Digital Image Processing

# Lecture 13. Color Image Processing

Autumn 2010

# Color Fundamentals

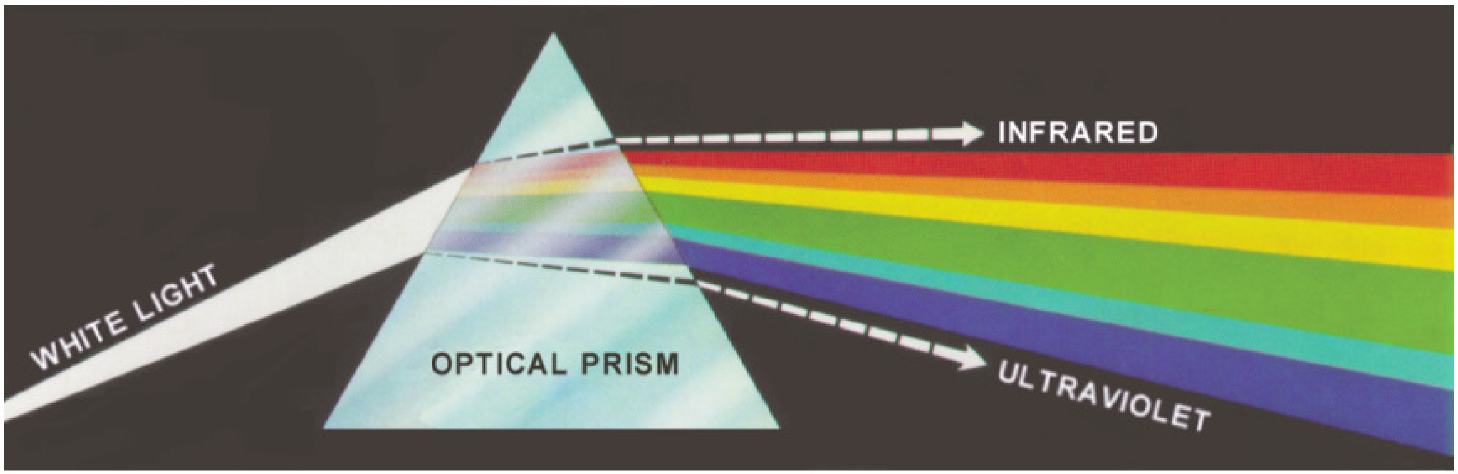



**FIGURE 6.1** Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

# Color Fundamentals

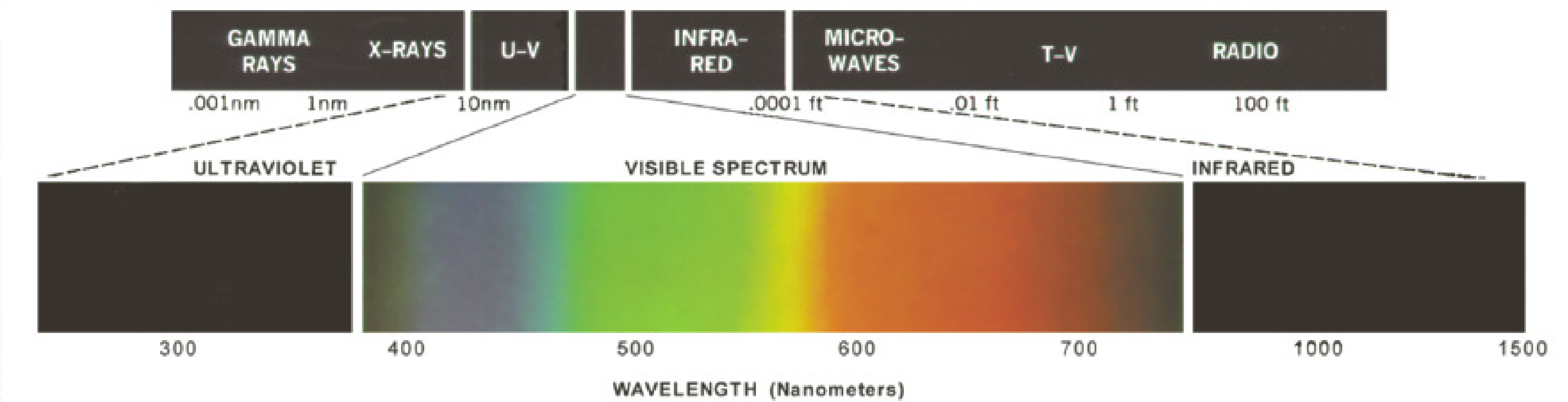
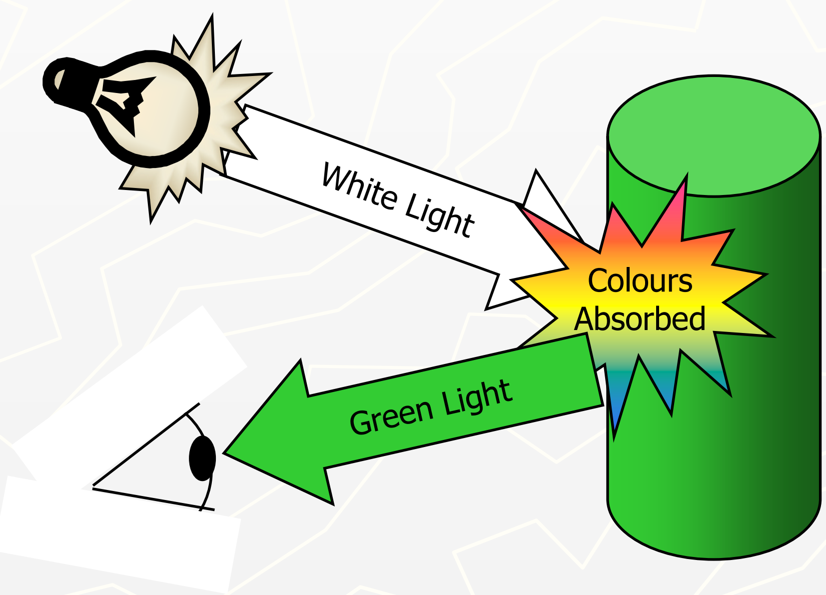



**FIGURE 6.2** Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

# Color Fundamentals

The colors that humans and most animals perceive in an object are determined by the nature of the light reflected from the object

- For example, green objects reflect light with wave lengths primarily in the range of 500 – 570 nm while absorbing most of the other energy at other wavelengths



# Color Fundamentals

- **Color Model**
  - **A mathematical system for representing color**

- The human eye combines 3 primary colors (using the 3 different types of cones) to discern all possible colors.

- Colors are just different light frequencies
  - red – 700nm wavelength
  - green – 546.1 nm wavelength
  - blue – 435.8 nm wavelength

- Higher frequencies are **cooler** colors

# Color Fundamentals

- 6 to 7 million cones in the human eye can be divided into three principal sensing categories, corresponding roughly to red, green, and blue.

65%: red 33%: green 2%: blue (blue cones are the most sensitive)

# Color Fundamentals

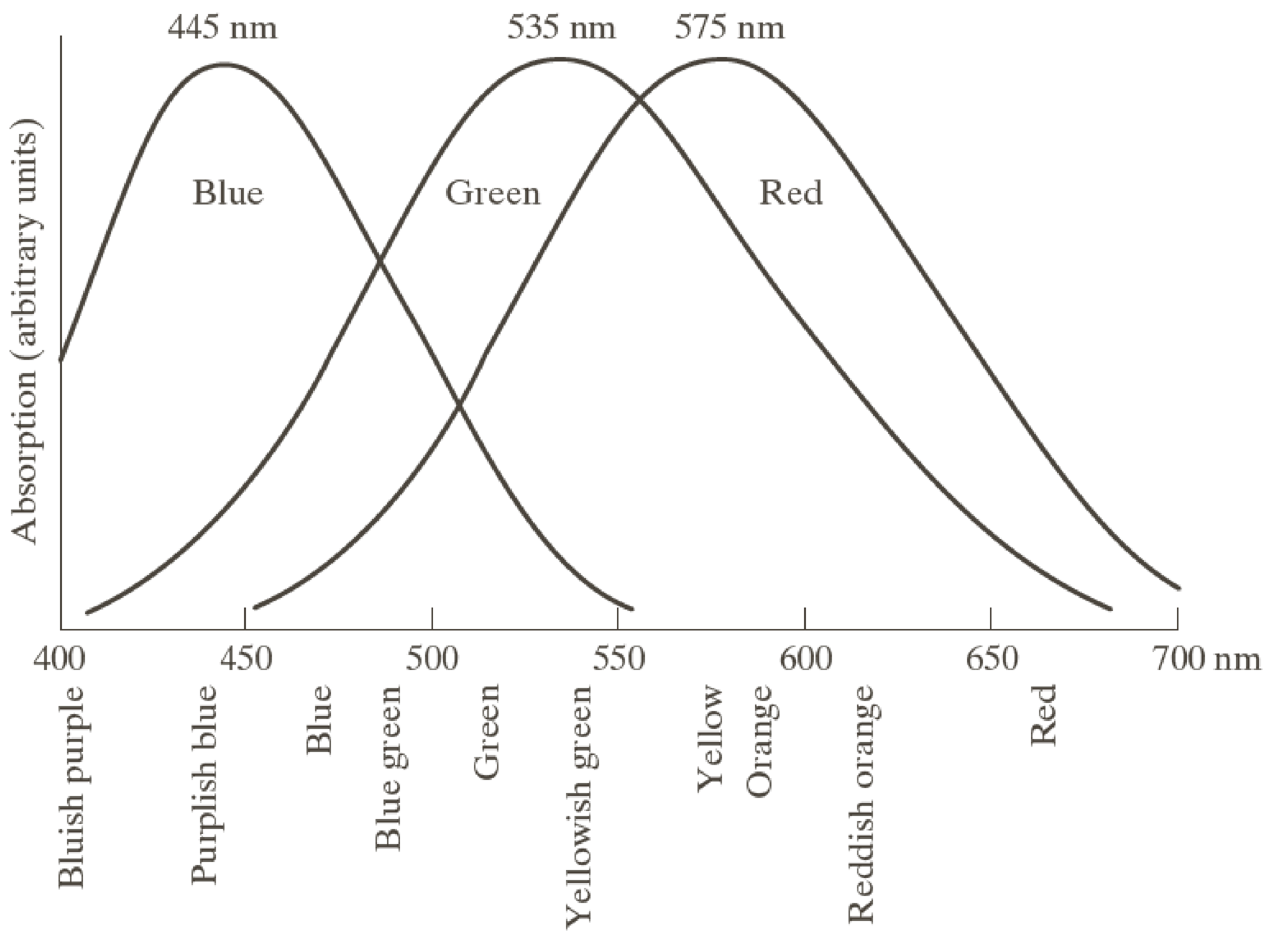



**FIGURE 6.3** Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

# Color Fundamentals

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

**brightness**: the achromatic notion of intensity.

**hue**: dominant wavelength in a mixture of light waves, represents dominant color as perceived by an observer.

**saturation**: relative purity or the amount of white light mixed with its hue.

# Color Fundamentals

3 basic qualities are used to describe the quality of a chromatic light source:

