Color Fundamentals

- The process followed by the human brain in perceiving and interpreting color is a physiopsychological phenomenon that is not yet fully understood, the physical nature of color can be expressed on a formal basis supported by experiment and theoretical results.
- In 1666, Sir Isaac Newton discovered that when a beam of sunlight passes through a glass prism, the emerging beam of light us not white but consist in stead of a continuous spectrum of colors ranging from violet at one end to red at the other.

Color Fundamentals

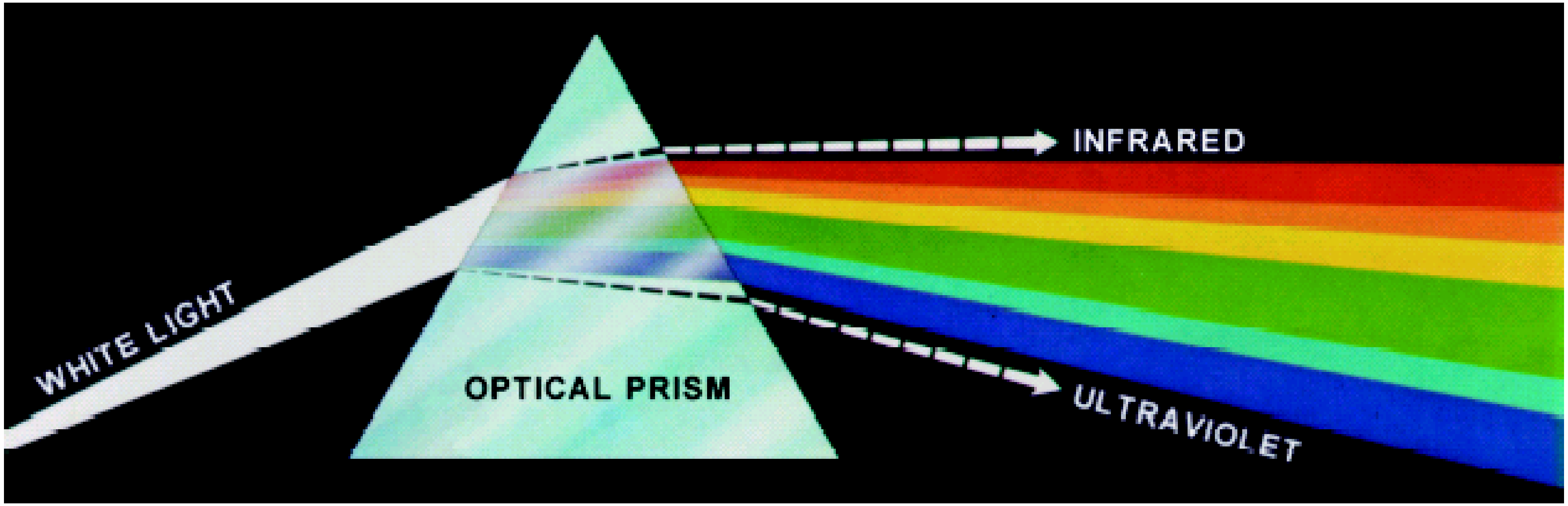
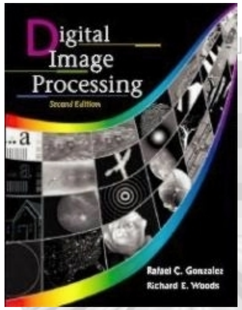


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)



Color Fundamentals

- Visible light is composed of a relatively narrow brand of frequencies in the electromagnetic spectrum.
- If the light is achromatic (void of color), its only attribute is its intensity, or amount.
- Achromatic light is what viewers see on a black and white television set.
- Chromatic light spans the electromagnetic spectrum from approximately 400 to 700 nm.

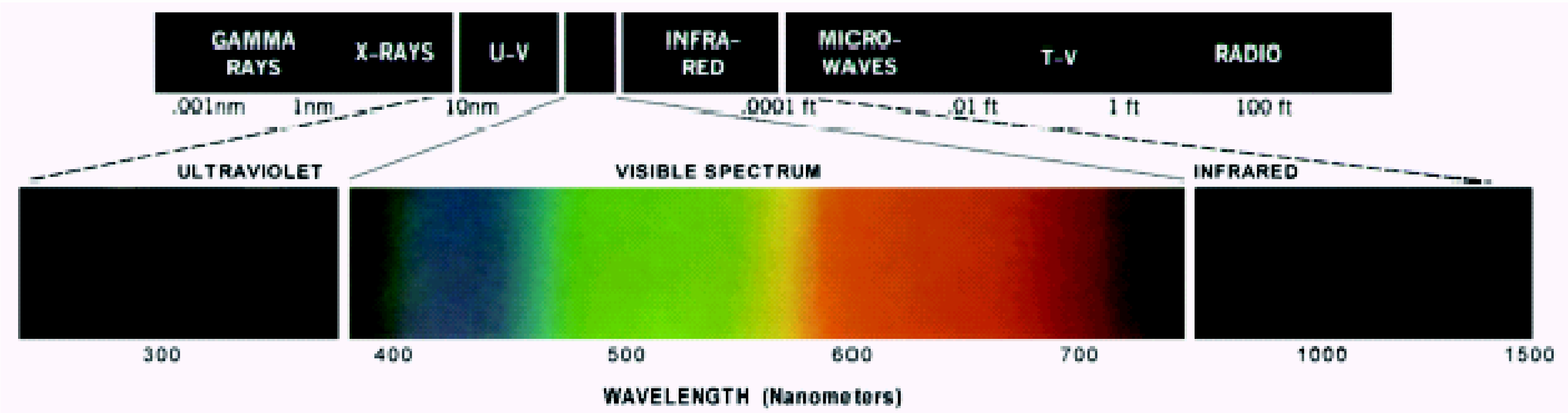


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

Color Fundamentals

- Three basic quantities are used to describe the quality of a chromatic light source: radiance, luminance, and brightness.
  - Radiance is the total amount of energy that flow from the light source, and it is usually measured in watts (W).
  - Luminance, measured in lumens (lm), gives a measure of the amount of energy 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

- 6 to 7 million cones in the human eye can 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 (but that blue cones are the most sensitive).
- Due to these absorption characteristics of the human eyes, colors are seen as variable combinations of the so-called primary colors red (R), green (G), and blue (B).

Color Fundamentals

- It is important to keep in mind that having 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.

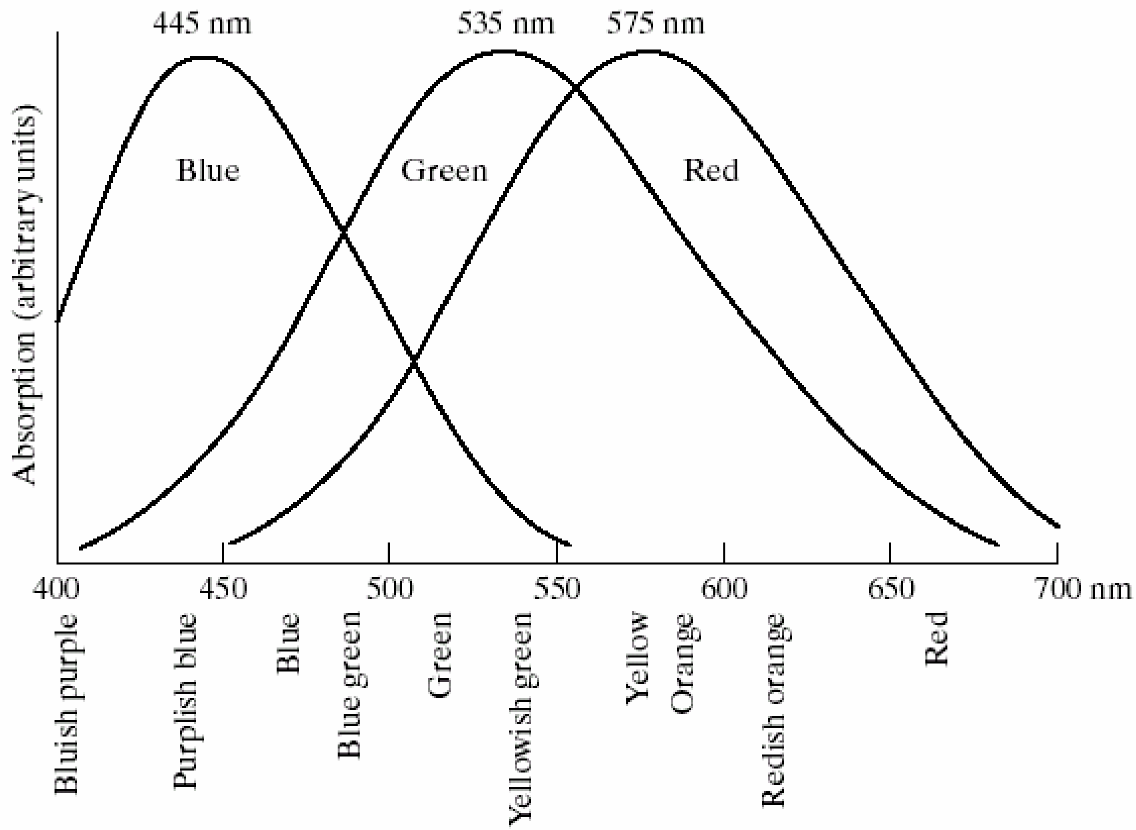
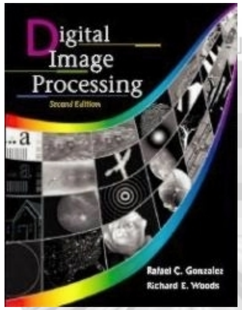
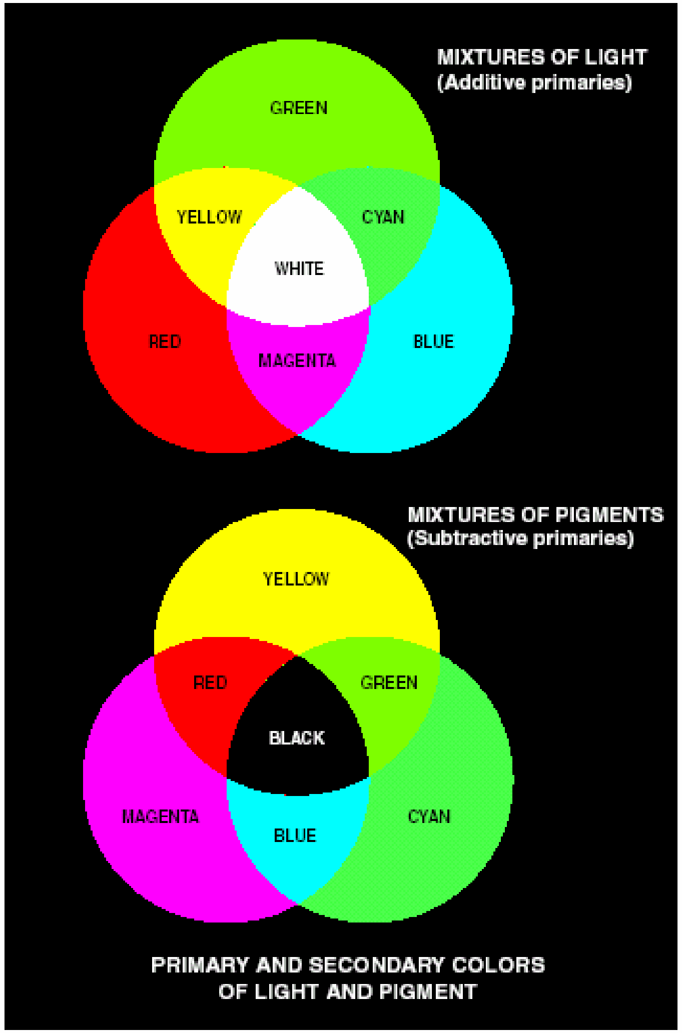


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

Color Fundamentals

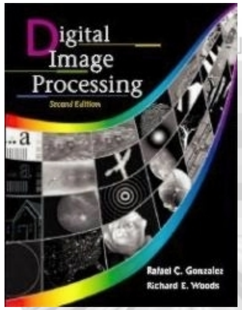
- The primary colors can be added to produce the secondary colors of light - magenta (red plus blue), cyan (green plus blue), and yellow (red plus green).





a
b

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



Color Fundamentals

- The characteristics generally used to distinguish one color from another are brightness, hue, and saturation.
- Hue is an attribute associated with the dominant wavelength in a mixture of light waves.
- Hue represent dominant color as perceived by an observer.
- Saturation refers to the relatives purity or the amount of white light mixed with a hue.

Color Fundamentals

- The pure spectrum color are fully saturation.
- Hue and saturation taken together are called chromaticity, and therefore, a color may be characterized by its brightness and chromaticity.

Color Fundamentals

- CIE chromaticity diagram (Fig 6.5), which show 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 from Eq.(6.1-4) by noting that z=1-(x+y).

$$x = \frac{X}{X+Y+Z} \quad (6.1-1)$$

$$y = \frac{Y}{X+Y+Z} \quad (6.1-2)$$

$$z = \frac{Z}{X+Y+Z} \quad (6.1-3)$$

$$x + y + z = 1 \quad (6.1-4)$$

Color Fundamentals

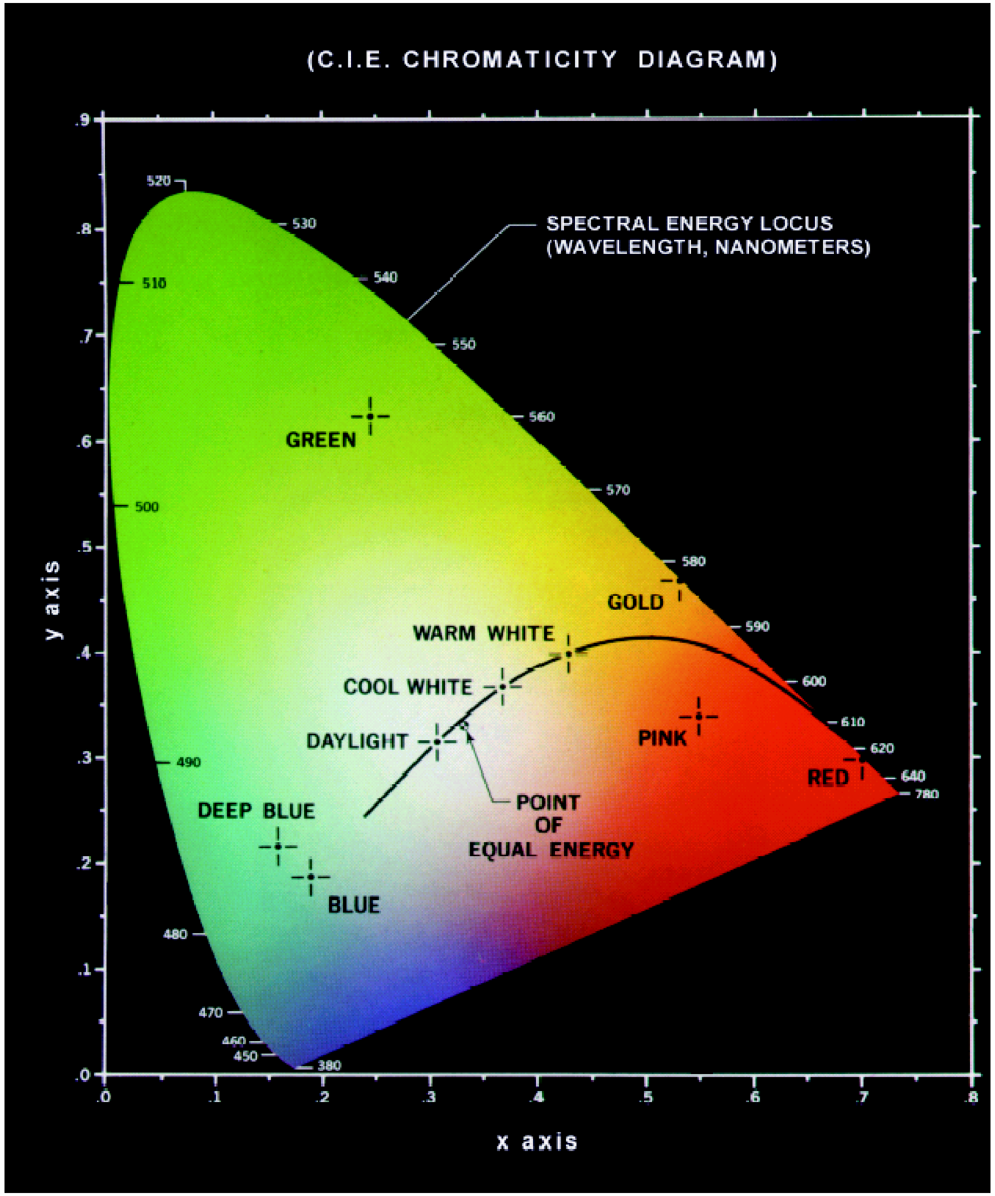
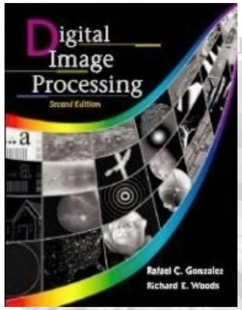


FIGURE 6.5 Chromaticity diagram. (Courtesy of the General Electric Co., Lamp Business Division.)

