EEE-6512: Image Processing and Computer Vision

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Lecture #6: Color

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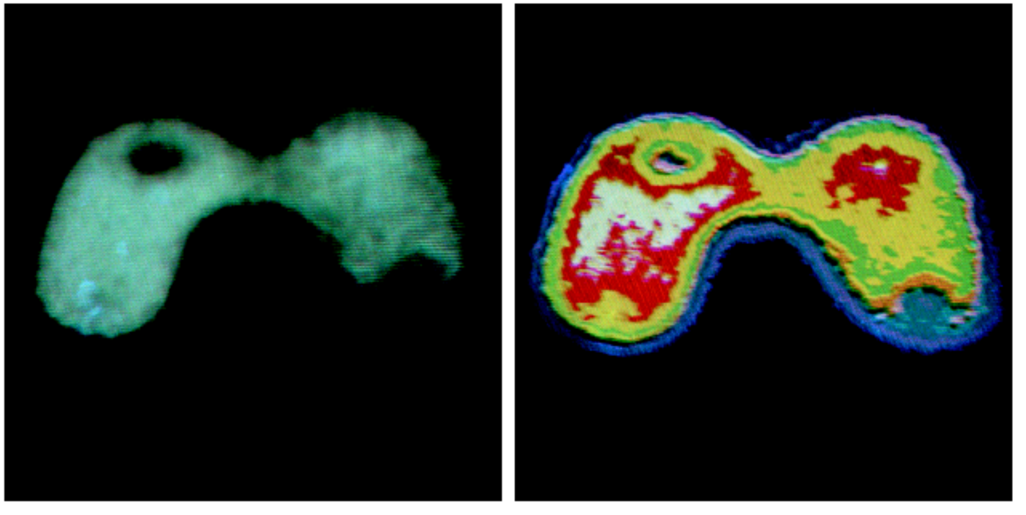
Outline

- Background
- Color Models
- Pseudocolor Image Processing
- Basics of Full-Color Image Processing
- Color Transformations
- Color Image Smoothing and Sharpening
- Using Color in Segmentation

Motivation

- Why use color in image processing?
  - Color is a powerful descriptor
    - Object identification and extraction
    - eg. Face detection using skin colors
  - Humans can discern thousands of color shades and intensities
    - c.f. Human discern only two dozen shades of grays



Motivation

- Two category of color image processing
  - **Full color processing**

    Images are acquired from full-color sensor or equipment
  - **Pseudo-color processing**
    - Previously, color sensors and processing hardware were not available
    - Colors are assigned to a range of monochrome intensities

Color fundamentals

- **Physical** phenomenon
  - Physical nature of color is known
- **Physiopsychological** phenomenon
  - How human brain perceive and interpret color?

Interesting Facts about Color

- **Men and women see color differently**
  - Women are better at distinguishing various shades of red (red-orange spectrum).
  - Women are better at distinguishing between close range of colors while men are better at recognizing fine details in a moving object.
- **Colors affect our depth perception (warm/light colors closer, cool/dark colors further)**
- **Colors affect the way that humans taste foods.**
- **Red can effect performance on exams.**
- **The color yellow can cause nausea.**

Interesting Facts about Color (cont.)

- **Different colors evoke different emotions.**
- **People perceive colors differently**
- **Colors do not exist!**

Color fundamentals (cont.)

- 1666, Isaac Newton

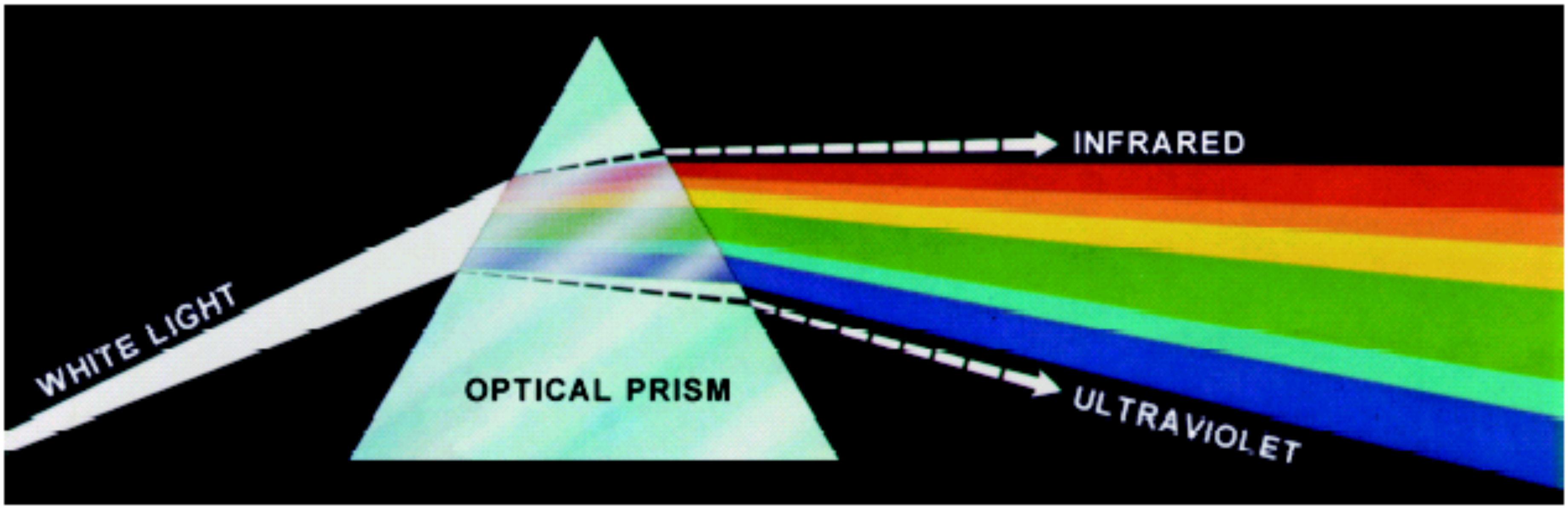


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

Visible light

- Chromatic light span the electromagnetic spectrum (EM) from 400 to 700 nm

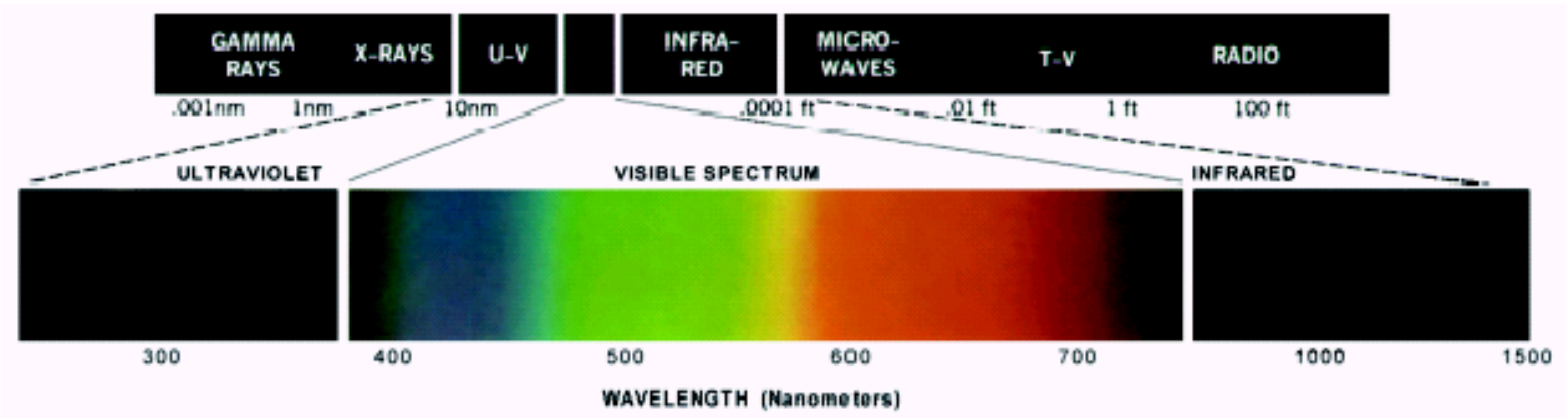
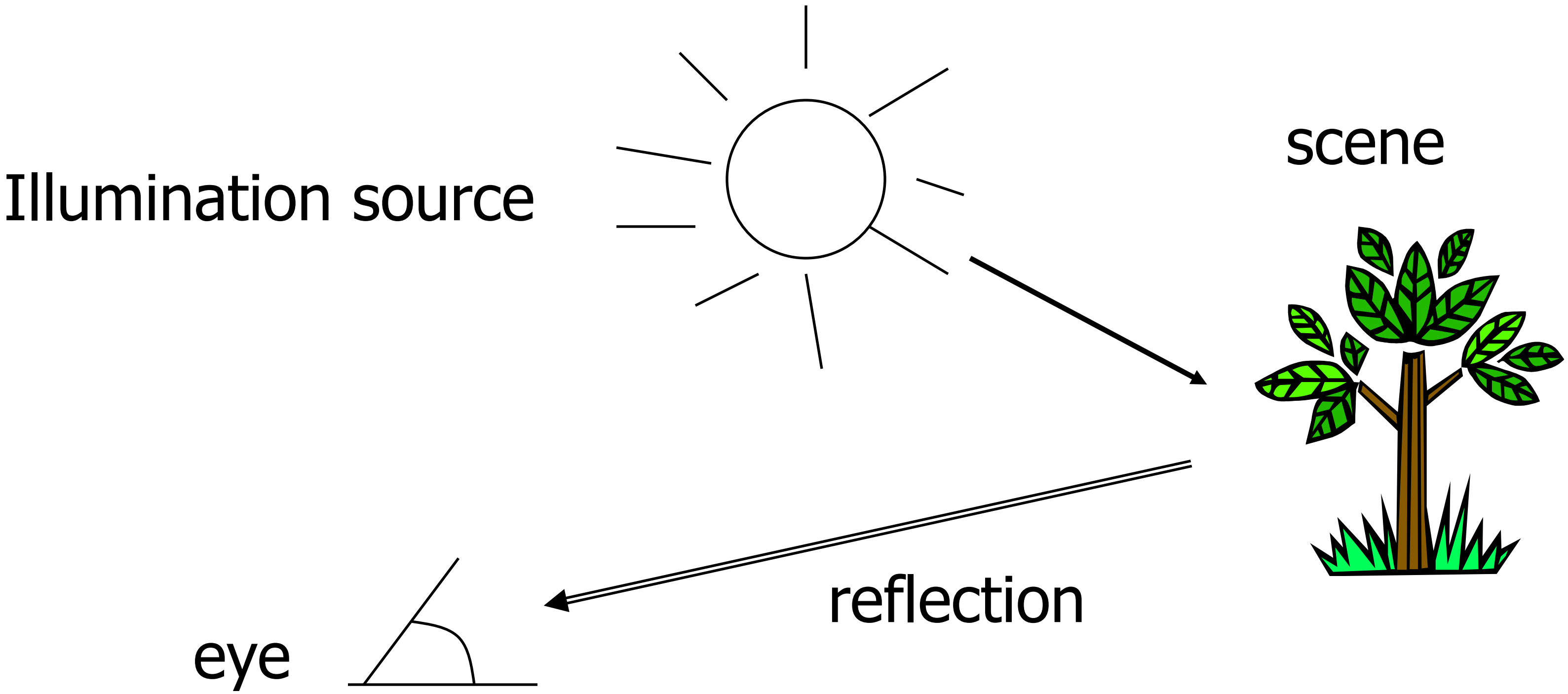


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

Color fundamentals (cont.)

- The color that human perceives in an object = the light reflected from the object



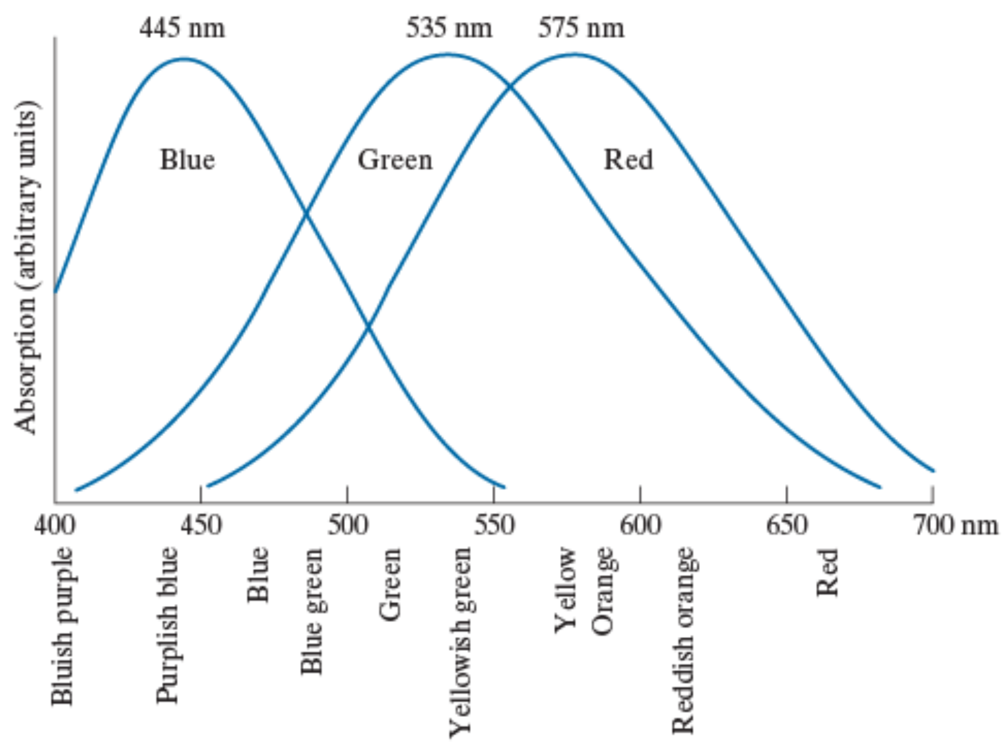
Physical quantities to describe a chromatic light source

- **Radiance:** total amount of energy that flow from the light source, measured in watts (W)
- **Luminance:** amount of energy an observer *perceives* from a light source, measured in lumens
  - Far infrared light: high radiance, but 0 luminance
- **Brightness:** subjective descriptor that is hard to measure, similar to the achromatic notion of intensity

How human eyes sense light?

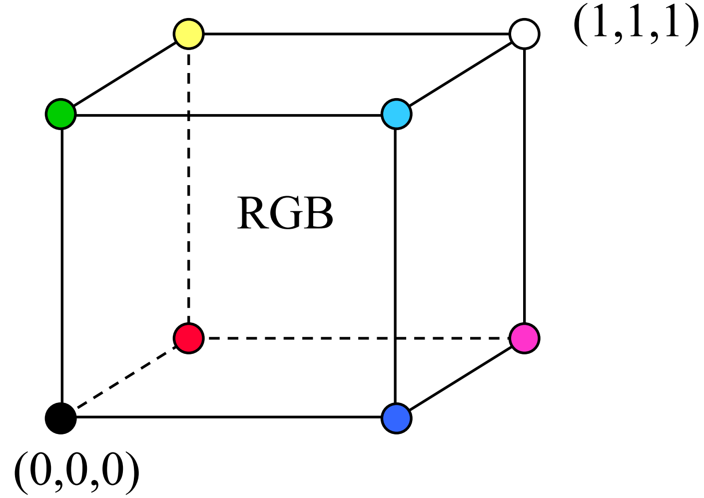
- Human eye does not perceive individual wavelengths
- 6~7M Cones are the sensors in the eye
- 3 principal sensing categories in eyes which integrate over parts of the spectrum.
  - Red light 65%, green light 33%, and blue light 2%

FIGURE 7.3
Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.



How human eyes sense light?

- It is therefore possible to characterise a psycho-visual colour by specifying the amounts of three primary colours: red, green and blue, mixed together.
- This leads to the standard RGB space used in television, computer monitors, etc.
- We specify the levels of R, G and B in the range [0, 1], but they can easily be extended to other ranges (8-bit integers for example).