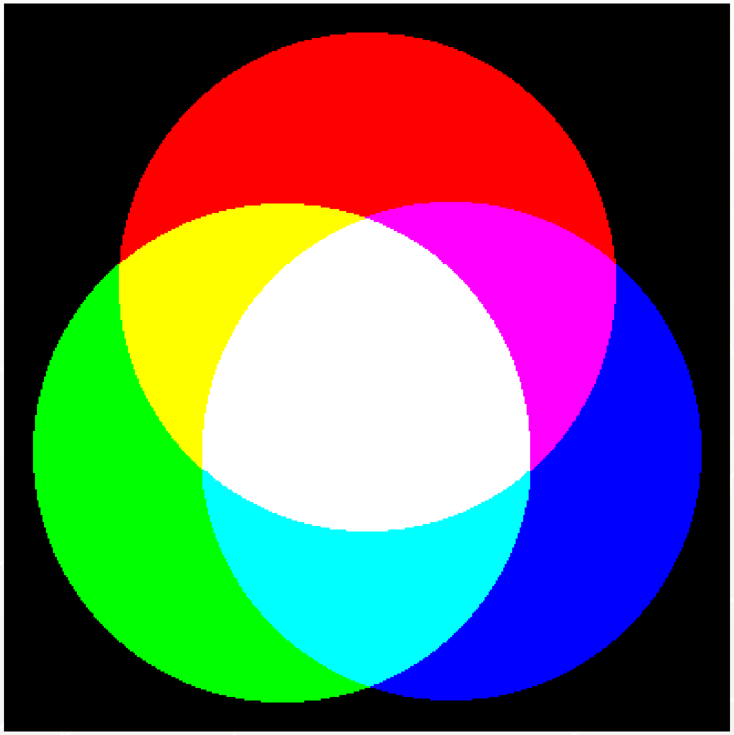
- **Radiance:** the total amount of energy that flows from the light source (measured in watts)
- **Luminance:** the amount of energy an observer *perceives* from the light source (measured in lumens)
  - Note we can have high radiance, but low luminance
- **Brightness:** a subjective (practically unmeasurable) notion that embodies the intensity of light

# Primary Colors

- Primary colors of light are additive
  - Primary colors are red, green, and blue
  - Combining red + green + blue yields white
- Primary colors of pigment are subtractive
  - Primary colors are cyan, magenta, and yellow
  - Combining cyan + magenta + yellow yields black

# RGB Color model

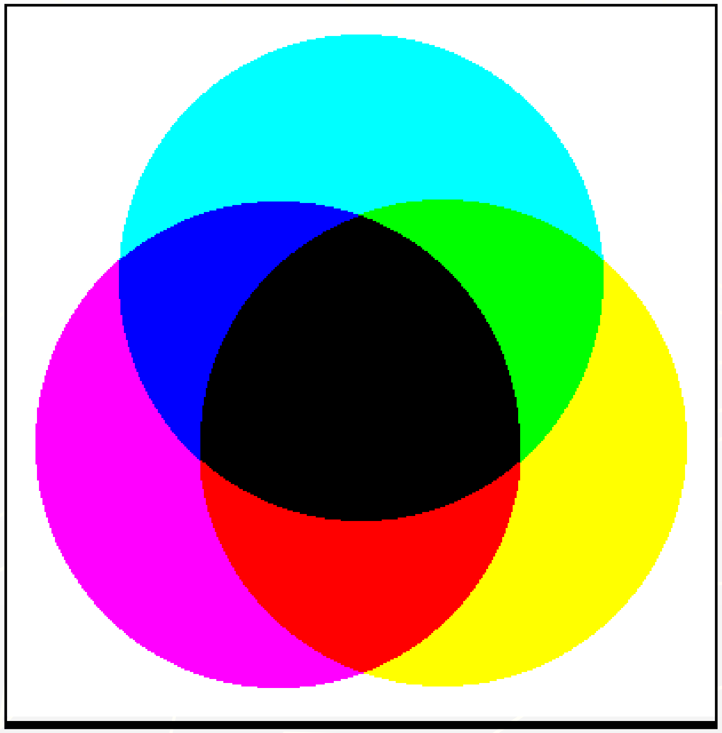
Source: www.mitsubishi.com



Active displays, such as computer monitors and television sets, emit combinations of red, green and blue light.  This is an **additive** color model

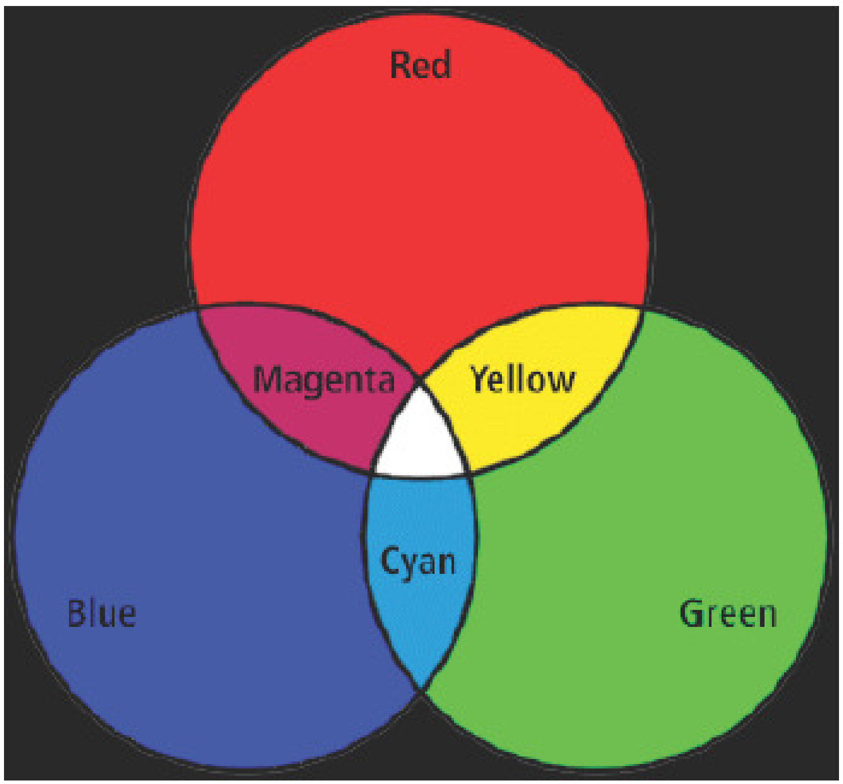
# CMY Color model

Source: www.hp.com

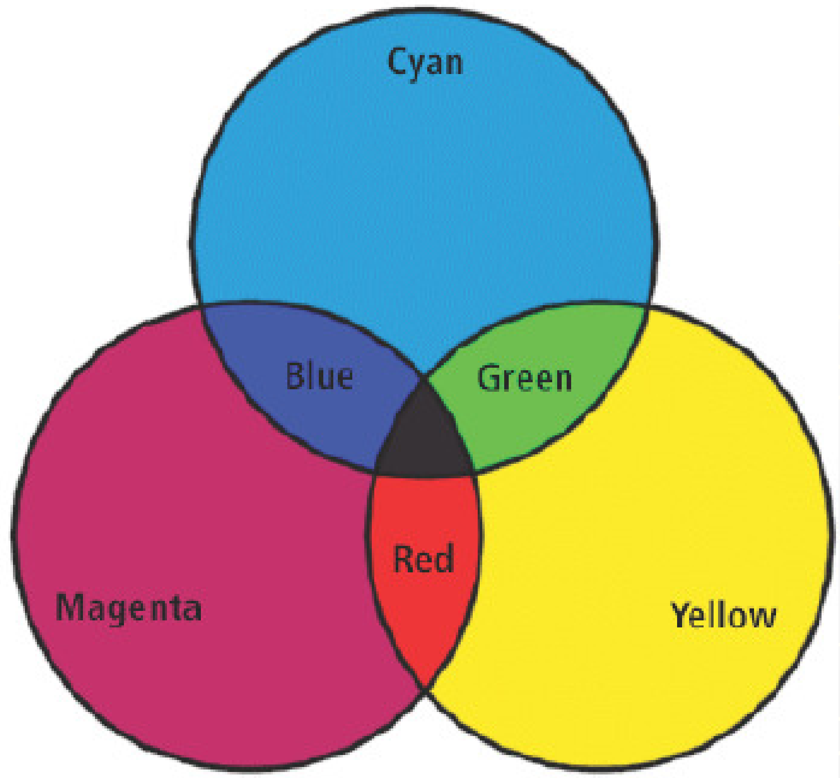


Passive displays, such as color inkjet printers, **absorb** light instead of emitting it.  Combinations of **cyan**, **magenta** and **yellow** inks are used. This is a **subtractive** color model.

