

test prints under controlled lighting until the final color appearance desired was reproduced. Due to the inherent nature of color negatives, they cannot be viewed directly. No original reference exists other than the scene (and our memory of the scene) where the image was photographed. The color print represents the reproduction, or *color rendering*, based upon how the photographer wished the print to represent the scene. It is often impossible to absolutely match a transparency to a reflective print since the dynamic range of a transparency is usually much greater. That didn't stop photographers and photo labs from making prints from film, nor the clients' acceptance that they had received a match from the original. It is worth noting that it is usually easier to match two somewhat similar media such as a transparency to a print compared to a print and an actual scene that we viewed originally with our own eyes.

### **Digital Images Are Just Numbers**

Enter computer imaging. It is important to understand that all a computer understands are series of numbers: long strings of zeros or ones. It is amazing that we can view what appears to be a full color image on our computers when in fact all we are working with are numbers. It is important to understand that color is a human perception, a sensation inside our brains. All the colors displayed on a computer system are just numeric values, and unfortunately, numbers don't tell us what a color looks like; rather, they provide a partial numeric recipe for color. For this reason, color management is vital when dealing with images on a computer. Think of it this way: suppose I supply a recipe for chocolate chip cookies but do not provide the unit for each ingredient in the recipe. The recipe provides each ingredient followed by a number. Without units we can't make the cookies. The numbers alone are not enough information to describe the cookies that will be produced. Likewise, R78/G103/B23 is not enough information to reproduce. Ultimately we need to see the colors and know that these colors will be reproduced as we desire when output (see Fig. 1-2).

### **The Pixel**

Digital images displayed on a computer are composed of *pixels* (short for "picture element"), the smallest building blocks of a digital file. Zoom into a digital image as far as you can within Photoshop and you'll see that the image is a mosaic of (usually) squares (pixels). Computers represent numeric values using the binary system, a method of counting using only the digits 0 and 1. Each pixel has a numeric value associated with it.

You may have heard of the term bit depth. The *bit depth* of a file refers to the number of bits (places or columns) available to each pixel. Early

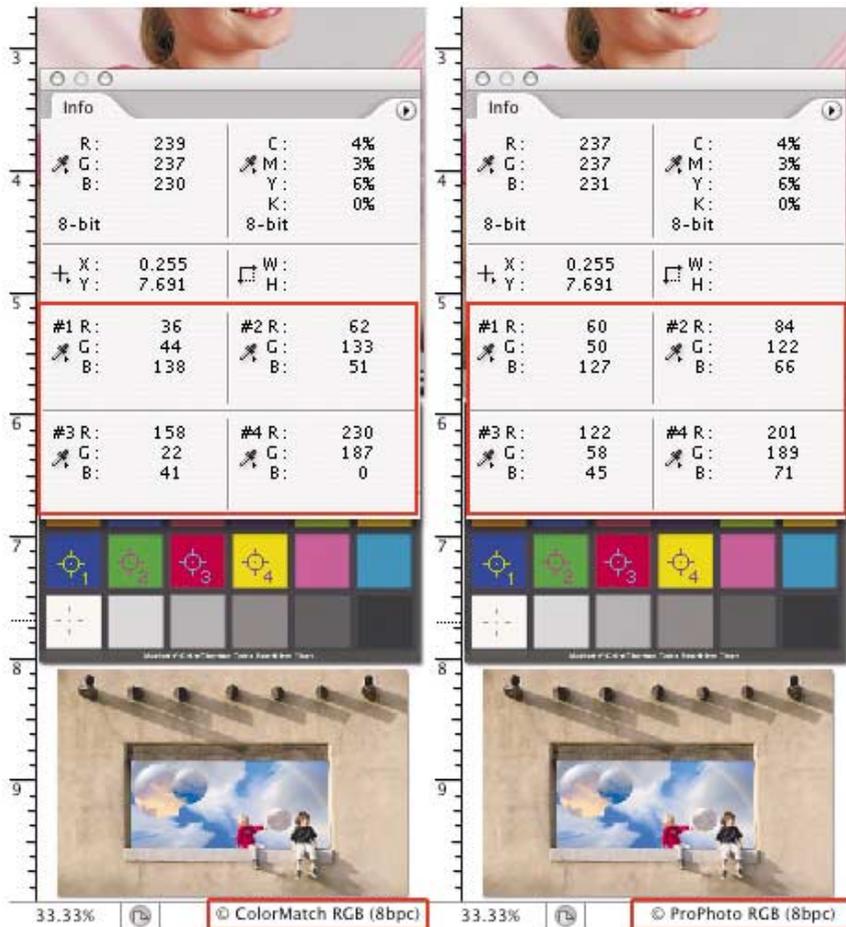


Fig. 1-2 Different color numbers can have the same color appearance as seen here. The colors in the Macbeth chart in both documents have the same color appearance but the numeric values are quite different due to one image being in ColorMatch RGB and the other in ProPhoto RGB, two different color spaces. This illustrates how numbers alone can't tell us what a color should look like.

computer images were composed of pixels that could be either black (0) or white (1). This is known as a 1-bit file. Each pixel has a single cell that can hold either a 1 or a 0. A 1-bit image isn't very exciting to look at! If we increase the number of bits per pixel to 2, more information can be represented. With 2 bits each pixel could contain the values 00, 01, 10, or 11. Such an image would have four possible values per pixel: black, dark gray, light gray, or white. A file of this type is said to have a bit depth of 2. How many values can be represented with 4 bits per pixel? Well, you could count in binary 0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111, 1000, . . . 1111 and you would find there are 16 possibilities, or you could do some simple math: 4 bits, 2 possibilities per bit (0 or 1) so that's  $2^4$  or  $2 \times 2 \times 2 \times 2 = 16$ . Files with a bit depth of 4 are often used on the Web to save space as 4 bits per pixel takes half the space of 8 bits

