

color



By Bruce Fraser

Color is so much a part of our lives, our culture, and even our language that we tend to take it for granted. Until, that is, we start running into problems with its communication and reproduction. It's probably safe to say that anyone making a living in a field that involves communicating color information—be they a designer, an artist, a printer, a photographer, or a color scientist—runs into plenty of such problems in the course of their work. We wind up wrestling with color-as-RGB, or with color-as-CMYK, or, if we're of a more adventurous bent, with YCC or LAB or some other TLA (three-letter acronym). What we all too often lose sight of is the simple fact that RGB and CMYK aren't color: they're colorants (and often very ambiguous ones) that will, at the end of our wrestling match, produce the sensation of color in the minds of the viewers at which they're aimed.

Despite all the advances in technology and science, our perception of color is a complex and mysterious process

in

With the growing trend toward managed color and measured color, one might think that color-matching problems are merely due to shortcomings in current technology, and that they'll soon be a thing of the past. But while colorimetry, spectrophotometry, process control, and all the other tools at our disposal can help make our color manufacturing processes more controllable and more predictable, it's important to recognize that our measuring instruments and our computers deal with color at one remove. In fact, it could be argued that they don't deal with color at all.

What is color? It's a sensation—like hunger or fatigue—that exists only in our minds. Like hunger and fatigue, it's caused by external factors that we can measure and quantify, but measuring those external factors is no more measuring color than counting calorie intake tells us how hungry we are, or measuring exercise tells us how fatigued. Color is our response to certain wavelengths of electromagnetic energy that make up the visible spectrum of light, and while we can measure quite precisely the stimuli that cause us to perceive color—the wavelengths of light—our response to those wavelengths is affected by a whole host of factors that we cannot. Physiology, psychology, culture, and even the language we speak all influence our color perception in subtle ways that resist quantification.

mind

The discussion that follows isn't designed to turn designers into color scientists; while some of it is technical in nature, it's intended to entertain, to inform, to provoke thoughts, and—no pun intended—to illuminate. For anyone working with color, it also has practical implications that go beyond simply explaining why things sometimes go horribly wrong. First, we'll look at the objective aspects of color—the things we can measure and quantify—and then we'll turn to the ways in which objective models of color fail to match our experience.

Taking light's measure

Light is a form of electromagnetic energy, a sibling of X-rays and radio waves. Our eyes are sensitive to a narrow slice of the electromagnetic spectrum, and color is our response to being stimulated by energy at those wavelengths. If color can be said to exist outside our heads, it's as a property of light. The light that's transmitted through or reflected from the objects in our world is the part of color that we can measure.

We can describe light in terms of its wavelength; the unit we use is the nanometer (nm), which is one-millionth of a meter. Visible light is that part of the electromagnetic spectrum whose wavelengths range from approximately 380 nm to about 750 nm. Immediately below this range lies ultraviolet radiation, while immediately above it lies infrared radiation, or heat. The hue we think of as blue lies below about 480 nm, green is approximately between 480 and 560 nm, yellow is between 560 and 590 nm, orange is between 590 and 630 nm, and red lies at wavelengths longer than 630 nm. Purple is the one common hue that isn't found in the visible spectrum—it's formed by mixing red and blue light from the two extremes of the spectrum.

But light doesn't exist as a single wavelength—at least, not outside the physics laboratory. Sir Isaac Newton's *OPTICKS: or A Treatise of the Reflections, Refractions, Inflections & Colours of Light* (London, 1730) isn't exactly an easy read, but it's amazing to see how many of the basic principles of color were first uncovered by his genius. He showed that when a beam of daylight is passed through a prism, the white light is dispersed into a spectrum: white light, therefore, is normally made up of all the visible wavelengths. Newton went further, and passed the spectrum produced by the prism through a narrow slit into a second prism, thereby isolating a region of the spectrum. He found that there was no further dispersion, and the color did not change. He had isolated part of the spectrum and confirmed that it didn't contain any of the other colors. He also reversed the process, and passed the dispersed spectrum through a prism to reconstitute white light. The behavior of prisms was well known before Newton's time, but it had been assumed that the prism somehow added color to the light; Newton's discovery was

that the colors were actually present in white light all along.