# RGB vs CMY

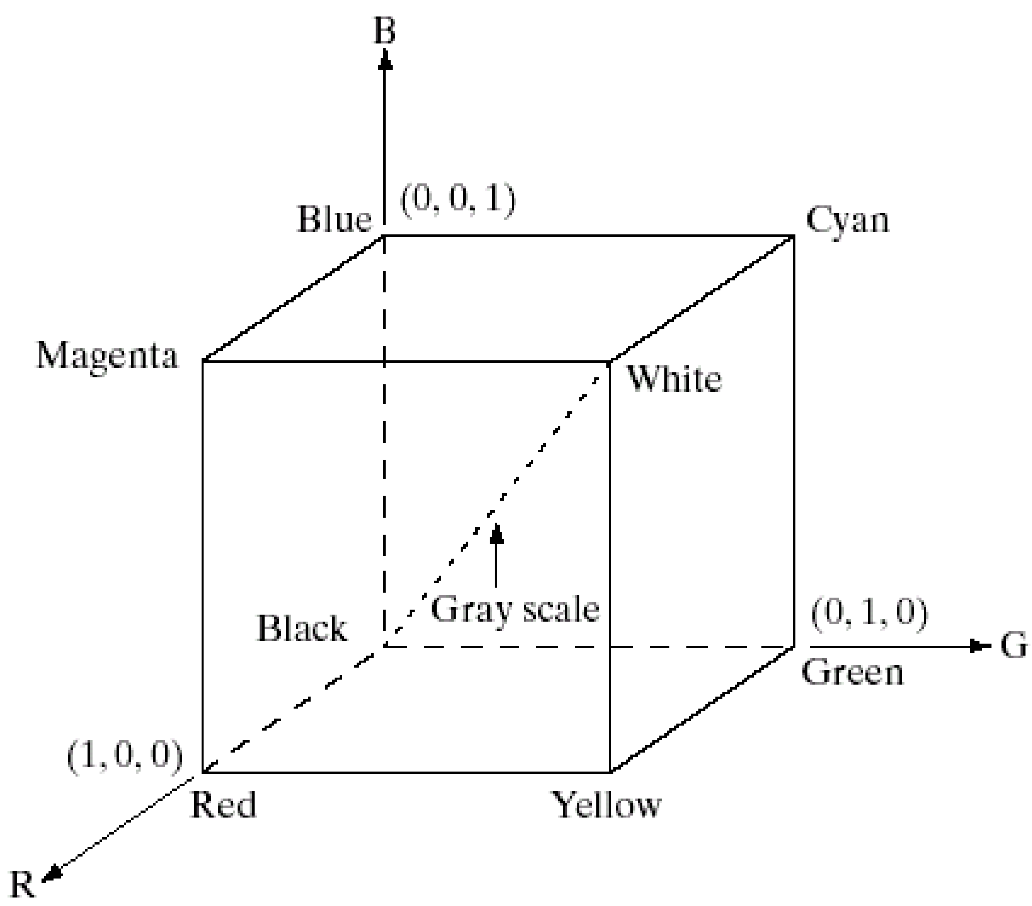


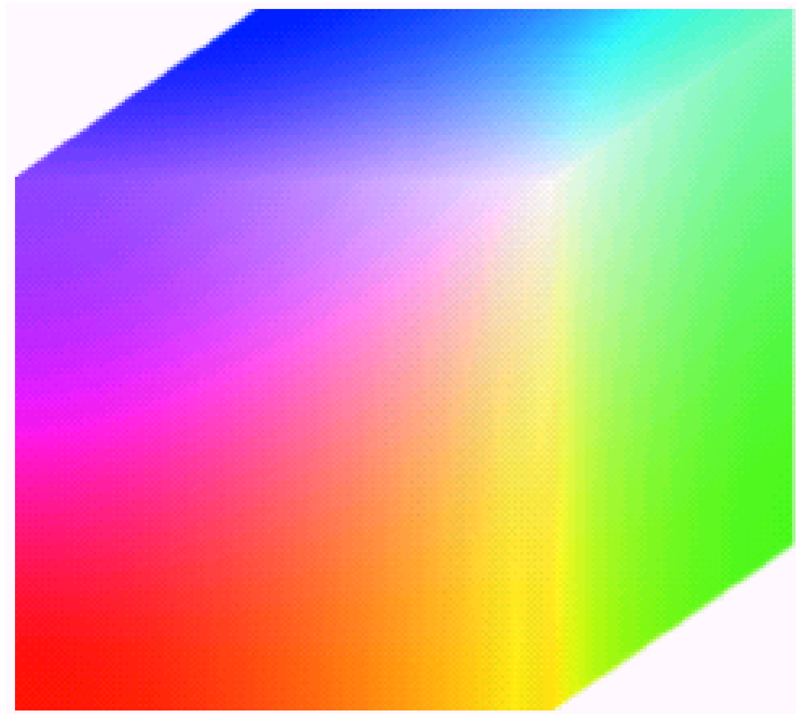

Magenta = Red + Blue
Cyan = Blue + Green
Yellow = Green + Red




Magenta = White - Green
Cyan = White - Red
Yellow = White - Blue

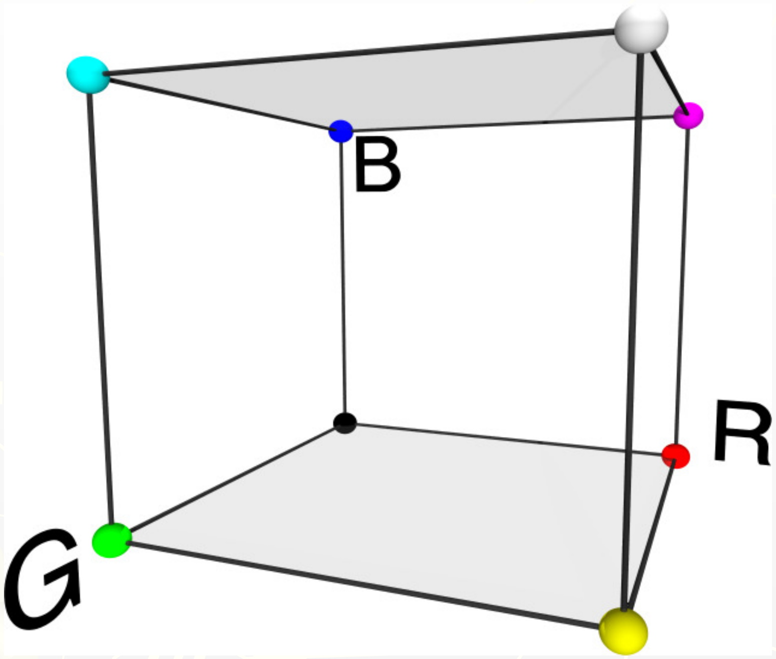
# RGB color cube

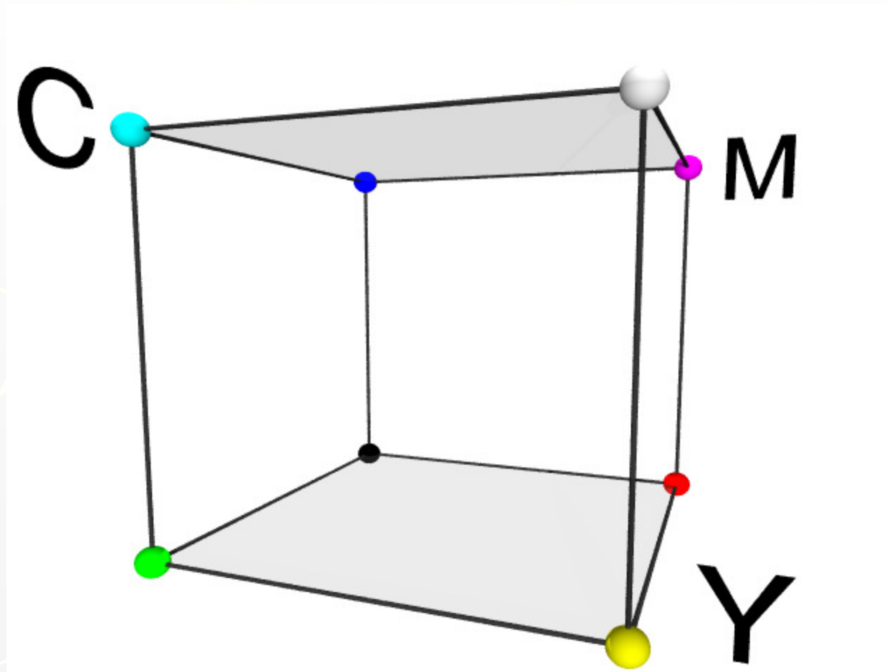


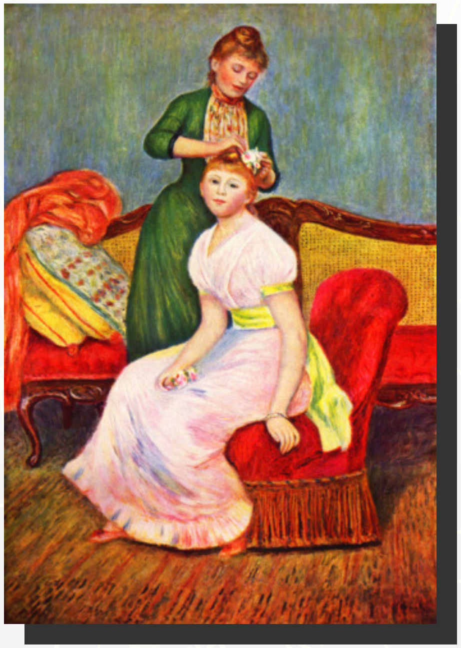
RGB 24-bit color cube

# RGB and CMY Color Cubes

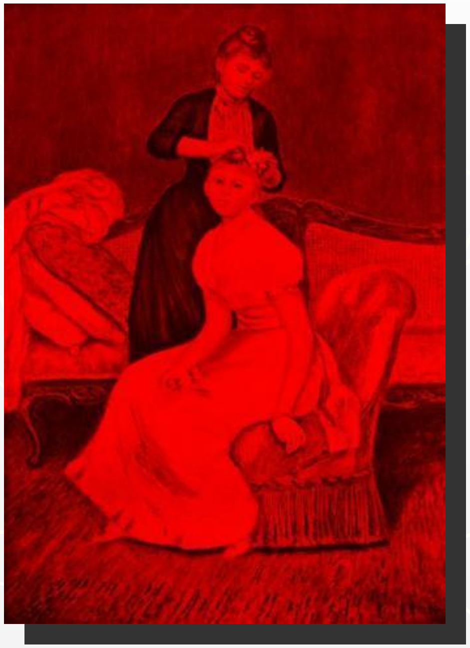


# RGB Example



Original

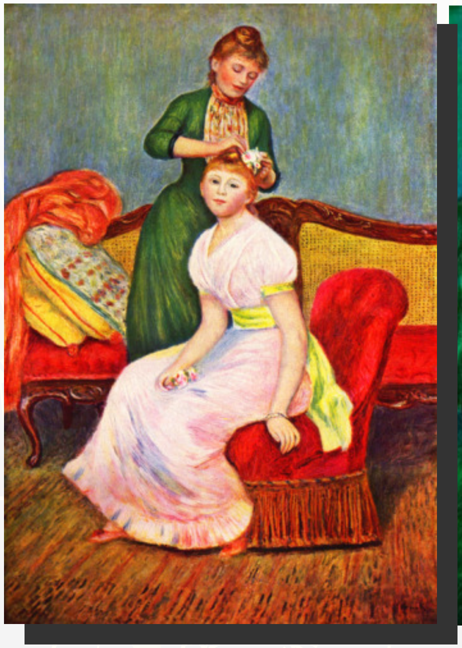


Red Band

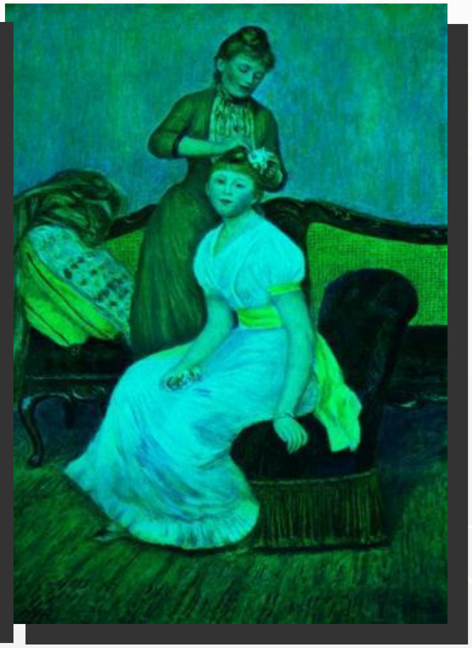
Green Band

Blue Band

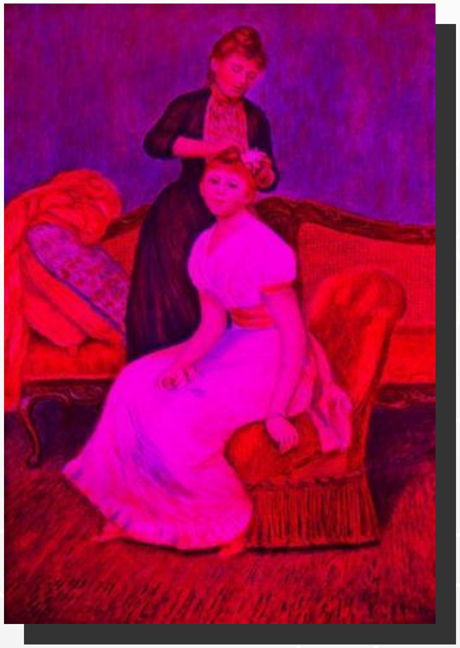
# RGB Example



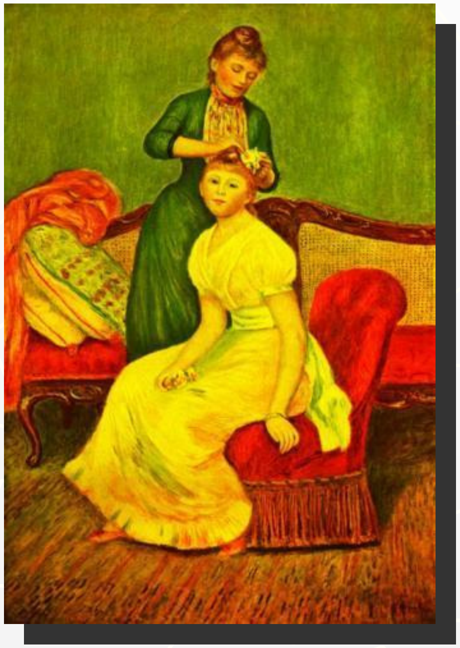
Original



No Red

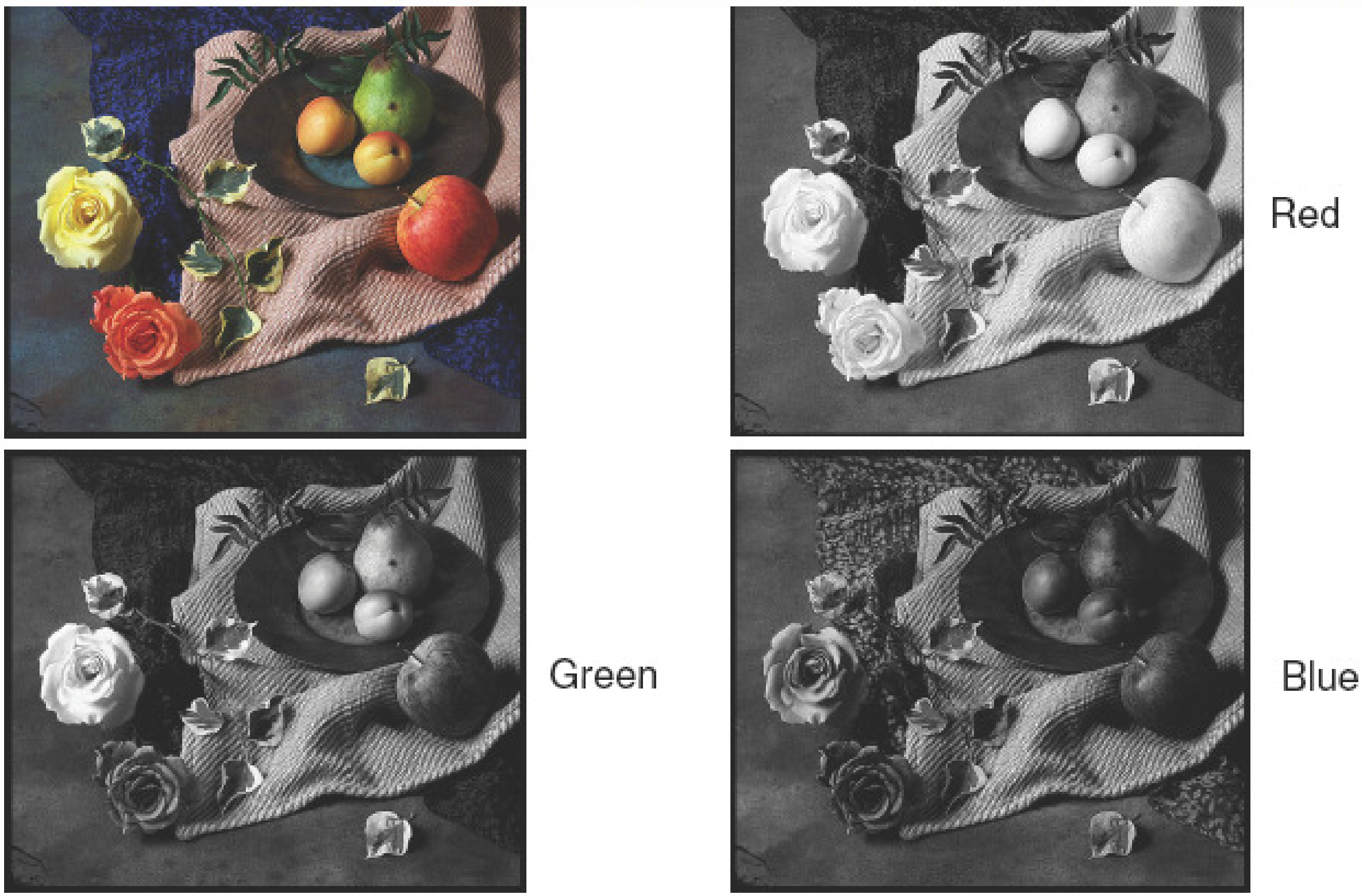


No Green



No Blue

# RGB Example



# The CMY and CMYK Color Models

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

Equal amounts of the pigment primaries, cyan, magenta, and yellow should produce black. In practice, combining these colors for printing produces a muddy-looking black.

To produce true black, the predominant color in printing, the fourth color, black, is added, giving rise to the CMYK color model.

CMY vs. CMYK

http://en.wikipedia.org/wiki/CMYK

# Subtractive mixing of inks

- Inks subtract light from white.
- Linearity depends on pigment properties
  - inks, paints, often hugely non-linear.
- Inks:  Cyan=White-Red, Magenta=White-Green, Yellow=White-Blue.
- For a good choice of inks, and good registration, matching is linear and easy
- eg. C+M+Y=White-White=Black, C+M=White-Yellow=Blue
- Usually require CMY and Black, because colored inks are more expensive, and registration is hard (CMYK)
