color system, the term used to represent the lightness of a color, as expressed in ten perceptually uniform steps ranging from 0 (black) to 10 (white).

N

nanometer

A unit of measurement used to describe wavelengths of light. A nanometer is 10-9 of a meter or one-millionth of a millimeter.

NIST

The National Institute for Standards and Technology.

nm

An abbreviation for nanometer.

noise

In electronics, undesired information caused by optical or electronic signal disturbances or static.

non-linear

See linear.

non-linear dispersion

See dispersion.

non-spectral color

See tristimulus color.

normal fluorescent lamp

See fluorescent lamp.

NTSC

An abbreviation for the National Television Standards Committee. The NTSC's color model represents the standard for display on televisions in the United States. (See also PAL.)

O

off-press proof

A color proof made without using a printing press, by using pigmented or dyed light-sensitive materials exposed with film negatives or positives. The best off-press proofing systems simulate press conditions such as dot gain so that the proof is an accurate prediction of what will happen on press.

opponent color theory of vision

Also known as the Hering theory, this holds that the number of primary hues distinguished by the human eye is not three, but four—red, yellow, green, and blue—that comprise two pairs of "opponent" hues red-green, and yellow-blue. Although long considered incompatible with the trichromatic theory of vision the modern views of color vision have reconciled the two theories by studying not only the three types of color receptors (cones) in the eye, but also the complex ways that these receptors are interconnected in the retina. The main thing to note from all of this is that the amazing complexity of the human visual system is what makes the "perfect color theory" so elusive.

optics

In a measurement instrument like a Colortron, the part of the instrument which deals with light itself: the lamps, lenses, and mirrors.

P, Q

page layout program

A program that allows you to perform desktop publishing operations, such as laying out pages and documents, placing graphics with text, and producing color separations.

PAL

An abbreviation for Phase Alternation by Line. This color model represents the standard for display on televisions in Western Europe. (See also NTSC.)

palette

A collection of colors. In ColorShop, a palette is a document that can be saved, reopened, and imported to other applications.

PANTONE®

(Also called the PANTONE Matching System®.) A color specification system designed and licensed by Pantone, Inc. consisting of color charts containing hundreds of preprinted color patches of specially blended inks used to identify, display, and communicate specific colors for reproduction in print. PANTONE® and PANTONE MATCHING SYSTEM® are registered trademarks of Pantone, Inc.

paper white

The color of the paper on which a color is printed. Because this contributes to the color you see, the paper white is often used as a reference white for color measurements.

patch

1) An area of color to be measured. 2) In ColorShop, an area in a Tool window or palette document window displaying a measured or computed color.

PCS

See profile connection space.

perceptually uniform

Term used to describe a color space or color model where distances correspond well to changes perceived by human viewers. For example, the CIELAB color space is designed so that the distance between any two points representing two colors, corresponds well to how "close" those colors appear to each other when viewed by a human test subject.

perfect absorber

A surface or object that absorbs 100% of all light striking it. (See also black body.)

perfect diffuser

A surface or object that reflects 100% of all light as diffuse reflection—in other words, a perfectly white surface.

perfect mirror

A surface or object that reflects 100% of all light as specular reflection.

perfect transmitter

A surface or material that transmits 100% of all light that strikes it, allowing it all to pass through without absorption—in other words, a perfectly transparent material. Glass, water, and even air are not perfect transmitters, as they absorb or scatter light passing through them, as can be seen in a layer of these materials that is very thick. The only truly perfect transmitter is a vacuum.

phosphor

A substance that glows when struck by radiation of certain wavelength. Phosphors are used to coat the inside of television tubes, computer monitors, and fluorescent lamps.

phosphorescence

The process or property of a material or object whereby incoming radiation is temporarily absorbed, and then re-emitted a short time later, so that the material continues to "glow" for a time after the source of incoming light is removed. (See also re-emission.)

photon

A fundamental unit of light or other electromagnetic radiation. Photons display some characteristics of a particle, and some of a wave. Each photon emitted by a light source has a characteristic energy, the wavelength of the photon.

photopigment

A protein molecule that reacts to light. There are four types of photopigments found in the human eye, resulting in the four types of photoreceptors.

photoreceptor

(Also called receptor.) A specialized cell in the human retina that reacts to light. There are four types of receptors in the human eye—rods and three types of cones— each of which has a characteristic sensitivity to different parts of the visible spectrum.