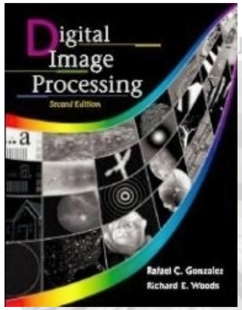
Color Fundamentals

- Any point not actually on the boundary but within the diagram represents some mixture o spectrum colors.
- 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

- The triangle in Figure 6.6 shows a typical range of colors (called the color gamut) produced by RGB monitors.
- The irregular region inside the triangle is representative of the color gamut of today's high-quality color printing devices.
- The boundary of the color printing gamut is irregular because color printing is a combination of additive and subtractive color mixing, a process that is much more difficult to control than that of displaying colors on a monitor.



Color Fundamentals

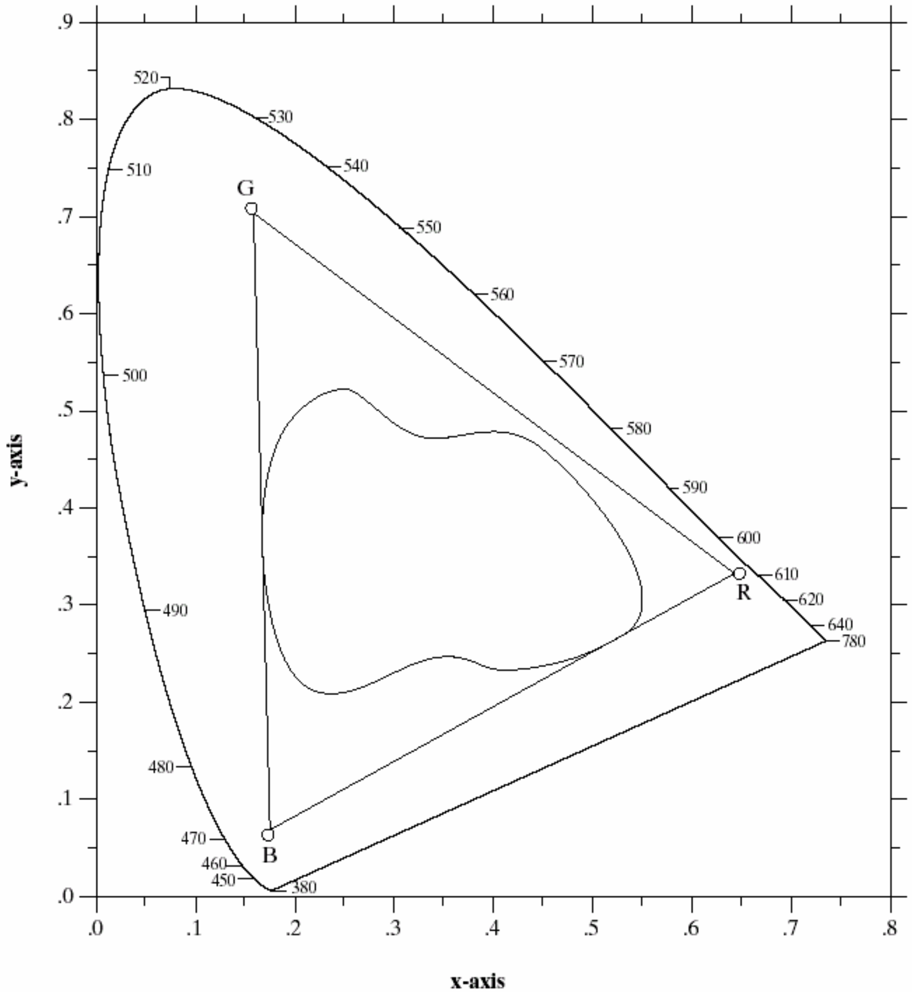


FIGURE 6.6 Typical color gamut of color monitors (triangle) and color printing devices (irregular region).

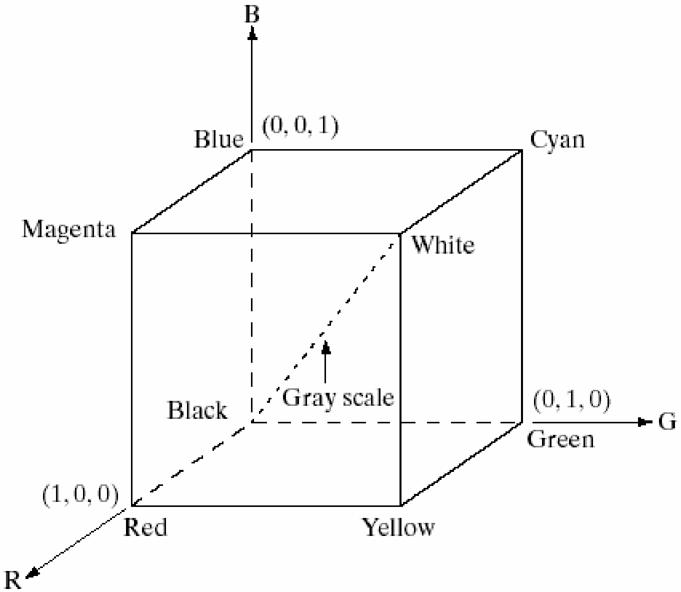
Color Models

- RGB (red, green, blue) model for color monitors and a board class of color video cameras.
- CMY (cyan, magenta, yellow) and CMYK (cyan, magenta, yellow, black) models for color printing.
- HIS (hue, saturation, intensity) model, which corresponds closely with the way humans describe and interpret color.
- The HIS model also has the advantage that it decouples the color and gray-scale information in an image, making it suitable for many of the gray-scale techniques.

The RGB Color Model

- RGB image in which each of the red, green, and blue images is an 8-bit image.
- The term full-color image is used often to denote a 24-bit RGB color image.

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).



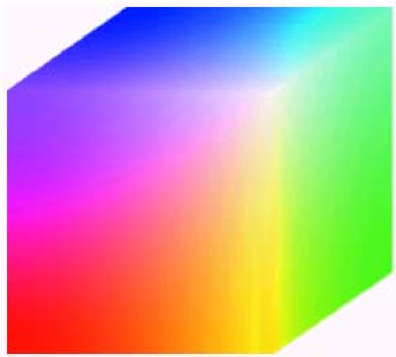
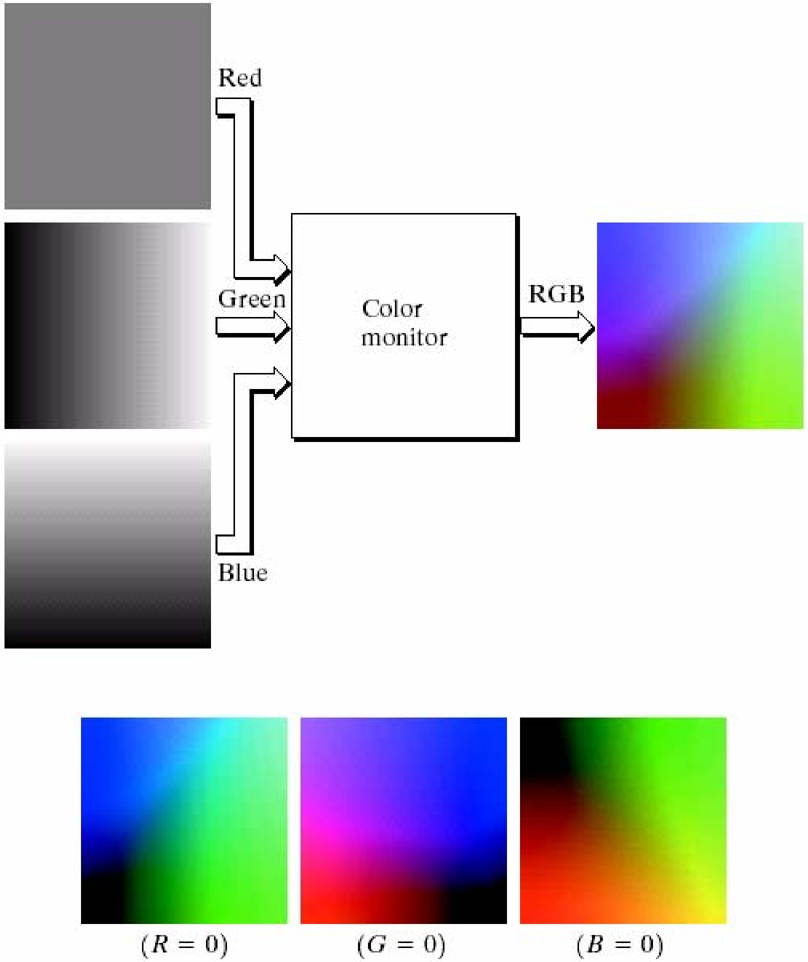


FIGURE 6.8 RGB 24-bit color cube.

The RGB Color Model

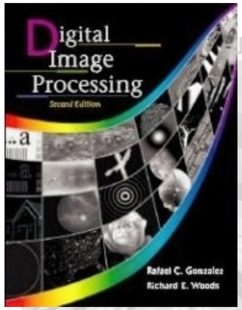


a
b

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.

The RGB Color Model

- Many systems in use today are limited to 256 colors.
- On the assumption that 256 colors is the minimum number of colors that can be reproduced faithfully by any system in which desired result is likely to be displayed.
- Leaving only 216 colors that are common to systems.



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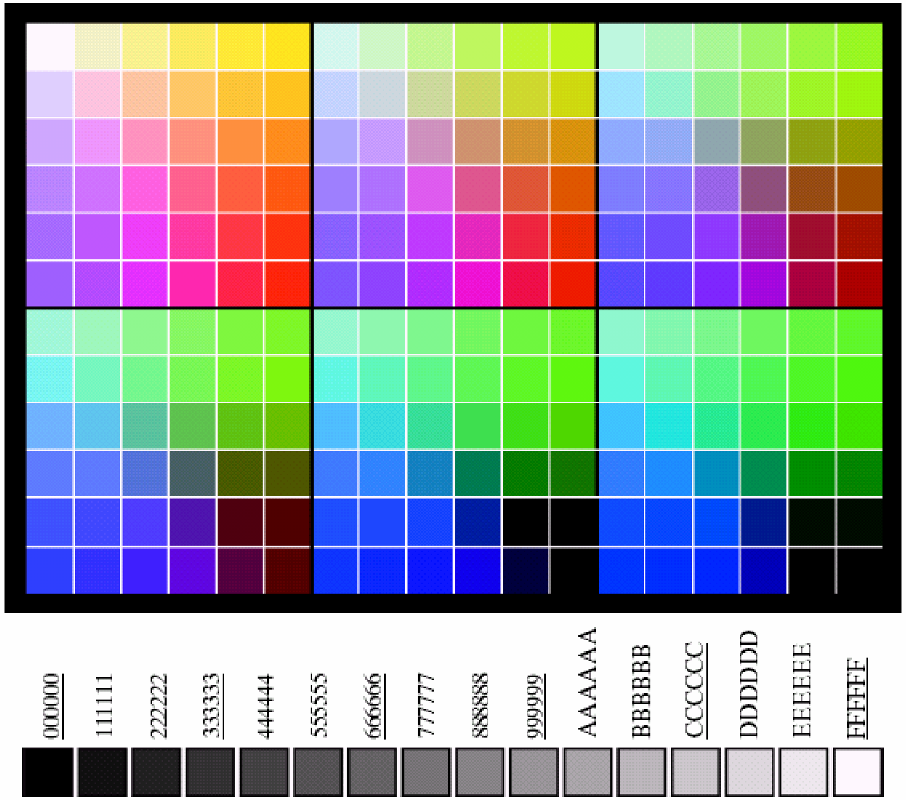
Number System	Color Equivalents					
Hex	00	33	66	99	CC	FF
Decimal	0	51	102	153	204	255

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



a
b

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).

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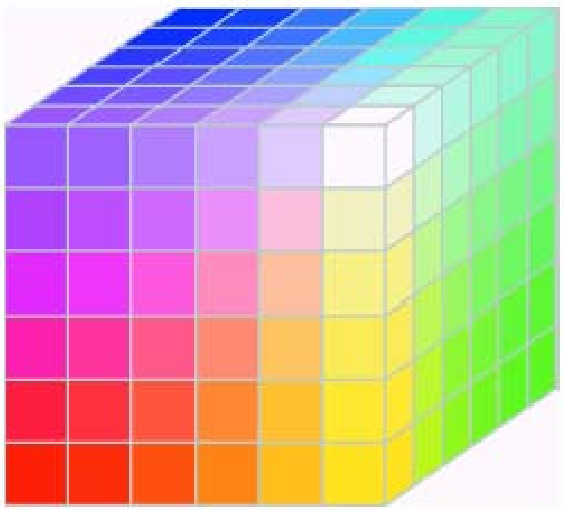

FIGURE 6.11 The RGB safe-color cube.

The CMY and CMYK Color Models

- Where, again, the assumption is that all color values have been normalized to the range [0,1].

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

The HIS Color Model

- When humans view a color object, we describe it by its hue, saturation, and brightness.
- Whereas saturation gives a measure of the degree to which a pure color is diluted by white light.
- 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.

