PART I

Fundamentals

In this introductory part, some basic principles of color and color measurement will be examined in the context of color-imaging systems. This examination will provide the foundation required for later discussions on color images, color encoding, and color management.

The part begins with a review of the techniques of color measurement, which are the bases of all methods of numerically representing color. Color-imaging systems then will be described—not in terms of specific technology, but in terms of the basic functions they must perform. The focus here, and throughout the book, will be on systems for which the ultimate goal is to produce images that are high-quality color reproductions of original images.

Two very different types of original images will be dealt with in these discussions. In some cases, the original will be a live image, such as an outdoor scene being recorded with a digital still camera. In other cases, the "original" itself will be a reproduction. For example, it might be a reflection print that is to be reproduced again by an imaging system composed of a scanner and printer. As will be seen, each type of original has to be treated quite differently.

In discussing and working with color-imaging products and systems, it is easy to become so enamored with the technology that the real objective gets lost. It is important, then, not to forget that when it comes to images, a human observer—not a measuring instrument—is the ultimate judge of what is good or bad. Thus, regardless of the type of original being considered, one rule will remain constant throughout this book: *The assessment of color quality will be made according to the judgments of human observers.*

As obvious as that idea may seem, an experience of a colleague of ours shows that it is sometimes overlooked. He had called the manufacturer of a color-management program, purchased for his home computer, to report a problem: yellow colors always came out greenish on his monitor. The person with whom he spoke cheerfully informed him that there was no need for concern. Those greenish colors really *were* yellow; they just did not look that way because computer monitors have an overall bluish cast to them. He was told that if he were to measure those yellows, as the manufacturer had done in designing the software, he would find that they were indeed yellow. His continued protests that he "did not care how

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they *measured*, they still *looked* greenish," were to no avail!

Since human judgments are to be the basis for determining the success or failure of color encoding and color reproduction, the basic characteristics of human color vision must be understood. These characteristics are introduced in Chapter 1, which begins with a review of color-measurement techniques that are based on the responses of a standardized representative human observer.

1
Measuring Color

Digital color encoding is, by definition, the numerical description of color in digital form. For example, in one particular color-encoding scheme, the set of digital values 40, 143, and 173 specifies a particular shade of red (the reason why will be explained later). The fact that color can be digitally encoded implies that it somehow can be measured and quantified.

But color itself is a perception, and perceptions exist only in the mind. How can one even *begin* to measure and quantify a human perception? Vision begins as light reaches the eyes; thus, a reasonable place to start is with the measurement of that light.

Light sources

In the color-science courses we often teach, students are asked to list factors they think will affect color. There usually are quite a few responses before someone mentions light sources. But perhaps this should be expected.

It is easy to take light sources, such as the sun and various types of artificial lighting, for granted. Yet unless there is a source of light, there is nothing to see. In everyday language we speak of "seeing" objects, but of course it is not the objects themselves that we see. What we see is *light* that has been reflected from or transmitted through the objects. We "prove" this in the classroom by switching off all the room lights and asking if anyone can see anything at all! This usually gets a laugh (and most often results in one or two students taking a quick nap)!

Because color begins with light, the colors that are seen are influenced by the characteristics of the light source used for illumination. For example, objects generally will look redder when viewed under a red light and greener when viewed under a green light. In order to measure color, then, it first is necessary to measure the characteristics of the light source providing the illumination.

More specifically, the *spectral power distribution* of the source, i.e., the power of its electromagnetic radiation as a function of wavelength, must be measured. Spectral power distributions can vary greatly for different types of light sources. Figure 1.1 shows, for example, the spectral power distributions for a tungsten light source and a particular type of fluorescent light source. Note that the power values in the figure are expressed in terms of relative power, not absolute power. Such relative measurements generally are sufficient for most, although not all, types of color measurements.

The most common source of light is, of course, the sun. The spectral power distribution of daylight—a mixture of sunlight and skylight—can vary greatly depending on solar altitude and on weather and atmospheric conditions. Figure 1.2 shows three of many possible examples of daylight. The undulations in each of the spectral power distributions are

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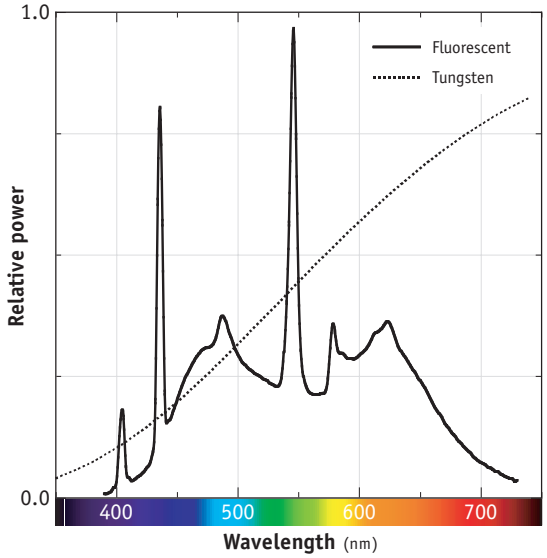

Figure 1.1 Comparison of the relative spectral power distributions for typical tungsten (dotted line) and fluorescent (solid line) light sources. The curves describe the relative power of each source's electromagnetic radiation as a function of wavelength.

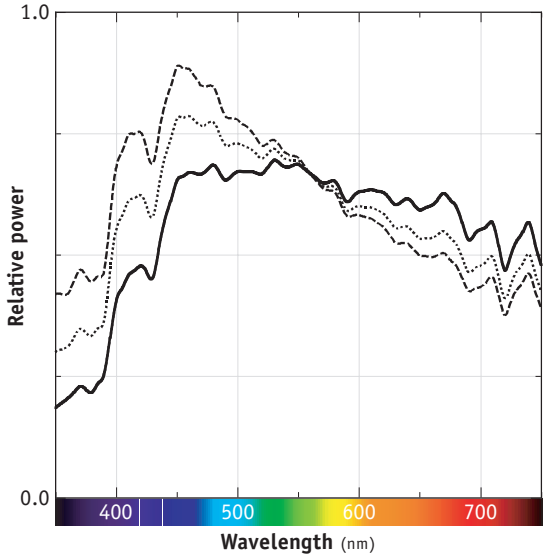

Figure 1.2 Relative spectral power distributions for three of many possible types of daylight illumination. The spectral characteristics of daylight can vary greatly depending on solar altitude, weather, and atmospheric conditions.

the result of filtration effects due to the atmospheres of the sun and the earth.

There can be a number of different light sources involved in a single digital imaging system, and each will affect the colors that ultimately are produced. For example, consider the system shown in Figure 1.3. An original scene is photographed on a color-slide film, and the slide is projected and also scanned. The scanned image is temporarily displayed on the monitor of a computer workstation, and a scan printer is used to expose a photographic paper to produce a reflection print that is then viewed.

There are six different light sources to consider in this system. First, there is the source illuminating the original scene. Another light source is used to project the slide for direct viewing. There is a light source in the slide-film scanner, which is used to illuminate the slide during scanning. The computer monitor also is a light source (the phosphors of its display emit light). The scan printer uses a light source to expose the photographic paper. Finally, a light source is used to illuminate the reflection print for viewing.

In later chapters, each of these uses of light sources will be discussed. For now, it is the measurement of color that is being discussed. Our immediate attention will be on the use of light sources to illuminate objects for viewing.

Objects

When light reaches an object, that light is absorbed, reflected, or transmitted. Depending on the chemical makeup of the object and certain other factors, the amount of light that is reflected or transmitted generally will vary at different wavelengths. For the purposes of color measurement, this variation is described in terms of spectral reflectance or spectral transmittance characteristics. These characteristics respectively describe the *fraction* of the incident power reflected or transmitted as a function of wavelength.