Problems with Processing Color Images

- When processing colour images, the following problems (amongst others) have to be dealt with:
  - The images are vectorial → 3 numbers are associated with each pixel.
  - The colours recorded by a camera are heavily dependent on the lighting conditions.



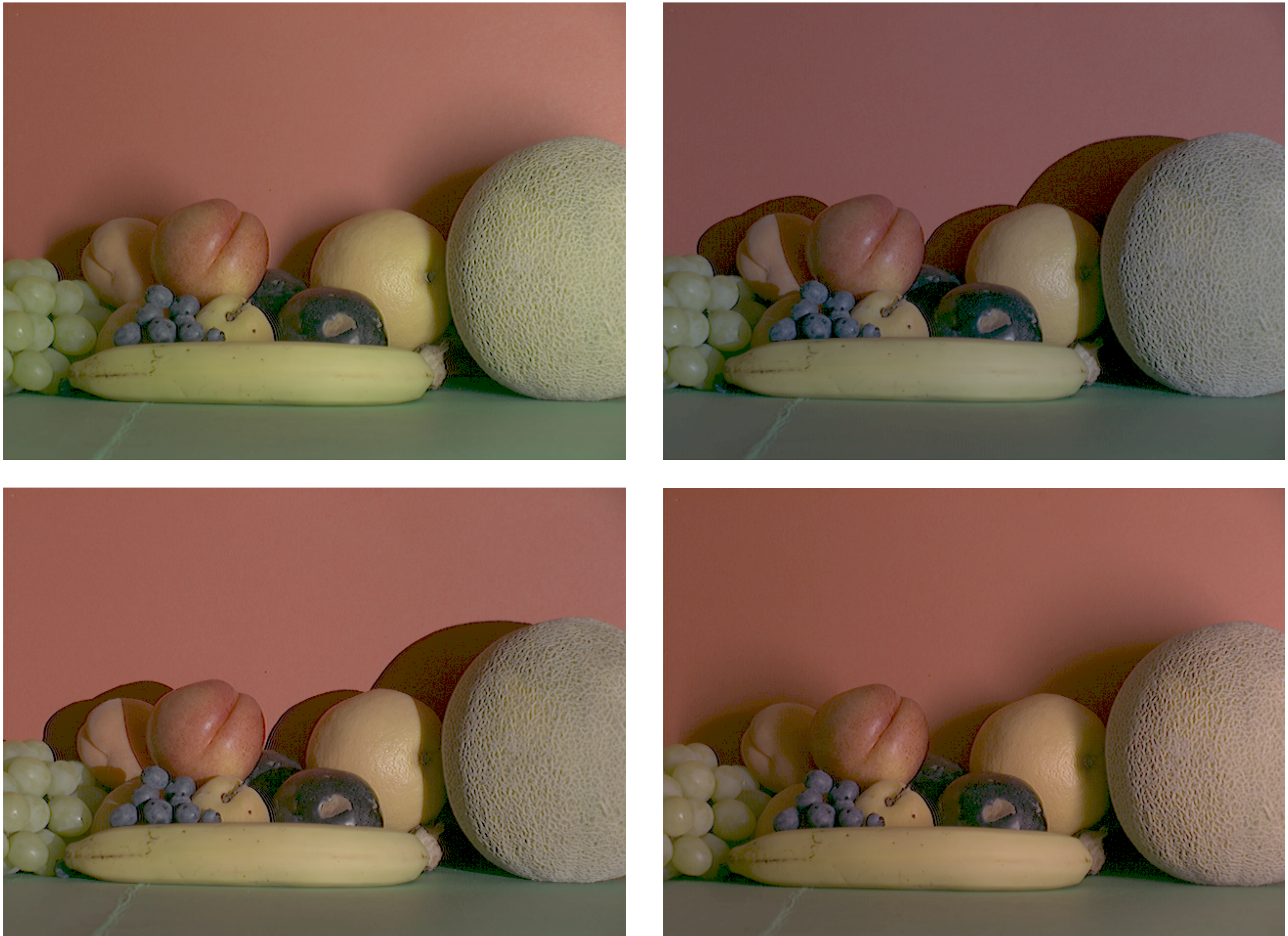

Lighting conditions

- The lighting conditions of the scene have a large effect on the colours recorded.

Image taken lit by a flash.

Image taken lit by a tungsten lamp.

The following four images of the same scene were acquired under different lighting conditions:

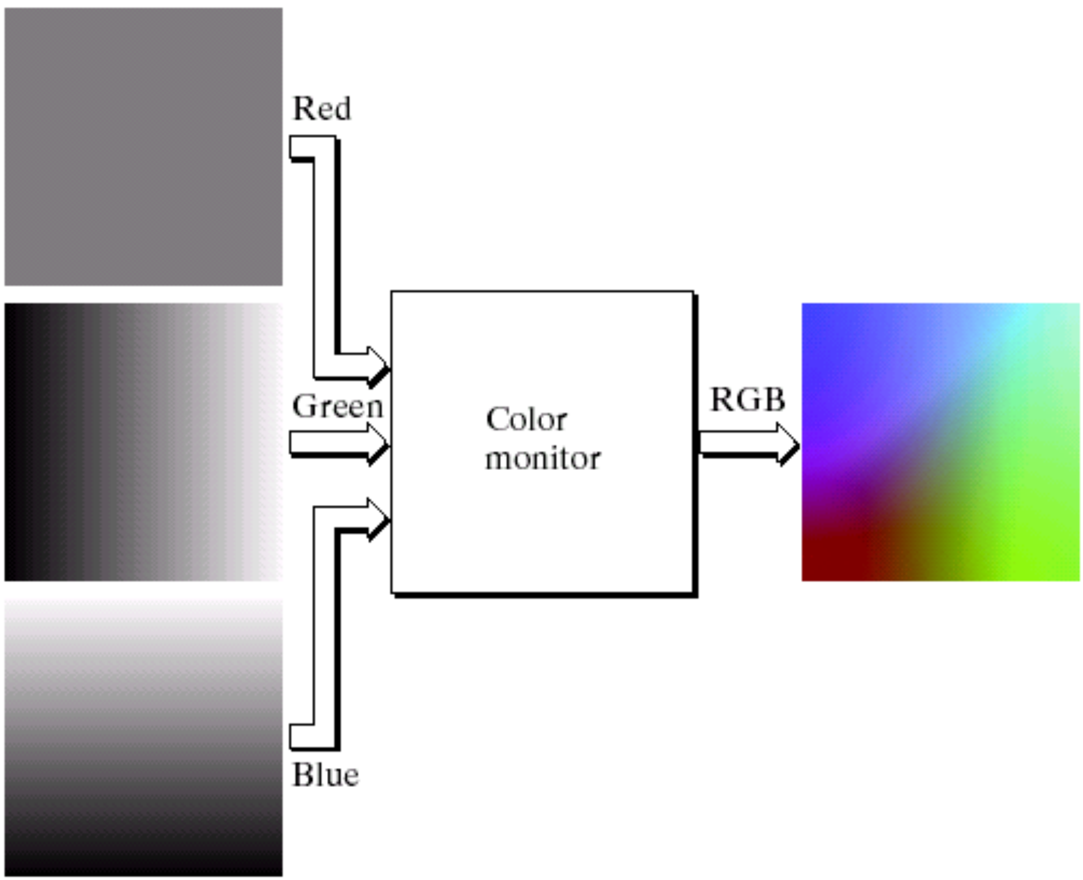


Primary and secondary colors

- In 1931, CIE (International Commission on Illumination) defines specific wavelength values to the primary colors (Secondary Pigment Colors)
  - B = 435.8 nm, G = 546.1 nm, R = 700 nm
  - However, we know that <u>no single color</u> may be called red, green, or blue
- Secondary colors: G+B=Cyan, R+G=Yellow, R+B=Magenta (Primary Pigment Colors)

Application of additive nature of light colors

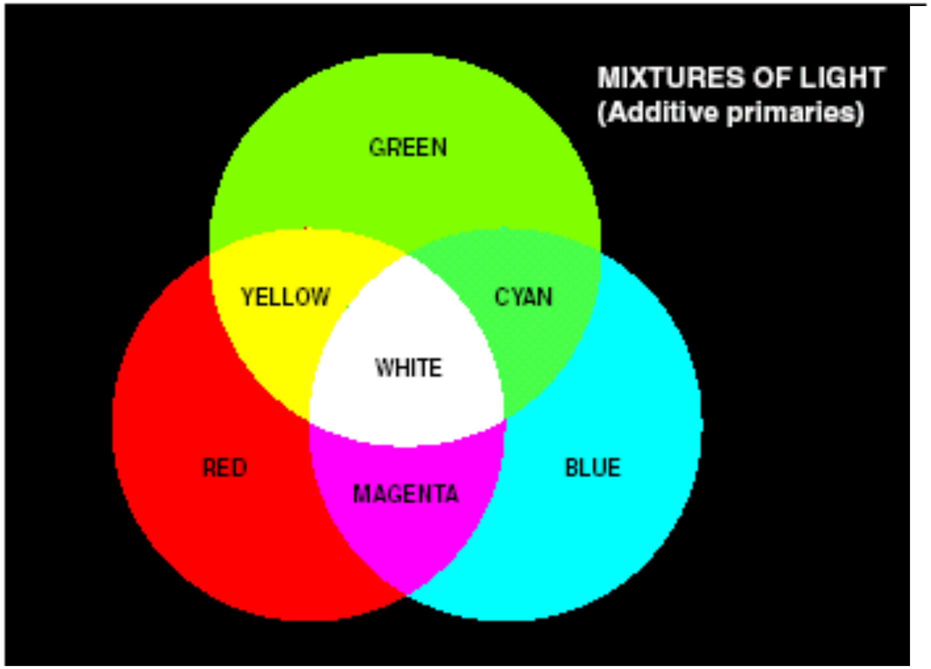
- Color TV

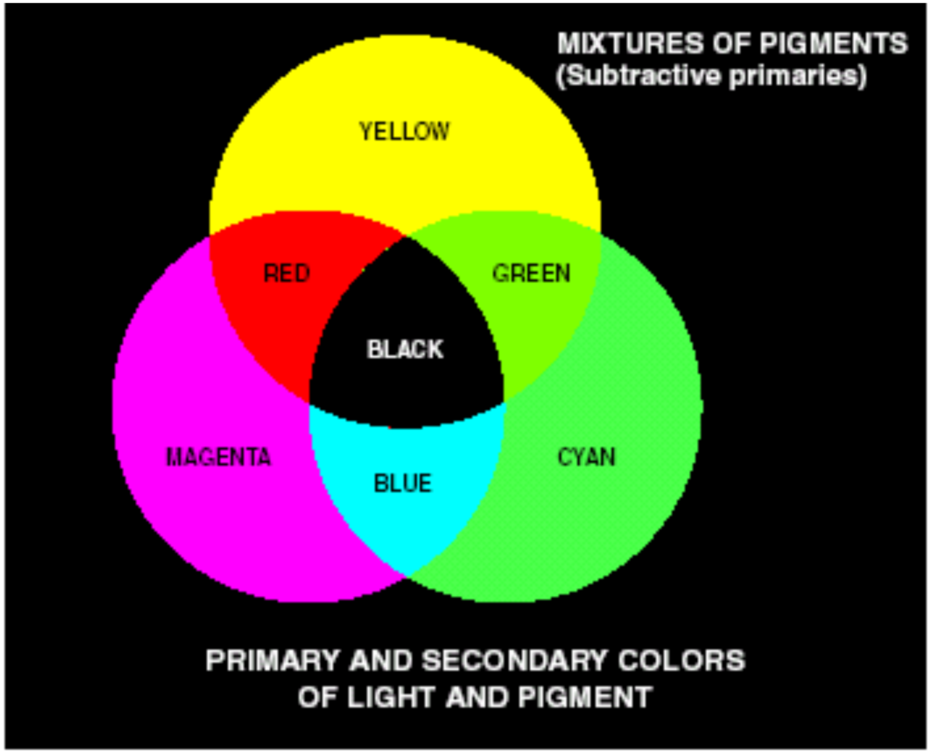


Primary colors of light v.s. primary colors of pigments

- Primary color of pigments
  - Color that subtracts or absorbs a primary color of light and reflects or transmits the other two

Color of light:	R	G	B
	↓	↓	↓
Color of pigments:	absorb R Cyan	absorb G Magenta	absorb B Yellow


MIXTURES OF LIGHT
(Additive primaries)
GREEN
YELLOW
CYAN
WHITE
RED
MAGENTA
BLUE


MIXTURES OF PIGMENTS
(Subtractive primaries)
YELLOW
RED
GREEN
BLACK
MAGENTA
BLUE
CYAN
PRIMARY AND SECONDARY COLORS
OF LIGHT AND PIGMENT

How is Color Characterized?

- The characteristics used to distinguish one color from another are **brightness**, **hue**, and **saturation**.
- **Brightness** embodies the achromatic notion of intensity.
- **Hue** is an attribute associated by the dominate wavelength in a mixture of light waves.
- **Saturation** refers to the relative purity or the amount of white light mixed with the hue. (Red vs. Pink)
- Hue and saturation taken together are called **chromaticity**, and therefore a color may be characterized by its brightness and chromaticity.

How is Color Characterized?

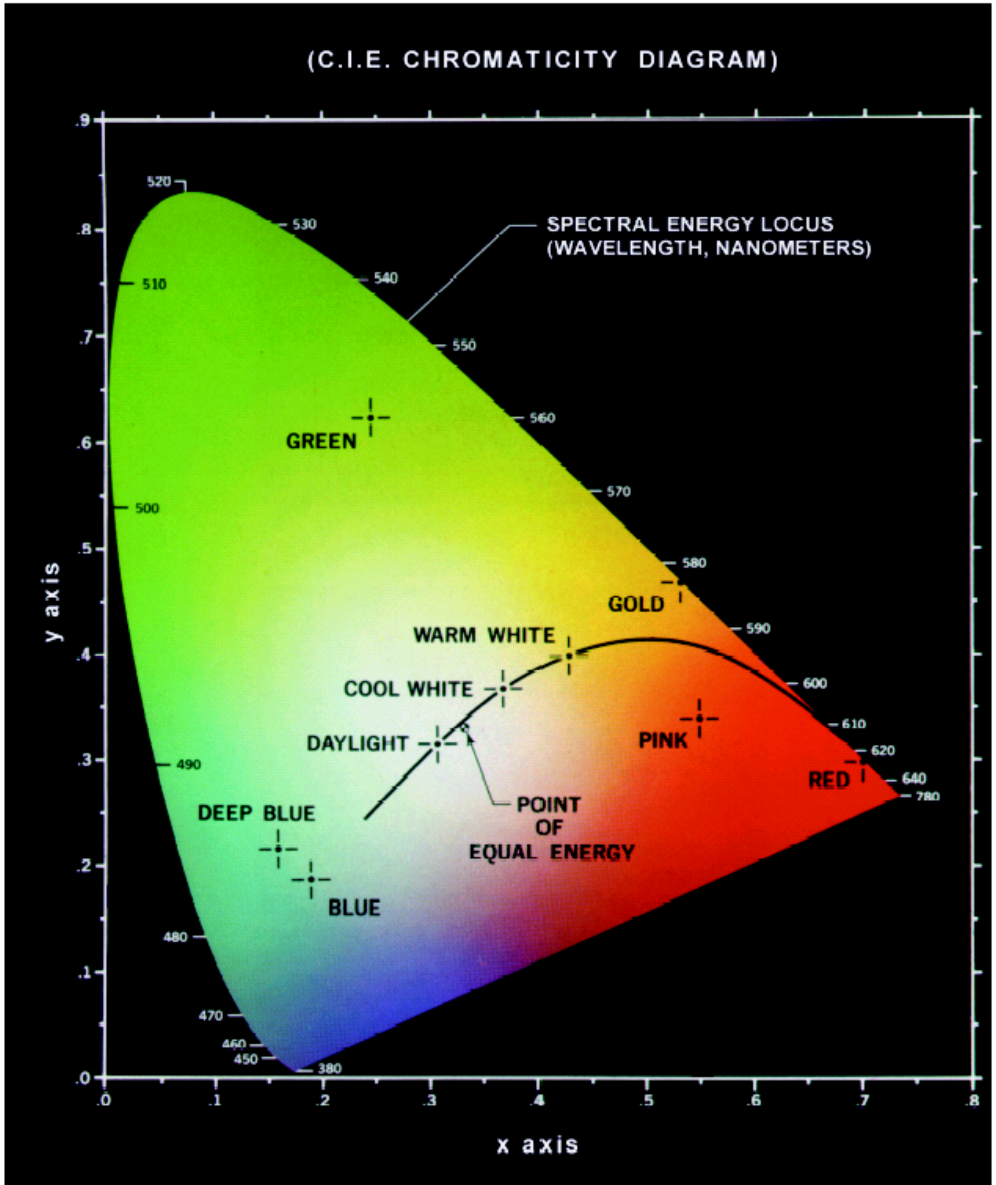
- The amounts of red, green, and blue needed to form any particular color are called the tristimulus values and are denoted as *X*, *Y*, and *Z* respectively.