- For good choice of inks, there is a linear transform between XYZ and CMY

# Color receptors and color deficiency

- In color normal people, there are three types of color receptor, called **cones**, which vary in their sensitivity to light at different wavelengths (shown by molecular biologists).
- Deficiency by optical problems in the eye, or by absent receptor types
  - Usually a result of absent genes.
- Some people have fewer than three types of receptor; most common deficiency is red-green color blindness in men.
- Color deficiency is less common in women; red and green receptor genes are carried on the X chromosome, and these are the ones that typically go wrong. Women need two bad X chromosomes to have a deficiency, and this is less likely.

# HSI Color Model

- Based on human perception of colors. **Color** is "decoupled" from **intensity**.
  - **HUE**
    - A subjective measure of color
    - Average human eye can perceive ~200 different colors
  - **Saturation**
    - Relative purity of the color. Mixing more "white" with a color reduces its saturation.
    - **Pink** has the same **hue** as **red** but less **saturation**
  - **Intensity**
    - The brightness or darkness of an object

# HSI Color Model


Source: http://www.cs.cornell.edu/courses/cs631/1999sp/

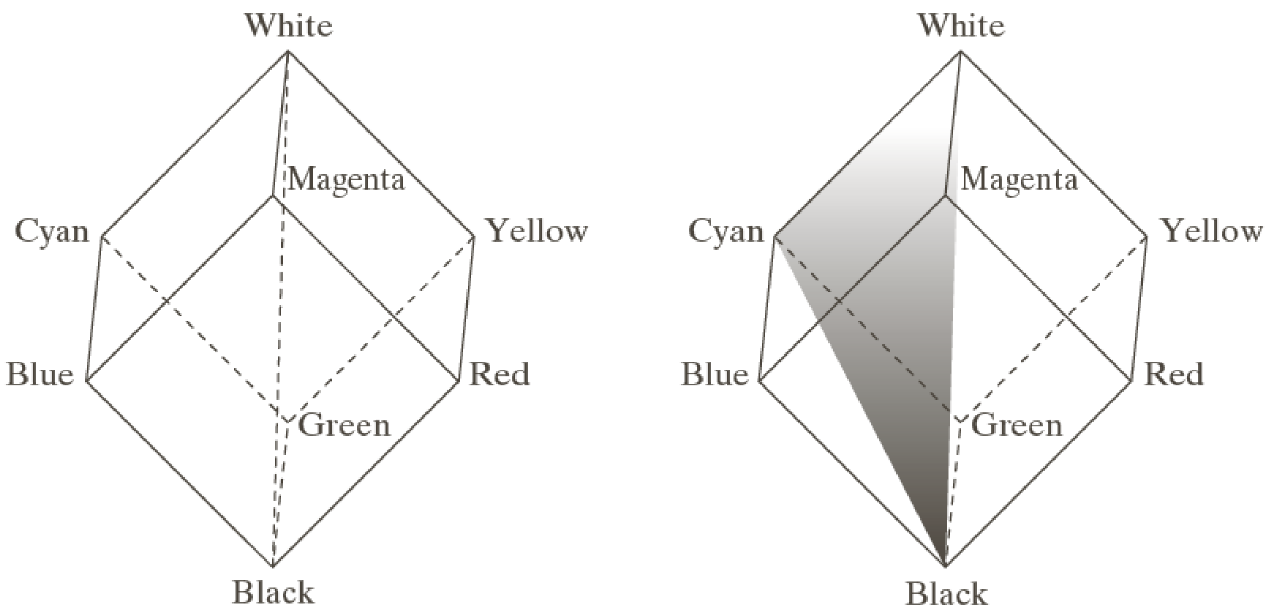
# HSI Color Model

- **Hue** is defined as an angle
  - 0 degrees is **RED**
  - 120 degrees is **GREEN**
  - 240 degrees is **BLUE**

- **Saturation** is defined as the percentage of distance from the center of the HSI triangle to the pyramid surface.
  - Values range from 0 to 1.