In most cases, an object's spectral characteristics will correlate in a straightforward way with the color normally associated with the object. For example,

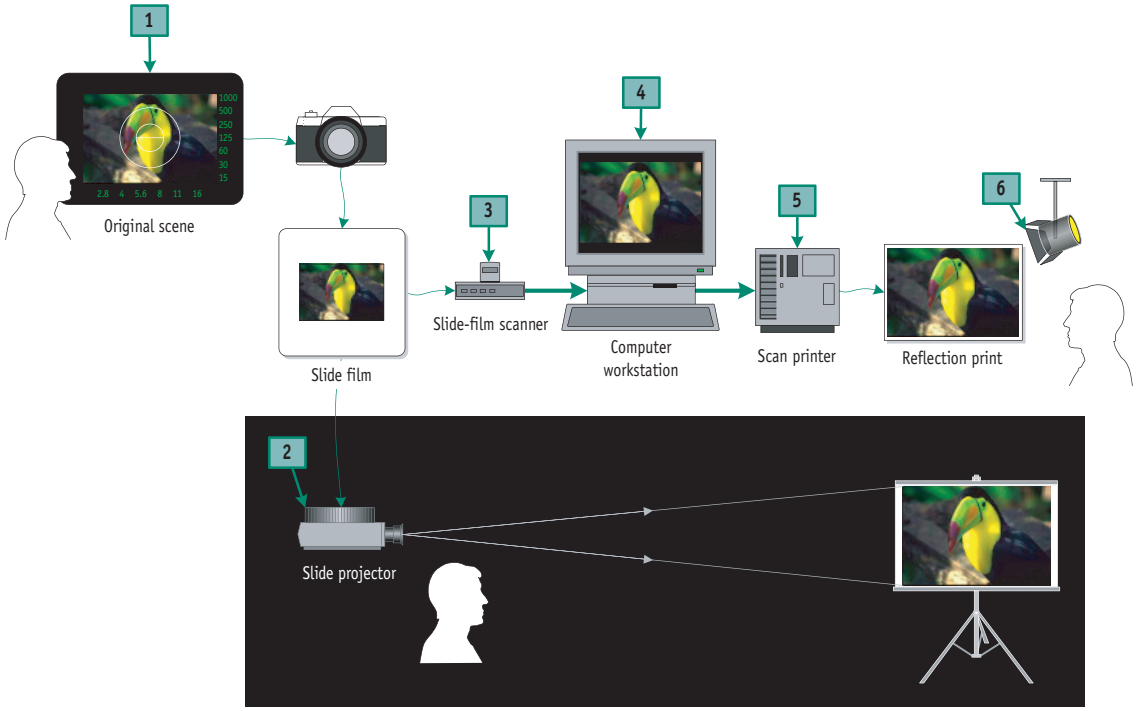

Figure 1.3 In this imaging system, there are six different light sources that contribute to the recording, reproduction, and viewing of colors.

the spectral reflectance characteristic shown in Figure 1.4 is for a red apple. The apple (generally) is seen as red because it reflects a greater fraction of red light (longer visible wavelengths) than of green light (middle visible wavelengths) or blue light (shorter visible wavelengths). Sometimes, however, the correlation of a color and its spectral reflectance characteristic is less obvious, as in the case of the two objects having the spectral reflectances shown in Figures 1.5a and 1.5b.

The object in Figure 1.5a is a particular type of flower, an ageratum. The flower appears blue to a human observer, even though it seems to have more red-light reflectance than blue-light reflectance. The object in Figure 1.5b is a sample of a dyed fabric, which appears green to a human observer, despite its unusual spectral reflectance that would seem to indicate otherwise.

In a moment, human color vision will be discussed, and the reason why these objects have color appearances that might not seem apparent from their spectral reflectances will be given. But before that can be done, it is necessary to discuss the role that objects play in the formation of what are referred to in color science as *color stimuli*.

Color stimuli

In color science, a "color" that is to be viewed or measured is referred to, more correctly, as a color stimulus. A color stimulus always consists of light. In some cases, that light might come directly from a light source itself, such as when an electronic display or the flame of a burning candle is viewed directly.

More typically, color stimuli are the result of light that has been reflected from or transmitted through various objects. For example, if the apple of Figure 1.4 is illuminated with the fluorescent light source of Figure 1.1, the resulting color stimulus will have the spectral power distribution shown in Figure 1.6.

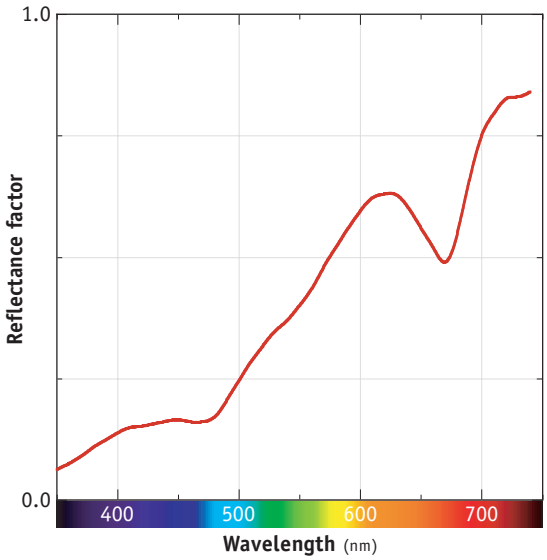

Figure 1.4 Spectral reflectance of a red Cortland apple. The apple generally is seen as red because it reflects a greater fraction of red light than of green light or blue light.

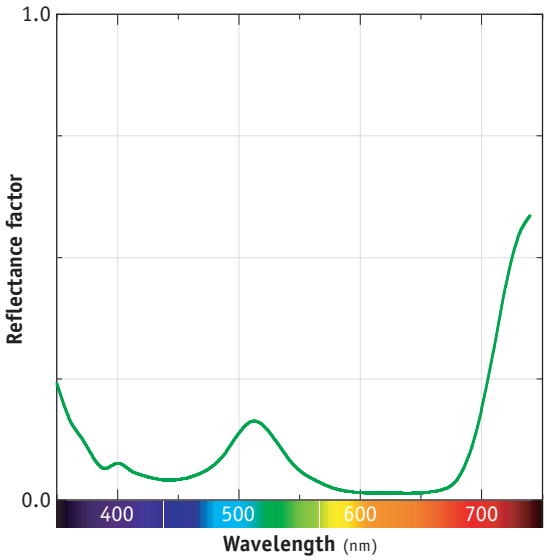

Figure 1.5b Spectral reflectance of a particular fabric sample. The fabric appears green, despite its having spectral characteristics that seem to indicate otherwise.

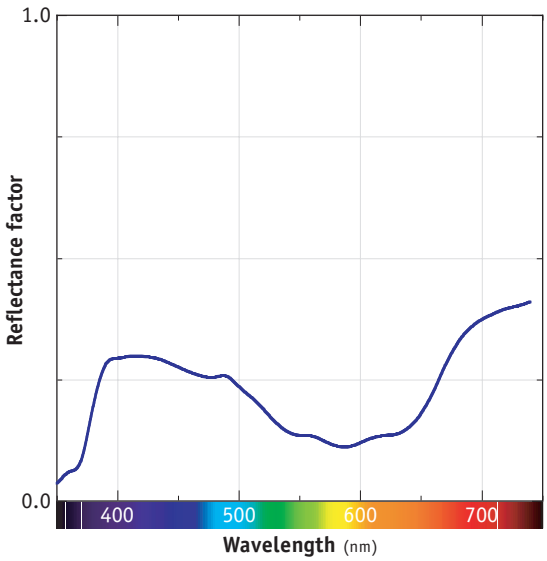

Figure 1.5a Spectral reflectance of an ageratum. The flower appears blue, even though it seems to have more red-light reflectance than blue-light reflectance.

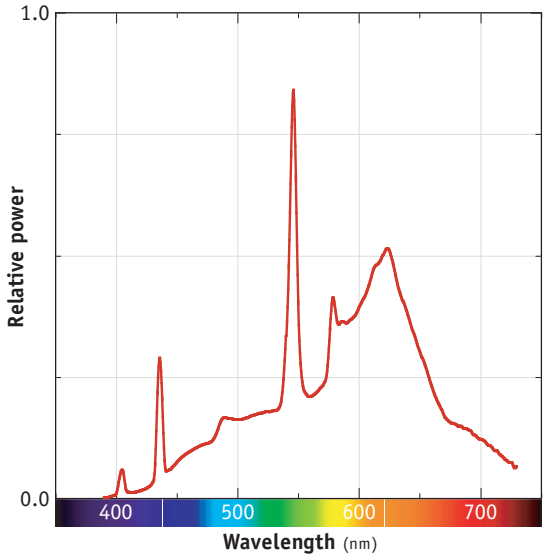

Figure 1.6 Spectral power distribution for a Cortland apple, illuminated with a fluorescent light source. In color science, such power distributions are called color stimuli.

