Color fundamentals

- When a beam of light passes through glass prism, the emerging beam of light consists of continuous spectrum of colors ranging from violet at one end to red at the other.
- Colors that humans perceive in an object are determined by the nature of the light reflected from the object.

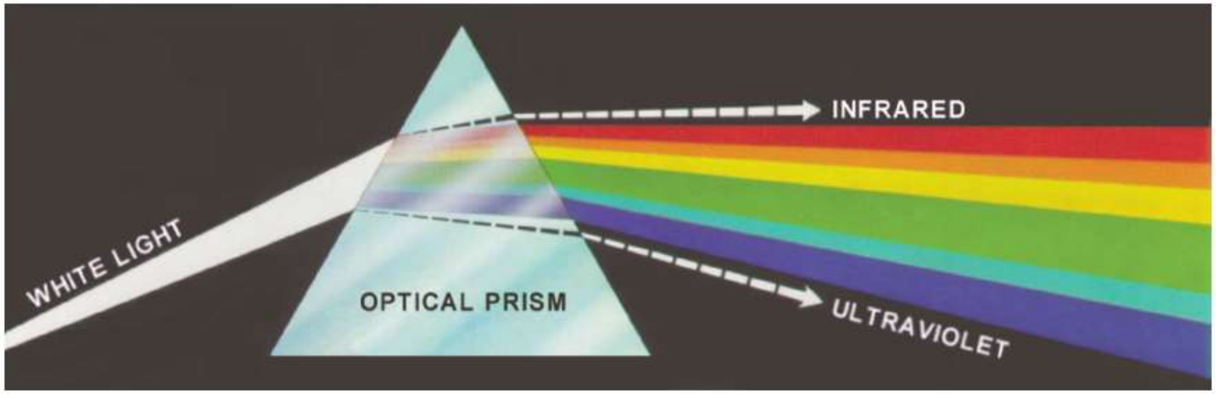


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

- Chromatic light spans the electromagnetic spectrum form approximately 400 to 700 nm.
- Three basic quantities used to describe the quality of a chromatic light source:
  - Radiance : amount of energy flows from the light source
  - Luminance : amount of energy an observer percieves
  - Brightness: is a subjective descriptor

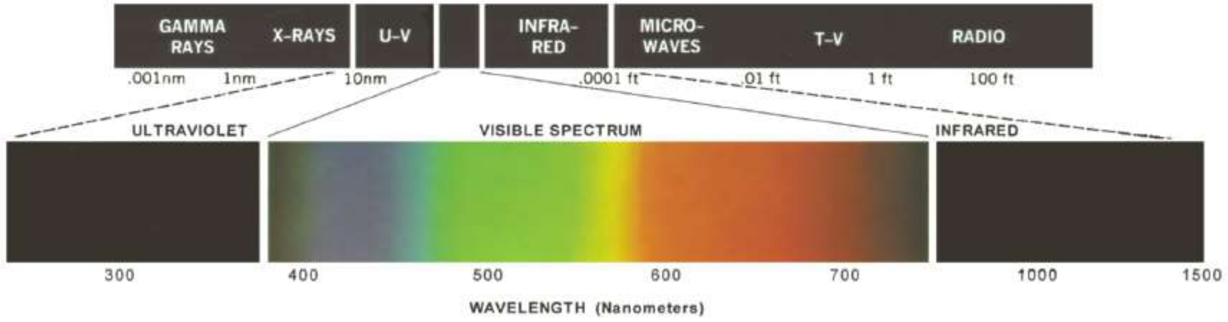


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

- Cones are the sensors in the eye responsible for color vision.
- 65% of cones are sensitive to red light
- 33% are sensitive to green light
- 2% are sensitive to blue light

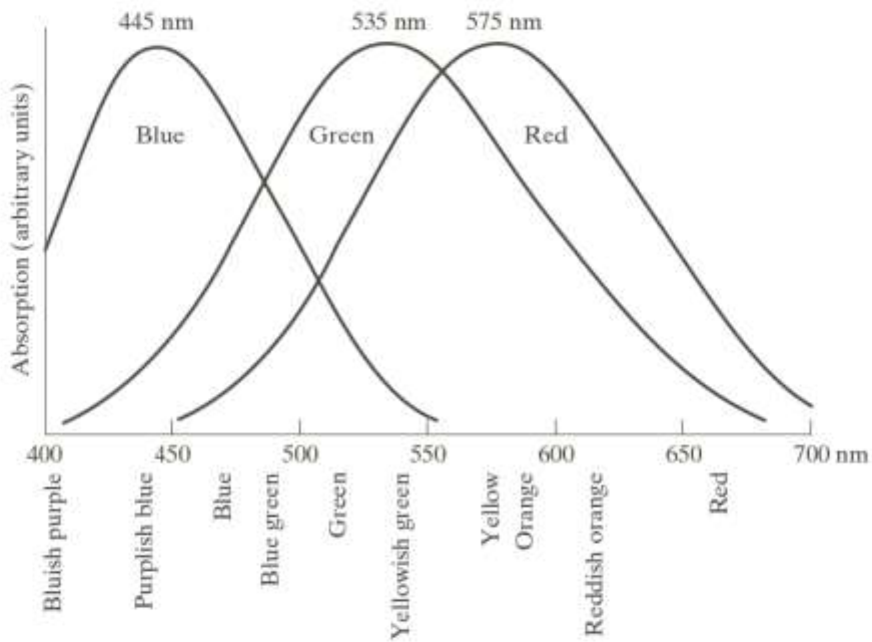
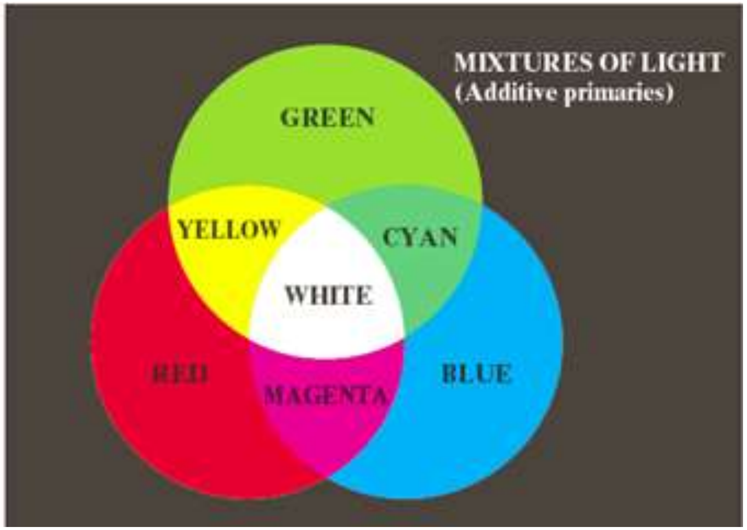


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

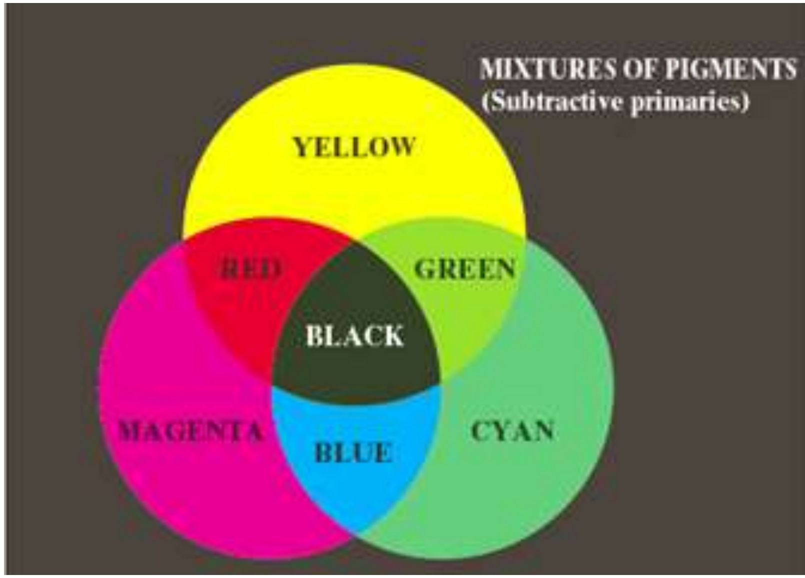
Primary and Secondary colors of light

- Red, Green and Blue are Primary colors of light.
- Primary colors are added to produce secondary colors
- Magenta(red + blue), Cyan(blue+ green), and Yellow (red+green) are secondary colors.
- Mixing three primaries produces white light.
- Or a secondary color with its opposite primary color in the right intensities produces white light.



Primary and Secondary colors of pigments or colorants

- Primary color of pigments or colorants is defined as the one that subtracts or absorbs a primary of light and reflects or transmits the other two.
- Therefore the primary colors of pigments are Magenta, Cyan and Yellow.
- And the secondary colors are Red, Green and Blue.
- A proper combination of the three pigment primaries produces black.
- Or a secondary with its opposite primary, produces black.



a
b
FIGURE 6.4 Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lamp Business Division.)

- Color television is an example of the additive nature of light colors.
- Color printer is an example of subtractive nature of light colors.

- The characteristics generally used to distinguish one color from another are ***brightness, hue,*** and ***saturation.***
- ***Brightness*** embodies the achromatic notion of intensity.
- **Hue** is an attribute associated with the dominant wavelength in a mixture of light waves.
- **Saturation** refers to the relative purity or the amount of white light mixed with a hue.
- Hue and saturation taken together are called chromaticity.

- 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 specified by its trichromatic coefficients, defined as