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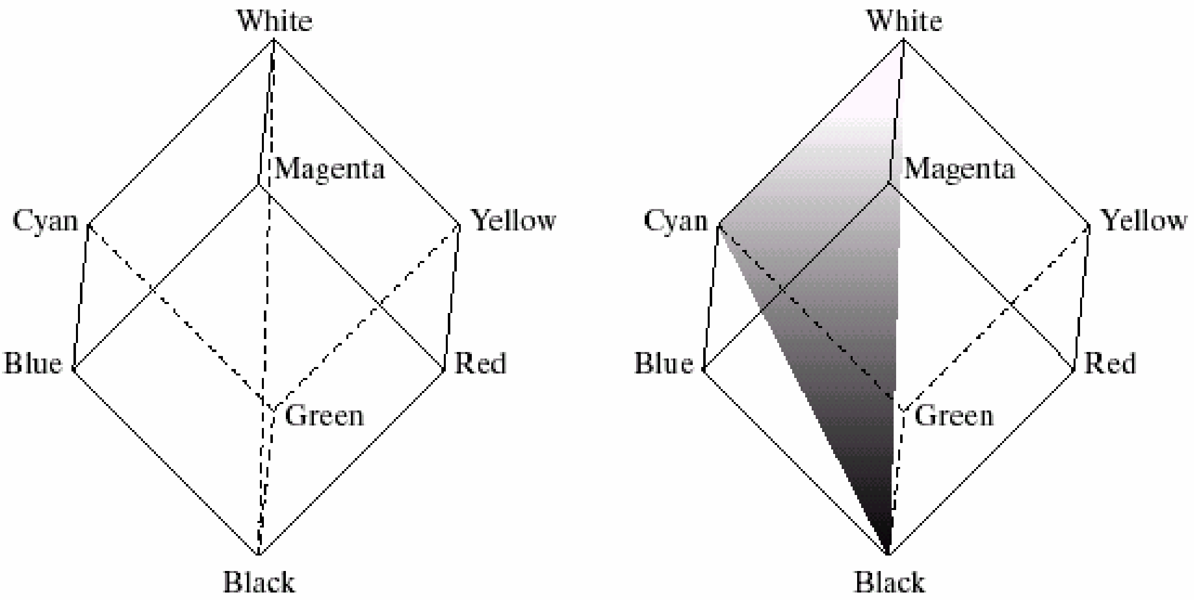

a b

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

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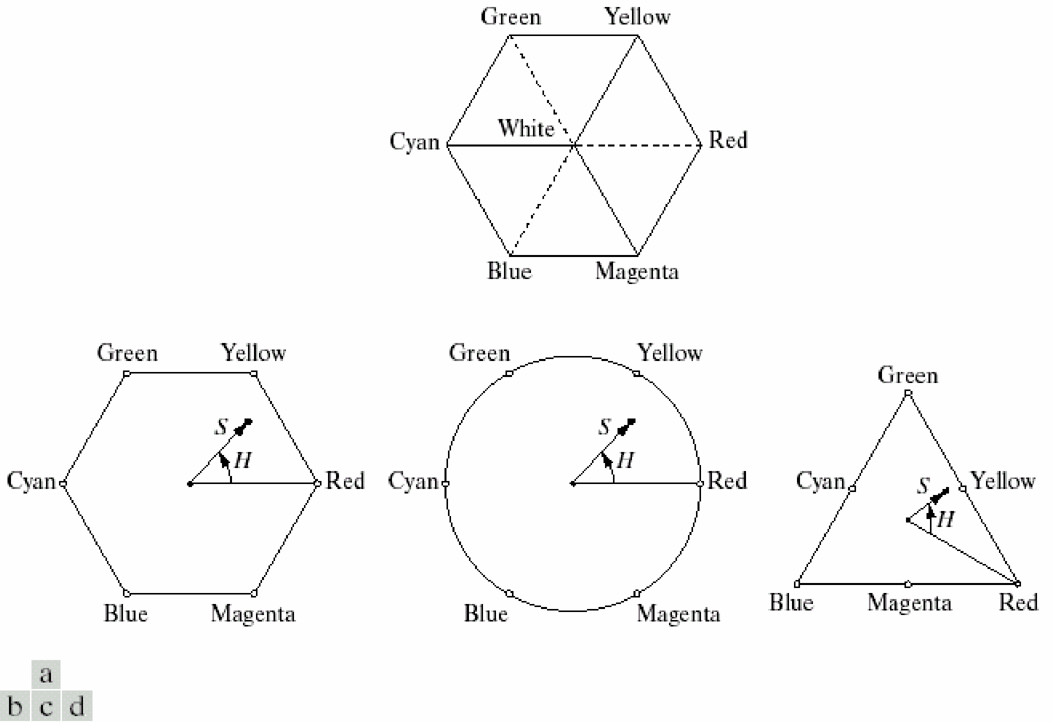

FIGURE 6.13 Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and the length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.

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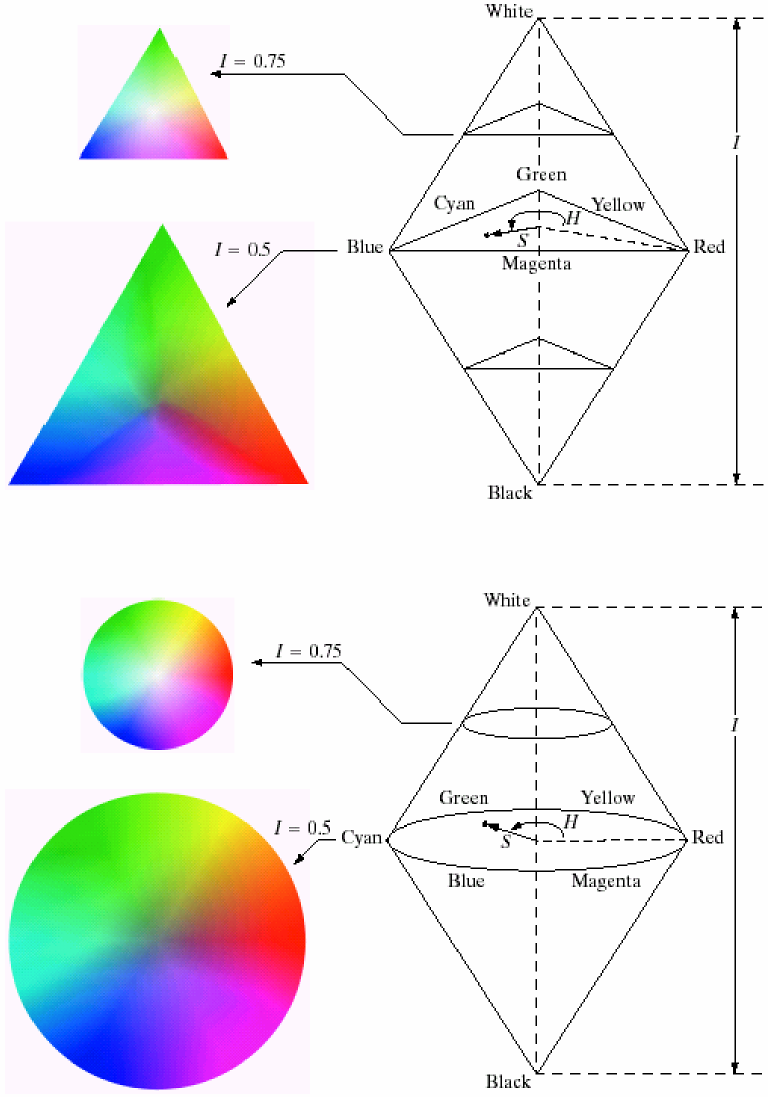


a
b

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

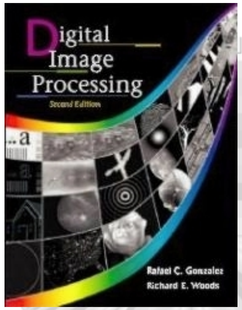
$$H = \begin{cases} \theta & if \quad B \le G \\ 360 - \theta & if \quad B > G \end{cases}$$

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

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

$$I = \frac{1}{3}(R+G+B)$$

It is assumed that the RGB values have been normalized to the range [0,1]



Converting colors from HSI to RGB

RG sector $\left(0^\circ \le H < 120^\circ\right)$

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

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

$$G = 1 - (R + B)$$

GB sector $\left(120^\circ \le H < 240^\circ\right)$

$$H = H - 120^\circ$$

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

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

$$B = 1 - (R + G)$$

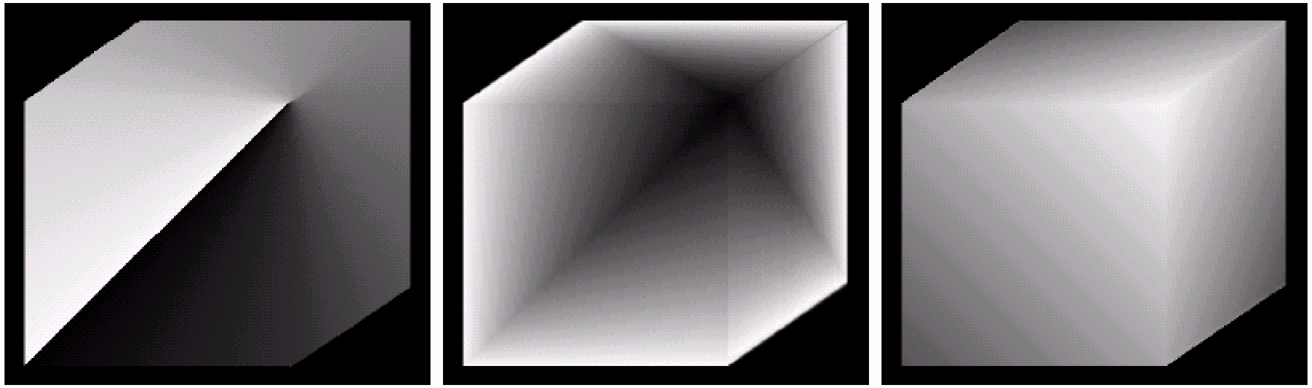
BR sector $\left(240^\circ \le H \le 360^\circ\right)$

$$H = H - 240^\circ$$

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

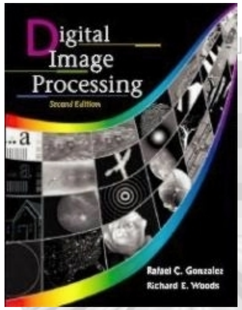
$$B = I\left[1 + \frac{S\cos H}{\cos\left(60^\circ - H\right)}\right]$$

$$R = 1 - (G + B)$$



a b c

FIGURE 6.15 HSI components of the image in Fig. 6.8. (a) Hue, (b) saturation, and (c) intensity images.



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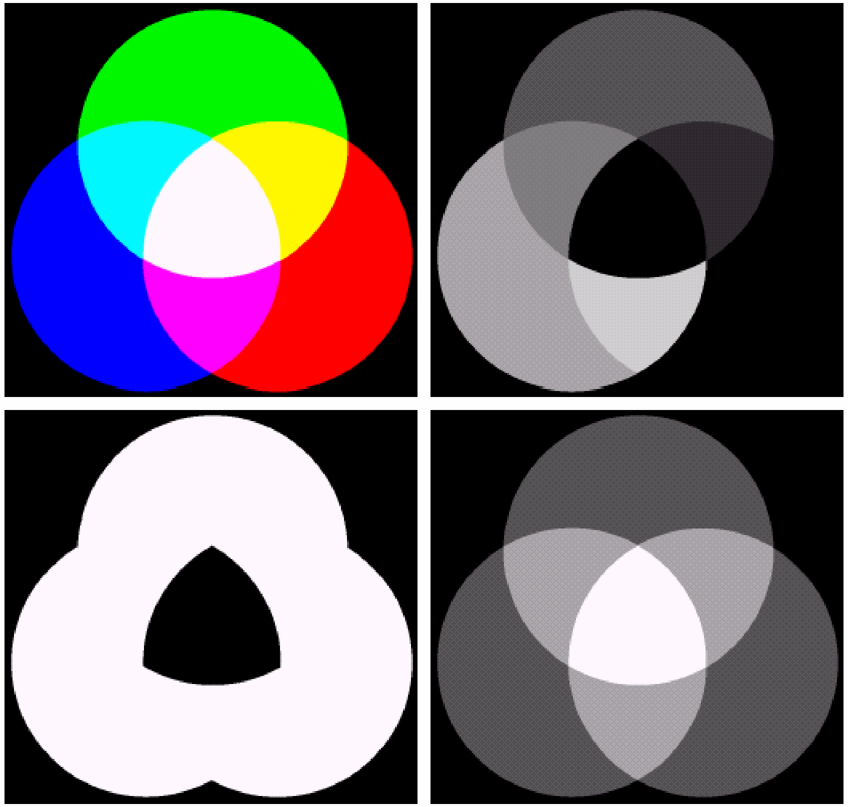
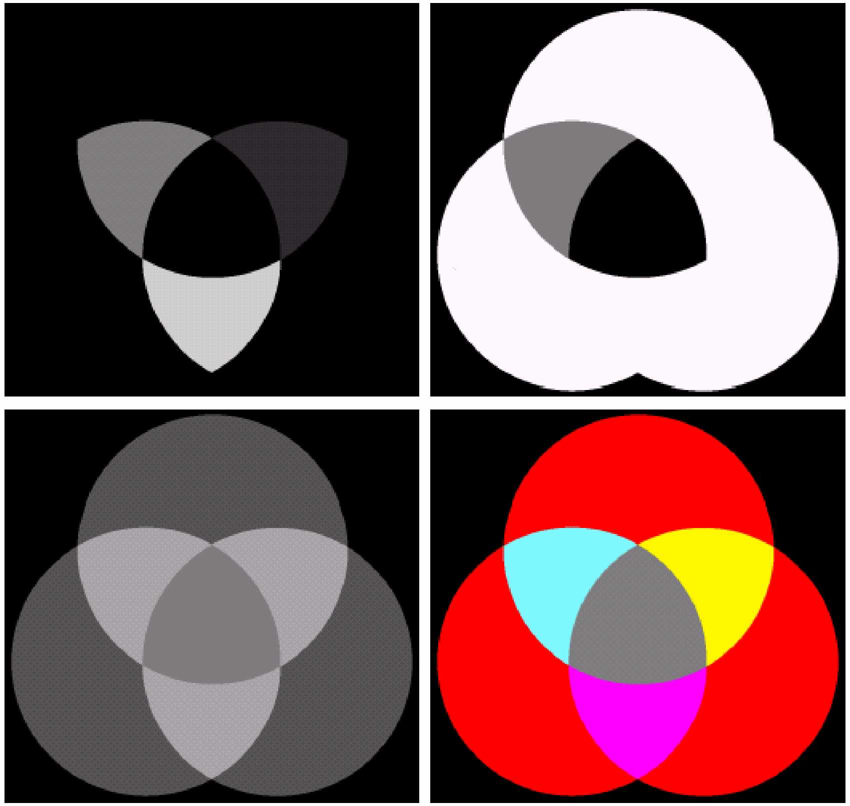


a b
c d

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



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.)

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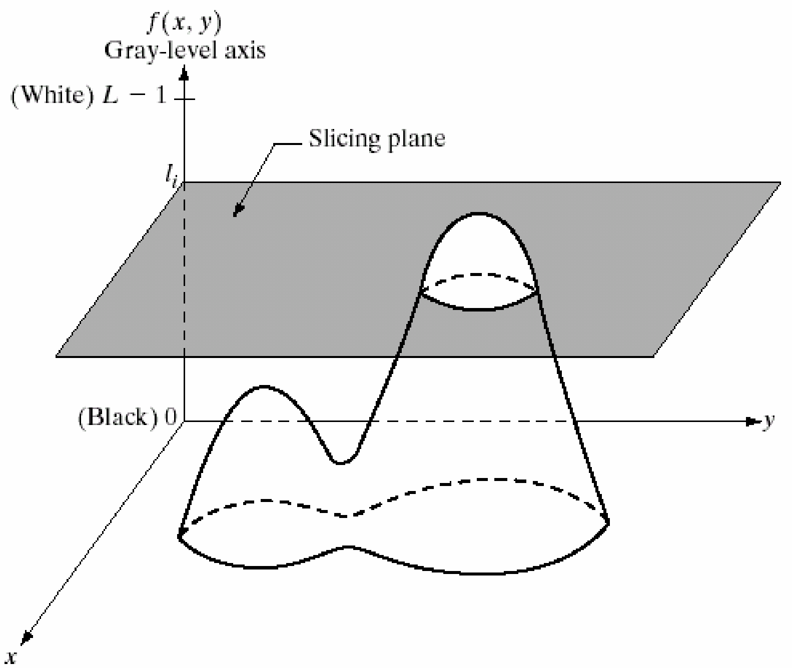

FIGURE 6.18 Geometric interpretation of the intensity-slicing technique.