- **Intensity** is denoted as the distance “up” the axis from black.
  - Values range from 0 to 1

# HSI Color Model




a b

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

# HSI Color Model

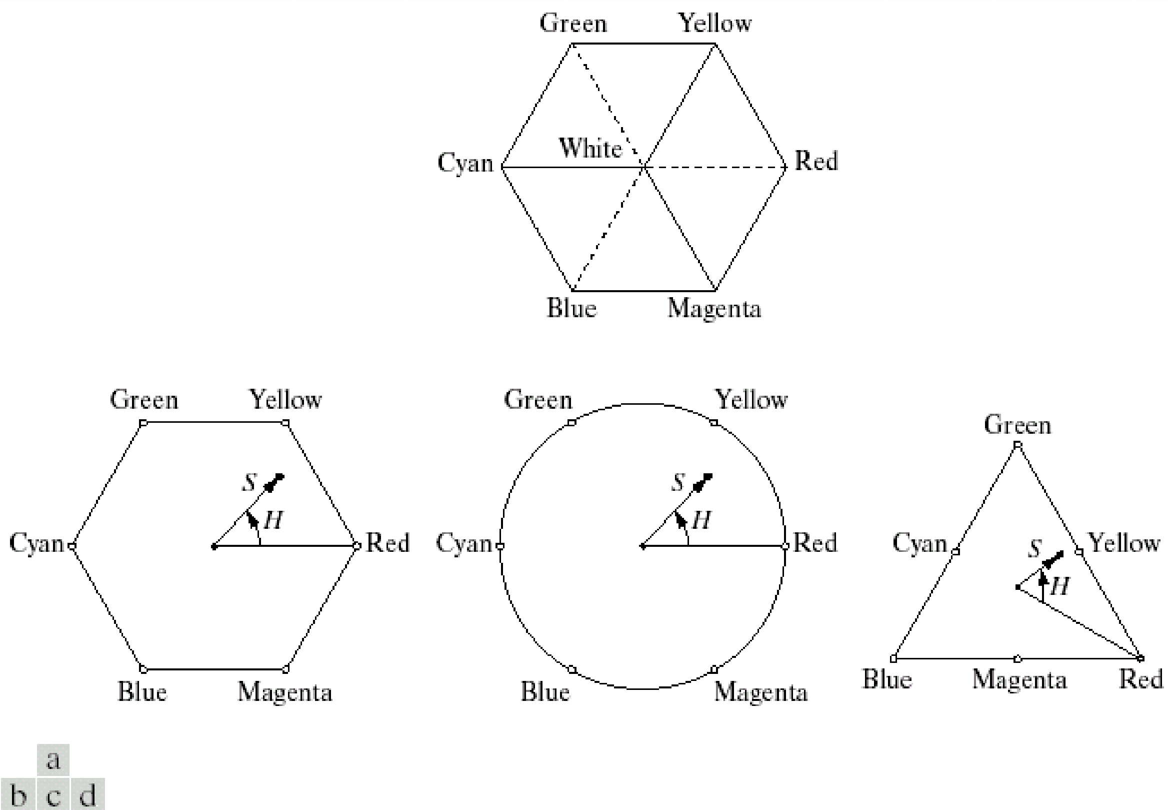
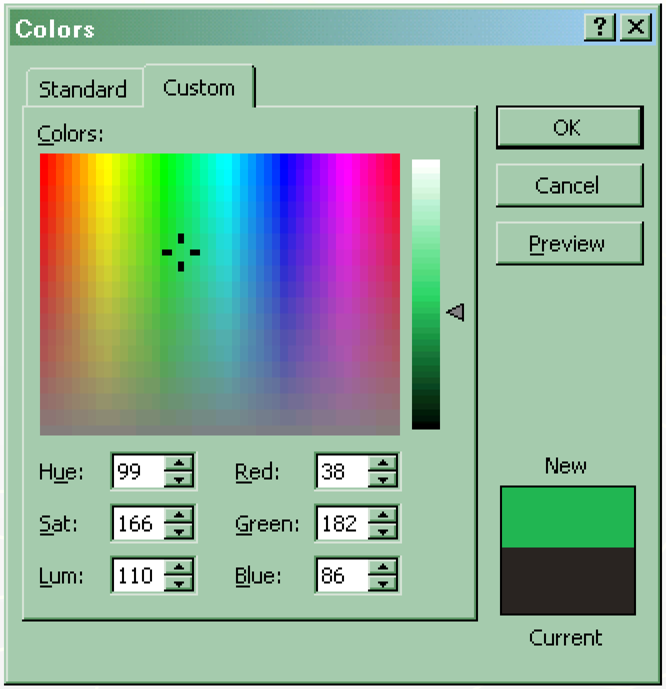



**FIGURE 6.13** Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and the length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity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

# HSI and RGB

RGB and HSI are commonly used to specify colors in software applications.

HSI has variants such as HSL and HSB both all of which model color in the same fundamental way.



# Conversion Between RGB and HSI

- Converting color from RGB to HSI

$$H = \begin{cases} \theta & \text{if } B \le G \\ 360-\theta & \text{if } B > G \end{cases} \quad \text{with } \theta = \cos^{-1}\left\{ \frac{\frac{1}{2}[(R-G)+(R-B)]}{\left[(R-G)^2+(R-B)(G-B)\right]^{\frac{1}{2}}} \right\}$$

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

$$I = \frac{1}{3}[R+G+B]$$

- Converting color from HSI to RGB

RG sector (0≤H<120)

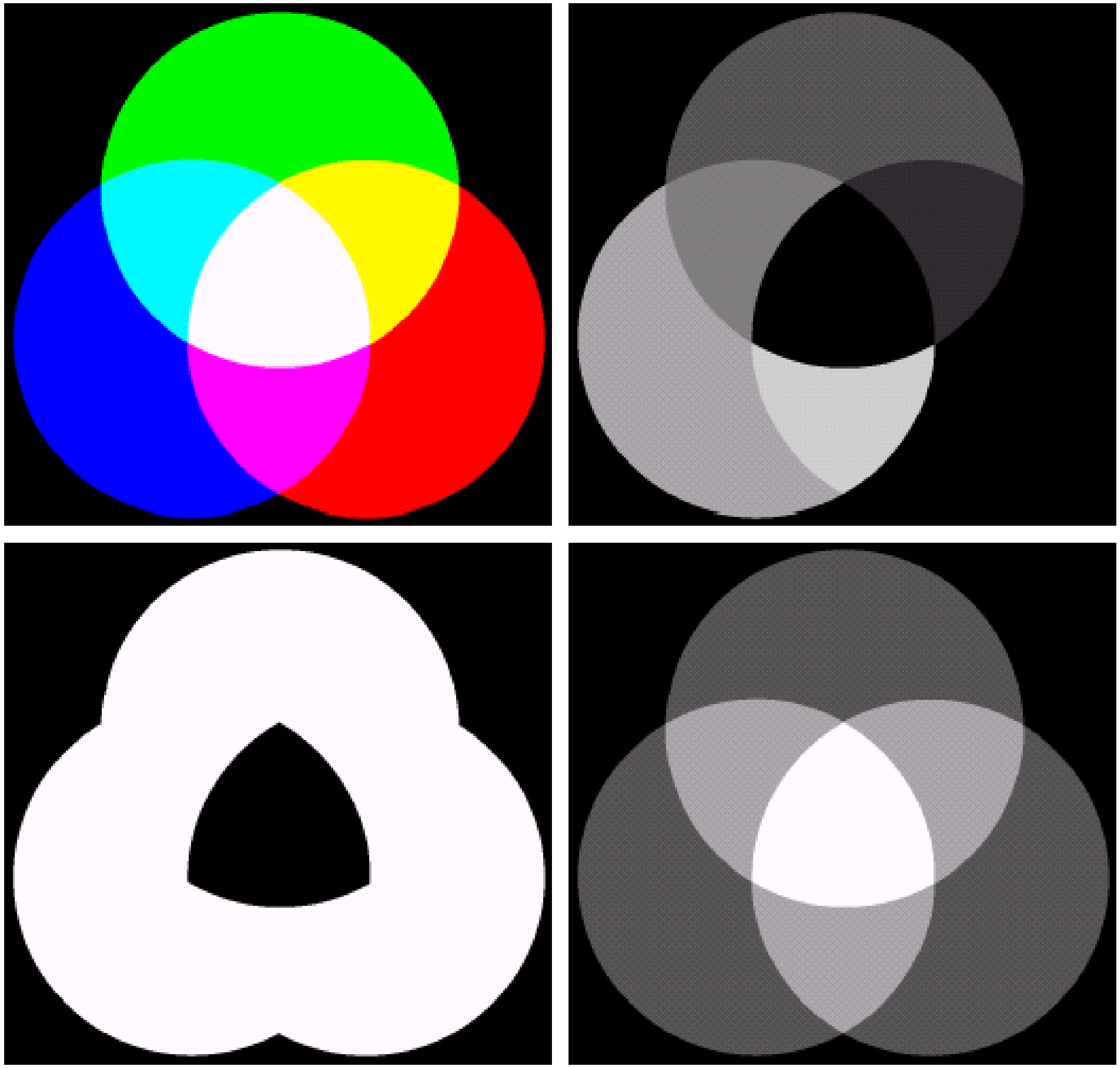
$$B = I(1-S)$$
$$R = I\left[1+\frac{S\cos H}{\cos(60-H)}\right]$$
$$G = 1-(R+B)$$

GB sector (120≤H<240)

$$R = I(1-S)$$
$$G = I\left[1+\frac{S\cos(H-120)}{\cos(60-(H-120))}\right]$$
$$B = 1-(R+G)$$

BR sector (240≤H<360)

$$G = I(1-S)$$
$$B = I\left[1+\frac{S\cos(H-240)}{\cos(60-(H-240))}\right]$$
$$R = 1-(G+B)$$



| 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 "Types"
(categorized by "color")

- **Binary Image**
  - has exactly two colors
- **Grayscale**
  - has no chromatic content
- **Color**
  - contains some pixels with color
  - more than two colors exist

# Color Depth

- **Describes the ability of an image to accurately reproduce colors**
  - Given as the "number of bits consumed by a single pixel"
  - Otherwise known as "**bits per pixel" (bpp)**

- **Binary images are _____ bpp?**
- **Grayscale images are typically _____ bpp?**
- **Color images are typically _____ bpp?**

| | |
|---|---|
| A | B |
| C | D |

A: 1 bpp
B: 2 bpp
C: 5 bpp
D: 24 bpp

# Tristimulus Values

- Tristimulus value
  - The amounts of red, green, and blue needed to form any particular color are called the **tristimulus values**, denoted by X, Y, and Z.
  - Only two chromaticity coefficients are necessary to specify the chrominance of a light.

