CHAPTER 4

Color

In the summer of 1997, I designed an experiment to measure human ability to trace paths between connected parts in a 3D diagram. Then, as is my normal practice, I ran a pilot study in order to see whether the experiment was well constructed. By ill luck, the first person tested was a research assistant who worked in my lab. He had far more difficulty with the task than anticipated—so much so that I put the experiment back on the drawing board to reconsider, without trying any more pilot subjects. Some months later, my assistant told me he had just had an eye test and the optometrist had determined that he was color blind. This explained the problems with the experiment. Although it was not about color perception, I had marked the targets red in my experiment. He therefore had had great difficulty in finding them, which rendered the rest of the task meaningless.

The remarkable aspect of this story is that my assistant had gone through 21 years of his life without knowing that he was blind to many color differences. This is not uncommon, and it strongly suggests that color vision cannot be all that important to everyday life. In fact, color vision is irrelevant to much of normal vision. It does not help us determine the layout of objects in space, how they are moving, or what their shapes are. It is not much of an overstatement to say that color vision is largely superfluous in modern life. Nevertheless, color is extremely useful in data visualization.

Color vision does have a critical function, which is hardly surprising because this sophisticated ability must surely provide some evolutionary advantage. Color helps us break camouflage. Some things differ visually from their surroundings only by their color. An especially important example is illustrated in Figure 4.1. If we have color vision, we can easily see the cherries hidden in the leaves. If we do not, this becomes much harder. Color also tells us much that is useful about the material properties of objects. This is crucial in judging the condition of our food. Is this fruit ripe or not? It this meat fresh or putrid? What kind of mushroom is this? It is also useful if we are making tools. What kind of stone is this? Clearly, these can be life-or-death decisions. In modern hunter–gatherer societies, men are the hunters and women are the gatherers.

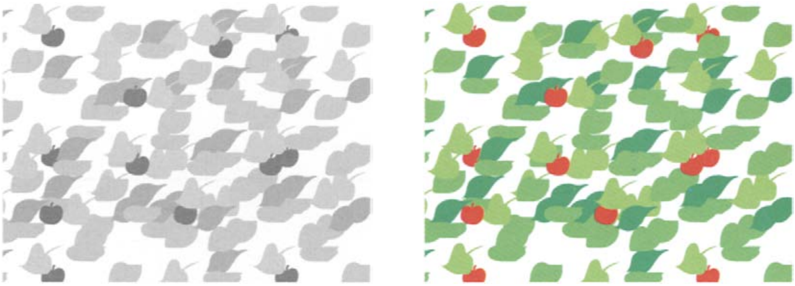


Figure 4.1 Finding the cherries among the leaves is much easier if we have color vision.

This may have been true for long periods of human evolution, which could explain why it is mostly men who are color blind. If they had been gatherers, they would have been more than likely to bring home poison berries—a selective disadvantage. In the modern age of supermarkets, these skills are much less valuable; this is perhaps why color deficiencies so often go unnoticed.

The role that color plays ecologically suggests ways that it can be used in information display. It is useful to think of color as an attribute of an object rather than as its primary characteristic. It is excellent for labeling and categorization, but poor for displaying shape, detail, or space. These points are elaborated in this chapter. We begin with an introduction to the basic theory of color vision to provide a foundation for the applications. The latter half of the chapter consists of a set of five visualization problems requiring the effective use of color; these have to do with color selection interfaces, color labeling, pseudocolor sequences for mapping, color reproduction, and color for multidimensional discrete data. Each has its own special set of requirements. Some readers may wish to skip directly to the applications, sampling the more technical introduction only as needed.

Trichromacy Theory

The most important fact about color vision is that we have three distinct color receptors, called cones, in our retinas that are active at normal light levels—hence *trichromacy*. We also have rods, sensitive at low light levels, but they are so overstimulated in all but the dimmest light that their influence on color perception can be ignored. Thus, in order to understand color vision, we need only consider the cones. The fact that there are only three receptors is the reason for the basic three-dimensionality of human color vision.

The term *color space* means an arrangement of colors in a three-dimensional space. In this chapter, a number of color spaces, designed for different purposes, are discussed. Complex transformations are sometimes required to convert from one color space to another, but they are all three-dimensional, and this three-dimensionality derives ultimately from the three cone types. This is the reason that there are three differently colored phosphors in a television tube—red,

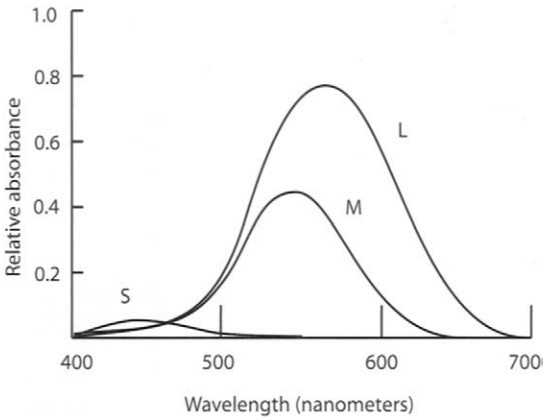


Figure 4.2 Cone sensitivity functions.

green, and blue—and this is the reason that we learn in school that there are three primary paint colors—red, yellow, and blue. It is also the reason that printers have a minimum of three colored inks for color printing—cyan, magenta, and yellow. Engineers should be grateful that humans have only three color receptors. Some birds, such as chickens, have as many as 12 different kinds of color-sensitive cells. A television set for chickens would require 12 electron beams and 12 differently colored phosphors!

Figure 4.2 shows the human cone sensitivity functions. The plots show how light of different wavelengths is absorbed by the different receptors. It is evident that two of the functions, L and M, which peak at 540 nanometers and 580 nanometers, overlap considerably; the third, S, is much more distinct, with peak sensitivity at 450 nanometers. The short-wavelength S receptor absorbs light in the blue part of the spectrum and is much less sensitive, which is another reason (besides chromatic aberration, discussed in Chapter 2) why we should not show detailed information such as text in pure blue on a black background.

Because only three different receptor types are involved in color vision, it is possible to match a particular patch of colored light with a mixture of just three colored lights, usually called *primaries*. It does not matter that the target patch may have a completely different spectral composition. The only thing that matters is that the matching primaries are balanced to produce the same response from the receptors as the patch of light to be matched. Figure 4.3(a) illustrates the three-dimensional space formed by the responses of the three cones.

Color Blindness

About 10% of the male population and about 1% of the female population have some form of color vision deficiency. The most common deficiencies are explained by lack of either the long-wavelength-sensitive cones (protanopia) or the medium-wavelength-sensitive cones

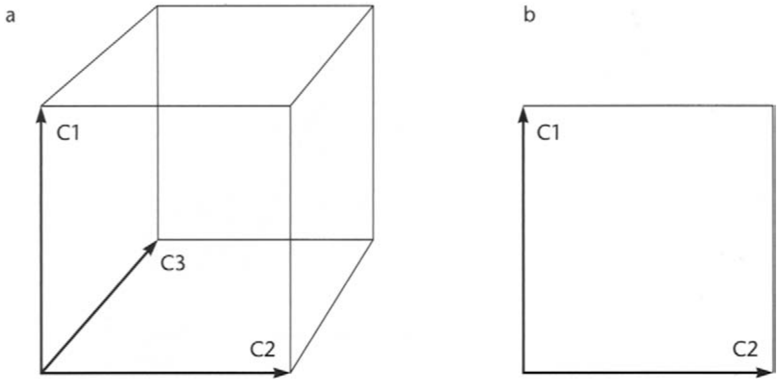


Figure 4.3 (a) Cone response space, defined by the response of each of the three cone types. (b) The space becomes two-dimensional in the case of the common color deficiencies.

(deuteranopia). Both protanopia and deuteranopia result in an inability to distinguish red and green, meaning that the cherries in Figure 4.1 are difficult for people with these deficiencies to see. One way to describe color vision deficiency is by pointing out that the three-dimensional color space of normal color vision collapses to a two-dimensional space, as shown in Figure 4.3(b). An unfortunate result of using color for information coding, is the creation of a new class of people with a disability. Color blindness already disqualifies applicants for some jobs such as those of telephone linespeople, because of the myriad colored wires, and pilots, because of the need to distinguish color-coded lights.

Color Measurement

The fact that we can match any color with a mixture of no more than three primary lights is the basis of *colorimetry*. An understanding of colorimetry is essential for anyone who wishes to specify colors precisely for reproduction.

We can describe a color by the following equation:

$$C \equiv rR + gG + bB \tag{4.1}$$

where C is the color to be matched, *R*, *G*, and *B* are the primary light sources to be used to create a match, and *r*, *g*, and *b* represent the amounts of each primary light. The *f* ≡ symbol is used to denote a perceptual match—the sample and the mixture of the red, green, and blue (rR, gG, bB) primaries look identical. Figure 4.4 illustrates the concept. Three projectors are set

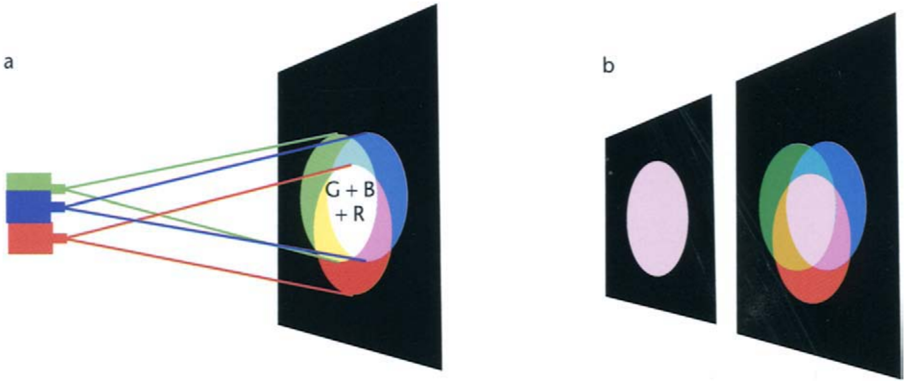


Figure 4.4 A color-matching setup. (a) When the light from three projectors is combined, the results are as shown. Yellow light is a mixture of red and green. Purple light is a mixture of red and blue. Cyan light is a mixture of blue and green. White light is a mixture of red, green, and blue. (b) Any other color can be matched by adjusting the proportions of red, green, and blue light.

up with overlapping beams. In the figure, the beams only partially overlap so that the mixing effect can be illustrated, but in a color-matching experiment they would overlap completely. To match the lilac-colored sample, the projectors are adjusted so that a large amount of light comes from the red and blue projectors and only a small amount of light comes from the green projector.

The *RGB* primaries form the coordinates of a color space, as illustrated in Figure 4.5. If these primaries are physically formed by the phosphor colors of a color monitor, this space defines the gamut of the monitor. In general, a *gamut* is the set of all colors that can be produced by a device or sensed by a receptor system.

It seems obvious that restrictions must be placed on this formulation. So far, we have assumed that the primaries are red, green and blue, but what if we were to choose other primary lights, for example, yellow, blue, and purple? We have stated no rule saying they must be red, green, and blue. How could we possibly reproduce a patch of red light out of combinations of yellow, blue, and purple lights? In fact, we can only reproduce colors that lie within the gamut of the three primaries. Yellow, blue, and purple would simply have a smaller gamut, meaning that if we used them, a smaller range of colors could be reproduced.

The relationship defined in Equation 4.1 is a linear relationship. This has the consequence that if we double the amount of light on the left, we can double the amount of light on each of our primaries and the match will still hold. To make the math simpler, it is also useful to allow the concept of negative light. Thus, we may allow expressions such as

$$C \equiv -rR + gG + bB \tag{4.2}$$

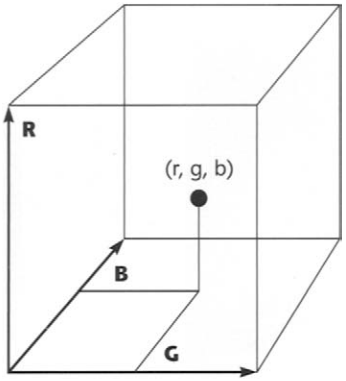


Figure 4.5 The three-dimensional space formed by three primary lights. Any color can be created by varying the amount of light produced by each of the primaries.

Although this concept may seem nonsensical, because negative light does not exist in nature, it is, in fact, practically useful in the following situation. Suppose we have a colored light that cannot be matched because it is outside the gamut of our three primary sources. We can still achieve a match by adding part of one of the primaries to our sample. If the test samples and the *RGB* primaries are all projected as shown in Figure 4.4, this can be achieved by swiveling one of the projectors around and adding its light to the light of the sample.

If the red projector were redirected in this way, we would have

$$C + rR \equiv gG + bB \tag{4.3}$$

which can be rewritten

$$C \equiv -rR + gG + bB \tag{4.4}$$

Once we allow the concept of negative values for the primaries, it becomes possible to state that *any* colored light can be matched by a weighted sum of *any* three distinct primaries.

Change of Primaries

Primaries are arbitrary from the point of view of color mixture—there is no special red, green, or blue light that must be used. Fundamental to colorimetry is the ability to change from one set of primaries to another. This gives us freedom to choose any set of primaries we want. We can choose as primaries the three phosphors of a monitor, three differently colored lasers, or some hypothetical set of lamps. We can even choose to base our primaries on the sensitivities of the human cone receptors. Given a standard way of specifying colors (using a standard set of primaries), we can use a transformation to create that same color on any number of different output devices. This transformation is described in Appendix A.

CIE System of Color Standards

We now have the foundations of a color measurement and specification system. We begin with an easily understood, though impractical, solution based on standardized primary lamps. Red, green, and blue lamps could be manufactured to precise specifications and set up in an instrument so that the amounts of red, green, and blue light falling on a standard white surface could be set by adjusting three calibrated dials, one for each lamp. Identical instruments, each containing sets of colored lamps, would be sent around the world to color experts. They would be very expensive. Then to give a precise color specification to someone with the standard instrument, we would simply need to make a color match by adjusting the dials and sending that person the dial settings. The recipient could then adjust his or her own standard lamps to reproduce the color.

Of course, although this approach is theoretically sound, it is not very practical. Standard primary lamps would be very difficult to maintain and calibrate. But we can apply the principle by creating a set of *abstract* primary lamps defined on the basis of the human receptor characteristics. This assumes that everyone has the same receptor functions. In fact, although humans do not display exactly the same sensitivities to different colors, with the exception of the color deficiencies, they come close. One of the basic concepts in any color standard is that of the *standard observer*. This is a hypothetical person whose color sensitivity functions are held to be typical of all humans. Most serious color specification is done using the Commission Internationale de l'Éclairage (CIE) system of color standards. These are based on standard observer measurements that were made prior to 1931. Color measuring instruments contain glass filters that are derived from the specifications of the human standard observer. One advantage is that glass filters are more stable than lamps.