**Definition**

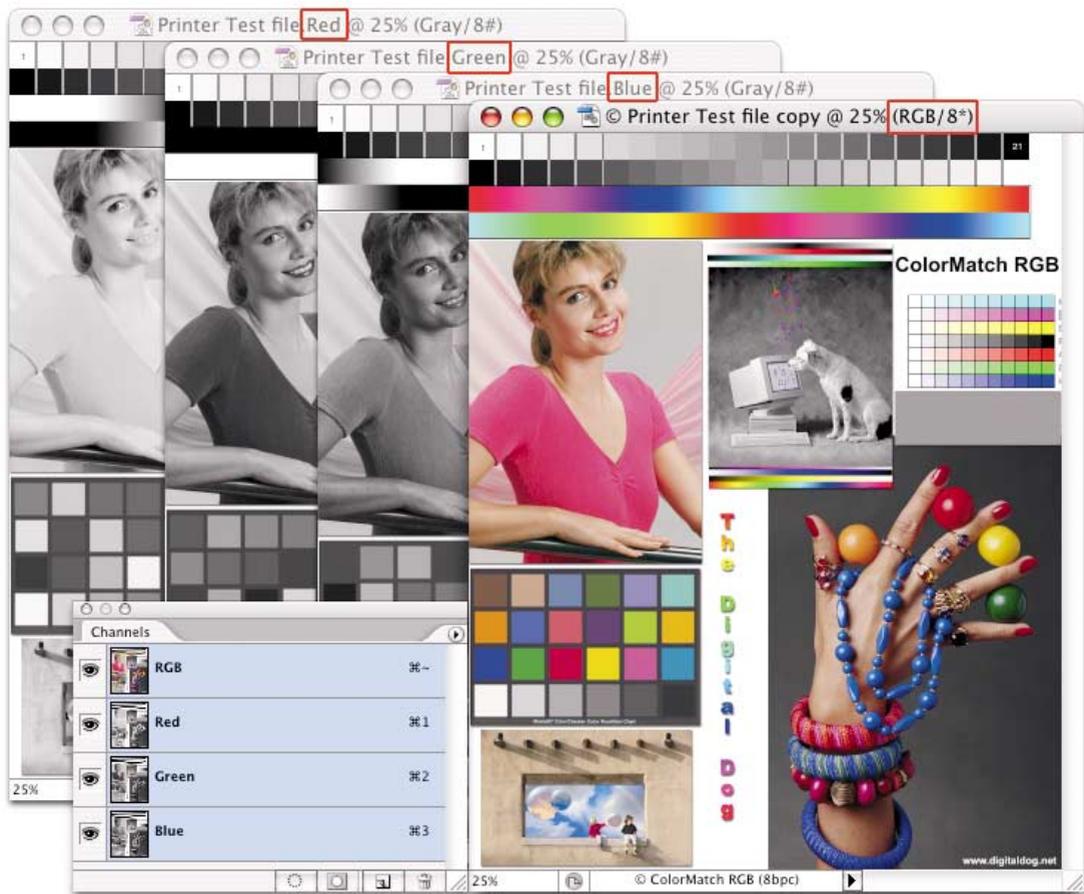
**Continuous Tone:** A term used to describe an unbroken, smooth, and uninterrupted tone making up an image. Rather than seeing an actual series of dots or a mosaic of dots or pixels, continuous tone describes how we see the world before us. A photographic print is considered continuous tone. Few output devices are truly continuous tone (some, like a Lightjet or my Fuji Pictography, are). However today, many devices simulate the effect of continuous tone even though they really produce a solid dot.

per pixel. Image files with a bit depth of 8 are very common,  $2^8 = 256$ , so these files can have 256 shades of gray per pixel.

Research has shown the minimum number of values needed to fool our eyes into seeing a **continuous tone** image is around 240. So 8 bits per pixel provides us with a file that appears continuous tone. Black is encoded as 0 and white is encoded as 255. Photoshop's histogram is one way to view the entire spread of tonal values from zero to 255 within an image. Photoshop's eyedropper tool and info palette is a way to view the actual numeric values of an individual pixel. With 8 bits or 256 different values, our computers can create a continuous tone Grayscale image. In order to create a color image, we simply need a file that contains three of these Grayscale channels or color planes: one for red, one for green, and one for blue. An RGB file is nothing more than a three-channel Grayscale file, where each channel contains 256 possible values for each color as seen in Fig. 1-3. This encoding method is often referred to as *24-bit color*. A 24-bit file contains three channels or planes with each of these channel composed of 8 bits of data. 24-bit color files have the potential to describe 16.7 million colors. If you look at the math involved to produce this enormous number of colors, you will see that a file composed of three channels (where each channel has 256 possible values) works out to  $256 \times 256 \times 256$ , or 16.7 million colors. As we will see, the ability to mathematically produce 16.7 million colors is a problem because it isn't possible to reproduce anything close to that number of actual colors on any output device.