If we look a little closer, we find that “white light” is itself something of an abstraction. The light from a northern sky—sometimes called “painter’s light”—is quite a bit bluer than direct sunlight, which is in turn bluer than the light from an incandescent light bulb. These light sources differ in the relative intensities of the different wavelengths. We can characterize the makeup of a light source by plotting the relative amount of energy at each wavelength: the resulting graph is called a spectral power distribution curve (see Figure 1).

How light interacts with objects

Even though we can talk about light having a certain color, the light itself isn’t colored. Rather, it’s the way the light interacts with objects that causes the stimulus that provokes our sensation of color. As Newton put it, “For the Rays to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour.” When light strikes an object, one or more of these things can happen: the light can be transmitted through the object, absorbed by it, or reflected by it.

When the light is transmitted through the object, we say that the object is transparent. In a colorless object, all the light is transmitted except for a small amount that is reflected at its surface. (That’s why we can see transparent objects like glass or water—if all the light were transmitted they’d be invisible.)

This kind of reflection happens whenever there’s a change in the *refractive index* of the material through which light is passing. Refractive index, which is sometimes thought of as an indication of transparency, is really a measure of how much light slows down as it passes through the material, relative to the speed of light in a vacuum. Whenever light encounters a change in refractive index, some light gets reflected, and the direction of the transmitted light beam changes. When you put one end of a stick into water, it appears to bend; but it isn’t the stick that’s bending, just the light that allows us to see the stick.

Refractive index is itself something of an abstraction, because it has a different effect on each wavelength of light: short waves slow down more than long ones, which is why a prism splits white light into a spectrum. This also explains why the sun seems to turn red at dawn

and sunset—the shorter blue and green wavelengths get deflected more than the longer

red ones. Although we know the theoretical times of sunrise and sunset exactly, we can’t actually predict exactly when an observer will see the sun appear to rise or set, because what the observer actually sees are the longer red wavelengths emitted by the sun, and the amount by which they’re bent depends on the atmospheric conditions.

Light can also be absorbed by an object. If the material absorbs part of the light and transmits the rest, it appears colored but still transparent. If all the light is absorbed, the material appears black and opaque. Some of the light energy that’s absorbed is usually converted to heat: black objects get hotter than white ones when exposed to intense light energy because they absorb more light.

Lastly, light can be reflected by an object. A glossy surface will produce *specular reflection*, where the incoming or incident beam and the outgoing or reflected beam are at equal angles relative to the surface. Mirrors are specular reflectors. But when we’re dealing with the scale of light wavelengths, perfectly smooth surfaces are rare: the irregularities in the surface of the finest astronomical telescope mirrors are around a tenth of the wavelength.

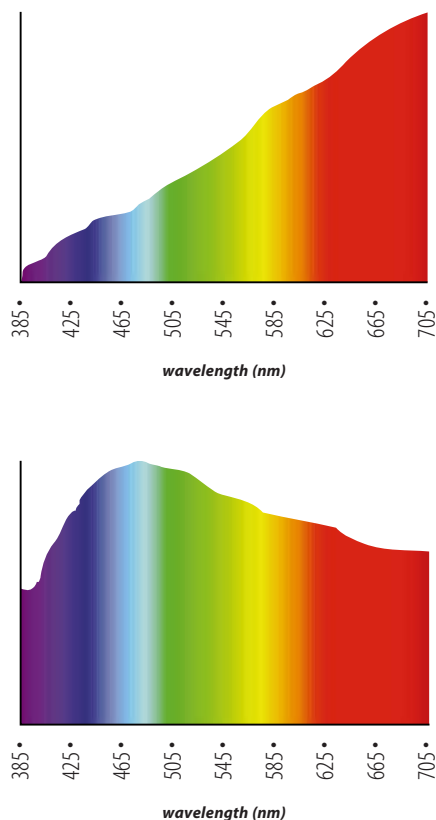
Most surfaces are much more irregular, and hence they scatter light in many different directions. Scattered light is termed *diffuse reflection*. If some light is scattered and some is transmitted, the object appears translucent; if all the light that strikes an object is either scattered or absorbed, the object appears opaque.

