B

Densitometry

Throughout this book, the word *density* refers specifically to optical density. Optical density measurements and density-measuring devices (densitometers) are important in color imaging for several reasons: most forms of color encoding are based directly or indirectly on density readings; most input and output devices are calibrated using density measurements; and most reflection and transmission scanners essentially are densitometers.

Figure B.1 illustrates the basic concept of optical density measurement. A densitometer consists of a light source, a means for inserting a sample to be measured, a photodetector, an amplifier, and some type of analog or digital density-value indicator. Density readings are made by measuring the amount of light with and without the sample in place.

For transmissive samples, the transmission density is determined from the transmittance factor of the sample. The transmittance factor, T, is the ratio of the amount of light transmitted, I_t, measured with the sample in place, to the amount of incident light, I_i, measured without the sample (Figure B.2). The transmission density, D_t, of the sample is the negative logarithm of its transmittance factor:

$$T = \frac{I_t}{I_i} \tag{B.1a}$$

$$D_t = \log_{10}\left(\frac{1}{T}\right) \quad \text{or} \quad -\log_{10} T \tag{B.1b}$$

The following examples may help to illustrate the basic relationships of sample transmission characteristics, measured transmittance factor, and computed transmission density:

- If a sample were a perfect transmitter, the amount of incident and transmitted light would be equal, the measured transmittance factor would be 1.00, and the computed transmission density of the sample would be zero.
- If a sample were perfectly opaque, the amount of transmitted light would be zero, the measured transmittance factor would be zero, and the computed transmission density would be infinite.
- If a sample transmitted one-quarter of the incident light, the measured transmittance factor would be 0.25, and the computed transmission density would be $-\log_{10}(0.25)$ or 0.602.

Reflection samples are measured similarly (Figure B.3). The ratio of the amount of light reflected by a sample, I_r, relative to that reflected by a perfect diffuse reflector, I_{ref}, is the reflectance factor, R. Reflection density, D_r, is the negative logarithm of the reflectance factor:

$$R = \frac{I_r}{I_{\text{ref}}} \tag{B.2a}$$

$$D_r = \log_{10}\left(\frac{1}{R}\right) \text{ or } -\log_{10} R \tag{B.2b}$$

Digital Color Management: Encoding Solutions, Second Edition Edward J. Giorgianni and Thomas E. Madden

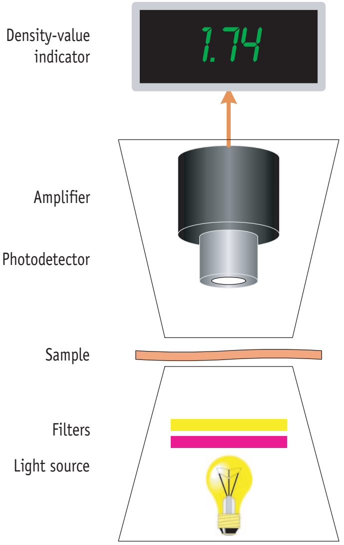

Figure B.1 Components of a basic optical densitometer.

The concept of density is quite straightforward for samples that are spectrally nonselective, i.e., samples that transmit (or reflect) light equally at all wavelengths of interest (Figure B.4). Since the transmittance or reflectance—and therefore the density—of

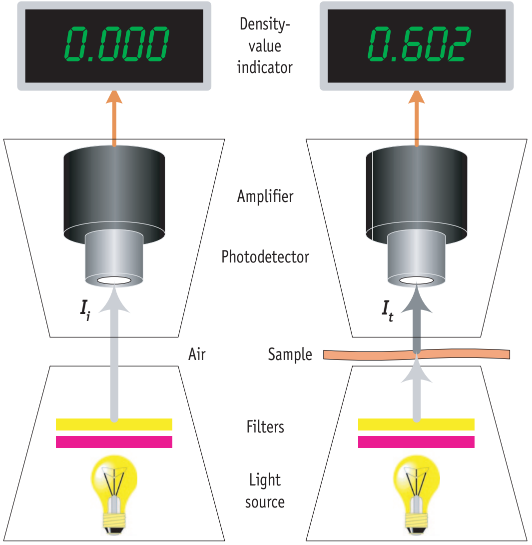

Figure B.2 Measurement of transmission density.