Note that 8-bits commonly is referred to as a *byte* (in case you were curious, 4 bits is a *nibble*). Therefore, if you have a file that is  $100 \times 100$  pixels and has 8 bits or 1 byte per pixel, that file is 10,000 bytes in size or about 10KB (1 kilobyte = 1024 bytes). If this were a color file with 3 bytes per pixel it would be about 30KB. We normally work with much bigger images in Photoshop, but the concept is the same. If a digital camera creates an image  $3072 \times 2048$ , that's 6,291,456 pixels times 3 bytes per pixel (RGB) or 18,874,368 bytes. Divide that by 1024 to get 18,432KB. Divide that by 1024 to get 18MB (megabytes). Now you know where all those numbers come from.

Enough math! The concept to understand here is how images are represented by pixels, and that each pixel has a numeric value based on its bit depth. Eight-bit Grayscale images are simple; a pixel can be one of 256 possible values. Color files are more complex since the pixel in question can be one of 256 values per color channel. In the example illustrated in Fig. 1-4, the color seen is three values: one for red, one for green, and one for blue. Here we have the ingredients for a single color pixel. A digital image may be composed of millions of pixels, all with various combinations of values. Knowing the value of our pixels is one thing, but what about the color of these pixels? Before that can be discussed, it is necessary to understand how we define color.

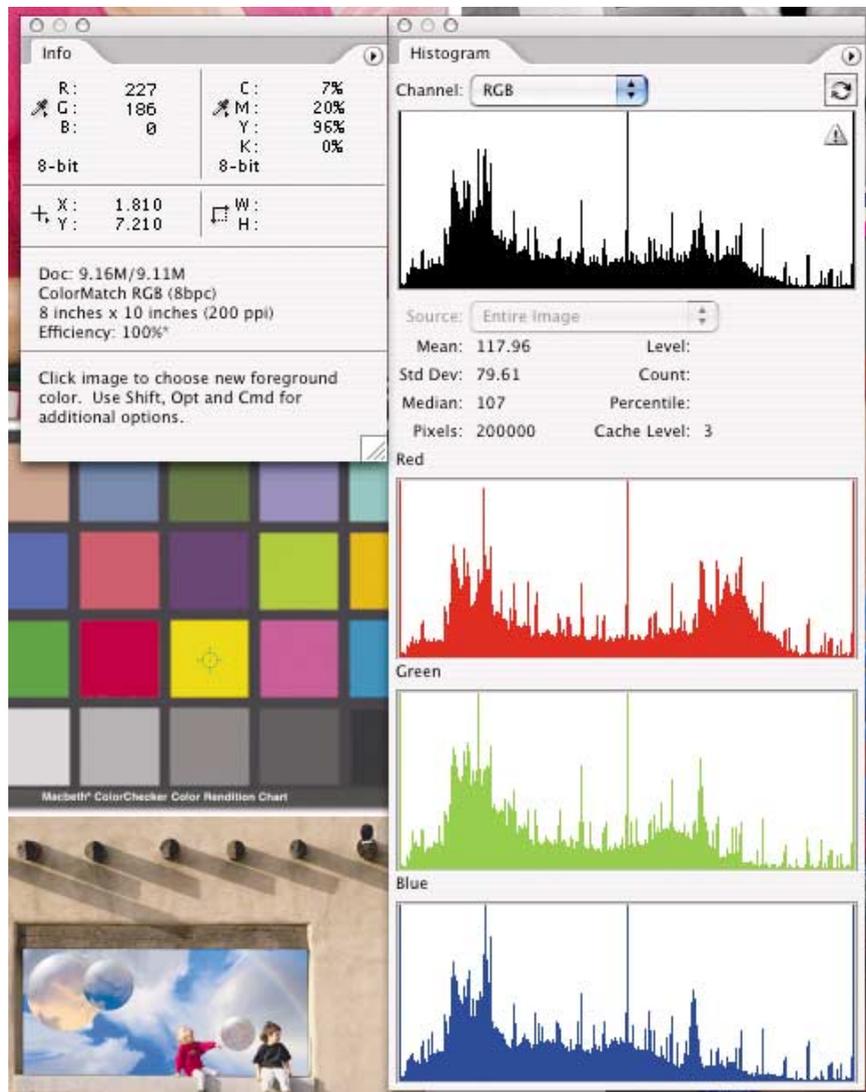


**Fig. 1-3** Photoshop allows users to view a full color composite image or the individual color channels that make up the composite as seen here. The channels are really Grayscale data—one for red, green, and blue—and when viewed together, a full color image can be produced as seen in the window in the lower right of Fig. 1-3. Notice the three Grayscale channels in the Channels palette.

## What Is Light, What Is Color?

In order for us to perceive the color of an object we need light to illuminate that object, and of course we need an observer (you or me) to see the object. It may seem like a rhetorical suggestion but imagine how the color of a red apple would appear in a room that is pitch black. Light and color is an important ingredient of photography, color management, and color theory. It's worth discussing in detail and (forgive me for saying), looking at in a new light.