Spectral behavior and color

Almost all objects exhibit a mixture of all the aforementioned behaviors with regard to light: they absorb some wavelengths and reflect or scatter others. The color appearance of the object depends on the degree to which different wavelengths are absorbed or scattered. An object that scatters all wavelengths equally appears white or gray, depending on the accompanying amount of light absorption. Light scattering by the molecules of the atmosphere produces the blue color of the sky; scattering from larger particles makes the clouds appear white.

We can characterize the color behavior of an object by plotting the

Figure 1



These graphs, called “spectral power distribution curves,” show the relative amounts of energy at different wavelengths that make up the light from an incandescent bulb (top) and daylight (bottom). While both might be called “white light,” their spectral makeup—and thus the way they’ll make colored objects look—varies considerably.

mind

relative amounts of energy that it reflects or transmits at each wavelength, to produce a spectral transmittance curve (for transparent materials) or spectral reflectance curve (for

opaque materials). These curves describe the spectral behavior of an object just as the spectral power distribution curve describes a light source. The stimulus our eyes receive depends on both the spectral makeup of the light source and the spectral behavior of the object that light source illuminates. If we know both, we can predict the nature of the stimulus exactly: this, in a nutshell, is what we measure when we talk about measuring color.

Before we turn to our response to light, we should look at one more phenomenon that has important implications for color reproduction. If we know the spectral makeup of both the light source and the object, we can predict the color appearance; but by the same token, altering the spectral makeup of the light is

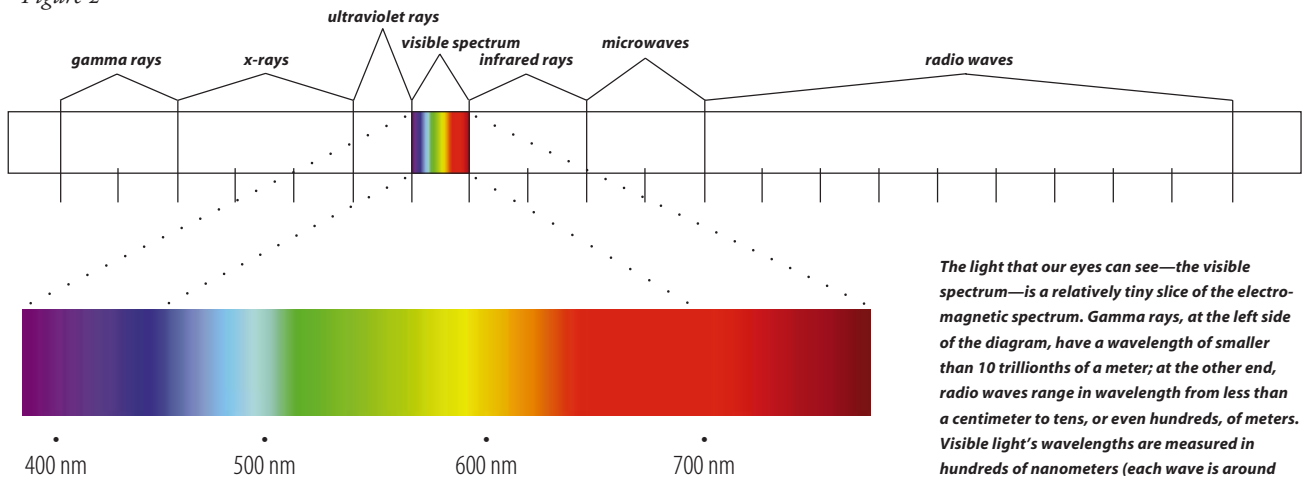
matches your fabric swatch in the paint store may surprise and disappoint when you use it in your home. Spectrophotometry can help us avoid these kinds of surprises, but it's considerably more likely to be found in a prepress or manufacturing environment than at your local paint store.