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

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

=> x+y+z=1. Thus, x, y (chromaticity coordinate) is enough to describe all colors

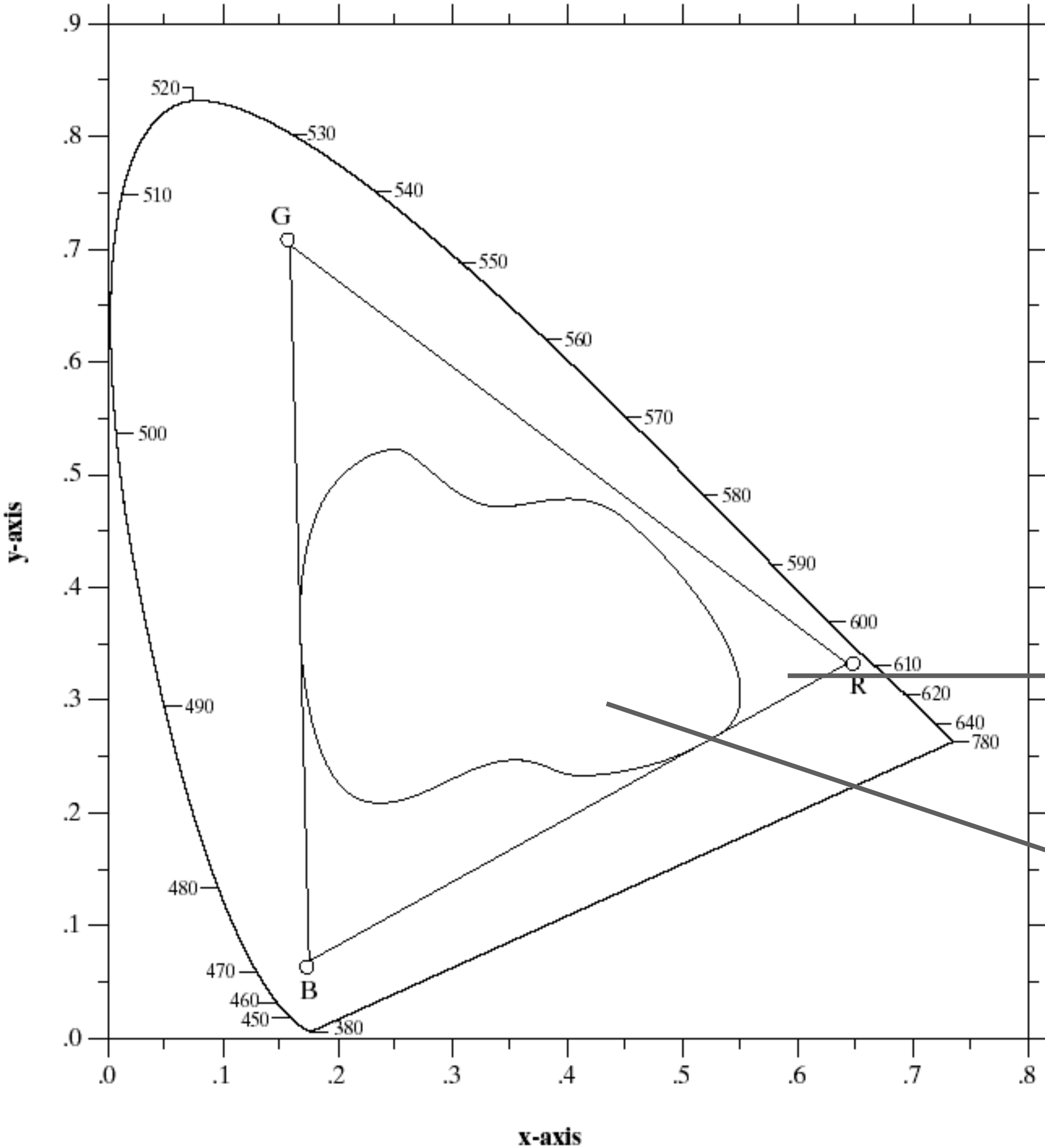
Another approach to specifying colors



The value of z is obtained using he equation:

$z = 1 - (x + y)$

By additivity of colors:
Any color inside the triangle can be produced by combinations of the three initial colors



RGB gamut of monitors

Color gamut of printers

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

Color Models

Color models

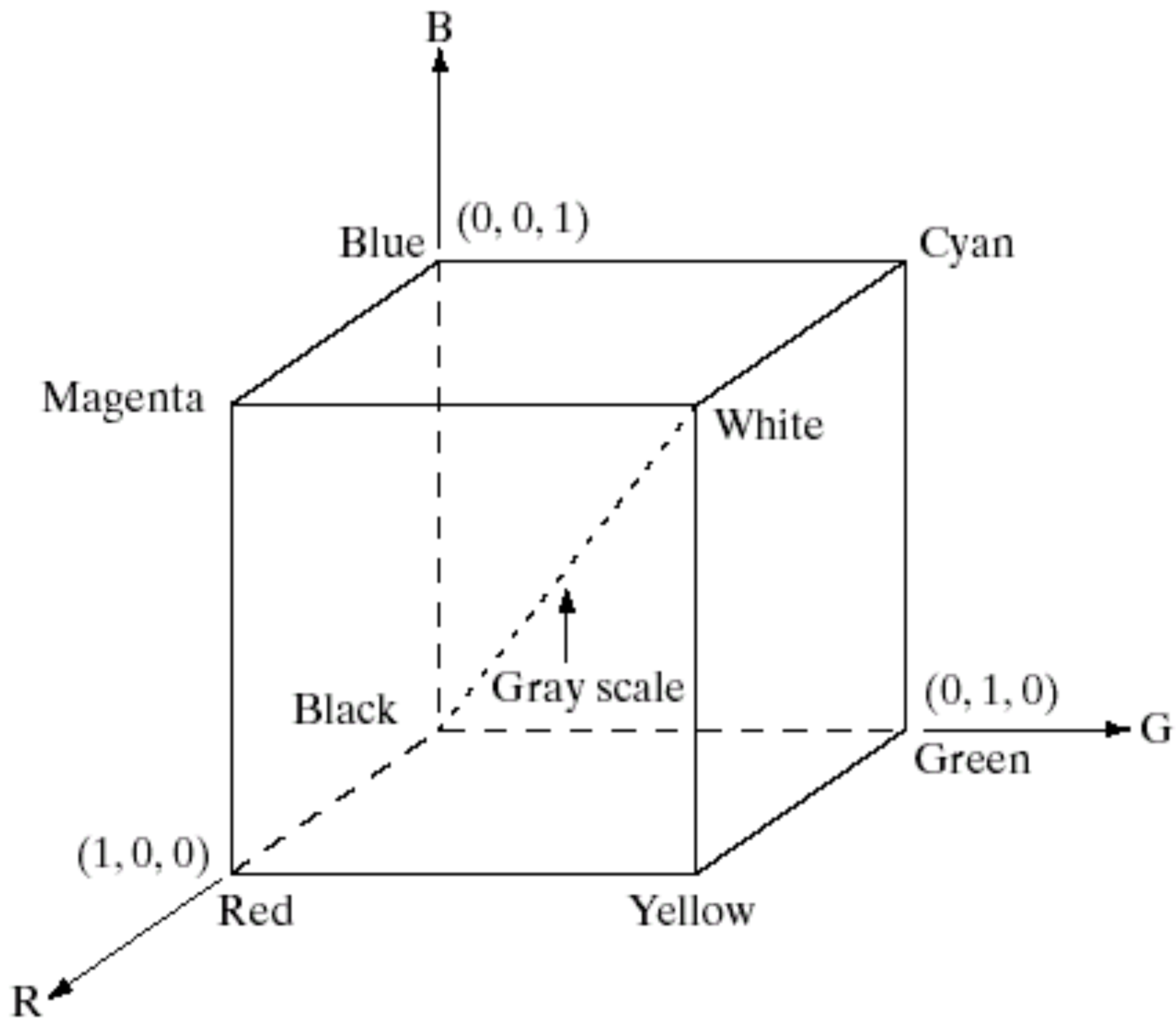
- Color model, color space, color system
  - Specify colors in a standard way
  - A coordinate system that each color is represented by a single point

- RGB model
- CYM model
- CYMK model
- HSI model

Suitable for hardware or applications

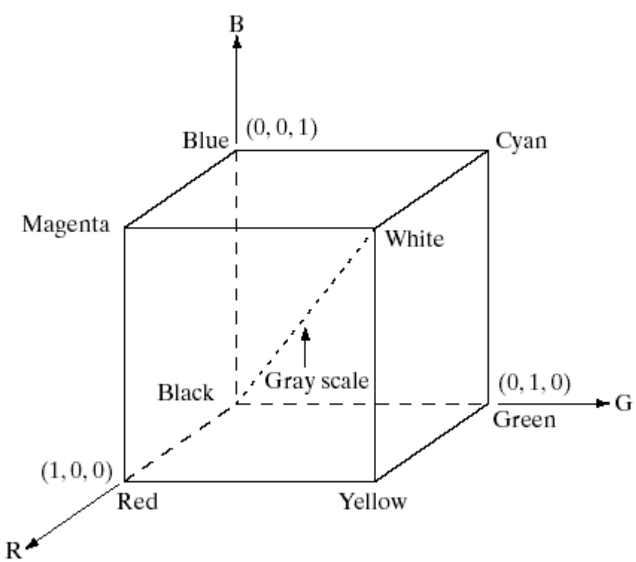
- match the human description

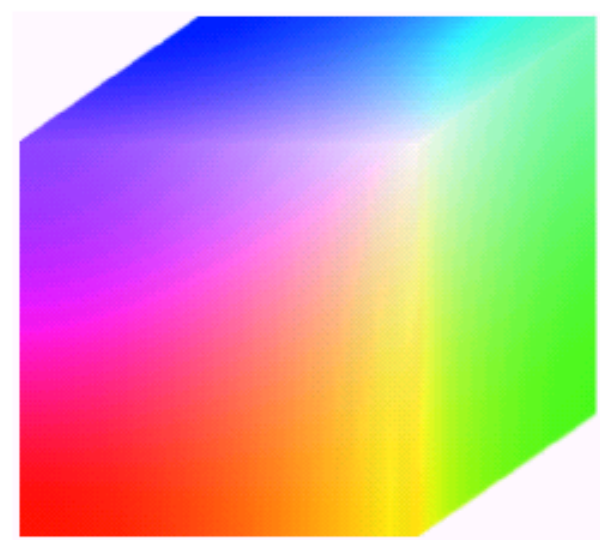
RGB color model



Pixel depth

- Pixel depth: the number of bits used to represent each pixel in RGB space
- Full-color image: 24-bit RGB color image
  - (R, G, B) = (8 bits, 8 bits, 8 bits)



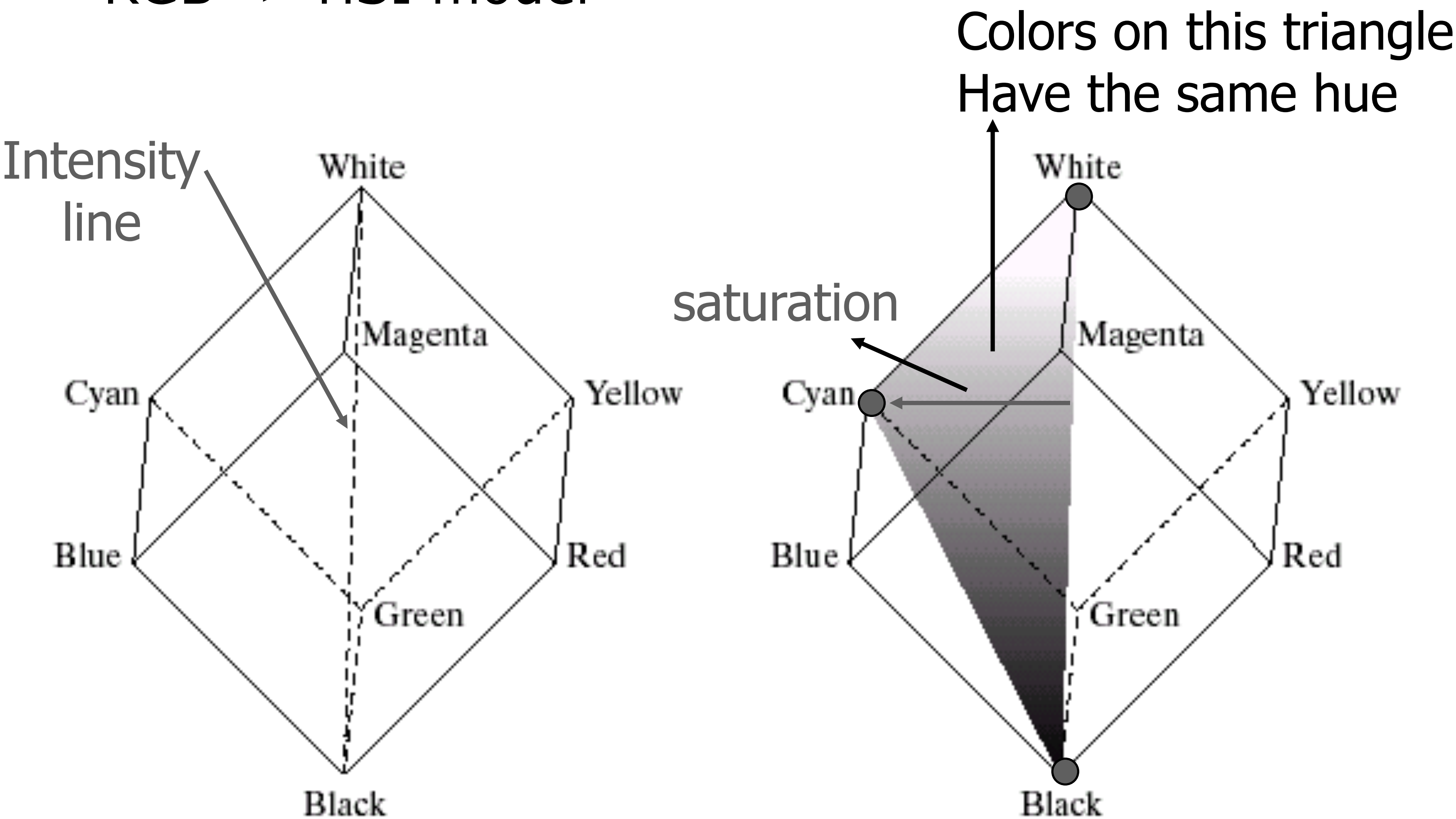


HSI color model

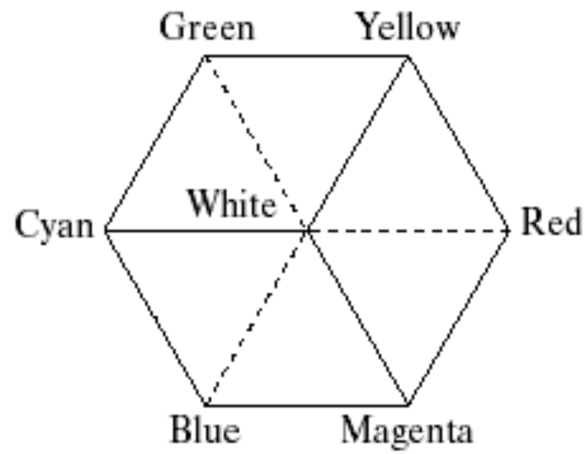
- Will you describe a color using its R, G, B components?
- Human describe a color by its hue, saturation, and brightness
  - **Hue:** color attribute
  - **Saturation:** purity of color (white->0, primary color->1)
  - **Brightness:** achromatic notion of intensity