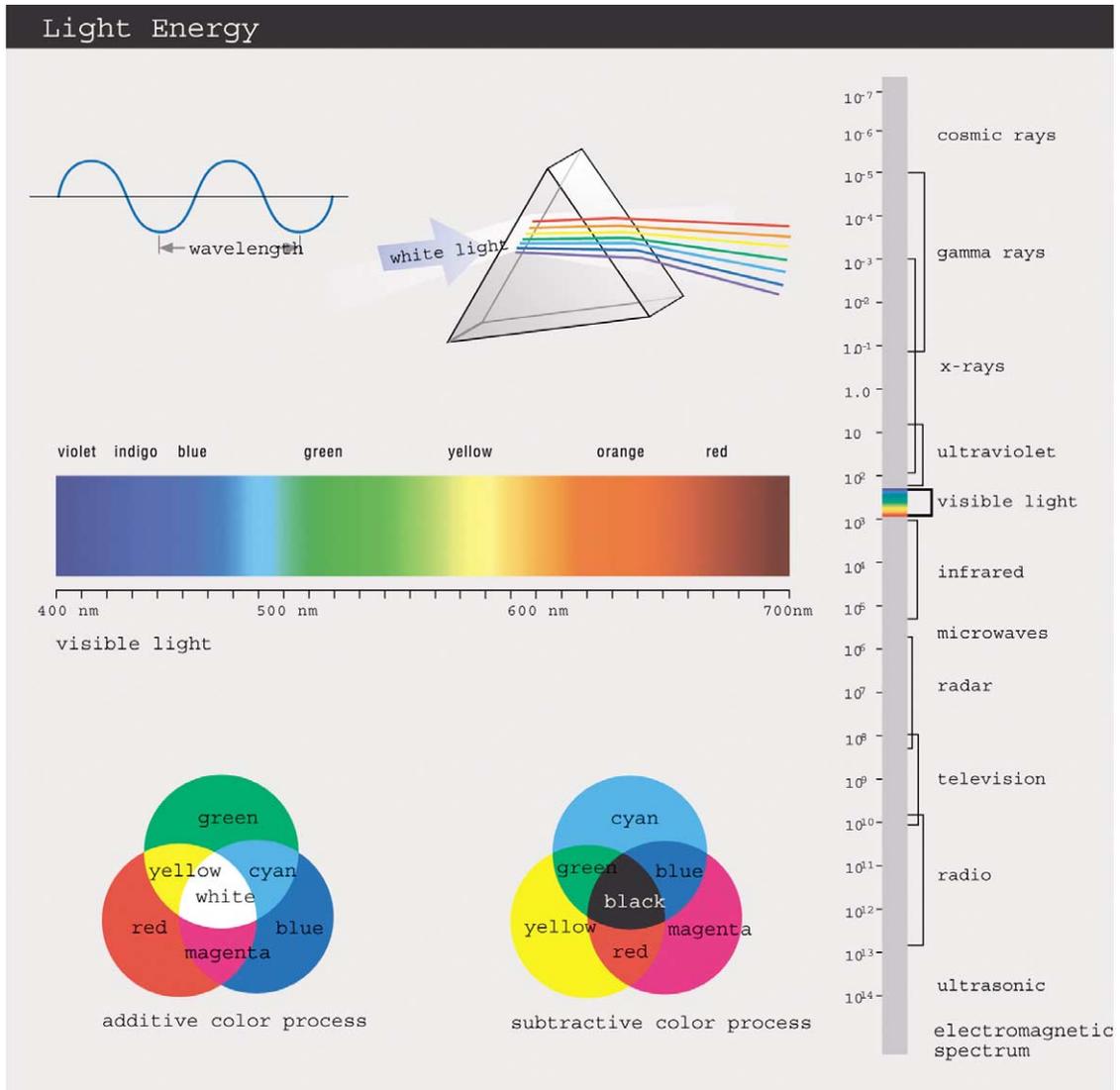
Light is a form electromagnetic radiation (energy) (see Fig. 1-5). One way to look at electromagnetic energy is as a wave. The waves frequency



**Fig. 1-4** The eyedropper tool in Photoshop shows a value of the yellow square, R227/G186/B0. Every pixel in an image may contain a different value. The Histogram to the right shows the distribution of values in each channel running from dark to light (left to right on the horizontal axis).

can be measured from crest to crest, in *nanometers* (nm; one billionth of a meter). Well illustrated in Fig. 1-5, there is a range of frequencies from approximately 400nm to 700nm that is visible to the eye. There are many other forms of electromagnetic radiation with wavelengths on either side of this range of visible energy (infrared, microwaves, and radio on one end the scale, ultraviolet to x-rays and gamma-rays on the other).

Much of what we know about light, an admittedly critical factor to seeing color, dates back to good old Isaac Newton and his fondness for



**Fig. 1-5** Light is a form of electromagnetic radiation. After being passed through a prism the visible light spectrum can be seen from violet (400 nm) to red (700 nm). This illustration also shows how both additive and subtractive primaries can produce white or black as well as many other colors. (Illustration Courtesy of GretagMacbeth)

playing with prisms. I recall an exercise with a prism during my elementary school days. The lesson showed that by passing white light through a prism, we are able to see the individual frequencies that comprise it. These frequencies show themselves as the colors of the rainbow. Newton’s prism sorted light rays by their wavelength since shorter wavelengths are bent (refracted) more than longer wavelengths. My dad

**Definition**

**Hue:** The pure spectral colors of the rainbow.

taught me about ROY-G-BIV, a mnemonic aid to remembering the order of colors in the spectrum: Red–Orange–Yellow–Green–Blue–Indigo–Violet, with a continuum of **hues** between each.

Most colors are not the pure spectral hues we see in the rainbow. We see these pure spectral colors only rarely from devices like lasers. Instead, most colors we experience are a mixture of many wavelengths at different intensities. A very important term to understand when discussing color is the *illuminant*. An illuminant is a description of a real or imaginary light source described by what scientists call a *spectral power distribution* curve (SPD). An SPD is a graph of intensity for each wavelength in the visible spectrum. Defined this way, illuminants are an absolute, unambiguous measurement of a light source.