The physiology and culture of color

So once you know the spectral makeup of both your light source and your object, you can predict exactly how the object's color will look, right? Unfortunately, no—not exactly. Knowing the spectral makeup of the stimulus that reaches an observer's eyes allows us to make a good prediction of the color sensation it will produce, but it isn't absolutely accurate because our human responses to that stimulus vary from individual to individual, and because even a single individual's response varies according to a host of other factors.

We still have a great deal to learn about the mechanism by which we see color, but it's clear that the eye is only a part of this

Figure 2



The light that our eyes can see—the visible spectrum—is a relatively tiny slice of the electromagnetic spectrum. Gamma rays, at the left side of the diagram, have a wavelength of smaller than 10 trillionths of a meter; at the other end, radio waves range in wavelength from less than a centimeter to tens, or even hundreds, of meters. Visible light's wavelengths are measured in hundreds of nanometers (each wave is around a 10,000th of a meter long).

sure to change the apparent color of the object—sometimes drastically. In other words, an object's color appearance will vary depending on the makeup of the light that illuminates it. This is why it's vitally important to use a known standard of lighting when you're working on critical color matching; it also explains why, despite the best efforts of the prepress industry, the single most common reason dissatisfied users cite when they return clothing purchased from a mail-order catalog is that the color wasn't what they expected. We can control the light source used in the production of the catalog, but we can't control the light source under which the consumer views it.

Another less obvious but more troubling phenomenon is that two objects that match in color under one light source may appear quite different under another light source. This phenomenon is known as *metamerism*, and two objects that exhibit this behavior are termed a *metameric pair*. The packaging that exactly matches the distinctive color of a plastic action figure under standard proofing lights may not match nearly as well under the very different lighting in the supermarket, and the paint that so exactly

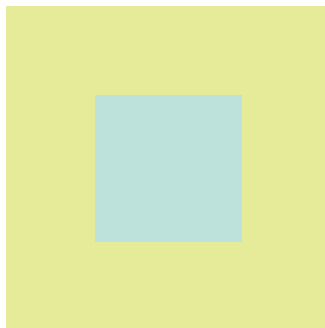
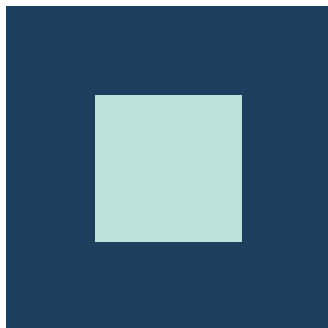
mechanism: the signal from the eye is subject to a great deal of interpretation by the brain. We know that the retinas in our eyes—the areas on which the image is formed—contain two different kinds of photoreceptors, rods and cones. The rods are more prevalent at the edges of the image area; they are very sensitive to dim light and to movement, but they don't contribute much to color vision. That's the task of the cones, which are more prevalent in the fovea centralis, the area in the center of the retina. It's generally accepted that our eyes contain three different kinds of cones, each sensitized to wavelengths that correspond approximately to red, green, and blue. This theory was first put forth by Thomas Young in 1801, on the simple grounds that the eye couldn't contain sensors for every possible wavelength, and was more thoroughly explored by Hermann von Helmholtz, who first described the red, green, and blue receptors in the eye and their spectral curves.

A huge number of color matching experiments have been carried out by the Commission Internationale de l'Éclairage (CIE) and other bodies, which have allowed us to arrive at a good statis-

Figure 3



The way we see any color is profoundly affected by context—by the other colors around it. As this example demonstrates, a pure hue appears very different on a background of its own hue and on a background of its complement.