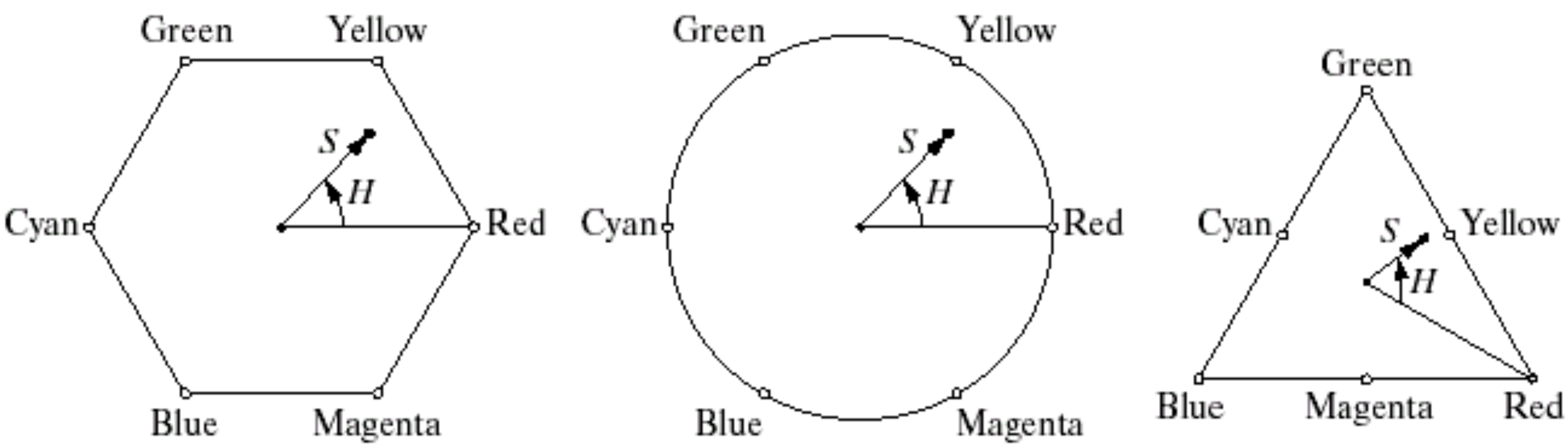
HSI color model (cont.)

- RGB -> HSI model

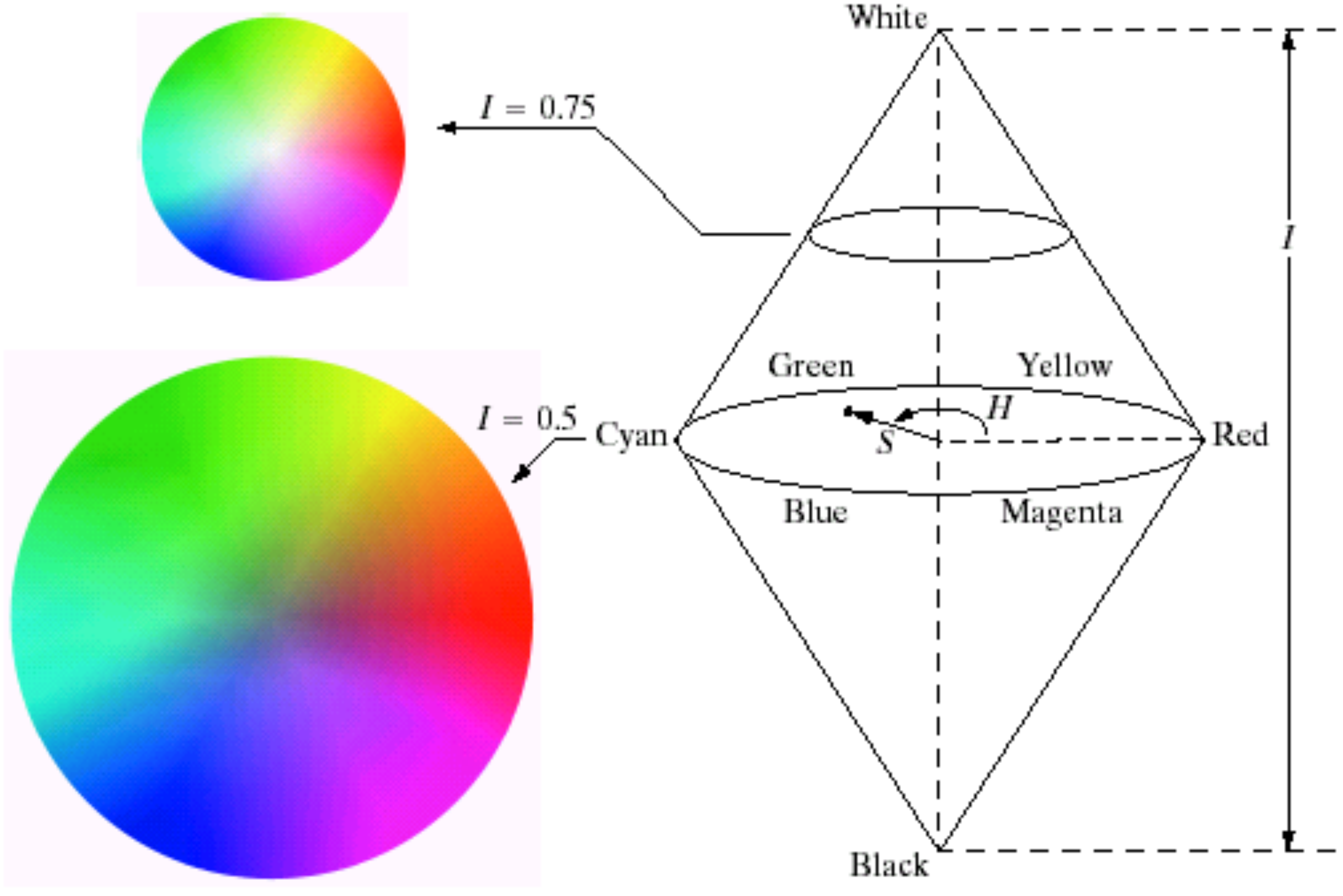


HSI model: hue and saturation





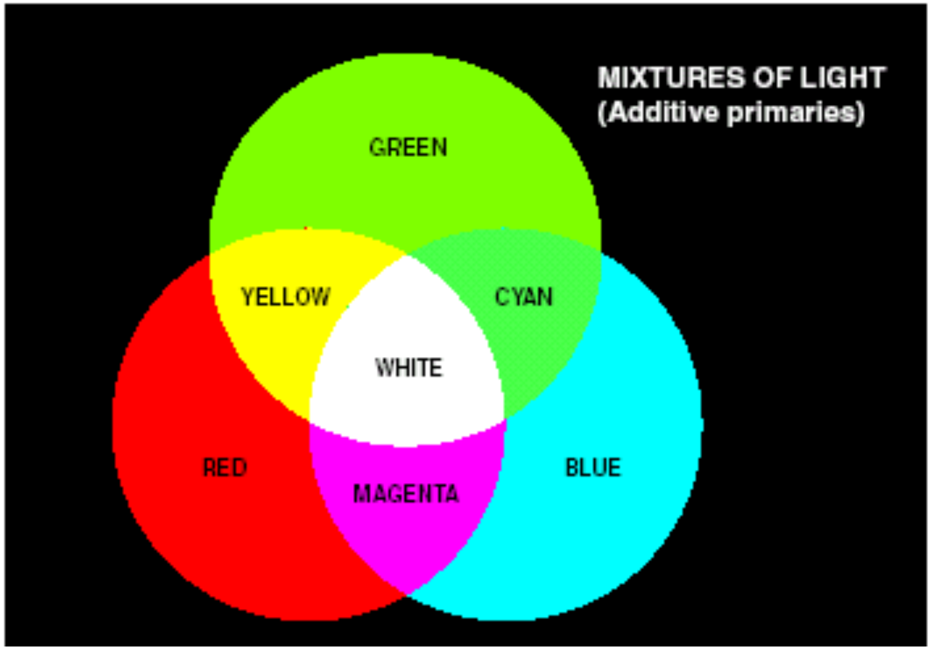
HSI model



CMY model (+Black = CMYK)

- CMY: secondary colors of light, or primary colors of pigments
- Used to generate hardcopy output

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



Converting Colors from RGB to HSI

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

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

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

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

Converting Colors from HSI to RGB

RG Sector: $0^\circ \le H < 120^\circ$

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

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

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

Converting Colors from HSI to RGB

GB Sector: $120^\circ \le H < 240^\circ$

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

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

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

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

Converting Colors from HSI to RGB

BR Sector: $240^\circ \le H < 360^\circ$

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

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

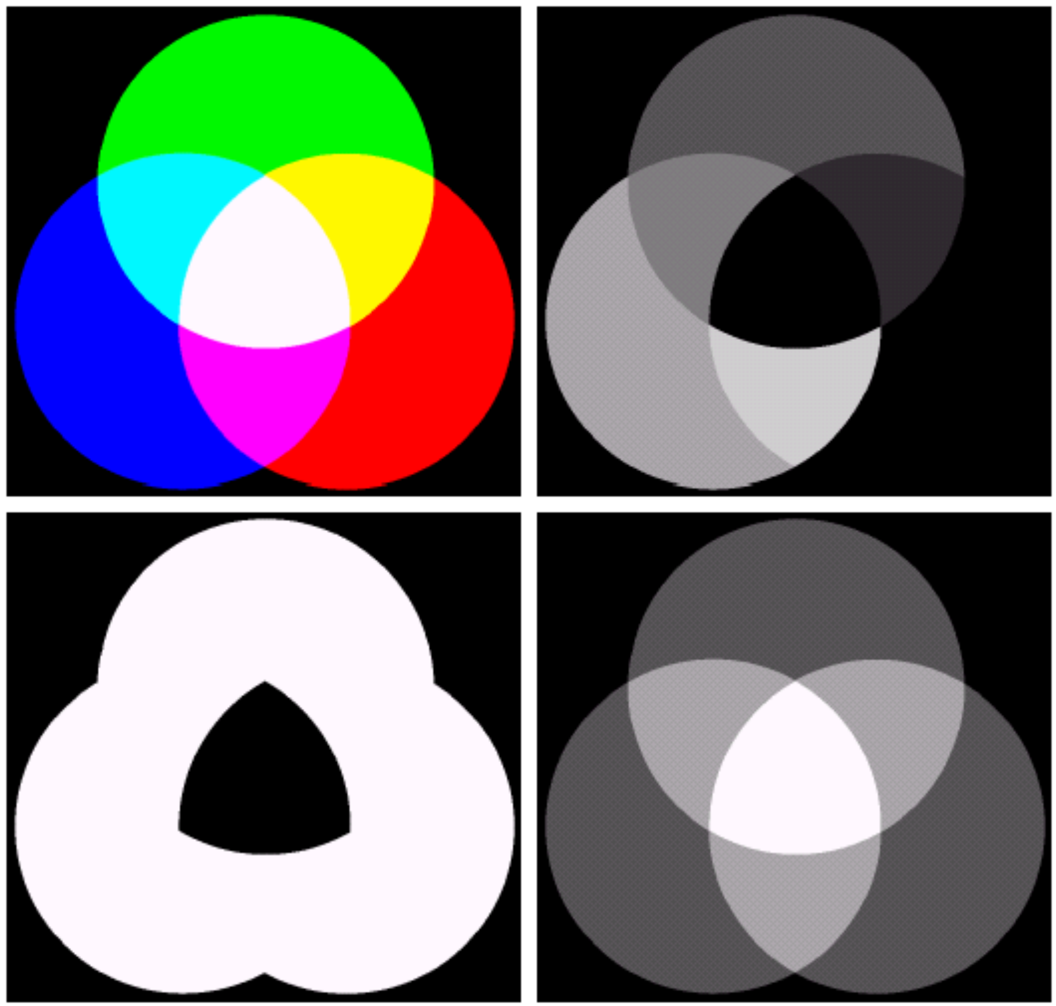
$$B = I\left[1 + \frac{S\cos H}{\cos(60^\circ - H)}\right]$$

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

HSI component images

R,G,B

Hue



saturation

intensity

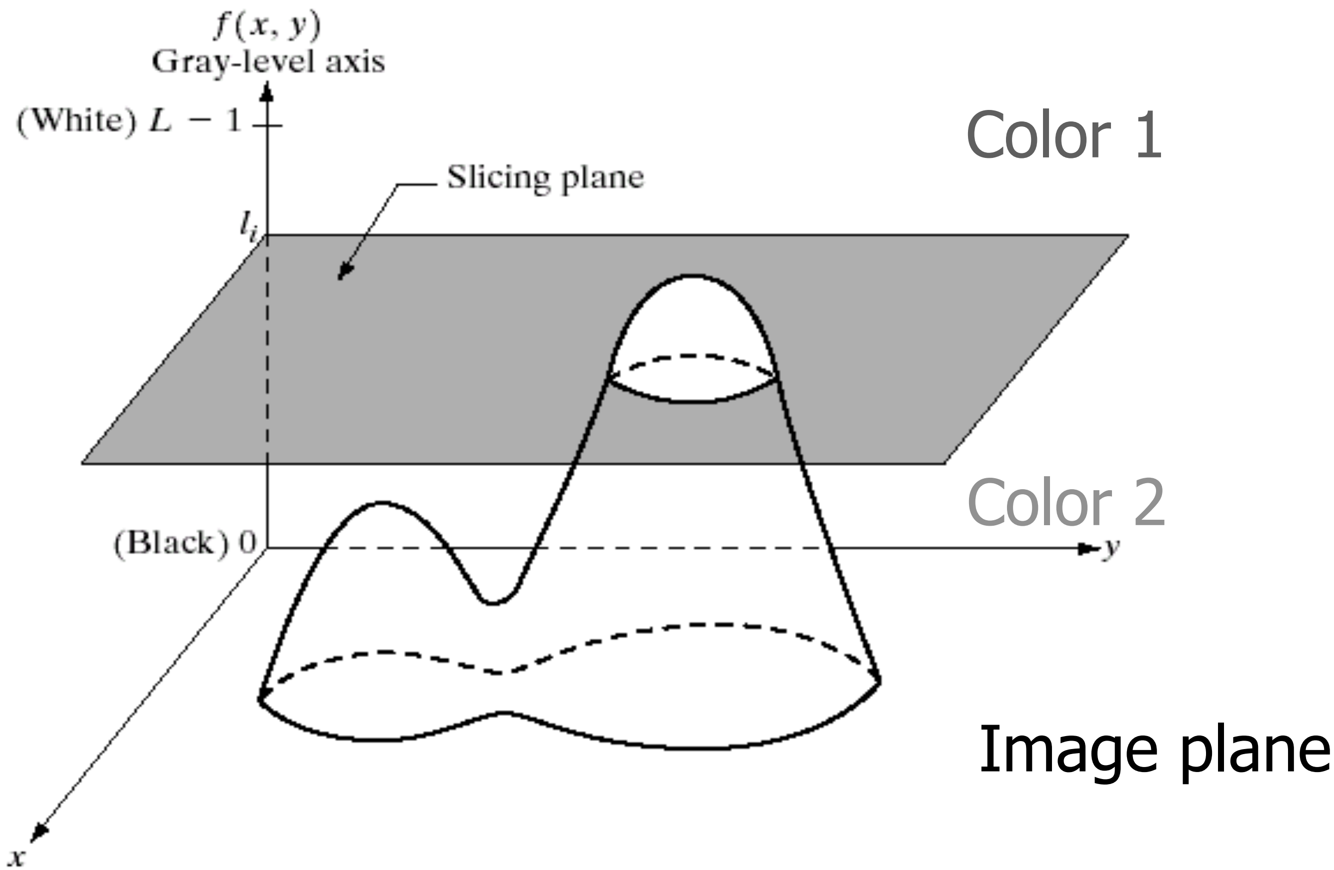
Pseudocolor Image Processing

Pseudo-color image processing

- **Assign colors to gray values** based on a specified criterion
- For **human visualization** and interpretation of gray-scale events
- Intensity slicing
- Gray level to color transformations