prepress proof

See off-press proof.

primary colors

Also called primaries. Colors that can be combined to form all other colors. (See also additive primaries and subtractive primaries.)

printer profile

See profile.

prism

A triangular-shaped piece of glass or other transparent material that uses refraction to separate light passing through into its component colors. (See also dispersion.)

process color

The simulation of "full color" by combining three or more primary colors (pigments or inks). The most common form of process color is four-color printing, although new methods using five, six, seven, or even more colors are becoming increasingly common. (See also CMYK, hi-fi color.)

profile

In a color management system, a file containing data representing the color reproduction characteristics of a device—producing a printer profile, monitor profile, scanner profile, or in general, device profile. A profile is created by using either calibration, or characterization, or a combination of both methods.

profile connection space

(Often abbreviated PCS.) In a color management system, the color space used as the intermediate space when converting from one device's color space to another.

profile, spectral

Term often used for the description of a color sample in terms of its spectral data. This should not be confused with the growing use of the word profile to mean a device description in a color management system—in fact, to avoid such confusion, the use of the alternative terms "spectral data," "spectral curve," or "spectral fingerprint" are encouraged.

proof

A visual preview or test of the expected final results of a printed piece. While a color proof is usually an off-press proof or a press proof, it may be produced on a color monitor set up to simulate press conditions.

purple line

Technical term for the line connecting the endpoints of the spectrum locus in the CIE chromaticity diagram. Colors on this line represent mixtures of 380- and 780-nm light. Colors below this line are outside the range of colors visible to the human eye. Also called the purple boundary.

R

rear-screen slide projector

A slide projector that works by projecting the slide onto a built-in translucent surface allowing you to view the projection from the opposite side.

receptor

See photoreceptor.

re-emission

Light or other radiation that leaves a surface or object as a result of incoming radiation— in other words incoming light that is not absorbed. Contrast this with emission which is radiation given off as a result of internal processes within an object, such as combustion. Re-emission of incoming radiation can happen in many ways: If each wavelength of incoming light leaves at the same wavelength, this is reflection or transmission. If some wavelengths of incoming radiation leave at a different wavelength, this is fluorescence. If the re-emission continues to occur after the source of incoming radiation is removed, this is phosphorescence.

reference

A definition or a measurement against which other measurements are compared.

reference white

A definition or a measurement of "white" against which other measurements are compared. For reflective measurements this would be either the paper white or absolute white. For transmissive measurements this would be either the light source used to illuminate the target material, or a combination of the light source and the clear film base. For emissive measurements, such as a light source or computer monitor, this would be the white point of the source.

reflectance

The percentage of light striking a surface that is re-emitted due to reflection.

reflection

The immediate return of light or other radiation by a surface without a change in wavelength. (See also re-emission.)

There are two main types of reflection: specular reflection is the light which reflects in the direction opposite to the incoming light, as in the light reflecting off a mirror; diffuse reflection is the light which reflects in all directions, such as the light reflecting off a sheet of paper. A sheet of glossy paper exhibits both types of reflection.

Reflective (Paper) Mode

In ColorShop, a measurement mode used to measure the color of ink on paper after you zero out the color of the paper.

reflectivity

See reflectance.

refraction

The bending of light as it passes through the boundary between two transparent materials with different optical properties, such as the boundary between air and glass. Shorter wavelengths bend less than longer ones: with a suitably shaped prism refraction can be used to separate light into its component colors.

relative reflectance

The reflectance measured relative to a reference white.

rendering intent

The strategy used by a color management system to deal with the differences between device gamuts. ICC and ColorSync™ 2.0 lets you choose one of four rendering intents to use depending on what color attributes you want to preserve at the expense of others.

resize box

On the Macintosh, the small icon in the lower right-hand corner of a window that you drag in order to change the window's size.

response filter

A filter used to achieve a certain response function.

response function

A curve that describes the sensitivity of a measurement device to different wavelengths of light. The response function is either inherent in the design of the optics and electronics of the instrument or can be implemented in software (provided the instrument can read spectral data) so that different response functions can be selected.

retina

The light-sensitive layer at the back of the eyeball which responds to light. The retina consists of nerves, blood vessels, and photoreceptors.

