UNIVERSITÀ DEGLI STUDI DI TRIESTE

Color image processing

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Introduction

Humans can discern thousands of color shades, compared to only about two dozen shades of gray.

Color image processing is divided into two major areas: *pseudo-* and *full-color* processing.

In the first category, the issue is one of assigning color(s) to a particular grayscale intensity or range of intensities.

In the second, images typically are acquired using a full-color sensor, such as a digital camera, or color scanner.

Color fundamentals

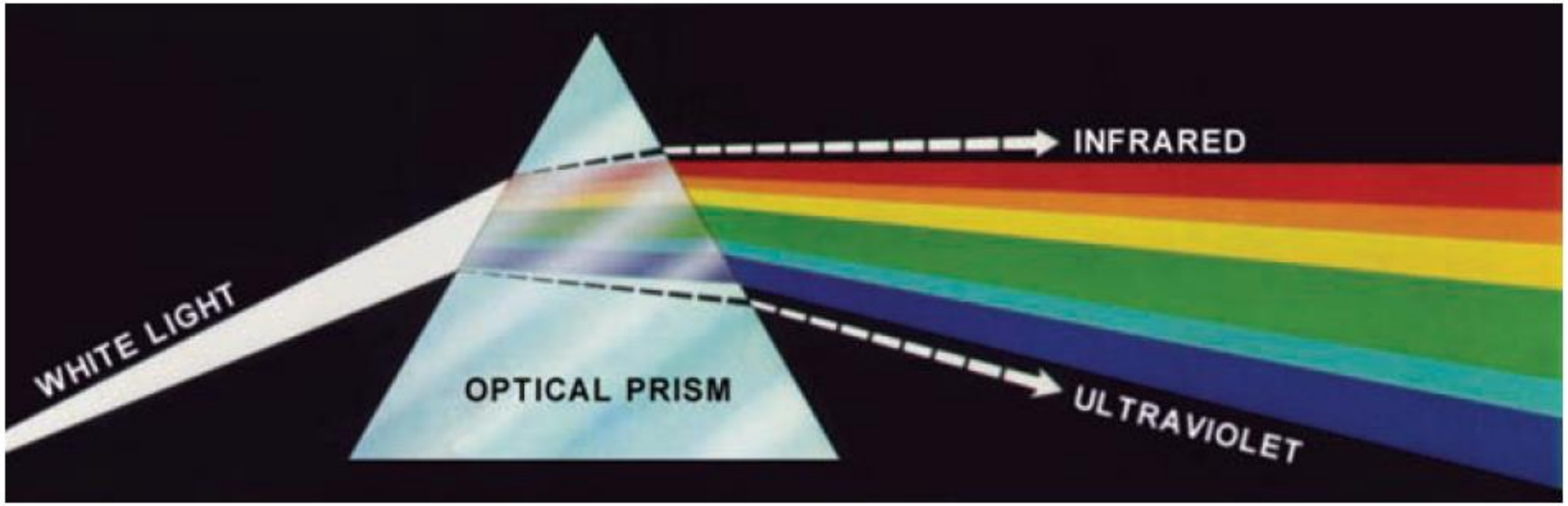
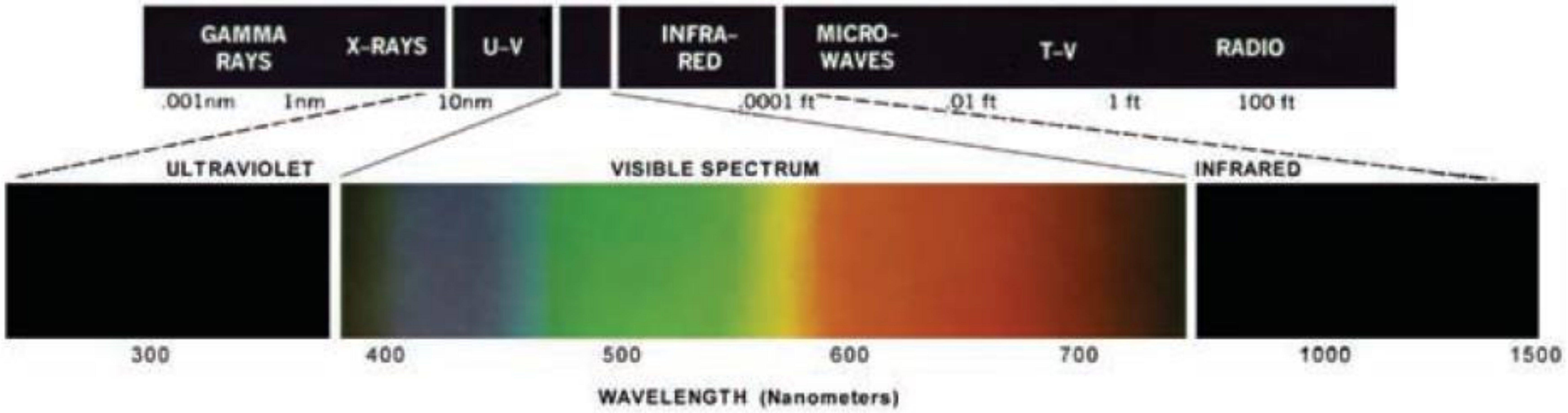


FIGURE 6.1
Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lighting Division.)

Color fundamentals

FIGURE 6.2
Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lighting Division.)



Color fundamentals

If the light is *achromatic* (void of color), its only attribute is its intensity.

The term *gray* (or *intensity*) *level* refers to a scalar measure of intensity that ranges from black, to grays, and finally to white.

Chromatic light spans the electromagnetic spectrum from approximately 400 to 700 nm.

Three basic quantities used to describe the quality of a chromatic light source are: **radiance**, **luminance**, and **brightness**.

Radiance is the total amount of energy that flows from the light source, and it is usually measured in watts (W).

Luminance, measured in lumens (lm), is a measure of the amount of energy that an observer perceives from a light source.

Brightness is a subjective descriptor that is practically impossible to measure. It embodies the achromatic notion of intensity, and is one of the key factors in describing color sensation.

Color fundamentals

Cones are the sensors in the eye responsible for color vision.

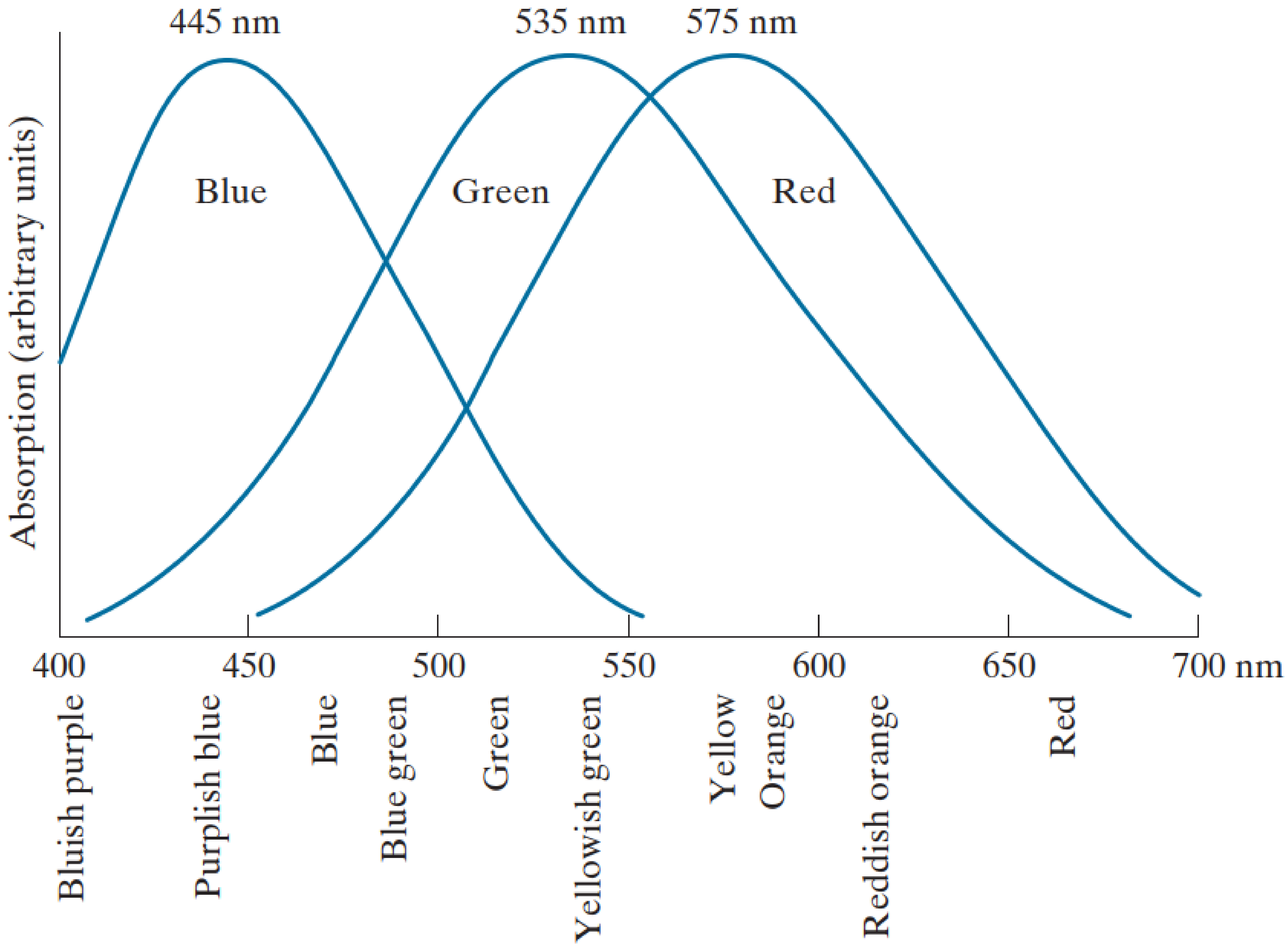
Detailed experimental evidence has established that the 6 to 7 million cones in the human eye can be divided into three principal sensing categories, corresponding roughly to red, green, and blue.

Approximately 65% of all cones are sensitive to red light, 33% are sensitive to green light, and only about 2% are sensitive to blue. However, the blue cones are the most sensitive.

Because of these absorption characteristics, the human eye sees colors as variable combinations of the so-called primary colors: red (R), green (G), and blue (B).

Color fundamentals

FIGURE 6.3
Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.



Color fundamentals

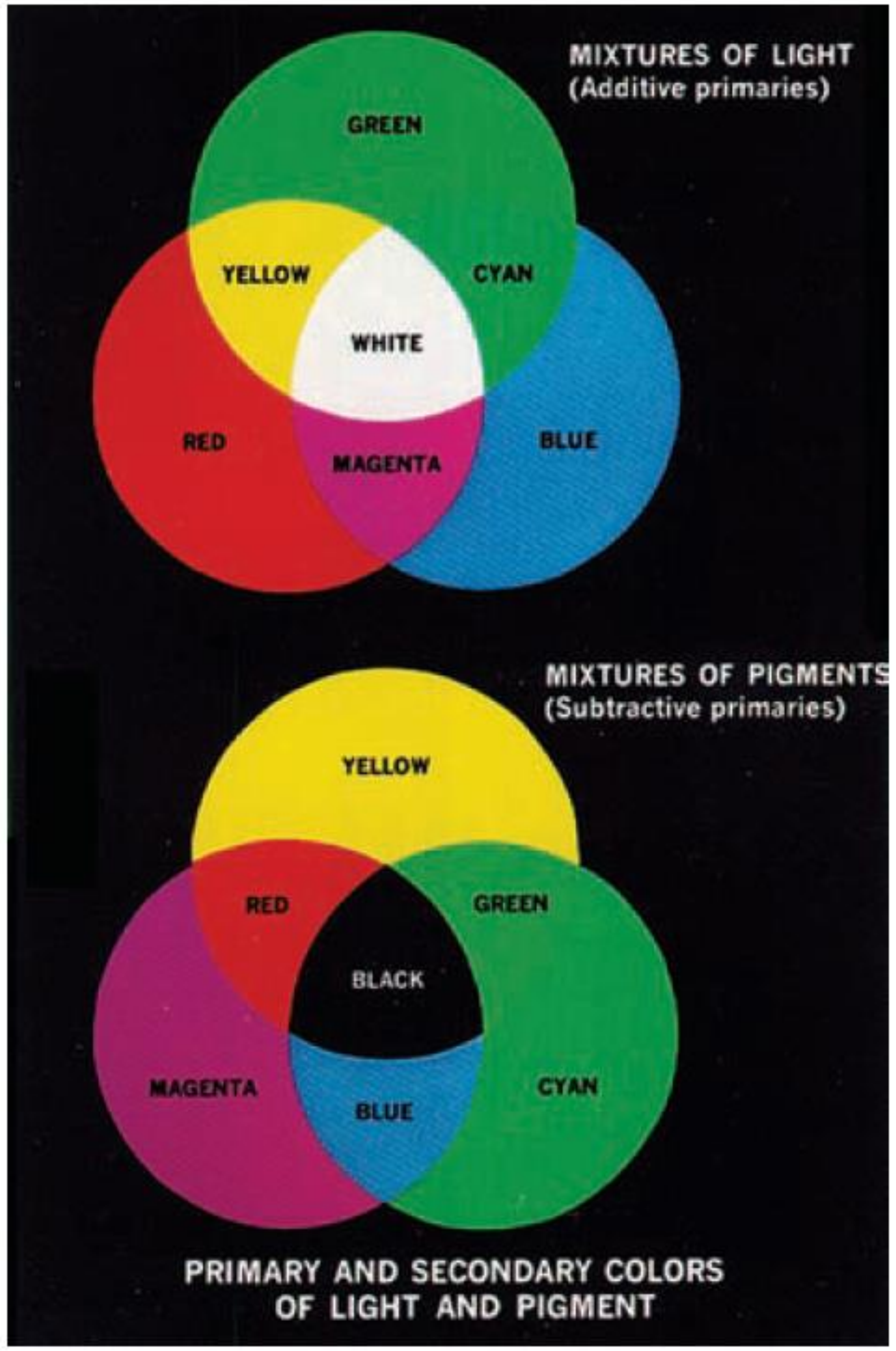
For the purpose of standardization, the CIE (Commission Internationale de l’Eclairage—the International Commission on Illumination) designated in 1931 the following specific wavelength values to the three primary colors: blue = 435.8 nm, green = 546.1 nm, and red = 700 nm.

It is **important to keep in mind that** defining three specific primary color wavelengths for the purpose of standardization **does not mean** that **these three** fixed **RGB components** acting alone **can generate all spectrum colors**.

Color fundamentals

a
b

FIGURE 6.4 Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lighting Division.)



Color fundamentals

The characteristics generally used to distinguish one color from another are **brightness**, **hue**, and **saturation**.

Brightness we have seen embodies the achromatic notion of intensity.

Hue is an attribute associated with the dominant wavelength in a mixture of light waves.

Hue represents dominant color as perceived by an observer.

Saturation refers to the relative purity or the amount of white light mixed with a hue.

The pure spectrum colors are fully saturated. Colors such as pink (red and white) and lavender (violet and white) are less saturated, with the degree of saturation being inversely proportional to the amount of white light added.

Hue and saturation taken together are called **chromaticity** and, therefore, a color may be characterized by its brightness and chromaticity.

Color fundamentals

The amounts of red, green, and blue needed to form any particular color are called the **tristimulus** values, and are denoted, X, Y, and Z, respectively.

A color is then specified by its **trichromatic coefficients**, defined as

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

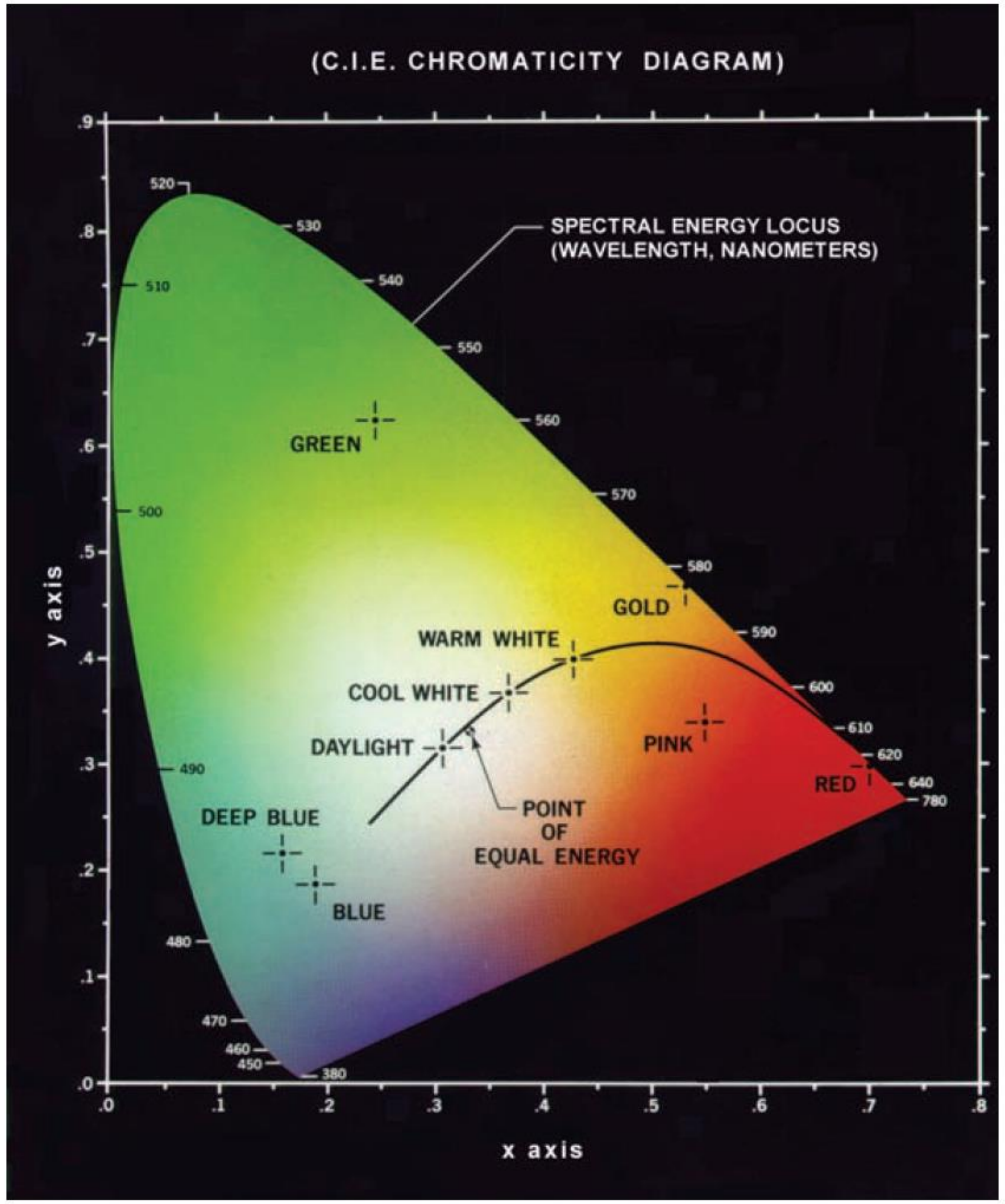
$$x + y + z = 1$$

For any wavelength of light in the visible spectrum, the tristimulus values needed to produce the color corresponding to that wavelength can be obtained directly from curves or tables that have been compiled from extensive experimental results.