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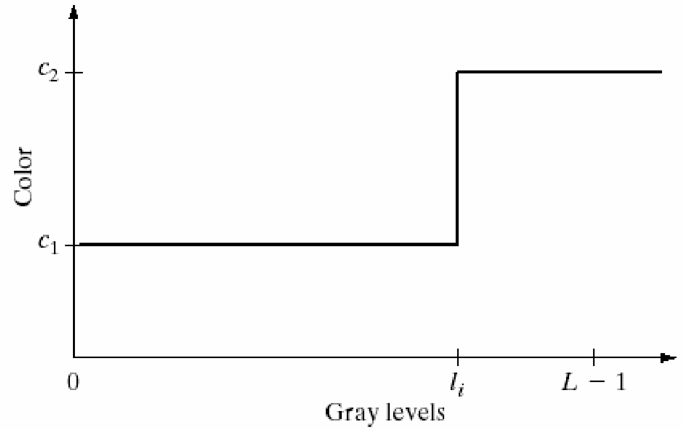

FIGURE 6.19 An alternative representation of the intensity-slicing technique.

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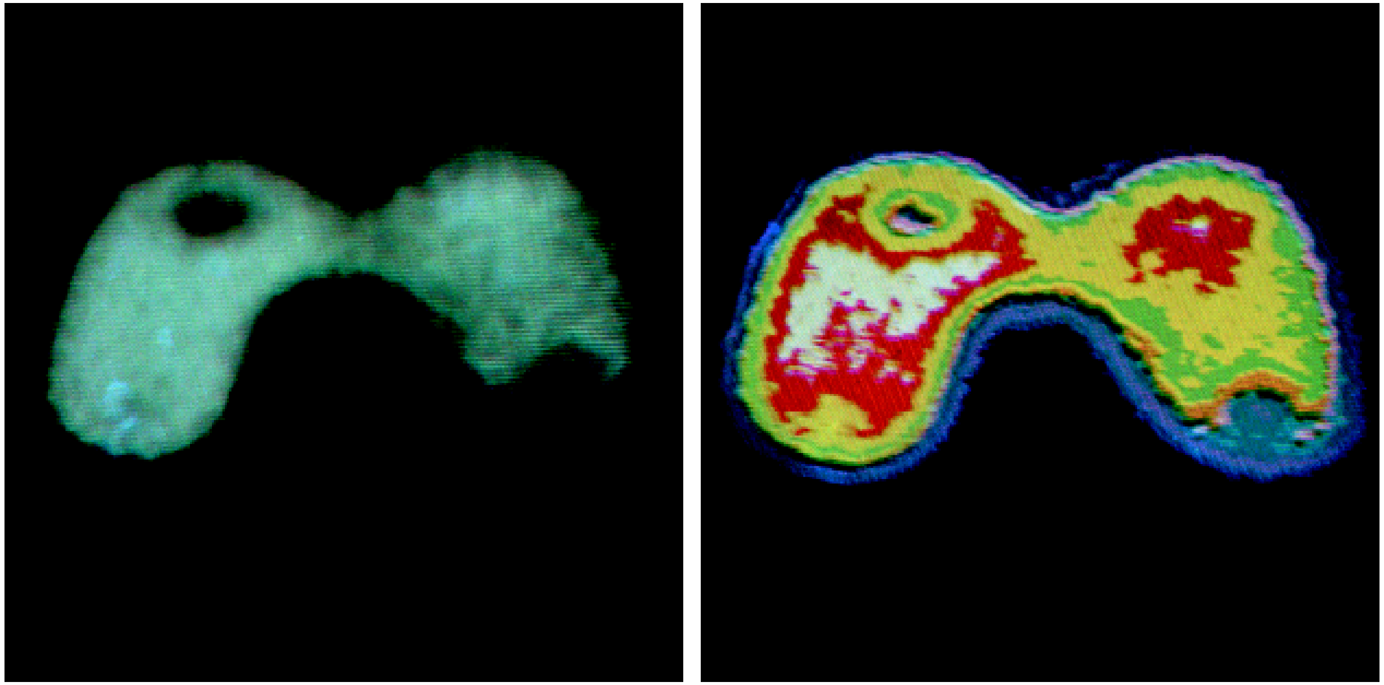

a b

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.)

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a
b

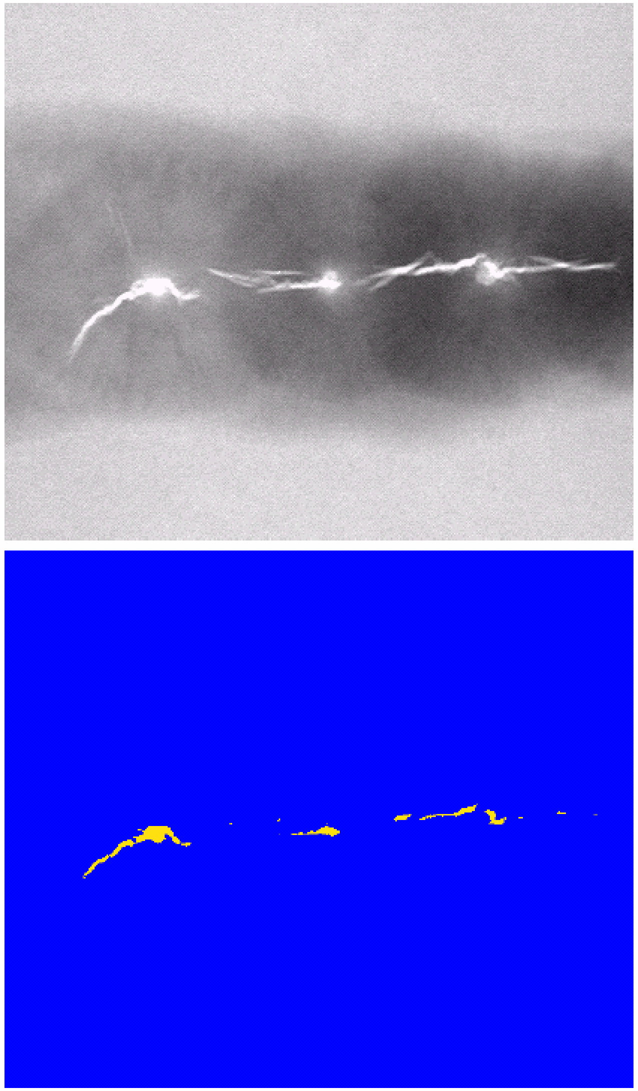

FIGURE 6.21 (a) Monochrome X-ray image of a weld. (b) Result of color coding. (Original image courtesy of X-TEK Systems, Ltd.)

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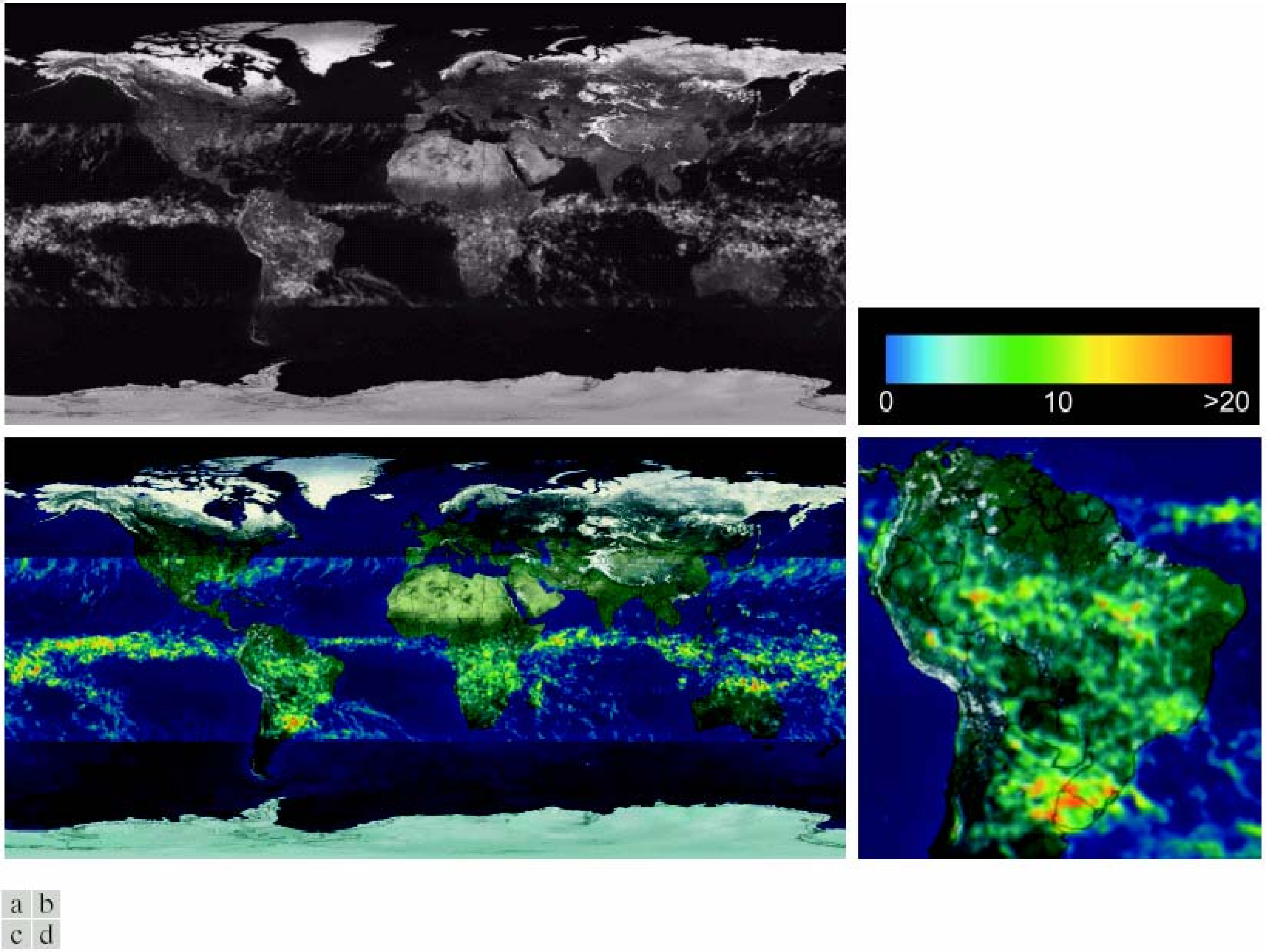

FIGURE 6.22 (a) Gray-scale image in which intensity (in the lighter horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South America region. (Courtesy of NASA.)

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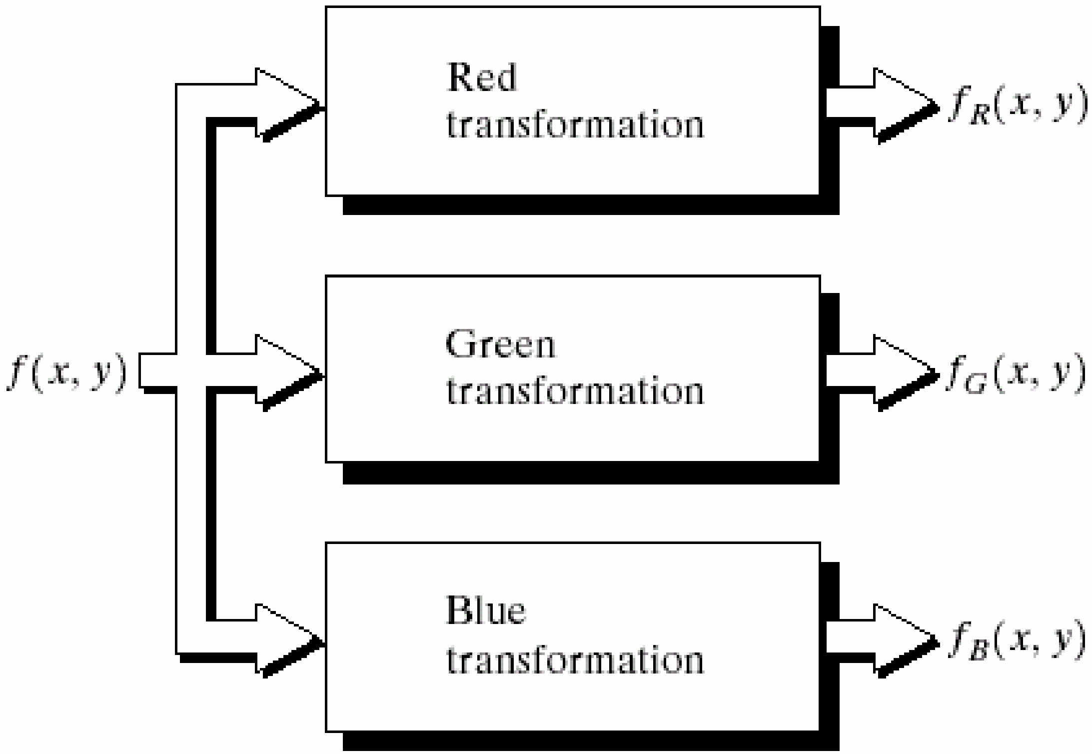

FIGURE 6.23 Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

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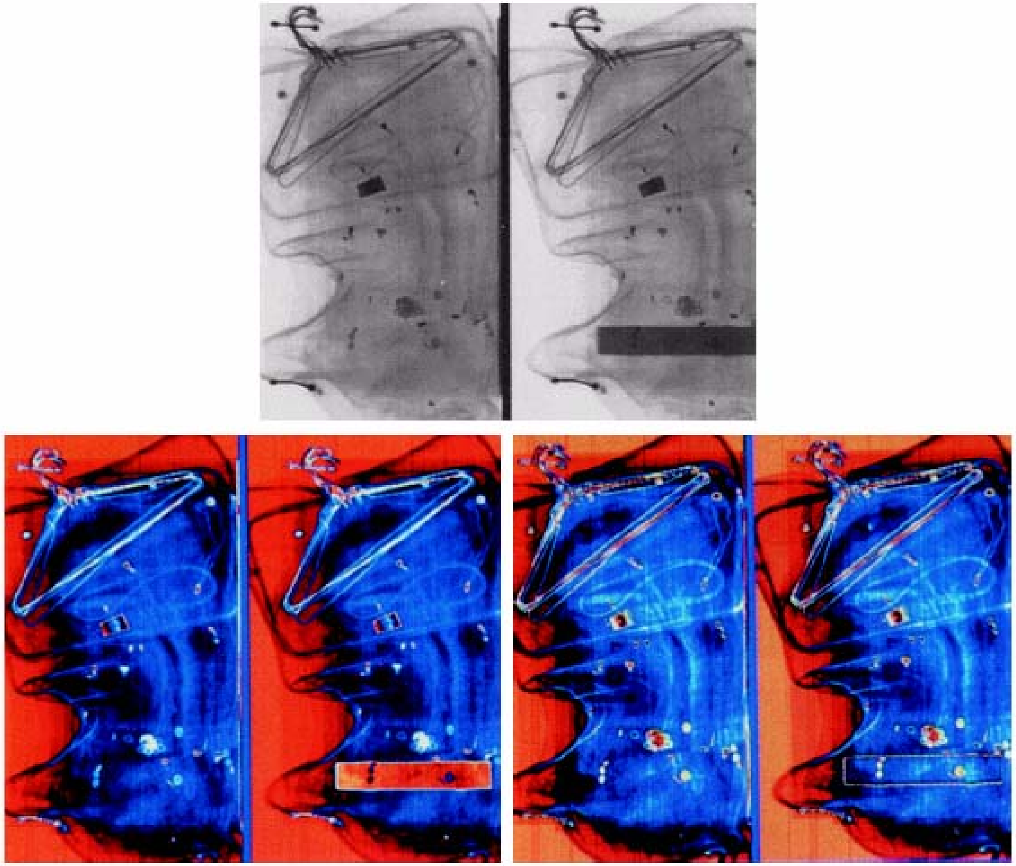

a
b c

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.)