RGB

Red / Green / Blue. A color model optimally suited for representing colors on certain devices: computer monitors, scanners, photoCDs, etc., in which each color is represented as a mixture of red, green, and blue light. (See also additive primaries.)

RGB color space

A color space based on the RGB color model, sometimes called simply an RGB space. Because each device has a slightly different definition of the RGB primaries, there are as many RGB color spaces as there are devices.

rods

The photoreceptors in the human eye that respond to low levels of light involved in night vision. Because we have only one kind of rod cell, night vision is inherently achromatic ("black-and-white").

S

sample

1) A target color to be measured. 2) In computer science, a discreet measurement or the action of taking such a measurement. For example, the Colortron Digital Color Ruler samples a target surface 32 times for each complete measurement—once for each band of the spectrum.

saturation

The attribute of a color by which it appears to be pure—containing no white or gray. A vivid rose color is extremely saturated, a pale pink is not. Unsaturated colors appear to be diluted with quantities of neutral gray. Totally saturated colors appear to be composed of a single wavelength. (See also chroma.)

scanner profile

See profile.

screening

A technique used to simulate different shades of gray or tones of color by varying the proportions of background (usually paper) and ink within an area. Screening can be used to print either an image consisting of many tones or a tint consisting of a single tone. The most common form of screening is the halftone.

scroll bars

On the Macintosh, the horizontal and / or vertical scrolling devices at the right side and / or bottom of a window or dialog box. Scrolling in any direction changes the current view and allows other parts of a window or dialog box to be displayed.

serial port

A connector that allows you to attach of certain devices to your computer. Generally printers and modems are attached to a serial port. On a Macintosh, a serial ports is indicated with either a printer or a modem icon.

shadows

The darkest tones in an image. (See also highlights and midtones.)

simultaneous contrast

An optical phenomenon which causes the perception of a color to be strongly influenced by adjacent and background colors. (See also chromatic adaptation and successive contrast.)

solid

Term given to a patch of solid ink—for example, a patch of pure cyan ink. When measuring tints of various values, always measure the paper white first, then measure the solid. Together these define the 0% and 100% tint values relative to which all other tints are computed.

space

1) The final frontier. 2) In mathematics, a collection of points, in which the location of each point is defined relative to three perpendicular lines or axes. Just as any set of two axes defines a plane, a set of three axes defines a space. Thus different sets of axes define different spaces. (See also color space and coordinate system.)

spectral

Adjective used to describe anything related to the spectrum or spectral data—in other words, divided into discreet bands representing the spectrum (e.g. spectral profile, spectral curve, spectral fingerprint, spectral response).

spectral data

Measured data representing the reflectance, transmittance, or relative emittance at discreet wavelengths of the spectrum. (See also profile and spectral).

spectrophotometer

A device that measures spectral data. Most spectrophotometers can report this data in either spectral form or converted to a tristimulus form.

spectrum

An arrangement of the components of electromagnetic energy in order of their wavelengths. The electromagnetic spectrum encompasses all wavelengths, while the visible spectrum encompasses only the visible range of wavelengths from about 380–700 nm. By itself the word spectrum usually refers to the visible spectrum and its separation into the colors of the rainbow.

spectrum locus

Technical term for the horseshoe-shaped curve in the CIE chromaticity diagram, on which lie all the pure colors of the visible spectrum. This curve defines the boundary of colors visible to the human eye. (See also purple line.)

specular reflection

See reflection.

spot color

A localized color assigned to a graphic or block of text, printed without the use of color separations.

Standard Illuminants

See illuminant A, illuminant B, illuminant C, and illuminants D.

Standard Observer

The observer standard adopted by the CIE to represent the response of the average human eye. The standard is expressed in the color-matching function using the imaginary primaries **X**, **Y**, and **Z**. The standard proposed in 1931 is based on color-matching experiments using a 2˚ field of view. In 1964 a Supplementary Standard Observer was added based on a 10˚ field of view to better model the slightly different data obtained with a field of view wider than 4˚. Unless otherwise specified, the CIE system assumes the 1931 2˚ observer.

Status A

A standard response function of a densitometer used for measurement of photographic products— such as prints, 35mm slides, and transparencies— intended for visual display using direct or projection methods.

status indicator

On a Colortron, the lights that indicate whether the instrument is on, whether it is measuring a color, and whether the battery pack needs to be recharged.