The CIE system uses a set of abstract primaries called *tristimulus values*; these are labeled XYZ. These primaries are chosen for their mathematical properties, not because they match any set of actual lights. One important feature of the system is that the Y tristimulus value is the same as luminance. More details of the way the system is derived are given in Appendix B.

Figure 4.6 illustrates the color volume created by the XYZ tristimulus primaries of the CIE system. The colors that can actually be perceived are represented as a gray volume entirely contained within the positive space defined by the axes. The colors that can be created by a set of three colored lights, such as the red, green, and blue monitor phosphors, are defined by the pyramid-shaped volume within the RGB axes as shown. This is the *monitor gamut*.

The CIE tristimulus system based on the standard observer is by far the most widely used standard for measuring colored light. For this reason, it should always be used when precise color

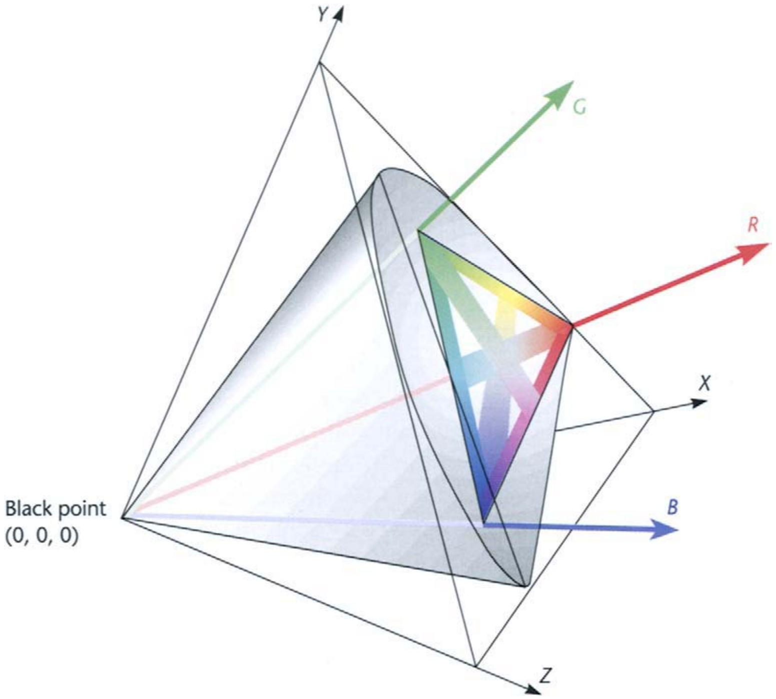


Figure 4.6 The *X*, *Y*, and *Z* axes represent the CIE standard virtual primaries. Within the positive space defined by the axes, the gamut of perceivable colors is represented as a gray solid. The colors that can be created by means of the red, green, and blue monitor primaries are also shown.

specification is required. Because a monitor is a light-emitting device with three primaries, it is relatively straightforward to calibrate a monitor in terms of the CIE coordinates. If a color generated on one monitor is to be reproduced on another, for example, a liquid crystal display, the best procedure is first to convert the colors into the CIE tristimulus values and then to convert them into the primary space of the second monitor.

The specification of surface colors is far more difficult than the specification of lights, because an illuminant must be taken into account and because, unlike lights, pigment colors are not additive. The color that results from mixing paints is difficult to predict. A treatment of surface color measurement is beyond the scope of this book, although later we will deal with perceptual issues related to color reproduction.

Chromaticity Coordinates

The three-dimensional abstract space represented by the *XYZ* coordinates is useful for specifying colors, but it is difficult to understand. As discussed in Chapter 3, there are good reasons for treating lightness, or luminance, information as special. In everyday speech, we often refer to the color of something and its lightness as different and independent properties. Thus, it is useful to have a measure that defines the hue and vividness of a color while ignoring the amount of light. *Chromaticity coordinates* have exactly this property through normalizing with respect to the amount of light.

To transform tristimulus values to chromaticity coordinates, use

$$\begin{aligned} x &= X/(X+Y+Z) \\ y &= Y/(X+Y+Z) \\ z &= Z/(X+Y+Z) \end{aligned} \tag{4.5}$$

Because $x + y + z = 1$, it is sufficient to use x, y values only. It is common to specify a color by its luminance, Y, and its x, y chromaticity coordinates (x, y, Y). The inverse transformation from x, y, Y to tristimulus values is

$$\begin{aligned} X &= Yx/y \\ Y &= Y \\ Z &= (1-x-y)Y/y \end{aligned} \tag{4.6}$$

Figure 4.7 shows a CIE x, y chromaticity diagram and graphically illustrates some of the colorimetric concepts associated with it. Here are some of the useful and interesting properties of the chromaticity diagram:

1. If two colored lights are represented by two points in a chromaticity diagram, the color of a mixture of those two lights will always lie on a straight line between those two points.
2. Any set of three lights specifies a triangle in the chromaticity diagram. Its corners are given by the chromaticity coordinates of the three lights. Any color within that triangle can be created with a suitable mixture of the three lights. Figure 4.7 illustrates this with typical monitor *RGB* primaries.
3. The *spectrum locus* is the set of chromaticity coordinates of pure monochromatic (single-wavelength) lights. All realizable colors fall within the spectrum locus.
4. The *purple boundary* is the straight line connecting the chromaticity coordinates of the longest visible wavelength of red light, about 700 nm, to the chromaticity coordinates of the shortest visible wavelength of blue, about 400 nm.

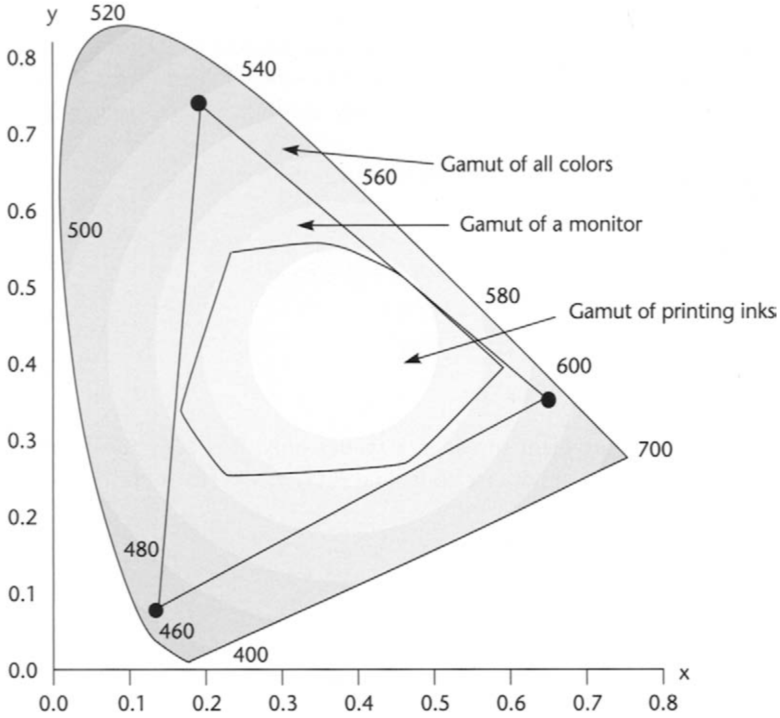


Figure 4.7 CIE chromaticity diagram with various interesting features added. The triangle represents the gamut of a computer monitor with long-persistence phosphors.

5. The chromaticity coordinates of equal-energy white (light having an equal mixture of all wavelengths) are 0.333, 0.333. But when a white light is specified for some application, what is generally required is one of the CIE standard illuminants. The CIE specifies a number that corresponds to different phases of daylight; of these, the most commonly used is D65. D65 was made to be a careful approximation of daylight with an overcast sky. It also happens to be very close to the mix of light that results when both direct sunlight and light from the rest of the sky fall on a horizontal surface. D65 also corresponds to a black-body radiator at 6500 degrees Kelvin. D65 has chromaticity coordinates $x = 0.313$, $y = 0.329$. Another CIE standard illuminant corresponds to the light produced by a typical incandescent tungsten source. This is illuminant A. Illuminant A has chromaticity coordinates $x = 0.448$, $y = 0.407$. This is considerably more yellow than normal daylight.

6. *Excitation purity* is a measure of the distance along a line between a particular pure spectral wavelength and the white point. Specifically, it is the value given by dividing the

distance between the sample and the white point by the distance between the white point and the spectrum line (or purple boundary). This measure defines the vividness of a color. A less technical, but commonly used, term for this quantity is *saturation*. More saturated colors are more vivid.

7. The complementary wavelength of a color is produced by drawing a line between that color and white and extrapolating to the opposite spectrum locus. Adding a color and its complementary color produces white.

The sets of chromaticity coordinates for two sets of typical monitor phosphors follow:

	Short-Persistence Phosphors			**Long-Persistence Phosphors**		
	Red	*Green*	*Blue*	*Red*	*Green*	*Blue*
x	0.61	0.29	0.15	0.62	0.21	0.15
y	0.35	0.59	0.063	0.33	0.685	0.063

The main difference between the two is that the long-persistence phosphor green (besides the fact that it glows for longer after being bombarded with electrons) is closer to being a pure spectral color than the short-persistence green. This makes the gamut larger. Short-persistence phosphors are useful for frame sequential stereoscopic displays because they reduce the bleeding of the image intended for one eye into the image intended for the other eye.

When a CRT display is used, the CIE tristimulus values of a color formed from some set of red, green, and blue settings can be calculated by the following formula:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \dfrac{X_R}{Y_R} & \dfrac{X_G}{Y_G} & \dfrac{X_B}{Y_B} \\ 1 & 1 & 1 \\ \dfrac{Z_R}{Y_R} & \dfrac{Z_G}{Y_G} & \dfrac{Z_B}{Y_B} \end{bmatrix} \begin{bmatrix} Y_R \\ Y_G \\ Y_B \end{bmatrix} \tag{4.7}$$

where x_R, y_R, and z_R are the chromaticity coordinates of the particular monitor primaries and Y_R, Y_B, and Y_G are the actual luminance values produced from each phosphor for the particular color being converted. Notice that for a particular monitor the transformation matrix will be constant; only the Y vector will change.

To generate a particular color on a monitor that has been defined by CIE tristimulus values, it is only necessary to invert the matrix and create an appropriate voltage to each of the red, green, and blue electron guns of the monitor. Naturally, to determine the actual value that must be specified, it is necessary to calibrate the monitor's red, green, and blue outputs in terms of luminance and apply gamma correction, as described in Chapter 3. Once this is done, the monitor can be treated as a linear color creation device with a particular set of primaries, depending on its phosphors. For more on monitor calibration, see Cowan (1983). It is also possible to purchase self-calibrating monitors adequate for all but the most demanding applications.

Color Differences and Uniform Color Spaces

Sometimes, it is useful to have a color space in which equal perceptual distances are equal distances in the space. Here are three applications:

Specification of color tolerances: When a manufacturer wishes to order a colored part from a supplier, such as a plastic molding for an automobile, it is necessary to specify the color tolerance within which the part will be accepted. It only makes sense for this tolerance to be based on perception, because ultimately it is the customer who decides whether the door trim matches the upholstery.

Specification of color codes: If we need a set of colors to code data, such as different wires in a cable, we would normally like those colors to be as distinct as possible so that they will not be confused.

Pseudocolor sequences for maps: Many scientific maps use sequences of colors to represent ordered data values. This technique, called *pseudocoloring*, is widely used in astronomy, physics, medical imaging, and geophysics.

The CIE *XYZ* color space is very far from being perceptually uniform. However, in 1978 the CIE produced a set of recommendations on the use of two uniform color spaces that are transformations of the *XYZ* color space. These are called the *CIElab* and the *CIEluv* uniform color spaces. The reason that there are two, rather than one, has to do with the fact that different industries, such as the paint industry, had already adopted one standard or the other. Also, the two standards have somewhat different properties that make them useful for different tasks. Only the *CIEluv* formula is described here. It is generally held to be better for specifying large color differences. However, one measurement made using the *CIElab* color difference formula is worth noting. Using *CIElab*, Hill et al. (1997) estimated that there are between two and six million discriminable colors available within the gamut of a color monitor.

The *CIEluv* equations are:

$$\begin{aligned} L^* &= 116(Y/Y_n)^{1/3} - 16 \\ u^* &= 13L^*(u' - u'_n) \\ v^* &= 13L^*(v' - v'_n) \end{aligned} \tag{4.8}$$

where

$$u' = \frac{4X}{X+15Y+3Z} \quad u'_n = \frac{4X_n}{X_n+15Y_n+3Z_n}$$
$$v' = \frac{9Y}{X+15Y+3Z} \quad v'_n = \frac{9Y_n}{X_n+15Y_n+3Z_n} \tag{4.9}$$

u' and v' are a projective transformation of the x, y chromaticity diagram, designed to produce a perceptually more uniform color space. X_n, Y_n, and Z_n are the tristimulus values of a reference white. To measure the difference between colors ΔE^*_{uv}, the following formula is used:

$$\Delta E^*_{uv} = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2} \tag{4.10}$$

The *CIEluv* system retains many of the useful properties of the *XYZ* tristimulus values and the x, y chromaticity coordinates.

The $u'v'$ diagram is shown in Figure 4.8. Its official name is the CIE 1976 uniform chromaticity **Scale** diagram, or UCS diagram. Because u', v' is a projective transformation, it retains the useful property that blends of two colors will lie on a line between the u', v' chromaticity coordinates. (It is worth noting that this is not a property of the *CIElab* uniform color space.)

The u^*, v^* values change the scale of u', v' with respect to the distance from black to white defined by the sample lightness L^* (recall from Chapter 3 that L^* requires Y_n, a reference white in the application environment). The reason for this is straightforward: the darker the colors, the fewer we can see. At the limit, there is only one color: black.

A value of 1 for ΔE^*_{uv} is an approximation to a *just noticeable difference* (*JND*).

Although they are useful, uniform color spaces provide, at best, only a rough first approximation. Perceived color differences are influenced by many factors. Contrast effects can radically alter the shape of the color space. Small patches of light give different results than large patches. In general, we are much more sensitive to differences between large patches of color. When the patches are small, the perceived differences are smaller, and this is especially true in the yellow–blue direction. Ultimately, with very small samples, small-field tritanopia occurs; this is the inability to distinguish colors that are different in the yellow–blue direction. Figure 4.9 shows two examples of small patches of color on a white background and the same set of colors in larger patches on a black background. Both the white background and the small patches make the colors harder to distinguish.