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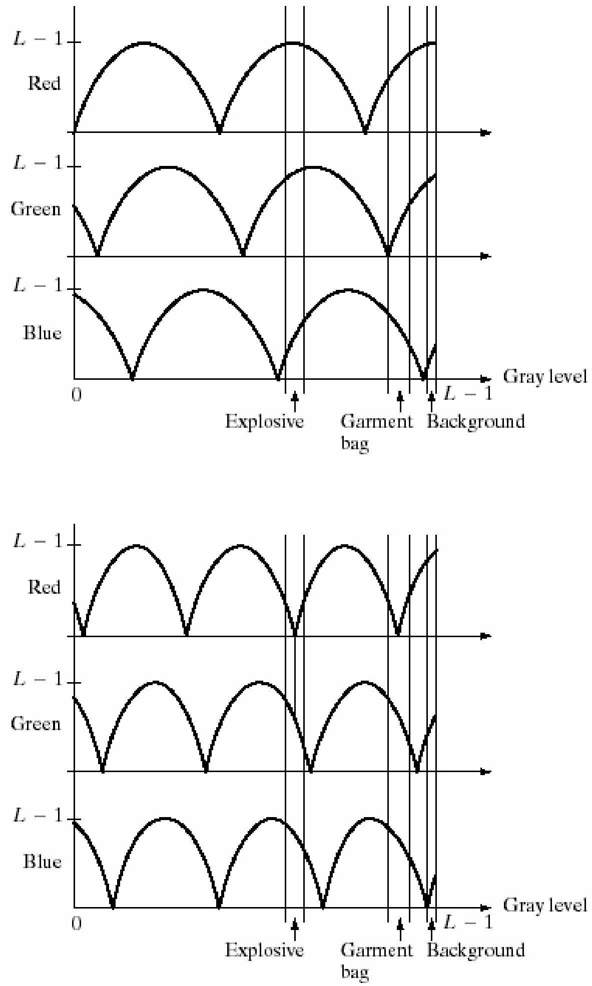

a
b

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

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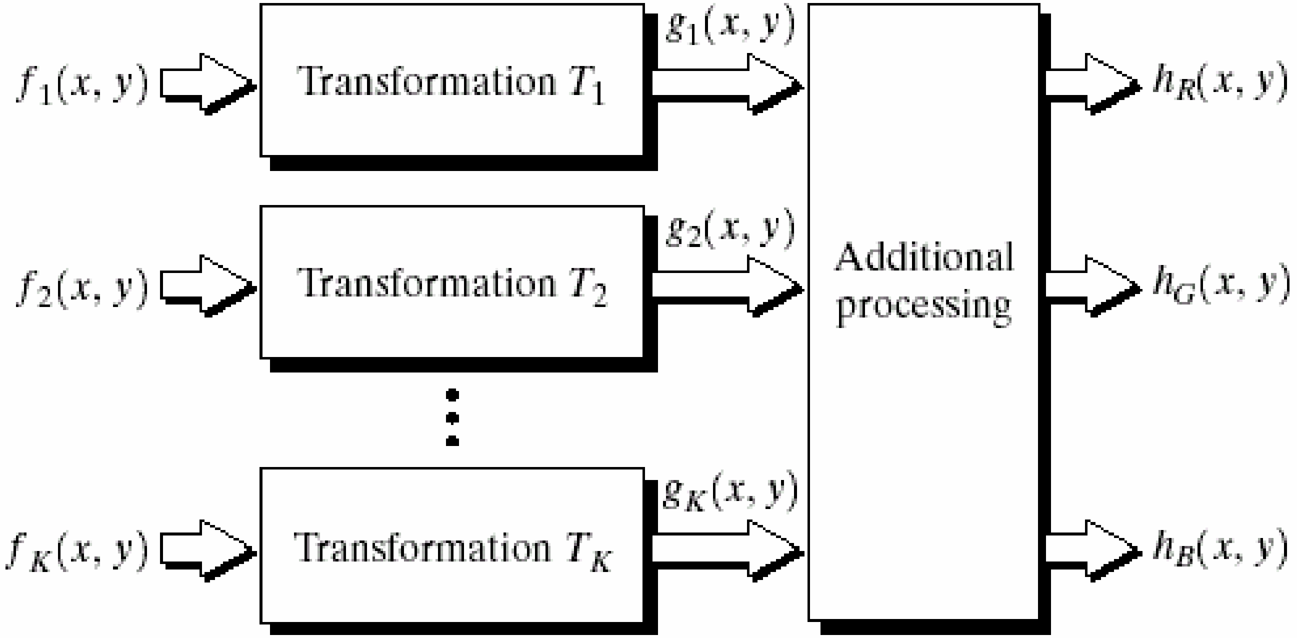

FIGURE 6.26 A pseudocolor coding approach used when several monochrome images are available.

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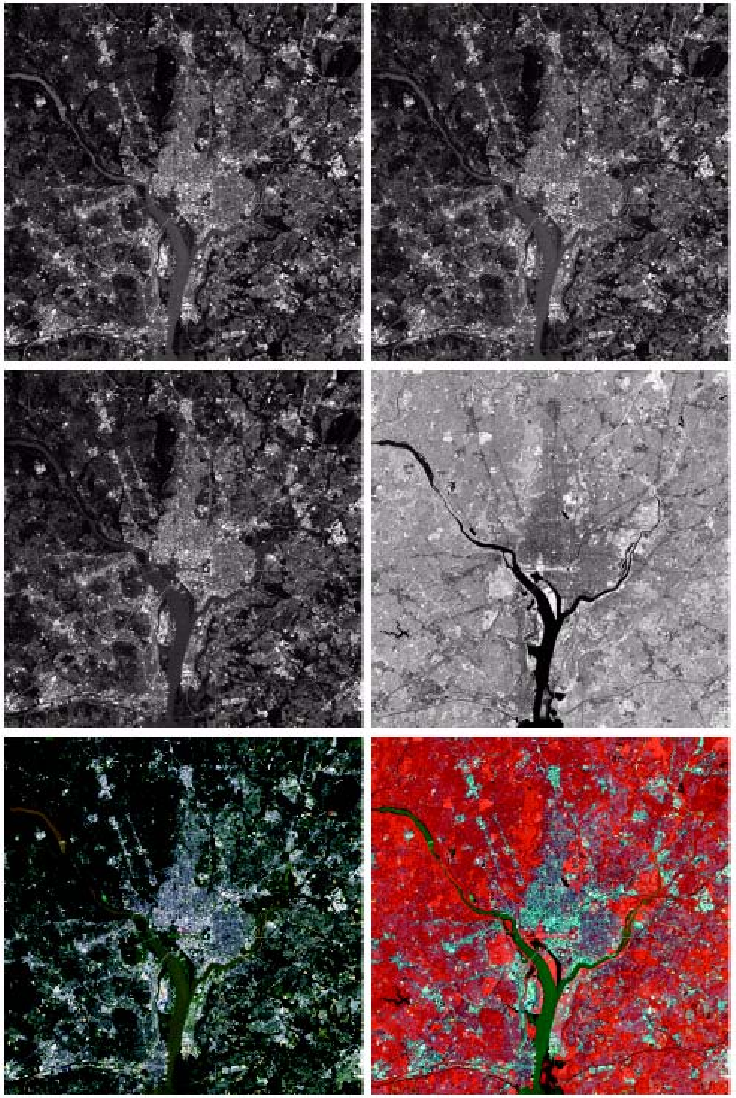

a b
c d
e f

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.)

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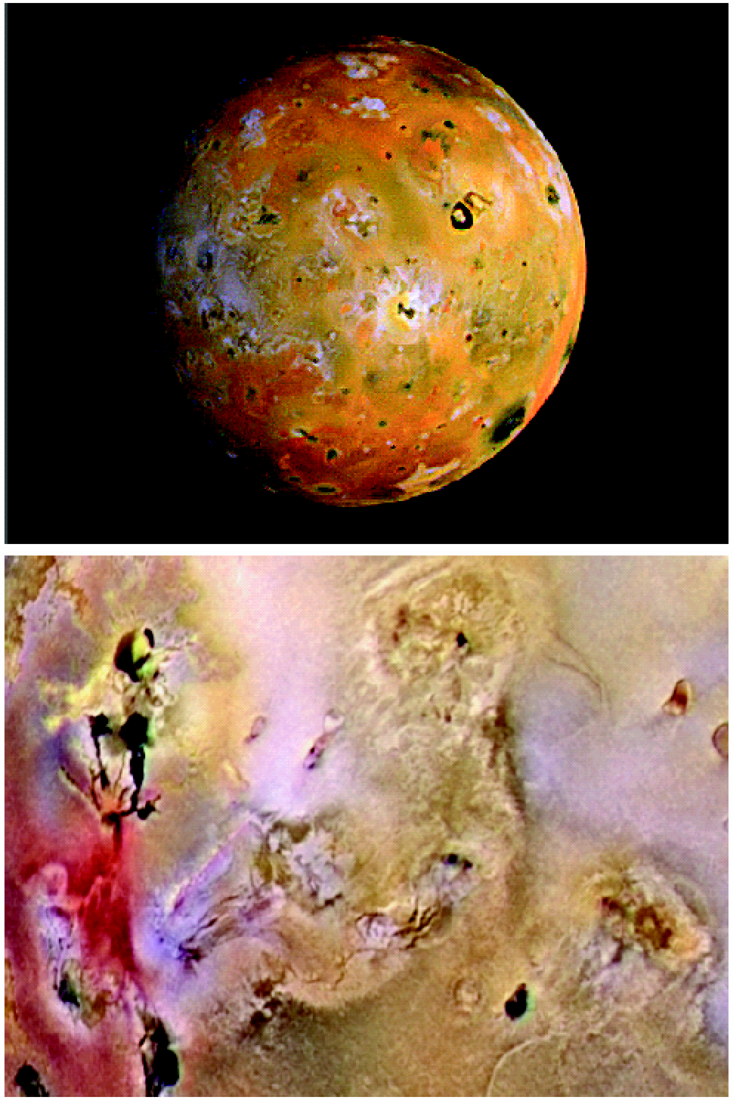

a
b

FIGURE 6.28 (a) Pseudocolor rendition of Jupiter Moon Io. (b) A close-up. (Courtesy of NASA.)

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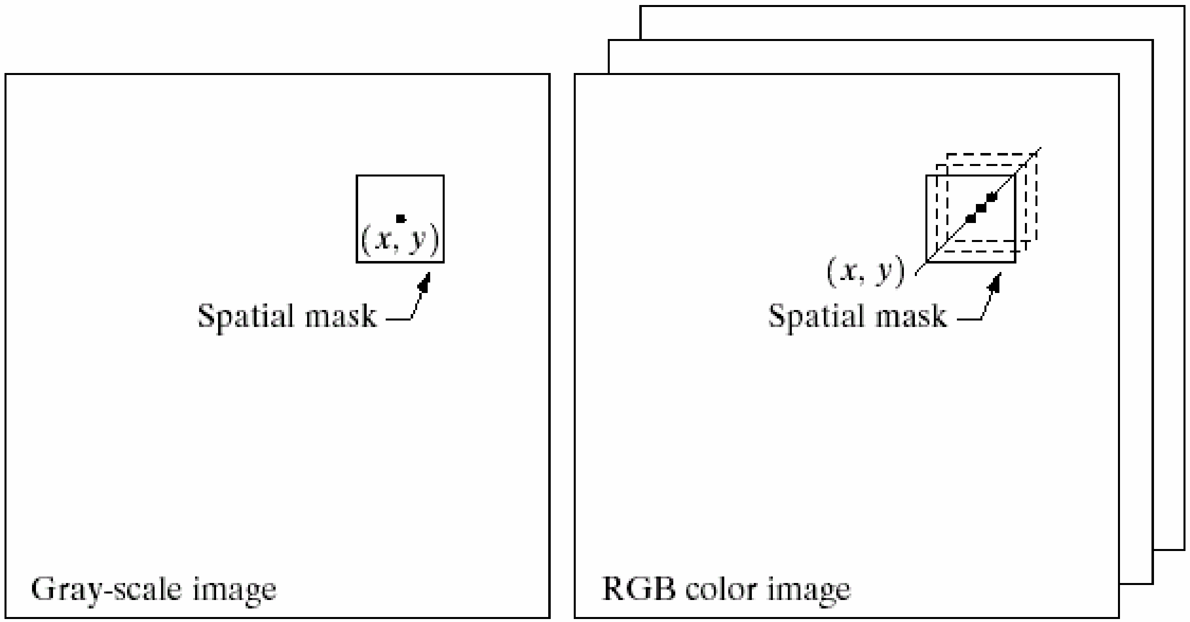
a b

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



Color Transformations Formulation

$$g(x, y) = T[f(x, y)]$$

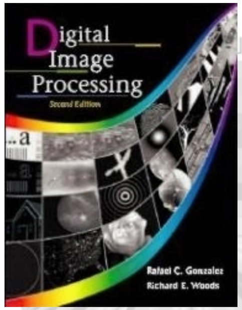
- The pixel value here are triplets or quartets.

$$s_i = T_i(r_1, r_2, \ldots, r_n), \quad i = 1,2,\ldots,n \quad (6.5-2)$$

- $\{T_1, T_2, \ldots, T_n\}$ is a set of transformation or color mapping functions that operate on r_i to produce s_i .
- If the RGB color space is selected, for example, n=3 and $r_1, r_2,$ and r_3 denote the red, green, and blue components of the input image.

Color Transformations Formulation

- Any of the color space components in Fig 6.30 can be used in conjunction with Eq.(6.5-2).
- In theory, any transformation can be performed in any color model.
- In practice, however, some operations are better suited to specific models.



Color Transformations Formulation

- Suppose, for example, that we wish to modify the intensity of the image in Fig 6.30(a) using
  $g(x, y) = kf(x, y)$
- In the HIS color space, this can be done with the simple transformation
  $s_3 = kr_3$ where $s_1 = r_1$ and $s_2 = r_2$
- Only HSI intensity component r_3 is modified.

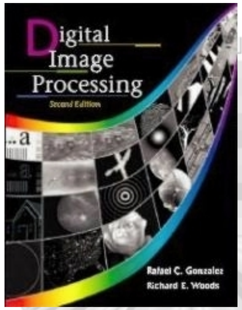
Color Transformations Formulation

- In the RGB color space, three components must be transformed:

$$s_i = kr_i \quad i = 1,2,3.$$

- The CMY space requires a similar set of linear transformations:

$$s_i = kr_i + (1 - k) \quad i = 1,2,3.$$



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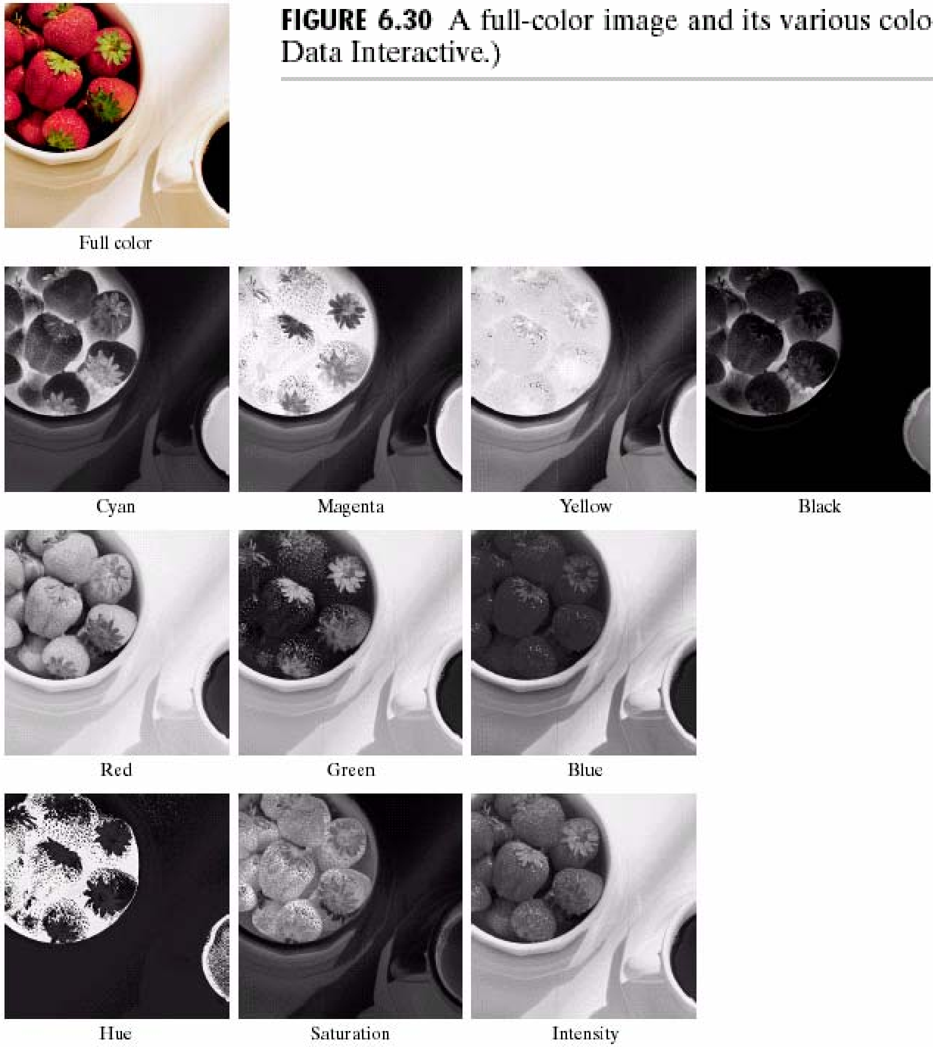

FIGURE 6.30 A full-color image and its various color-space components. (Original image courtesy of Med-Data Interactive.)