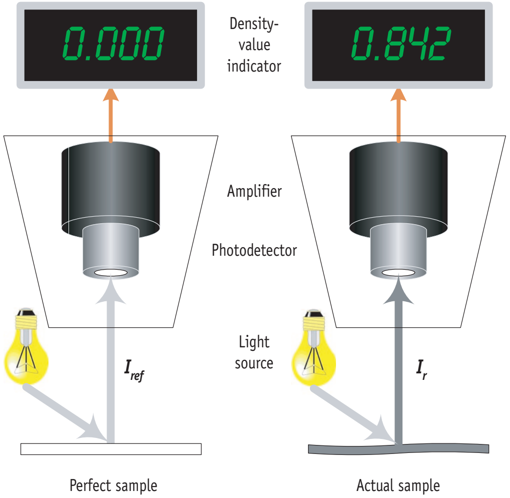

Figure B.3 Measurement of reflection density.

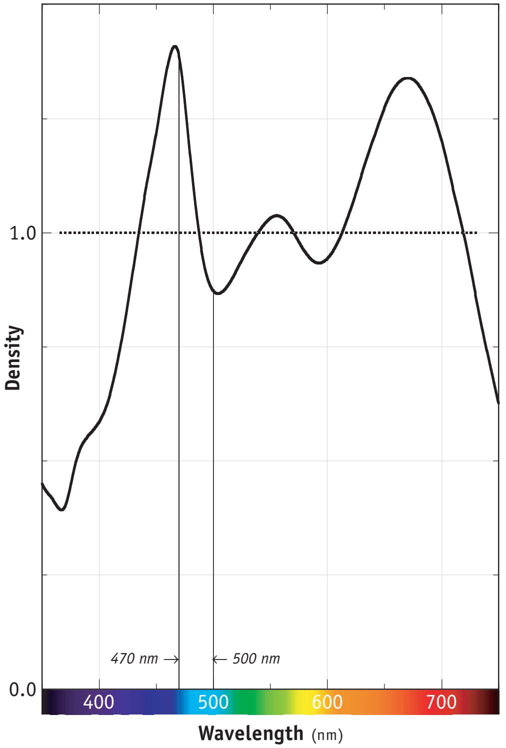

Figure B.4 This spectrally selective sample (solid line) has a density of 1.39 at 470 nm, but a density of only 0.87 at 500 nm. A spectrally nonselective sample, such as the one shown by the dotted line, has equal densities at all wavelengths of interest.