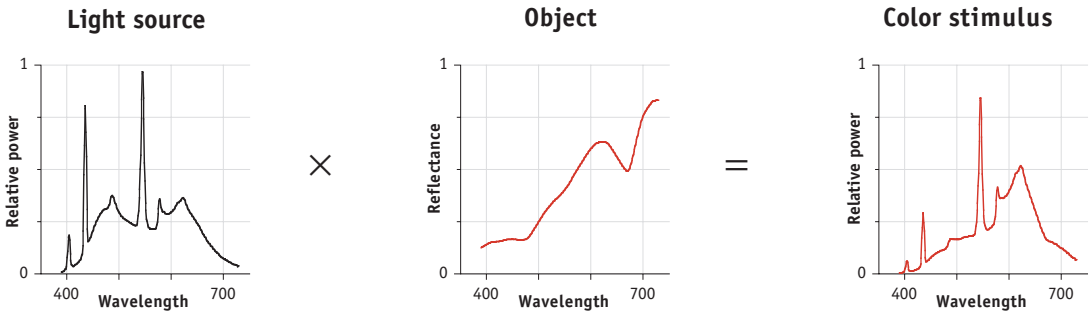

Figure 1.7 Calculation of the spectral power distribution of a color stimulus. The distribution is the product of the spectral power distribution of the light source and the spectral reflectance of the object.

The spectral power distribution of this stimulus is the *product* of the spectral power distribution of the fluorescent source and the spectral reflectance characteristic of the apple. The spectral power distribution of the stimulus is calculated simply by multiplying the power of the light source by the reflectance of the object at each wavelength, as shown in Figure 1.7.

It is important to emphasize that for a reflective or transmissive object, the color stimulus results from *both* the object and the light source. If a different light source having a different spectral power distribution illuminates an object, the color stimulus in turn will change. For example, if the apple of Figure 1.4 is illuminated with the tungsten light source of Figure 1.1, a color stimulus having the spectral power distribution shown in Figure 1.8 will be produced.

As Figure 1.8 shows, the tungsten-illuminated stimulus is very different from that produced by fluorescent illumination of the same apple. What this means is that the color of an object is *not* invariant, nor is it determined solely by the object itself. A "red" apple can be made to appear almost *any* color (or even no color at all), depending on how it is illuminated.

The concept of the color stimulus is the foundation of all methods of representing color images in numerical form. Every spatial point in a scene or image has an associated spectral power distribution. So any live scene, any image being scanned, any electronically displayed image, or any illuminated hard-copy image can be treated as a collection of individual color stimuli. These stimuli can be measured by an instrument, and they can be detected by the sensors of an imaging device.

Most importantly, it is these color stimuli that are seen by a human observer. In order to make meaningful assessments of color stimuli, then, it will

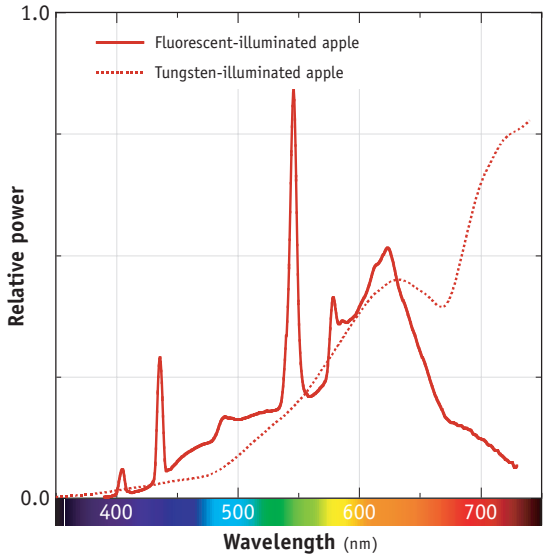

Figure 1.8 Comparison of the spectral power distributions for two stimuli—an apple illuminated by a tungsten light source (dotted line) and the same apple illuminated by a fluorescent light source (solid line).

be necessary to examine how they are detected and interpreted by the human visual system.

Human color vision

Although instruments can measure color stimuli in terms of their spectral power distributions, the eye does not interpret color stimuli by analyzing them in a comparable wavelength-by-wavelength manner. Instead, human color vision derives from the responses of just three types of photoreceptors (cones) contained in the retina of the eye. The approximate *spectral sensitivities* of these photoreceptors—their relative sensitivity to light as a function of wavelength—are shown in Figure 1.9.

Note that the sensitivity of the human visual system rapidly decreases above 650 nm (nanometers). That is why the blue flower discussed earlier appears blue, despite its reflectance at longer visible wavelengths (Figure 1.10a). The human visual system also has very little sensitivity to wavelengths below 400 nm, so the fabric discussed earlier looks green despite its high reflectances in the shorter-wavelength and longer-wavelength regions (Figure 1.10b).

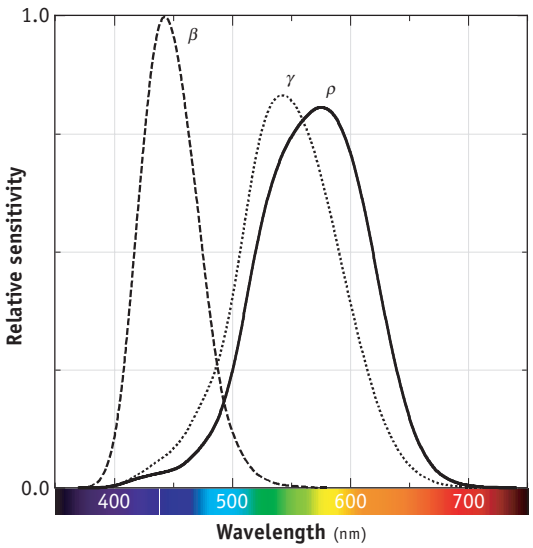

Figure 1.9 Estimated spectral sensitivities ρ, γ, and β of the three types of photoreceptors of the human eye. (The curves, derived from Estevez, 1979, have been normalized to equal area.)

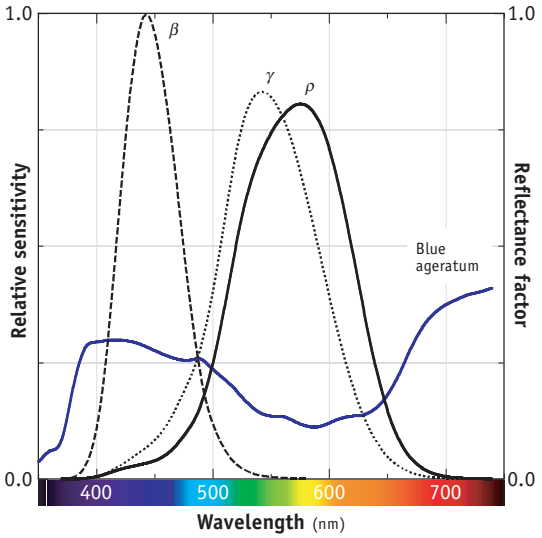

Figure 1.10a Estimated human spectral sensitivities, co-plotted with the ageratum spectral reflectance from Figure 1.5a. The sensitivity of the human visual system rapidly decreases above 650 nm, so the flower looks blue despite its reflectance at longer wavelengths.