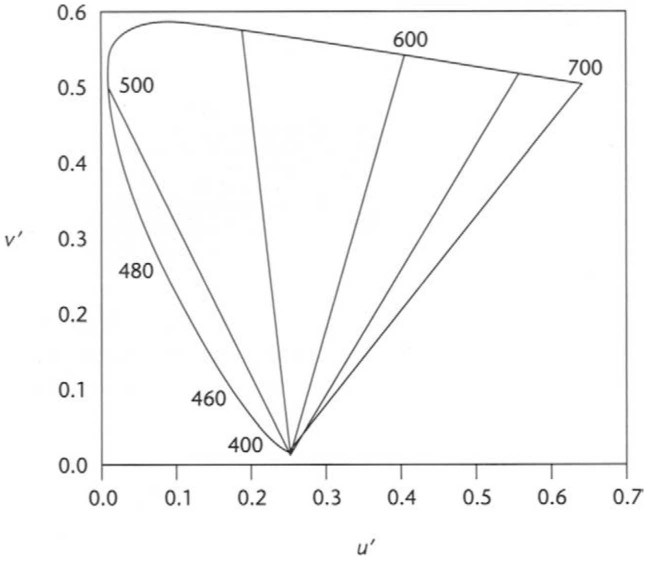


Figure 4.8 CIE *Lu′v′* UCS diagram. The lines radiating from the lower part of the diagram are tritanopic confusion lines. Colors that differ along these lines can still be distinguished by the great majority of color-blind individuals.

Opponent Process Theory

Late in the nineteenth century, German psychologist Ewald Hering proposed the theory that there are six elementary colors and that these colors are arranged perceptually as opponent pairs along three axes: black–white, red–green, and yellow–blue (Hering, 1920). In recent years, this principle has become a cornerstone of modern color theory, supported by a large variety of experimental evidence (see Hurvich, 1981, for a review). Modern opponent process theory has a well established physiological basis: input from the cones is processed into three distinct channels immediately after the receptors. The luminance channel (black–white) is based on input from all the cones. The red–green channel is based on the difference of long- and middle-wavelength cone signals. The yellow–blue channel is based on the difference between the short-wavelength cones and the sum of the other two. These basic connections are illustrated in Figure 4.10.

There are many lines of scientific evidence for the opponent process theory. These are worth examining, because they illuminate a number of applications.

Naming

We often describe colors using combinations of color terms, such as “yellowish green” or “greenish blue.” However, certain combinations of terms never appear. People never use “reddish green”

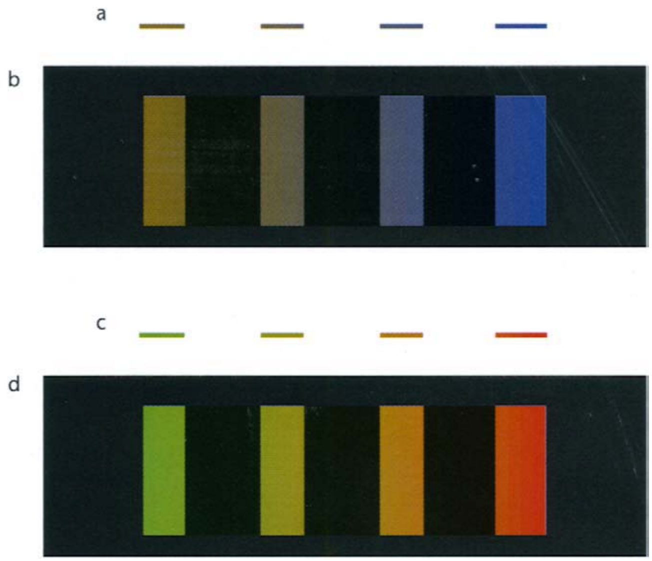


Figure 4.9 (a) Small samples of a yellow-to-blue sequence of colors on a white background. (b) The same yellow-to-blue sequence with larger samples on a black background. (c) Small samples of a green-to-red sequence on a white background. (d) The same green-to-red sequence with larger samples on a black background.

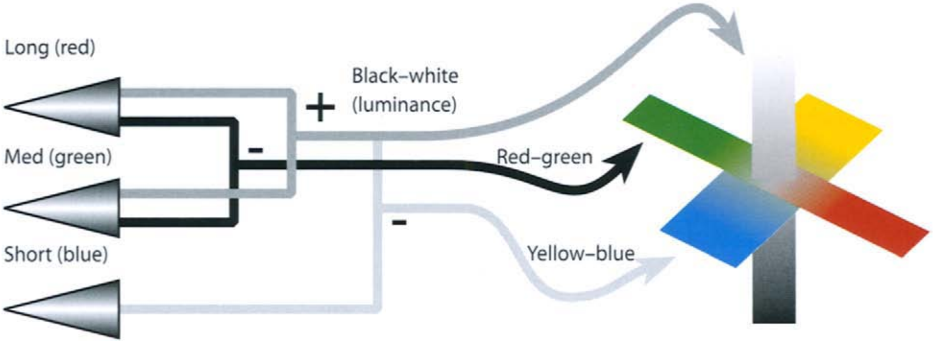


Figure 4.10 In the color opponent process model, cone signals are transformed into black–white (luminance), red–green, and yellow–blue channels.

or "yellowish blue," for example. Because these colors are polar opposites in the opponent color theory, these pairings should not occur (Hurvich, 1981).

Cross-Cultural Naming

In a remarkable study of more than 100 languages from many diverse cultures, anthropologists Berlin and Kay (1969) showed that primary color terms are remarkably consistent across cultures (Figure 4.11). In languages with only two basic color words, these are always black and white; if a third color is present, it is always red; the fourth and fifth are either yellow and then green, or green and then yellow; the sixth is always blue; the seventh is brown, followed by pink, purple, orange, and gray in no particular order. The key point here is that the first six terms define the primary axes of an opponent color model. This provides strong evidence that the neural basis for these names is innate. Otherwise, we might expect to find cultures where lime green or turquoise is a basic color term. The cross-cultural evidence strongly supports the idea that certain colors, specifically, red, green, yellow, and blue, are far more valuable in coding data than others.

Unique Hues

There is something special about yellow. If subjects are given control over a device that changes the spectral hue of a patch of light, and are told to adjust it until the result is a pure yellow, neither reddish nor greenish, they do so with remarkable accuracy. In fact, they are typically accurate within 2 nm (Hurvich, 1981).

Interestingly, there is good evidence for two unique greens. Most people set a pure green at about 514 nm, but about a third of the population sees pure green at about 525 nm (Richards, 1967). This may be why some people argue about the color turquoise; some people consider it to be a variety of green, whereas others consider it to be a kind of blue.

It is also significant that unique hues do not change a great deal when the overall luminance level is changed (Hurvich, 1981). This supports the idea that chromatic perception and luminance perception really are independent.

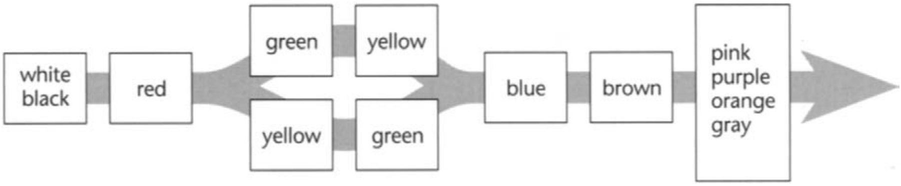


Figure 4.11 This is the order of appearance of color names in languages around the world, according to the research of Berlin and Kay (1969). The order is fixed, with the exception that sometimes yellow is present before green and sometimes the reverse is the case.

Neurophysiology

Neurophysiological studies have isolated classes of cells in the primary visual cortexes of monkeys that have exactly the properties of opponency required by the opponent process theory. Red–green and yellow–blue opponent cells exist, and other configurations do not appear to exist (de Valois and de Valois, 1975).

Categorical Colors

There is evidence that certain colors are canonical in a sense that is analogous to the philosopher Plato's theory of forms. Plato proposed that there are ideal objects, such as an ideal horse or an ideal chair, and that real horses and chairs can be defined in terms of their differences from the ideal. Something similar appears to operate in color naming. If a color is close to an ideal red or an ideal green, it is easier to remember. Colors that are not basic, such as orange or lime green, are not as easy to remember.

There is evidence that confusion between color codes is affected by color categories. Kawai et al. (1995) asked subjects to identify the presence or absence of a chip of a particular color. The subjects took much longer if the chip was surrounded by distracting elements that were of a different color but belonged to the same color category than if the chip was surrounded by distracting elements that were equally distinct according to the sense of a uniform color space but crossed a color category boundary.

Post and Greene (1986) carried out an extensive experiment on the naming of colors produced on a computer monitor and shown in a darkened room. They generated 210 different colors, each in a two-degree (of visual angle) patch with a black surround. Figure 4.12 illustrates the color areas that were given a specific name with at least 75% reliability. A number of points are worth noting:

- The fact that only eight colors plus white were consistently named, even under these highly standardized conditions, strongly suggests that only a very small number of colors can be used effectively as category labels.
- The pure monitor red was actually named orange most of the time. A true color red required the addition of a small amount from the blue monitor primary.
- The specific regions of color space occupied by particular colors should not be given much weight. The data was obtained with a black background. Because of contrast effects, different results are to be expected with white and colored backgrounds.

Properties of Color Channels

From the perspective of data visualization, the different properties of the color channels have profound implications for the use of color. The most significant differences are between the two chromatic channels and the luminance channel, although the two color channels also differ from each other.

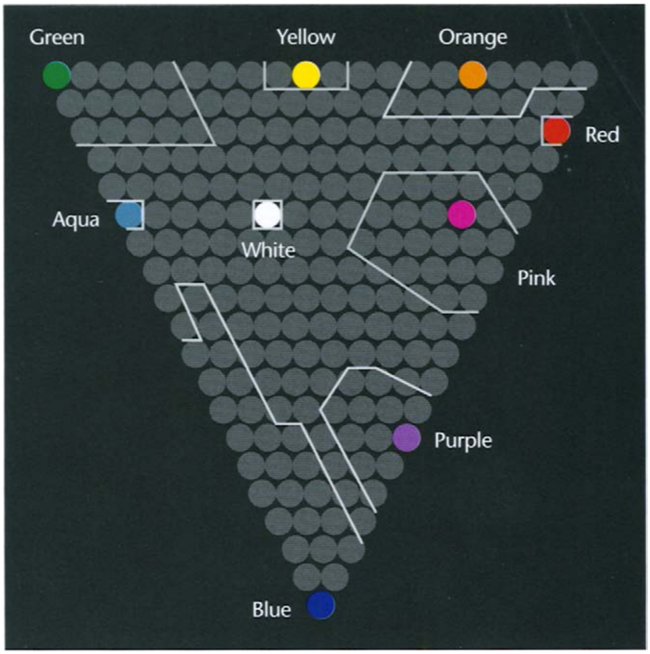
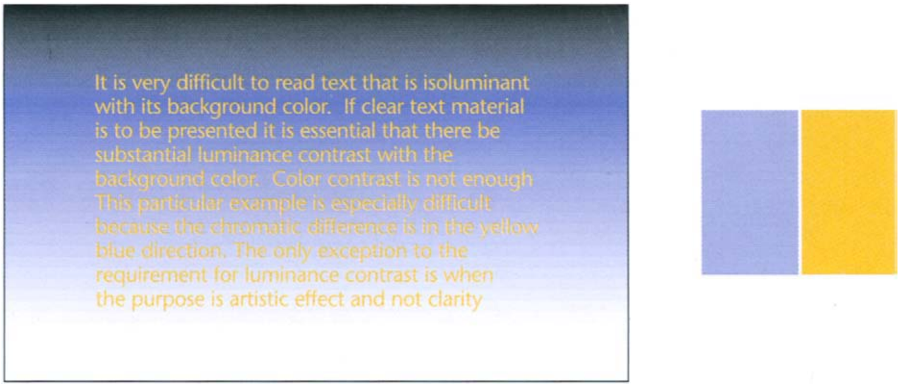


Figure 4.12 The results of an experiment in which subjects were asked to name 210 colors produced on a computer monitor. Outlined regions show the colors that were given the same name with better than 75% probability.

To display data on the luminance channel alone is easy; it is stimulated by patterns that vary only from black to white through shades of gray. But with careful calibration (which must be customized to individual subjects), patterns can be constructed that vary only for the red–green or the yellow–blue channel. A key quality of such a pattern is that its component colors must not differ in luminance. This is called an *isoluminant* or *equiluminous* pattern. In this way, the different properties of the color channels can be explored and compared with the luminance channel capacity.

Spatial Sensitivity

According to a study by Mullen (1985), the red–green and yellow–blue chromatic channels are each only capable of carrying about one-third the amount of detail carried by the black–white channel. Because of this, purely chromatic differences are not suitable for displaying any kind of fine detail. Figure 4.13 illustrates this problem with colored text on an equiluminous background. In the part of the figure where there is only a chromatic difference between the text and the back-



It is very difficult to read text that is isoluminant with its background color. If clear text material is to be presented it is essential that there be substantial luminance contrast with the background color. Color contrast is not enough This particular example is especially difficult because the chromatic difference is in the yellow blue direction. The only exception to the requirement for luminance contrast is when the purpose is artistic effect and not clarity

Figure 4.13 Yellow text on a blue gradient. Note how difficult it is to read the text where luminance is equal, despite a large chromatic difference.

ground, the text becomes very difficult to read. Generally, when detailed information of any kind is presented with color coding, it is important that there be considerable luminance contrast in addition to color contrast, especially if the colored patterns are small.

Stereoscopic Depth

It appears to be impossible, or at least very difficult, to see stereoscopic depth in stereo pairs that differ only in terms of the color channels (Lu and Fender, 1972; Gregory, 1977). Thus, stereo space perception is based primarily on information from the luminance channel.

Motion Sensitivity

If a pattern is created that is equiluminous with its background and contains only chromatic differences, and that pattern is set in motion, something strange occurs. The moving pattern appears to move much more slowly than a black-against-white pattern moving at the same speed (Anstis and Cavanaugh, 1983). Thus, motion perception appears to be primarily based on information from the luminance channel.

Form

We are very good at perceiving the shapes of surfaces based on their shading. However, when the shading is transformed from a luminance gradient into a purely chromatic gradient, the impression of surface shape is much reduced. Perception of shape and form appears to be processed mainly through the luminance channel (Gregory, 1977).

To summarize this set of properties, the red–green and yellow–blue channels are inferior to the luminance channel in almost every respect. The general implications for data display are clear. Purely chromatic differences should *never* be used for displaying object shape, object motion, or detailed information such as text. From this perspective, color would seem almost irrelevant and certainly a secondary method for information display. Nevertheless, when it comes to coding information, using color to display data categories is usually the best choice. To see why, we need to look beyond the basic processes that we have been considering thus far.

Color Appearance

The value of color (as opposed to luminance) processing, it would appear, is not in helping us to understand the shape and layout of objects in the environment. Color does not help the hunter aim an arrow accurately. Color does not help us see shape from shading and thereby plan a hike through a valley, although it does help us distinguish vegetation types. Color does not help use stereoscopic depth when we reach out to grasp a tool. But color is useful to the gatherer. Food, in the forest or on the savannah, is often distinct because of its color. This is especially true of fruits and berries. Color creates a kind of visual attribute of objects: this is a red berry. That is a yellow door. Color names are used as adjectives because colors are perceived as attributes of objects. This suggests a most important role for color in visualization—namely, the coding of information. Visual objects can represent complex data entities, and colors can naturally code attributes of those objects.