Not only hue is affected by context, but apparent lightness or darkness as well. These two blue squares are the same color, yet the one on the left appears lighter because it's on a dark background.



Color relationships can affect how large an object looks. Here the inner squares are the same size, but the inner orange square, which is brighter than its background, appears larger than the inner dark-green square.

mind

tical picture of the range of human color vision. Almost all these experiments involve the observer viewing a split screen through an aperture. One half of the screen is

illuminated by a target color while the other half is illuminated by three primary-colored sources, typically red, green, and blue, over which the observer has control. The observer manipulates the primary colors until they match the target color.

About 8 percent of men and fewer than half a percent of women have some degree of color blindness, caused either by the lack of some of the necessary cones or by some defect in the neural pathway from the eye to the brain. The majority of color-blindness sufferers have some difficulty distinguishing between reds and greens; total color blindness is very rare indeed. But color blindness aside, “normal” color vision varies considerably—not only from individual to individual, but also even for a single individual.

One easily explicable physical factor that affects color sensitivity is the field of view. Since the color-sensitive cones are concentrated in the central area of the retina, we tend to see colors somewhat more acutely when they’re displayed in a narrow field of view, about 2 degrees, than we do when they’re spread out over a larger area.

The CIE was forced to take note of this when it developed the CIE family of perceptually based color spaces. CIE Lab is often thought of as a single color space, but it’s really a whole family of color spaces with different illuminants and, since 1964, different observers. The original CIE XYZ 1931 color space defined a Standard Observer, but in 1964 discrepancies in the blue-green area of the spectrum for angles of view wider than 2 degrees led them to define two Standard Observers, which became known as the Two-degree Observer and the Ten-degree Observer.

Our color vision is also affected by fatigue, and by common drugs such as nicotine and caffeine, which reduce the amount of oxygen in the bloodstream. Emotional states may also have an effect on color vision. Phrases such as “seeing red,” “feeling blue,” “green with envy,” “black humor,” and “brown study” may contain more literal truth than one might think, since it’s clear that emotions have demonstrable physiological effects.

All these physiological factors affect the signal that the eye sends to the brain. What our minds do with those signals is still another story. Perception isn’t a passive act. In many ways, we see what we expect to see, filtering out that which we deem extraneous and concentrating on the patterns that are familiar to us. This is as true with color as with anything else.

Property rights

Many attempts have been made over the years to provide a way of thinking about and discussing color relationships. The vast majority of these systems define color in terms of three properties, which have various different names in the different systems. The fact that so many independent thinkers have come up with variations of the same system suggests that it models our innate color perception system—that our minds actually interpret the signals our eyes generate in terms of these three attributes. One of the most highly developed and widely used systems was the

one developed by Albert Munsell, who codified these three basic attributes of color as hue, value, and chroma.

Hue is the property that distinguishes a pure color from other pure colors, the property that gives a color its name. It’s the property that’s conferred by wavelength. Value is the property of a color that makes it appear to contain more or less light, from black at one extreme to white at the other. Note that it’s based on appearance, not on actual measured light energy: yellow has a higher value than blue, even if the samples of yellow and blue contain exactly the same amount of energy. Chroma is the purity of a color: neutral gray has the lowest possible chroma, while pure hues have the highest possible chroma.

One reason Munsell’s system is noteworthy is that it separates the achromatic component, value, from the clearly colorful hue and chroma. This allows us to represent colors two-dimensionally, as a color wheel. Newton transformed the spectrum into a circle centuries before Munsell, but Munsell’s color wheel, unlike Newton’s, is perceptually uniform—that is, the distance between two points in the wheel always corresponds to the same amount of perceived difference between colors. Other color wheels, such as the one found in Apple’s hue-saturation-brightness Color Picker, aren’t perceptually uniform, but they show the same relationships among colors.