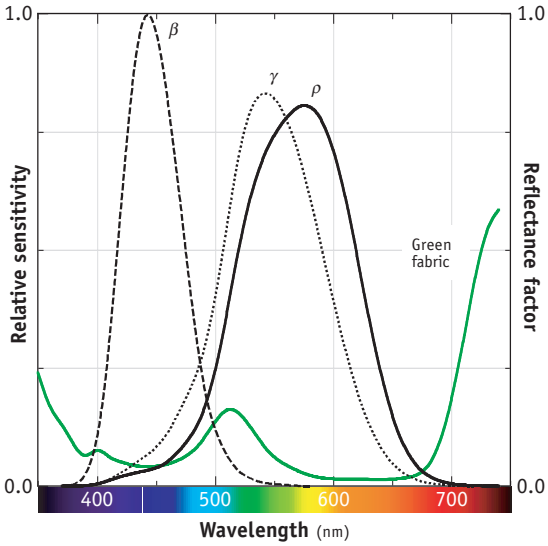

Figure 1.10b Estimated human spectral sensitivities, co-plotted with the fabric spectral reflectance from Figure 1.5b. The fabric looks green despite its high reflectances at shorter and longer wavelengths.

While this trichromatic (three-channel) analysis might seem rather inelegant, it actually is the beginning of an exquisite process that is capable of great subtlety. This process allows the human visual system to distinguish very small differences in stimulation of the three types of photoreceptors. In fact, it has been estimated that stimulation of these photoreceptors to various levels and ratios can give rise to about *10 million* distinguishable color sensations!

Because of the trichromatic nature of human vision, however, it is quite possible that two color stimuli having very different spectral power distributions will appear to have identical color. This can occur if the two color stimuli happen to produce equivalent stimulations of the photoreceptors (Figure 1.11). Two such stimuli are called a *metameric pair*, and the situation is referred to as *metamerism*.

While at first this may seem to be a problem, metamerism actually makes color-imaging systems (and digital color encoding) practical. Because of metamerism, it is not necessary either to record or to reproduce the actual spectral power distribution of an original color stimulus. It is only necessary for an imaging system to produce a displayed stimulus that is a *visual equivalent* of the original, i.e., a stimulus that produces the same appearance. For example, in Figure 1.12 the color stimulus produced by the CRT is indistinguishable in color from the original, although its spectral power distribution obviously is very different.

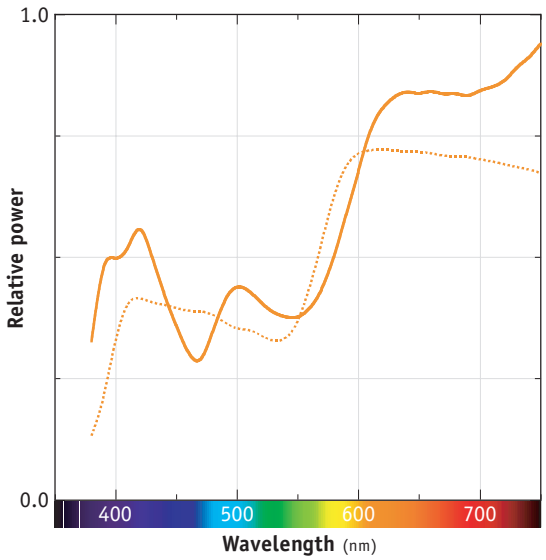

Figure 1.11 An example pair of metameric color stimuli. The two stimuli produce equivalent stimulations of the eye's photoreceptors. Metameric stimuli match in color appearance when viewed under identical conditions, but they have different spectral power distributions.

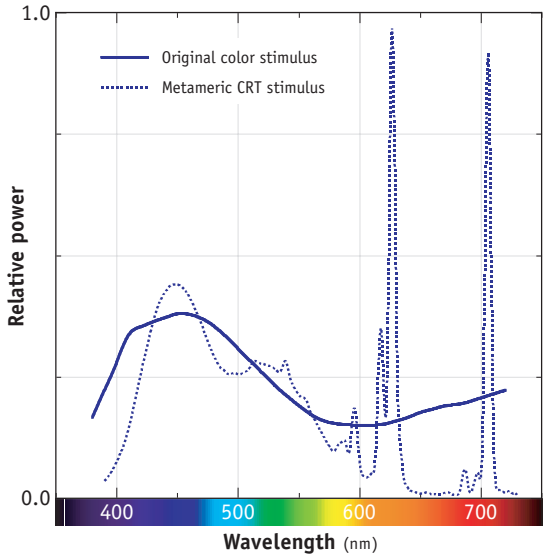

Figure 1.12 Spectral power distributions for an original color stimulus and a metameric (visually equivalent) color stimulus produced by a CRT display.

As mentioned earlier, the spectral power distribution of a stimulus generally is a product of a spectral power distribution of a light source and a spectral reflectance of an object (self-luminous displays are an exception). It is important to emphasize that metamerism involves the matching of *stimuli*, not the matching of *objects*. The significance of this distinction is that two objects, having different spectral reflectances, may match metamerically under one light source, but not under another.

For example, a color copier may be capable of scanning original reflection images and producing copies that metamerically match those originals. However, if the spectral characteristics of the light source used for viewing the original images and the copies are changed the stimuli involved also will have changed, and it is likely that the copies will no longer

match the originals. This is an important issue that will be revisited in later discussions on color-imaging systems and color-encoding methods.

Colorimetry

In the design of color-imaging systems and color-encoding schemes, it is important to be able to predict when two color stimuli will visually match. The science of *colorimetry* provides the basis for such predictions, and it is the foundation on which all color science is built.

Colorimetry provides methods for specifying a color stimulus by relating the measurement of its spectral power to the trichromatic responses of a defined standard observer. Doing so allows the prediction of metamerism. If two color stimuli produce the *same* trichromatic responses, those stimuli are, by definition, metameric. They will look the same (to a standard observer) if they are viewed under identical conditions.

Colorimetry is founded on a classic series of color-matching experiments that allowed the trichromatic properties of human vision to be studied and characterized. In a typical color-matching experiment, an observer views a small circular field that is split into two halves, as illustrated in Figure 1.13.

In the course of the experiment, light of a particular test color is used to illuminate one half of the field. The other half is illuminated by the superposition of light from three independent sources. *Independent* in this context means that none of the sources can be visually matched by a mixture of the other two. The independent sources (which usually are red, green, and blue) are called color *primaries*.

In performing a color-matching experiment, an observer adjusts the amounts (*intensities*) of the three color primaries until their mixture appears to match the test color. The amounts of the primaries required to produce the match are called the *tristimulus values* of the test color, for that set of color primaries. If the experiment is performed sequentially,

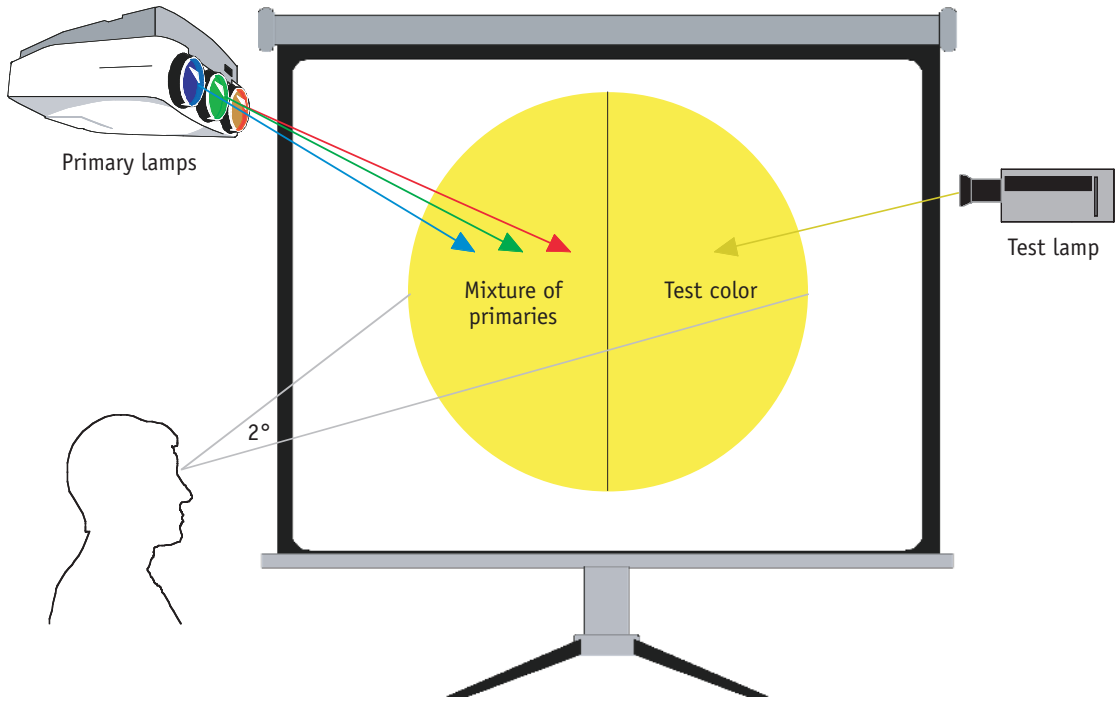

Figure 1.13 A classic color-matching experiment. A test color illuminates one half of the field, while the other half is illuminated by superposed light from three primaries. The intensities of the primaries needed to match a test color are called tristimulus values.