Color is normally a surface attribute of an object. The *XYZ* tristimulus values of a patch of light physically define a color, but they do not tell us how it will look. Depending on the surrounding colors in the environment and a whole host of spatial and temporal factors, the same physical color can look very different. If it is desirable that color appearance be preserved, it is important to pay close attention to surrounding conditions. In a monitor-based display, a large patch of standardized reference white will help ensure that color appearance is preserved. When colors are reproduced on paper, viewing them under a standard lamp will help preserve their appearance. In the paint and fabric industries, where color appearance is critical, standard viewing booths are used. These booths contain standard illumination systems that can be set to approximate daylight or a standard indoor illuminant, such as a typical tungsten light bulb or halogen lamp.

The mechanisms of surface lightness constancy, discussed at some length in Chapter 3, generalize to trichromatic color perception. Both chromatic adaptation and chromatic contrast occur and play a role in color constancy. Differential adaptation in the cone receptors helps us to discount the color of the illumination in the environment. When there is colored illumination, different classes of cone receptors undergo independent changes in sensitivity. Thus, when the illumination contains a lot of blue light, the short-wavelength cones become relatively less sensitive than the others. The effect of this is to shift the neutral point at which the three receptor types are in equilibrium, such that more blue light must be reflected from a surface for it to seem white. This, of course, is exactly what is necessary for color constancy. That adaptation is effective in maintaining constancy is evident from the fact that not many people are aware how much yellower ordinary tungsten room lighting is than daylight.

Color Contrast

Chromatic contrast also occurs in a way that is similar to the lightness contrast effects discussed and illustrated in Chapter 3. Figure 4.14 shows a color contrast illusion. It has been shown that contrast effects can distort readings from color-coded maps (Cleveland and McGill, 1983; Ware, 1988). Contrast effects can be theoretically accounted for by activity in the color opponent channels (Ware and Cowan, 1982). However, as with lightness contrast, the ultimate purpose of the contrast-causing mechanism is to help us see surface colors accurately by revealing differences between colored patches and background regions.

From the point of view of the monitor engineer and the user of color displays, the fact that colors are perceived relative to their overall context has the happy consequence of making the eye relatively insensitive to poor color balance. A visit to a television store will reveal that when television sets are viewed side by side, the overall color of the pictures can differ strikingly, yet when they are viewed individually, they are all acceptable. Of course, because the state of adaptation is governed by the light of the entire visual field, and a television screen takes up only part of the field, this adaptation will necessarily be incomplete.

Saturation

When describing color appearance in everyday language, people use many terms in rather imprecise ways. Besides using color names such as *lime green*, *mauve*, *brown*, *baby blue*, and so on,

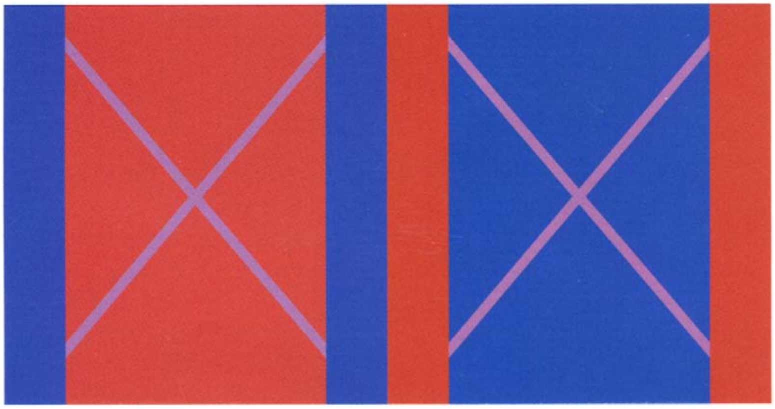


Figure 4.14 A color contrast illusion. The *X* pattern is identical on both sides, but it seems bluer on the red background and pinker on the blue background.

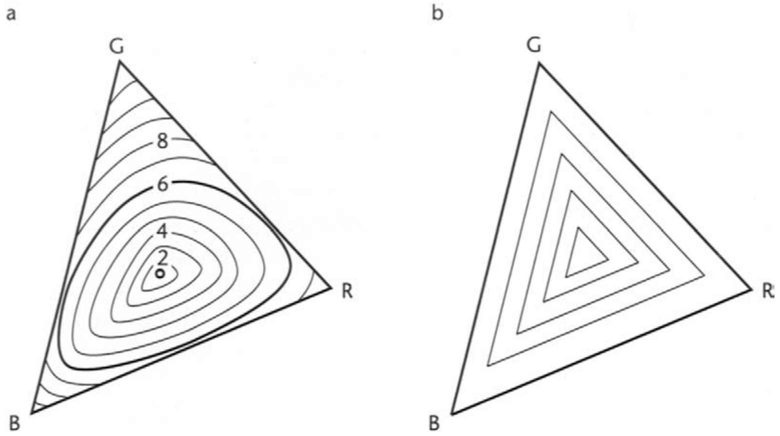


Figure 4.15 (a) The triangle represents the gamut of colors obtained using a computer monitor plotted in CIE chromaticity coordinates. The contours show perceptually determined equal-saturation contours. (b) Equal-saturation contours created using the HSV color space, also plotted in chromaticity coordinates.

people also use adjectives such as *vivid*, *bright*, and *intense* to describe colors that seem especially pure. Because these terms are used so variably, scientists use the technical term *saturation* to denote how pure colors seem to the viewer. A high-saturation color is vivid and a low-saturation color is close to black, white, or gray. In terms of the color opponent channels, high-saturation colors are those that give a strong signal on one or both of the red–green and yellow–blue channels.

Equal saturation contours have been derived from psychophysical experiments (Wyszecki and Stiles, 1982). Figure 4.15(a) shows a plot of equal saturation values in a CIE chromaticity diagram. It is clear that it is possible to obtain much more highly saturated red, green, and blue colors on a monitor than yellow, cyan, or purple values.

Brown

Brown is one of the most mysterious colors. Brown is dark yellow. Whereas people talk about a light green or a dark green, a light blue or a dark blue, yellow is different. When colors in the vicinity of yellow and orange yellow are darkened, they turn to shades of brown and olive green. Unlike red, blue, and green, brown requires that there be a reference white somewhere in the vicinity for it to be perceived. Brown appears qualitatively different to orange yellow. There is no such thing as an isolated brown light in a dark room, but when a yellow or yellowish orange is presented with a bright white surround, brown appears. The relevance to visualization is that if color sets are being devised for the purposes of color coding—for example, a set of blues, a set of reds, and a set of greens—brown may not be recognized as belonging to the set of yellows.

Applications of Color in Visualization

So far, this chapter has been mainly a presentation of the basic theory underlying color vision and color measurement. Now we shift the emphasis to applications of color, for which new theory will be introduced only as needed. We will examine five different application areas: color selection interfaces, color labeling, color sequences for map coding, color reproduction, and color for multidimensional discrete data display. Each of these presents a different set of problems, and each benefits from an analysis in terms of the human perception of color.

Application 1: Color Specification Interfaces and Color Spaces

In data visualization programs, drawing applications, and CAD systems, it is often essential to let users choose their own colors. There are a number of approaches to this user interface problem. The user can be given a set of controls to specify a point in a three-dimensional color space, a set of color names to choose from, or a palette of predefined color samples.

Color Spaces

The simplest color interface to implement on a computer involves giving someone controls to adjust the amounts of red, green, and blue light that combine to make a patch of color on a monitor. The controls can take the form of sliders, or the user can simply type in three numbers. This provides access, in a straightforward way, to any point within the *RGB* color cube shown in Figure 4.5. However, although it is simple, many people find this kind of control confusing. For example, most people do not know that to get yellow you must add red and green. There have been many attempts to make color interfaces easier to use.

One of the most widely used color interfaces in computer graphics is based on the HSV color space (Smith, 1978). This is a simple transformation from hue, saturation, and value (HSV) coordinates to *RGB* monitor coordinates. In Smith's scheme, hue represents an approximation to the visible spectrum by interpolating in sequence from red to yellow to green to blue and back to red. Saturation is the distance from monitor white to the purest hue possible given the limits of monitor phosphors. Figure 4.16 shows how hue and saturation can be laid out in two dimensions, with hue on one axis and saturation on the other, based on the HSV transformation of monitor primaries. As Figure 4.15(b) shows, HSV creates only the crudest approximation to perceptually equal-saturation contours. *Value* is the name given to the black–white axis. Some color specification interfaces based on HSV allow the user to control hue, saturation, and value variables with three sliders.

Color theory suggests that, in a computer interface for selecting colors, there are good reasons for separating a luminance (or lightness) dimension from the chromatic dimensions. A common method is to provide a single slider control for the black–white dimension and to lay out the two opponent color dimensions on a chromatic plane. The idea of laying out colors on a plane has a long history; for example, a color circle is a feature of a color textbook created for artists by

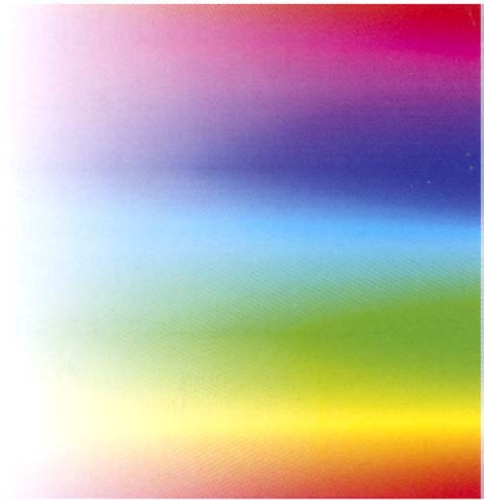


Figure 4.16 This plot shows hue and saturation, based on Smith's transformation (1978) of the monitor primaries.

Rood (1897). With the invention of computer graphics, it has become far simpler to create and control colors, and many ways of laying out colors are now available. Figure 4.17 illustrates a sampling of four different geometric color layouts, each of them embodying the idea of a chromatic plane.

Figure 4.17(a) shows a color circle with red, green, yellow, and blue defining opposing axes. Many such color circles have been devised over the past century. They differ mainly in the spacing of colors around the periphery.

Figure 4.17(b) shows a color triangle with the monitor primaries, red, green, and blue, at the corners. This color layout is convenient because it has the property that mixtures of two colors will lie on a line between them (assuming proper calibration).

Figure 4.17(c) shows a color square with the opponent color primaries, red, yellow, green, and blue, at the corners (Ware and Cowan, 1990).

Figure 4.17(d) shows a color hexagon with the colors red, yellow, green, cyan, blue, and magenta at the corners. This represents a plane through the single-hexcone color model (Smith, 1978). The hexagon representation has the advantage that it gives both the monitor primaries, red, green, and blue, and the print primaries, cyan, magenta, and yellow, prominent positions around the circumference.

To create a color interface using one of these color planes, it is necessary to allow the user to pick a sample from the color plane and adjust its lightness with a luminance slider. In some interfaces, when the luminance slider is moved, the entire plane of colors becomes lighter and darker according to the currently selected level. For those interested in implementing color interfaces, Foley et al. (1990) provide algorithms for a number of color geometries.

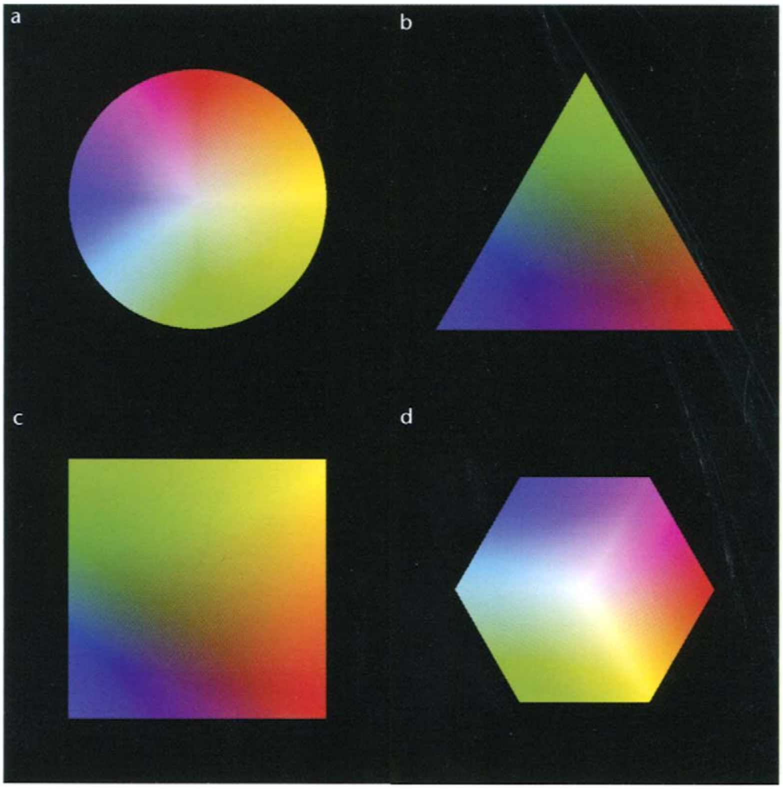


Figure 4.17 There are a number of simple transformations of the *RGB* monitor primaries to provide a color plane with an orthogonal lightness axis. Four of these are illustrated here: (a) Circle. (b) Triangle. (c) Square. (d) Hexagon.

The problem of the best color selection interface is by no means resolved. Experimental studies have failed to show that one way of controlling color is substantially better than another (Schwarz et al., 1987; Douglas and Kirkpatrick, 1996). However, Douglas and Kirkpatrick have provided evidence that good feedback about the location of the color being adjusted in color space can help in the process.

Color Naming

The facts that there are so few widely agreed-upon color names and that color memory is so poor suggest that choosing colors by name will not be useful except for the simplest applications. People agree on red, green, yellow, blue, black, and white as labels, but not much more. Nevertheless, it is possible to remember a rather large number of color names and use them accurately under controlled conditions. Displays in paint stores generally have a standard illuminant and standard background for sample strips containing several hundred samples. Under these circumstances, the specialist can remember and use as many as 1000 color names. But many of the names are idiosyncratic; the colors corresponding to "taupe," "fiesta red," and "primrose" are imprecisely defined for most of us. In addition, as soon as these colors are removed from the standard booth, they will change their appearance because of adaptation and contrast effects.

A standardized color naming system called the Natural Color System (NCS) has been developed based on Hering's opponent color theory (1920). NCS was developed in Sweden and is widely used in England and other European countries. In NCS, colors are characterized by the amounts of redness, greenness, yellowness, blueness, blackness, and whiteness that they contain. As shown in Figure 4.18, red, green, yellow, and blue lie at the ends of two orthogonal axes. Intervening "pure" colors lie on the circle circumference, and these are given numbers by sharing out 100 arbitrary units. Thus, a yellowish orange might be given the value Y70R30, meaning 70 parts yellow and 30 parts red. Colors are also given independent values on a black–white axis by allocating a blackness value between 0 and 100. A third color attribute, intensity (roughly corresponding to saturation), describes the distance from the gray-scale axis. For example, in NCS, the color "spring nymph" becomes 0030-G80Y20, which expands to blackness 00, intensity 30, green 80, and yellow 20 (Jackson et al., 1994). The NCS system combines some of the advantages of a color geometry with a reasonably intuitive and precise naming system.