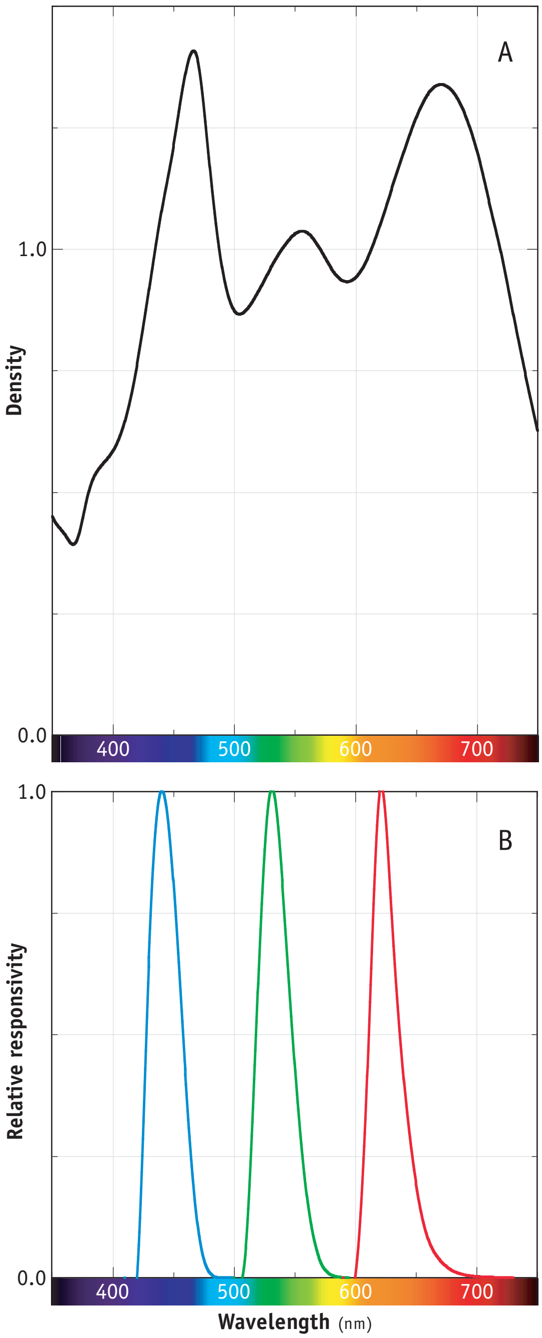

Figure B.5 A spectrally selective sample and a set of red, green, and blue spectral responsivities. The sample (A) has RGB density values of 1.10, 0.97, and 1.11 when measured by a densitometer having the RGB responsivities shown in B.

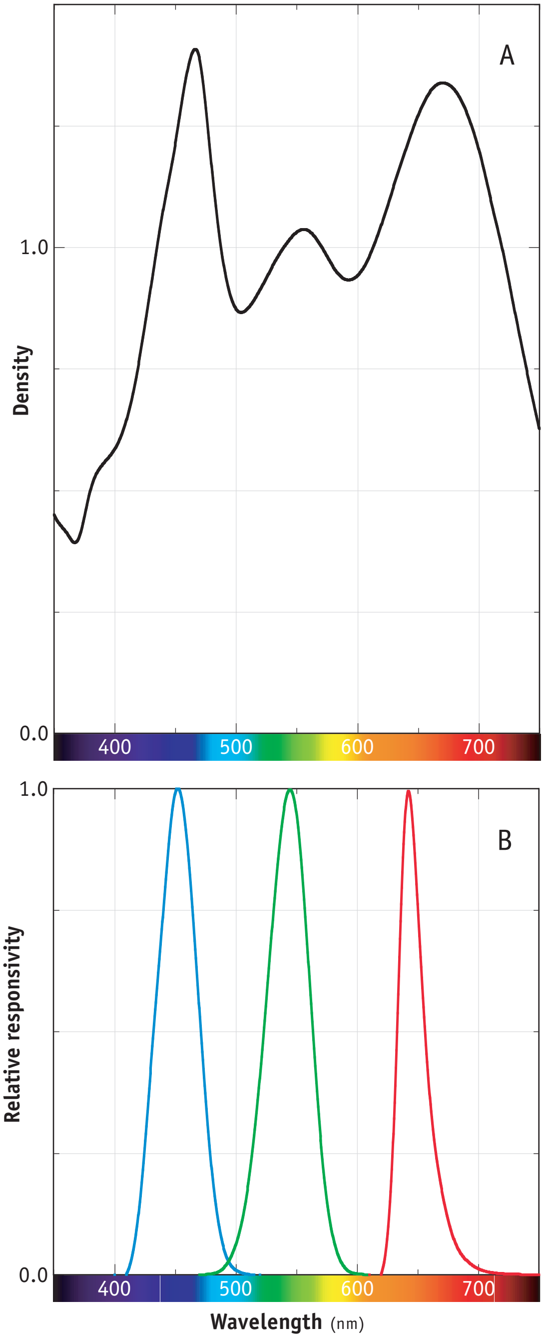

Figure B.6 A spectrally selective sample, identical to that shown in Figure B.5, and a different set of red, green, and blue spectral responsivities. The sample (A) has RGB density values of 1.24, 1.00, and 1.16 when measured by a densitometer having the RGB responsivities shown in B.

such samples is the same at every wavelength, it will not matter which wavelengths are used in their measurement.