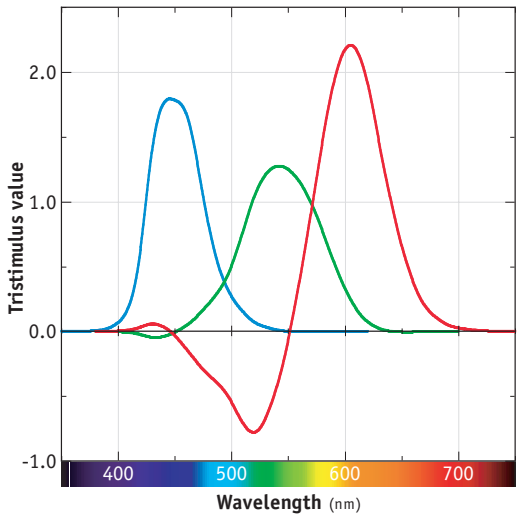

Figure 1.14 A set of color-matching functions resulting from a matching experiment performed using a particular set of red, green, and blue primaries (monochromatic light, wavelengths of 700.0, 546.1, and 435.8 nm).

using a series of test colors of monochromatic light for each of the visible wavelengths (from about 380 nm to about 780 nm), a set of three curves called *color-matching functions* is obtained. Color-matching functions represent the tristimulus values (the amounts of each of the primaries) needed to match a defined amount of light at each spectral wavelength. Figure 1.14 shows a set of color-matching functions resulting from a matching experiment performed using a particular set of red, green, and blue primaries. The color-matching functions that result will differ when different sets of color primaries are used, and they also may differ somewhat from observer to observer.

Notice that some of the tristimulus values of Figure 1.14 are *negative*. These negative values result from the fact that when the color-matching experiment is performed using monochromatic test colors, some of those test colors cannot be matched by *any* combination of the three primaries. In these cases, light from one or more of the primaries is *added* to the light of the *test color* (Figure 1.15). A match then

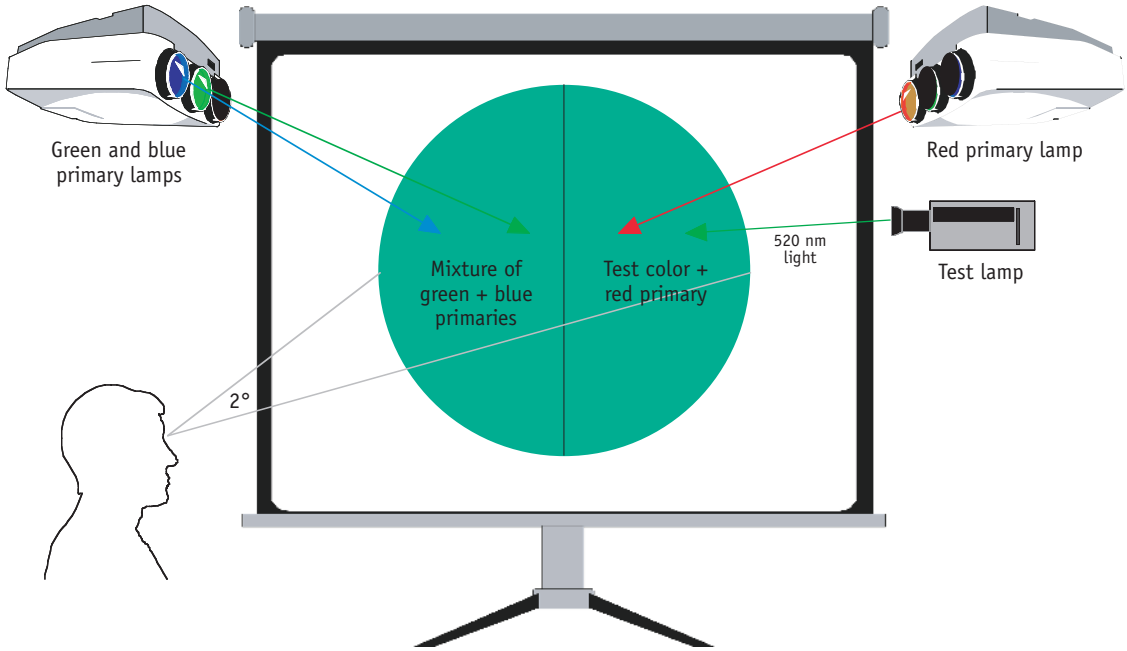

Figure 1.15 In this color-matching experiment, the test color of wavelength 520 nm cannot be matched by any combination of light from the three primaries. A match can be obtained, however, by adding light from the red primary to the test color.

can be achieved by adjusting the primaries in this configuration. Light that is added to the test color can be considered to have been *subtracted* from the mixture of the primaries. The amount of any primary added to the test color therefore is recorded as a negative tristimulus value.

It is very important to know that the color-matching functions for *any* set of physically realizable primaries will have *some* negative values. This fact will be of great significance in later discussions on a number of topics, including the signal processing requirements of color-imaging systems and the ranges of colors that can be represented by various color-encoding schemes.

The number of possible sets of color primaries is, of course, unlimited. It follows, then, that there also must be an unlimited number of corresponding sets of color-matching functions. Yet it can be shown that *all* sets of color-matching functions for a given observer are simple linear combinations of one another. A matrix operation therefore can be used to transform one set of color-matching functions to another.

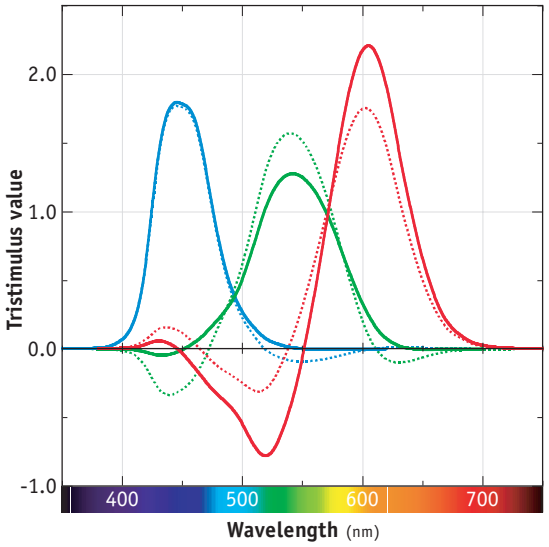

Figure 1.16 All sets of color-matching functions are linear transformations of all other sets. The set shown by the dotted-line functions $\bar{r}_2(\lambda)$, $\bar{g}_2(\lambda)$, $\bar{b}_2(\lambda)$ was derived from the set shown by the solid-line functions $\bar{r}_1(\lambda)$, $\bar{g}_1(\lambda)$, $\bar{b}_1(\lambda)$ using the linear matrix transformation given in Equation (1.1).

For the example given in Figure 1.16, the set of color-matching functions $\bar{r}_2(\lambda)$, $\bar{g}_2(\lambda)$, and $\bar{b}_2(\lambda)$ was derived from another set of color-matching functions $\bar{r}_1(\lambda)$, $\bar{g}_1(\lambda)$, and $\bar{b}_1(\lambda)$ by using the following linear matrix transformation:

$$\begin{bmatrix} \bar{r}_2(\lambda) \\ \bar{g}_2(\lambda) \\ \bar{b}_2(\lambda) \end{bmatrix} = \begin{bmatrix} 0.7600 & 0.2851 & 0.0790 \\ 0.0874 & 1.2053 & -0.1627 \\ 0.0058 & -0.0742 & 0.9841 \end{bmatrix} \begin{bmatrix} \bar{r}_1(\lambda) \\ \bar{g}_1(\lambda) \\ \bar{b}_1(\lambda) \end{bmatrix} \tag{1.1}$$

As will be seen later, this type of matrix transformation is fundamental in color science, color signal processing, and color encoding.