Another important term is *spectrophotometry*. When you shine an illuminant on a patch of color and measure the light reflected back you have an exact map of the color in the form of a curve. This type of spectrophotometric data, often referred to as the Spectral Data, is very important to color management. The device used to take this kind of measurement is called a *spectrophotometer*.

The phenomenon of “color” exists only inside our brain, a sensation in the mind created by various frequencies of light falling upon the retina. A red apple does not emit red light. Rather, it absorbs all the shorter wavelengths of light shining on it and reflects the longer wavelengths. A receptor in the retina that is sensitive to longer wavelengths is stimulated and sends a signal to the visual cortex. The shorter wavelength receptors do not send a signal. The visual cortex processes this pattern of signals and associates them with a sensation of color. Another part of the brain associates that sensation with the word “red” so you can describe the color using language.

**Definition**

**Primary colors:** Basic color building blocks used to create other colors. The most common primaries are red, green, and blue, the additive primaries of light. Another common primary system is cyan, magenta, and yellow. Referred to as the subtractive primaries, these colors of pigment each subtract one of the additive primaries from white light. Note that not all color systems necessarily use red, green, and blue as primary colors. Green is not a primary color when mixing paint, but yellow, red, and blue are.

It is important to note that due to the primitive nature of our visual system (we have only three color receptors), many very different mixes of frequencies produce the exact same sensation in our brain. This means that two colors with very different spectral properties may look identical. This is what allows us to simulate colors on a printed page or on a computer screen using very different methods.

Many years after Sir Isaac, other scientists discovered that they could simulate many colors with only three **primaries**: red, green, and blue. These are known as additive primaries of light. If we start with none of these colors, we have no light, and thus black. As we begin adding certain proportions of red, green, and blue light, we can simulate most colors. When we have equal amounts of each, we perceive neutral colors (from dark gray to white) as seen in Fig. 1-5. We are adding the colors together, thus the term *additive primaries*.

CMY (Cyan/Magenta/Yellow) is a cousin of RGB, known as the *subtractive primaries*. We start with white, perhaps something like paper, and add density, using CMY colorant (inks, dyes, toner, or pigments) until we reach black as seen in Fig. 1-5. This is the opposite of the additive RGB

process. We are actually subtracting red, green, and blue from the white light striking the paper. When white light strikes cyan pigment, green and blue is reflected and red is absorbed. When white light strikes magenta pigment, red and blue is reflected and green is absorbed. When white light strikes yellow pigment, red and green is reflected and blue is absorbed. This CMY process is how color printing works. As we subtract certain proportions of red, green, and blue, we simulate colors just as we do using RGB. Printing the maximum of all three colors subtracts all light, thus we get black—at least in theory. The inverse of red is cyan. The opposite of green is magenta and the opposite of blue is yellow. You can see how CMY/RGB have a bit of a ying yang kind of relationship.

In the theory of subtractive color, maximum amounts of CMY create black. However, in the real world, with most printing processes, instead of black, we end up with a muddy brown. This is due to the impurity of CMY colorants. For this reason we add a black colorant. CMYK is CMY with the addition of K or black colorant. K is also known as *Key* or, depending on whom you ask, assigned to describe black because the acronym or letter “B” was used to describe blue (remember RGB?). In any case, CMYK is the color process used in offset printing and usually referred to as four-color process.

## Color Models and Color Spaces

Since color is a sensation that ultimately happens in our brain, how can we quantify something like red? What is red other than a word we use to describe what is essentially a sensation of light? I mentioned that computers understand only numbers; however, the necessity of describing colors numerically goes well beyond computers. Using numbers to define a color is useful. Having a specific set of values to describe the light itself is much more accurate than an ambiguous word like red. The terms color space and color model are used often in both color management and computer imaging. It’s necessary for us to define and understand what they both mean.

A *color model* is a method of grouping numeric values by a set of primaries. Most color models have three primary components (e.g., RGB, CMY, LCH, HSV, L\*a\*b\*). Some application-specific color models use more components, for example, CMYK. Photoshop and other image editing applications work with multiple color models. Some scientific color models such as x,y,Y or L\*a\*b\* encompass all of human vision and have a defined scale such that a particular color will always have the same set of values. It’s quite useful to be able to assign a numeric value to a color based upon how humans perceive colors. Other color models such as RGB or CMYK have no standard defined scale or reference. These color models are abstractions and cannot describe a specific color without first defining the scale or reference. Having an RGB value such as R10/G30/B50 does not tell us how to reproduce that color; the values

provided are simply a ratio of the primary components (in this case RGB) without a necessary scale. In this example we know there's more blue than red, more green than red, but not as much green as blue. Without a scale to tell us the actual amounts we can't reproduce this color. This is where a color space comes into play. A color space provides this additional and necessary information.

Think for a minute about the term *color space*. The first word, color, is fairly obvious. Let's look at the term space in context. I have three sets of numbers to define red, green, and blue (R10/G130/B50) but how red or green or blue are these values? What is the scale? It is possible to plot any three primary values in three dimensions by treating the primaries as coordinates in space. This creates a solid or volume that represents all possible colors in that color space. This is a color space! The color space exists within the larger universe of human vision. Each color space is in a different position relative to this universe. Thus the same RGB values in each color space will be in a different location.