In imaging applications, however, samples generally are made up of dyes, inks, or pigments that are spectrally selective, like the selective sample also shown in Figure B.4. When the density of a sample varies with wavelength, it no longer can be said that the sample has a particular density unless the spectral characteristics of the measurement also are specified. For example, the spectrally selective sample in Figure B.4 has a density of 1.39 if measured at 470 nm, but it has a density of only 0.87 if measured at 500 nm.

For color measurements, red, green, and blue densities generally are measured. But, again, the spectral characteristics of those measurements must be specified. For example, in Figure B.5, the sample has *RGB* densities of 1.10, 0.97, and 1.10 respectively when measured using a densitometer having the spectral responsivities shown. In Figure B.6, the same sample has RGB densities of 1.24, 1.00, and 1.16 respectively when measured using a densitometer having somewhat different spectral responsivities.

In this book, several different types of density measurements, based on different spectral responsivities, are used: visual densities; ISO Status A *and* Status M densities; scanner densities; and printing densities.

Visual densities, which are used throughout the book to express grayscale characteristics, are measured according to a responsivity equivalent to the CIE *XYZ* $\bar{y}(\lambda)$ function (Figure B.7). This measurement yields the CIE *XYZ* *Y* tristimulus value, and visual density, D_v, is computed from that value as follows:

$$D_v = -\log_{10}\left(\frac{Y}{100}\right) \tag{B.3}$$

Status A densities are measured using the red, green, and blue responsivities specified by the International Organization for Standardization (ISO) for Status A densitometers (Figure B.8). Status A densitometers are used in measuring photographic reflection prints and slides and other types of imaging media that are designed to be viewed directly. Note, however, that these responsivities are spectrally narrow. They were not designed to correspond to visual sensitivities; they were determined such that each channel primarily measures just one image-forming dye. The blue channel primarily measures the relative amount of yellow dye. Similarly, the green channel primarily measures the relative amount of magenta dye, and the red channel primarily measures the relative amount of cyan dye. This type of measurement is useful for monitoring media manufacturing operations and subsequent image-forming processes.

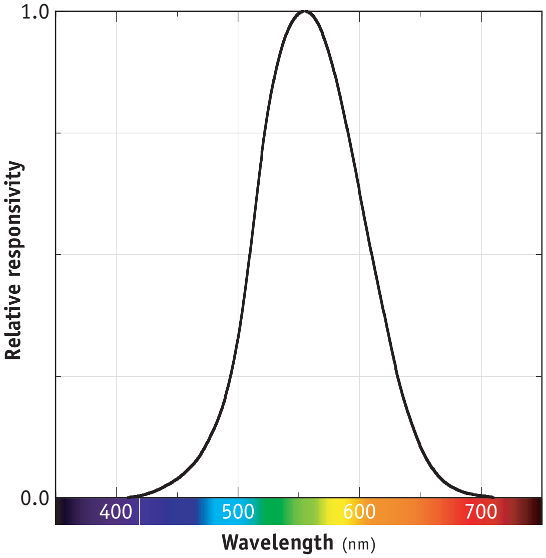

Figure B.7 The CIE *XYZ* $\bar{y}(\lambda)$ function, sometimes called the spectral luminous efficiency function, $V(\lambda)$.

Status M densities are measured using the red, green, and blue responsivities specified by the ISO for Status M densitometers (Figure B.9). Status M densitometers are used in measuring photographic negative media. Like those of Status A densitometers, the responsivities of Status M densitometers are spectrally narrow so that each channel primarily measures just one image-forming dye. Status M measurements are useful for monitoring negative-film manufacturing operations and subsequent chemical processing.