In North America, other systems are more popular than NCS. The Pantone system is widely used in the printing industry, and the Munsell system is an important reference for surface colors. The Munsell system is useful because it provides a set of standard color chips designed

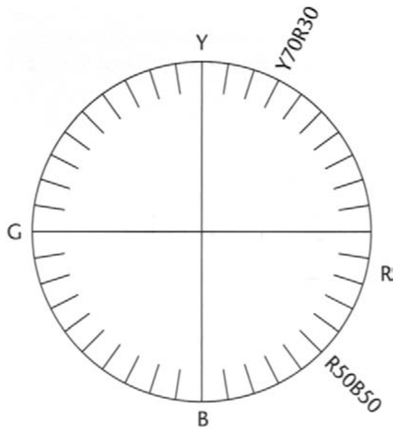


Figure 4.18 The Natural Color System (NCS) circle, defined midway between black and white. Two example color names are shown in addition to the "pure" opponent color primaries. One is an orange yellow and the other is purple.

to represent equal perceptual spacing in a three-dimensional mesh. (Munsell color chips and viewing booths are available commercially, as are Pantone products.) The NCS, Pantone, and Munsell systems were originally designed to be used with carefully printed paper samples providing the reference colors, but computer-based interfaces to these systems have been developed as part of illustration and design packages. Rhodes and Luo (1996) describe a software package that enables transformations between the different systems using the CIE as an intermediate standard.

Color Palette

When the user wishes to use only a small set of standardized colors, providing a color palette is a good solution to the color selection problem. Often, color selection palettes are laid out in a regular order according to one of the color geometries defined previously. It is useful to provide a facility for the user to develop a personal palette. This allows for consistency in color style across a number of visualization displays. Another valuable addition to a color user interface is a method for showing a color sample on differently colored backgrounds. This allows the designer to understand how contrast effects can affect the appearance of particular color samples.

Sometimes a color palette is based on one of the standard color sets used by the fabric industry or the paint industry. If this is the case, the monitor must be calibrated so that colors actually appear as specified. In addition, the lighting surrounding the monitor must be taken into account, as discussed in Chapter 3. Ideally, the monitor should be set up carefully with a standard surround and little or no ambient light falling directly on the screen. This includes having a room light such that the standard white in the set of color samples on the screen closely matches the appearance of a standard white in the room environment.

Application 2: Color for Labeling

The technical name for labeling an object is *nominal information coding*. A nominal code does not have to be orderable; it simply must be remembered and recognized. Color can be extremely effective as a nominal code. When we wish to make it easy for someone to classify visual objects into separate categories, giving the objects distinctive colors is often the best solution. One of the reasons that color is considered effective is that the alternatives are generally worse. For example, if we try to create gray-scale codes that are easily remembered and unlikely to be confused, we find that four is about the limit: white, light gray, dark gray, and black. Given that white will probably be used for the background and black is likely to be used for text, this leaves only two. In addition, using the gray scale as a nominal code may interfere with shape or detail perception. Chromatic coding can often be employed in a way that only minimally interferes with data presented on the luminance channel.

There are many perceptual factors to be considered in choosing a set of color labels.

1. **Distinctness:** A uniform color space, such as *CIEluv*, can be used to determine the degree of perceived difference between two colors that are placed close together. However, when

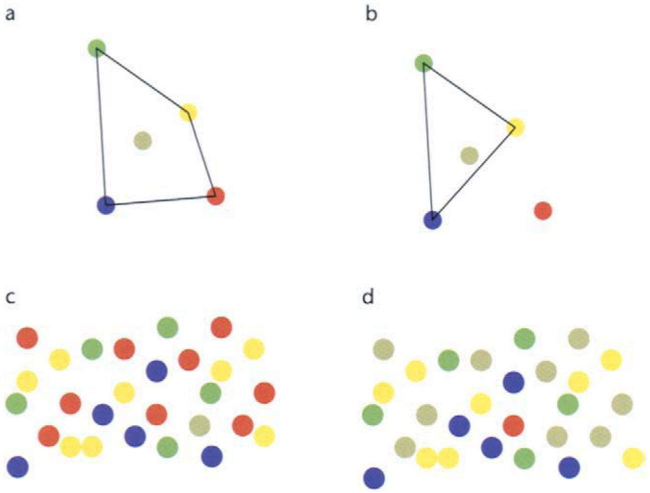


Figure 4.19 The convex hull of a set of colors is defined as the area within a rubber band that is stretched around the colors when they are defined in CIE tristimulus space. Although illustrated in two dimensions here, the concept can easily be extended to three dimensions. (a) Gray is within the convex hull of red, green, yellow, and blue. (b) Red lies outside the convex hull of green, blue, yellow, and gray. (c) The gray dot is difficult to find in a set of red, green, yellow, and blue dots. (d) The red dot is easy to find in a set of green, blue, yellow, and gray dots.

we are concerned with the ability to distinguish a color *rapidly* from a set of other colors, different rules may apply. Bauer et al. (1996) showed that the target color should lie outside the convex hull of the surrounding colors in the CIE color space. This concept is illustrated in Figure 4.19. The issues related to coding for rapid target identification are discussed further in Chapter 5.

2. **Unique hues:** The unique hues—red, green, yellow, and blue, as well as black and white—are special in terms of the opponent process model. These colors are also special in the color vocabularies of languages worldwide. Clearly, these colors provide natural choices when a small set of color codes is required. In addition, work on color confusion suggests that no two colors should be chosen from the same category, even though they may be relatively far apart in color space. We should avoid using multiple shades of green as codes, for example.

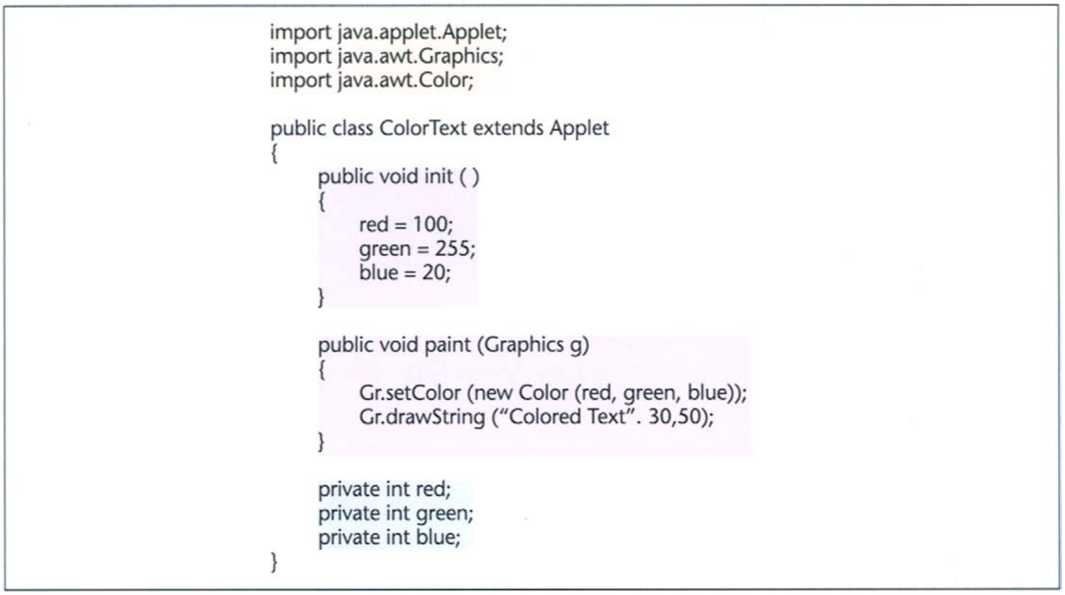
3. **Contrast with background:** In many displays, color-coded objects can be expected to appear on a variety of backgrounds. Simultaneous contrast with background colors can dramatically alter color appearance, making one color look like another. This is one reason why it is advisable to have only a small set of color codes. A method for reducing contrast effects is to place a thin white or black border around the color-coded object. This device is commonly used with signal lights; for example, train signals are displayed

on large black background discs. In addition, we should never display codes using purely chromatic differences with the background. There should be a significant luminance difference in addition to the color difference.

4. **Color blindness:** Because there is a substantial color-blind population, it may be desirable to use colors that can be distinguished even by people who are color blind. Recall that the majority of color-blind people cannot distinguish colors that differ in a red–green direction. Almost everyone can distinguish colors that vary in a yellow–blue direction, as shown in Figure 4.8. Unfortunately, this drastically reduces the design choices that are available.
5. **Number:** Although color coding is an excellent way to display category information, only a small number of codes can be rapidly perceived. Estimates vary between about five and ten codes (Healey, 1996).
6. **Field size:** Color-coded objects should not be very small; especially if the color differences are in a yellow–blue direction, at least half a degree of visual angle is probably a minimum size. Very small color-coded areas should not be used, to avoid the small-field color blindness illustrated in Figure 4.9. In general, the larger the area that is color-coded, the more easily colors can be distinguished. Small objects that are color-coded should have strong, highly saturated colors for maximum discrimination. When large areas of color coding are used, for example, with map regions, the colors should be of low saturation and differ only slightly from one another. This enables small, vivid color-coded targets to be perceived against background regions. When colors are used to highlight regions of black text, they should be light (minimum luminance contrast with the white paper) and also of low saturation (see Figure 4.20). This will minimize interference with the text.
7. **Conventions:** Color-coding conventions must sometimes be taken into account. Some common conventions are red = hot, red = danger, blue = cold, green = life, green = go. However, it is important to keep in mind that these conventions do not necessarily cross cultural borders. In China, for example, red means life and good fortune, and green means death.

The following is a list of 12 colors recommended for use in coding. They are illustrated in Figure 4.21.

1. Red
2. Green
3. Yellow
4. Blue
5. Black
6. White
7. Pink
8. Cyan
9. Gray
10. Orange
11. Brown
12. Purple



```
import java.applet.Applet;
import java.awt.Graphics;
import java.awt.Color;

public class ColorText extends Applet
{
        public void init ( )
        {
                red = 100;
                green = 255;
                blue = 20;
        }

        public void paint (Graphics g)
        {
                Gr.setColor (new Color (red, green, blue));
                Gr.drawString (“Colored Text”. 30,50);
        }

        private int red;
        private int green;
        private int blue;
}
```

Figure 4.20 When large areas are color-coded, low-saturation light colors can be used on a white background. This interferes much less with detailed information in the text.

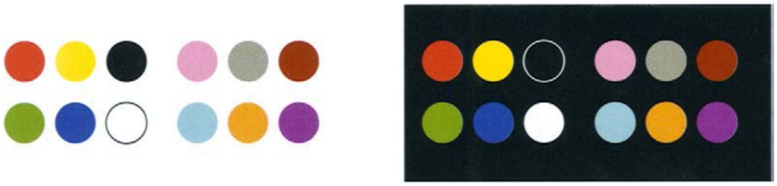


Figure 4.21 A set of 12 colors for use in labeling. The same colors are shown on a white and a black background.

These colors have widely agreed-upon category names and are reasonably far apart in color space. The first four colors, together with black and white, are chosen because they are the unique colors that mark the ends of the opponent color axes. The entire set corresponds to the 11 color names found to be the most common in the cross-cultural study carried out by Berlin and Kay, with the addition of cyan. The colors in the first set of six would normally be used before choosing any from the second set of six.

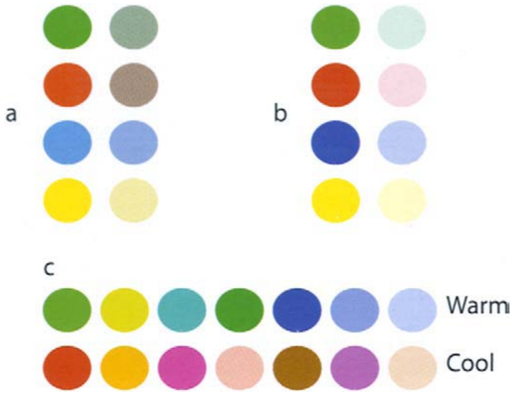


Figure 4.22 Families of colors. (a) Pairs related by hue, family members differ in saturation. (b) Pairs related by hue, family members differ in saturation and lightness. (c) A family of warm hues and a family of cool hues.

Sometimes it is useful to generate codes into families. This can be done by using hue as a primary attribute denoting family membership, with secondary values mapped to a combination of saturation and lightness. Figure 4.22 illustrates. Generally, we cannot expect to get away with more than two different color steps in each family. The canonical red, green, yellow, and blue hues make good categories for defining families. Family members then can be distinguished from one another by saturation, as in Figure 4.22(a), or even better, by saturation and lightness, as in Figure 4.22(b). Interior designers often consider a family of warm colors (nearer to red in color space) to be distinct from a family of cool colors (nearer to blue and green in color space), although the psychological validity of this is questionable.

Application 3: Color Sequences for Data Maps

Pseudocoloring is the technique of representing continuously varying map values using a sequence of colors. Pseudocoloring is used widely for astronomical radiation charts, medical imaging, and many other scientific applications. Geographers use a well-defined color sequence to display height above sea level—lowlands are always colored green, which evokes vegetation, and the scale continues upward, through brown, to white at the peaks of mountains. Figure 4.23 shows a map of gravitational variations over the North Atlantic, displayed with high-gravitation areas coded red and low-gravitation areas coded purple. Intermediate values are coded with a sequence of colors that roughly approximates the visible-light spectrum.

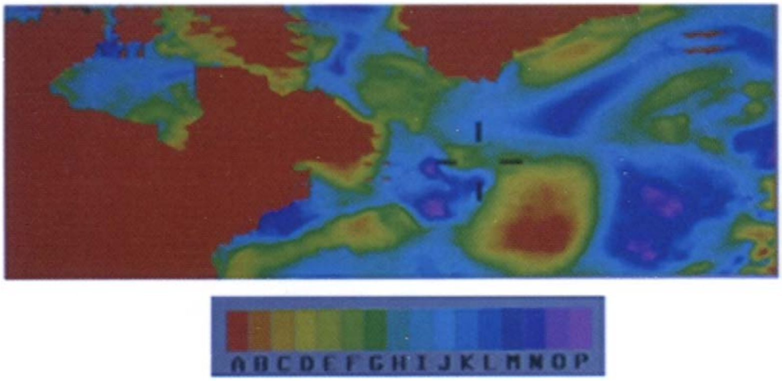


Figure 4.23 Gravitational variation over the North Atlantic is revealed using a spectrum-approximation pseudocolor sequence.