Another approach for specifying colors is to use the **CIE chromaticity diagram**, which shows color composition as a function of x (red) and y (green).

Color fundamentals

FIGURE 6.5
The CIE chromaticity diagram. (Courtesy of the General Electric Co., Lighting Division.)



Color fundamentals

For any value of x and y, the corresponding value of z (blue) is $z = 1 - (x + y)$.

The positions of the various spectrum colors—from violet at 380 nm to red at 780 nm—are indicated around the boundary of the tongue-shaped chromaticity diagram.

Any point not actually on the boundary, but within the diagram, represents some mixture of the pure spectrum colors.

The point of equal energy corresponds to equal fractions of the three primary colors; it represents the CIE standard for white light.

Any point located on the boundary of the chromaticity chart is fully saturated.

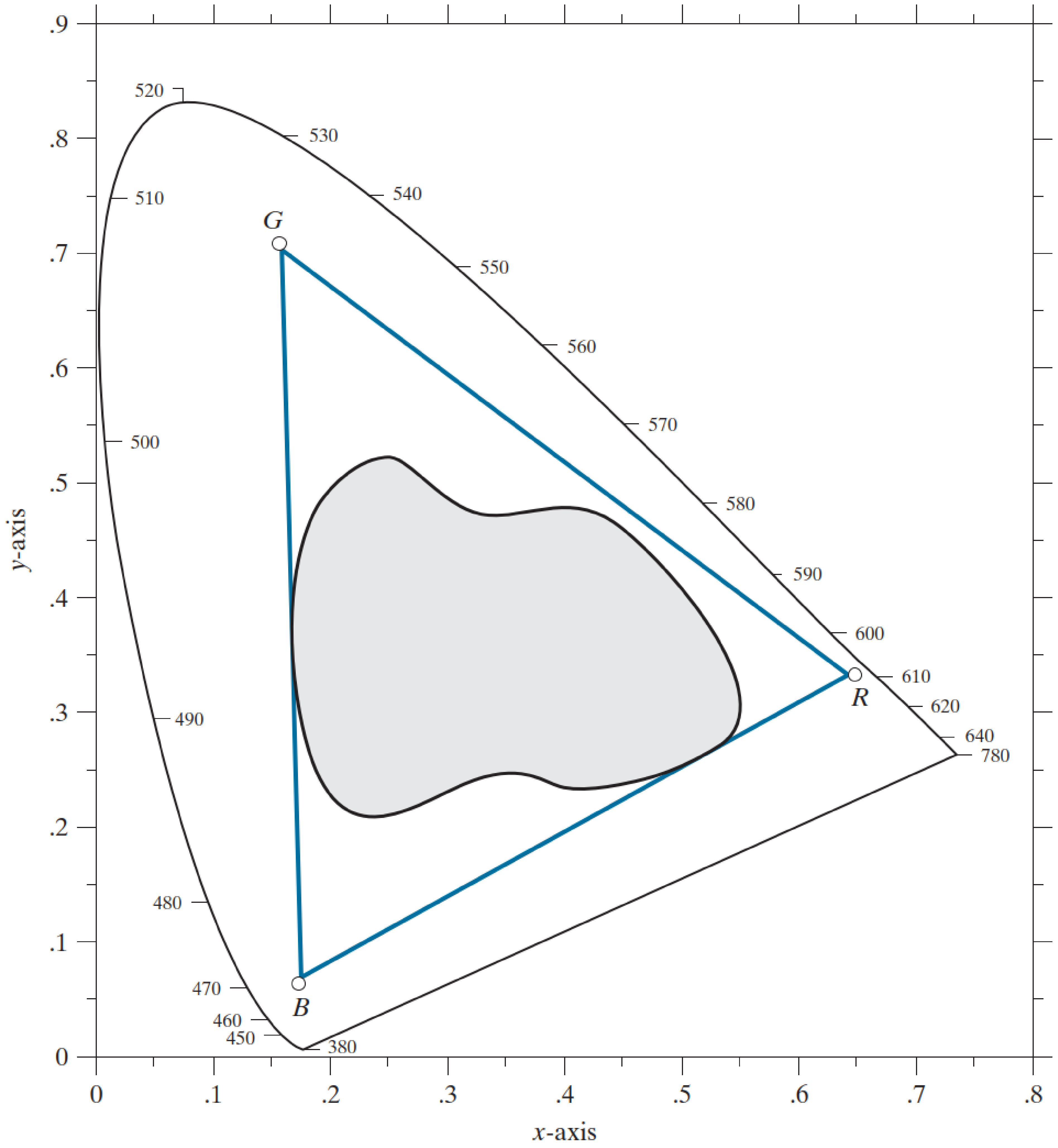
As a point leaves the boundary and approaches the point of equal energy, more white light is added to the color, and it becomes less saturated.

The saturation at the point of equal energy is zero.

The chromaticity diagram is useful for color mixing because a straight-line segment joining any two points in the diagram defines all the different color variations that can be obtained by combining these two colors additively.

Color fundamentals

FIGURE 6.6
Illustrative color gamut of color monitors (triangle) and color printing devices (shaded region).



Color models

The purpose of a color model (also called a color space or color system) is to facilitate the specification of colors in some standard way.

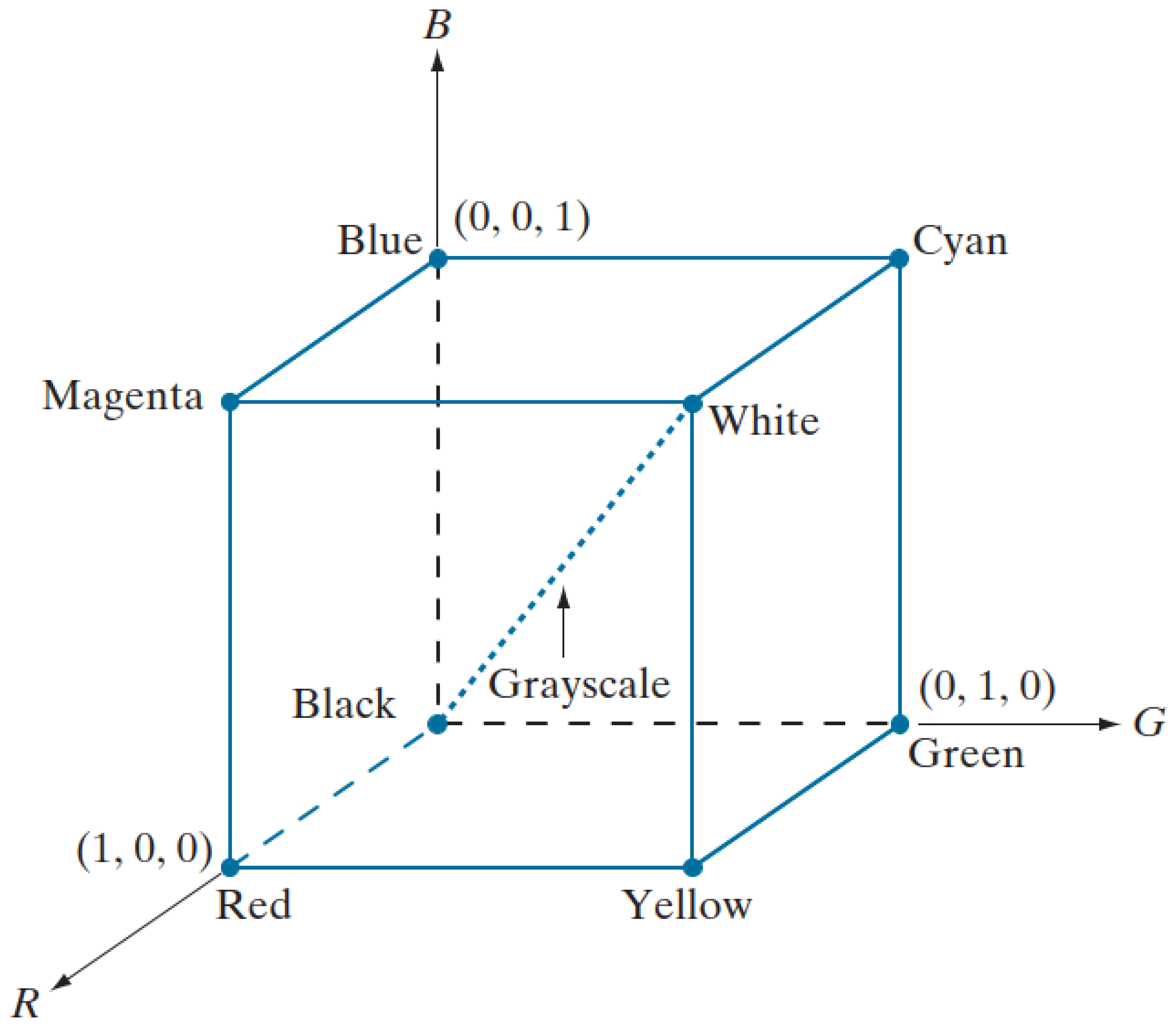
A color model is a specification of **(1)** a **coordinate system**, and **(2)** a **subspace** within that system, such that each color in the model is represented by a single point contained in that subspace.

Most color models in use today are oriented either toward hardware or toward applications, where color manipulation is a goal.

The hardware-oriented models most commonly used in practice are the **RGB** (red, green, blue) model for color monitors and a broad class of color video cameras; the **CMY (cyan, magenta, yellow)** and **CMYK (cyan, magenta, yellow, black)** models for color printing; and the **HSI (hue, saturation, intensity)** model, which corresponds closely with the way humans describe and interpret color.

Color models: RGB model

FIGURE 6.7 Schematic of the RGB color cube. Points along the main diagonal have gray values, from black at the origin to white at point (1, 1, 1).



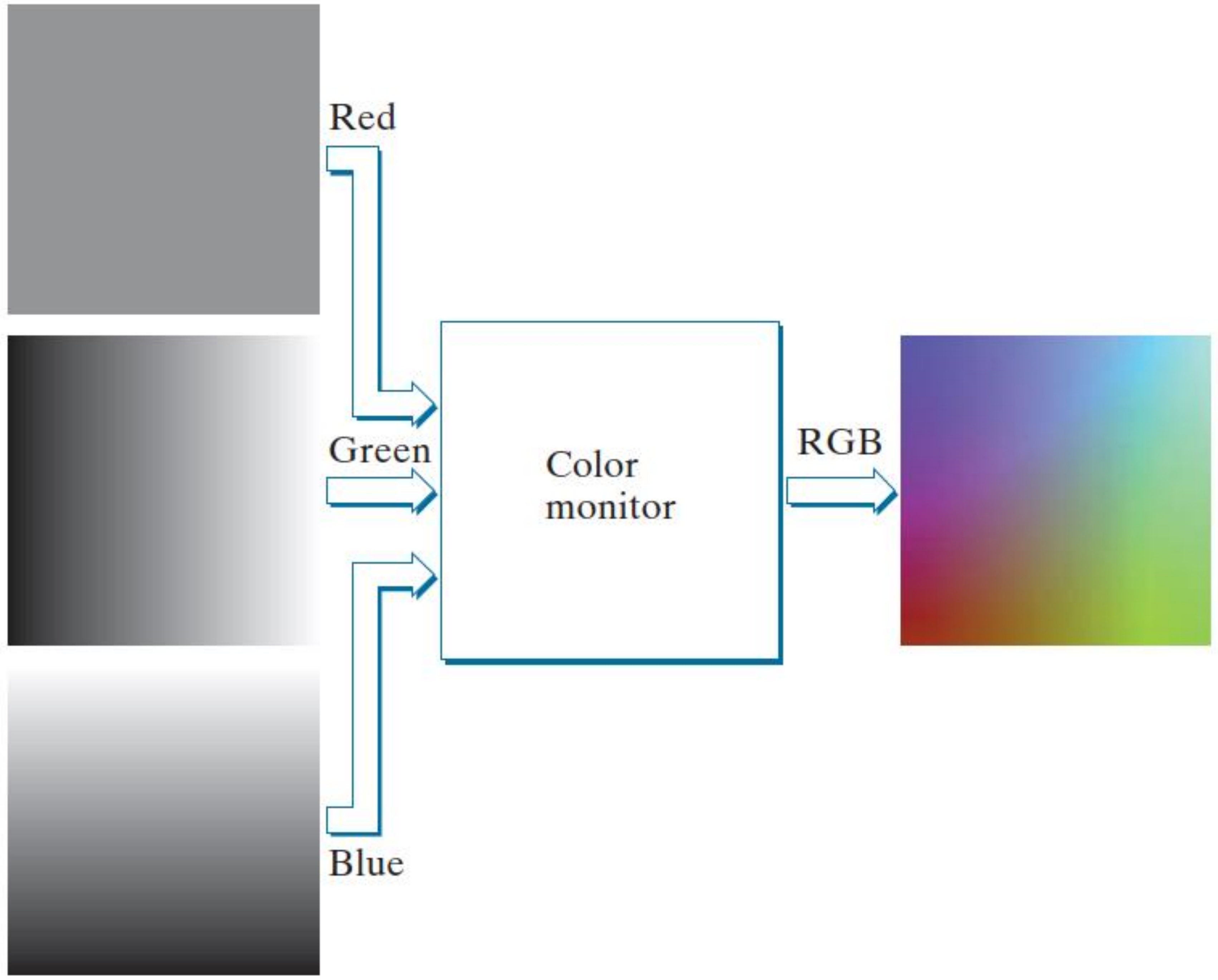
Color models: RGB model

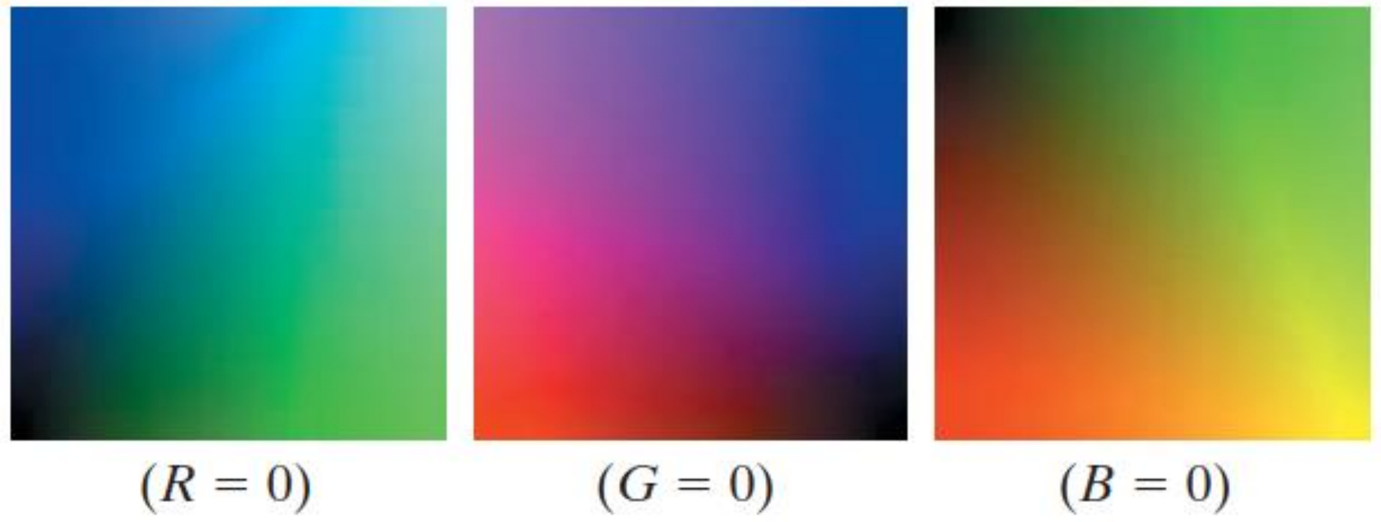
FIGURE 6.8
A 24-bit RGB color cube.

Color models: RGB model

a
b

FIGURE 6.9
(a) Generating the RGB image of the cross-sectional color plane (127, G, B).
(b) The three hidden surface planes in the color cube of Fig. 6.8.





Color models: CMY and CMYK models

Conversion from RGB to CMY:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Conversion for RGB to CMYK:

$$K = \min(C, M, Y)$$

If $K = 1$,

$$C = 0$$

$$M = 0$$

$$Y = 0$$

Otherwise,

$$C = (C - K)/(1 - K)$$

$$M = (M - K)/(1 - K)$$

$$Y = (Y - K)/(1 - K)$$

Color models: HSI color model

When humans view a color object, we describe it by its hue, saturation, and brightness.

Brightness is a subjective descriptor that is practically impossible to measure. It embodies the achromatic notion of intensity. This quantity definitely is measurable and easily interpretable.

The **HSI (hue, saturation, intensity) color model**, decouples the intensity component from the color-carrying information (hue and saturation) in a color image.

As a result, the HSI model is a useful tool for developing image processing algorithms based on color descriptions that are natural and intuitive to humans, who, after all, are the developers and users of these algorithms.