Scanner densities are densities measured by an input scanner having a particular set of *effective spectral responsivities*, *ESR* (λ). The effective responsivities are the product of the spectral sensitivity of the sensor and the spectral characteristics of any

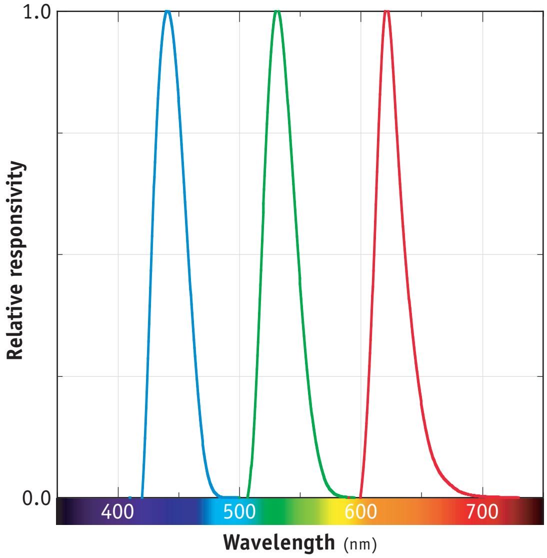

Figure B.8 Spectral responsivities for an ISO Status A densitometer.

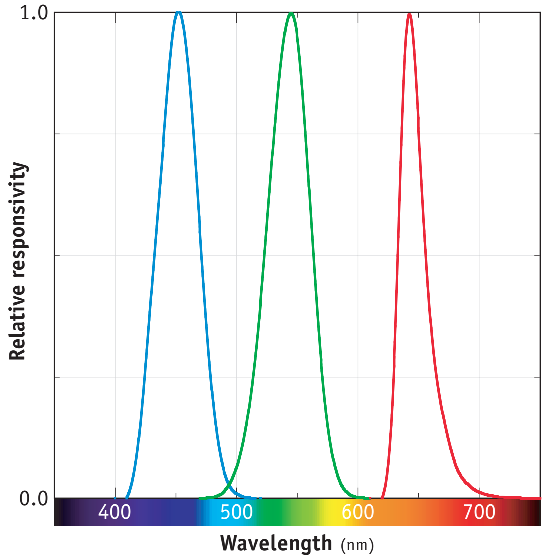

Figure B.9 Spectral responsivities for an ISO Status M densitometer.

components in the optical chain that contribute to the overall spectral responses. These components include the scanner light source, lenses, mirrors, and filters. For example, the effective responsivity for one of the color channels of a scanner would be

$$ESR(\lambda) = S(\lambda)\,M(\lambda)\,L(\lambda)\,F(\lambda)\,SS(\lambda) \qquad \text{(B.4)}$$

where $ESR(\lambda)$ is the effective responsivity of the channel, $S(\lambda)$ is the spectral power distribution of the scanner light source, $M(\lambda)$ is the spectral reflectance of a mirror, $L(\lambda)$ is the spectral transmittance of a lens, $F(\lambda)$ is the spectral transmittance of a filter (or a series of filters) in the optical path of the particular color channel, and $SS(\lambda)$ is the spectral sensitivity of the sensor.

Printing densities are the densities that would be measured by a real or computational densitometric device having effective spectral responsivities equivalent to those of a particular photographic print medium and a specified printer. These effective responsivities are the product of the spectral sensitivity of the print medium and the spectral characteristics of any components in the printer that contribute to the overall spectral responses, such as the printer light source, lenses, mirrors, and filters. For example, the effective red spectral responsivity would be

$$ESR_r(\lambda) = S(\lambda)\,M(\lambda)\,L(\lambda)\,F(\lambda)\,SS_r(\lambda) \qquad \text{(B.5)}$$

where $ESR_r(\lambda)$ is the red-channel effective responsivity, $S(\lambda)$ is the spectral power distribution of the printer light source, $M(\lambda)$ is the spectral reflectance of a mirror in the printer optics, $L(\lambda)$ is the spectral transmittance of the printer lens, $F(\lambda)$ is the spectral transmittance of a filter (or a series of filters) in the optical path of the particular color channel, and $SS_r(\lambda)$ is the red spectral sensitivity of the print medium.