$$x = X/(X+Y+Z)$$

$$y = Y/(X+Y+Z)$$

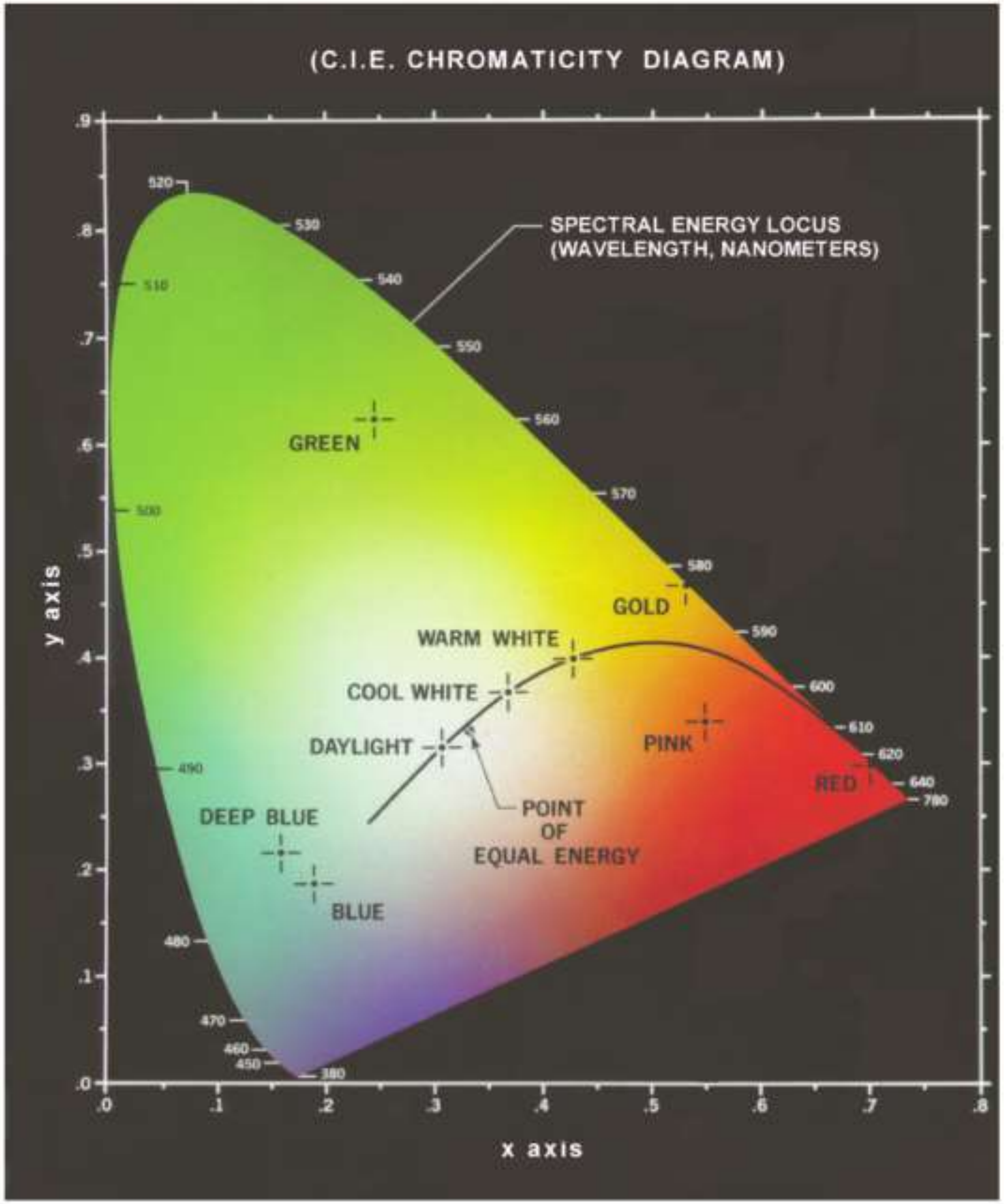
$$z = Z/(X+Y+Z)$$

- It is noted from these equations that

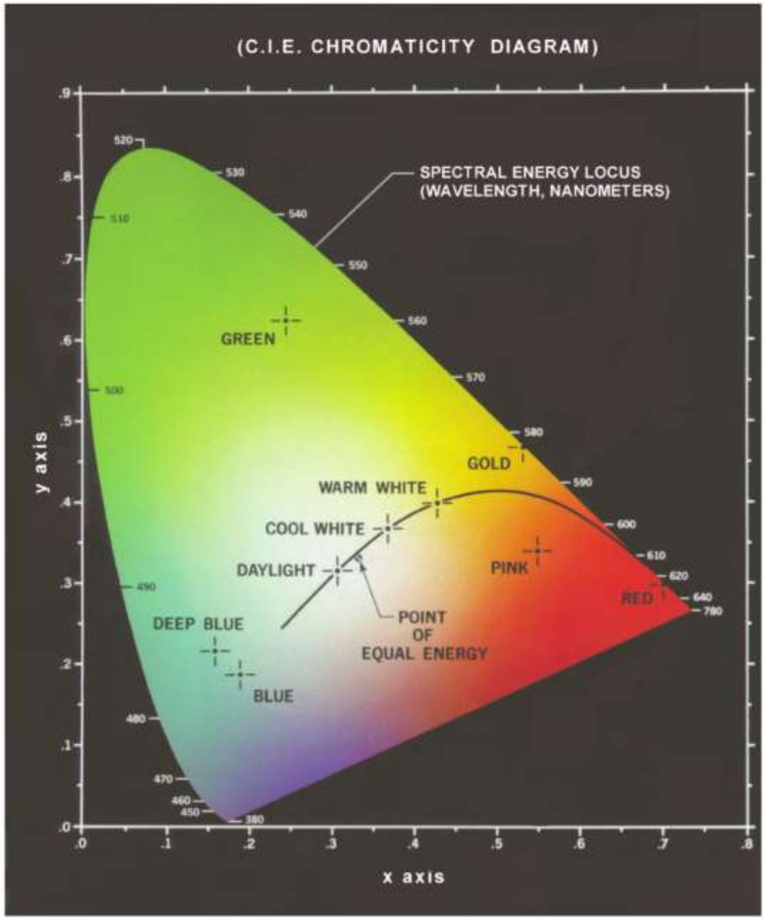
$$x+y+z = 1$$

- The tristimulus values needed to produce the color corresponding to a wavelength can be obtained from curves or tables
- Those curves and tables have been compiled from extensive experimental results

- Another approach for specifying colors is to use the CIE chromaticity diagram.
- Chromaticity diagram shows color composition as a function of x(red) and y(green).
- For any value of x and y the corresponding value of z(blue) is obtained by z = 1- (x+y).



- Give the percentage of red(X), green(Y) and blue(Z) light required to generate the point labeled warm white in chromatic diagram
- Answer:
  - From chromatic diagram, *x =0.43 and y = 0.4. Since x +y +z =1, it follows that z = 0.17. These are the trichromatic coefficients.*
  - *We are interested in tristimulus* values *X, Y, and Z, which are related to the trichromatic coefficients*
  - Note however, that all the tristimulus coefficients are divided by the same constant, so their percentages relative to the trichromatic coefficients are the same as those of the coefficients.
  - Therefore, the answer is *X = 0.43, Y =0.40, and Z =0.17.*



Color models

- Color model is a specification of a coordinate system and a subspace within that system.
- Each color is represented by a single point in that coordinate system.
- Color models are either hardware oriented (color monitors and printers) or application oriented (graphics for animation).
- Hardware oriented models are
  - RGB(red, green , blue) model used for color monitors
  - CMY(cyan, magenta, yellow) or CMYK(cyan, magenta, yellow, black) models used for printers
- Application oriented model is HSI(hue, saturation, intensity)
- HSI model corresponds closely with the way humans describe and interpret color.

The RGB Color Model

- This model is based on a cartesian coordinate system.
- The color subspace of interest is the cube.
- RGB primary values are at three corners.
- Cyan, Magenta, and yellow are at three other corners.
- Black is at the origin.
- White is at corner farthest from the origin.
- The gray scale (points of equal RGB values) extends from black to white along the line joining these points.
- The different colors in this model are points on or inside the cube.

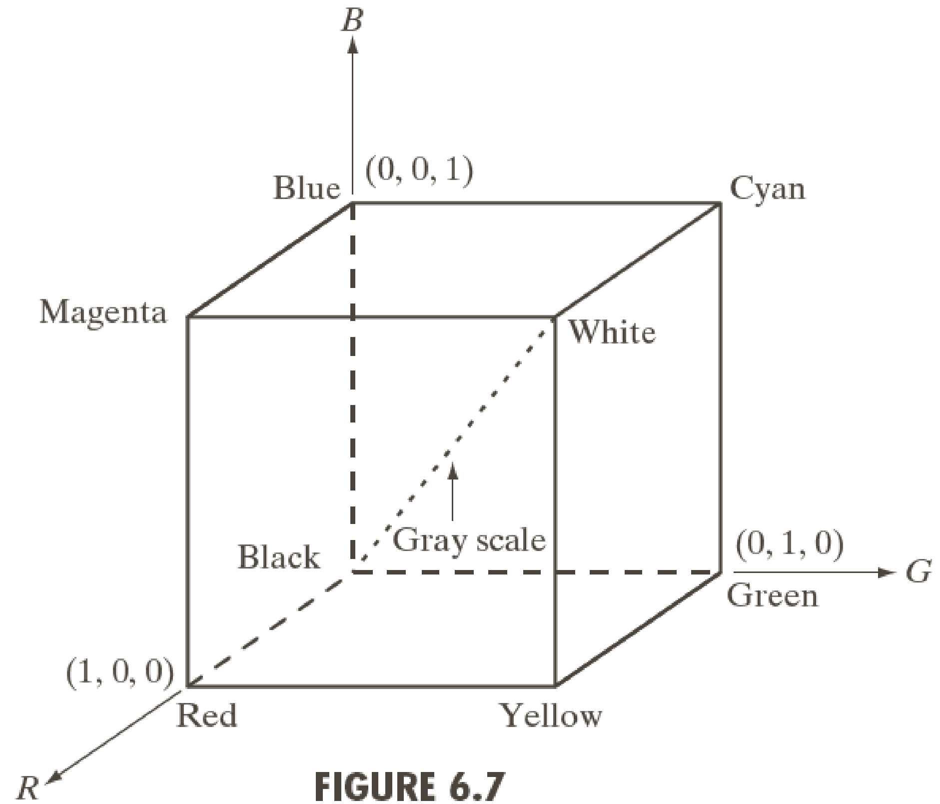


FIGURE 6.7 Schematic of the RGB color cube. Points along the main diagonal have gray values, from black at the origin to white at point (1, 1, 1).

The RGB Color Model

- The color values are normalized.
- So all values of R, G, B are in the range [0, 1]

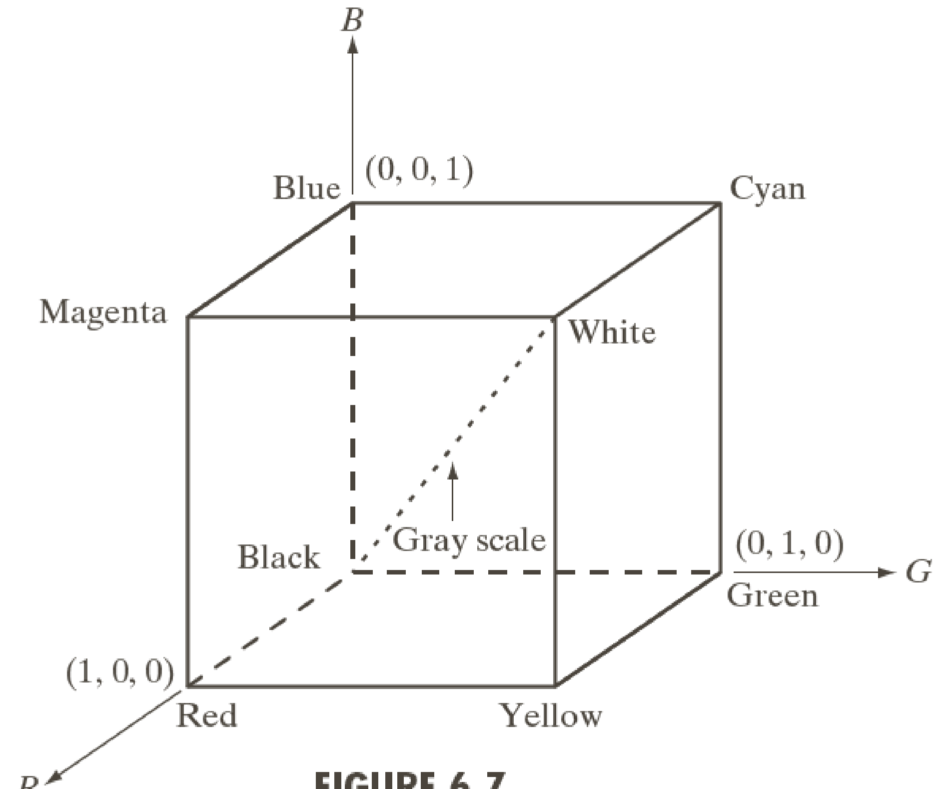


FIGURE 6.7 Schematic of the RGB color cube. Points along the main diagonal have gray values, from black at the origin to white at point (1, 1, 1).

- Images represented in RGB color model consist of three component images, one for each primary color.
- When fed into an RGB monitor, these three images combine on the screen to produce a composite color image.
- The number of bits used to represent each pixel in RGB space is called the pixel depth.
- Consider an RGB image in which each of the red, green, and blue images is an 8-bit image.
- Under these conditions each RGB color pixel is said to have a depth of 24 bits.
- The total number of colors in a 24-bit RGB image is

$$(2^8)^3 = 16{,}777{,}216$$

- The below figure shows the 24-bit RGB color cube.

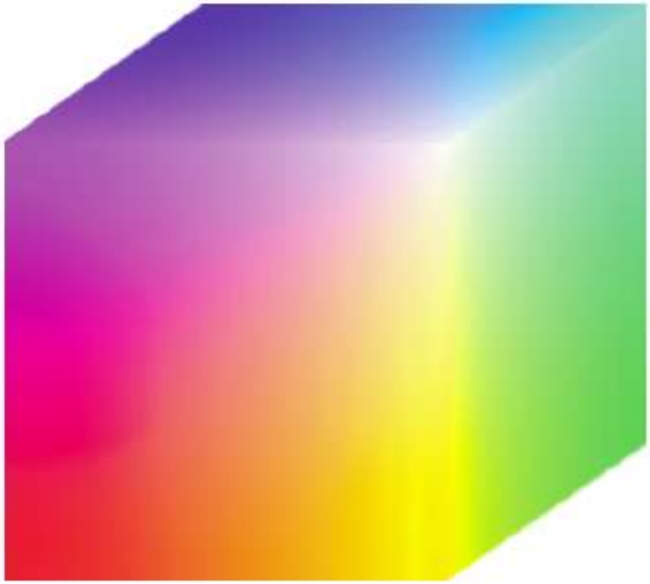


FIGURE 6.8 RGB 24-bit color cube.