Color models: HSI color model

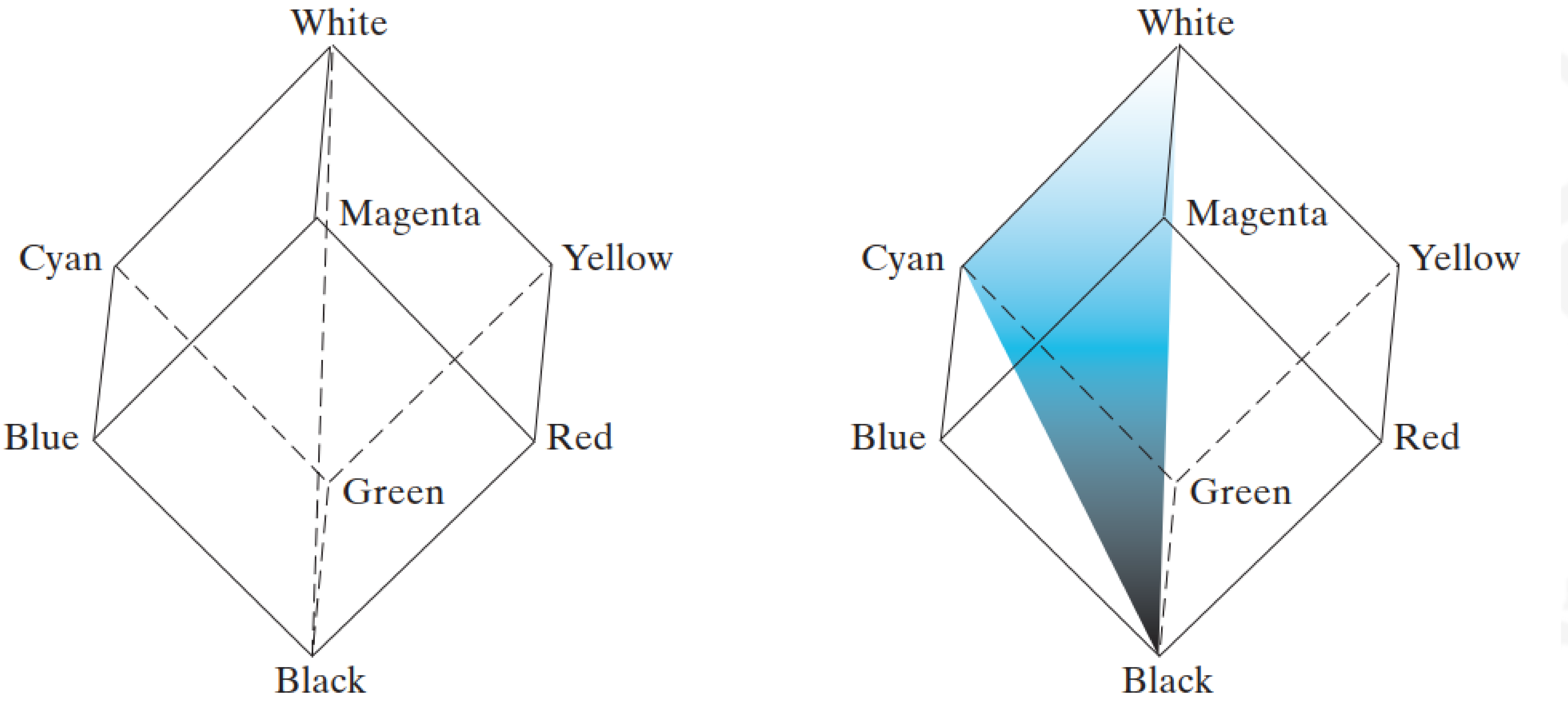


FIGURE 6.10 Conceptual relationships between the RGB and HSI color models.

Color models: HSI color model

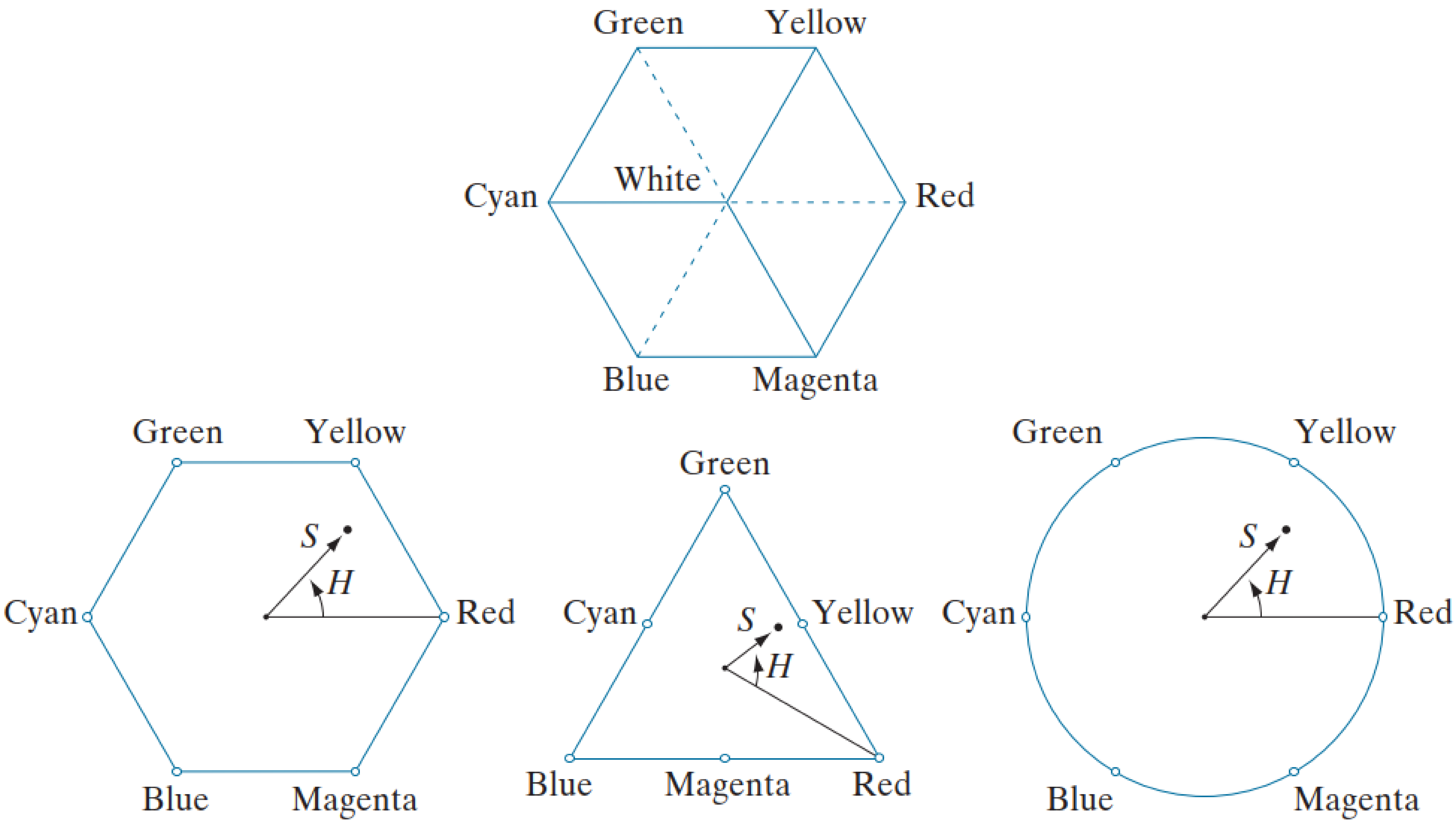
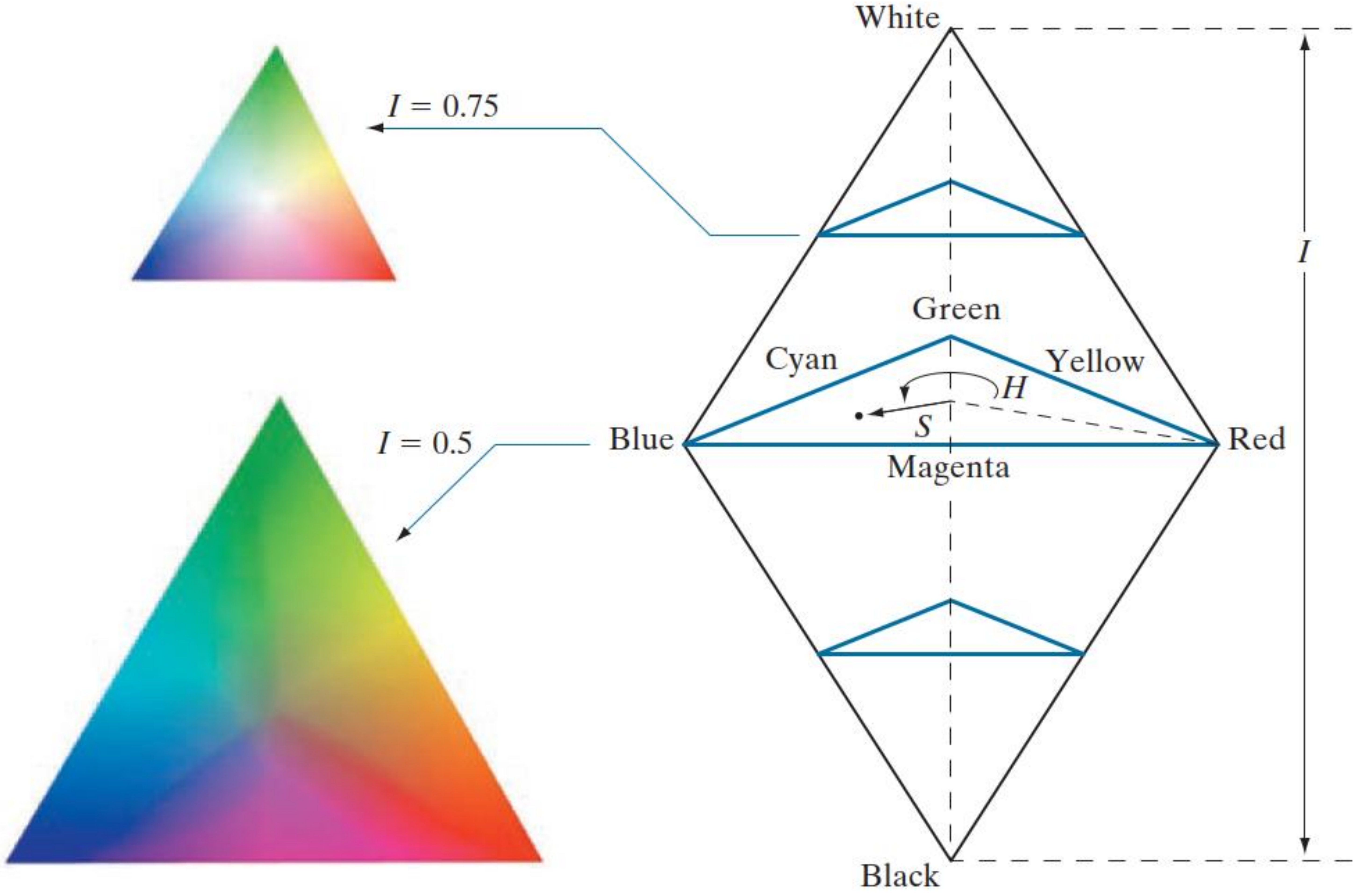


FIGURE 6.11 Hue and saturation in the HSI color model. The dot is any color point. The angle from the red axis gives the hue. The length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.

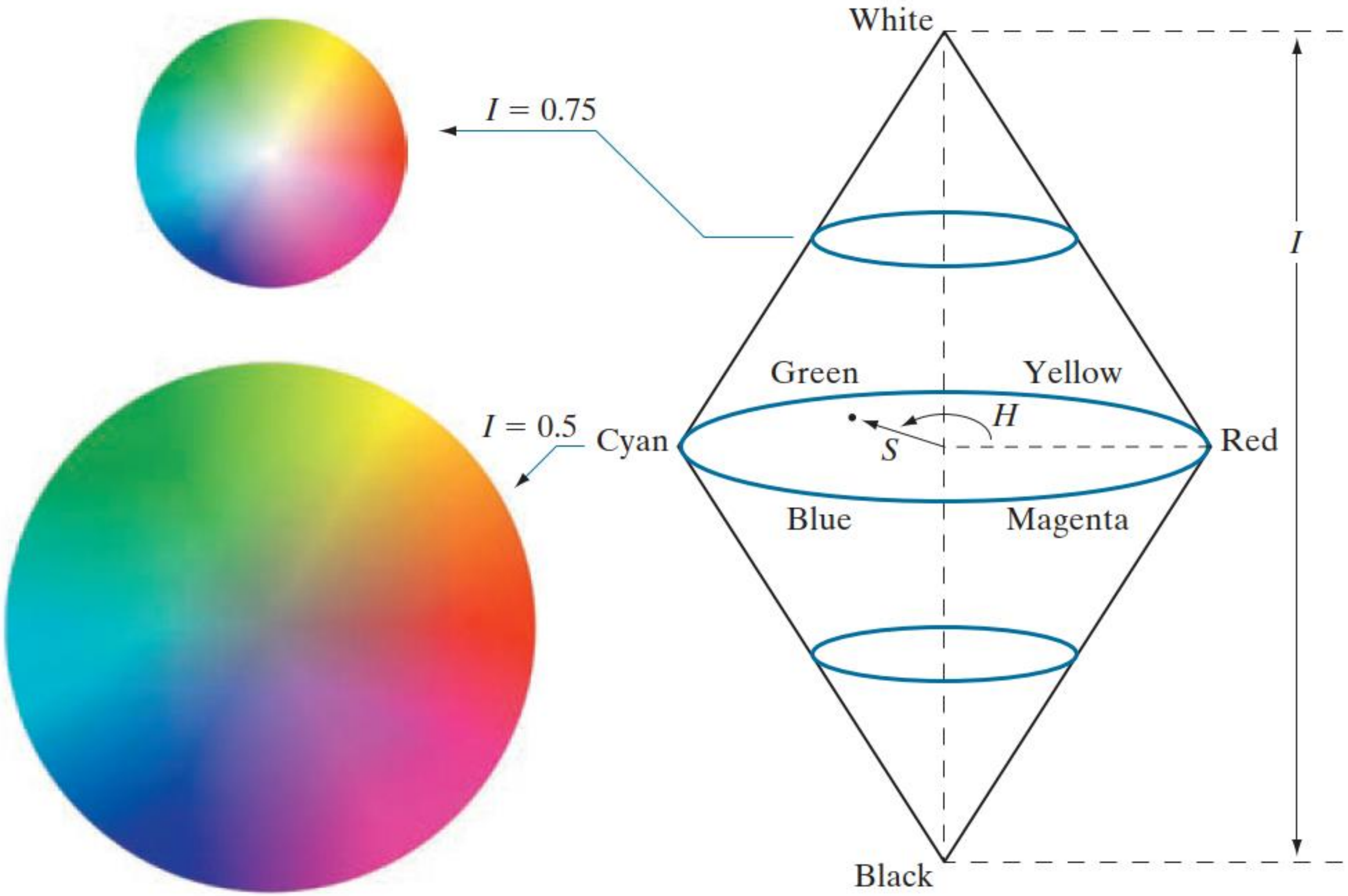
Color models: HSI color model



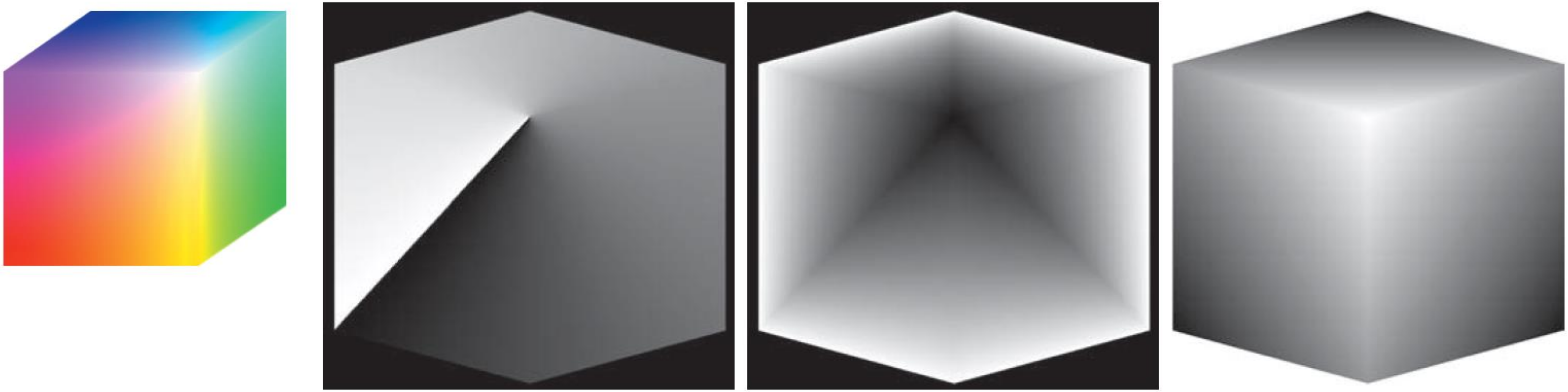
a
b

FIGURE 6.12
The HSI color model based on (a) triangular, and (b) circular color planes. The triangles and circles are perpendicular to the vertical intensity axis.