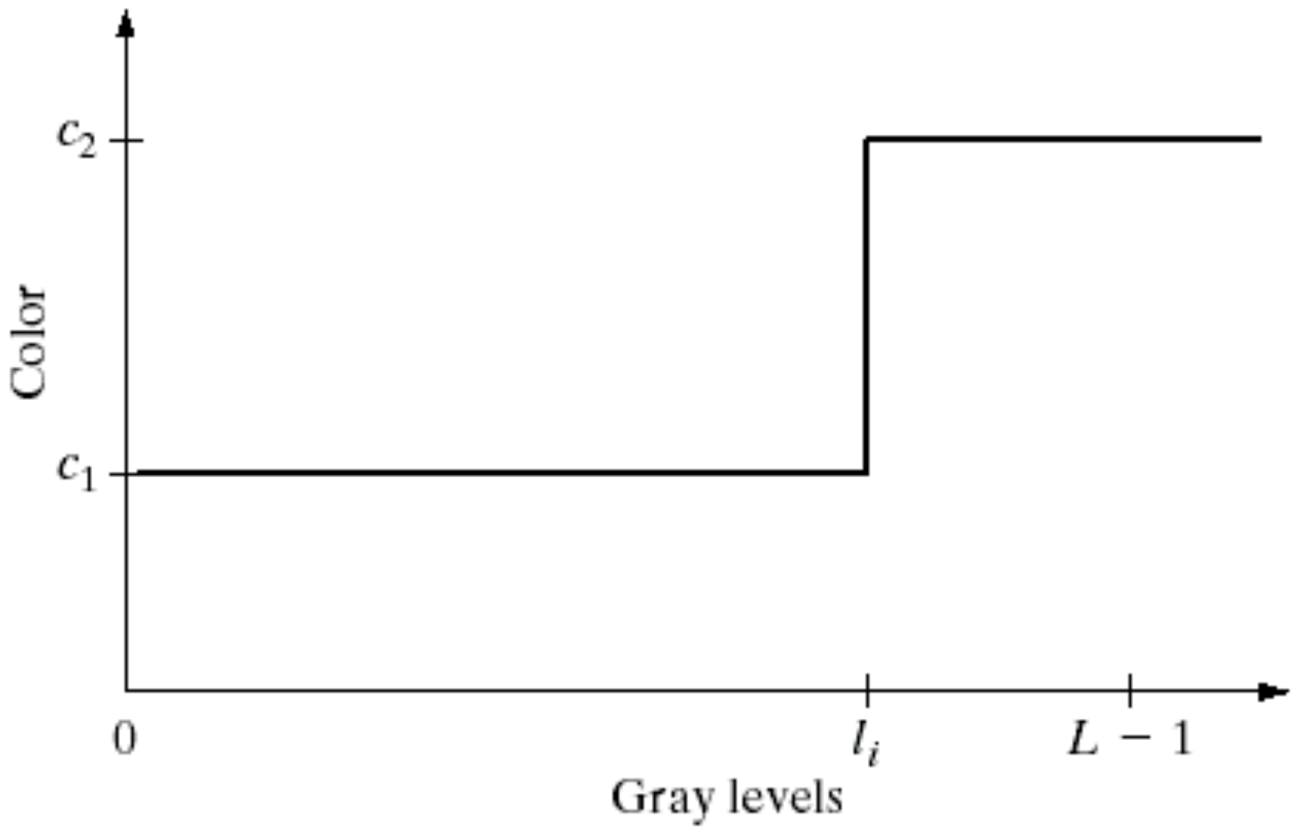
Intensity slicing

- 3-D view of intensity image



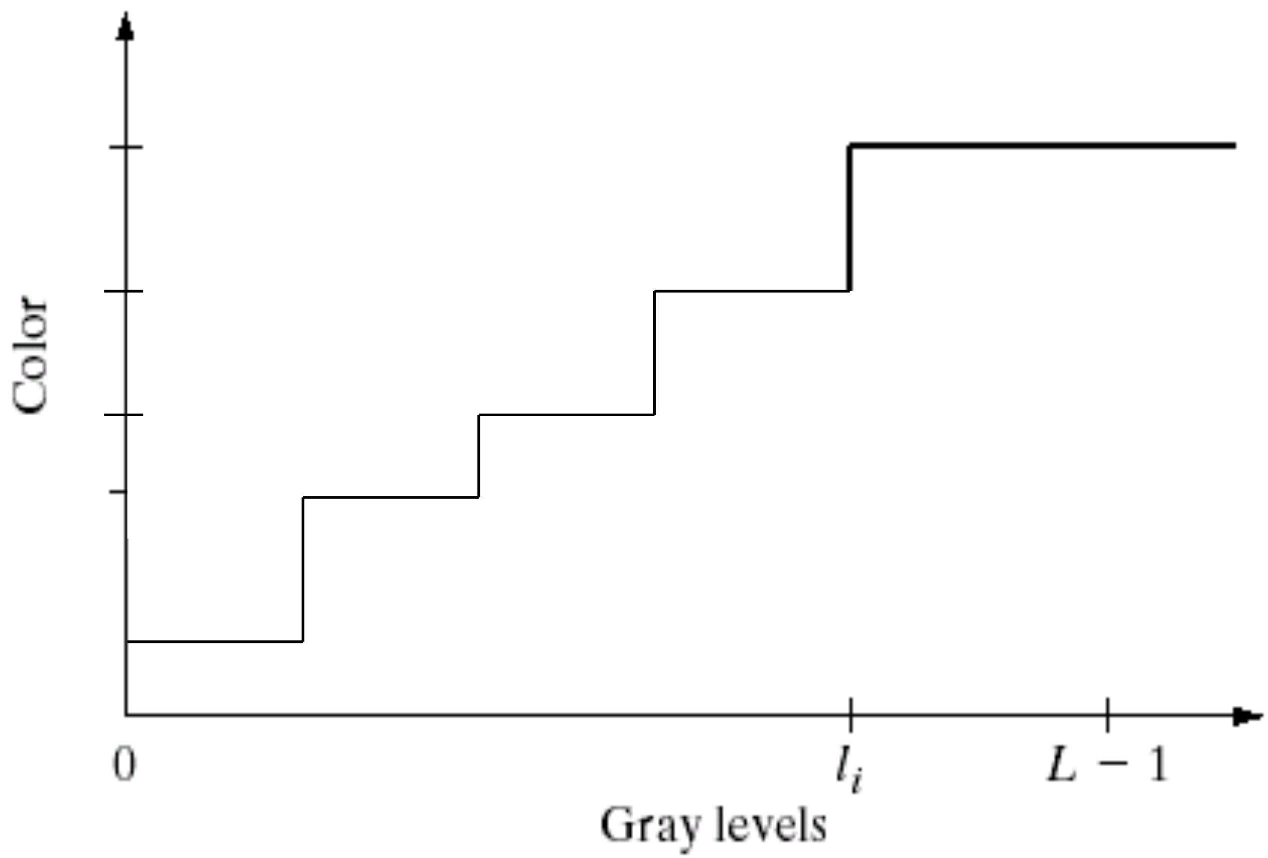
Intensity slicing (cont.)

- Alternative representation of intensity slicing

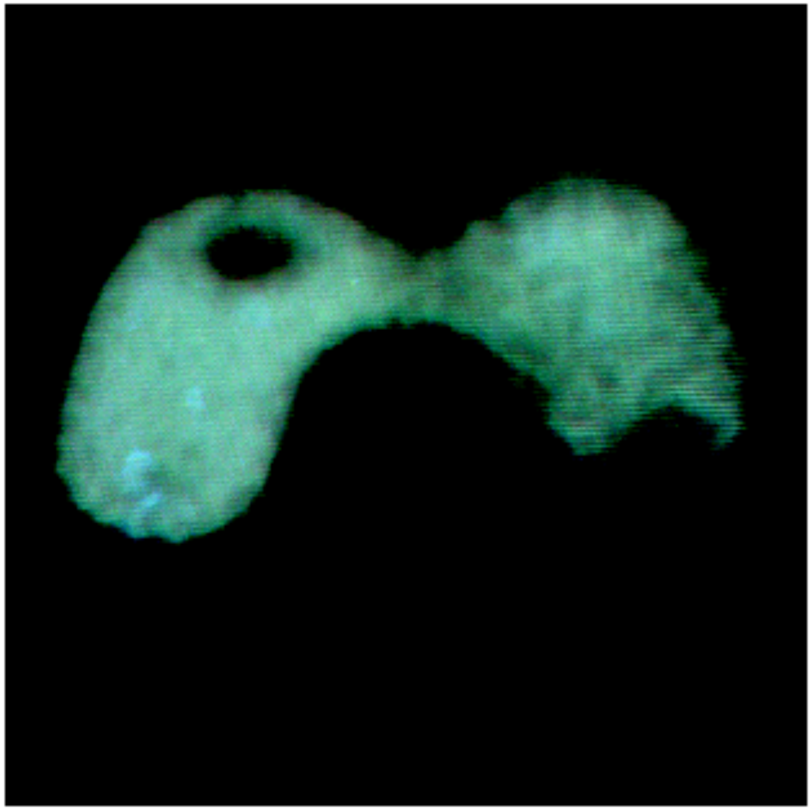


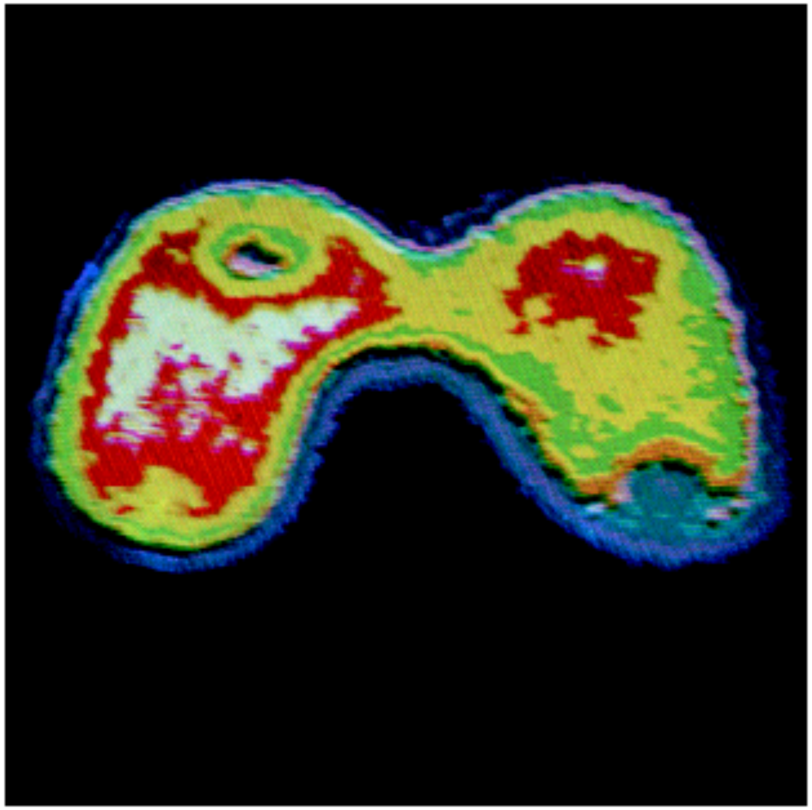
Intensity slicing (cont.)