$$X + Y + Z = 1$$

# CIE Chromacity Diagram

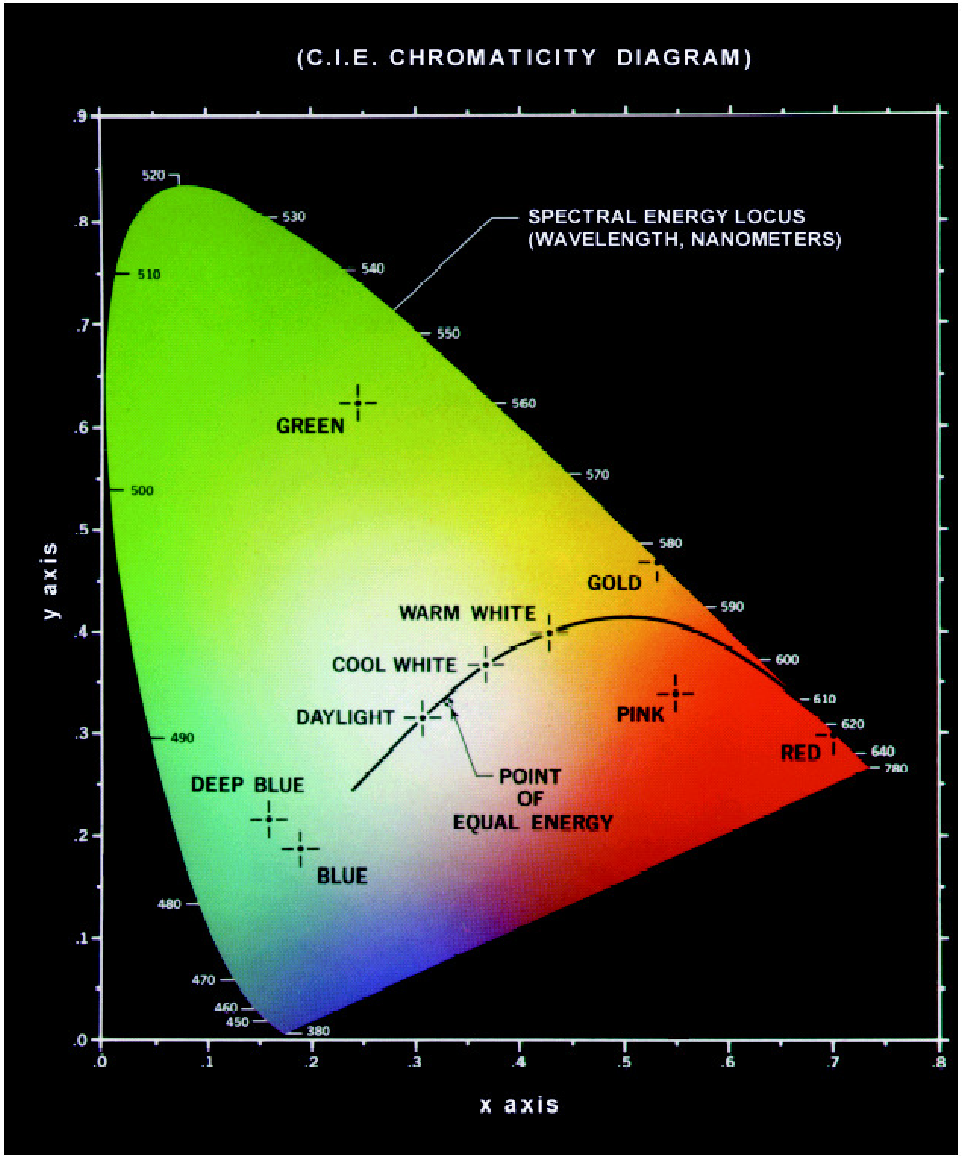
Specifying colors systematically can be achieved using the CIE **chromacity diagram**

On this diagram the x-axis represents the proportion of red and the y-axis represents the proportion of red used

The proportion of blue used in a color is calculated as:

$$z = 1 - (x + y)$$

# CIE Chromacity Diagram (cont…)




Green: 62% green, 25% red and 13% blue

Red: 32% green, 67% red and 1% blue

# CIE Chromacity Diagram (cont…)

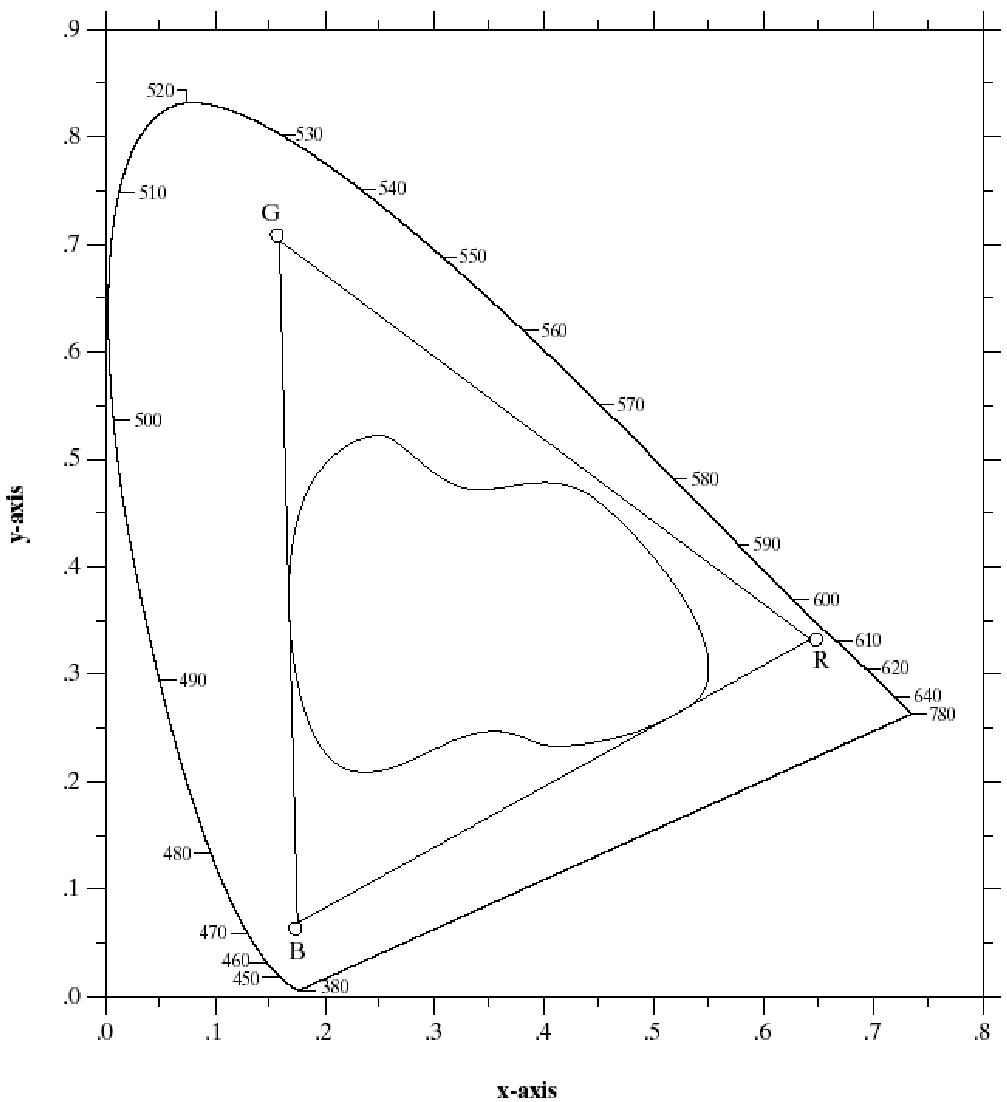
- Any color located on the boundary of the chromacity chart is fully saturated

- The point of equal energy has equal amounts of each color and is the CIE standard for pure white

- Any straight line joining two points in the diagram defines all of the different colors that can be obtained by combining these two colors additively

- This can be easily extended to three points

# CIE Chromacity Diagram (cont…)




- ►This means the entire color range cannot be displayed based on any three colors
- ►The triangle shows the typical color gamut produced by RGB monitors
- ►The strange shape is the gamut achieved by high quality color printers

# Color Models

- Specify three primary or secondary colors
  - Red, Green, Blue.
  - Cyan, Magenta, Yellow.
- Specify the luminance and chrominance
  - – HSB, HSI or HSV (Hue, saturation, and brightness, intensity or value)
- Amplitude specification:
  - 8 bits per color component, or 24 bits per pixel
  - Total of 16 million colors

# Comparison of Different Color Spaces


Much details than other bands (can be used for processing color images)

# Pseudocolor Image Processing

- The process of assigning colors to gray values based on a specified criterion.