The red transmittance factor T_r, for a sample having the spectral transmittance measured according to the red-channel effective spectral responsivity, can be calculated as follows:

$$T_r = k_r \sum_{\lambda} T(\lambda)\,ESR_r(\lambda) \qquad \text{(B.6)}$$

where k_r is a normalizing factor, determined such that $T_r = 1.00$ when the sample is a perfect transmitter. The red printing density, PD_r, of the sample

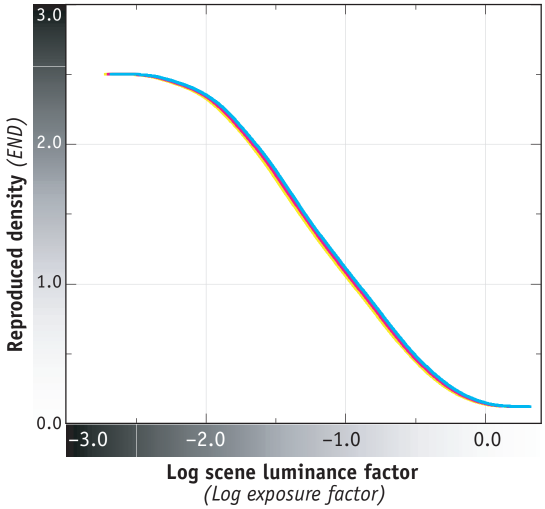

Figure B.10 The equal equivalent neutral density (END) values of the cyan, magenta, and yellow colorants of this grayscale indicate that the grayscale is colorimetrically neutral throughout its exposure range.

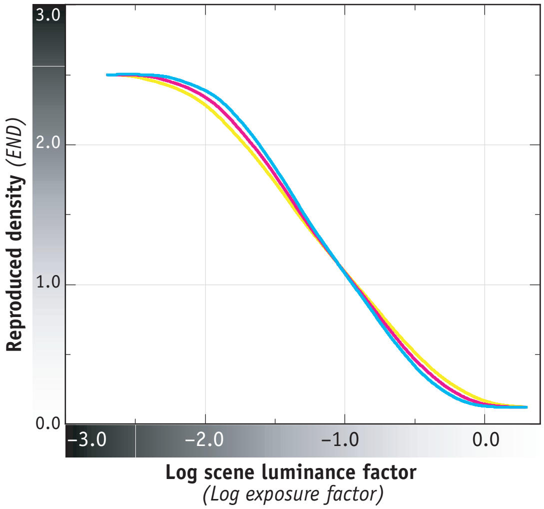

Figure B.11 The unequal equivalent neutral density (END) values of the cyan, magenta, and yellow colorants of this grayscale indicate that the grayscale is not colorimetrically neutral throughout its exposure range. The grayscale is colorimetrically cyan-blue at lower exposure levels and colorimetrically yellow-red at higher exposure levels.

then can be calculated as follows:

$$PD_r = -\log_{10}(T_r) \tag{B.7}$$

Green and blue effective responsivities, transmittance factors, and printing-density values can be calculated similarly.

Equivalent neutral densities (ENDs) are a measure of the relative amounts of the colorants of a medium. Throughout this book, grayscales or color scales plotted in terms of cyan, magenta, and yellow densities are expressed in terms of END values. The END value of a given amount of one colorant is the visual density that would result if the appropriate amounts of the other colorants were added such that a colorimetric neutral is formed, based on a specified viewing illuminant. In Figure B.10, for example, the cyan, magenta, and yellow END values are equal to each other throughout the grayscale characteristic curve. This means that at every exposure level, each corresponding dye amount has just the right amounts of the other two dyes to form a colorimetric neutral, which indicates that the grayscale is colorimetrically neutral throughout its exposure range. In Figure B.11, the unequal END values of the cyan, magenta, and yellow scales indicate that the grayscale is not colorimetrically neutral at every exposure level. At higher exposures, the comparatively high yellow and low cyan END values indicate that the grayscale is colorimetrically yellow-red in that region. At lower exposures, the comparatively high cyan and low yellow END values indicate that the grayscale is colorimetrically cyan-blue in that region. As discussed in Chapter 7, in some situations it can be preferable for a grayscale not to be colorimetrically neutral and thus to have unequal END values.