Going back to the chocolate chip cookie analogy, suppose a color model is a cookie recipe with only three ingredients. I give you this recipe, which simply calls for 1-flour, 8-butter, and 2-chocolate chips. You don't have enough information to make the cookies. However if I provide you the recipe with a specific scale—1 *cup* of flour, 8 *tablespoons* of butter, and 2 *cups* of chocolate chips—I've provided the necessary information, the scale, to make a dozen chocolate chip cookies. If I provide additional information such as the brand of chocolate chips, you can reproduce exactly the same cookies I made. I can give you the cookie recipe in the metric scale such as liters and grams and you can still makes the same cookies even though the numbers are different. A color space is a color model that has a known reference *and* scale, in this case primaries (the ingredients) and scale (specific quantities of these ingredients).

Let's use an RGB color model as an example, but keep in mind that this could be true for CMYK or other color models. Suppose I specify a color as R10/G130/B50 and specify a color reference by saying the color space is Adobe RGB (1998), which defines the scale of the RGB primaries; the color coordinates of this color space. The R10/G130/B50 set of numbers can now reproduce a color by anyone with the proper tools since the reference and scale have been defined. Different RGB color spaces use a different scale of red, green, and blue primaries. Adobe RGB (1998) and sRGB (two color spaces that will be discussed in great detail) are different color spaces, however both are based on the RGB color model using RGB primaries. Although each color space uses the same three primary ingredients (R, G, and B), the specific colorimetric scale of each color space is different. The maximum of red, green, and blue are more saturated in the Adobe RGB (1998) color space than the sRGB color space. Even though R0/G255/B0 is the greenest green ingredient in both Adobe RGB (1998) and sRGB, knowing that the scale is different in both color spaces explains why this green value is more saturated in Adobe

RGB (1998). This also illustrates how R0/G255/B0 alone can't tell us how green this color is. There are hundreds if not thousands of different RGB color spaces just as there are hundreds if not thousands of different devices that create or reproduce RGB; same color model, different scale. The same is true for many other color models such as CMYK, HSB, Grayscale, and so on.

## Device-Dependent Color Spaces

It is sometimes useful to think of color spaces based upon their origin. A scanner or digital camera creates data in a color space specific to that device. This is due to the fact that the actual filters used are different. An Epson printer or a printing press each have a different color space as well. This is due to the fact that the inks used to create the image have different characteristics. All these color spaces are considered device-dependent. The primaries in these color spaces are derived from the colorants or filters of the device.

Other color spaces are synthetic or abstract and have no direct relationship to any specific device. The primaries of these color spaces were chosen by their creators for other purposes. For example, there are color spaces that were created for editing images. Within Photoshop these are referred to as *working spaces*, a term created by Adobe.

The two most common color models we work with are RGB and CMYK. Every capture device, be it a scanner or digital camera, produces some unique flavor of RGB. Many printers accept RGB data for output whereas others require CMYK data. Both RGB and CMYK are known as *device-dependent* color spaces. That means if we send the identical RGB file, which are just numbers, to 10 different printers, we'll end up with 10 different color prints. The devices themselves all take the same numbers and produce different colors, which is a significant problem. Another way to look at this is that if we had 10 different printers and wanted to produce identical colors on each, we would need 10 different recipes (color spaces). As you can see, this makes life quite complicated. Fortunately, color management allows us to create the correct color space and values for each device.

The device-dependent nature of RGB and CMYK (as well as other color models like Grayscale) is yet another reason why "working by the numbers" can be so difficult. What is the correct RGB value to produce a specific shade of red on an Epson 2200 running matte paper? What is the correct RGB value to produce the same shade of red on a Fuji Pictography 4500 running gloss paper (if that's even possible)? There are thousands upon thousands of RGB and CMYK color spaces, just as there are thousands upon thousands of RGB input and output devices as well as CMYK output devices. Each device produces and requires a different and unique recipe of RGB, CMYK, or Grayscale. Keeping track of all these color spaces and producing the right values of RGB or CMYK requires

### Definition

**Working space:** A color space specifically optimized for editing images in a product like Photoshop. Working space like Adobe RGB 1998 and so on are not based on real-world devices but are synthetic, mathematical spaces that are ideal for image editing. Working spaces are discussed in great detail in Chapter 2.

some method of defining not only how each device behaves but also a method of creating these values.

Next time you hear the terms RGB and CMYK, you should immediately realize “I don’t have enough information.” Having just RGB or CMYK values does not allow you to reproduce that color or image as it was intended. The next time someone supplies you with RGB or CMYK data, be sure to ask what color space it’s in. If they don’t know you might want to explain that you don’t have an appetite for mystery meat.

## Device-Independent Color Spaces

In addition to device-dependent color spaces, there are also *device-independent* color spaces. These color spaces encompass all of human vision. The most common is called CIELAB (or  $L^*a^*b^*$ ; often written as LAB, although technically the  $*$  should be used). Back in 1931, the CIE (Commission Internationale de L’Éclairage, also known as International Commission on Illumination), a group of color scientists, conducted a series of experiments and tests on humans to determine how they perceive color. The tests involved showing groups of volunteers a sample color under very controlled conditions whereby each subject adjusted the intensity of red, green, and blue lights until the mix of the three matched the sample color. This allowed the CIE to specify precisely the stimulus response of the human eye.