- A cross sectional plane through the center of the cube and parallel to the GB-plane is the plane (127,G,B) for G, B = 0,1,2,.....255
- Here we used the actual pixel values rather than the normalized values in the range [0, 1]

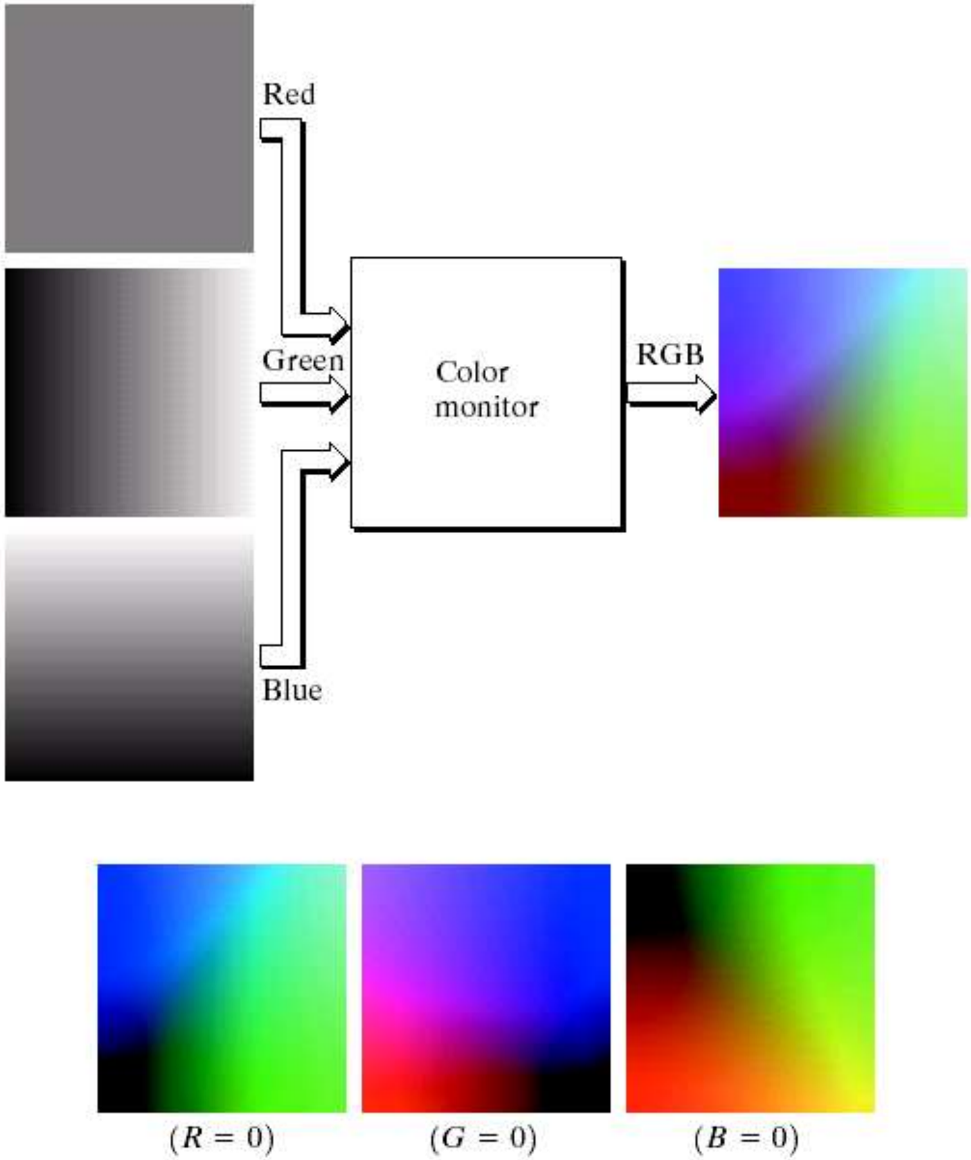


FIGURE 6.9 (a) Generating the RGB image of the cross-sectional color plane $(127, G, B)$. (b) The three hidden surface planes in the color cube of Fig. 6.8.

Safe colors

- Many of the computer systems in use today are limited to 256 colors.
- Forty of these 256 colors are known to be processed differently by various operating systems.
- The remaining 216 colors are common to most systems.
- These 216 colors form the set called safe RGB colors.

- Each of these safe colors is formed from three RGB values.
- These RGB values can only be 0, 51, 102, 153, 204, or 255.
- Thus RGB triplets of these values give us 6x6x6 = 216 possible values.
- It is customary to express these values in Hexa decimal number system as shown below

Number System	Color Equivalents					
Hex	00	33	66	99	CC	FF
Decimal	0	51	102	153	204	255

TABLE 6.1 Valid values of each RGB component in a safe color.

Safe RGB colors

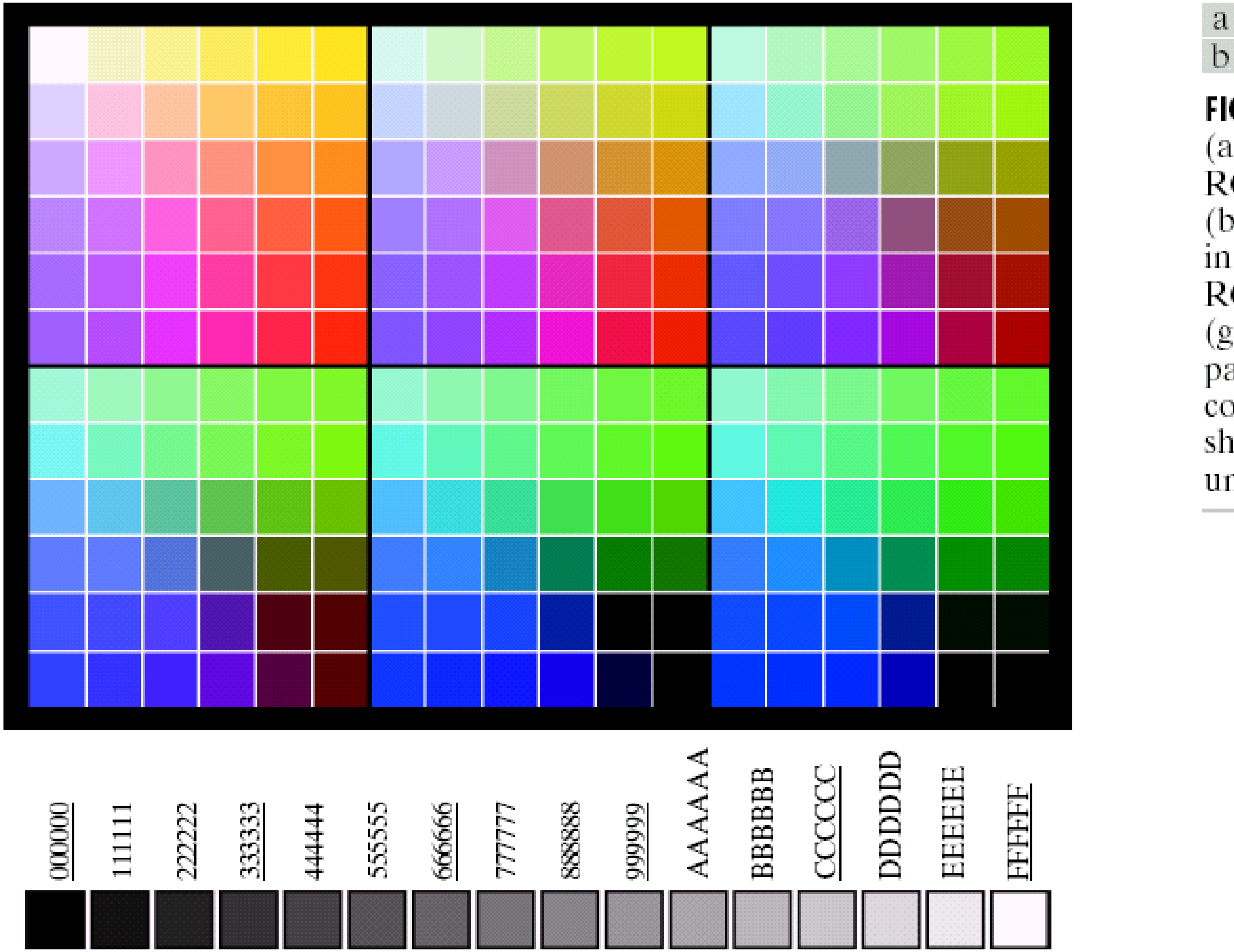


FIGURE 6.10 (a) The 216 safe RGB colors. (b) All the grays in the 256-color RGB system (grays that are part of the safe color group are shown underlined).

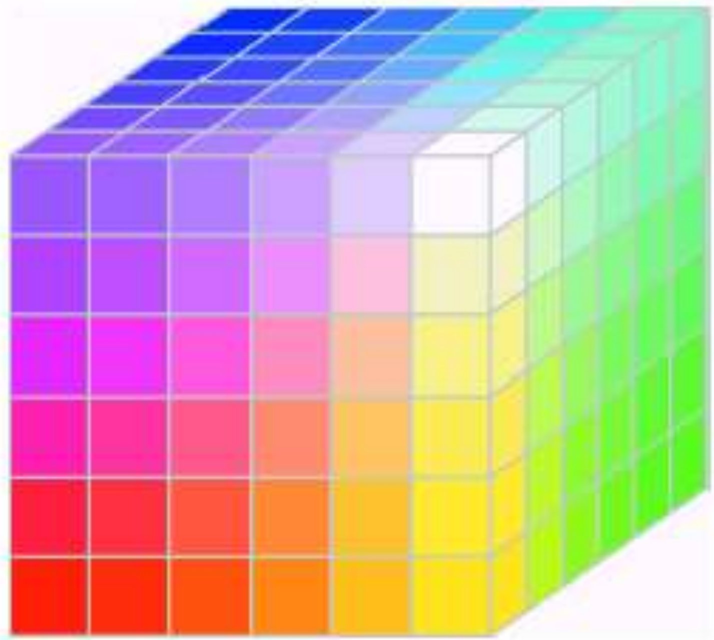


FIGURE 6.11 The RGB safe-color cube.

CMY and CMYK color models

- Cyan, Magenta, and Yellow are the secondary colors of light or, alternatively primary colors of pigments.
- Devices such as color printers and copiers that deposit colored pigments on paper require CMY data input or perform an RGB to CMY conversion internally.

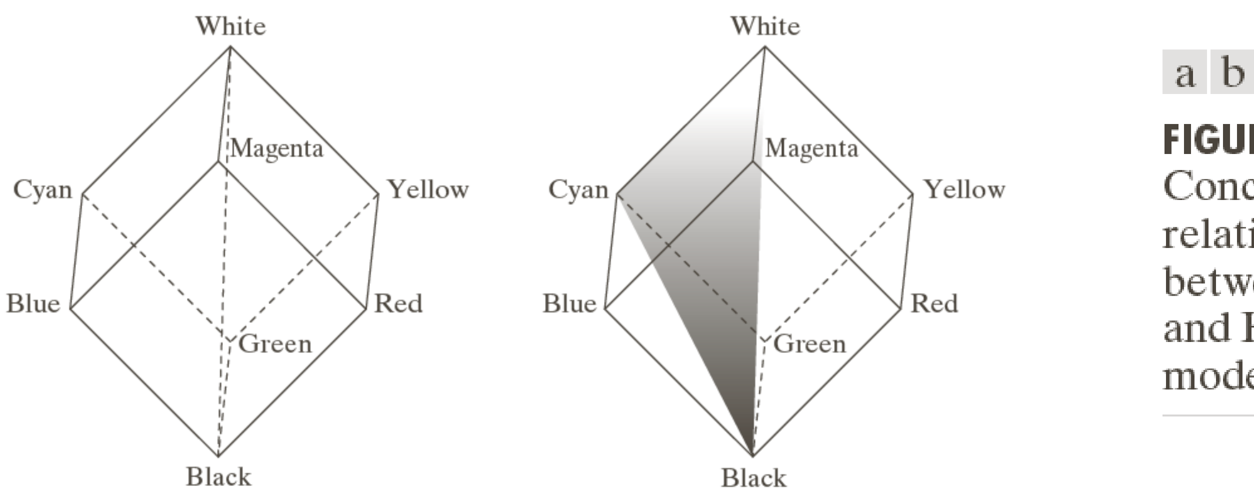


FIGURE 6.12 Conceptual relationships between the RGB and HSI color models.