Status M

A standard response function of a densitometer used for measurement of prepress films, such as camera films, that are to be printed on photographic paper but are not meant to be viewed directly.

Status T

A standard response function of a densitometer used for measurement of off-press proofs, press proofs, and press sheets.

stimuli

Plural of stimulus.

stimulus

Something that elicits a response. In a color-matching experiment each stimulus is a light of a particular color—often so carefully defined that it contains only light of a particular wavelength. (See also tristimulus.)

subtractive color mixture

Color that results from mixing colorants (for example, dyes, inks, or pigments) of different spectral distribution. Each color subtracts the wavelengths of its complement from the white light reflecting off the paper. For example, yellow ink subtracts blue wavelengths from white. (See also additive color mixture.)

subtractive primaries

Three colorant (for example, dyes, inks or pigments) that can be combined to reproduce all other colors by subtractive color mixture. The most common examples of subtractive primaries are the complements of red, green, and blue, namely cyan, magenta, and yellow. (See also CMY, CMYK, and additive primaries.)

successive contrast

An optical phenomenon whereby the eye's adaptation to one color affects the color seen immediately afterwards. (See also simultaneous contrast.)

T

three-band fluorescent lamp

See fluorescent lamp.

tint

A printed patch or area consisting of a single shade of gray, or tone of color (for example a 50%-gray or a 30%-cyan patch). Tints are printed using the technique of screening (usually a halftone).

tolerance

See difference tolerance.

tone curve

A graph showing the relationship of the input values of a device or system to its output values. The input values are usually shown on the horizontal axis and the output values on the vertical.

A gamma curve is a form of tone curve typical of uncorrected devices, such as monitors and printers.

Toolbox

In ColorShop, the floating palette that displays icons for each of the installed ColorShop tools. Click a tool's icon to display that tool.

tools

In ColorShop, the specialized mini-applications that allow you to examine, manipulate, and analyze various attributes of the colors in a ColorShop palette.

traceable to NIST

A phrase used to describe a calibration system whose accuracy can be traced back to an original standard produced by the NIST. For example, a Colortron is calibrated using the Colortron Calibration Target which in turn is calibrated at the factory relative to a master ceramic white tile of known reflectance issued and carefully measured by the NIST.

transformation

An equation or algorithm which defines how colors are converted from one color system to another. For example, there is a transformation algorithm to determine how a set of CMYK values would translate to an RGB system.

Transmissive (Film) Mode

In ColorShop, a measurement mode used to measure color or density for materials which require light shining through them for visibility.

transmissive measurements

Measurements of film or other transparent materials.

transmittance

The percentage of light that passes through a transmissive material.

T-Ref™

A printed reference card available from the gamut and used to verify a densitometer's conformance to Status T response. The Colortron Calibration Target is printed using the identical materials, specifications, and printer—in fact, the same print run—as used for the latest edition of the T-Ref.

trichromat

A person who requires three primaries to match colors in a color-matching experiment—in other words a normal observer.

trichromatic

Of, or consisting of, three colors. This is synonymous with the strictest definition of tristimulus as referring to amounts of three stimuli required to match a target stimulus.

trichromatic theory of vision

Also known as the Young-Helmholtz theory and based in part on the work of Maxwell, this theory holds that all colors can be simulated using just three primary colors. It also maintains that this can be completely explained by the three types of color receptors (cones) in the human eye. (See also opponent color theory of vision.)

triplet

In mathematics, a group of three values. The subtle point to note is that the three numbers are to be considered a single object—as often indicated with the notation (x, y, z). For example, a color in an RGB color space is a single object represented by a triplet of color values, (r, g, b), where **r**, **g**, and **b** are the amounts, respectively, of red, green and blue required to simulate the color on a given device.

tristimulus

Of, consisting of, or derived from, three stimuli. In the strictest sense tristimulus refers to amounts of the three stimuli, in a color-matching experiment, required to match the target stimulus—a definition which would admit only additive primaries systems like RGB and CIE XYZ to the tristimulus category. The more commonly accepted definition is expanded to include not only subtractive primaries systems like CMY, but also any color model that can be computed from existing tristimulus models, such as HSB (computed from RGB) and CMYK (derived from CMY).

Tristimulus values are either measured (using a colorimeter) or computed from other tristimulus values.