The most common coding scheme used by physicists is a color sequence that approximates the physical spectrum, like that shown in Figure 4.23. Although this sequence is widely used in physics and other disciplines and has some useful properties, it is not a *perceptual* sequence. This can be demonstrated by the following test. Give someone a series of gray paint chips and ask them to place these in order. They will happily comply with either a dark-to-light ordering or a light-to-dark ordering. Give the same person paint chips with the colors red, green, yellow, and blue and ask them to place them in order, and the result will be varied. For most people, the request will not seem particularly meaningful. They may even use an alphabetical ordering. This demonstrates that the whole spectrum is not perceptually ordered, although *short sections* of it are. For example, sections from red to yellow, yellow to green, and green to blue all vary monotonically (they continuously increase or decrease) on both the red–green and yellow–blue channels.

It is useful to consider the problem of selecting a pseudocoloring sequence in terms of Stevens's (1946) taxonomy of measurement scales into nominal, ordinal, interval, and ratio categories.

Nominal Pseudocolor Sequences (Labeling Regions)

A *nominal* pseudocolor sequence is one designed to enable rapid visual classification of regions where the values within the regions have no particular order (i.e., no "greater than" relationship holds for the values). For example, Figure 4.24 gives two examples that classify the physiography of the seabed of the Arctic Ocean. In 4.24(a) only three colors—red, yellow, and green—are used to provide visual segmentation into three distinct regions. In 4.24(b), nine different regions are labeled by color. The considerations in selecting colors for nominal sequences are the same as for color labeling. The colors should be chosen to be visually distinct from one another. In

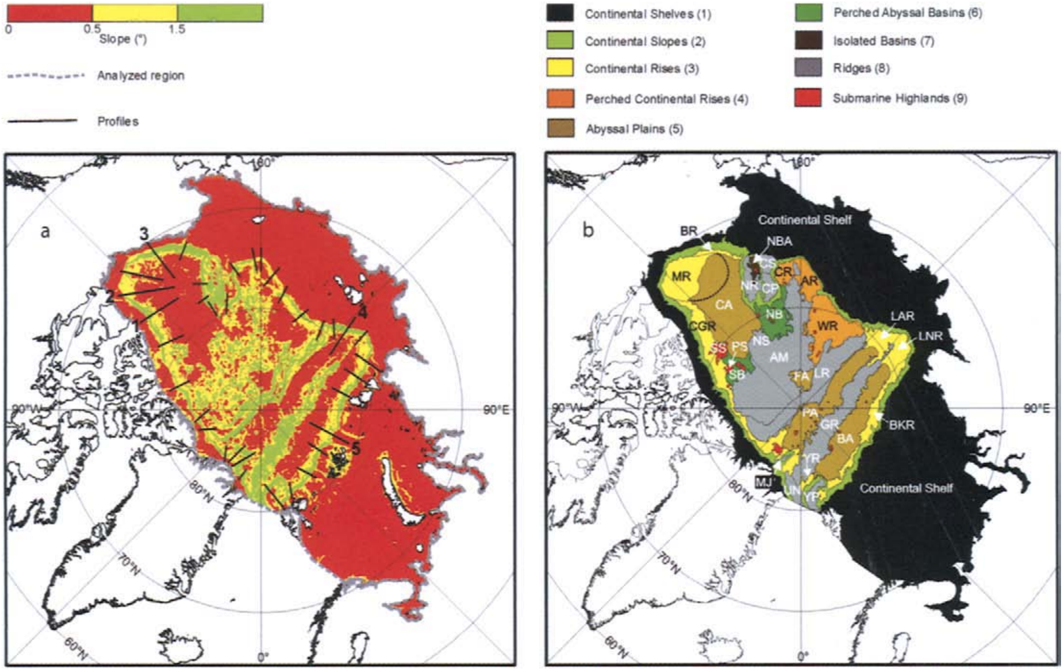


Figure 4.24 Color sequences designed for classification rather than the display of continuous variables. The physiographic features of the Arctic seafloor are illustrated. *Courtesy of Martin Jakobsson.*

general, a nominal set of colors should be custom designed based on the number of colors required and on the need to display additional symbols on top of the colors. If the overlaid symbols are to be black or dark, then the background color codes should be light, or vice versa, to give luminance contrast. If the overlaid symbols are colored, then the colored areas of the background should have low saturation.

Ordinal Pseudocolor Sequences

An *ordinal* pseudocolor sequence is one in which the monotonic ordering of data values in different parts of the display can be perceived. If value B lies between value A and value C, the color codes should perceptually have the same ordering. For ordinal values to be correctly and rapidly interpreted, it is important that the color sequence increases monotonically with respect to one or more of the color opponent channels. Such a monotonic ordering can be obtained straightforwardly by using a black-white, red-green, or yellow-blue sequence. But it can also be obtained with a saturation sequence or with any relatively straight line through opponent color space. If it is important to show detail in the data, then it is essential to have a sequence that varies according to the luminance (black–white) channel because of the capacity of this channel to convey high spatial frequency information (Ware, 1988; Rogowitz and Treinish, 1996). Figures 4.25(a) and (b) show ozone concentration data presented as a gray-scale sequence and as a color-saturation sequence. The saturation shows far less detail. For comparison, Figure 4.25(c) shows a spectrum approximation. (Images from Rheingans, 1999.) This is not perceptually ordinal but clearly shows different regions of the data map. Sometimes a spectrum approximation sequence can be effective, because the perceptual system tends to segment it into red, green, yellow, and blue regions. As long as the boundaries match significant data classes, the result will be clear.

Sometimes we may wish to overlay pseudocolored information on a shaded surface. In this case, an isoluminant color map should be employed to avoid distorting the perceived surface shape through shape-from-shading information. There will be a loss of ability to show detail through the pseudocoloring, but this cannot be avoided. Although it is often important to have a color key in a visualization that allows values to be read back from the display, it should be noted that the results are likely to be quite inaccurate due to simultaneous contrast between parts of the display (Cleveland and McGill, 1983; Brewer, 1996b). We found that these errors could be substantial: 20% of the scale on average when using gray scales and saturation scales (Ware, 1988). Using a spectrum sequence dramatically reduced contrast errors to less than half a step

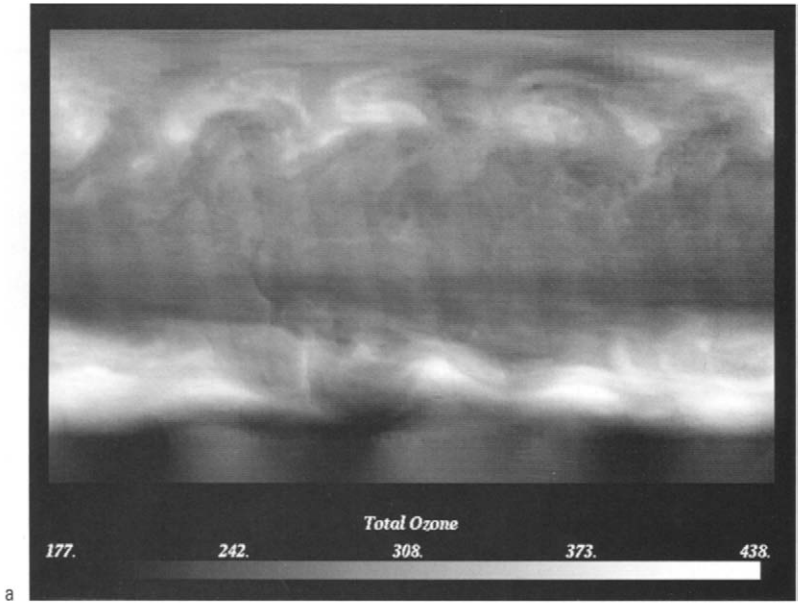


Figure 4.25 A map of ozone concentrations in the atmosphere is shown: (a) As a black–white sequence. (b) As a saturation sequence. (c) As a spectrum-approximation sequence. *Images courtesy of Penny Rheingans (Rheingans, 1999).*

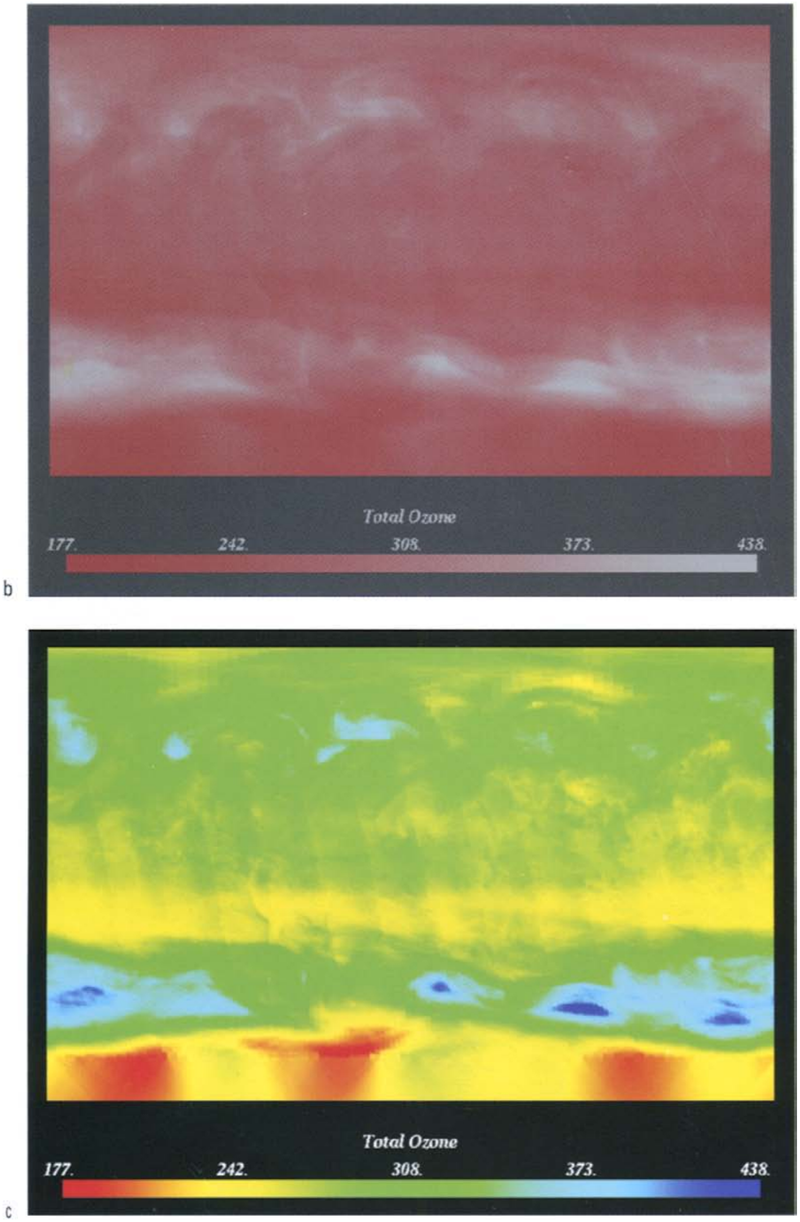


Figure 4.25 *Continued*

on average. This can be attributed to contrast effects in each opponent channel canceling when a sequence zigzags with respect to the individual color channels.

Some authors have recommended that, for clarity, color sequences should constitute a straight line through a perceptual color space, such as *CIEluv* or *CIElab* (Robertson and O'Callaghan, 1988; Levkowitz and Herman, 1992). This would rule out the spectrum approximation sequence. Further, Spence et al. (1999) found that a color sequence combining variation in brightness, saturation, and hue was the most effective in a task requiring the rapid detection of low and high points in an image. It is possible to construct color sequences that combine the advantages of monotonicity in luminance, so as to show detail, with a variety of colors, to reduce contrast and enable accurate readings from a color key. The result is a kind of spiral in color space that cycles through a variety of hues while continuously increasing in lightness (Ware, 1988). Figure 4.26 gives an example using the same gravity data displayed in Figure 4.23.

Interval Pseudocolor Sequences

An *interval* sequence is one in which each unit step of the sequence represents an equal change in magnitude of the characteristic being displayed across the whole range of the sequence. In terms of color, this suggests using a uniform color space in which equal perceptual steps correspond to equal metric steps (Robertson and O'Callaghan, 1988). Another way to produce clearly discernible intervals is to introduce steps deliberately in the color sequence (a banded color sequence). The example illustrated in Figure 4.27 is not a map but an economic forecast. Increasing uncertainty in the prediction is shown by means of clearly visible color steps, each of which represents a 5% increase in the uncertainty level.

The traditional way to display an interval sequence is through the use of isovalue contours. Contour maps show the pattern of equal heights or other physical attributes with great precision, but using them to understand the overall shape of a terrain or an energy field takes considerable

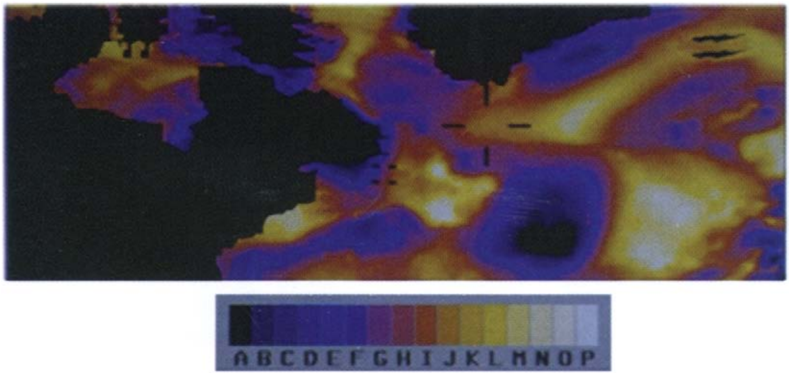


Figure 4.26 The same data shown in Figure 4.23, pseudocolored with a sequence that provides a kind of upward spiral in color space; each color is lighter than the preceding one.

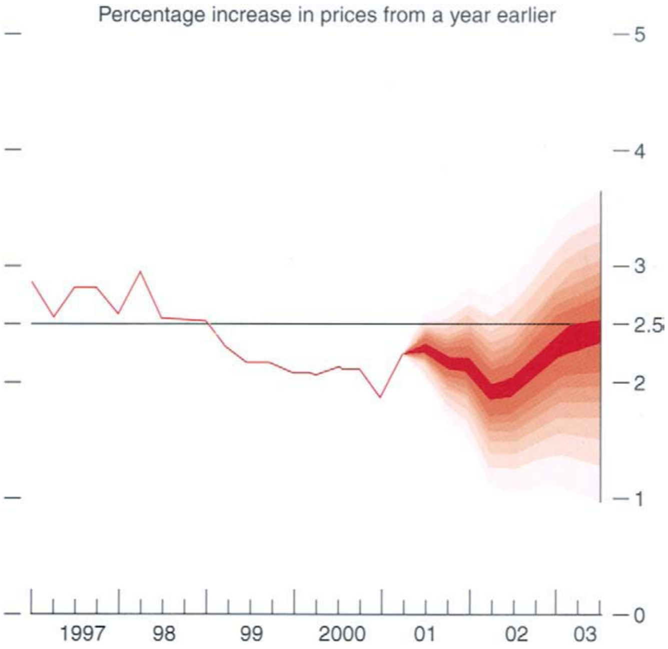


Figure 4.27 An economic forecast with estimated uncertainty. Color steps each show a 5% increase in uncertainty.

skill and experience. To support unskilled map readers, contours can be usefully combined with pseudocoloring, as shown in Figure 4.28. A well-designed pseudocolor sequence or artificially shaded height map is usually much better for the nonexpert than an unenhanced set of contours. It may also be better for the expert when rapid decision making or data fusion is required.