Color models: HSI color model



Color models: HSI color model



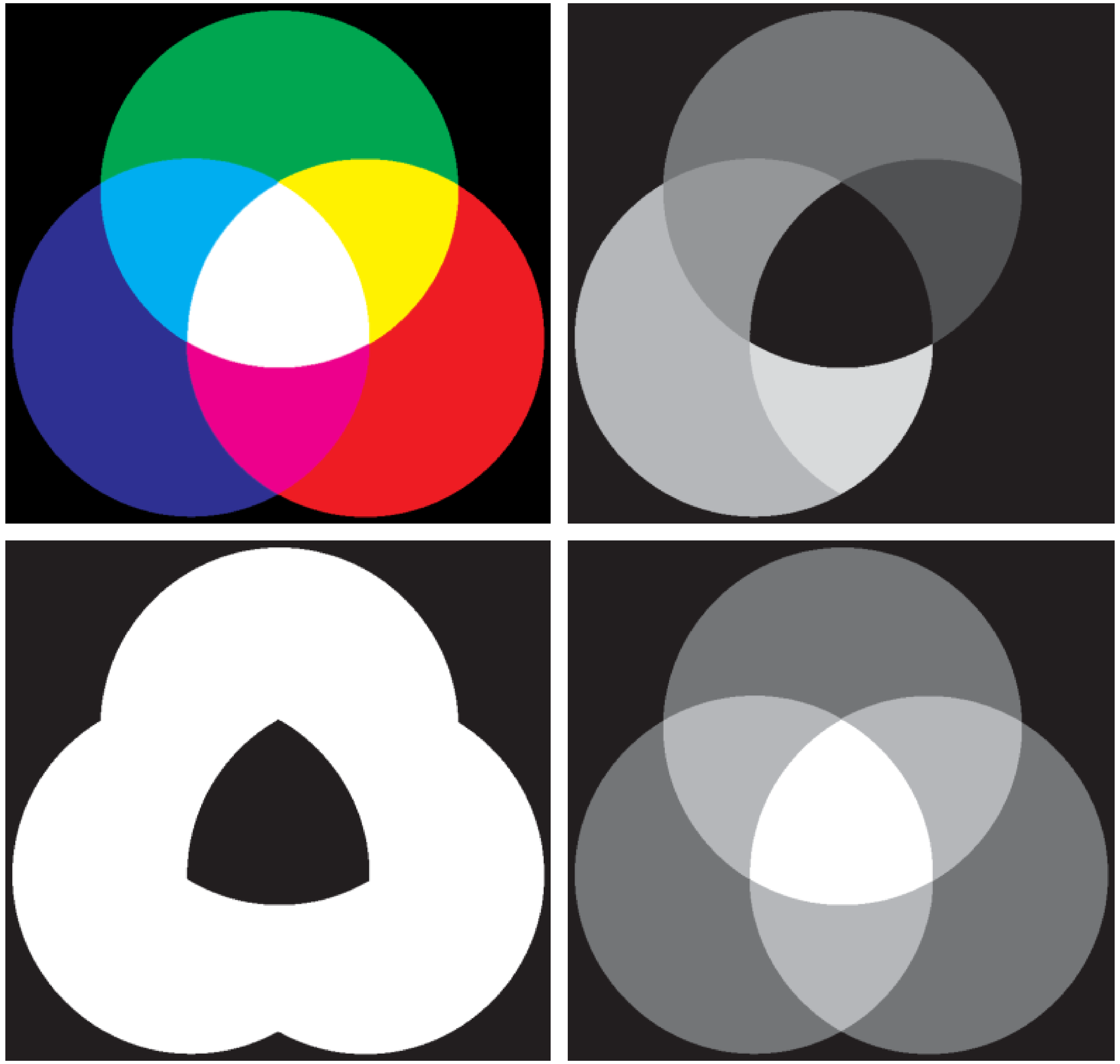
a b c

FIGURE 6.13 HSI components of the image in Fig. 6.8: (a) hue, (b) saturation, and (c) intensity images.

Color models: HSI color model

a	b
c	d

FIGURE 6.14
(a) RGB image and the components of its corresponding HSI image:
(b) hue,
(c) saturation, and
(d) intensity.



Pseudocolor image processing

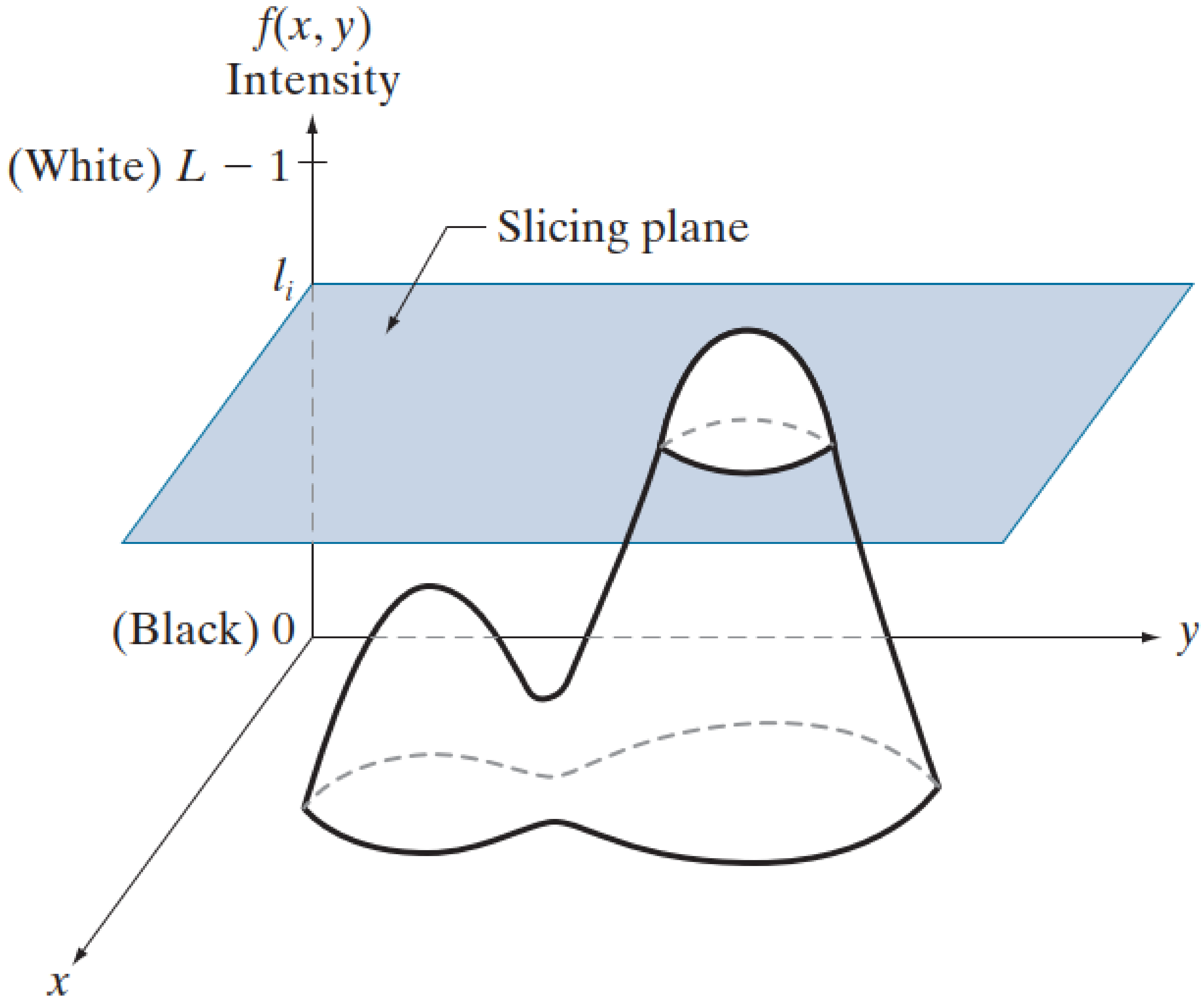
Pseudocolor (sometimes called **false color**) image processing consists of assigning colors to gray values based on a specified criterion.

The term pseudo or false color is used to differentiate the process of assigning colors to achromatic images from the processes associated with true color images.

The principal use of pseudocolor is for human visualization and interpretation of grayscale events in an image or sequence of images.

Intensity slicing

FIGURE 6.16
Graphical interpretation of the intensity-slicing technique.



Intensity slicing

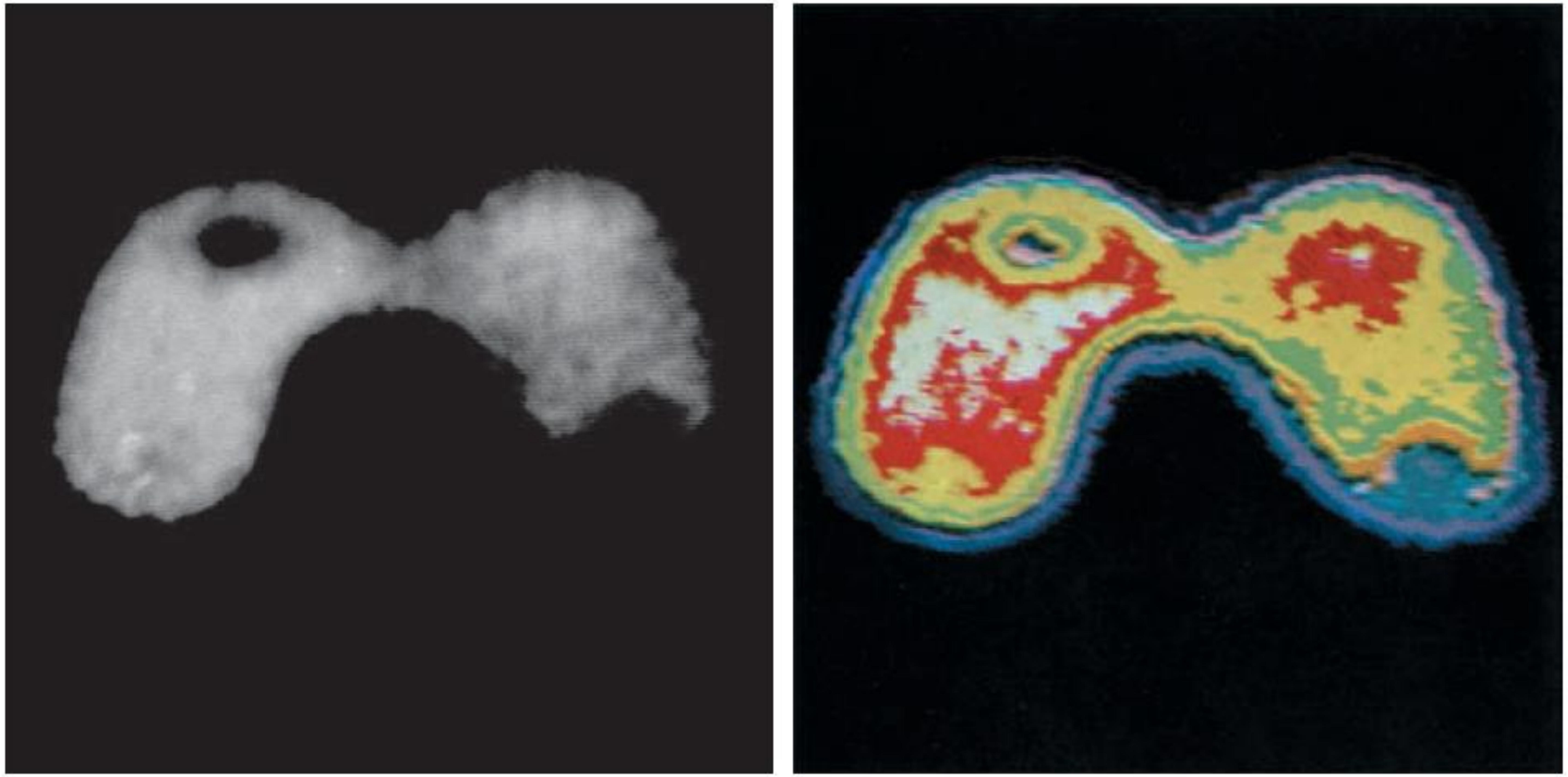
Let $[0, L-1]$ represent the grayscale, let level ℓ_0 represent black [$f(x, y) = 0$], and level ℓ_{L-1} represent white [$f(x, y) = L-1$]. Suppose that P planes perpendicular to the intensity axis are defined at levels $\ell_1, \ell_2, \ldots, \ell_P$. Then, assuming that $0 < P < L-1$, the P planes partition the grayscale into $P+1$ intervals, $I_1, I_2, \ldots, I_{P+1}$.

Intensity to color assignments at each pixel location (x, y) are made according to the equation

$$\text{if } f(x, y) \in I_k, \text{ let } f(x, y) = c_k$$

where c_k is the color associated with the k-th intensity interval ℓ_k, defined by the planes at $\ell = k-1$ and $\ell = k$.

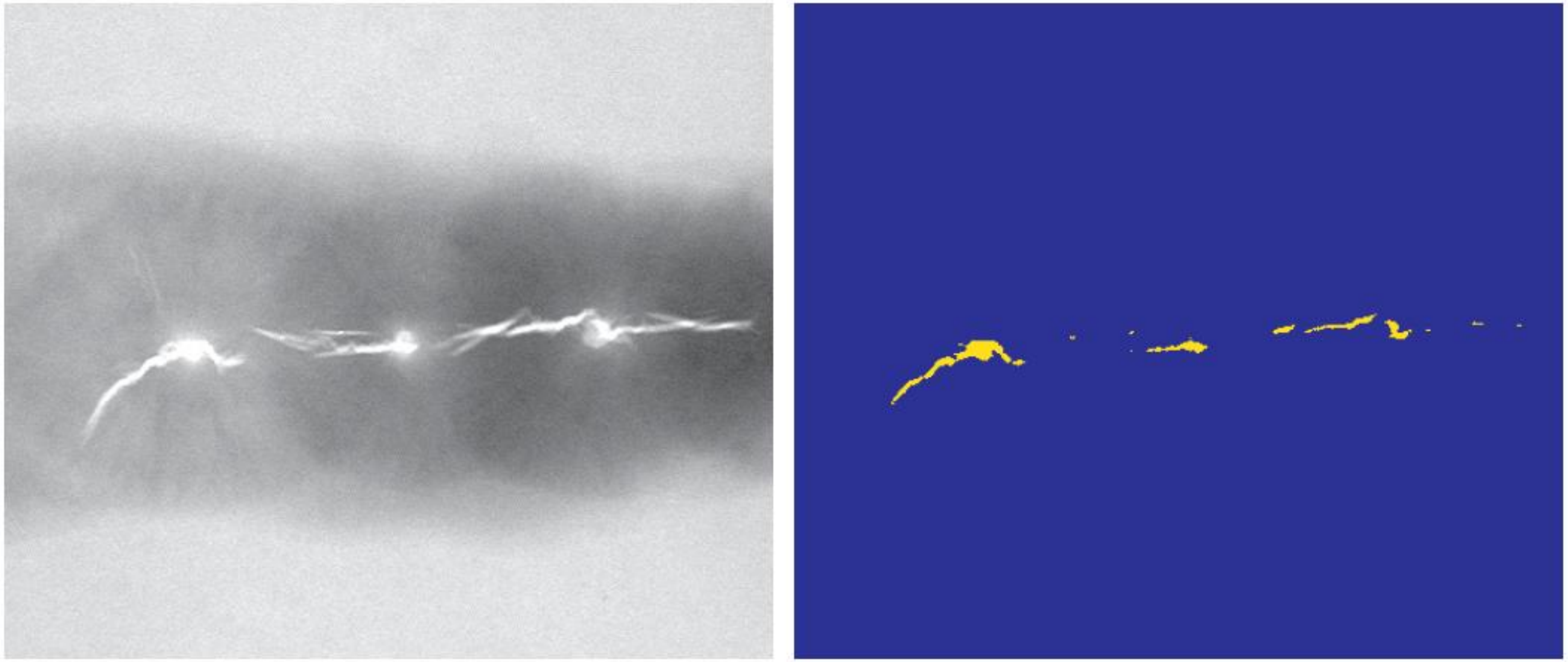
Intensity slicing



a b

FIGURE 6.18
(a) Grayscale image of the Picker Thyroid Phantom.
(b) Result of intensity slicing using eight colors.
(Courtesy of Dr. J. L. Blankenship, Oak Ridge National Laboratory.)

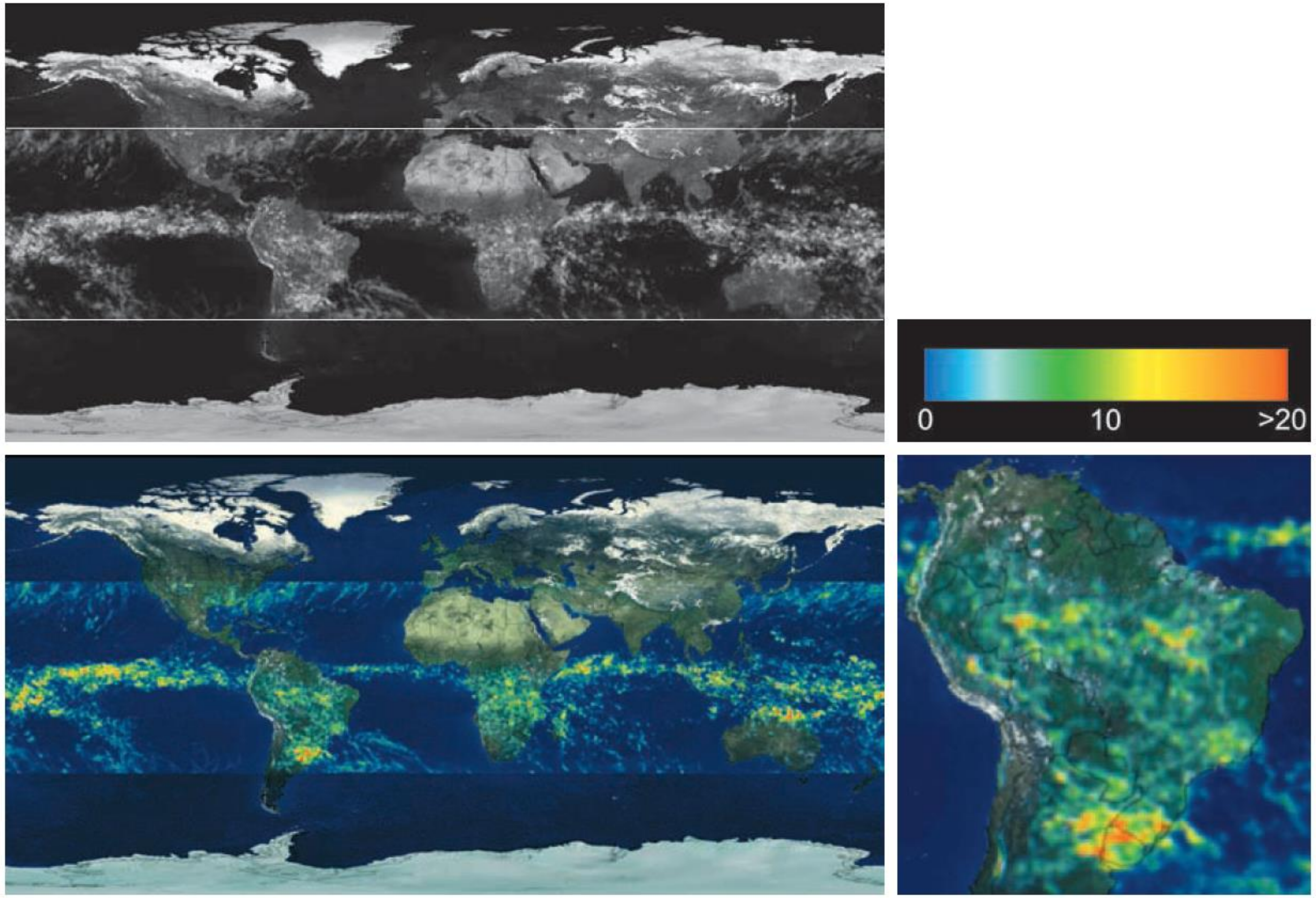
Intensity slicing



a b

FIGURE 6.19
(a) X-ray image of a weld.
(b) Result of color coding. (Original image courtesy of X-TEK Systems, Ltd.)