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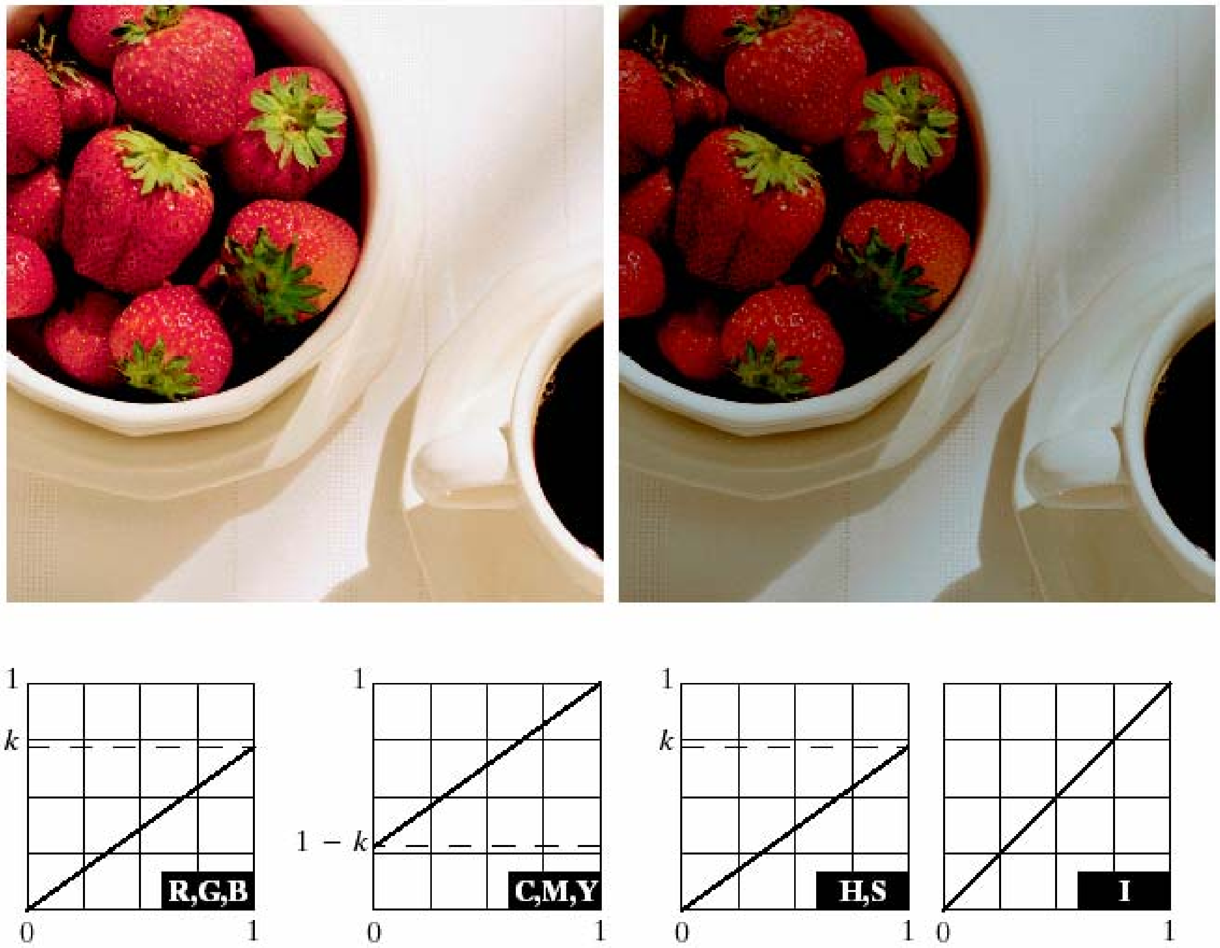

FIGURE 6.31 Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c)–(e) The required RGB, CMY, and HSI transformation functions. (Original image courtesy of MedData Interactive.)

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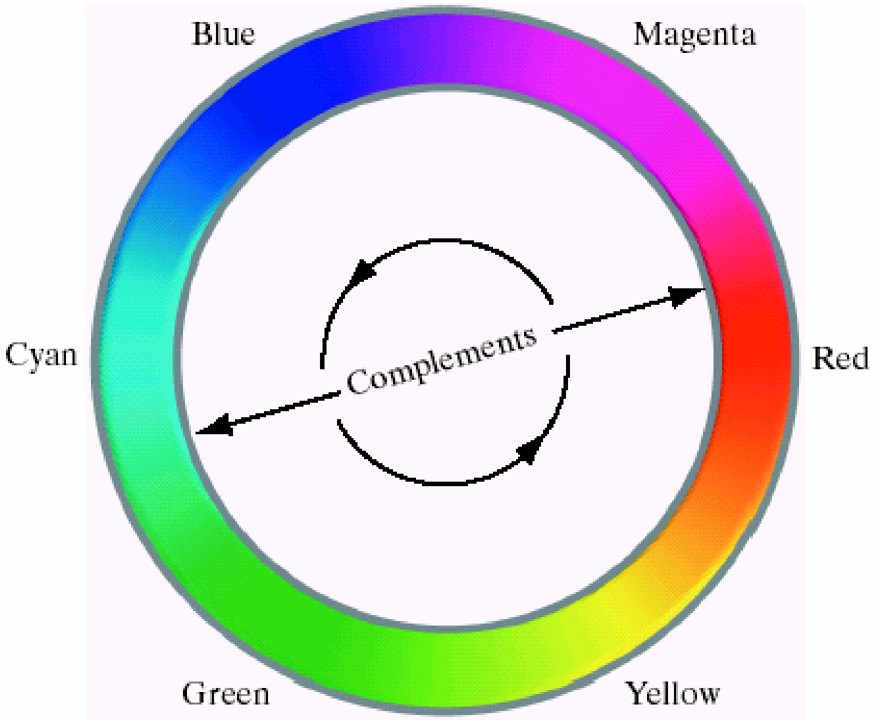

FIGURE 6.32 Complements on the color circle.

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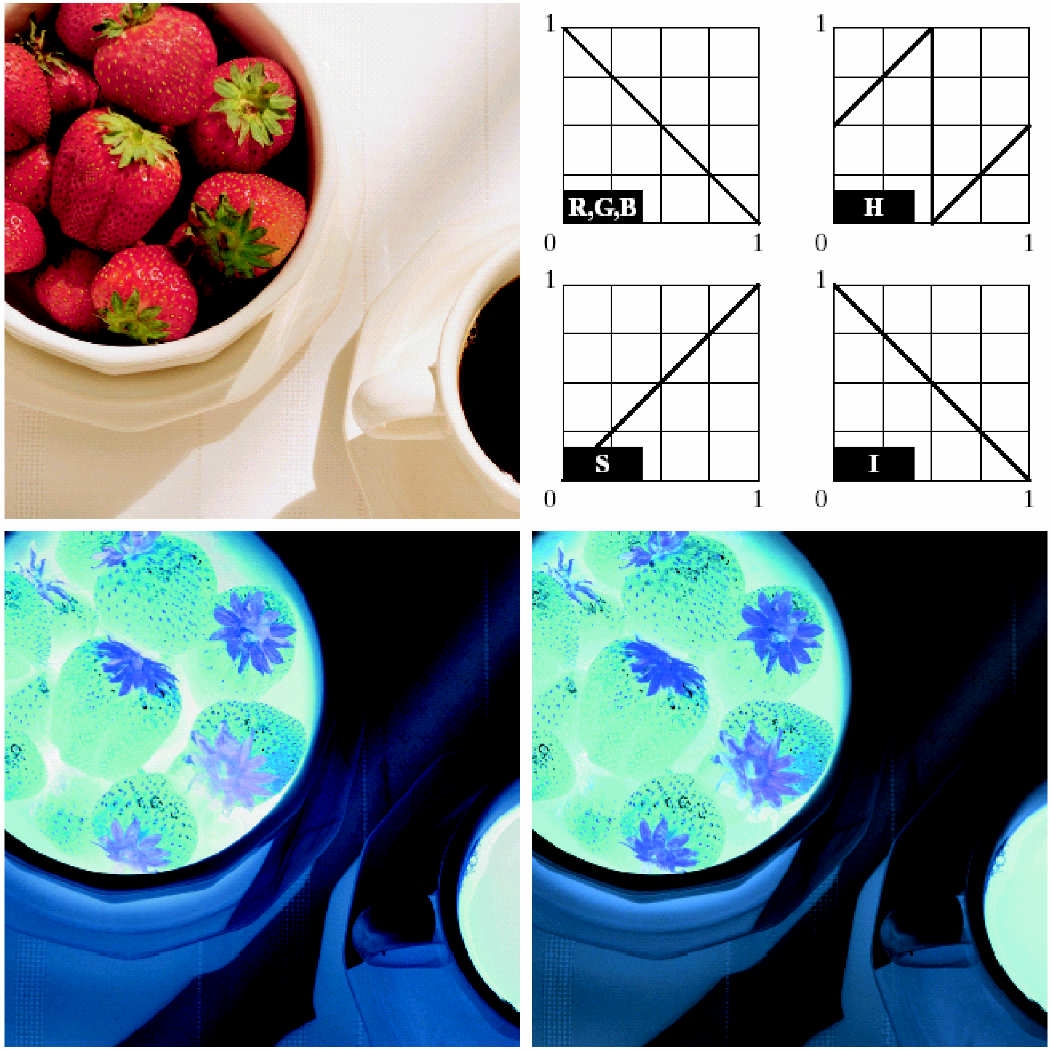

a b
c d

FIGURE 6.33 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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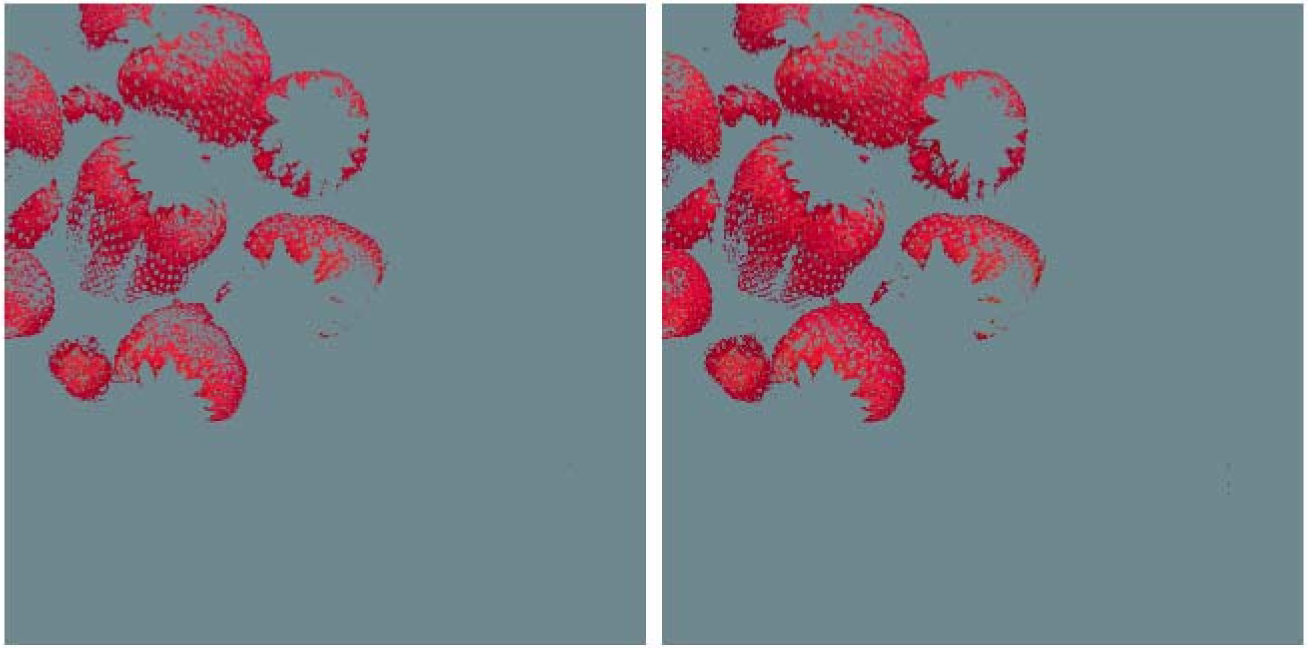
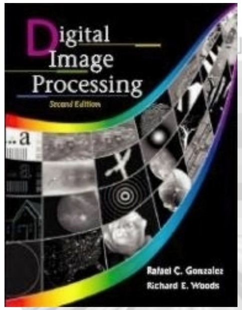


a b

FIGURE 6.34 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

- A device-independent color model
- The success of this approach is a function of the quality of the color profiles used to map each device to the model and the model itself.
- The model of choice for many color management system (CMS) is the CIE *L*a*b* model.



Tone and Color Corrections

$$L^* = 116 \cdot h\left(\frac{Y}{Y_w}\right) - 16$$

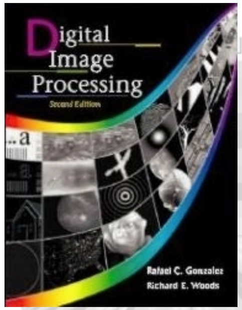
$$a^* = 500\left[h\left(\frac{X}{X_w}\right) - h\left(\frac{Y}{Y_w}\right)\right]$$

$$b^* = 200\left[h\left(\frac{Y}{Y_w}\right) - h\left(\frac{Z}{Z_w}\right)\right]$$

where

$$h(q) = \begin{cases} \sqrt[3]{q} & q > 0.008856 \\ 7.787q + 16/116 & q \le 0.008856 \end{cases}$$

X_w, Y_w, and Z_w are reference white tristimulus values



Tone and Color Corrections

- Like the HIS system, the *L*a*b* system is an excellent decoupler of intensity (represented by lightness *L**) and color (represent by *a** for red minus green and *b** for green minus blue).
- The tonal range of an image, also called its *key type*, refer to its general distribution of color intensities.
- Most of the information in *high-key* images are located predominantly at low intensities; *middle-key* images lie in between.

Example 6.9

- Transformations for modifying image tones normally are selected interactively.
- The idea is to adjust experimentally the image's brightness and contrast to provide maximum detail over a suitable range of intensities.
- In the RGB and CMY(K) spaces, this means all three (or four) color components with the same transformation function; in the HSI color space, only the intensity component is modified.
- The S-shaped curve in the first row of the figure is detail for boosting contrast.