Ratio Pseudocolors

A *ratio* sequence is an interval sequence that has a true zero and all that this implies: the sign of a value is significant; one value can be twice as large as another. Expressing this in a color sequence is a tall order. No known visualization technique is capable of accurately conveying ratios with any precision. However, a sequence can be designed that effectively expresses a zero point and numbers above and below zero. Brewer (1996a) calls such sequences *diverging* sequences, whereas Spence and Efendov (2001) call them *bipolar* sequences.

Such sequences typically use a neutral value on one or more opponent channels to represent zero, and diverging colors (on one or more channels) to represent positive and negative quantities, respectively. For example, gray may be used to represent zero, increasing redness to represent positive quantities, and increasing blueness to represent negative quantities. In a target-detection study, Spence and Efendof (2001) found that a red–green sequence was most effective,

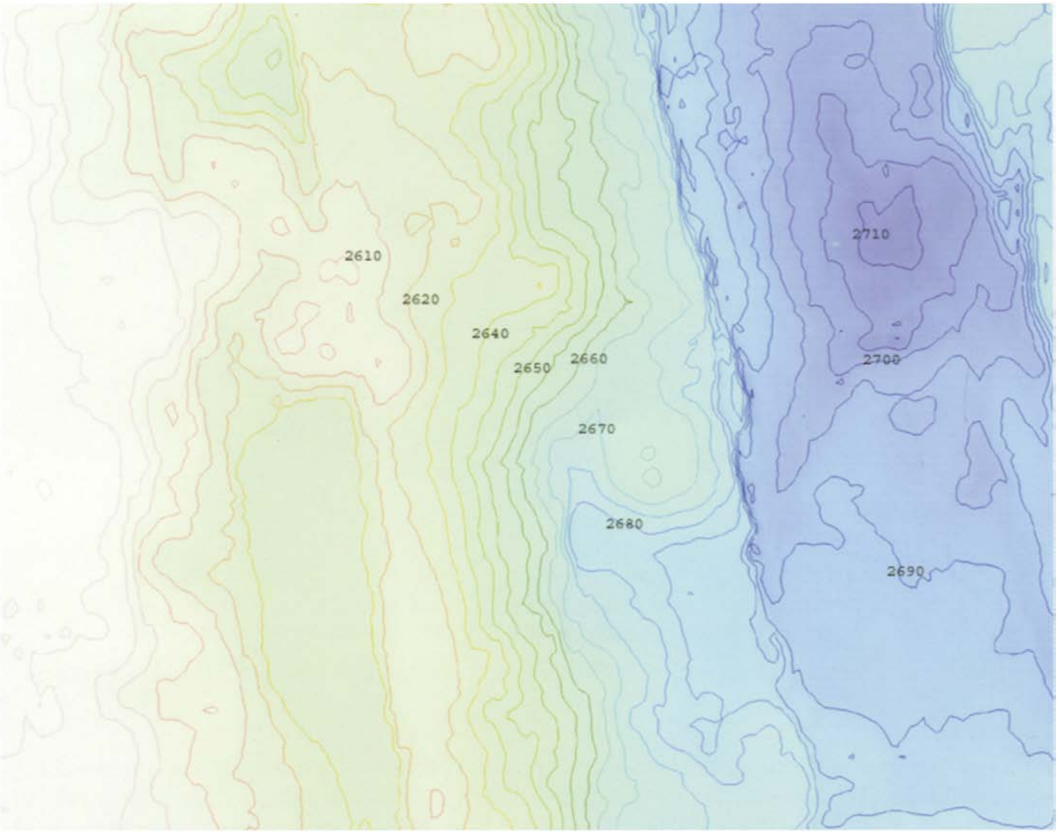


Figure 4.28 A map containing both contours and a pseudocolor sequence. *Data, courtesy of Dana Yoerger at the Woods Hole Oceanographic Institution, represents a section of the Juan de Fuca Ridgecrest in the northeastern Pacific Ocean.*

confirming the greater information-carrying capacity of this channel than the yellow–blue channel.

The example in Figure 4.29 shows a map of the stock market provided by SmartMoney.com. Market capitalization is represented by area, luminance encodes the magnitude of value change in the past year, and green-red encodes gain-loss. The Web site also gives users the option of a yellow–blue coding, suitable for most color-blind individuals.

Sequences for the Color Blind

Some color sequences will not be perceived by people who suffer from the common forms of color blindness: protanopia and deuteranopia. Both cause an inability to discriminate red from

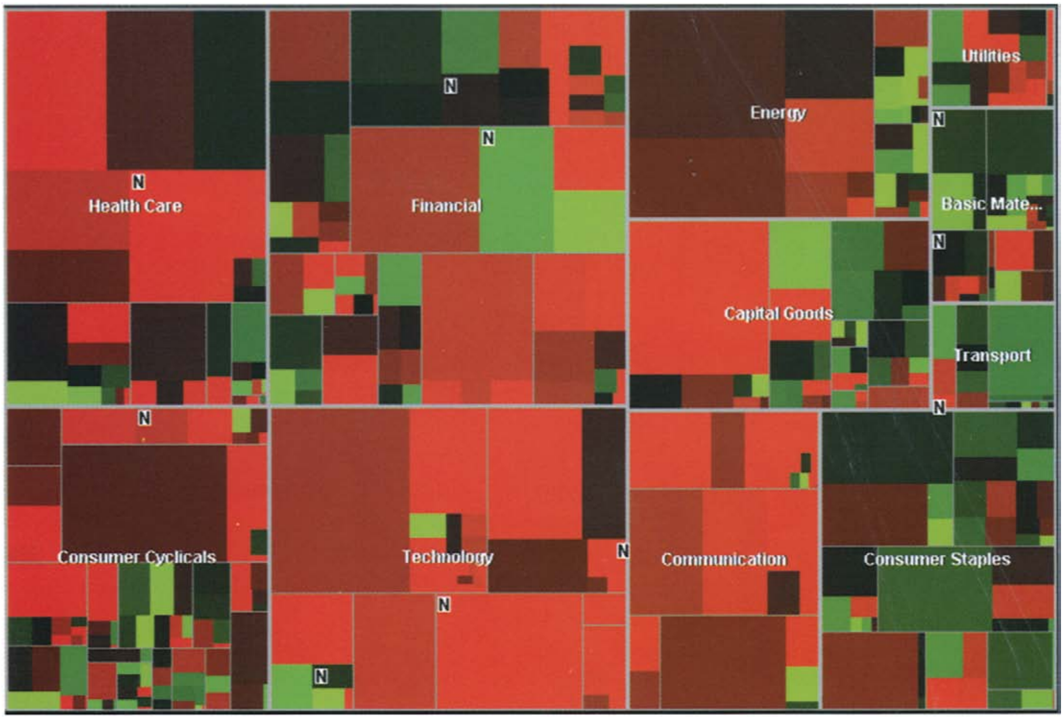


Figure 4.29 A color sequence with black representing zero. Increasing positive values are shown by increasing amounts of red. Increasing negative values are shown by increasing amounts of green. The map itself is a form of treemap (Johnson and Schneiderman, 1991). *Courtesy of SmartMoney.com.*

green. Sequences that vary mainly on a black-to-white scale or on a yellow-to-blue dimension (this includes green to blue and red to blue) will still be clear to color-blind people. Figure 4.30 shows two sequences that will be acceptable to these individuals. Meyer and Greenberg (1988) provide a detailed analysis of color sequences designed for common forms of color blindness.

Bivariate Color Sequences

Because color is three-dimensional, it is possible to display two or even three dimensions using pseudocoloring (Trumbo, 1981). Indeed, this is commonly done in the case of satellite images, in which invisible parts of the spectrum are mapped to the red, green, and blue monitor primaries. Although this mapping is simple to implement and corresponds to capabilities of the display device, (which usually has red, green, and blue phosphors,) such a scheme does not map the data values to perceptual channels. In general, it is better to map data dimensions to perceptual color dimensions. For example

Variable one→hue
Variable two→saturation

or

Variable one→hue
Variable two→lightness

Figure 4.31 gives an example of a bivariate color sequence from Brewer (1996a) that maps one variable to yellow–blue variation and the other to a combination of light–dark variation and saturation. It suffers from the usual problem that the low-saturation colors are difficult to distinguish.

As a word of caution, it should be noted that bivariate color maps are notoriously difficult to read. Wainer and Francolini (1980) carried out an empirical evaluation of a color sequence designed for U.S. census data and found that that it was essentially unintelligible. One approach to a solution is to apply a uniform color space; Robertson and O'Callaghan (1986) discuss how

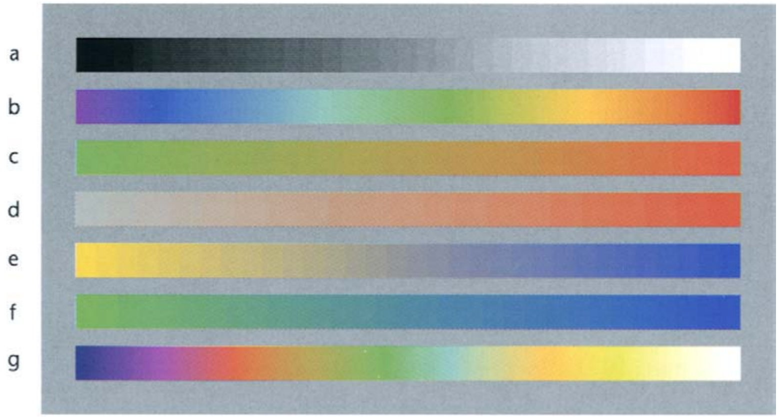


Figure 4.30 Seven different color sequences: (a) Gray scale. (b) Spectrum approximation. (c) Red–green. (d) Saturation. (e) and (f) Two sequences that will be perceived by people suffering from the most common forms of color blindness. (g) A sequence of colors in which each color is lighter than the previous one.

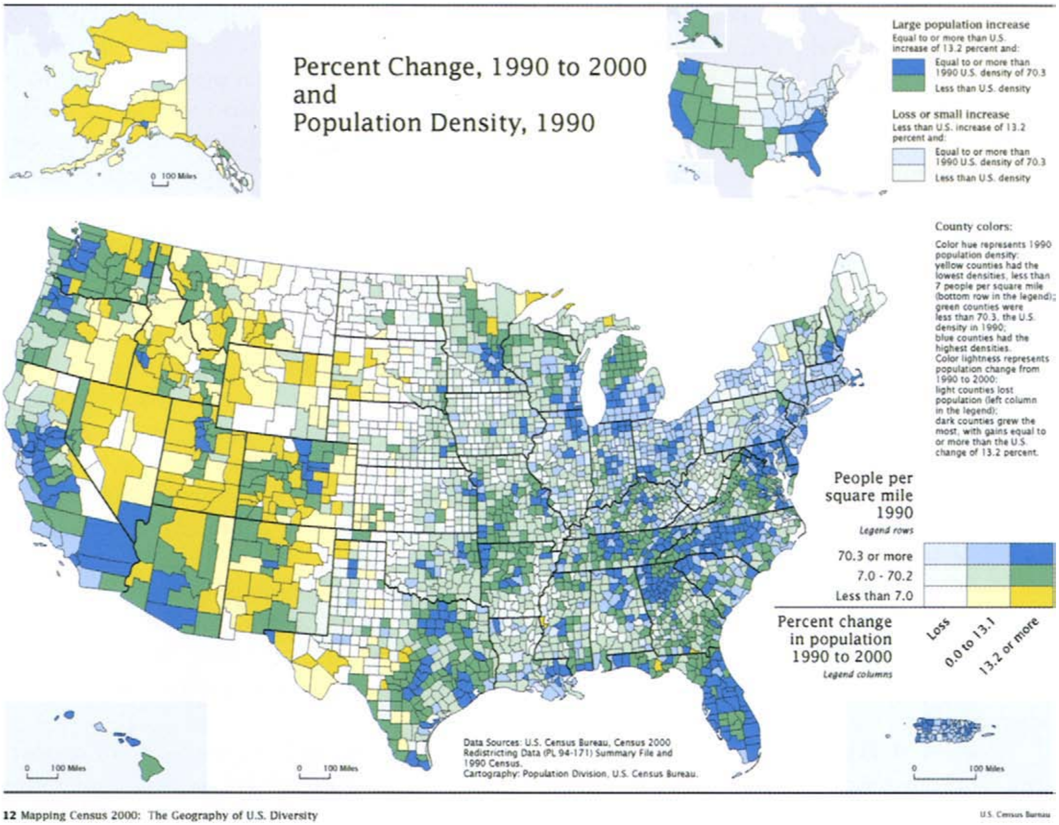

Percent Change, 1990 to 2000
and
Population Density, 1990
Large population increase
Equal to or more than U.S. increase of 13.2 percent and:
Equal to or more than 1990 U.S. density of 70.3
Less than U.S. density
Loss or small increase
Less than U.S. increase of 13.2 percent and:
Equal to or more than 1990 U.S. density of 70.3
Less than U.S. density
County colors:
Color hue represents 1990 population density: yellow counties had the lowest densities, less than 7 people per square mile (bottom row in the legend); green counties were less than 70.3, the U.S. density in 1990; blue counties had the highest densities. Color lightness represents population change from 1990 to 2000: light counties lost population (left column in the legend); dark counties grew the most, with gains equal to or more than the U.S. change of 13.2 percent.
People per square mile 1990
Legend rows
70.3 or more
7.0 - 70.2
Less than 7.0
Percent change in population 1990 to 2000
Legend columns
Loss
0.0 to 13.1
13.2 or more
0 100 Miles
0 100 Miles
0 100 Miles
0 100 Miles
Data Sources: U.S. Census Bureau, Census 2000 Redistricting Data (PL 94-171) Summary File and 1990 Census.
Cartography: Population Division, U.S. Census Bureau.
12 Mapping Census 2000: The Geography of U.S. Diversity
U.S. Census Bureau

Figure 4.31 A bivariate pseudocoloring scheme using saturation and lightness for one variable and yellow–blue hue for the other. *Courtesy of Cindy Brewer.*

to do this. But distinctness may not lead to something that is interpretable. We do not seem to be able to read different color dimensions in a way that is highly separable. Generally, when the goal is to display two variables on the same map, it may be better to use visual texture, height difference, or another channel for one variable and color for the other, thus mapping data dimensions to more perceptually separable dimensions. Pseudocoloring is only one way to display a 2D scalar field. Often, mapping the scalar field to artificial height and shading the resulting surface with an artificial light source using standard computer graphics techniques is a better alternative. Using shading to reveal map data is discussed in Chapter 7. Using shading in combination with chromatic pseudocoloring is often an effective way to reveal bivariate surfaces. There are many considerations that go into making a color sequence that displays desired quantities without significant distortions, thus making it unlikely that any predefined set of colors will exactly suit a particular data set and visualization goal. To show both overall form and detail, and to provide the ability to read values from a key, it is often desirable to emphasize certain features in the data by using a deliberately nonuniform sequence. Assigning more variation in color to a particular data range will lead to its visual emphasis. Generally, the best way to achieve an effective color sequence is to place a good color editing tool in the hands of someone who understands both the data display requirement and the perceptual issues of color sequence construction (Guitard and Ware, 1990).