- More slicing plane, more colors



Application 1

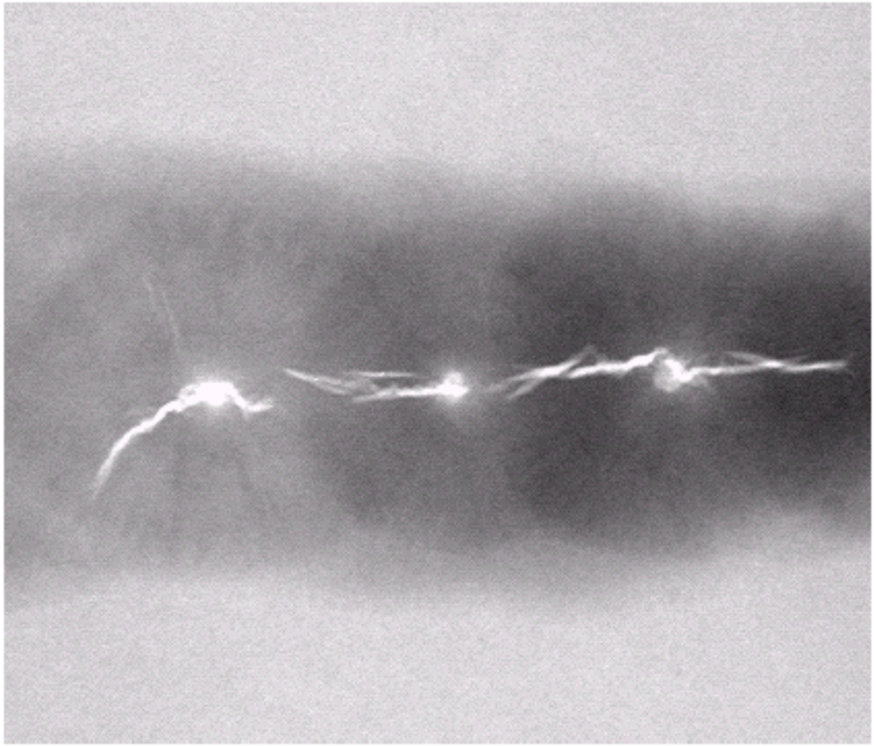


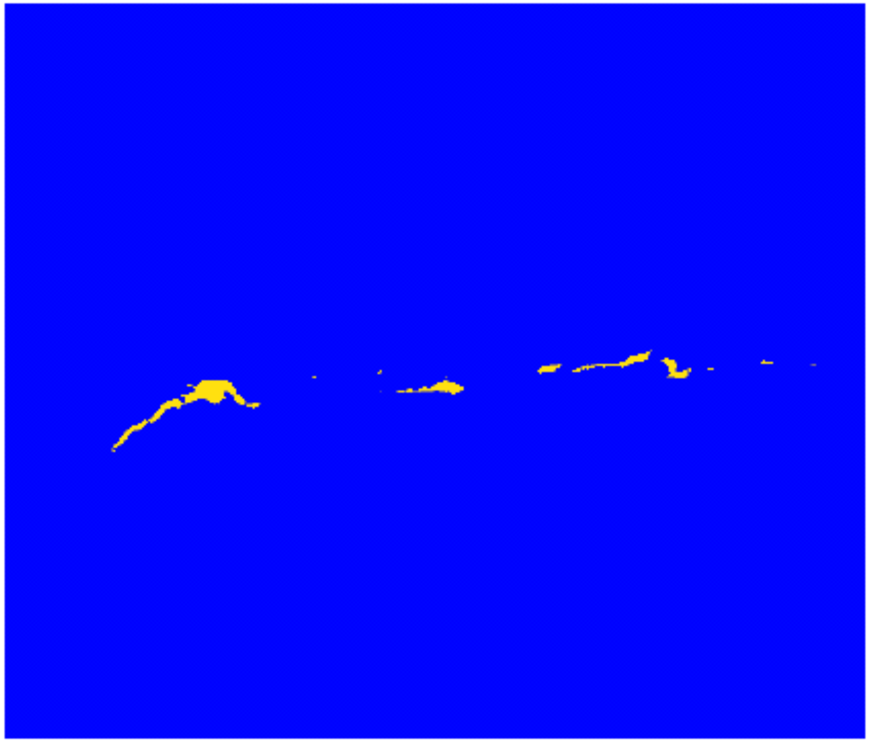


Radiation test pattern → 8 color regions

* See the gradual gray-level changes

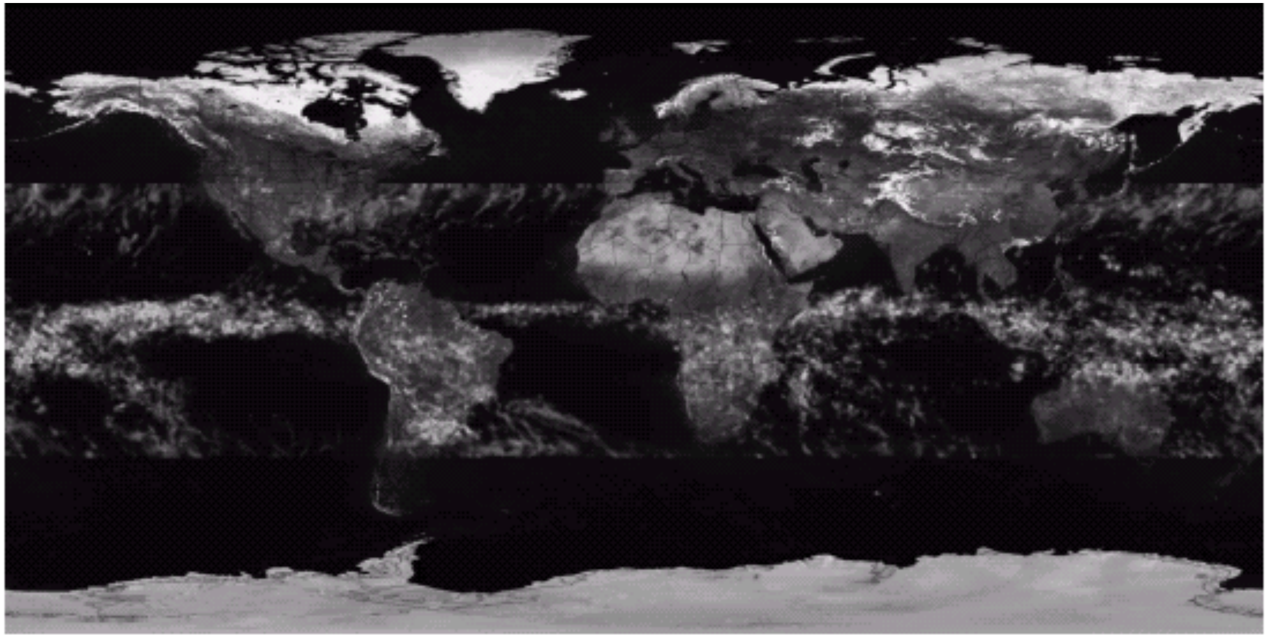
Application 2



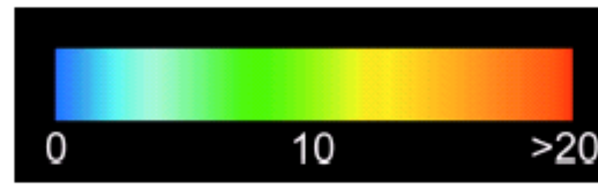


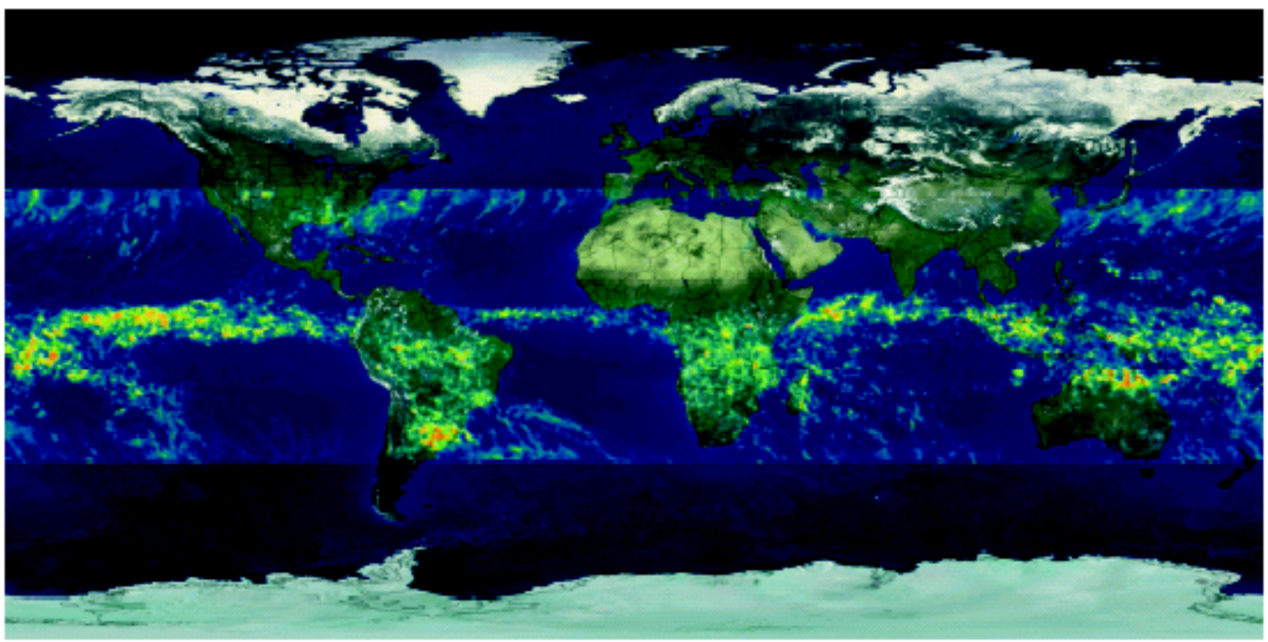
X-ray image of a weld

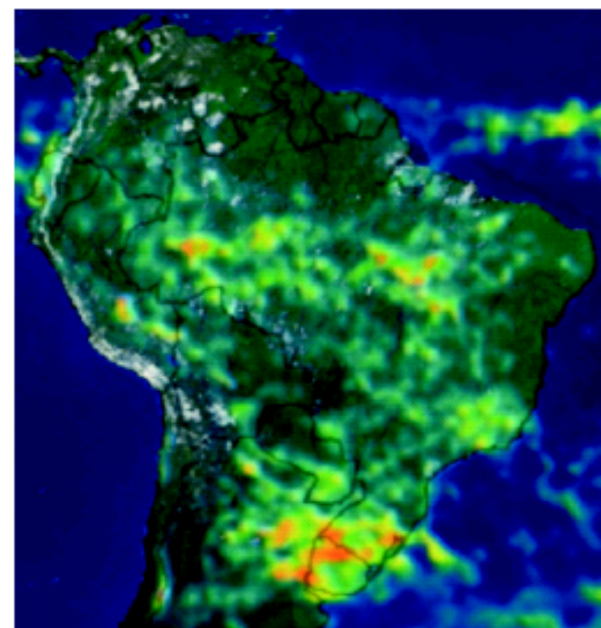
Application 3



Rainfall statistics

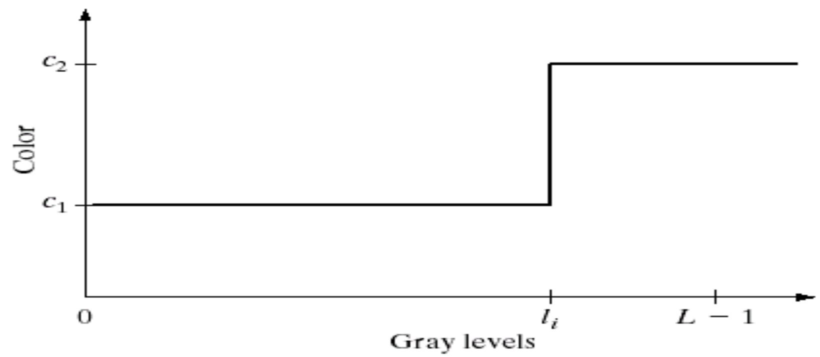




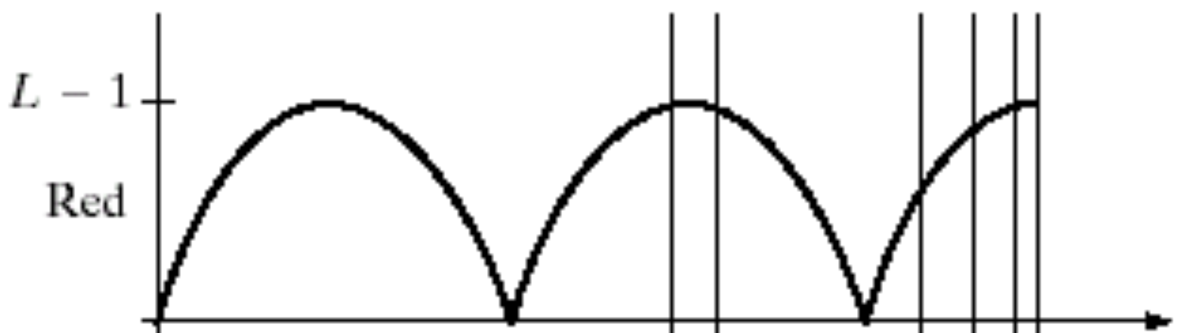


Gray level to color transformation

- Intensity slicing: piecewise linear transformation



- General Gray level to color transformation



Gray level to color transformation

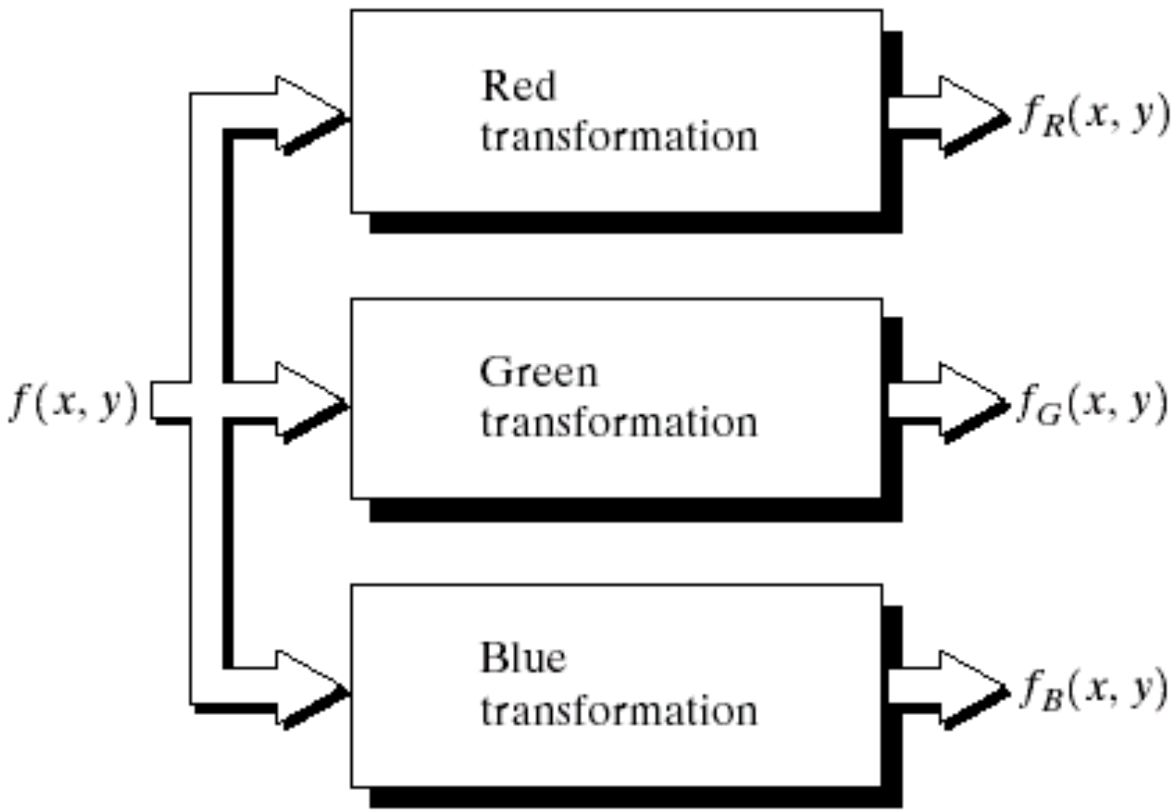
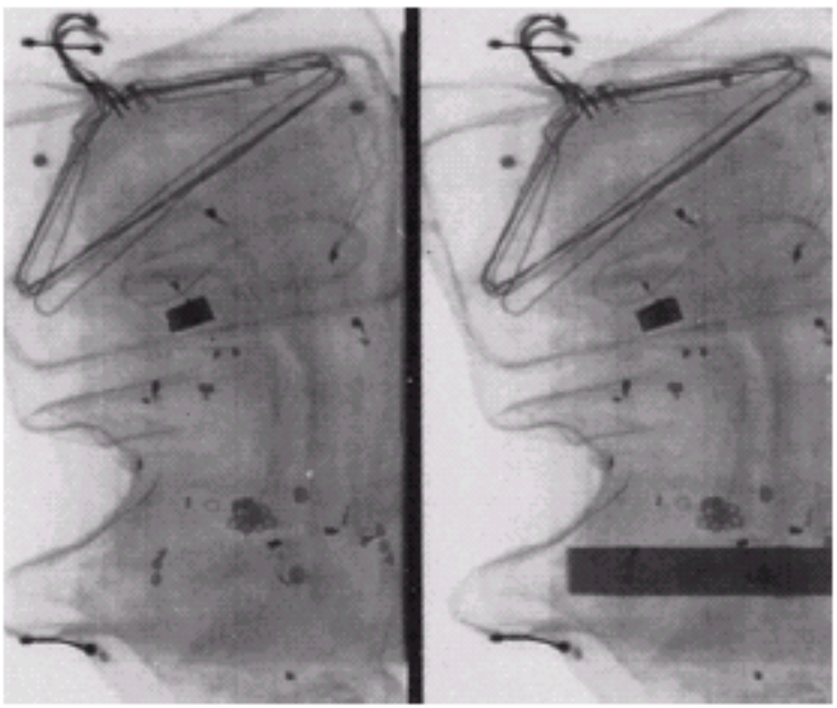
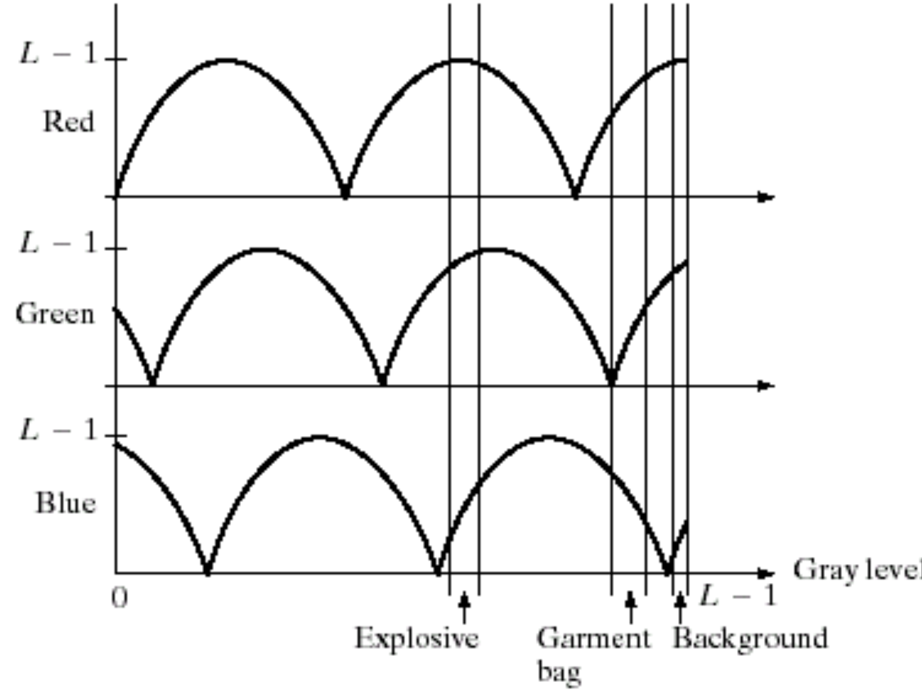
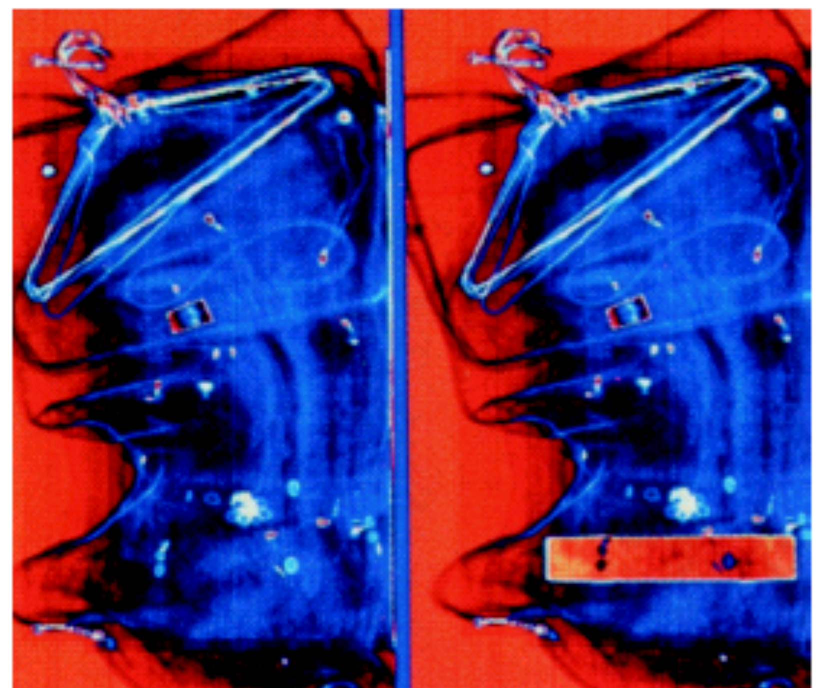