- The conversion is performed using the simple operation

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

all color values are to be normalized to the range [0,1].

- The above equation demonstrates that light reflected from a surface coated with pure cyan does not contain red (that is C = 1- R in the equation)
- Similarly, pure magenta does not reflect green and pure yellow does not reflect blue.
- Equal amounts of the pigment primaries,cyan, magenta and yellow produces black.

- The equation also reveals that RGB values can be obtained easily from a set of CMY values by subtracting the individual CMY values from 1.
- Equal amounts of the pigment primaries , cyan, magenta and yellow produces black.
- In practice, combining these colors for printing produces a muddy-looking black.
- So in order to produce true black (which is a predominant color in printing) , a fourth color, black, is added , giving rise to the CMYK color model.

- Convert the given pixel value (127,100,250) , in RGB color model to CMY model.
- Normalize the RGB values

R = 127/255 = 0.49

G = 100/255 = 0.39

B = 250/255 = 0.98

Applying the conversion formula

C = 1- 0.49 = 0.51

M = 1 - 0.39 = 0.61

Y = 1 - 0.98 = 0.02

So the pixel value in CMY model is (0.51,0.61,0.02)

HSI Color Model

- The RGB and CMY are not well suited for describing colors in terms that are practical for human interpretation.
- When humans view a color object, we describe it by its hue, saturation and brightness.
- Hue is color attribute that describes a pure color(pure yellow,orange or red).
- Saturation gives a measure of the degree to which pure color is diluted by white light.
- Brightness embodies the achromatic notion of intensity

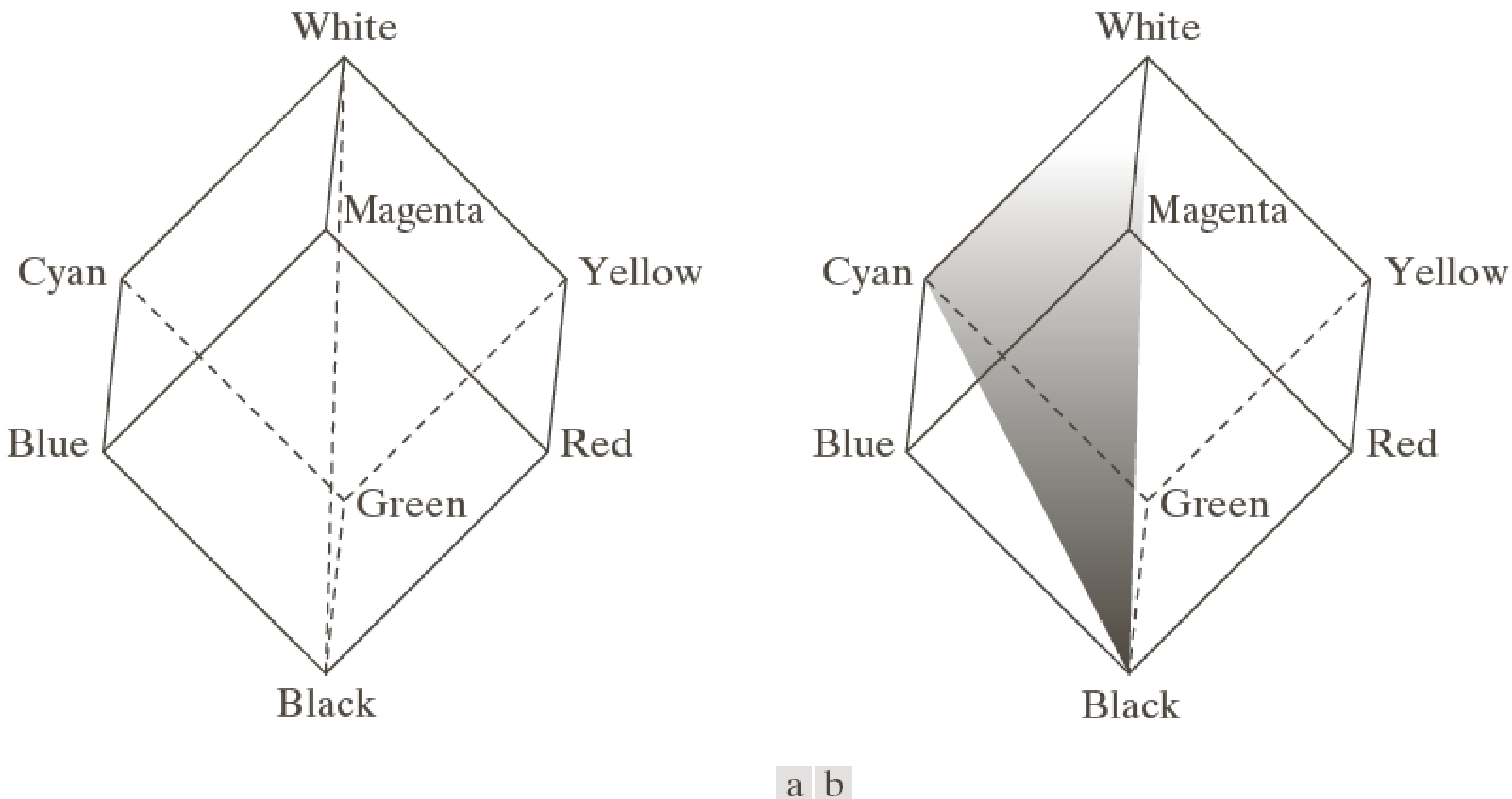


FIGURE 6.12 Conceptual relationships between the RGB and HSI color models.

- HSI color space is represented by a vertical intensity axis and the locus of color points that lie on planes perpendicular to this axis.
- As planes move up and down the intensity axis the boundaries defined by the intersection of each plane with the faces of the cube have either a triangular or hexagonal shape.
- The hue of an arbitrary point is determined by an angle from some reference point.
- Usually an angle of zero degrees from the red axis designates 0 hue, and the hue increases counter clockwise from there.
- The saturation is the length of the vector from the origin to the point.
- The intersection of the plane containing the point with intensity axis would give us the intensity value in the range [0,1].

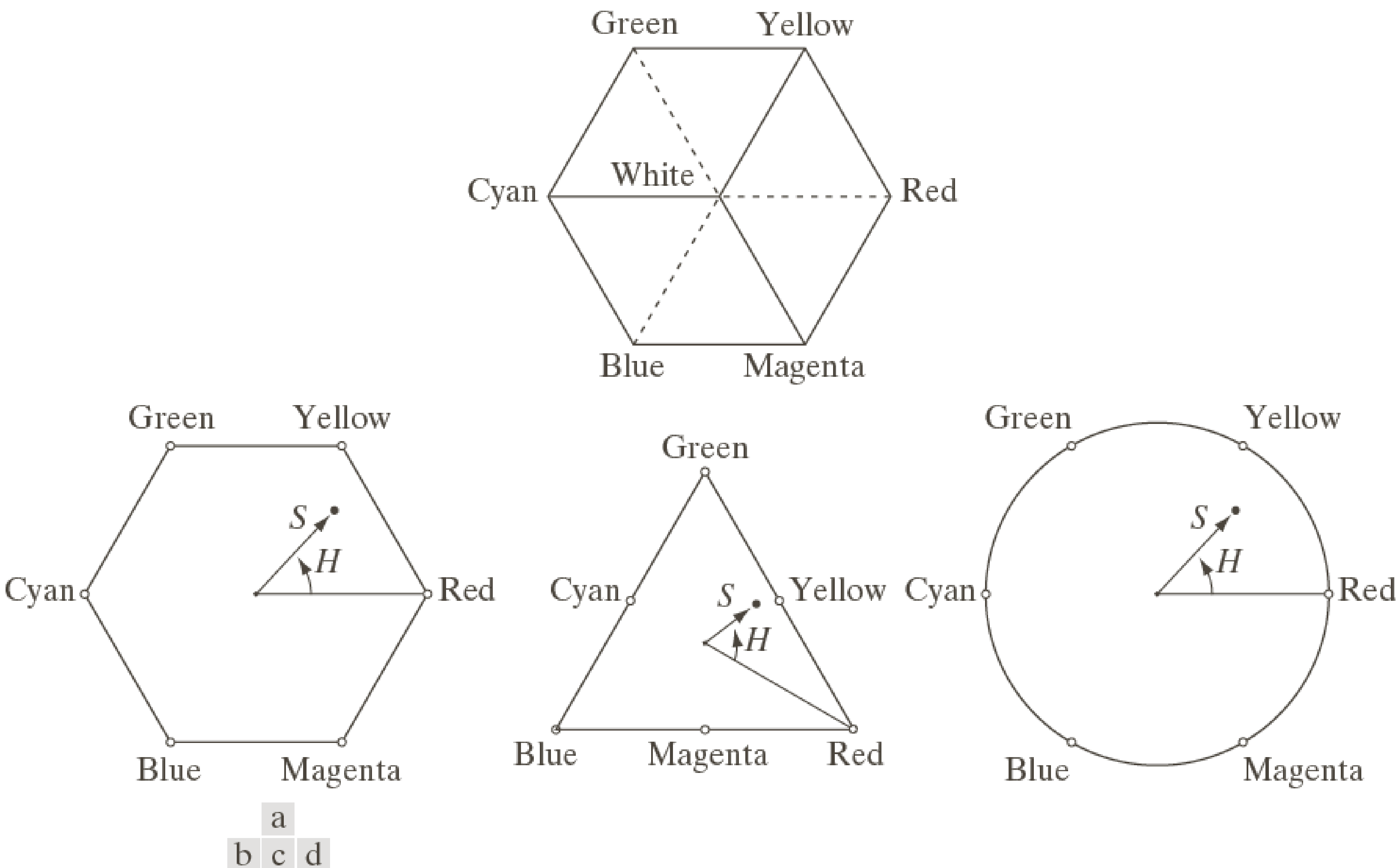
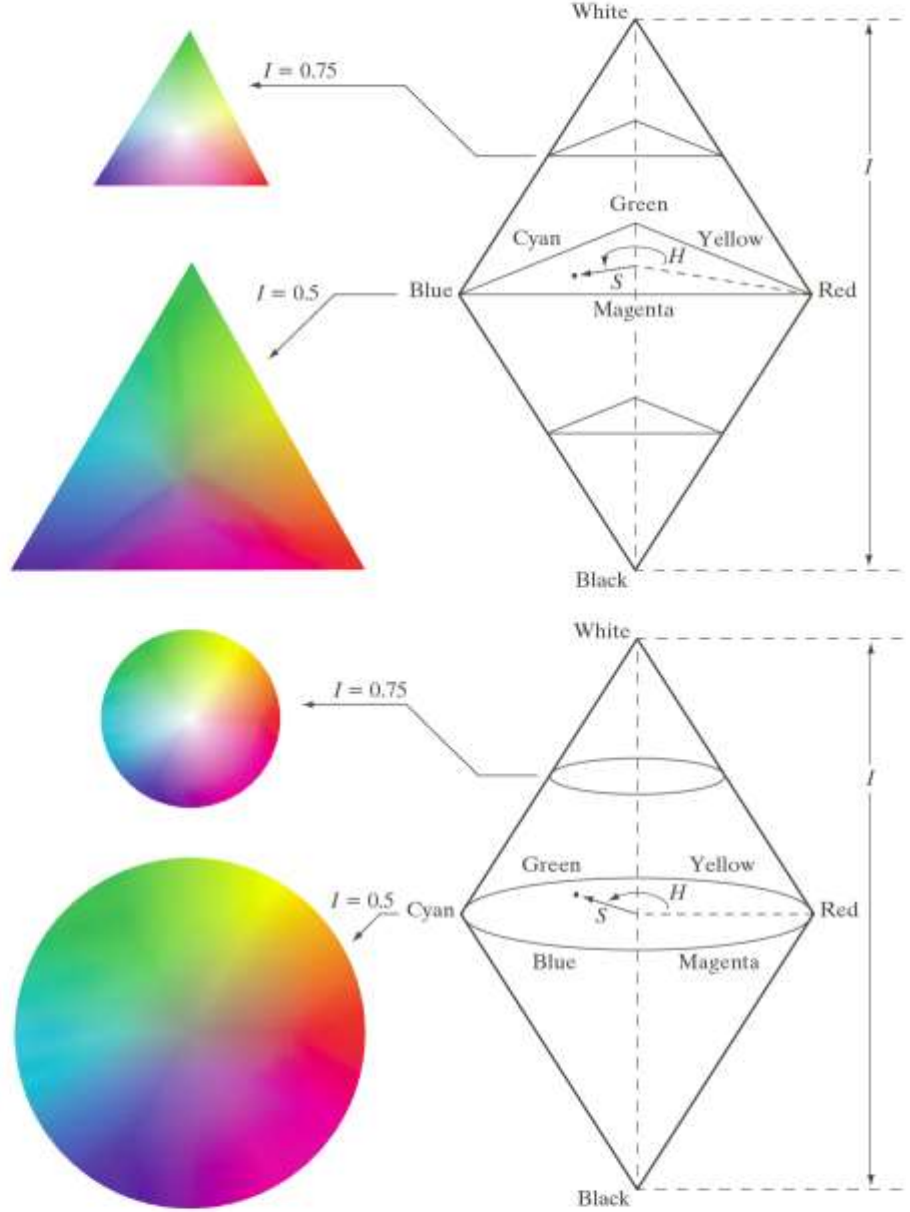


FIGURE 6.13 Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and the length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.



a
b

FIGURE 6.14 The HSI color model based on (a) triangular and (b) circular color planes. The triangles and circles are perpendicular to the vertical intensity axis.