Intensity slicing

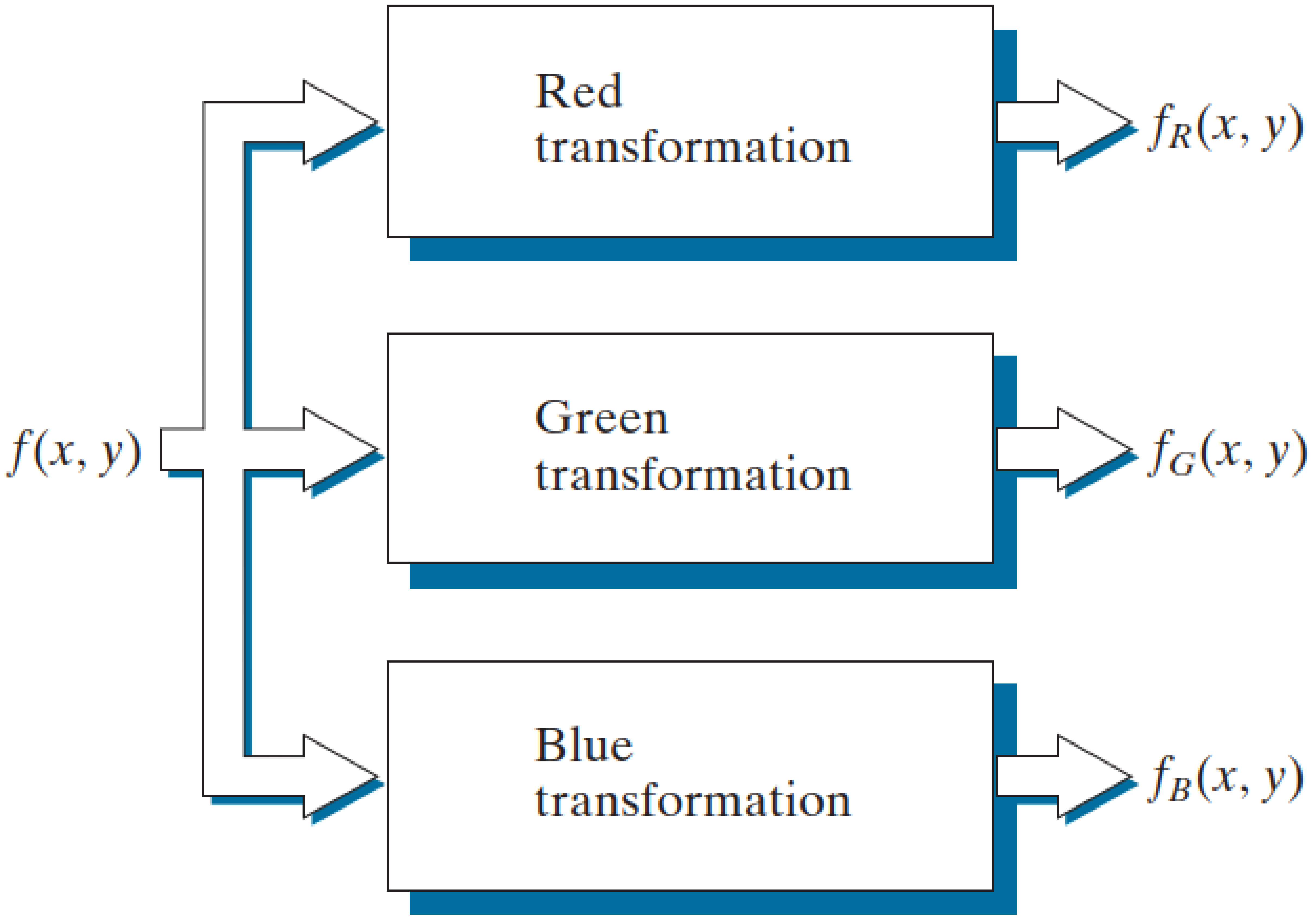


a b
c d

FIGURE 6.20 (a) Grayscale image in which intensity (in the horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South American region. (Courtesy of NASA.)

Intensity to color transformation

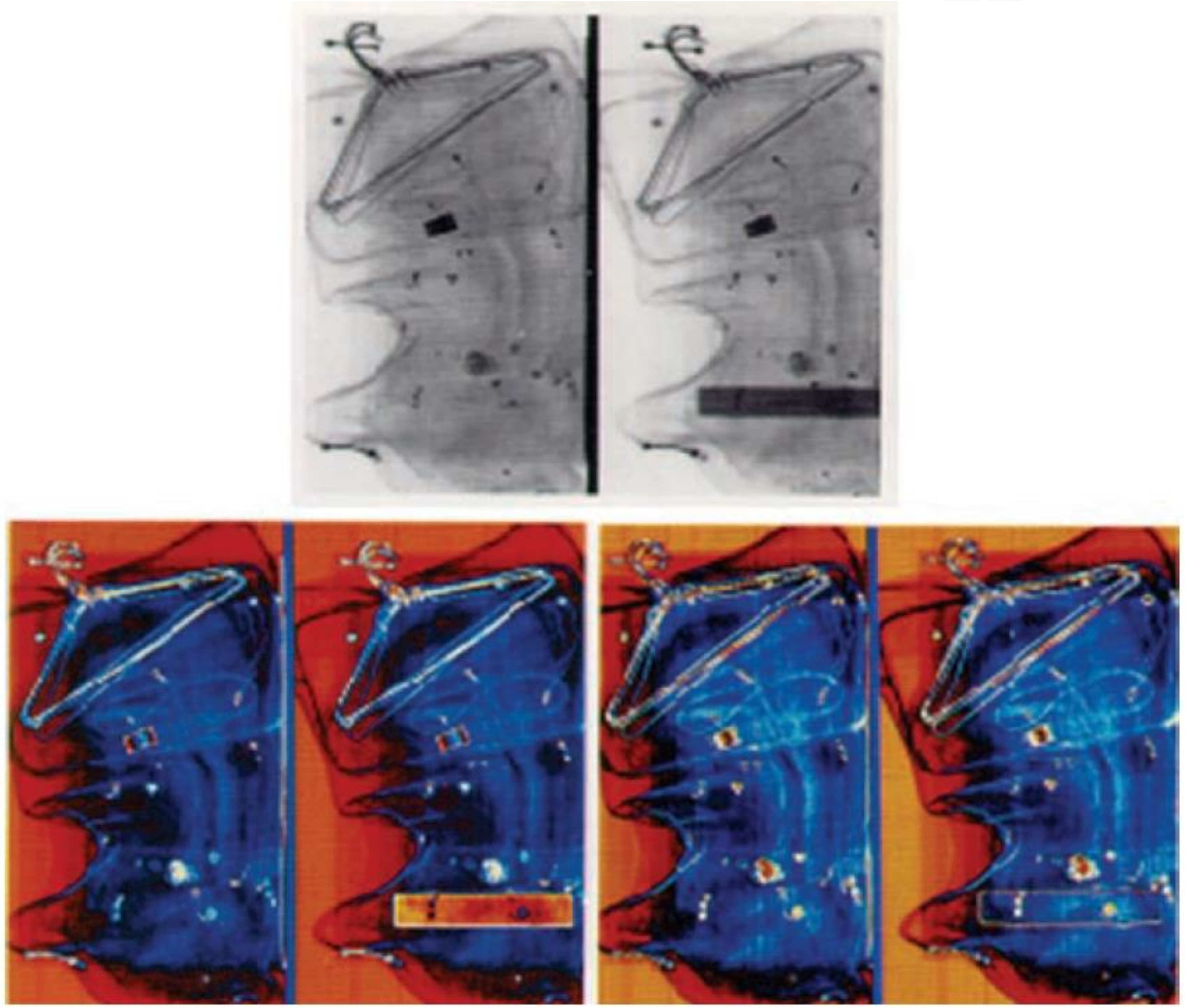
FIGURE 6.21
Functional block diagram for pseudocolor image processing. Images f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.



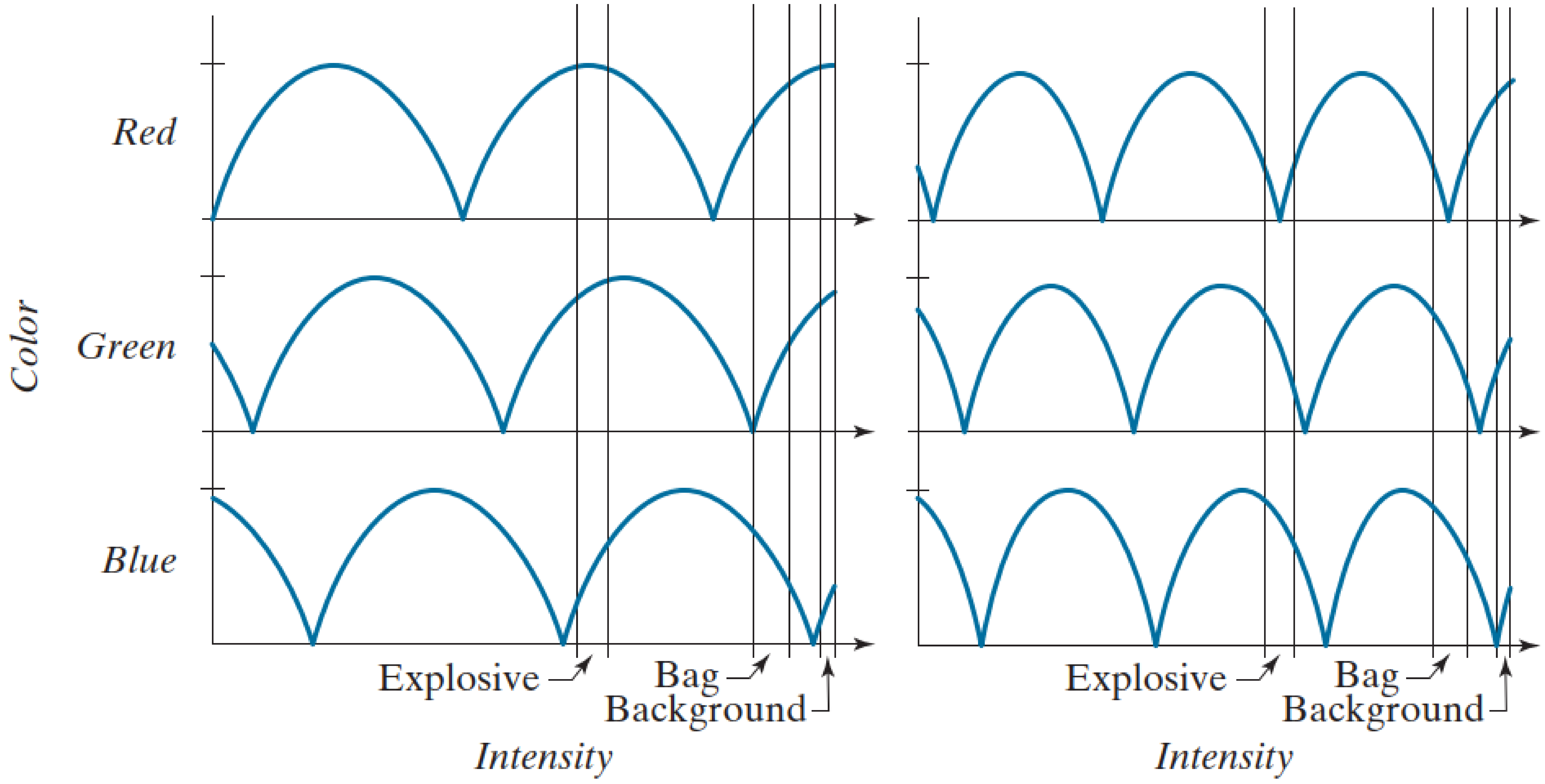
Intensity to color transformation

a	
b	c

FIGURE 6.22 Pseudocolor enhancement by using the gray level to color transformations in Fig. 6.23. (Original image courtesy of Dr. Mike Hurwitz, Westinghouse.)



Intensity to color transformation

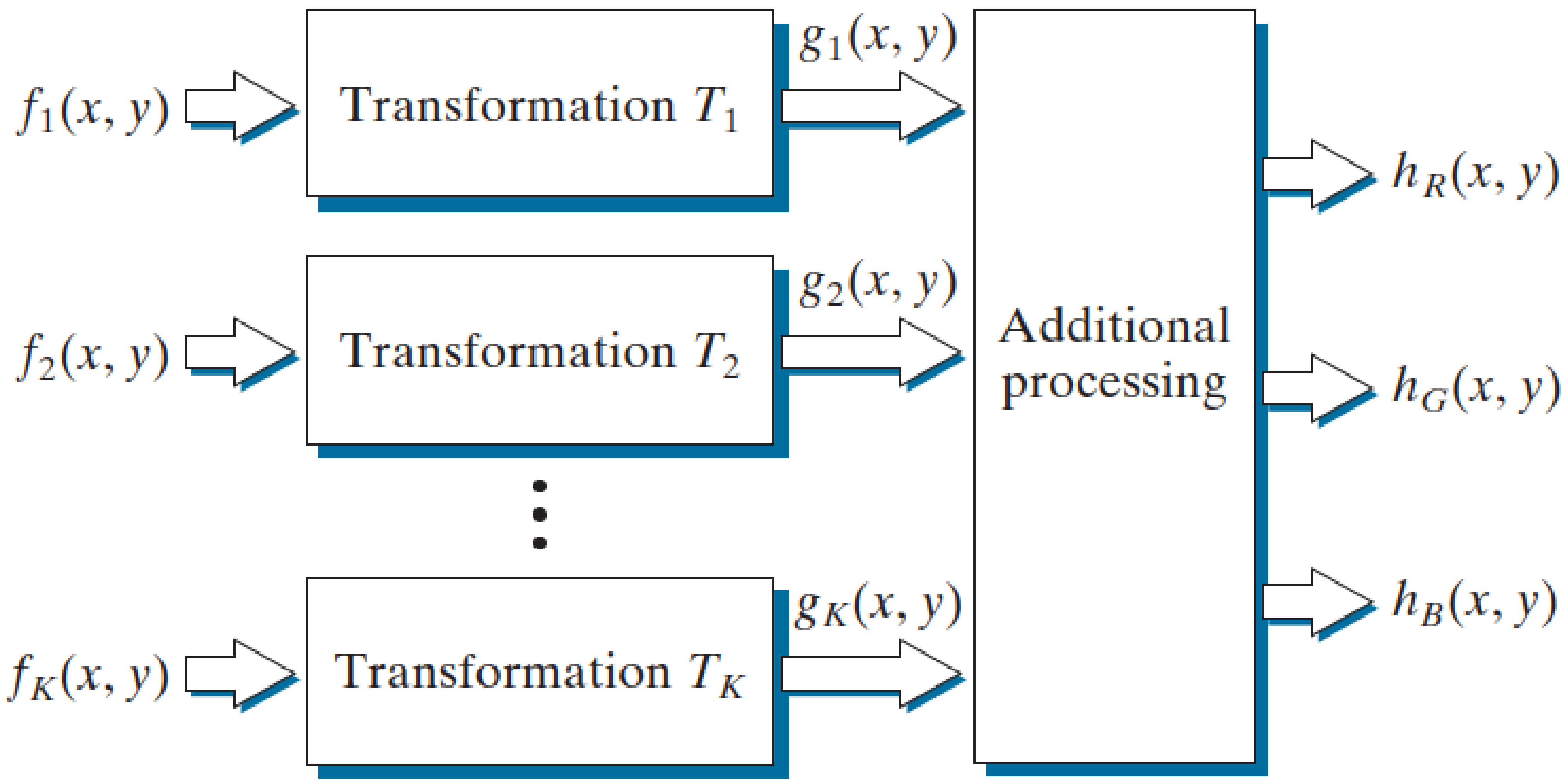


a b

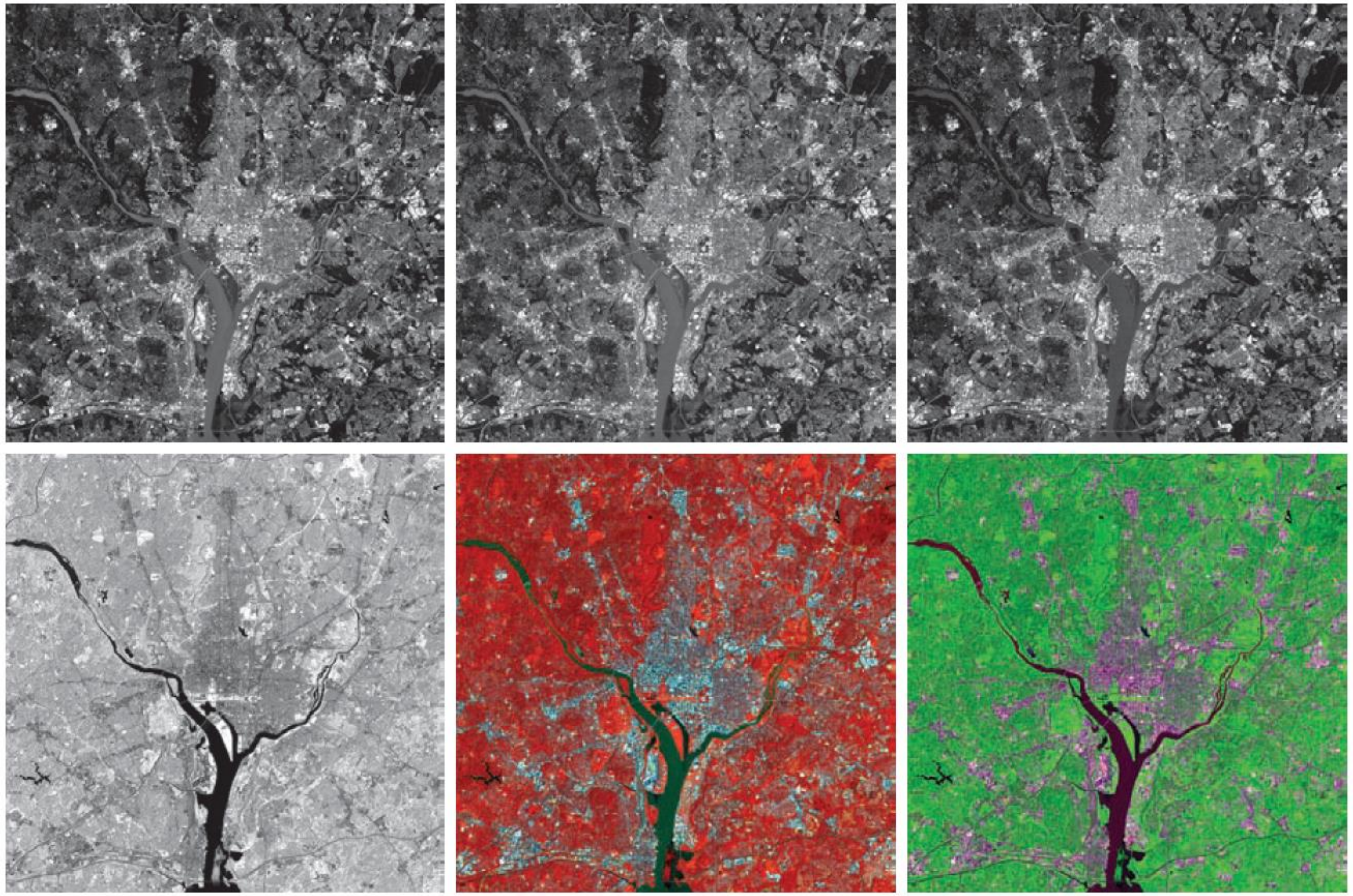
FIGURE 6.23
Transformation functions used to obtain the pseudocolor images in Fig. 6.22.