FIGURE 6.23 Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

Application 1

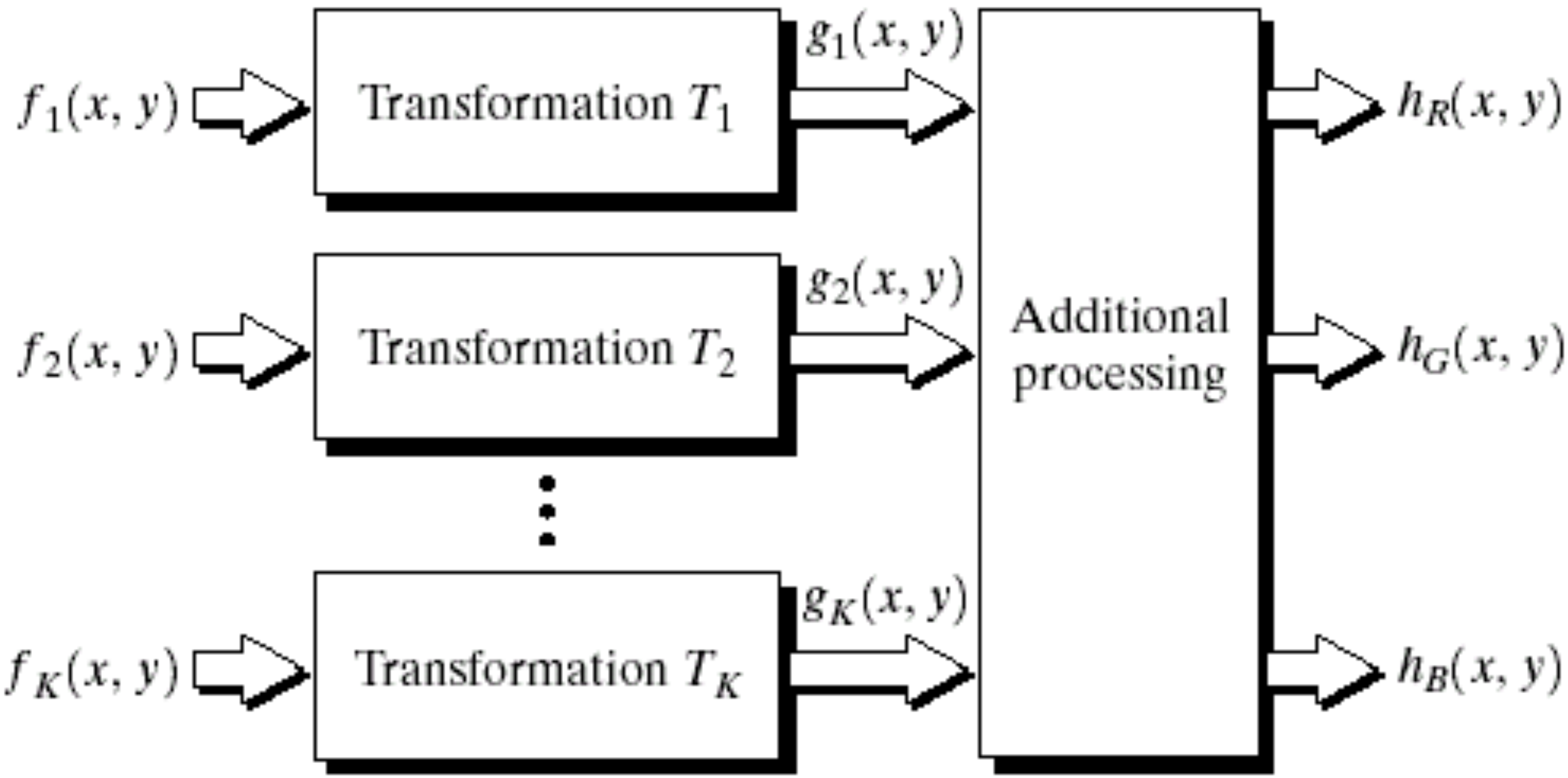




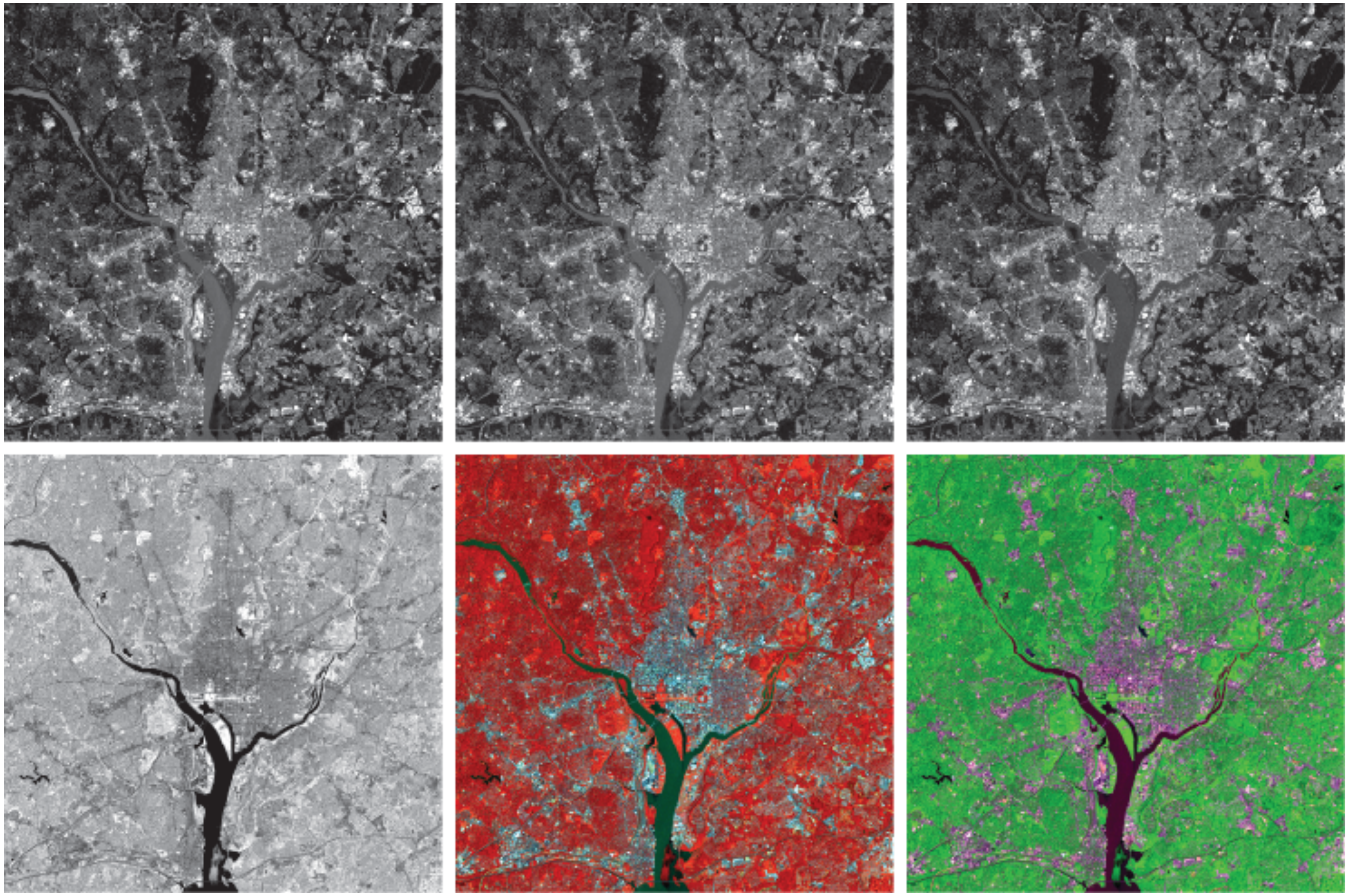


Combine several monochrome images

Example: multi-spectral images



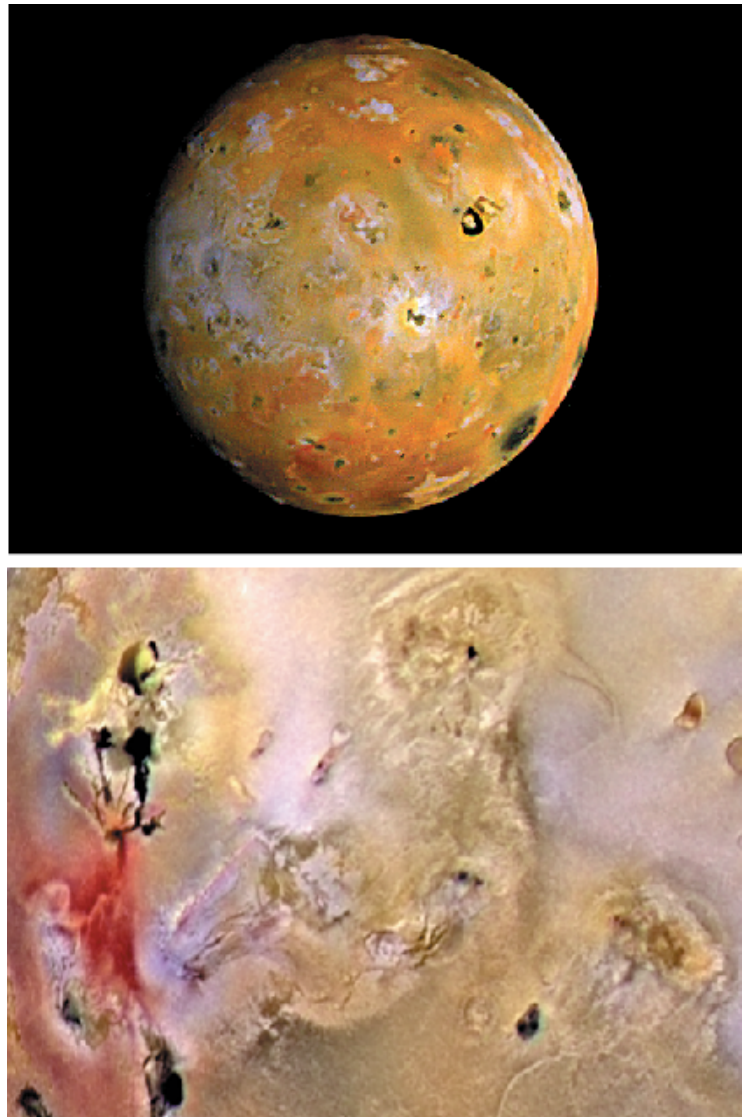
Color Coding Multispectral Images



a b c
d e f

FIGURE 7.25 (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.)

Pseudo Coloring using Sensor Images



a
b

FIGURE 7.26
(a) Pseudocolor rendition of Jupiter Moon Io. (b) A close-up. (Courtesy of NASA.)

Basics of Full-Color Image Processing

Color pixel

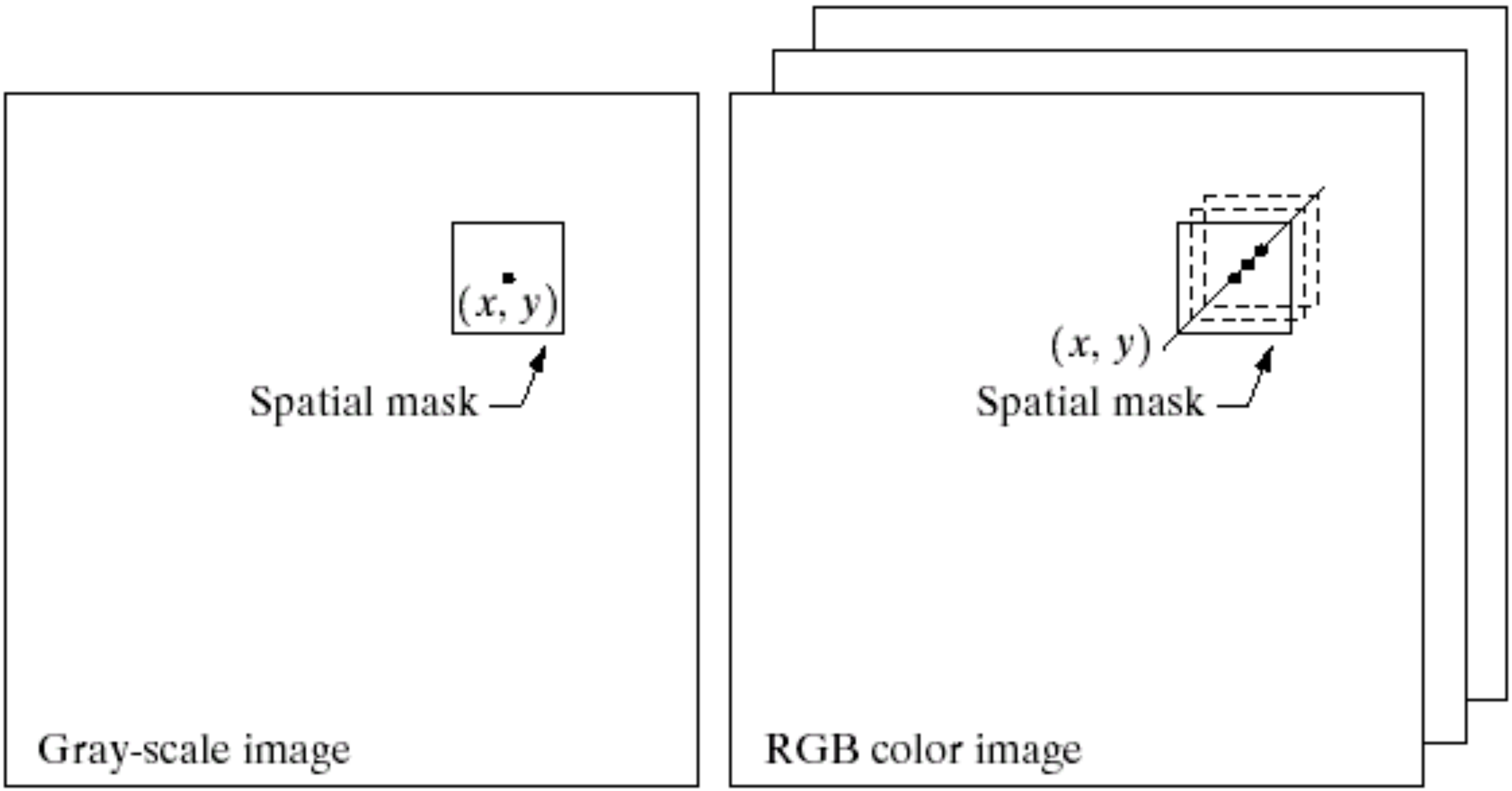
- A pixel at (x,y) is a vector in the color space
  - RGB color space

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

c.f. gray-scale image

f(x,y) = I(x,y)

Example: spatial mask



How to deal with color vector?