Application 4: Color Reproduction

The problem of color reproduction is essentially one of transferring color appearances from one display device, such as a computer monitor, to another device, such as a sheet of paper. The colors that can be reproduced on a sheet of paper depend on such factors as the color and intensity of the illumination. Northern daylight is much bluer than direct sunlight or tungsten light, which are both quite yellow, and is prized by artists for this reason. Halogen light is more balanced. Also, monitor colors can be reproduced only within the range of printing inks; therefore, it is neither possible nor meaningful to reproduce colors directly using a standard measurement system such as the CIE *XYZ* tristimulus values.

As we have discussed, the visual system is built to perceive relationships between colors rather than absolute values. For this reason, the solution to the color reproduction problem lies in preserving the color relationships as much as possible, not the absolute values. It is also important to preserve the white point in some way, because of the role of white as a reference in judging other colors.

Stone et al. (1988) describe a process of gamut mapping designed to preserve color appearance in a transformation between one device and another. The set of all colors that can be produced by a device is called the *gamut* of that device. The gamut of a monitor is larger than that of a color printer, as shown in Figure 4.7. Stone et al. describe the following set of heuristic principles to create good mapping from one device to another:

- The gray axis of the image should be preserved. What is perceived as white on a monitor should become whatever color is perceived as white on paper.
- Maximum luminance contrast (black to white) is desirable.
- Few colors should lie outside the destination gamut.
- Hue and saturation shifts should be minimized.
- An overall increase of color saturation is preferable to a decrease.

Figure 4.32 illustrates, in two dimensions, what is in fact a three-dimensional set of geometric transformations designed to accomplish the principles of gamut mapping. In this example, the process is a transformation from a monitor image to a paper hardcopy, but the same principles and methods apply to transformations between other devices.

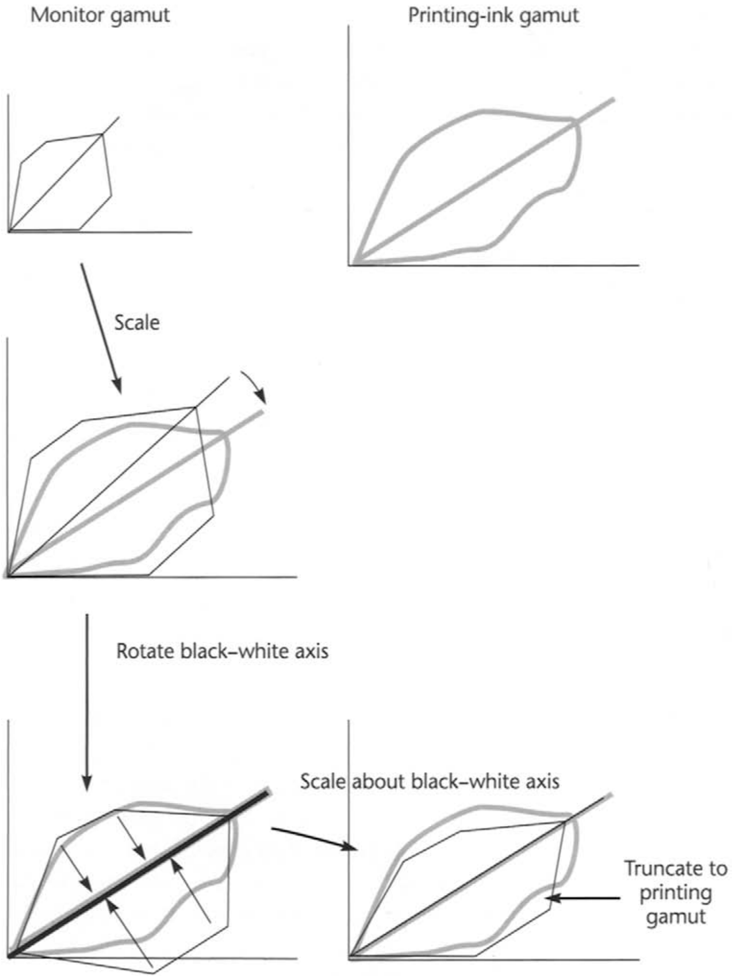


Figure 4.32 Illustration of the basic geometric operations in gamut mapping between devices, as defined by Stone et al. (1988).

1. **Calibration:** The first step is to calibrate the monitor and the printing device in a common reference system. Both can be characterized in terms of CIE tristimulus values. The calibration of the color printer must assume a particular illuminant.
2. **Range scaling:** To equate the luminance range of the source and destination images, the monitor gamut is scaled about the origin until the white of the monitor has the same luminance as the white of the paper on the target printer.

3. **Rotation:** What we perceive as neutral white on the monitor and on the printed paper can be very different, depending on the illumination. In general, in a printed image, the white is defined by the color of the paper. Monitor white is usually defined by the color that results when the red, green, and blue monitor primaries are set to their maximum values. To equate the monitor white with the paper white, the monitor gamut is rotated so as to make the white axes collinear.
4. **Saturation scaling:** Because colors can be achieved on a monitor that cannot be reproduced on paper, the monitor gamut is scaled radially with respect to the black–white axis to bring the monitor gamut within the range of the printing gamut. It may be preferable to leave a few colors outside the range of the target device and simply truncate them to the nearest color on the printing-ink gamut boundary.

For a number of reasons, it may not always be possible to apply these rules automatically. Different images may have different scaling requirements; some may consist of pastel colors that can easily be handled, whereas others may have vivid colors that must be truncated. The approach adopted by Stone et al. is to design a set of tools that support these transformations, making it easy for an educated technician to produce a good result. However, this elaborate process is not feasible with off-the-shelf printers and routine color printing. In these cases, the printer drivers will contain heuristics designed to produce generally satisfactory results. They will contain assumptions about such things as the gamma value of the monitor displaying the original image and methods for dealing with oversaturated colors. Sometimes, the heuristics embedded in devices can lead to problems. In our laboratory, we usually find it necessary to start a visualization process with very muted colors to avoid oversaturated colors on videotape or in paper reproduction.

Another issue that is important in color reproduction is the ability of the output device to display smooth color changes. Neural lateral inhibition within the visual system tends to amplify small artificial boundaries in smooth gradients of color as Mach bands. This sensitivity makes it difficult to display smoothly shaded images without artifacts. Because most output devices cannot reproduce the 16 million colors that can be created with a monitor, considerable effort has gone into techniques for generating a pattern of color dots to create the overall impression of a smooth color change. Making the dots look random is important to avoid aliasing artifacts (discussed in Chapter 2). Unless care is taken, artifacts of color reproduction can produce spurious patterns in scientific images.

Application 5: Color for Exploring Multidimensional Discrete Data

One of the most interesting but difficult challenges for data visualization is to support exploratory data analysis. Visualization can be a powerful tool in data mining, in which the goal is often a kind of general search for relationships and data trends. For example, marketing experts often collect large amounts of data about individuals in potential target populations. The variables that are collected might include age, income, educational level, employment category, tendency to purchase chocolate, and so on. If the marketer can identify a particular cluster of values in this population that are related to the likelihood of purchasing a product, this can result in better targeted, more effective advertising. Each of the measured variables can be thought of as a data dimension. The task of finding particular market segments is one of finding distinct clusters in the multidimensional space that is formed by these many variables.

Sometimes a scientist or a data analyst approaches data with no particular theory to test. The goal is to explore the data for meaningful and useful information in masses of mostly meaningless numbers. Plotting techniques have long been tools of the data explorer. In essence, the process is to plot the data, look for a pattern, and interpret the findings. Thus, the critical step in the discovery process is an act of perception. For example, the four scatter plots in Figure 4.33 illustrate very different kinds of data relationships. In the first, there are two distinct clusters, perhaps suggesting distinct subpopulations of biological organisms. In the second, there is a clear negative linear relationship between two measured variables. In the third, there is a curvilinear, inverted U-shaped relationship. In the fourth, there is an abrupt discontinuity. Each of these patterns will lead to a very different hypothesis about underlying causal relationships between variables. If any of the relationships were previously unknown, the researcher would be rewarded with a discovery.

Problems can arise in exploring data when more than two dimensions of data are to be displayed. It is possible to extend the scatter plot to three dimensions using the techniques for providing strong 3D spatial information, such as stereoscopic displays (see Chapter 8). What do we do, though, about data with more than three dimensions?

One solution for multidimensional data display is the generalized drafter's plot (Chambers et al., 1983) shown in Figure 4.34(a). In this technique, all pairs of variables are used to create two-dimensional scatter plots. Although the generalized drafter's plot can often be useful, it suffers from a disadvantage: it is very difficult to see data patterns that are present only when three or more data dimensions are taken into account.

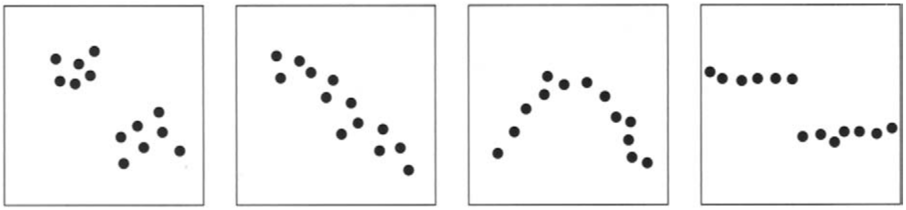


Figure 4.33 Visual exploratory data analysis techniques involve representing data graphically in order to understand relationships between data variables.

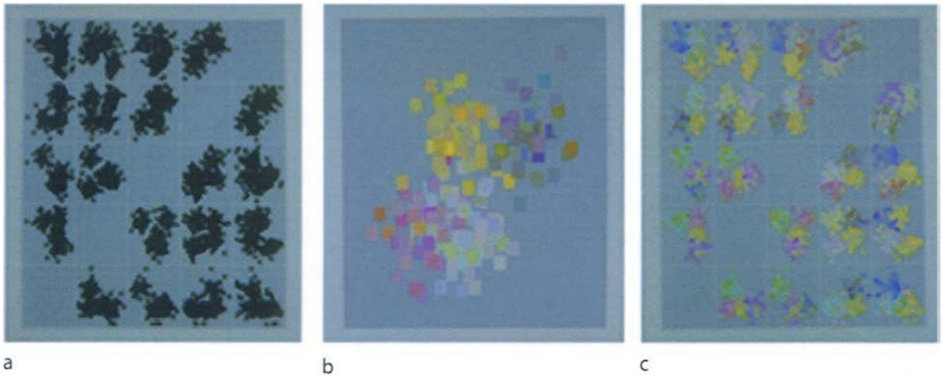


Figure 4.34 Five-dimensional data is presented: (a) In a generalized drafter's plot without color dimension mapping. (b) In a scatter plot with color dimension mapping. (c) In a generalized drafter's plot with color dimension mapping.

Color mapping can be used to extend the number of displayable data dimensions to five or six in a single scatter plot, as shown in Figure 4.34(b). We developed a simple scheme for doing this (Ware and Beatty, 1988). The technique is to create a scatter plot in which each point is a colored patch rather than a black point on a white background. Up to five data variables can be mapped and displayed as follows:

Variable 1 → *x*-axis position

Variable 2 → *y*-axis position

Variable 3 → amount of red

Variable 4 → amount of green

Variable 5 → amount of blue

In a careful evaluation of cluster perception in this kind of display, we concluded that color display dimensions could be as effective as spatial dimensions in allowing the visual system to perceive clusters. For this task, at least, the technique produced an effective five-dimensional window into the data space.

There is a negative aspect of the color-mapped scatter plot. Although identifying clusters and other patterns can be easy using this technique, interpreting them can be difficult. A cluster may appear greenish because it is low on the red variable rather than high on the green variable. The use of color can help us to identify the presence of multidimensional clusters and trends, but once the presence of these trends has been ascertained, other methods are needed to analyze them. An obvious solution is to map data variables to the color opponent axes described earlier. However, our experiments with this practice showed that the results were still not easy to interpret and that it was difficult to make efficient use of the color space.

Adding color is by no means the only way to extend a scatter plot to multiple dimensions, although it is one of the best techniques. In Chapter 5, we will consider other methods, which use shape and motion.

Conclusion

There has been more research on the use of color in visualization than any other perceptual issue. Nevertheless, the important lessons are relatively few, and we summarize them here.

- To show detail in a visualization, *always* have considerable luminance contrast between foreground and background information. Never make the difference only through chromatic variation. This should be obvious in the case of text, although many PowerPoint presentations still violate this rule. It also applies to such problems as the visual display of flow fields, where small color-coded arrows or particle traces are used.
- Use only a few colors if they are distinct codes. It is easy to select six distinct colors, but if 10 are needed they must be chosen with care. If the background is varied, then attempting to use more than 12 colors as codes is likely to result in failure.
- Black or white borders around colored symbols can help make them distinct by ensuring a luminance contrast break with surrounding colors.
- Red, green, yellow, and blue are hard-wired into the brain as primaries. If it is necessary to remember a color coding, these colors are the first that should be considered.
- When color-coding large areas, use muted colors, especially if colored symbols are to be superimposed.
- Small color-coded objects should be given high-saturation colors.
- When a perceptually meaningful ordering is needed, use a sequence that varies monotonically on at least one of the opponent color channels. Examples are red to green, yellow to blue, low saturation to high saturation, and dark to light. Variation on more than one channel is often better, such as pale yellow to dark blue.
- If it is important to show variations above and below zero, use a neutral value to represent zero and use increases in saturation toward opposite colors to show positive and negative values.
- Color contrast can cause large errors in the representation of quantity. Contrast errors can be reduced with borders around selected areas, or by using muted, relatively uniform backgrounds.
- For the reproduction of smooth color sequences, several million colors are needed under optimal viewing conditions. In this case, care must be taken to calibrate the monitor and to take into account monitor gamma values.

- When reproducing complex, continuously shaded images, it is critical to preserve the color relationships and to make sure that, under the particular lighting conditions, neutral values are perceived as neutral.
- Beware of oversaturating colors, especially when a printed image is to be the end product.

It is impossible to keep a discussion of color entirely segregated in one chapter. Color affects every aspect of visualization and is mentioned in many other chapters, especially Chapter 5, which places color in the context of other methods for coding information.