Figure 4

The combination of yellow and black has been shown to provide the highest contrast under varying lighting conditions. That’s why it was chosen for international warning signs. It’s also probably no coincidence that stinging insects like bees and wasps have that color scheme: stinging is their last resort, since it kills them. They want to be noticed.

color in mind

Like anything else, color is subject to fads—how many Harvest Gold or Avocado appliances are manufactured today?—but the color

wheel reveals some basic color relationships at a glance. For instance, complementary colors lie opposite one another. Many simple but effective color schemes use the softer of the two colors as the dominant color and the brighter one as an accent. Colors that lie one-third of the way around the wheel from one another are contrasting colors: some combinations clash violently, where others can be quite harmonious. Hues that lie close together on the wheel are called analogous colors. Colors that lie along a line from the center to the circumference share the same hue, and differ only in saturation or purity: brick red and tomato red share hue, but tomato red lies closer to the wheel's edge.

These relationships are innate, not dictated by fashion or culture, and they give rise to some interesting optical illusions (see the illustrations in Figure 3, on page 46, and Figure 5 at right). Designers can and do exploit these illusions in many different ways. For example, light-colored type on a dark-colored background always seems to jump off the page toward the reader, while dark-colored type on a light background tends to recede into the page.

Even the language we speak affects our perception of color. Newton divided the rainbow into seven color regions—red, orange, yellow, green, blue, indigo, and violet—but he took pains to point out that the spectrum is in fact continuous, not bunched into bands, something more casual observers often overlook. The Russian language divides the rainbow into eight colors rather than seven, distinguishing between those pale blues that tend toward cyan and the darker ones that head toward indigo.

Some rain-forest languages don't contain words for the concept of hue at all: they describe objects in terms of their greenness or brownness, their lightness or darkness, and their shininess or mattiness, since those are the characteristics of the environment in which they're found.

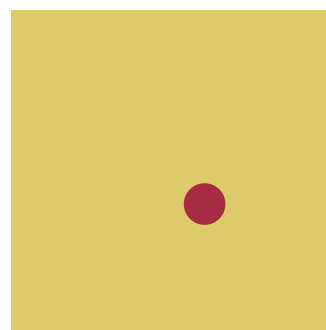
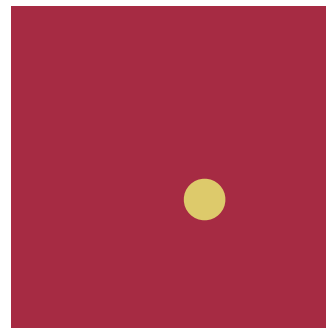
Learning to see color

We should learn several lessons from all this. The most important is that it's dangerous if not futile to pick colors in isolation: we see colors in context, and that context includes the surrounding colors. If you use a brightly colored Hawaiian-shirt desktop pattern on your monitor, it will almost certainly skew the way you see colors. So, for that matter, will wearing a Hawaiian shirt!

Lighting is critical, too. If your lighting changes constantly, so will your color perception. Prepress houses use light booths with a standard color "temperature": this is useful in keeping color consistent, but it's important for designers to bear in mind that the ultimate consumers of their work probably won't have proofing-standard lighting. It's usually a good idea to look at roughs under a variety of lighting conditions. If you can anticipate the lighting conditions under which your work will be seen, design for them—a restaurant usually has very different lighting from an office, for example.

Color measurement can help us keep color consistent throughout the production chain, but its limitations are important to

Figure 5



The light-colored dot appears to “pop out” of the dark background, while the dark dot on light seems to sit further back than its surrounding field. Both effects can be exploited when placing colored type on a colored background.

remember. We can measure colors only in isolation from one another; we see color only in context. I've seen many a project in which the color science was “right,” but the outcome looked wrong. When we design with color, we can use color science and color measurement to remove what uncertainties we can. But in the end, we must use our eyes to decide what looks good—while remembering the tricks they can play. ■

Bruce Fraser is a San Francisco-based writer specializing in color-publishing issues. He is a contributing editor for MacWEEK and MacUser, and is coauthor of Real World Photoshop 3, from Peachpit Press (reviewed on page 37).