Converting colors from RGB to HSI

- Given an image in RGB color format, the H component of each RGB pixel is obtained using the equation

$$H = \begin{cases} \theta & \text{if } B \leq G \\ 360 - \theta & \text{if } B > G \end{cases}$$

with

$$\theta = \cos^{-1}\left\{\frac{\frac{1}{2}[(R-G)+(R-B)]}{[(R-G)^2+(R-B)(G-B)]^{1/2}}\right\}$$

- The saturation component is given by

$$S = 1 - \frac{3}{(R+G+B)}[\min(R,G,B)]$$

- The intensity component is given by $I = \frac{1}{3}(R+G+B)$

- Given an RGB color pixel value (125,200,100) . Obtain its corresponding HSI pixel values.
- The first step is to normalize RGB values to the scale [0,1] as shown below.

R = 125/255 = 0.49

G = 200/255 = 0.78

B = 100/255 = 0.39

The above values are used for obtaining H,S,and I values.

$$\theta = cos^{-1}\left\{\frac{\frac{1}{2}[\,(0.49-0.78)+(0.49-0.39)]}{[(0.49-0.78)^2+(0.49-0.39)(0.78-0.39)]^{\frac{1}{2}}}\right\}$$

$$\theta = cos^{-1}\left\{\frac{\frac{1}{2}[\,(-0.29)+(0.1)]}{[(-0.29)^2+(0.1)(0.39)]^{\frac{1}{2}}}\right\}$$

$$\theta = cos^{-1}\left\{\frac{-0.09}{0.35}\right\}$$

$$\theta = cos^{-1}\{-0.26\} = 105.07\ degrees$$

$$Since\ B \le G\ , \qquad Hue\ (H) = \ \theta = 105.07\ degrees$$

$$Saturation\ (S\ ) = \ 1 - \frac{3}{0.49+0.78+0.39}[\min(0.49{,}0.78{,}0.39)]$$

$$= 1 - \frac{3}{1.66}[0.39]$$

$$= \ 1 - 0.70 \ = \ 0.3$$

$$Intensity\ (I) = \frac{1}{3}\ (0.49+0.78+0.39) = \ \frac{1}{3}\ (1.66) = \ 0.55$$

Converting colors from HSI to RGB

- Given values of HSI in the interval [0,1].
- To find corresponding RGB values, the applicable equations depend on the value of H.

RG sector ($0° \leq H < 120°$): When H is in this sector, the RGB components are given by the equations

$$B = I(1 - S) \tag{6.2-5}$$

$$R = I\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \tag{6.2-6}$$

and

$$G = 3I - (R + B) \tag{6.2-7}$$

GB sector ($120° \leq H < 240°$): If the given value of H is in this sector, we first subtract 120° from it:

$$H = H - 120° \qquad (6.2\text{-}8)$$

Then the RGB components are

$$R = I(1 - S)$$

$$G = I\left[1 + \frac{S \cos H}{\cos(60° - H)}\right]$$

and

$$B = 3I - (R + G)$$

BR sector ($240° \le H \le 360°$): Finally, if H is in this range, we subtract 240° from it:

$$H = H - 240° \tag{6.2-12}$$

Then the RGB components are

$$G = I(1 - S) \tag{6.2-13}$$

$$B = I\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \tag{6.2-14}$$

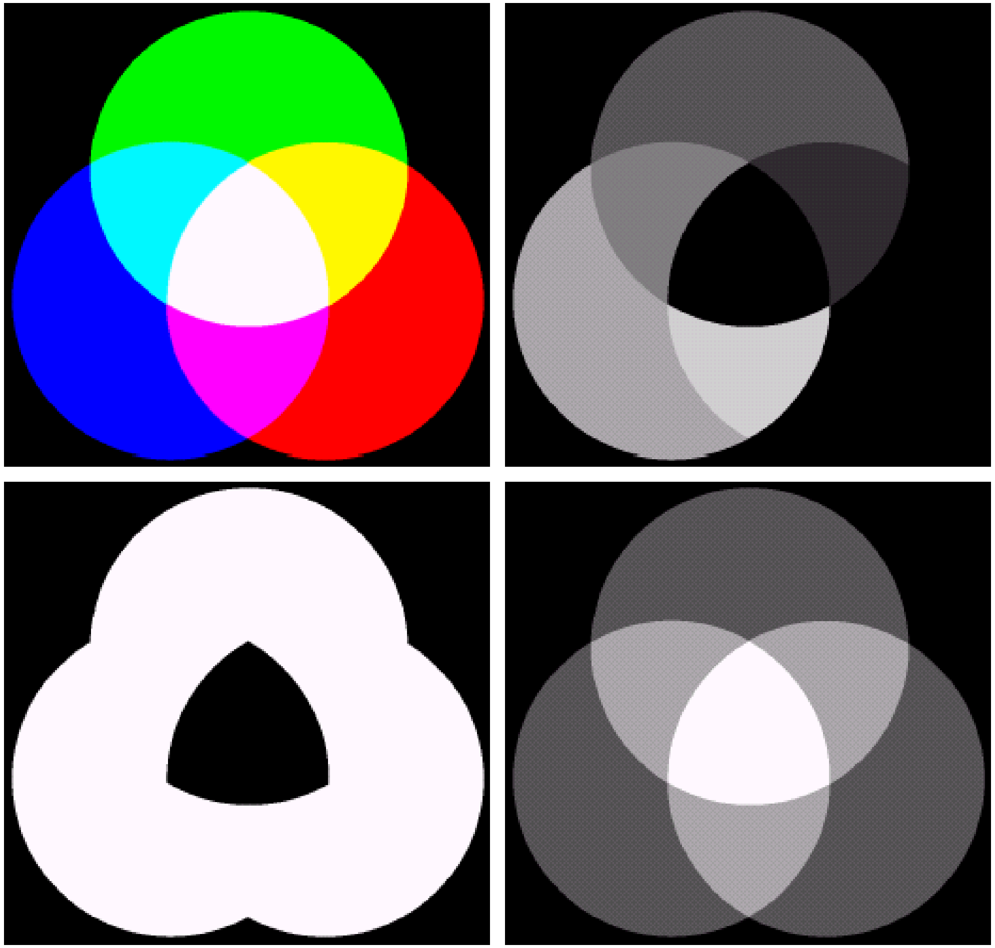
and

$$R = 3I - (G + B) \tag{6.2-15}$$

- Given HSI color pixel values (85degrees,0.8,0.5). Obtain its corresponding RGB pixel values.

HSI component images

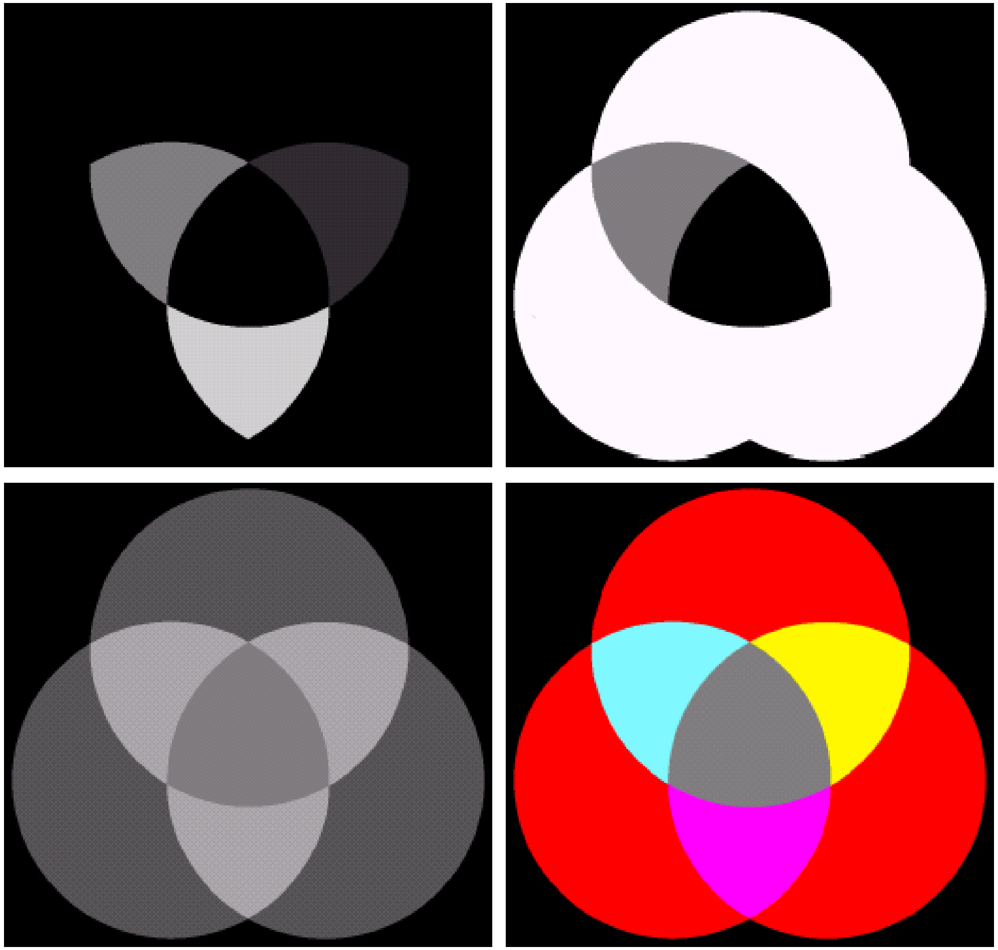
- HSI image have three component images
  - Hue component image
  - Saturation component image
  - Intensity component image
- To change the individual color of any region in the RGB image, we change the corresponding values in hue component image keeping S and I unchanged.
- To change saturation (purity) of the color of any region, we make changes in saturation component image of the region keeping H and I unchanged.
- Similarly comments apply to change average intensity of any region.
- Of course these changes can be made simultaneously.



a b
c d

FIGURE 6.16 (a) RGB image and the components of its corresponding HSI image: (b) hue, (c) saturation, and (d) intensity.

- Image (a) is obtained by changing to 0 the pixels corresponding to blue and green regions of 6.16(b)
- In (b) we reduced by half the saturation of the cyan region in S component image from fig 6.16(c)
- In (c) we reduced by half the intensity of the central white region of fig 6.16(d)
- (d) is the modified HSI image converted to RGB



a	b
c	d

FIGURE 6.17 (a)–(c) Modified HSI component images. (d) Resulting RGB image. (See Fig. 6.16 for the original HSI images.)