- Intensity Slicing

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

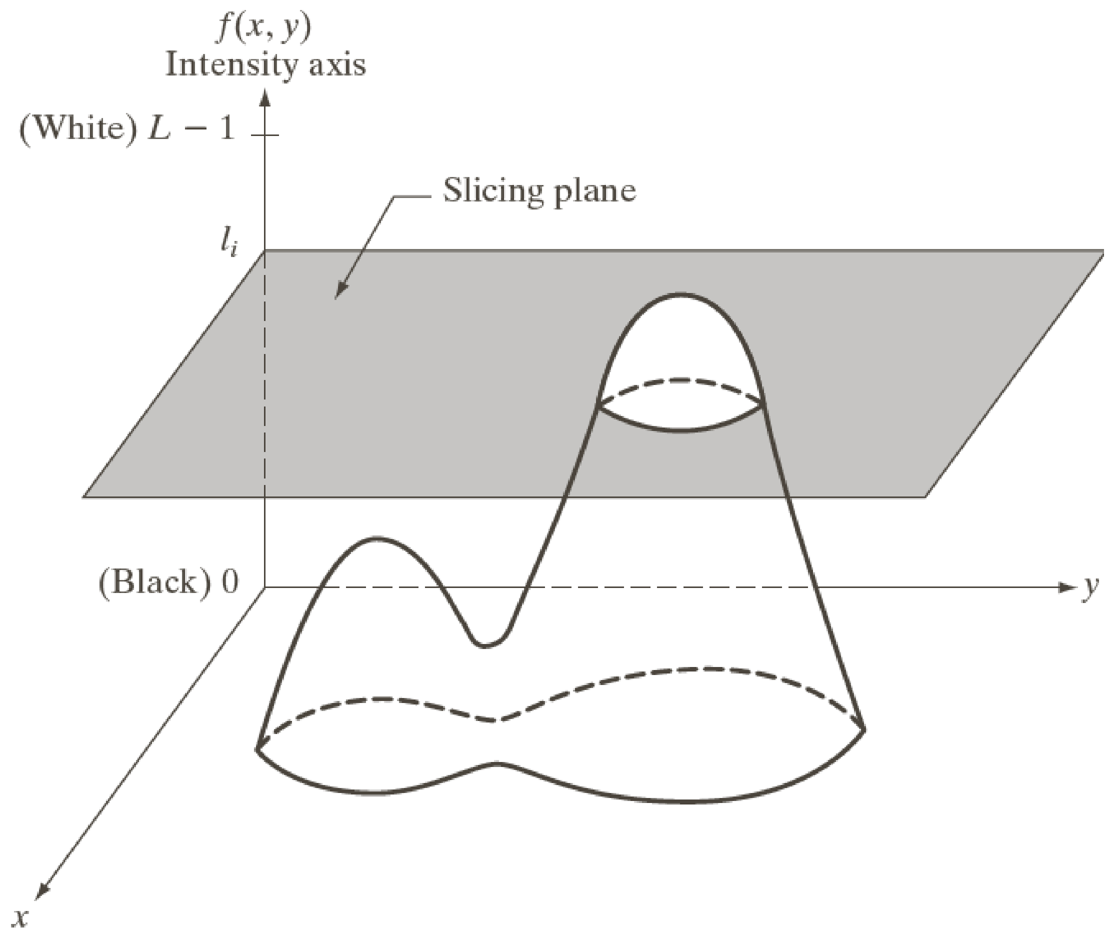



**FIGURE 6.18** Geometric interpretation of the intensity-slicing technique.

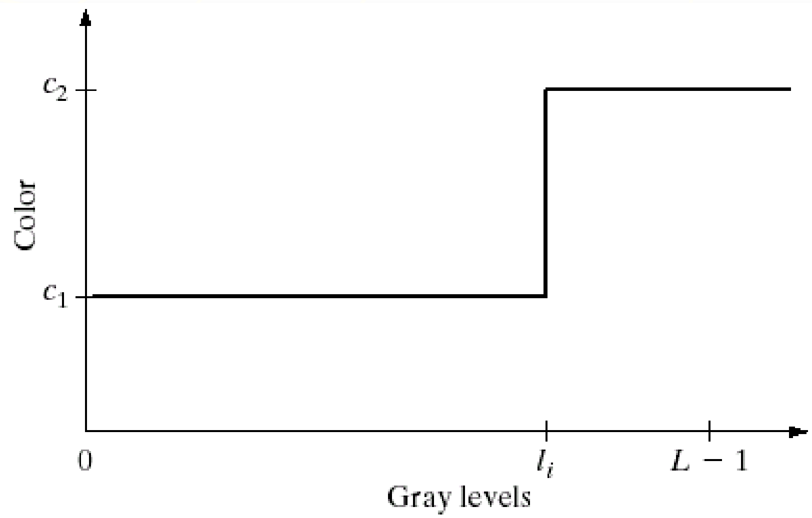
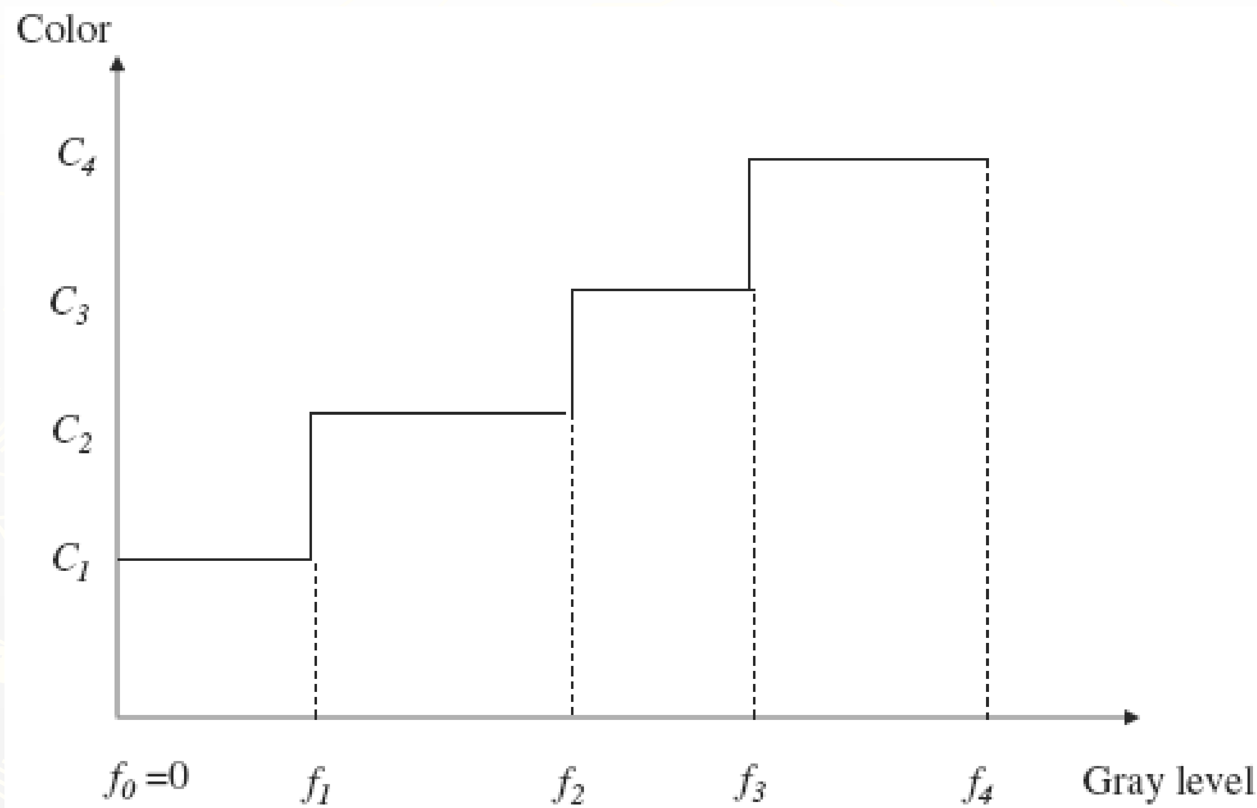
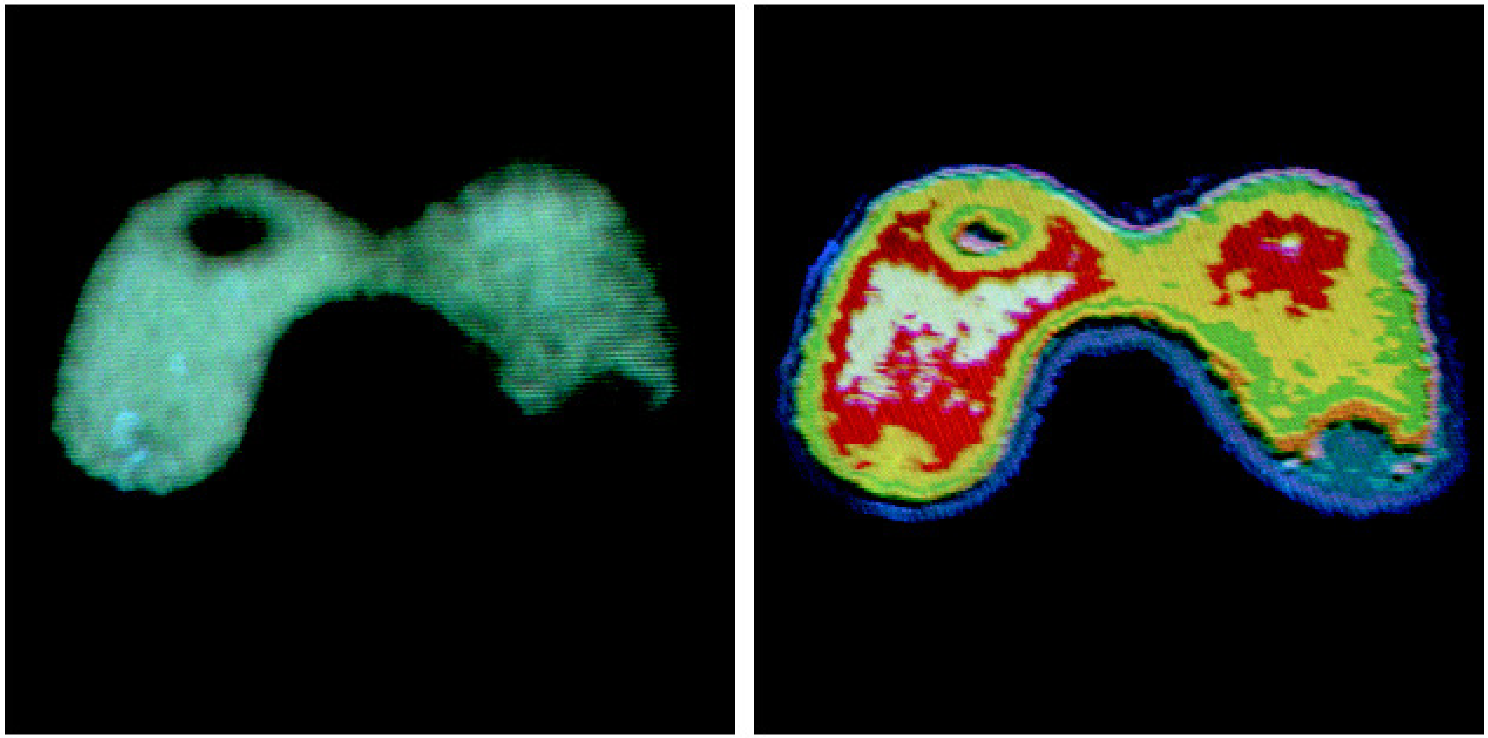



**FIGURE 6.19** An alternative representation of the intensity-slicing technique.

# Intensity Slicing




- Pixels with gray-scale (intensity) value in the range of ($f_{i-1}$ , $f_i$) are rendered with color *Ci*