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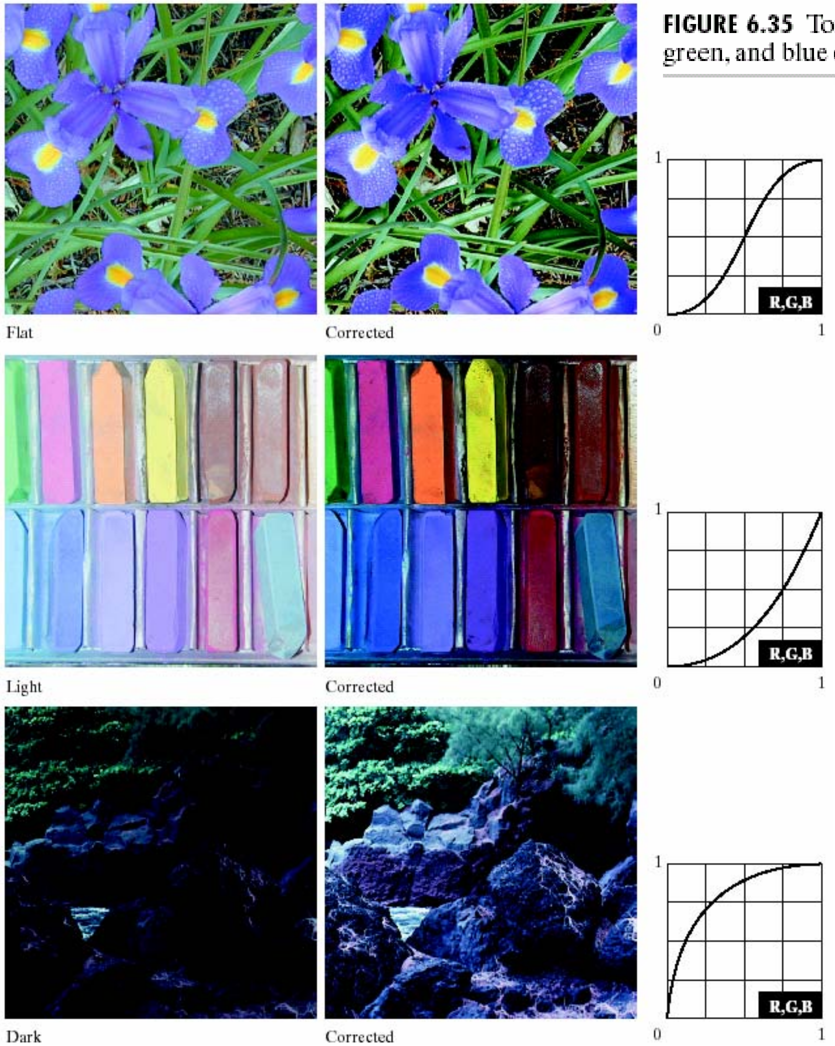

FIGURE 6.35 Tonal corrections for flat, light (high key), and dark (low key) color images. Adjusting the red, green, and blue components equally does not alter the image hues.

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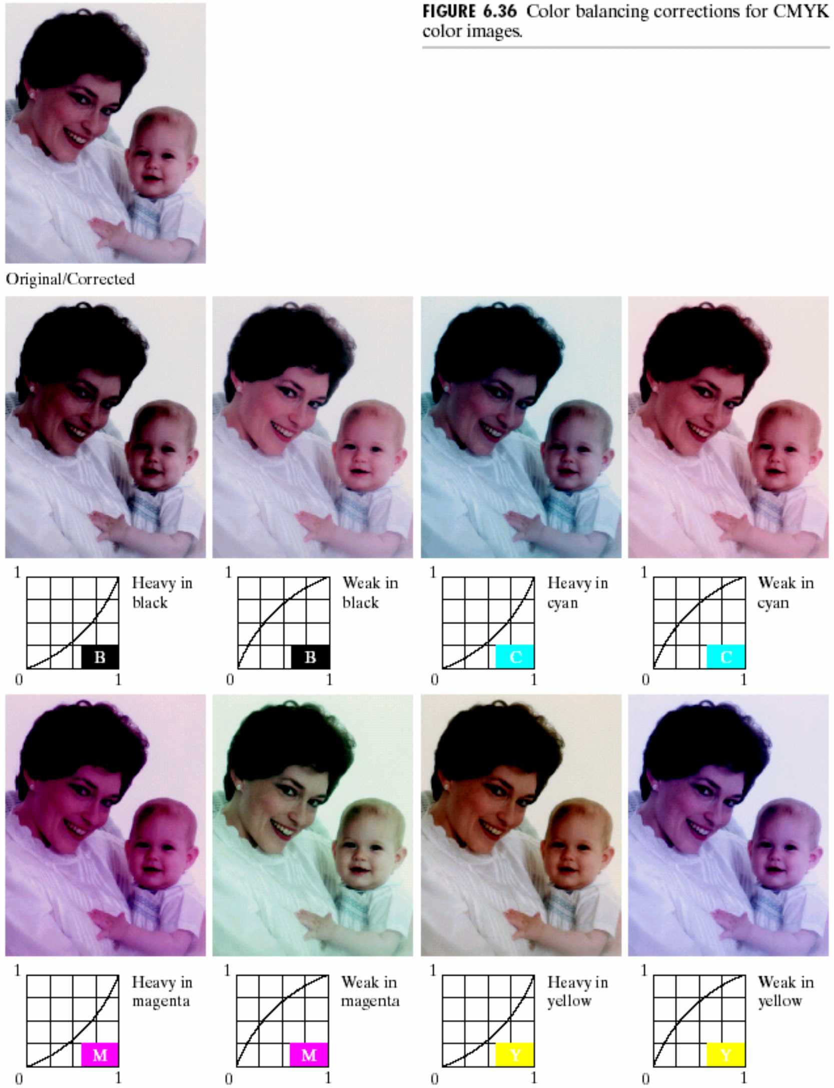

FIGURE 6.36 Color balancing corrections for CMYK color images.

Histogram Processing

- Histogram processing transformations of Section 3.3 can be applied to color images in an automated way.
- As might be expected, it is generally unwise to histogram equalize the component of a color image independently.
- This results in erroneous color.
- A more logical approach is to spread the color intensities uniformly, leaving the colors themselves (e.g., hues) unchanged.
- The HSI color space is ideally suited to this type of approach.

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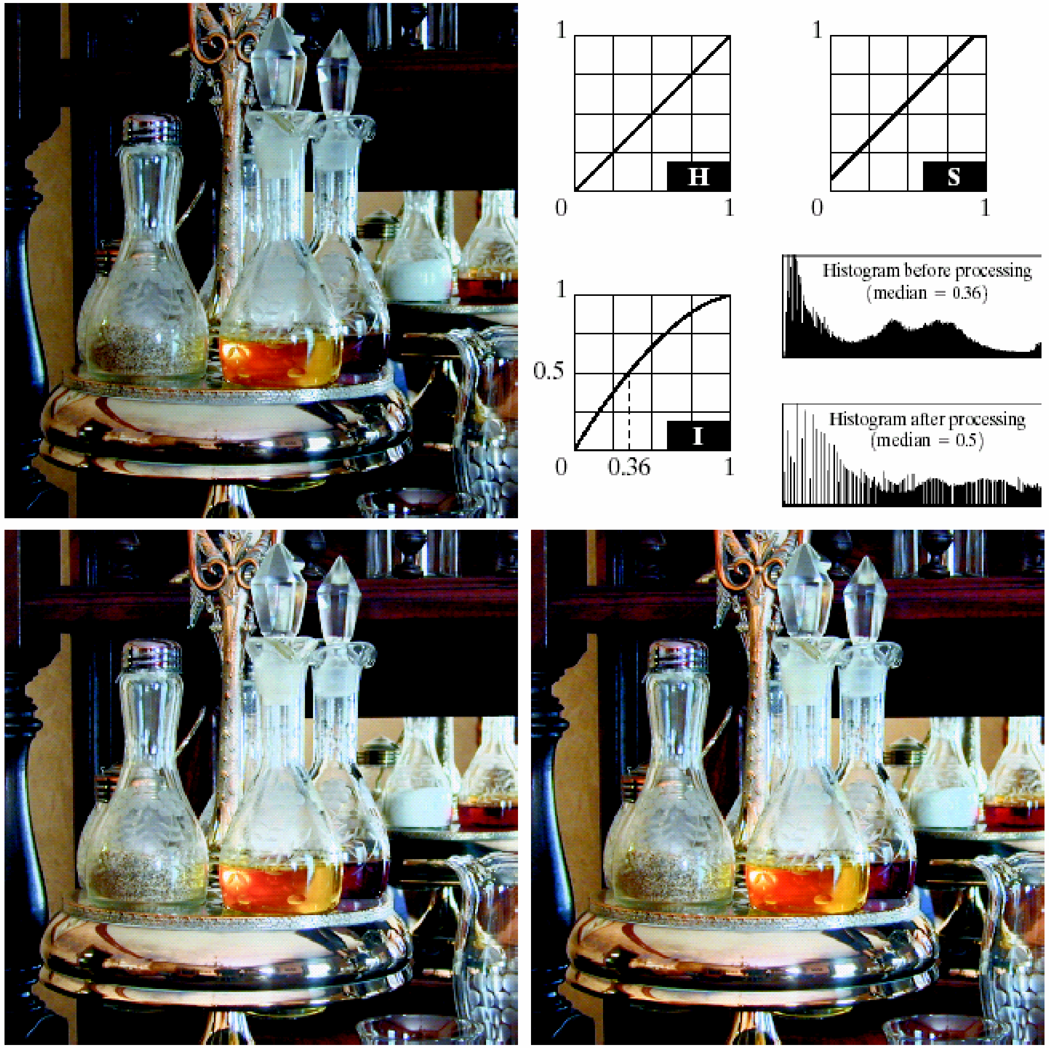

a b
c d

FIGURE 6.37 Histogram equalization (followed by saturation adjustment) in the HSI color space.

Smoothing and Sharpening
Color Image Smoothing

$$\bar{c}(x,y) = \frac{1}{K}\sum_{(x,y)\in S_{xy}} c(x,y)$$

$$\bar{c}(x,y) = \begin{bmatrix} \frac{1}{K}\sum_{(x,y)\in S_{xy}} R(x,y) \\ \frac{1}{K}\sum_{(x,y)\in S_{xy}} G(x,y) \\ \frac{1}{K}\sum_{(x,y)\in S_{xy}} B(x,y) \end{bmatrix}$$

Thus, we conclude that smoothing by neighborhood averaging can be carried out on a per-color-plane basis.

Example 6.12

- HSI color model is that it decouples intensity (closely related to gray scale) and color information,
- This makes it suitable for many gray-scale processing techniques and suggests that is might be more efficient to smooth only the intensity component of the HSI representation.

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a b
c d

FIGURE 6.38 (a) RGB image. (b) Red component image. (c) Green component. (d) Blue component.

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a b c

FIGURE 6.39 HSI components of the RGB color image in Fig. 6.38(a). (a) Hue. (b) Saturation. (c) Intensity.

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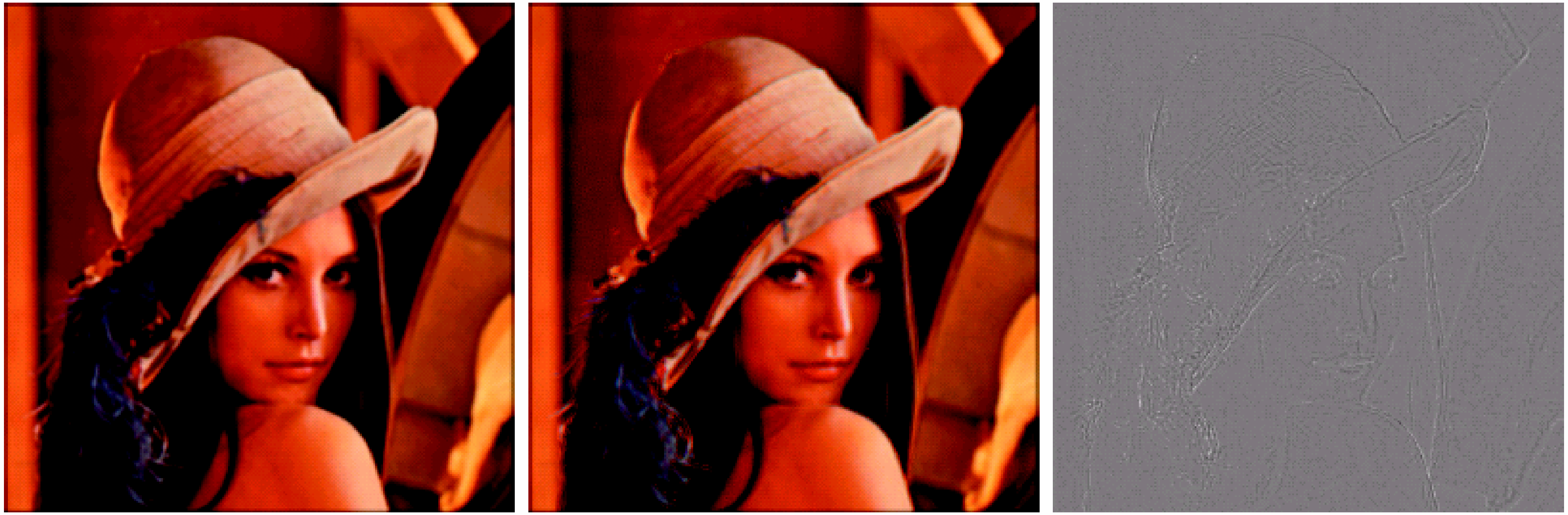

a b c

FIGURE 6.40 Image smoothing with a 5 × 5 averaging mask. (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 Sharpening

$$\nabla^2\left[c(x,y)\right] = \begin{bmatrix} \nabla^2 R(x,y) \\ \nabla^2 G(x,y) \\ \nabla^2 B(x,y) \end{bmatrix}$$

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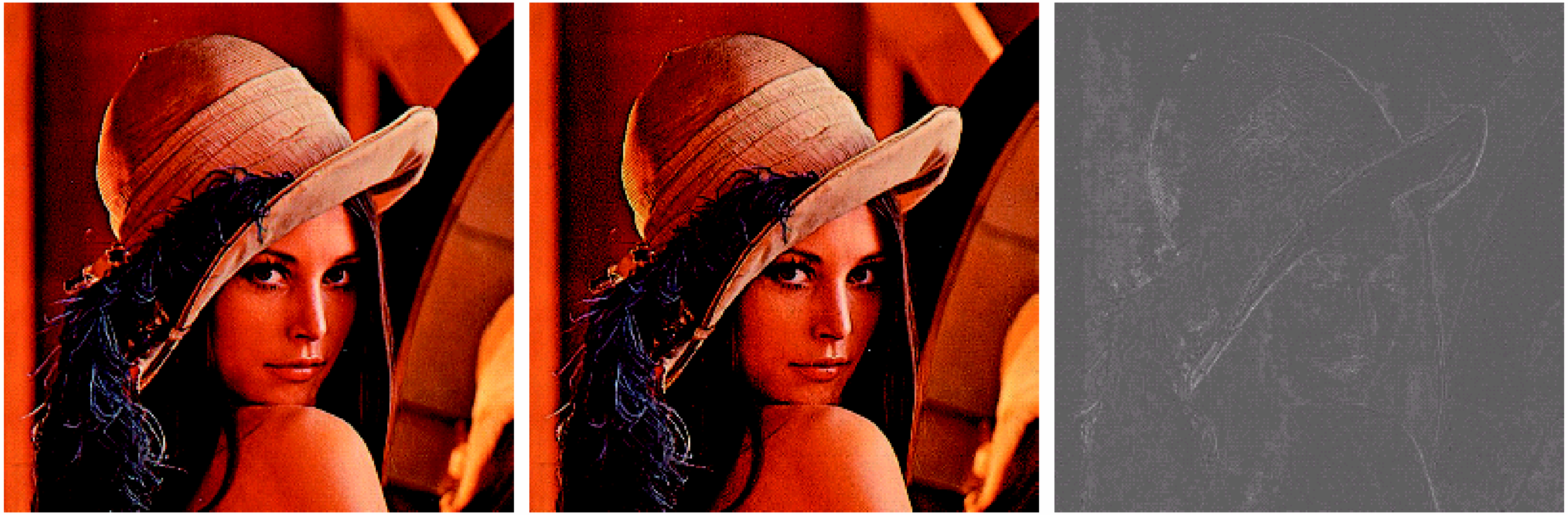

a b c

FIGURE 6.41 Image sharpening with the Laplacian. (a) Result of processing each RGB channel. (b) Result of processing the intensity component and converting to RGB. (c) Difference between the two results.