Pseudocolor Image Processing

- Pseudocolor(also called false color) image processing consists of assigning colors to gray values based on a specified criterion.
- The principal use of pseudocolor is for human visualization and interpretation of gray-scale events in an image or sequence of images.
- Two methods of generating pseudocolor images
  - Intensity slicing
  - Gray level to color transformations

Intensity Slicing

- The technique of intensity (sometimes called density) slicing and color coding is one of the simplest examples of pseudocolor image processing.

In general, the technique may be summarized as follows. Let $[0, L-1]$ represent the gray scale, 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 $l_1, l_2, \ldots, l_P$. Then, assuming that $0 < P < L-1$, the P planes partition the gray scale into $P+1$ intervals, $V_1, V_2, \ldots, V_{P+1}$. Intensity to color assignments are made according to the relation

$$f(x, y) = c_k \qquad \text{if } f(x, y) \in V_k \tag{6.3-1}$$

where c_k is the color associated with the kth intensity interval V_k defined by the partitioning planes at $l = k-1$ and $l = k$.

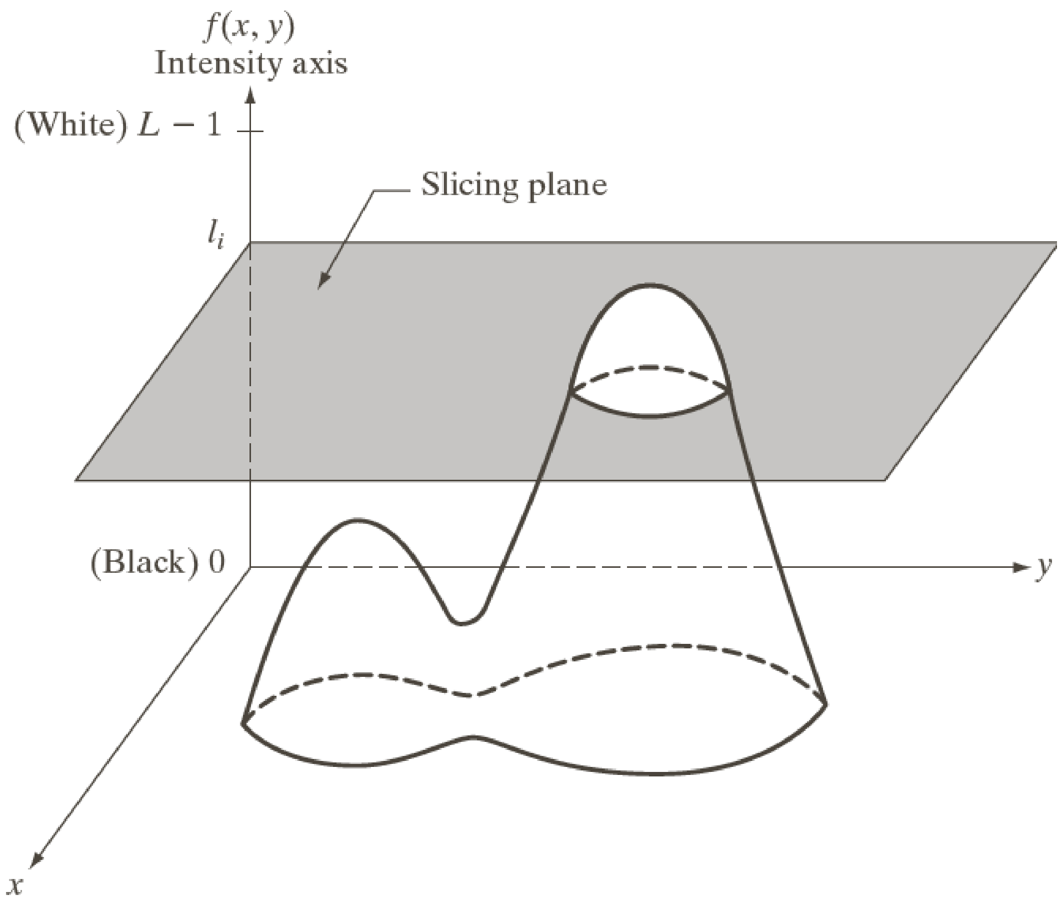


FIGURE 6.18 Geometric interpretation of the intensity-slicing technique.

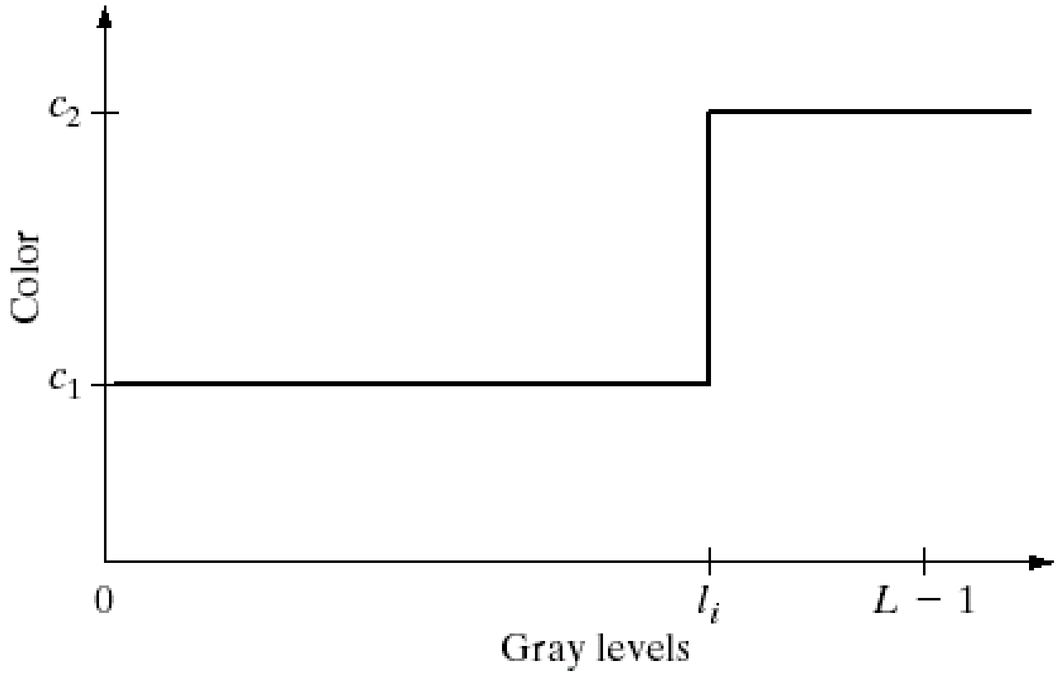
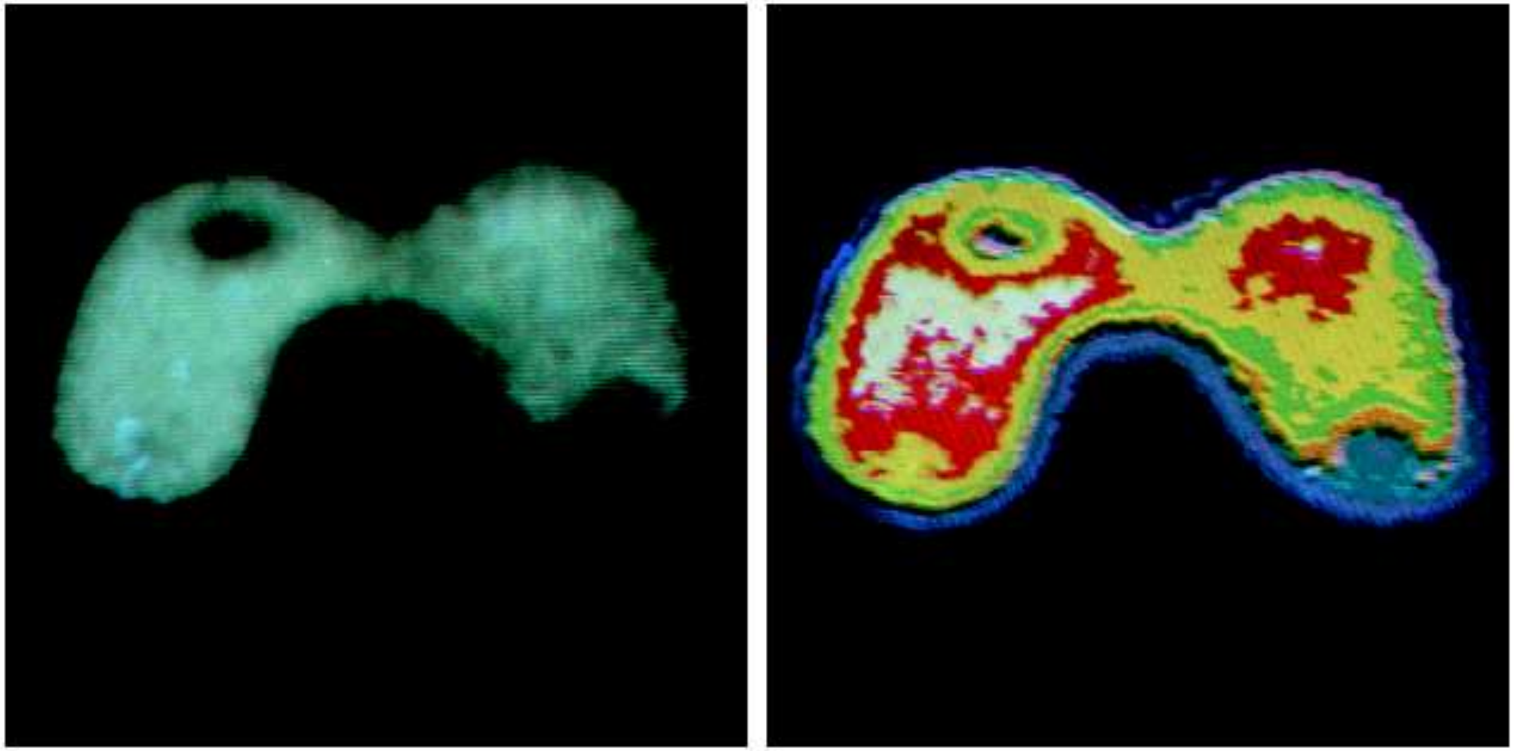


FIGURE 6.19 An alternative representation of the intensity-slicing technique.