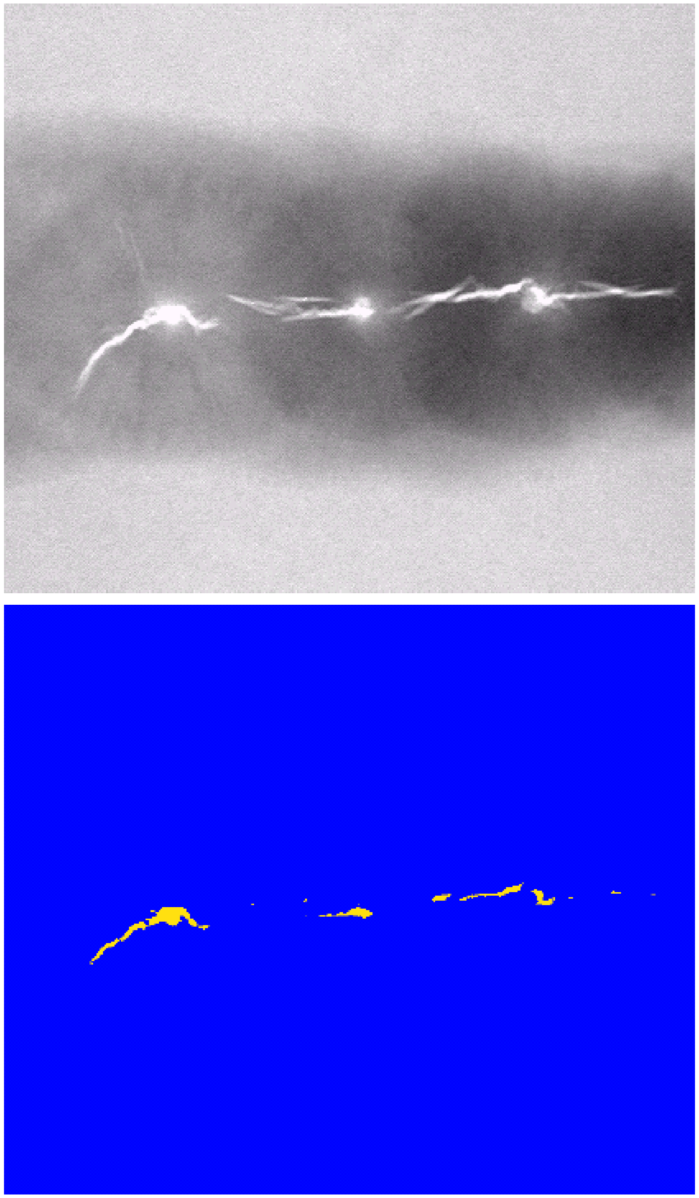


a b

**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.)



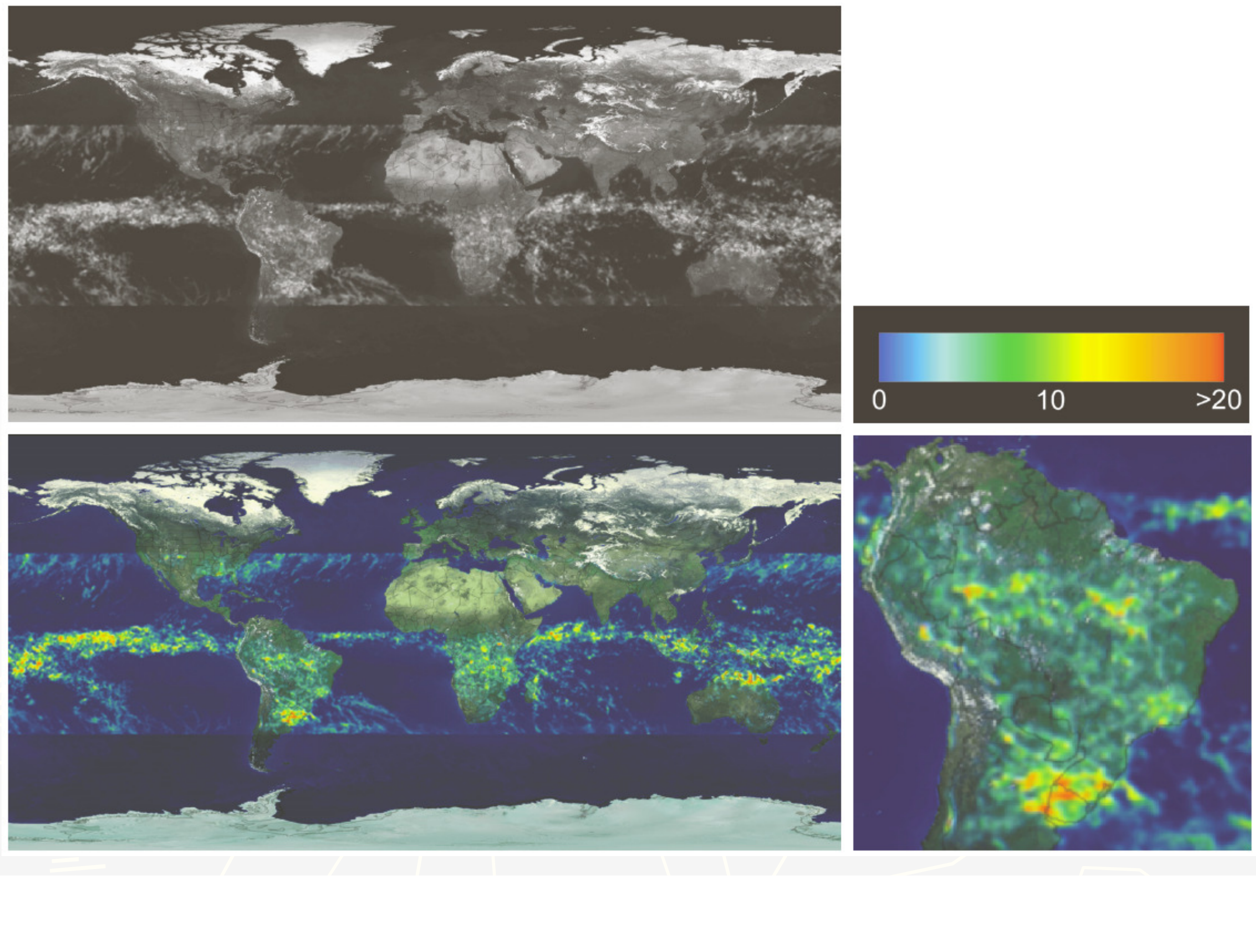



**FIGURE 6.22** (a) Gray-scale image in which intensity (in the lighter horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South American region. (Courtesy of NASA.)

# Pseudocolor Image Processing

- Intensity to Color Transformation

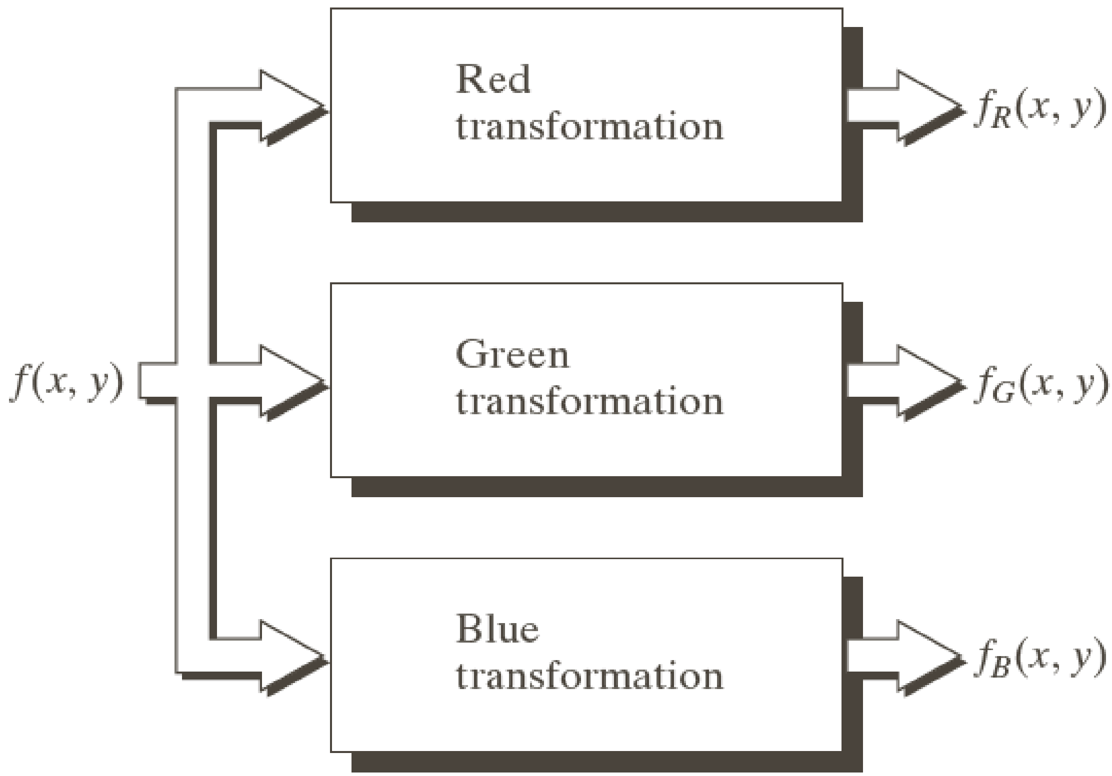
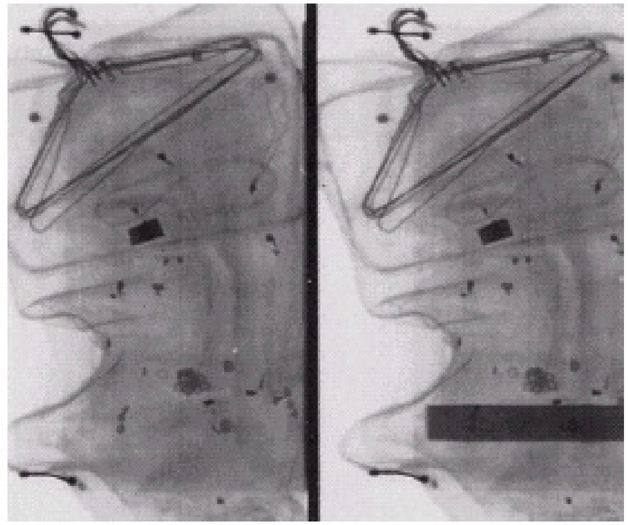



**FIGURE 6.23** Functional block diagram for pseudocolor image processing. $f_R$, $f_G$, and $f_B$ are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

The images are obtained from an airport X-ray scanning system.
The left contains ordinary articles and the right contains the same articles as well as a block of simulated plastic explosives.



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.)

# Basics of Full-Color Image Processing

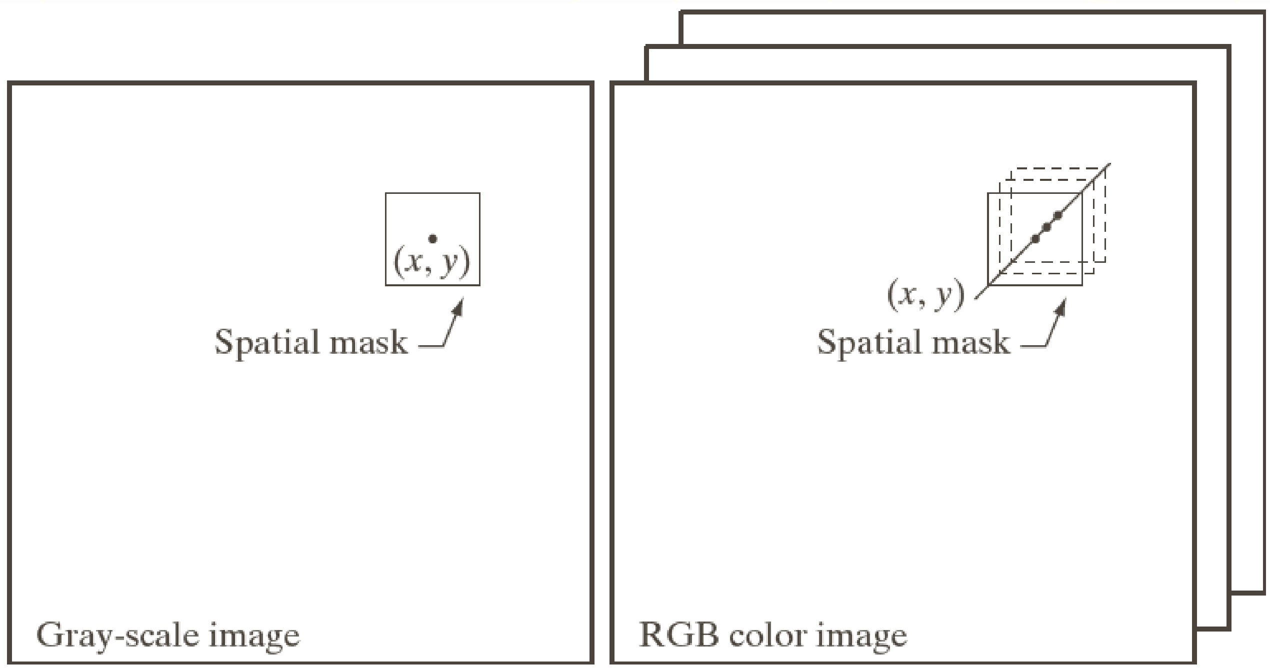
Let $c$ represent an arbitrary vector in RGB color space:

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

At coordinates $(x, y)$,

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

# Basics of Full-Color Image Processing




a b

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

# Color Image Smoothing

Let $S_{xy}$ denote the set of coordinates defining a neighborhood centered at $(x, y)$ in an RGB color image. The average of the RGB component vectors in this neighborhood is

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

| a | b |
|---|---|
| c | d |

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


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

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

The Laplacian of vector c is

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

a b c

**FIGURE 6.41** Image sharpening with 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.

# Color Edge Detection (1)

Let r, g, and b be unit vectors along the R, G, and B axis of RGB color space, and define vectors

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

and

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

# Color Edge Detection (2)

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

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

and

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

# Color Edge Detection (3)

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

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

The value of the rate of change at ($x$, $y$) in the direction of $\theta(x, y)$, is given by

$$F_\theta(x, y) = \left\{\frac{1}{2}\left[\left(g_{xx} + g_{yy}\right) + \left(g_{xx} - g_{yy}\right)\cos 2\theta(x, y) + 2g_{xy}\sin 2\theta(x, y)\right]\right\}^{1/2}$$

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).

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).