The CIE came up with the term *standard observer* to describe a hypothetical average human viewer and his or her response to color. Furthermore, the results of these tests produced a mathematical model of a color space formulated not on any real-world device, but rather on how we humans (the standard observer) actually perceive color. This core color model is called CIE XYZ (1931). This is the color model from which all other device-independent color models are created. Like the RGB color model with three additive primaries, CIE XYZ uses three spectrally defined imaginary primaries: X, Y, and Z. These X, Y, and Z primaries may be combined to describe all colors visible to the standard observer. Also in 1931, a synthetic space called CIE xyY was created, which itself is derived from CIE XYZ. In 1976, CIELAB and CIELUV were added to the mix of these device-independent color spaces. The CIELAB color space is a synthetic, theoretical color space derived from XYZ. Unlike the original, CIELAB has the advantage of being perceptually uniform (sort of . . .). That simply means that a move of equal value in any direction at any point within the color space produces a similar perceived change to the standard observer.

The XYZ color space is based on three quantities or stimuli. The geek term for describing this is *tristimulus values* (three stimuli). Technically the term *tristimulus values* refers to the XYZ values of the original CIE XYZ color model although you will often hear people describe tristimulus

values when defining a color in RGB or CMY (or using any three values). This is incorrect. Since our aim is to keep the color-geek-speak to a minimum, it's not important to know the differences in the various CIE constructed color models, but rather to recognize that a color space such as CIELAB is based on how we see color. What you should keep in mind here is that using a set of three values, any color can be specified exactly and mapped in three-dimensional space to show its location in reference to all other colors. This can be useful! There are no capture or output devices that directly reproduce CIELAB; however, this color space allows us to translate any color from one device to another.

As we've seen, device-dependent color spaces are unique to the device. Device-independent color spaces encompass all of human vision and are not linked to a specific device. It is for this reason that values provided in a device-independent color space is never ambiguous. Although it is possible to take a document and convert it into LAB (as it is named) within Photoshop, LAB is not an intuitive color space in which to edit files. As we will see, there is little reason to do this.

---

### Sidebar

---

**White Point and Color Temperature:** We don't think of white as being a color. Nevertheless, white is a color, and there are many different colors of white. Just look at two different sheets of paper side by side and you'll likely see that even though both appear white, they aren't the same. One sheet may appear brighter and cooler (bluish) or warmer (yellowish) than the other sheet.

*White point* describes the color of the brightest white of a particular device, such as a printer or display or even light itself. In the preceding example, the white point of a printer would be based upon the white of the paper used to produce a print. As another example, we may have two monitors side by side, both emitting the brightest white they can (in this example, R255/G255/B255), yet one may produce a white that appears bluer than the other. This is due to the difference in the white point of the two displays. We can measure and describe this white point colorimetrically.

There are several ways to describe the color of the white point; *color temperature* is a term most commonly understood by those in photography, although as you will see, it is not the best way. Photographers have been taught for years that tungsten film has a color temperature of 3400 K (**Kelvin**; a unit of temperature). Lower Kelvin values appear more red, and as the Kelvin values get higher, the color becomes more blue. In actuality, a color temperature is a *range* of colors correlated to the temperature of a theoretical object known as a *blackbody radiator*. The blackbody reflects no light and emits energy in shorter wavelengths as it is being heated. Imagine a black cast iron pan on a very hot stove. As it is heated, it begins to glow dark red. As the temperature increases, shorter wavelengths are emitted, causing the color of the light emitted by the skillet to appear orange, then yellow-white, then blue-white. The tungsten filament of a light bulb behaves similarly to the blackbody and radiates energy in the form of light because its temperature is so great (around 3200 K). If all light sources were true blackbodies,

#### Definition

**Kelvin:** A unit of absolute temperature. An object at zero Kelvin has no energy. This is often referred to as absolute zero (the coldest any object can be).

---

a particular color temperature would produce the same color of light. Because natural materials are not theoretical blackbodies, heating them to a specific temperature creates deviates from the theoretical color, from magenta to green. This is why we use the term *correlated color temperature* (CCT), because many colors of white may correlate to the same blackbody color temperature. This is illustrated in Fig. 1-6A. If you have a color meter that reports color temperature of a light source, many light sources that appear different could read the same.

Different illuminants can have the same correlated color temperature. You may recall that the definition of illuminants is that of a light source that is defined spectrally. This is one reason why the CIE defined the *standard illuminants*, which have fixed chromaticities and spectra (see Fig. 1-6B). These illuminants are defined spectrally, meaning a certain amount of energy at each wavelength across the spectrum. It became clear that that in order to control the conditions under which the colors were viewed, it was necessary to precisely specify the light (illuminants). An example of standard illuminants are the *D illuminants* (D for daylight) such as D50 or D65. Many people, and even software products, use D65 and 6500 K interchangeably as if they were identical. This is not the case. D65 is an exact color, it is not a range of colors. There are differences in each definition!<sup>2</sup> If you examine both Figs. 1-6A and then 1-6B you will see the differences. Some software products specify both D65 and 6500 K as choices for white point. When you see this, the 6500 K option refers to the exact color of a theoretical blackbody at 6500 Kelvin. It's important to understand the principles of white point and color temperature when we undertake the task of calibrating our displays or decide under what viewing conditions we will view our prints.