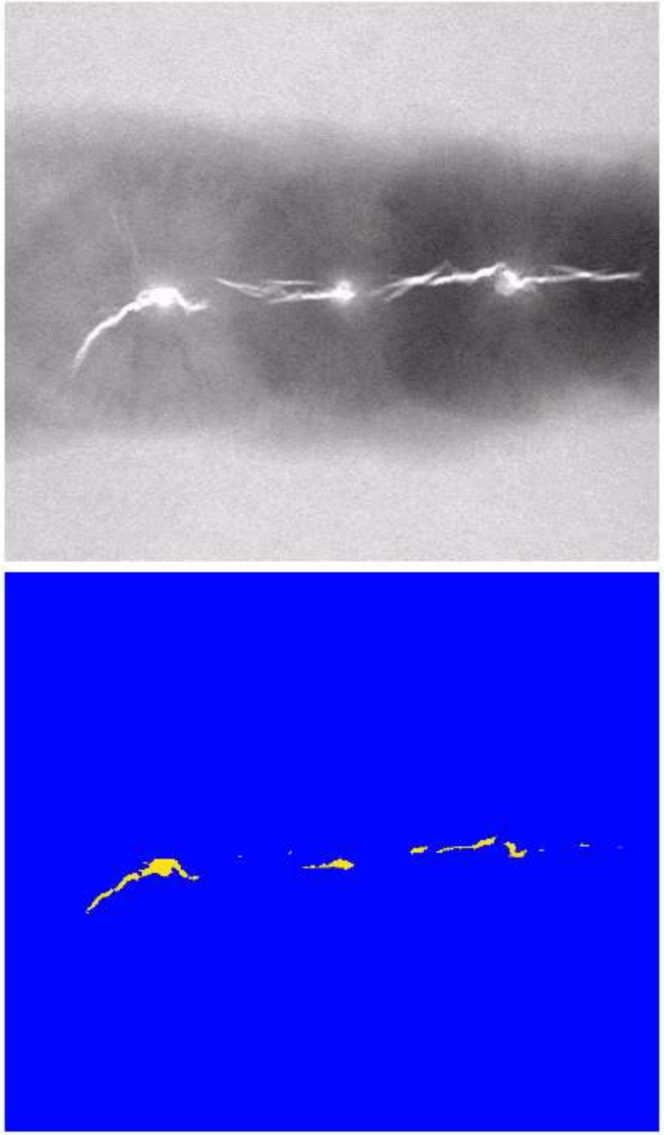


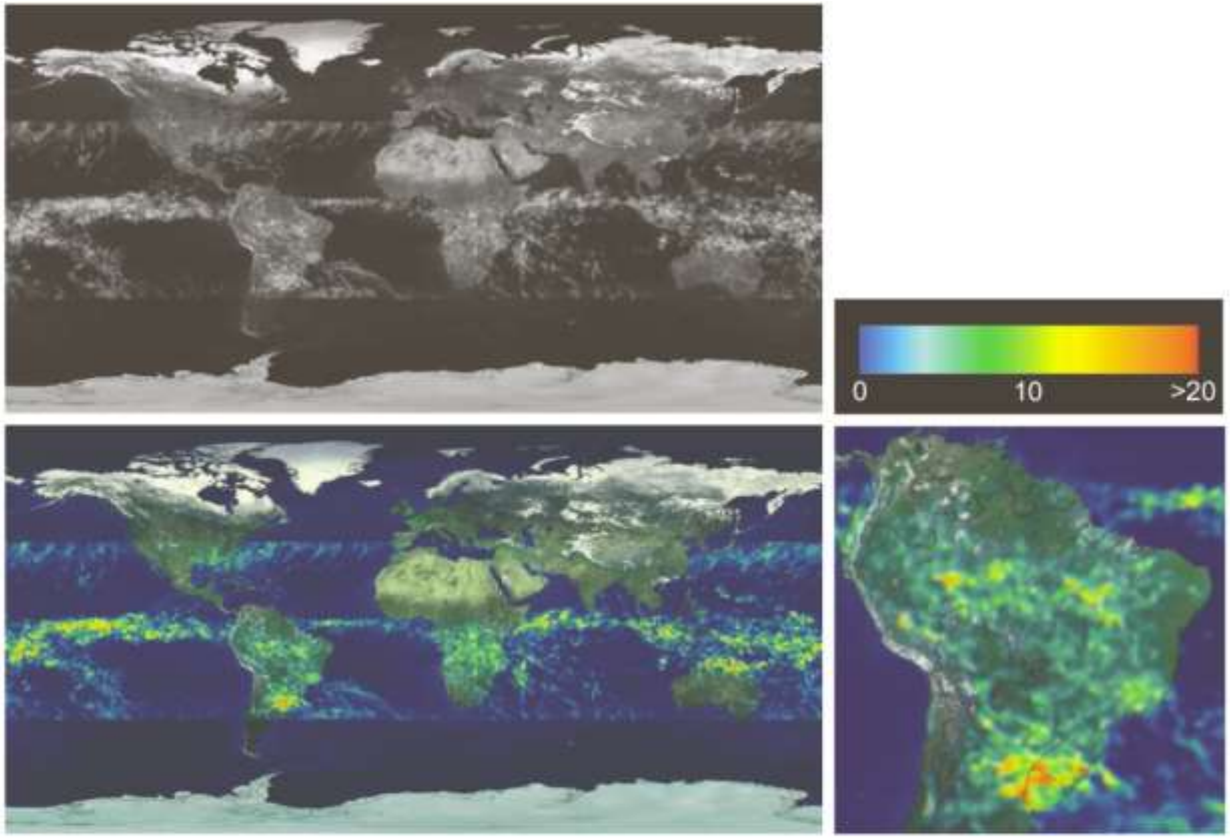
a b

FIGURE 6.20 (a) Monochrome image of the Picker Thyroid Phantom. (b) Result of density slicing into eight colors. (Courtesy of Dr. J. L. Blankenship, Instrumentation and Controls Division, Oak Ridge National Laboratory.)

a
b

FIGURE 6.21 (a) Monochrome X-ray image of a weld. (b) Result of color coding. (Original image courtesy of X-TEK Systems, Ltd.)





a b
c d

FIGURE 6.22 (a) Gray-scale image in which intensity (in the lighter 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.)

Gray level to Color Transformation

- The idea underlying this approach is to perform three independent transformations on the intensity of any input pixel.
- The three results are then fed separately into the red, green, and blue channels of a color television monitor.
- Thus producing a composite image whose color content is modulated by the nature of the transformation functions.

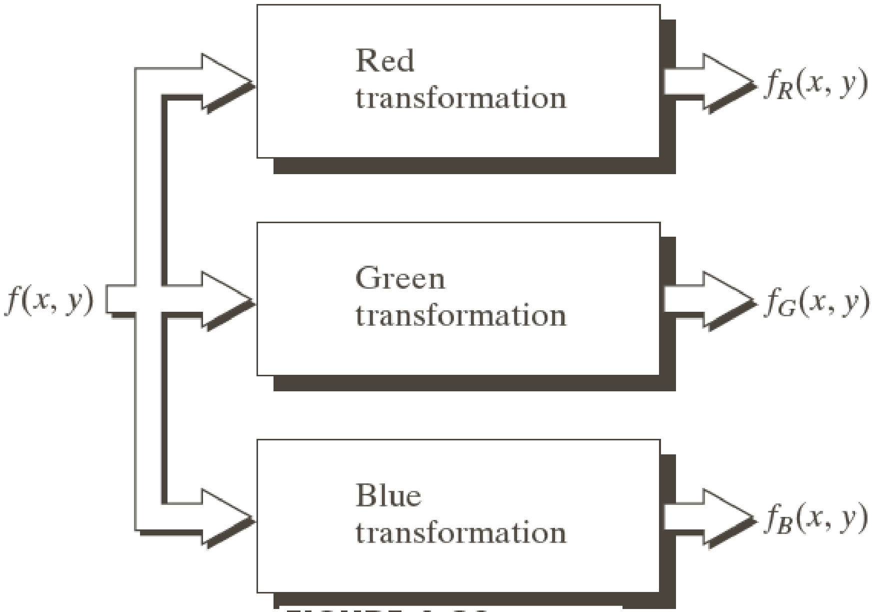
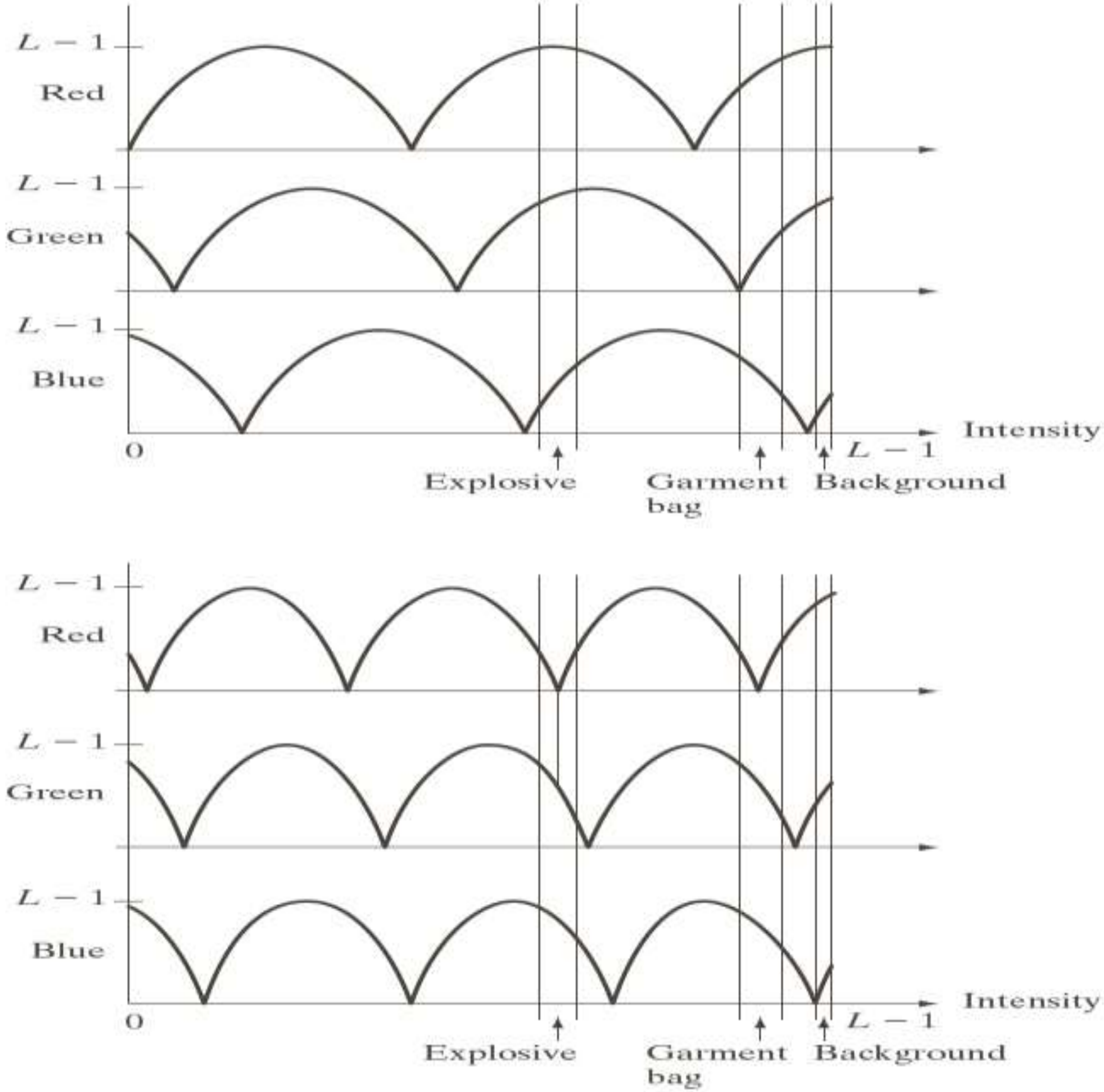


FIGURE 6.23 Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.



a
b

FIGURE 6.25 Transformation functions used to obtain the images in Fig. 6.24.

- Changing the phase and frequency of each sinusoid can emphasize (in color) ranges in the gray scale

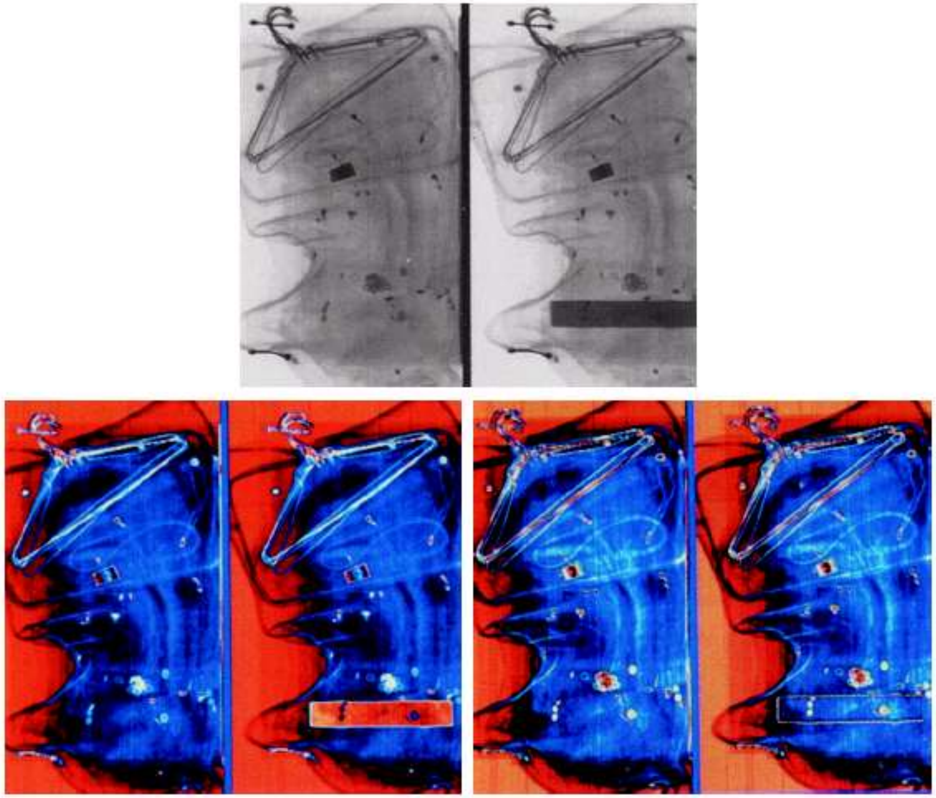


FIGURE 6.24 Pseudocolor enhancement by using the gray-level to color transformations in Fig. 6.25. (Original image courtesy of Dr. Mike Hurwitz, Westinghouse.)