CIE colorimetry

In 1931 the Commission Internationale de l'Éclairage (International Commission on Illumination), the *CIE*, adopted one set of color-matching functions to define a *Standard Colorimetric Observer* (Figure 1.17) whose color-matching characteristics are representative of those of the human population having normal color vision. Although the CIE could have used any set of color-matching functions,

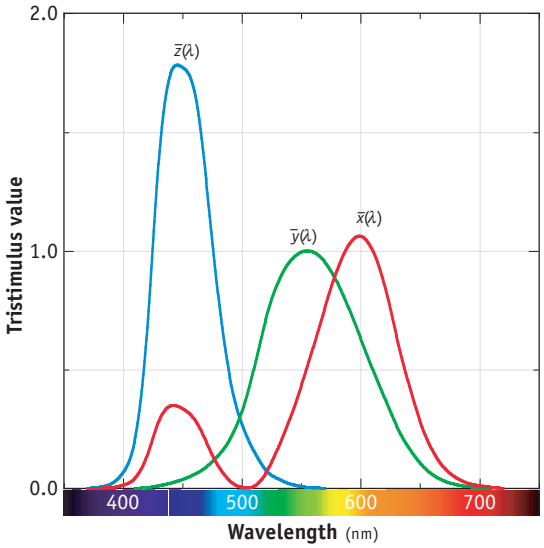

Figure 1.17 A set of color-matching functions adopted by the CIE to define a Standard Colorimetric Observer.

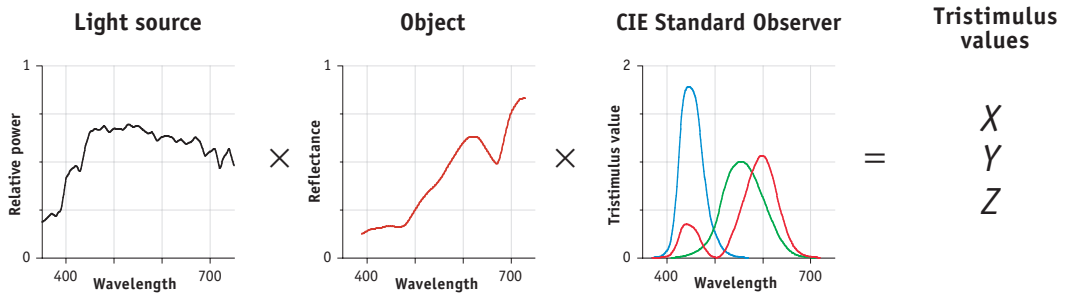

Figure 1.18 Calculation of CIE *XYZ* tristimulus values.

including a set equivalent to average ρ, γ, and β cone-response functions, this particular set was chosen for its mathematical properties.

The CIE Standard Colorimetric Observer color-matching functions are used in the calculation of *CIE tristimulus values* X, Y, and Z which quantify the trichromatic characteristics of color stimuli. The X, Y, and Z tristimulus values for a given object (characterized by its spectral reflectance or transmittance) that is illuminated by a light source (characterized by its spectral power distribution) can be calculated for the CIE Standard Colorimetric Observer (characterized by the CIE color-matching functions) by summing the products of these distributions over the wavelength (λ) range of 380 to 780 nm (usually at 5 nm intervals). This process is illustrated in Figure 1.18. The calculations of X, Y, and Z are shown in the following equations:

$$X = k \sum_{\lambda=380}^{780} S(\lambda)\, R(\lambda)\, \bar{x}(\lambda)$$
$$Y = k \sum_{\lambda=380}^{780} S(\lambda)\, R(\lambda)\, \bar{y}(\lambda) \qquad (1.2)$$
$$Z = k \sum_{\lambda=380}^{780} S(\lambda)\, R(\lambda)\, \bar{z}(\lambda)$$

where X, Y, and Z are CIE tristimulus values; $S(\lambda)$ is the spectral power distribution of a light source; $R(\lambda)$ is the spectral reflectance of a reflective object (or spectral transmittance of a transmissive object); $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$are the color-matching functions of the CIE Standard Colorimetric Observer; and k is a normalizing factor. By convention, k usually is determined such that $Y = 100$ when the object is a perfect white. A *perfect white* is an ideal, nonfluorescent, isotropic diffuser with a reflectance (or transmittance) equal to unity throughout the visible spectrum (Figure 1.19). *Isotropic* means that incident light is reflected (or transmitted) equally in all directions. The brightness of a perfect white therefore is independent of the direction of viewing.

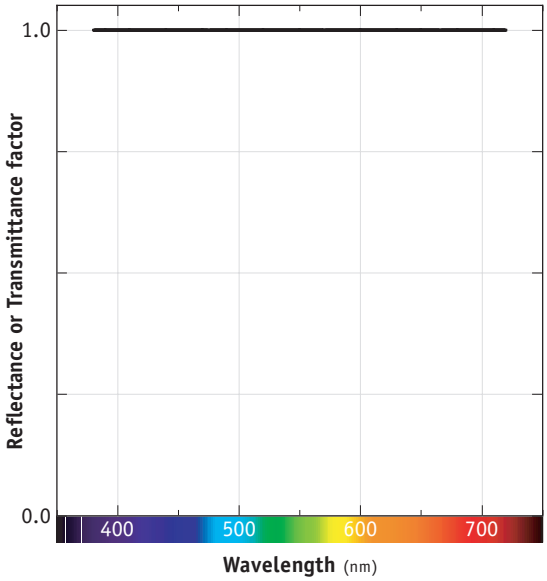

Figure 1.19 Spectral characteristic for a perfect white reflector or transmitter of light.

It was emphasized earlier that the color-matching functions for any set of physically realizable primaries will have negative values at some wavelengths. Yet the color-matching functions for the CIE Standard Colorimetric Observer (Figure 1.17) have *no* negative regions. This was accomplished by first defining a set of *imaginary* primaries and then determining the color-matching functions for those primaries. *Imaginary primaries* correspond to hypothetical illuminants having negative amounts of power at some wavelengths. For example, the imaginary "green" illuminant of Figure 1.20 has positive power in the green spectral region, but it has negative power in the blue and red regions.

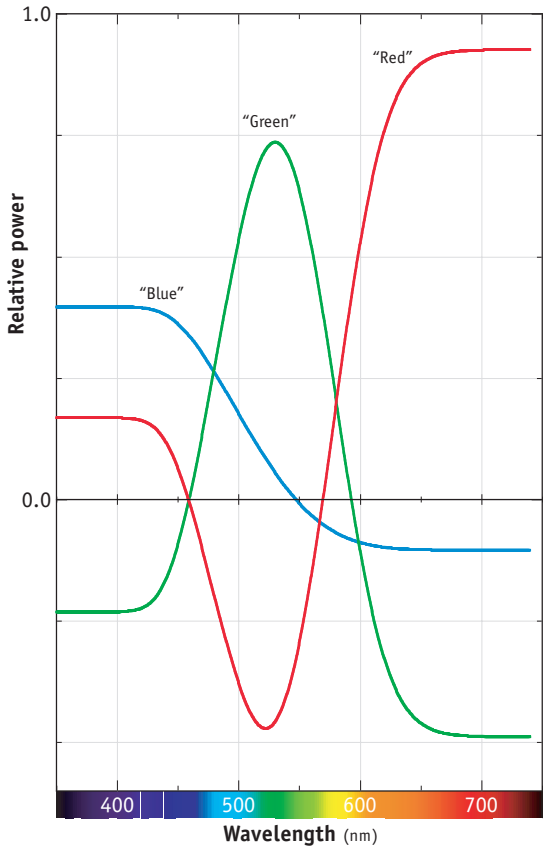

Figure 1.20 A set of spectral power distributions corresponding to a set of imaginary "red," "green," and "blue" primaries. Imaginary primaries correspond to hypothetical illuminants having negative amounts of power at some wavelengths.