The term tristimulus color space can be thought of as any color system where each color is defined as a triplet of numbers. This definition holds for the most part, but there are a few exceptions: CMYK is generally considered a tristimulus color model, although each color requires four numbers to describe it. The Munsell color system defines each color in terms of three values, hue, value, and chroma—but is technically not tristimulus because you cannot derive these values by measurement or computation. They must be looked up in a table or color library, like a PANTONE® color.

tristimulus color

In ColorShop, any color for which spectral data is unavailable (sometimes called a non-spectral color). Such colors arise because they are produced by some means other than measurement or copying from a color library—for example, by importing a color from another application, or by using certain tools, such as the Color Harmony Tool, which produce non-spectral colors. If you start with a spectral color and use the Colorimeter Tool to edit the color's tristimulus values, this converts the color into a tristimulus color—i.e. since spectral data cannot be derived from the new tristimulus values, spectral data is no longer available.

tristimulus color space

See tristimulus.

tristimulus values

The triplet of values representing a color in a tristimulus color space.

tristimulus values, CIE

The **X**, **Y**, and **Z** values representing a color in the CIE XYZ color space.

tungsten

A rare metallic element (symbol: **W**) with a high melting point used in filaments of stable incandescent lamps. The lamps in a Colortron are tungsten lamps.

tweening

Finding a color between two other colors.

U

ultraviolet

Term used to describe radiation in the nonvisible range of the electromagnetic spectrum just below the violet end of the visible spectrum (below 380 nm).

V

value, Munsell

See Munsell value.

variable-bandwidth

See bandwidth.

video card

(Also called a "video board") the circuitboard or card in your computer that communicates with your monitor. (Sometimes this is built into the main circuit-board, the "mother board", of the computer.) The job of the video card is to convert the digital RGB values computed by your computer to the analog signal expected by the CRT.

viewing booth

An enclosure often used in the graphic arts industry for evaluating proofs and printed materials under controlled lighting conditions. (See also illuminants D.)

visible spectrum

The range of the electromagnetic spectrum between about 380 to 700 nm, that is visible to the human eye.

visual field

See field of view.

Von Kries transformation

(After J. A. von Kries.) A mathematical correction applied to tristimulus values to compensate for chromatic adaptation of the eye. ColorShop applies this automatically (although you can turn it off), to best simulate the appearance of colors under one white point when your eye is adapted to a different white point—that of your monitor.

W

wavelength

The crest-to-crest distance between two periodic waves. Often represented by the Greek letter λ (lambda).

white point

The chromaticity of a white light source or other emissive object. For example, if you display "white" on two side-by-side RGB monitors—where "white" is defined by 100% red / 100% green / 100% blue—one monitor may look distinctly blue compared to the other, while the second monitor appears yellow or red. In other words, the monitors have different white points. Similarly, incandescent light is much yellower than daylight.

The white point of an emissive object is expressed in one of two ways: by giving the white point's correlated color temperature or its chromaticity coordinates. Correlated color temperature is more commonly used for description purposes, while chromaticity coordinates are better for computation or for display and comparison on a chromaticity chart.

X

xenon arc lamp

A lamp that works by passing a high-voltage current through pressurized xenon gas to produce a very bright light with spectral characteristics very close to daylight. Xenon lamps are used in film projectors in cinemas, floodlighting, flash-photography, and in graphic arts light booths.

Y

yellow

The complement of blue.

Z

zero out

To remove the effects of an element from a measurement. For example, when measuring ink on paper, you may want to zero out the color of the paper to determine the ink color alone.

USING THIS ONLINE GUIDE

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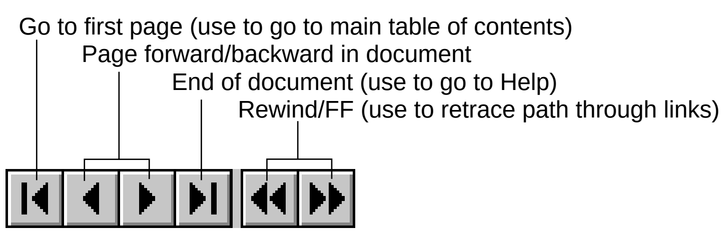
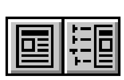
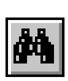



Use these buttons to hide / show bookmarks. Use the bookmarks as a table of contents.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