Intensity to color transformation

FIGURE 6.24
A pseudocolor coding approach using multiple grayscale images. The inputs are grayscale images. The outputs are the three components of an RGB composite image.



Intensity to color transformation



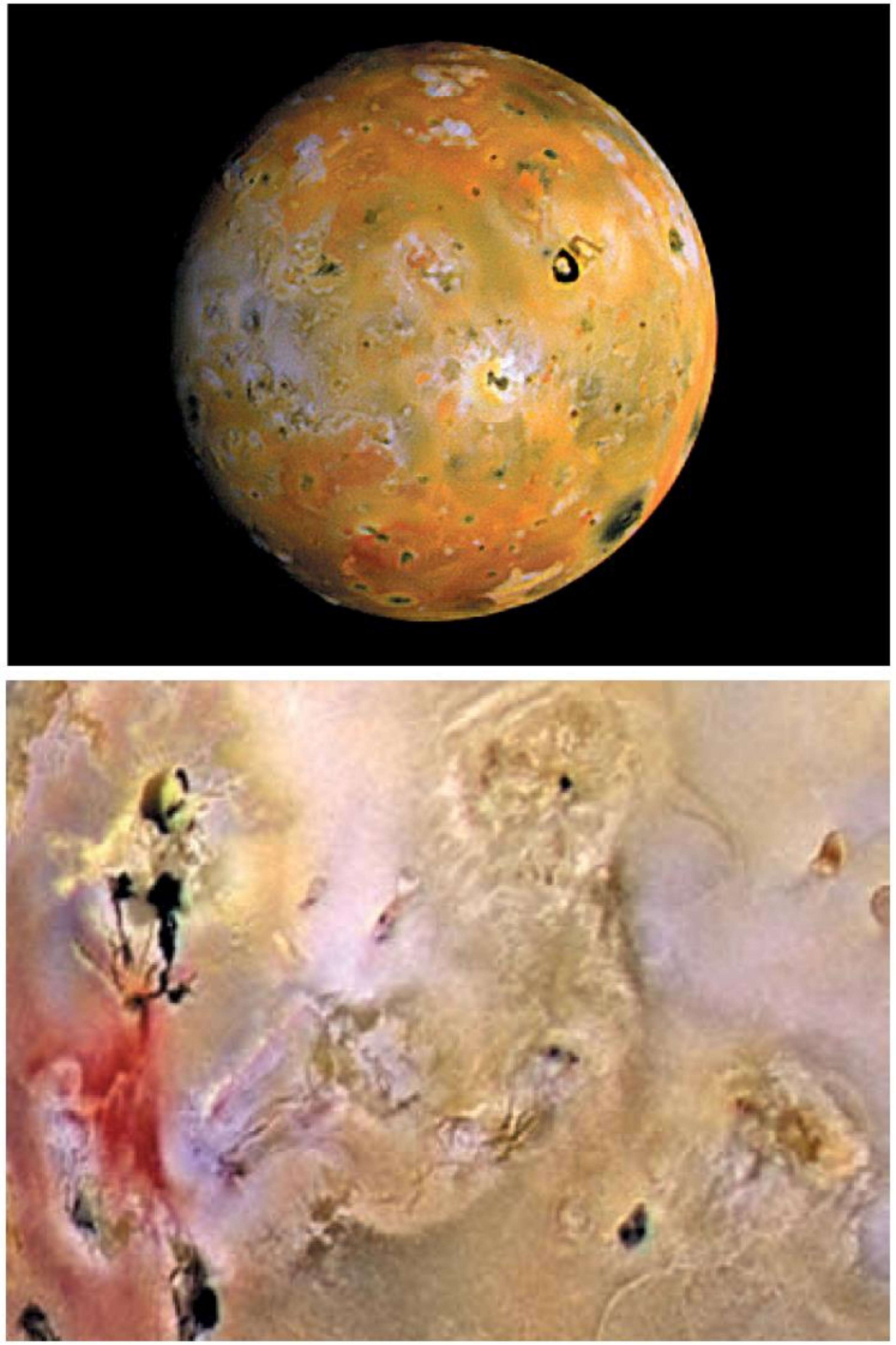
a b c
d e f

FIGURE 6.25 (a)–(d) Red (R), green (G), blue (B), and near-infrared (IR) components of a LANDSAT multispectral image of the Washington, D.C. area. (e) RGB color composite image obtained using the IR, G, and B component images. (f) RGB color composite image obtained using the R, IR, and B component images. (Original multispectral images courtesy of NASA.)

Intensity to color transformation

a
b

FIGURE 6.26
(a) Pseudocolor rendition of Jupiter Moon Io. (b) A close-up. (Courtesy of NASA.)



Full-color image processing

Full-color image processing approaches fall into two major categories:

In the first category, we process each grayscale component image individually, then form a composite color image from the individually processed components.

In the second category, we work with color pixels directly.

Let **c** represent an arbitrary vector in RGB color space:

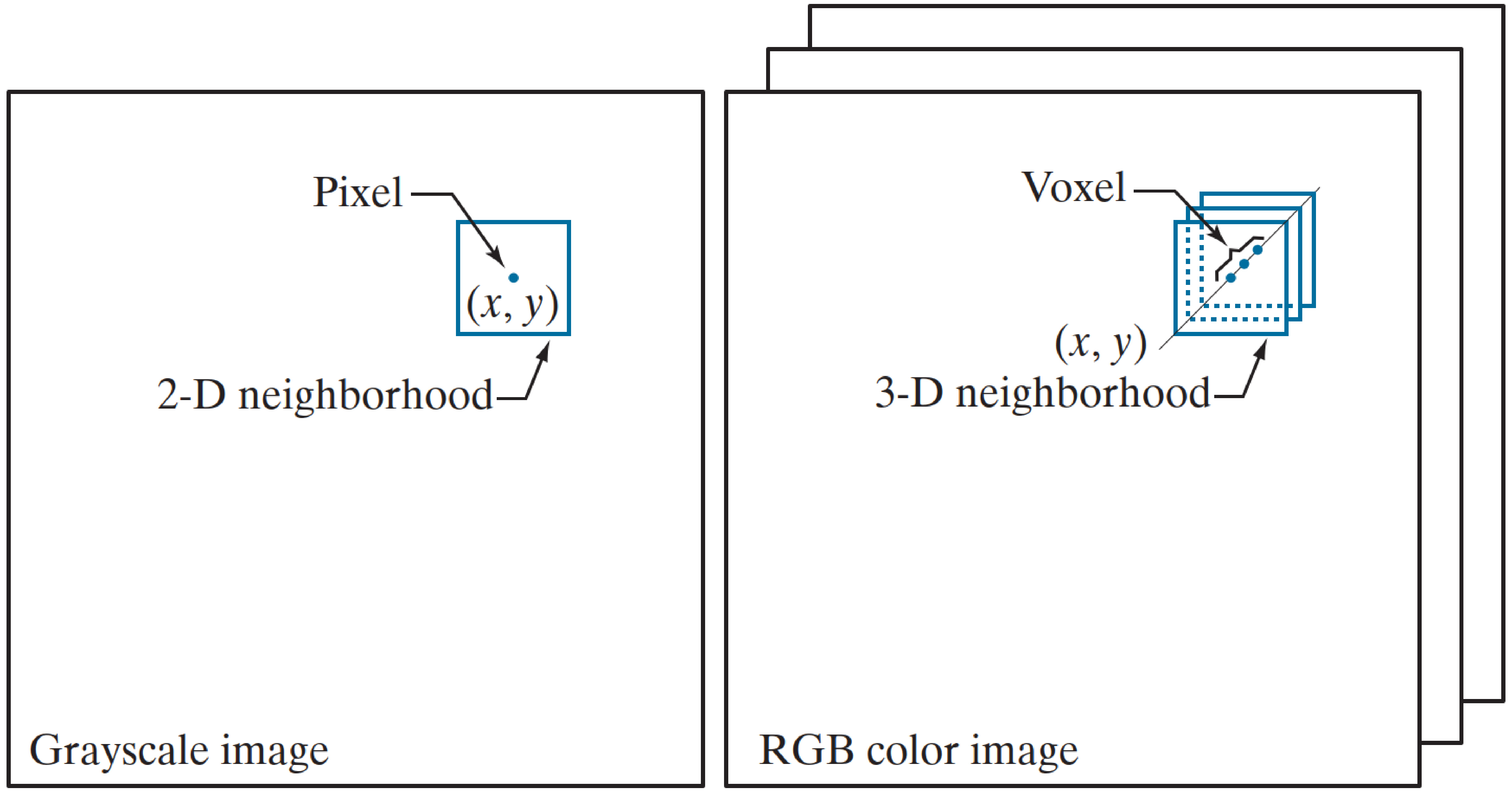
$$\mathbf{c}(x,y) = \begin{bmatrix} c_R(x,y) \\ c_G(x,y) \\ c_B(x,y) \end{bmatrix} = \begin{bmatrix} R(x,y) \\ G(x,y) \\ B(x,y) \end{bmatrix}$$

When points have more than two components, we call them **voxels**.

Full-color image processing

In order for per-component-image and vector-based processing to be equivalent two conditions have to be satisfied:

1) the process has to be applicable to both vectors and scalars;
2) the operation on each component of a vector (i.e., each voxel) must be independent of the other components.



a b

FIGURE 6.27 Spatial neighborhoods for grayscale and RGB color images. Observe in (b) that a *single* pair of spatial coordinates, (x, y), addresses the same spatial location in all three images.

Color transformations

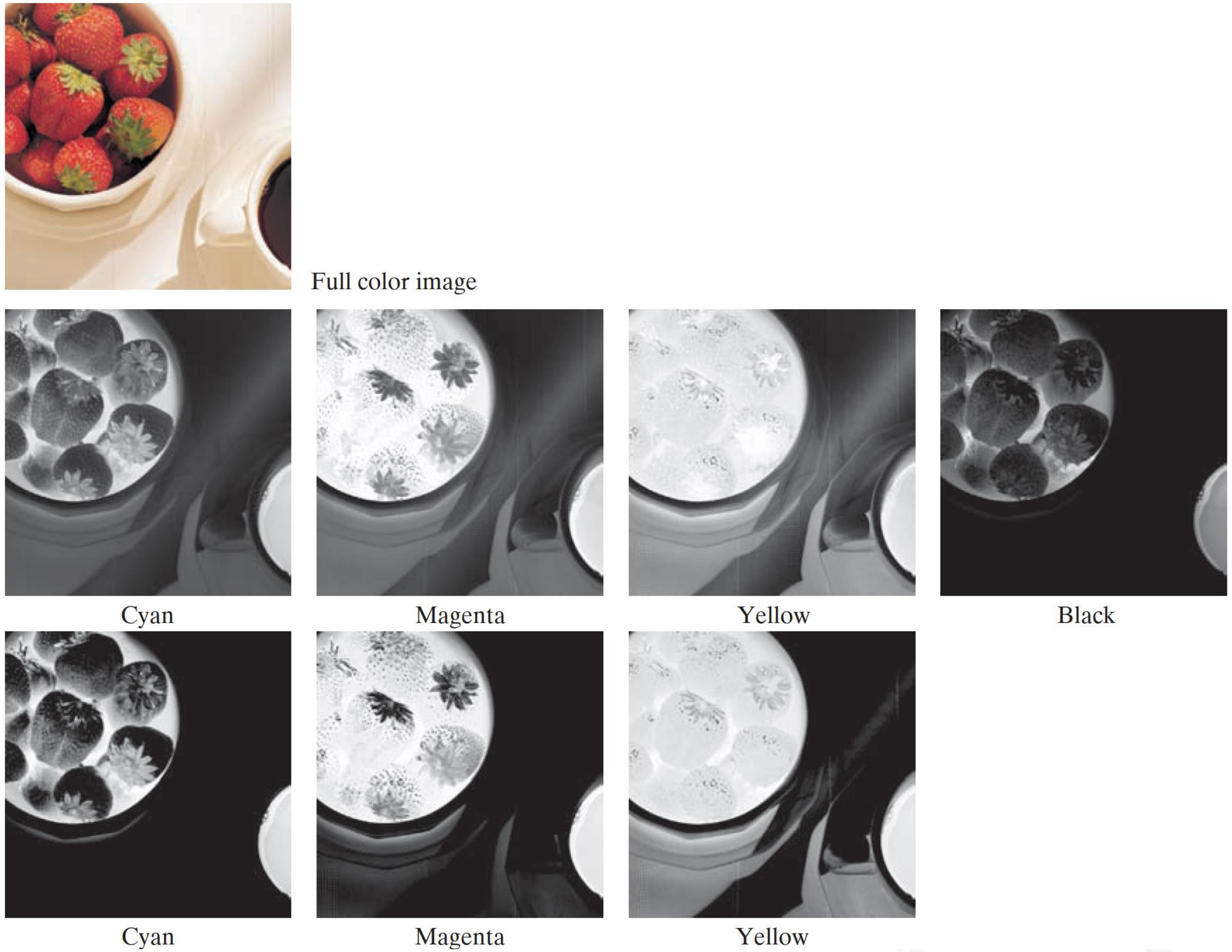
We model color transformations for multispectral images using the general expression

$$s_i = T_i(r_i) \qquad i = 1,2,\ldots,n$$

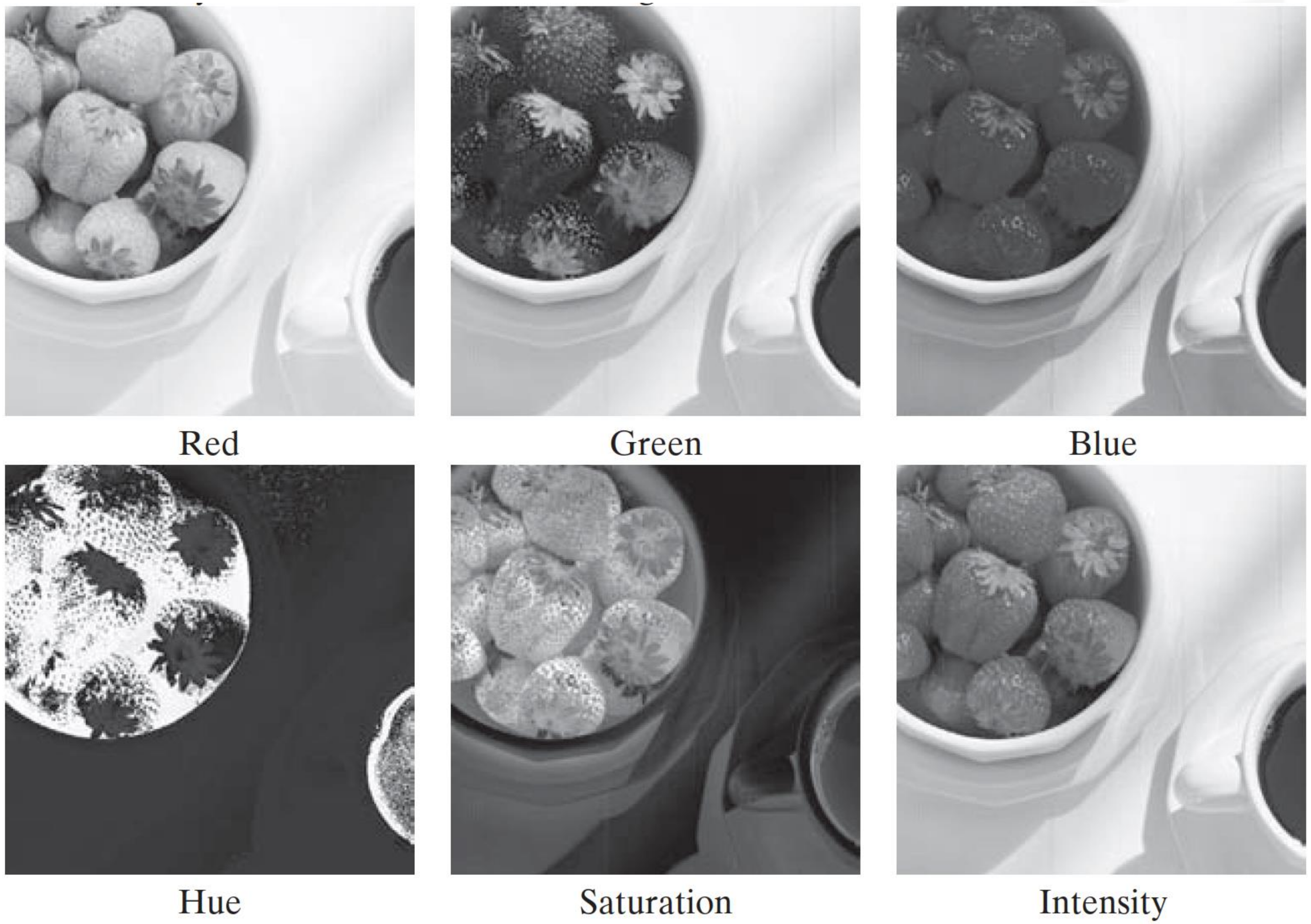
where n is the total number of component images, r_i are the intensity values of the input component images, s_i are the spatially corresponding intensities in the output component images, and T_i are a set of **transformation** or **color mapping functions** that operate on r_i to produce s_i.