Color coding of multispectral images

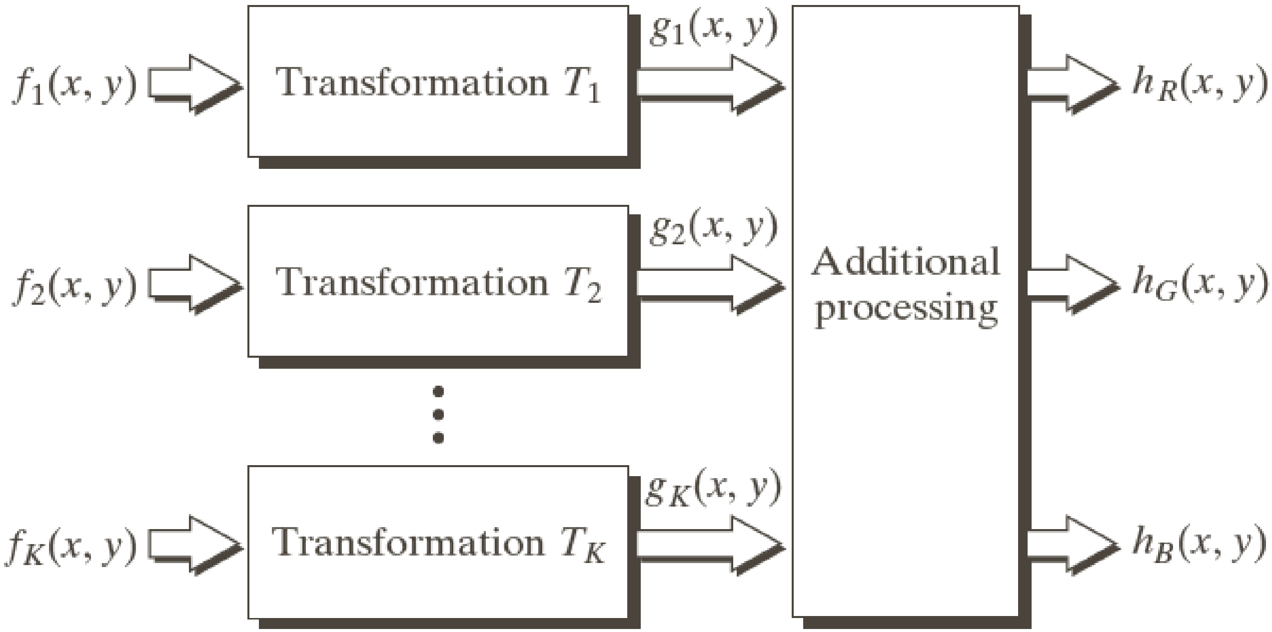


FIGURE 6.26 A pseudocolor coding approach used when several monochrome images are available.

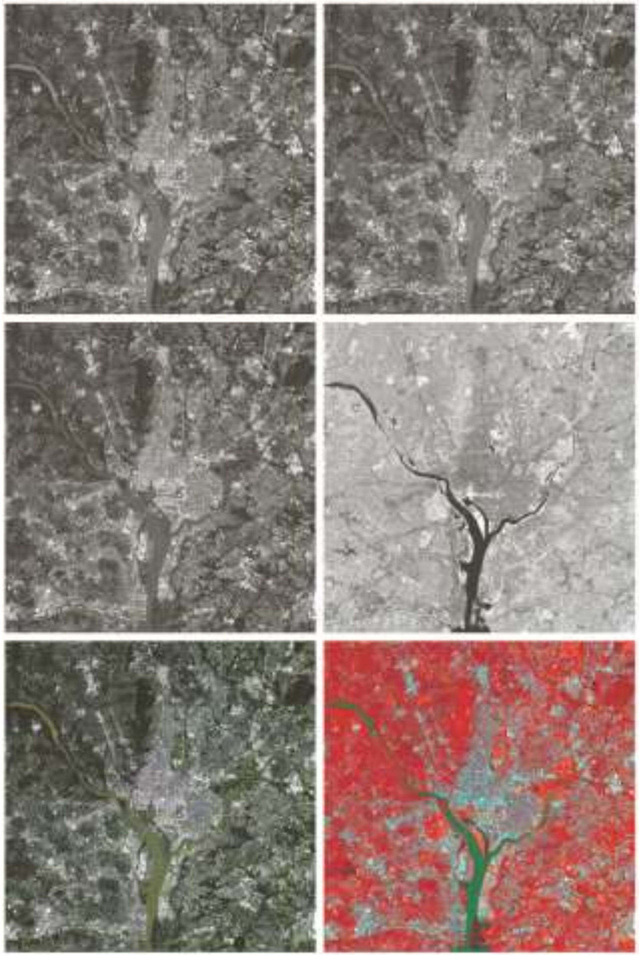


FIGURE 6.27 (a)–(d) Images in bands 1–4 in Fig. 1.10 (see Table 1.1). (e) Color composite image obtained by treating (a), (b), and (c) as the red, green, blue components of an RGB image. (f) Image obtained in the same manner, but using in the red channel the near-infrared image in (d). (Original multispectral images courtesy of NASA.)

a b
c d
e f

Basics of Full-Color Image Processing

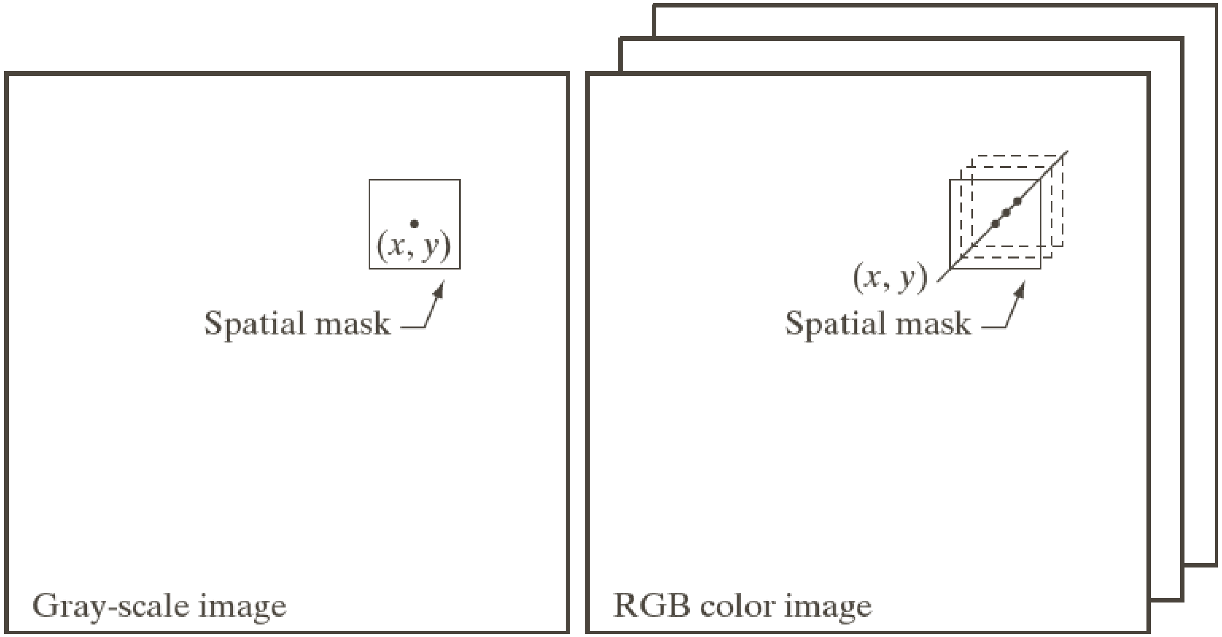
- Full color image processing approaches fall into two major categories.
- In the first category, we process each component image individually and then form a composite processed color image from the individually processed components.
- In the second category, we work with color pixels directly.
- Color pixels are vectors.
- Let **c** represent an arbitrary vector in RGB color space:

$$c = \begin{bmatrix} c_R \\ c_G \\ c_B \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Color components are function of coordinates (x,y). So we use the notation

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

- For an image of size M X N, there are MN such vectors, **c**(x,y) ,
  for x = 0,1,2,.....,M-1; y = 0,1,2,............,N-1.
- The results of individual color component processingare not always equivalent to direct processing in color vector space.
- In such case we must formulate new approaches.
- In order for per-color-component and vector based processing to be equivalent, two conditions have to be satisfied:
  – First, the process has to be applicable to both vectors and scalars.
  – Second, the operation on each component of a vector must be independent of the other components.



a b

FIGURE 6.29 Spatial masks for gray-scale and RGB color images.

Chapter 6
Color Image Processing

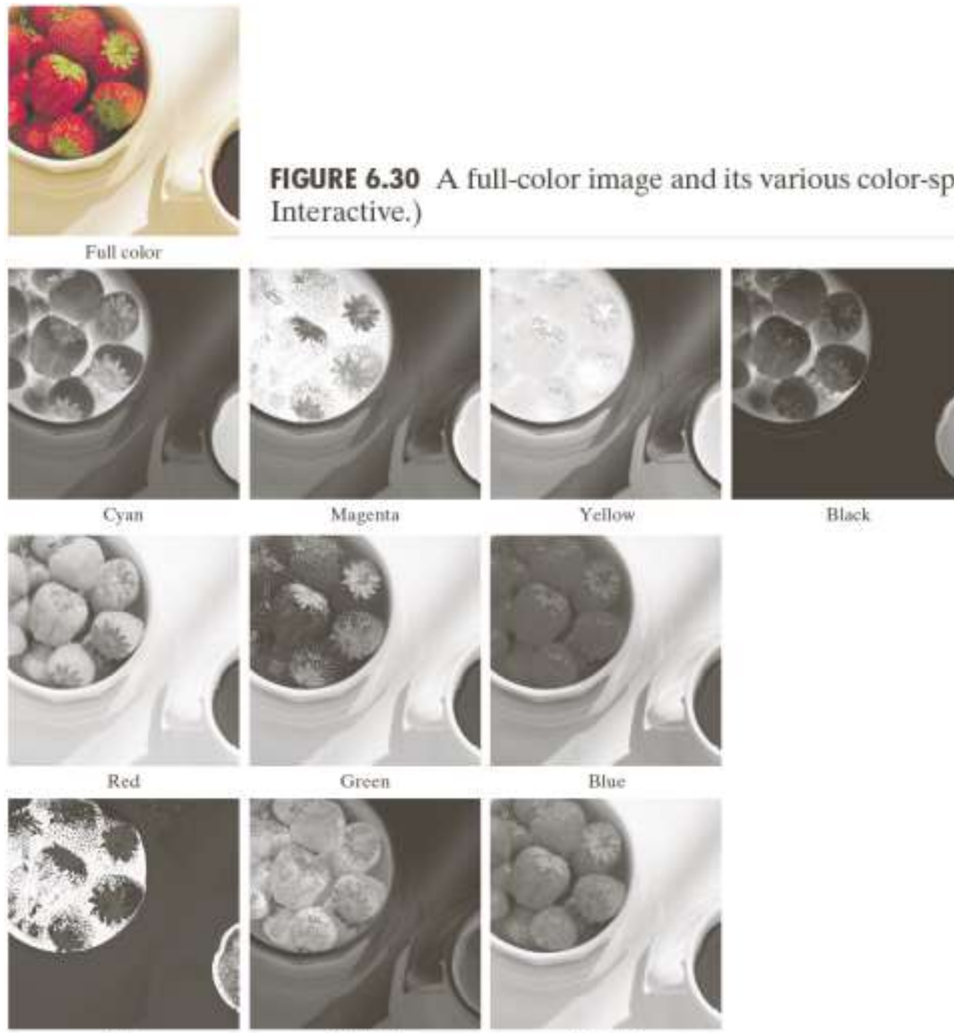


FIGURE 6.30 A full-color image and its various color-space components. Interactive.)