While such primaries are not physically realizable, they nevertheless are very useful mathematical concepts. When they are chosen appropriately, their corresponding color-matching functions are positive at all wavelengths. Such functions are mathematically convenient because they eliminate negative values in the tristimulus calculations. (This may not seem very important today, but years ago people had to perform these calculations by hand!) Also, because the CIE Standard Colorimetric Observer color-matching functions are all positive, it is possible to construct instruments called *colorimeters*. The *spectral responsivities*—relative response to light as a function of wavelength—of a colorimeter directly correspond to the color-matching functions of the CIE Standard Colorimetric Observer. A colorimeter therefore can provide a direct measure of the CIE *XYZ* tristimulus values of a color stimulus.

Another operational convenience of the CIE color-matching functions is that the Y tristimulus value corresponds to the measurement of *luminance*. The measurement of luminance is of particular importance in color-imaging and color-encoding applications because luminance is an approximate correlate of one of the principal visual perceptions—the perception of *brightness*. When all other factors are equal, a stimulus having a higher measured luminance value will appear to be brighter than an otherwise identical stimulus having a lower measured luminance value.

Various mathematical normalizations, such as the scaling provided by the factor k in Equations (1.2), are performed in colorimetric computations. The following normalizations and definitions specifically relate to the measurement of luminance values:

- The normalization may be such that Y tristimulus values are evaluated on an absolute basis and expressed in units of luminance, typically candelas per square meter (cd/m^2). Such values are properly referred to as luminance values. However, throughout this book there will be certain instances when it is particularly important to emphasize that absolute, not relative, amounts of light are being referred to. In these instances, the somewhat

redundant expression *absolute luminance values* will be used to provide that emphasis.

- When the normalization is such that the Y tristimulus value for a perfect white object is 1.0, normalized Y values are called luminance-factor values.
- When the normalization is such that the Y tristimulus value for a perfect white object is 100, normalized Y values are called *percent luminance-factor values.*

Although the X and Z tristimulus values have no direct perceptual correlates, they are used in the calculation of tristimulus-value ratios called *chromaticity coordinates*. The chromaticity coordinates x, y, and z describe the qualities of a color stimulus apart from its luminance. They are derived from the tristimulus values as follows:

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z} \qquad (1.3)$$
$$z = \frac{Z}{X+Y+Z}$$

A plot of y versus x is called a *chromaticity diagram* (Figure 1.21a). The horseshoe-shaped outline is the *spectrum locus*, which is a line connecting the points representing the chromaticities of the spectrum colors. In the figure, the ends of the spectrum locus are connected by a straight line known as the *purple boundary*. The chromaticity coordinates of *all* physically realizable color stimuli lie within the area defined by the spectrum locus and the purple boundary.

Figure 1.21b shows the locations of the chromaticity coordinates of the real *RGB* primaries corresponding to the color-matching functions of Figure 1.14. The triangle formed by connecting those locations encloses the chromaticity coordinates of all color stimuli that can be matched using positive (including zero) amounts of those real primaries. Also indicated are the locations of the chromaticities of the imaginary *XYZ* primaries corresponding to the color-matching functions of the CIE Standard Colorimetric Observer. Note that the triangle formed by connecting those locations encloses the entire area defined by the spectrum locus and the purple boundary. That is why all real color stimuli can be matched using positive amounts of those imaginary primaries.

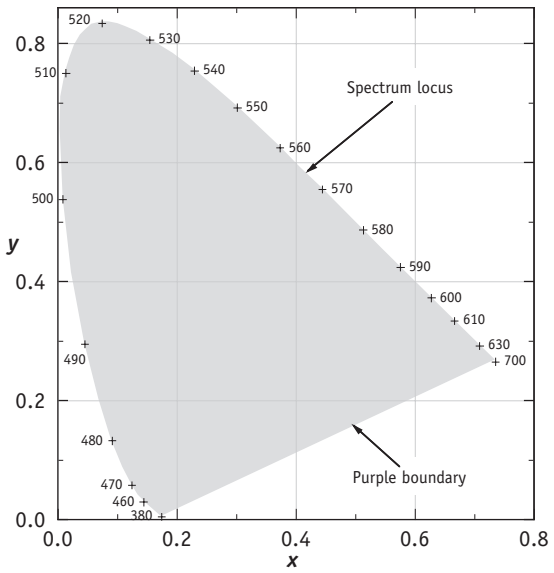

Figure 1.21a CIE x, y chromaticity diagram. The chromaticity coordinates define the qualities of a color stimulus apart from its luminance. The chromaticity coordinates of all physically realizable color stimuli lie within the area defined by the spectrum locus and the purple boundary.

The CIE also has recommended the use of other color-coordinate systems, derived from *XYZ* in which perceived differences among colors are represented more uniformly than they are on an x, y chromaticity diagram. These recommendations include the CIE 1976 u', v' Metric Chromaticity Coordinates and the CIE 1976 $L^*a^*b^*$ (CIELAB) and CIE 1976 $L^*u^*v^*$ (CIELUV) color spaces. (Refer to Appendix A for more details regarding these color spaces.)

All of the CIE coordinate systems are quite useful for specifying small color *differences* between color stimuli (CIE colorimetry was, in fact, developed specifically for that purpose), but it is essential to understand that *none of these systems specifies the appearance of those stimuli*. The reason for this will be discussed in Chapter 3. For now, the reader should

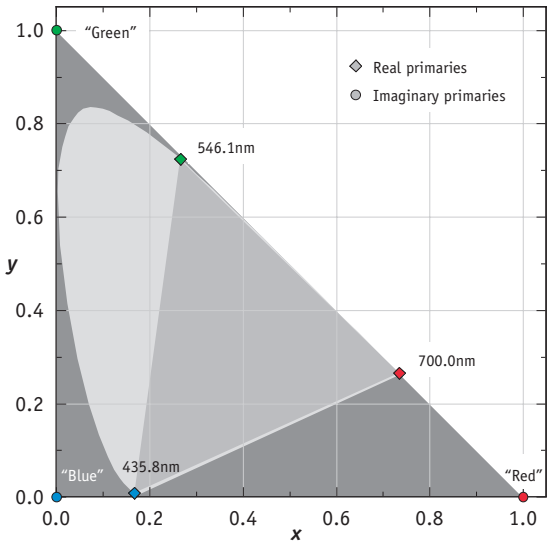

Figure 1.21b Chromaticity coordinates of the real primaries corresponding to the color-matching functions of Figure 1.14, and those of the imaginary primaries corresponding to the color-matching functions of Figure 1.17. The triangle formed by connecting the chromaticity coordinates of a set of primaries encloses the chromaticity coordinates of all color stimuli that can be matched using all-positive amounts of those primaries.

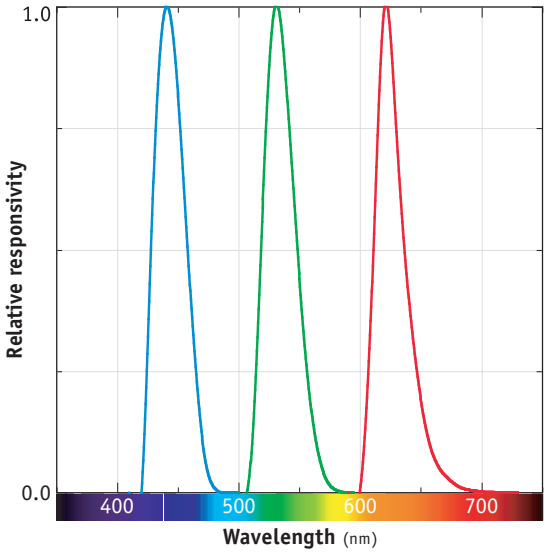

Figure 1.22a Red, green, and blue spectral responsivities for an ISO Status A densitometer.

be cautioned that this fact is commonly misunderstood and, as a consequence, CIE coordinate systems frequently are misinterpreted and misused as if they describe color appearance. The distinction between colorimetry and color appearance may seem subtle and of interest only to color scientists. In practice, however, failures to recognize that distinction have been responsible for the demise of numerous color-encoding methods, color-management systems, and entire color-imaging systems.