Color Segmentation

- Segmentation in HSI color space
- Segmentation in RGB Vector Space
- Color Edge Detection

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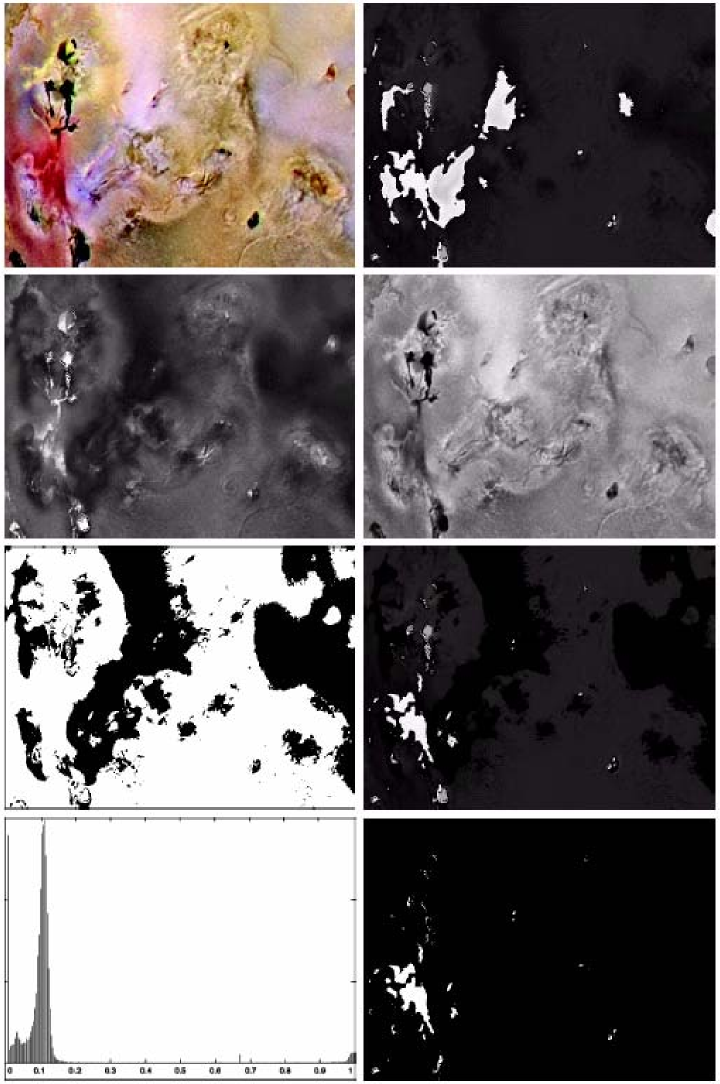


a b
c d
e f
g h

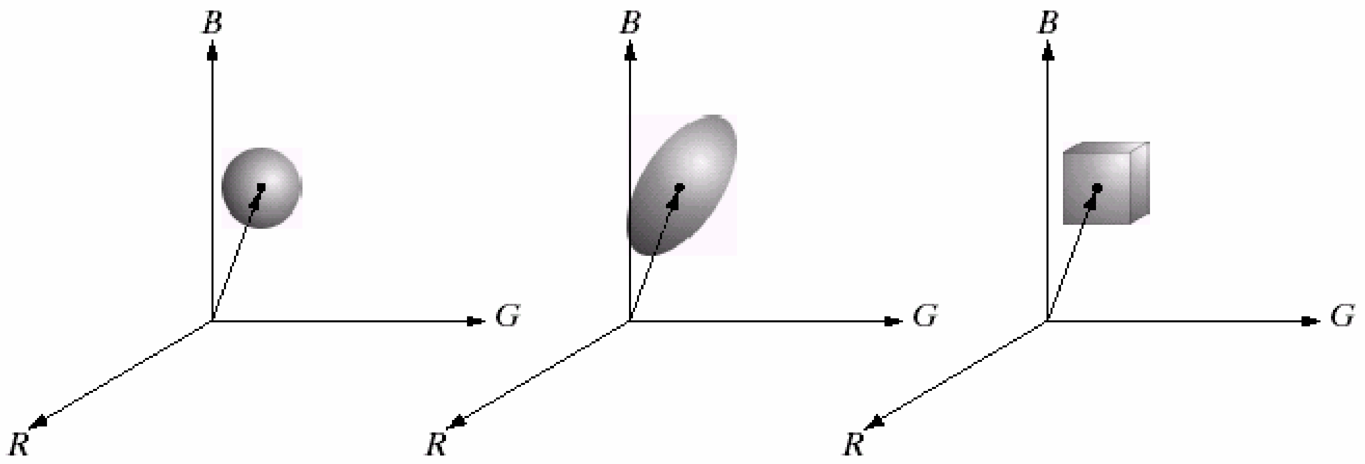
FIGURE 6.42 Image segmentation in HSI space. (a) Original. (b) Hue. (c) Saturation. (d) Intensity. (e) Binary saturation mask (black = 0). (f) Product of (b) and (e). (g) Histogram of (f). (h) Segmentation of red components in (a).

Segmentation in RGB Vector Space

$$D(z,a) = \|z-a\|$$

$$= \left[(z-a)^T (z-a)\right]^{\frac{1}{2}}$$

$$= \left[(z_R - a_R)^2 + (z_G - a_G)^2 + (z_B - a_B)^2\right]^{\frac{1}{2}}$$



a b c

FIGURE 6.43 Three approaches for enclosing data regions for RGB vector segmentation.

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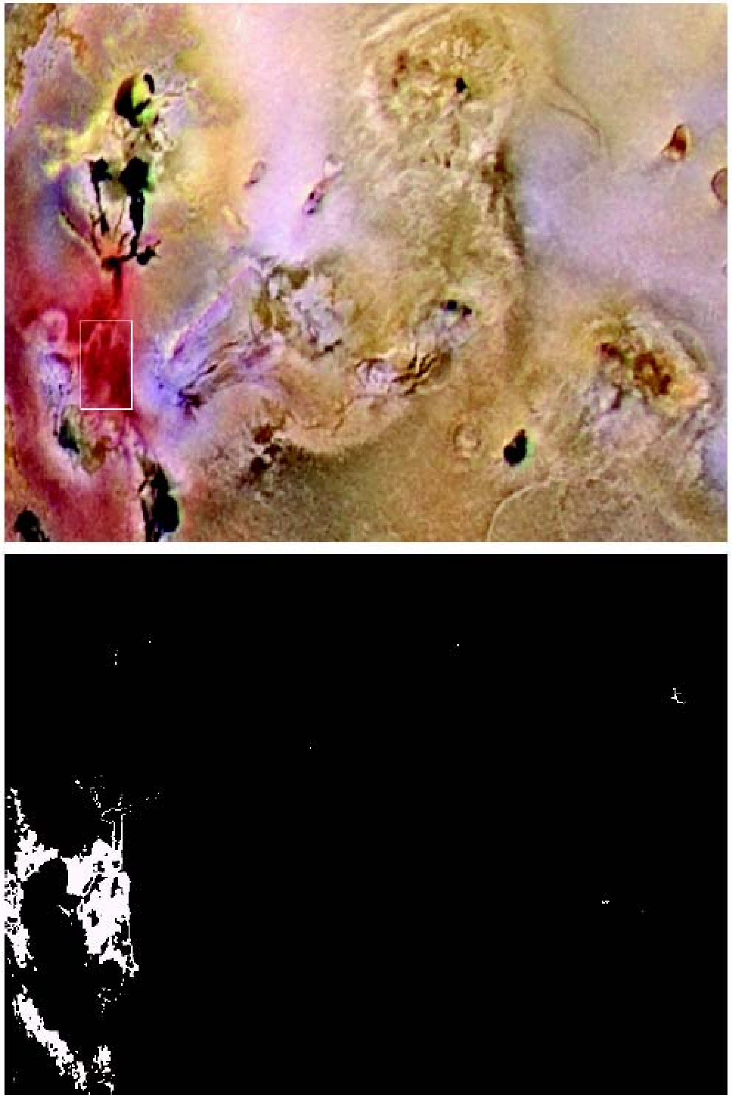

a
b

FIGURE 6.44 Segmentation in RGB space. (a) Original image with colors of interest shown enclosed by a rectangle. (b) Result of segmentation in RGB vector space. Compare with Fig. 6.42(h).

Color Edge Detection

$$u = \frac{\partial R}{\partial x} r + \frac{\partial G}{\partial x} g + \frac{\partial B}{\partial x} b$$

$$v = \frac{\partial R}{\partial y} r + \frac{\partial G}{\partial y} g + \frac{\partial B}{\partial y} b$$

$$g_{xx} = u \cdot u = u^T u = \left|\frac{\partial R}{\partial x}\right|^2 + \left|\frac{\partial G}{\partial x}\right|^2 + \left|\frac{\partial B}{\partial x}\right|^2$$

$$g_{yy} = v \cdot v = v^T v = \left|\frac{\partial R}{\partial y}\right|^2 + \left|\frac{\partial G}{\partial y}\right|^2 + \left|\frac{\partial B}{\partial y}\right|^2$$

$$g_{xy} = u \cdot v = u^T v = \frac{\partial R}{\partial x}\frac{\partial R}{\partial y} + \frac{\partial G}{\partial x}\frac{\partial G}{\partial y} + \frac{\partial B}{\partial x}\frac{\partial B}{\partial y}$$

Color Edge Detection

The direction of maximum rate of change of c(x,y) is given by this angle

$$\theta = \frac{1}{2}\tan^{-1}\left[\frac{2g_{xy}}{\left(g_{xx} - g_{yy}\right)}\right]$$

rate of change at (x,y), in the direction of θ , is given by

$$F(\theta) = \left\{\frac{1}{2}\left[\left(g_{xx} + g_{yy}\right) + \left(g_{xx} - g_{yy}\right)\cos 2\theta + 2_{xy}\sin 2\theta\right]\right\}^{\frac{1}{2}}$$

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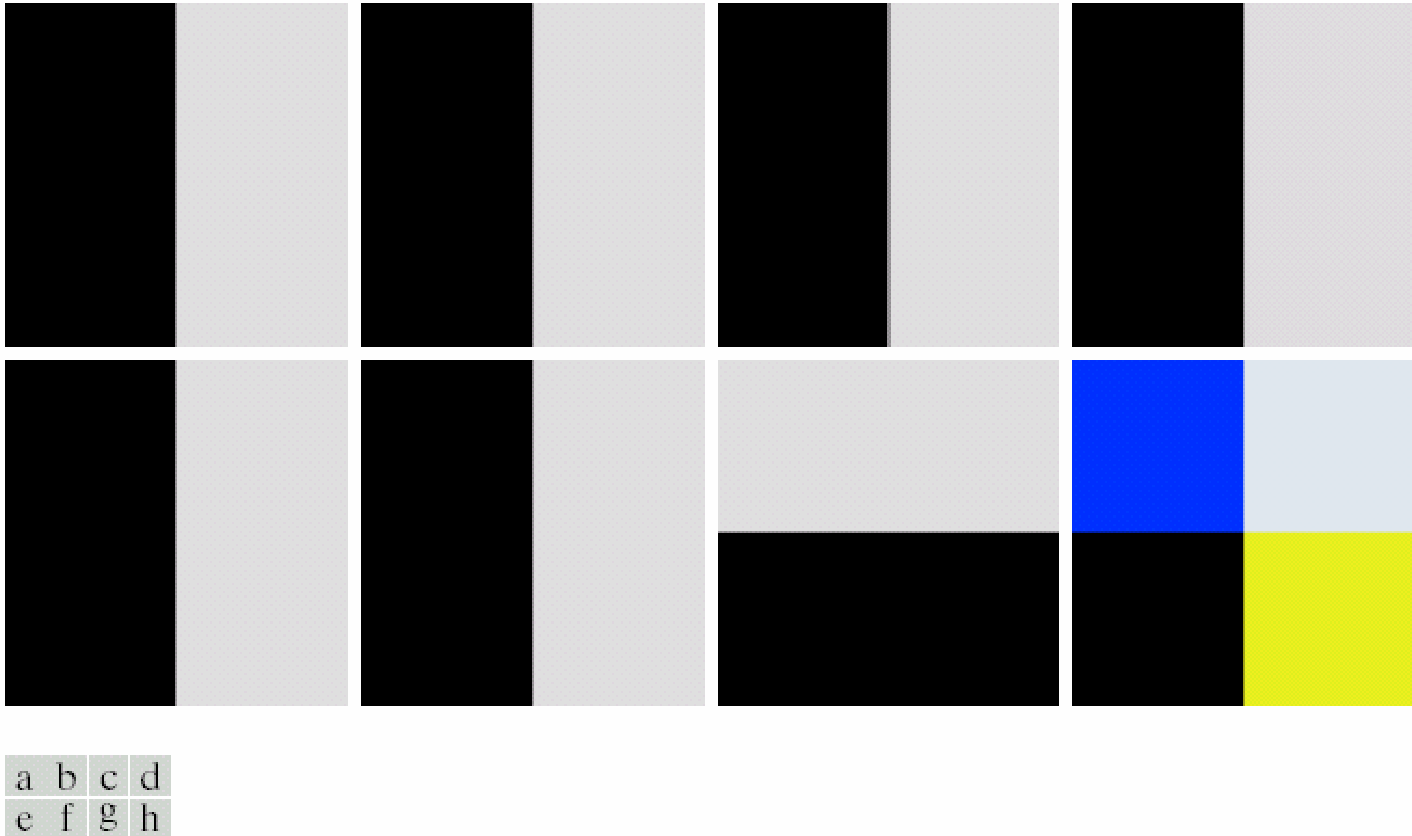

FIGURE 6.45 (a)–(c) *R*, *G*, and *B* component images and (d) resulting RGB color image. (f)–(g) *R*, *G*, and *B* component images and (h) resulting RGB color image.

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a b
c d

FIGURE 6.46
(a) RGB image.
(b) Gradient computed in RGB color vector space.
(c) Gradients computed on a per-image basis and then added.
(d) Difference between (b) and (c).

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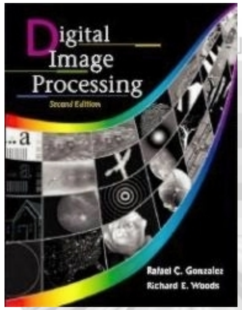
a b c

FIGURE 6.47 Component gradient images of the color image in Fig. 6.46. (a) Red component, (b) green component, and (c) blue component. These three images were added and scaled to produce the image in Fig. 6.46(c).



Noise in Color Images

- In cases when, say, only one RGB channel is affected by noise, conversation to HSI spreads the noise to all HSI component images.

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a b
c d

FIGURE 6.48 (a)–(c) Red, green, and blue component images corrupted by additive Gaussian noise of mean 0 and variance 800. (d) Resulting RGB image. [Compare (d) with Fig. 6.46(a).]

a b c

FIGURE 6.49 HSI components of the noisy color image in Fig. 6.48(d). (a) Hue. (b) Saturation. (c) Intensity.

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a b
c d

FIGURE 6.50 (a) RGB image with green plane corrupted by salt-and-pepper noise. (b) Hue component of HSI image. (c) Saturation component. (d) Intensity component.

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a b
c d

FIGURE 6.51 Color image compression. (a) Original RGB image. (b) Result of compressing and decompressing the image in (a).