The fact that i is also a subscript on T means that, in principle, we can implement a different transformation for each input component image.

Color transformations



Color transformations



Color transformations

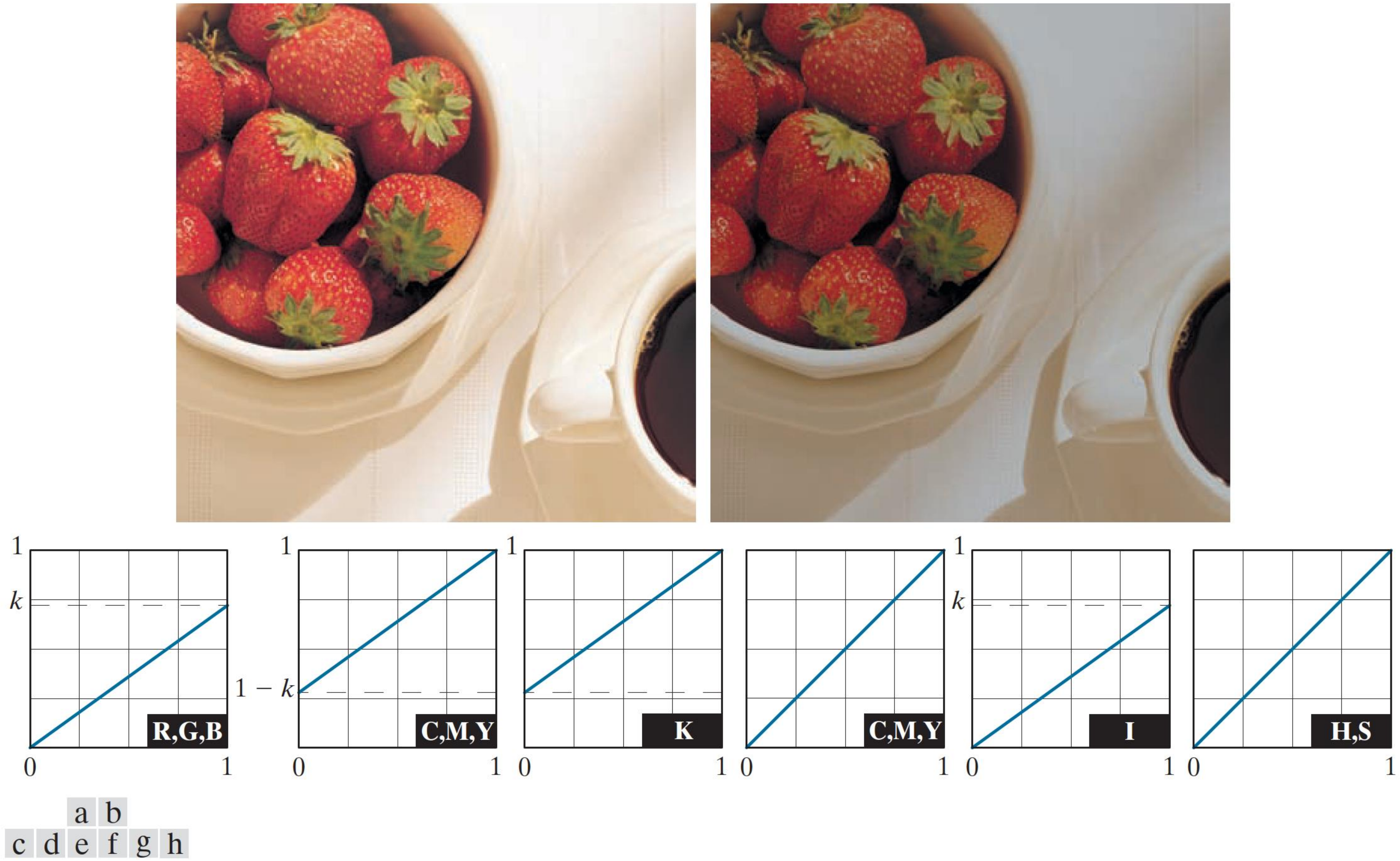


FIGURE 6.29 Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c) The required RGB mapping function. (d)–(e) The required CMYK mapping functions. (f) The required CMY mapping function. (g)–(h) The required HSI mapping functions. (Original image courtesy of MedData Interactive.)

Color complements

The **color circle** (also called the **color wheel**) originated with Sir Isaac Newton, who in the seventeenth century created its first form by joining the ends of the color spectrum.

The color circle is a visual representation of colors that are arranged according to the chromatic relationship between them.

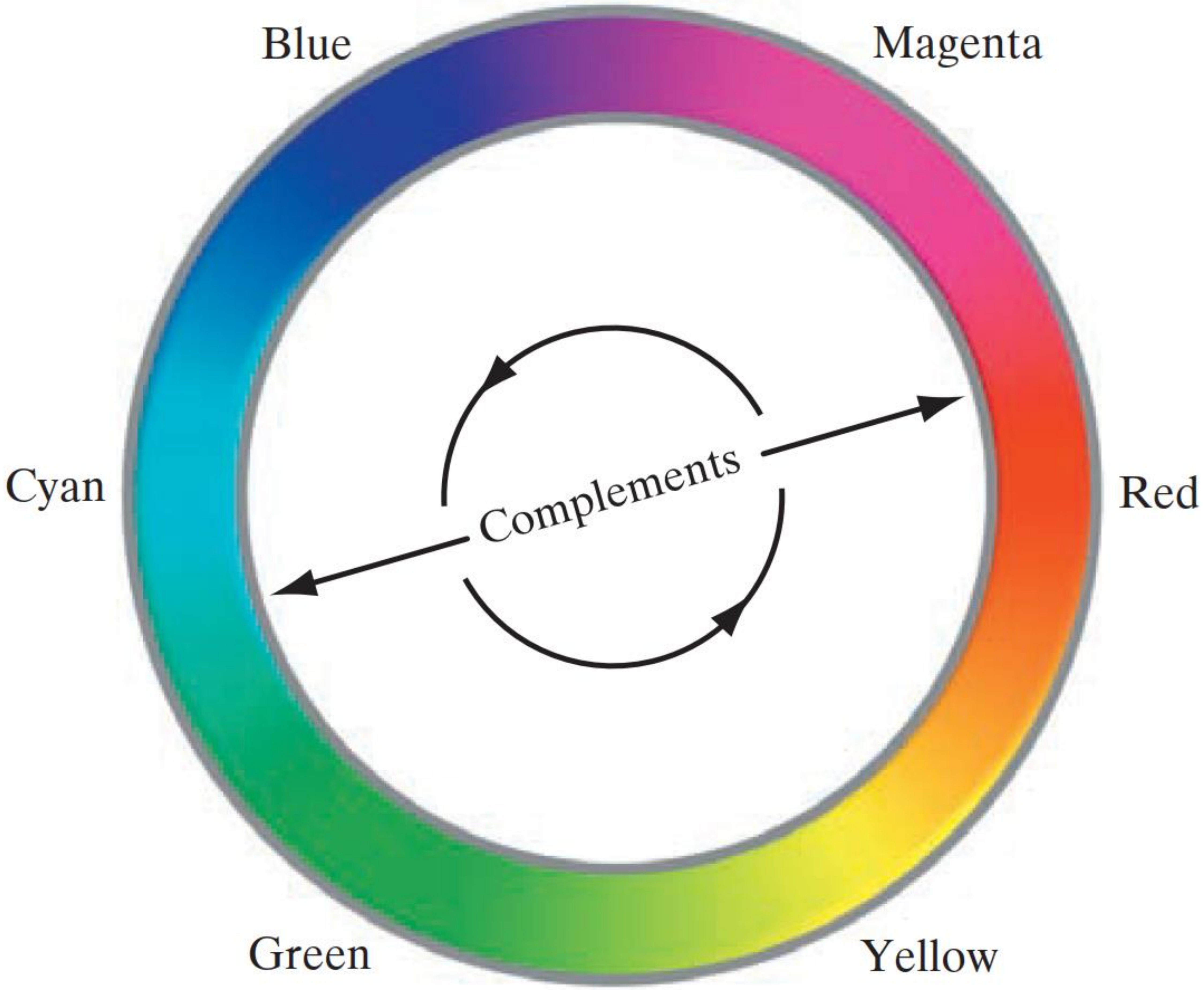
The circle is formed by placing the primary colors equidistant from each other.

Then, the secondary colors are placed between the primaries, also in an equidistant arrangement.

The net result is that hues directly opposite one another on the color circle are complements

Color complements

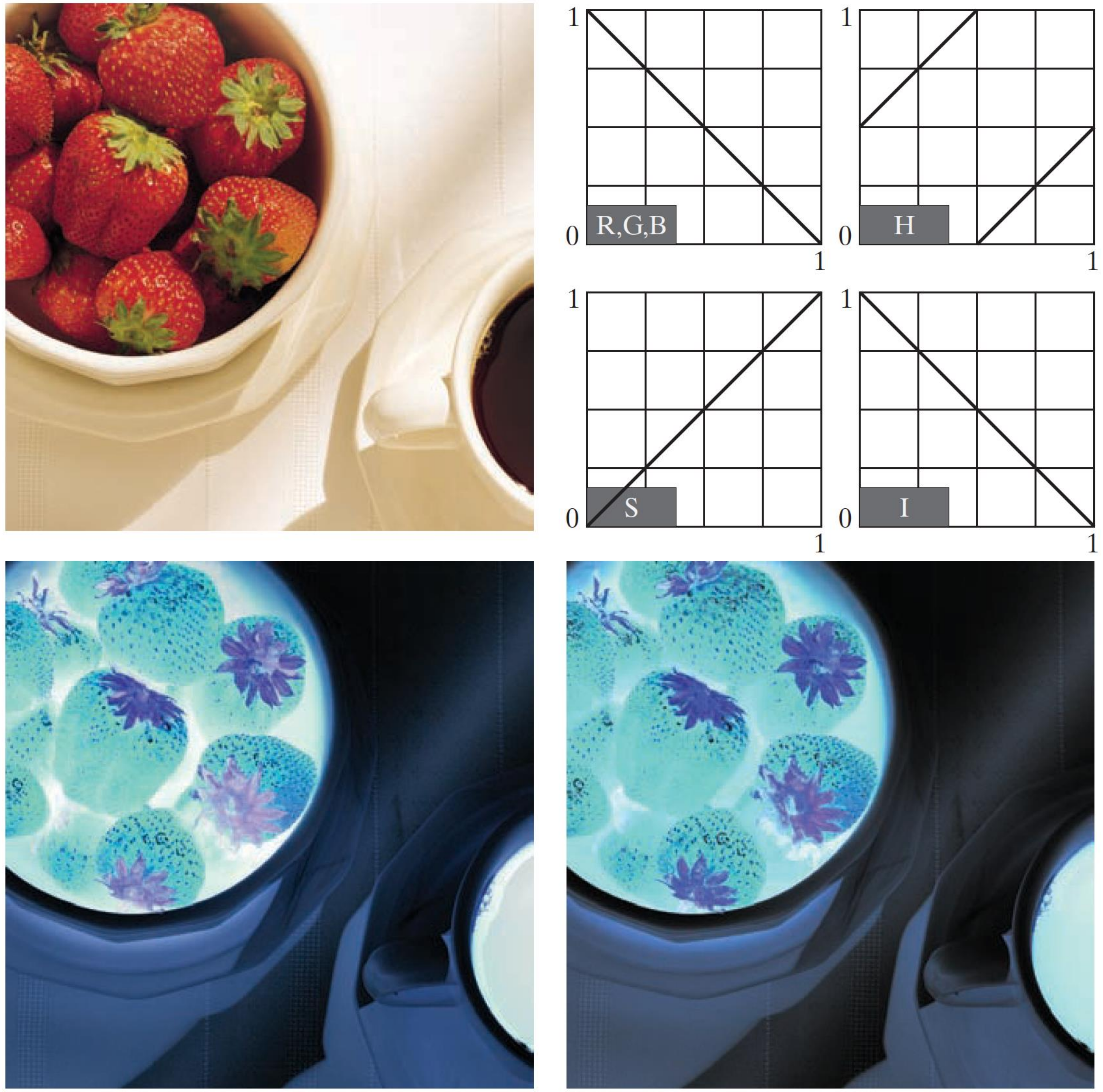
FIGURE 6.30
Color complements on the color circle.



Color complements

a b
c d

FIGURE 6.31 Color complement transformations. (a) Original image. (b) Complement transformation functions. (c) Complement of (a) based on the RGB mapping functions. (d) An approximation of the RGB complement using HSI transformations.



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Color slicing

Highlighting a specific range of colors in an image is useful for separating objects from their surroundings.

The basic idea is either to:

(1) display the colors of interest so that they stand out from the background; or

(2) use the region defined by the colors as a mask for further processing.

One of the simplest ways to "slice" a color image is to map the colors outside some range of interest into a nonprominent neutral color. If the colors of interest are enclosed by a cube (or hypercube for $n > 3$) of width W and centered at a prototypical color with components $(a_1, a_2, \ldots, a_n)$, the necessary set of transformations are given by

$$s_i = \begin{cases} 0.5 & \text{if} \left[\left| r_j - a_j \right| > \frac{W}{2} \right]_{\text{any } 1 \le j \le n} \\ r_i & \text{otherwise} \end{cases} \qquad i = 1, 2, \ldots, n$$

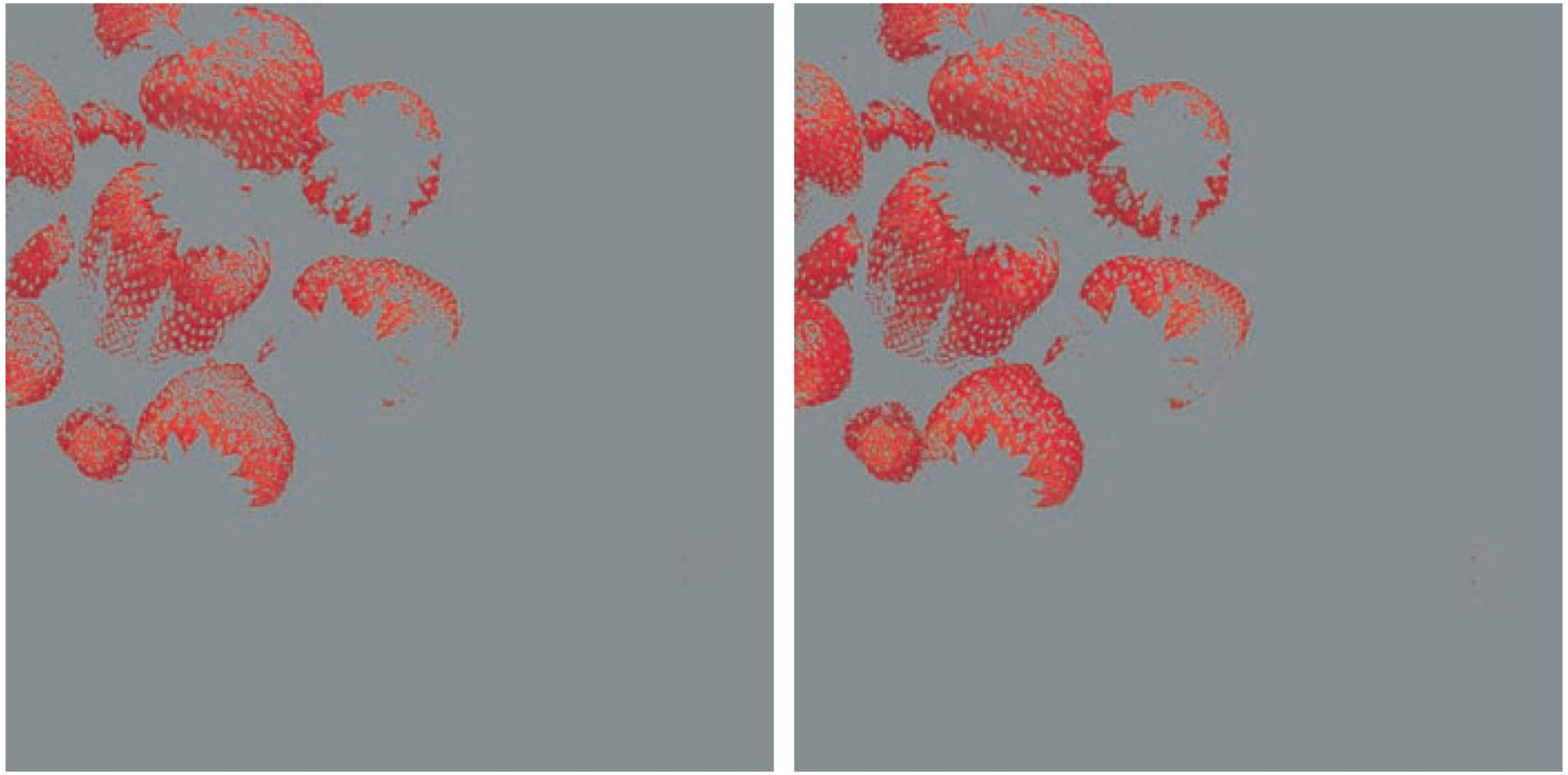
Color slicing

If a sphere is used to specify the colors of interest,

$$s_i = \begin{cases} 0.5 & \text{if } \sum_{j=1}^{n} \left(r_j - a_j\right)^2 > R_0^2 \\ r_i & \text{otherwise} \end{cases} \qquad i = 1, 2, \ldots, n$$

Here, R_0 is the radius of the enclosing sphere (or hypersphere for $n > 3$) and $(a_1, a_2, \ldots, a_n)$ are the components of its center (i.e., the prototypical color).

Color slicing



a b

FIGURE 6.32 Color-slicing transformations that detect (a) reds within an RGB cube of width $W = 0.2549$ centered at (0.6863, 0.1608, 0.1922), and (b) reds within an RGB sphere of radius 0.1765 centered at the same point. Pixels outside the cube and sphere were replaced by color (0.5, 0.5, 0.5).

Tone and color corrections

Problems involving an image's tonal range need to be corrected before color irregularities, such as over- and under-saturated colors, can be resolved.

The tonal range of an image, also called its **key type**, refers to its general distribution of color intensities.