Other color measurements

In addition to CIE colorimetry, there are other types of color measurements that are relevant to color imaging and color encoding. Of particular importance in imaging applications involving hardcopy media is the measurement of *optical density*. Optical density values can be measured using instruments called *densitometers*. (Refer to Appendix B for more details regarding densitometers and densitometric measurements.)

Optical densities of color media generally are measured using three-channel (or sometimes four-channel) densitometers. The spectral responsivities for these instruments are defined by industry standards. Figure 1.22a, for example, shows the specified red, green, and blue spectral responsivities for an ISO Standard Status A densitometer.

Status A densitometers are widely used for measurements of photographic media and other types of hardcopy media that are meant to be viewed directly by an observer. That fact might seem to suggest that Status A density values must provide information equivalent to that provided by CIE colorimetric values, but that is not the case. Status A spectral responsivities do not correspond to those of a CIE Standard Observer, as shown in Figure 1.22b, or to any other set of visual color-matching functions. As a result, two spectrally different objects that metamerically match under a particular illuminant (i.e., their stimuli have the same CIE *XYZ* values) are unlikely to have matched red, green, and blue Status A values.

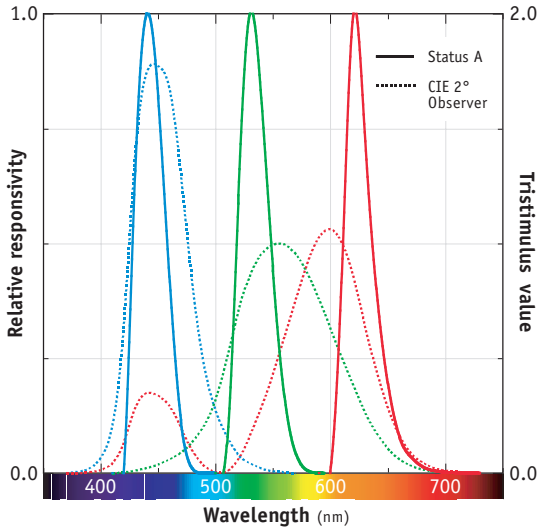

Figure 1.22b Comparison of ISO Status A spectral responsivities to the color-matching functions of the CIE Standard Colorimetric Observer (normalized to equal area).

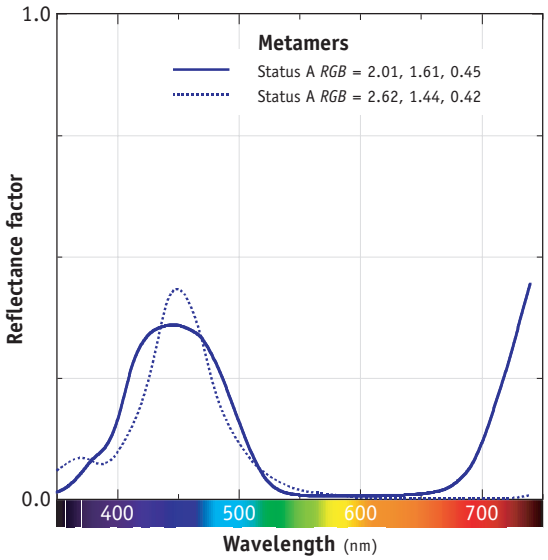

Figure 1.23 Spectral reflectances of two objects that metamerically match under a particular illuminant but that have very different *RGB* Status A density values.

For example, Figure 1.23 shows the spectral reflectances of two objects. Although these objects metamerically match under a particular illuminant, their red, green, and blue Status A density values *differ* by −0.61, 0.17, and 0.03 respectively. The converse also is true: a pair of objects having the same red, green, and blue Status A values is unlikely to be a metameric pair. Figure 1.24 shows the spectral reflectances of two different objects. While these objects have identical Status A densities, their X, Y, and Z tristimulus values, under a particular illuminant, differ by 15.7, 14.6, and −0.8 respectively.

Film scanners and reflection scanners (Figure 1.25) are used for color measurement of hardcopy input images on digital color-imaging systems. While various sets of red, green, and blue spectral responsivities are used in different types of color scanners, those responsivities seldom correspond to a set of color-matching functions. Most scanners, therefore, essentially are *densitometers*; they are *not* colorimeters. As will be shown later, that is a critical distinction that must be taken into account in the digital encoding of scanned colors.

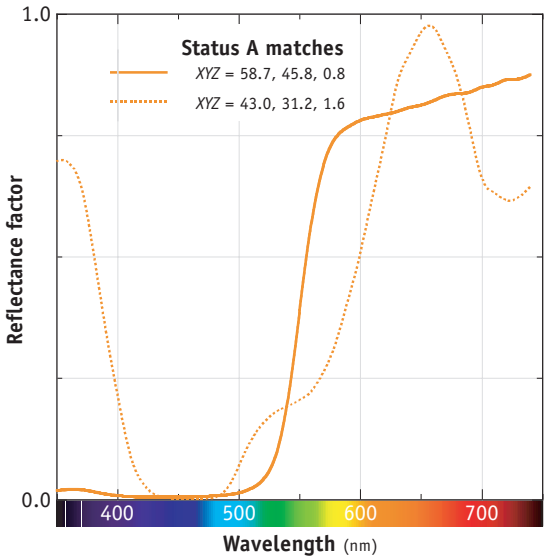

Figure 1.24 Spectral reflectances of two objects that have identical *RGB* Status A density values but that do not match metamerically.

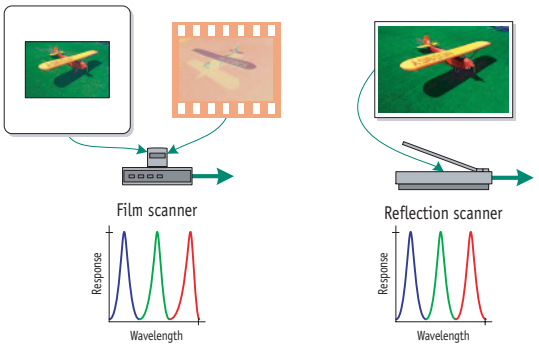

Figure 1.25 A film scanner and a reflection scanner. The spectral responsivities of most scanners do not correspond to a set of color-matching functions. Therefore, most scanners are densitometers, not colorimeters.

Stimuli produced by self-luminous display devices, such as CRTs, often are measured in terms of light intensity. Three-channel instruments, which are somewhat similar to densitometers, can make simultaneous readings of red-light, green-light, and blue-light intensities. Various types of single-channel instruments also can be used in the measurement of self-luminous displays. When such instruments are used, separate red-light, green-light, and blue-light readings can be made by sequentially sending individual red, green, and blue signals to the display device that is to be measured.

Summary of key issues

- All vision is a response to light.
- Light sources are characterized by their spectral power distributions.
- Objects are characterized by their spectral reflectances or transmittances.
- Color stimuli generally are produced by a light source and an object; stimuli are characterized by their spectral power distributions.
- Scenes and images are collections of individual color stimuli.
- Human color vision is trichromatic.
- Metameric color stimuli differ spectrally but match in appearance.
- CIE colorimetry allows the prediction of metameric matching between color stimuli; metameric colors have the same CIE *XYZ* tristimulus values.
- CIE colorimetry was developed for specifying the trichromatic properties of color stimuli.
- CIE colorimetric values can indicate how much the appearance of two stimuli will differ, if the differences in their trichromatic properties are sufficiently small.
- CIE colorimetric values such as CIE *XYZ* tristimulus values, CIE $L^*a^*b^*$ values, and CIE $L^*u^*v^*$ values do not describe color appearance.
- Densitometers are used to measure the optical densities of hardcopy media. Their spectral responsivities do not correspond to any set of visual color-matching functions.
- A colorimeter directly measures CIE *XYZ* tristimulus values.
- Most image scanners essentially are densitometers and not colorimeters; their spectral responsivities generally do not correspond to any set of visual color-matching functions.