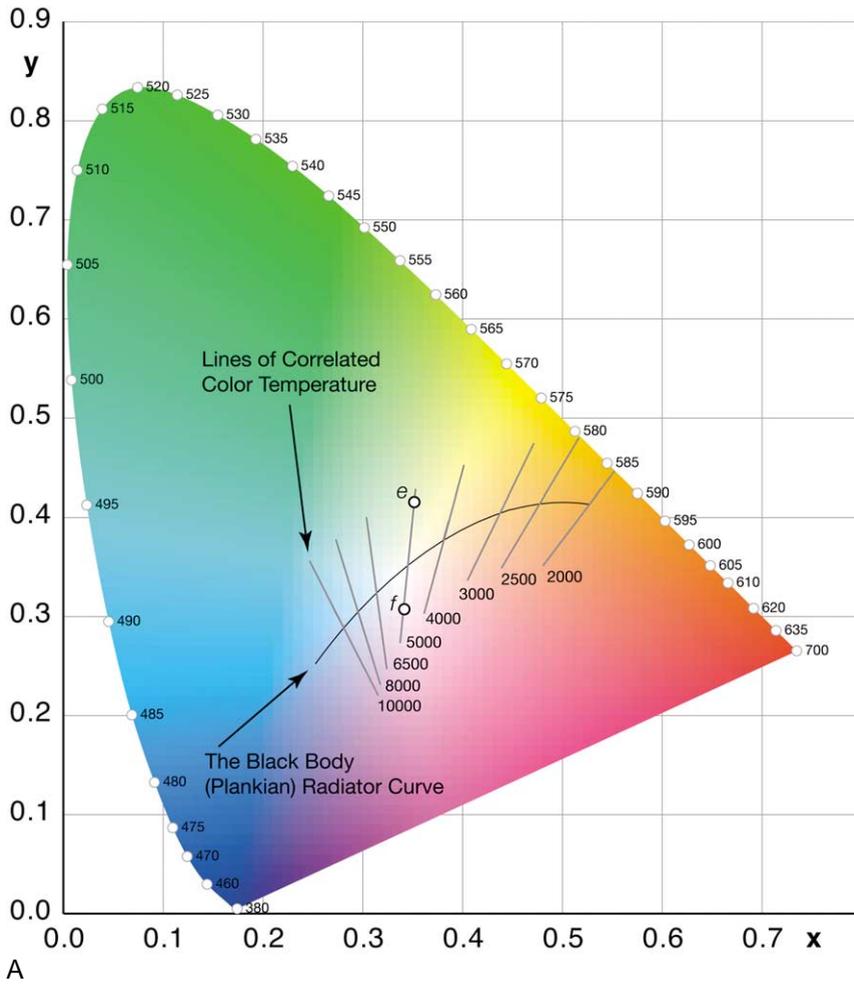
---

<sup>2</sup>I defer to an excellent post by Bruce Lindbloom on the ColorSync list that I think clarifies the difference for those that need to know. Caution: geek alert!

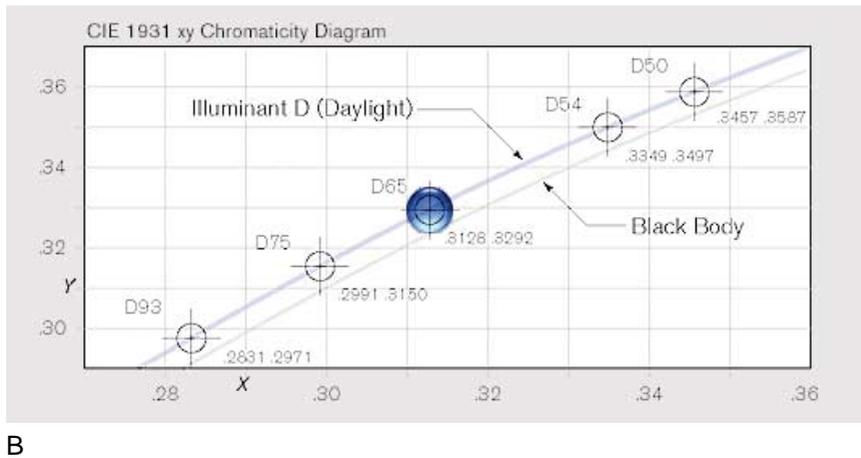
- a) D65 is a spectral power distribution (a certain amount of energy at each wavelength across the visible spectrum).
- b) D65 is a tristimulus value; the D65 spectrum, when viewed by the CIE standard observer, produces an XYZ triplet (or xyY if you prefer).
- c) 6500 K blackbody radiator is a spectral power distribution.
- d) 6500 K is blackbody tristimulus value; the 6500 K blackbody spectrum, when viewed by the CIE standard observer, produces an XYZ triplet—similar to, but slightly different from, the one found in (b).
- e) Correlated color temperature takes a color's chromaticity coordinate (x,y) and finds the particular blackbody temperature whose chromaticity coordinate (d) is closest to it. Note that there are many different colors that have the same correlated color temperature. So a spectrum is very precise and unique. Its xyY is less precise and unique. Its CCT is even less precise and unique.

D65 is a unique SPD (there exists only one). A color whose CCT is 6500 K is not unique (there are infinitely many different xyY and SPDs that share it).

---



**Fig. 1-6A** The lines of correlated color temperature and their relationship to the blackbody curve are seen in this illustration. The lines of CCT run roughly perpendicular to the blackbody from green/yellow to orange/violet. Take note that all the colors along a line of CCT can be labeled with the same color temperature. The colors marked "e" and "f" in the diagram may both be described as 5000 K. (Illustration by Karl Lang)



**Fig. 1-6B** This screen capture from the Sony Artisan display software illustrates a close-up of the blackbody curve and above it, what is known as the daylight curve. Here the standard illuminants are plotted. The spectra of the D illuminants can be converted to  $xy$  and plotted on the CIE Chromaticity diagram as this daylight curve.