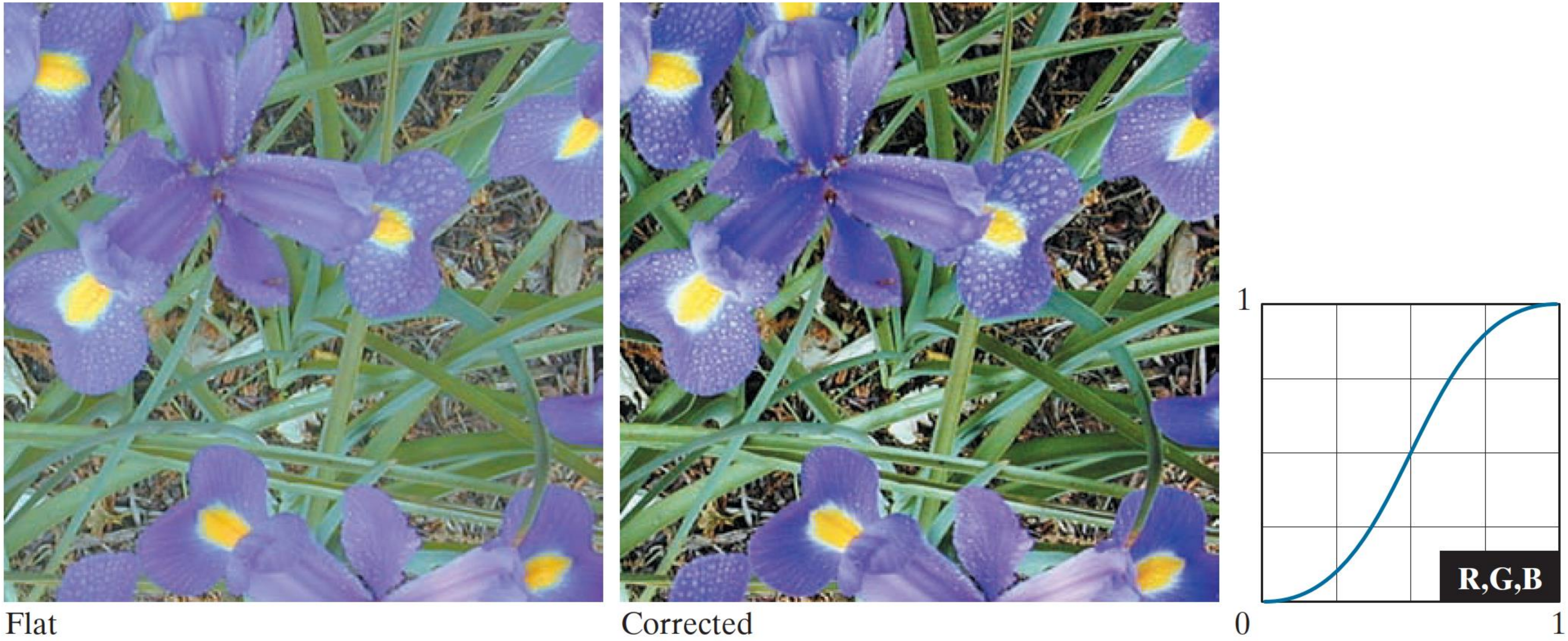
Most of the information in **high-key images** is concentrated at high (or light) intensities;

the colors of **low-key images** are located predominantly at low intensities; and

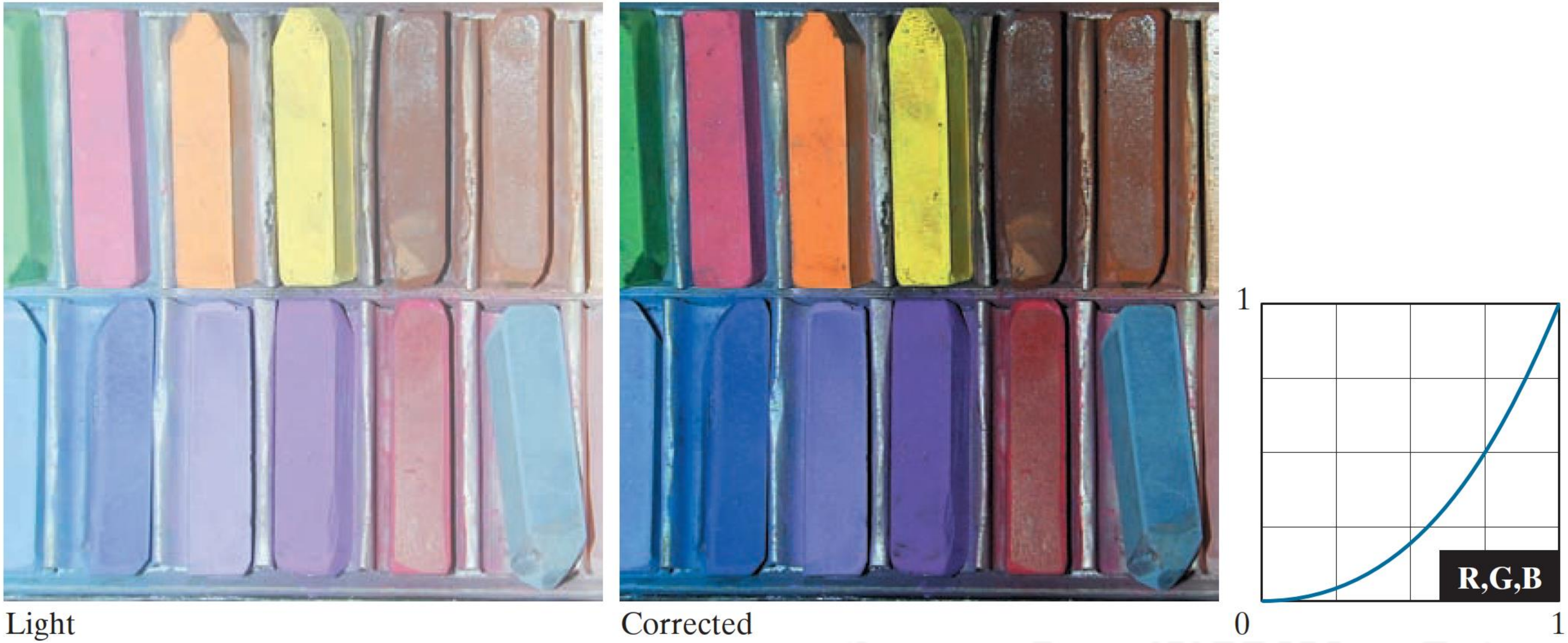
middle-key images lie in between.

As in the grayscale case, it is often desirable to distribute the intensities of a color image equally between the highlights and the shadows.

Tone and color corrections



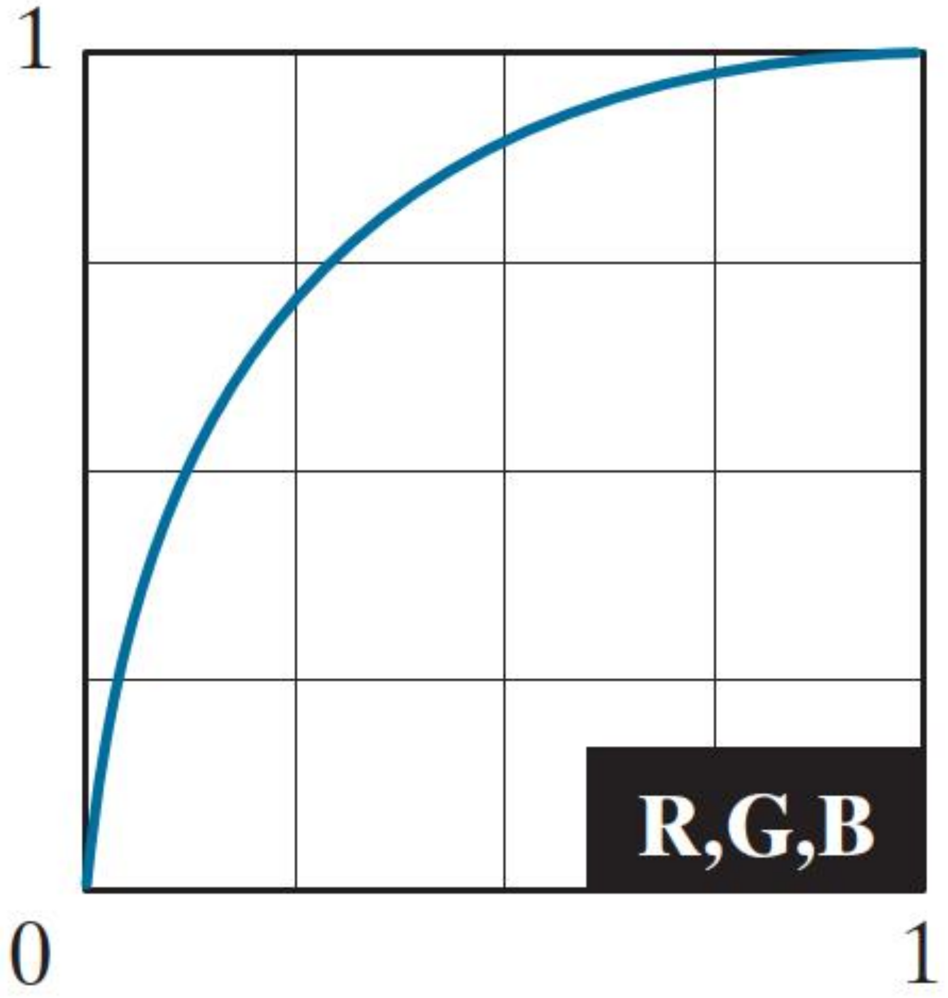
Tone and color corrections



Tone and color corrections

Dark

Corrected



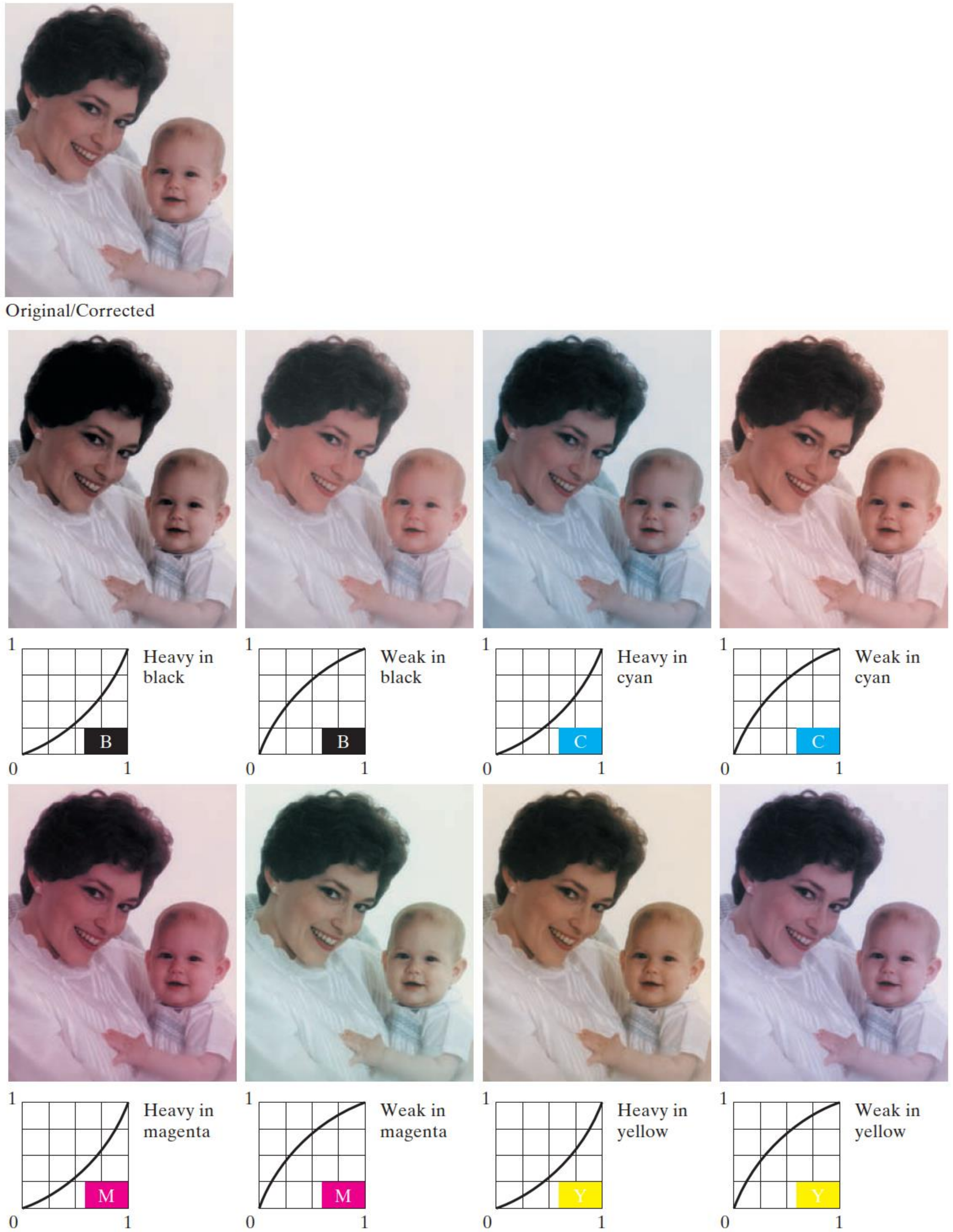
Tone and color corrections

Any color imbalances are addressed after the tonal characteristics of an image have been corrected.

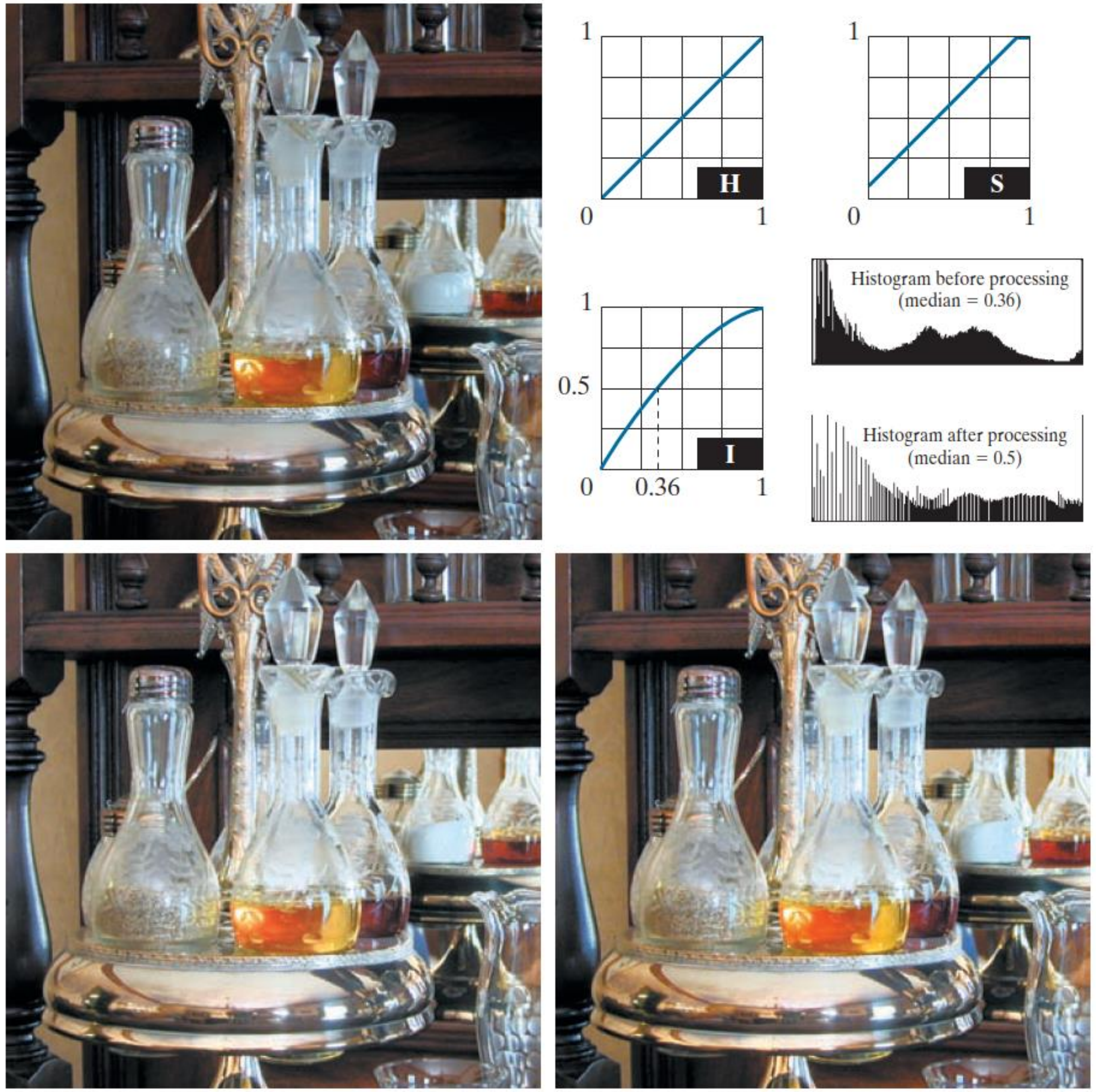
Although color imbalances can be determined directly by analyzing a known color in an image with a color spectrometer, accurate visual assessments are possible when white areas, where the RGB or CMY(K) components should be equal, are present.

Skin tones are excellent subjects for visual color assessments because humans are highly perceptive of proper skin color.

Tone and color corrections



Histogram processing



a b
c d

FIGURE 6.35 Histogram equalization (followed by saturation adjustment) in the HSI color space.

Color image smoothing and sharpening

a b
c d

FIGURE 6.36
(a) RGB image.
(b) Red component image.
(c)Green component.
(d) Blue component.

Color image smoothing and sharpening

FIGURE 6.37 HSI components of the RGB color image in Fig. 6.36(a). (a) Hue. (b) Saturation. (c) Intensity.

Color image smoothing and sharpening

a b c

FIGURE 6.38 Image smoothing with a 5×5 averaging kernel. (a) Result of processing each RGB component image (b) Result of processing the intensity component of the HSI image and converting to RGB. (c) Difference between the two results.

Color image smoothing and sharpening

a b c

FIGURE 6.39 Image sharpening using the Laplacian. (a) Result of processing each RGB channel. (b) Result of processing the HSI intensity component and converting to RGB. (c) Difference between the two results.

Study:

- Rafael Gonzalez, Richard Woods, “Digital Image Processing”, 4th edition, Pearson, 2018
  - Chapter 6.1, 6.2, 6.3, 6.4, 6.5,6.6