- **Per-color-component processing**
  - Process each color component
- **Vector-based processing**
  - Process the color vector of each pixel
- **When can the above methods be equivalent?**
  - Process can be applied to both scalars and vectors
  - Operation on each component of a vector must be independent of the other component

Two spatial processing categories

Similar to gray scale processing studied before, we have two major categories

- **Pixel-wise** processing (Color Transformations)
- **Neighborhood** processing (Smoothing/Sharpening)

Color Transformations

Color transformation

Processing the components of a color image within the context of a single color model

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

$$s_i = T_i\left(r_1, r_2, \ldots, r_n\right), \qquad i = 1,2,\ldots,n$$

Color components of g

Color components of f

Color mapping functions

Use which color model in color transformation?

- Theoretically, any transformation can be performed in any color model
- Practically, some operations are better suited to specific color model
  - There are some problems when working with hue in the HSI color space (discontinuity where 0 and 360 degrees meet) and hue is undefined for a saturation of 0.

Example: modify intensity of a color image

a b
c d e

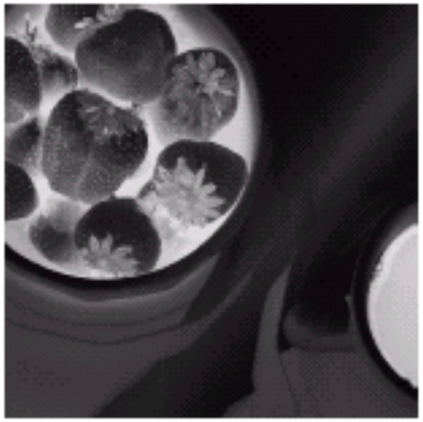
FIGURE 6.31 Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c)–(e) The required RGB, CMY, and HSI transformation functions. (Original image courtesy of MedData Interactive.)

$$g(x, y) = kf(x, y)$$

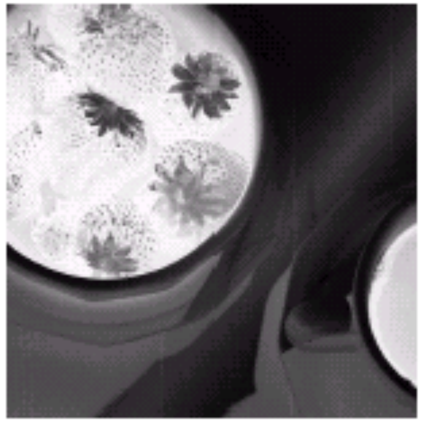
$$s_i = kr_i \qquad i = 1,2,3$$

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

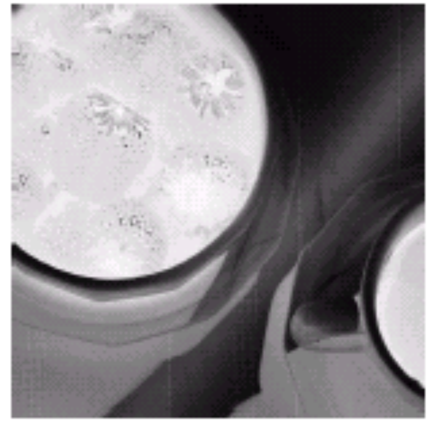
$$s_1 = r_1$$
$$s_2 = r_2$$
$$s_3 = kr_3$$



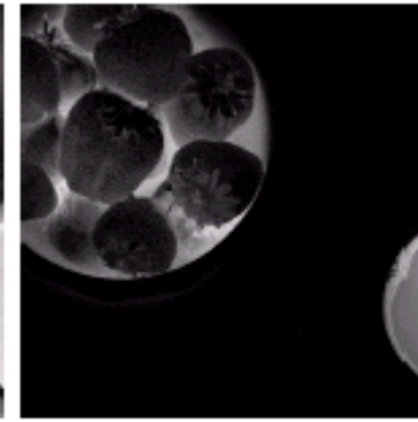
Cyan



Magenta



Yellow



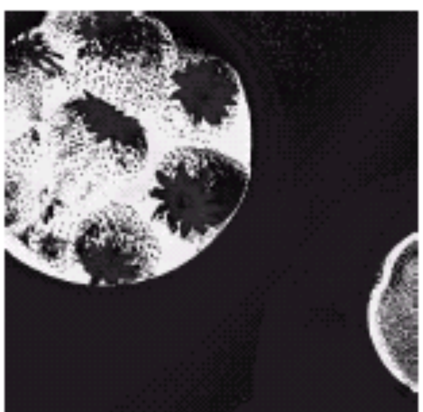
Black

Red

Green

Blue

Full color



Hue

Saturation

Intensity

Color Complements

Why?

- They are analogous to grayscale negatives.
- Color complements are useful for enhancing detail that is embedded in dark regions of a color image.

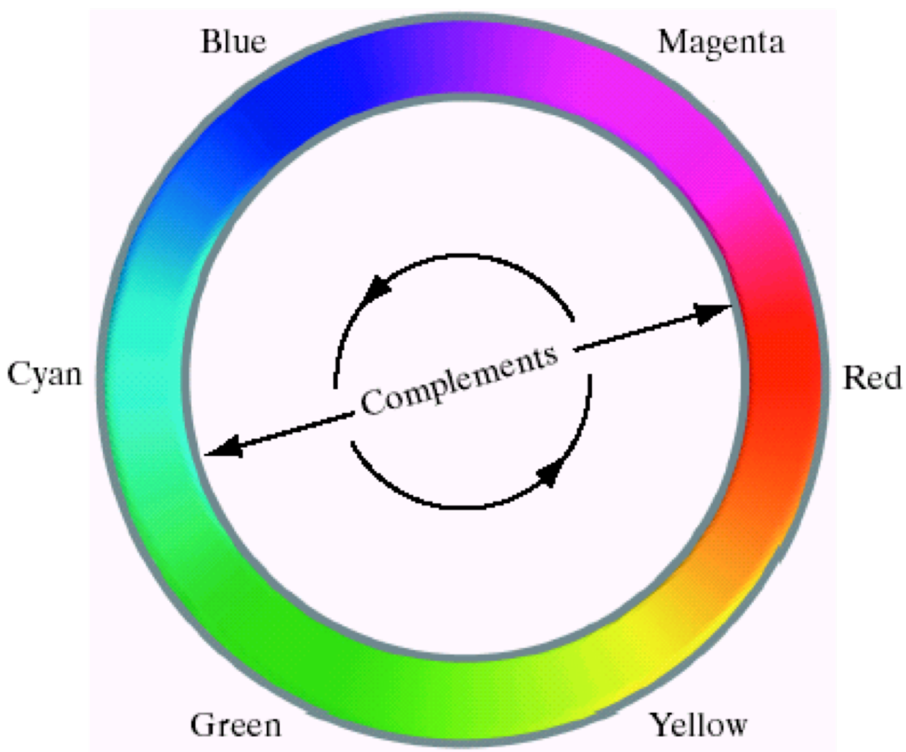
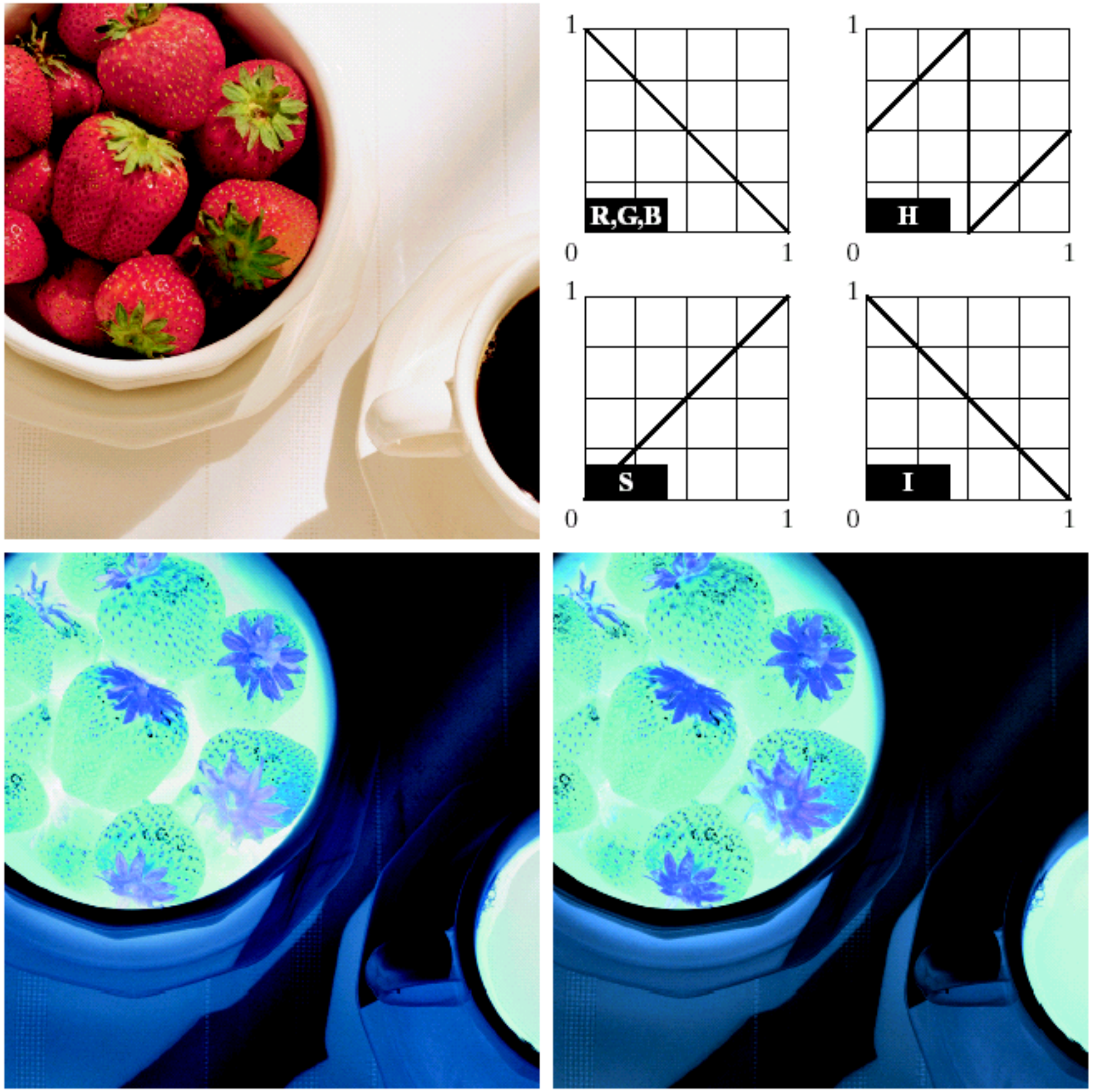


FIGURE 6.32
Complements on the color circle.

Color Transformation Using Color Complement



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.

Color Slicing

Color Slicing

Why?

Highlighting a specific range of colors in an image

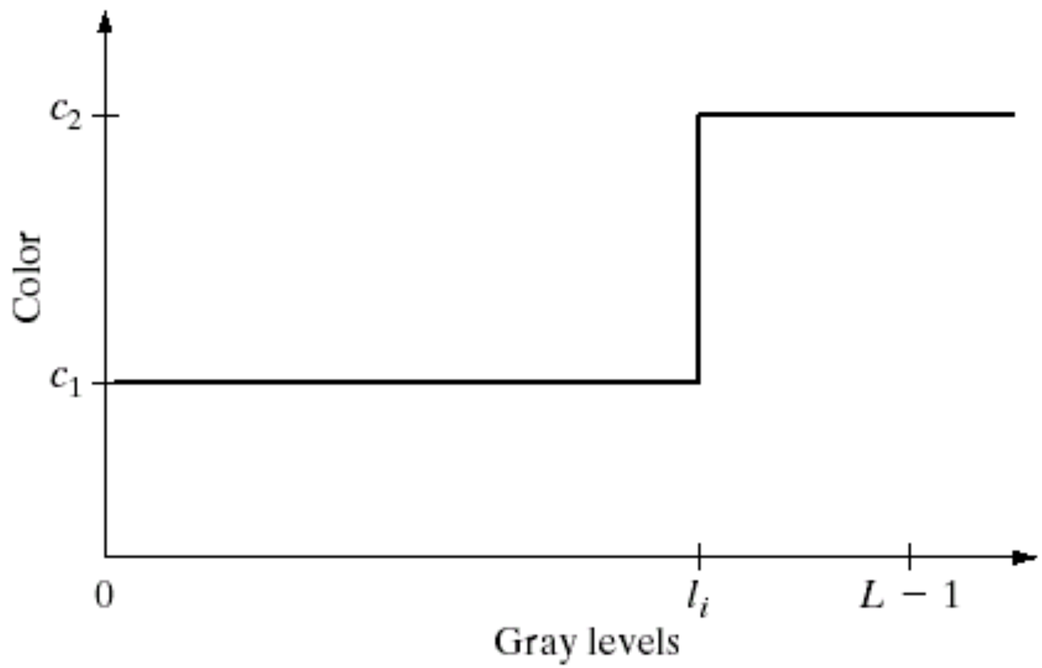
Basic Idea:

- Display the colors of interest so they stand out from the background.
- Use the region defined by the colors as a mask for further processing.

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

Color slicing

- Recall the pseudo-color intensity slicing



1-D intensity

Color Slicing

1. Colors of interest are enclosed by ***cube*** (or ***hypercube*** for n>3)

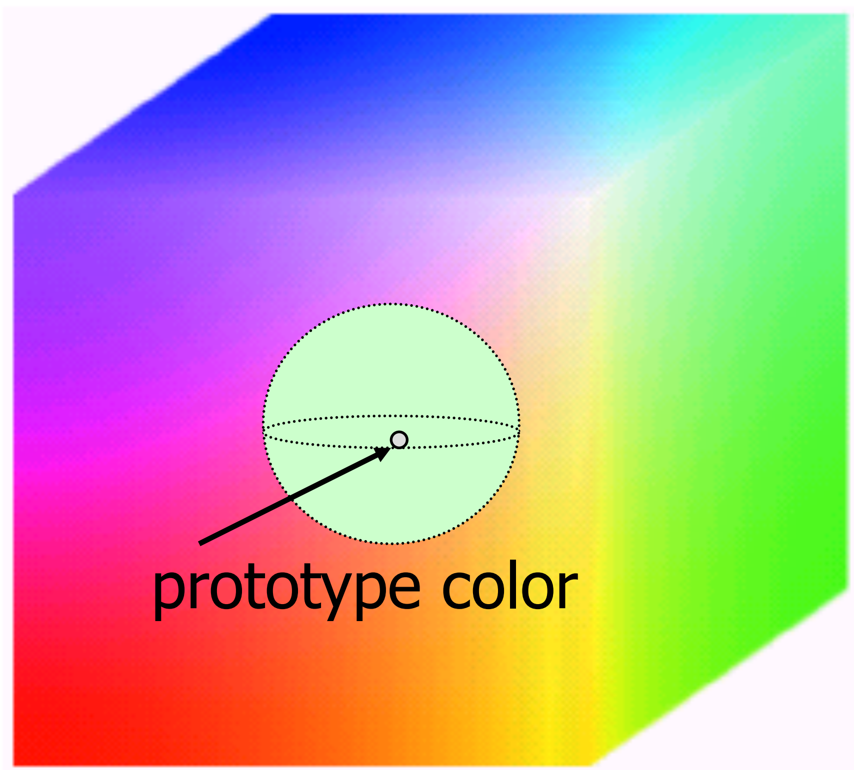
$$s_i = \begin{cases} 0.5 & if \left[\left| r_j - a_j \right| > \dfrac{W}{2} \right]_{any 1 \leq j \leq n} \\ r_i & otherwise \end{cases} , \qquad i = 1,2,\ldots,n$$

2. Colors of interest are enclosed by ***Sphere***

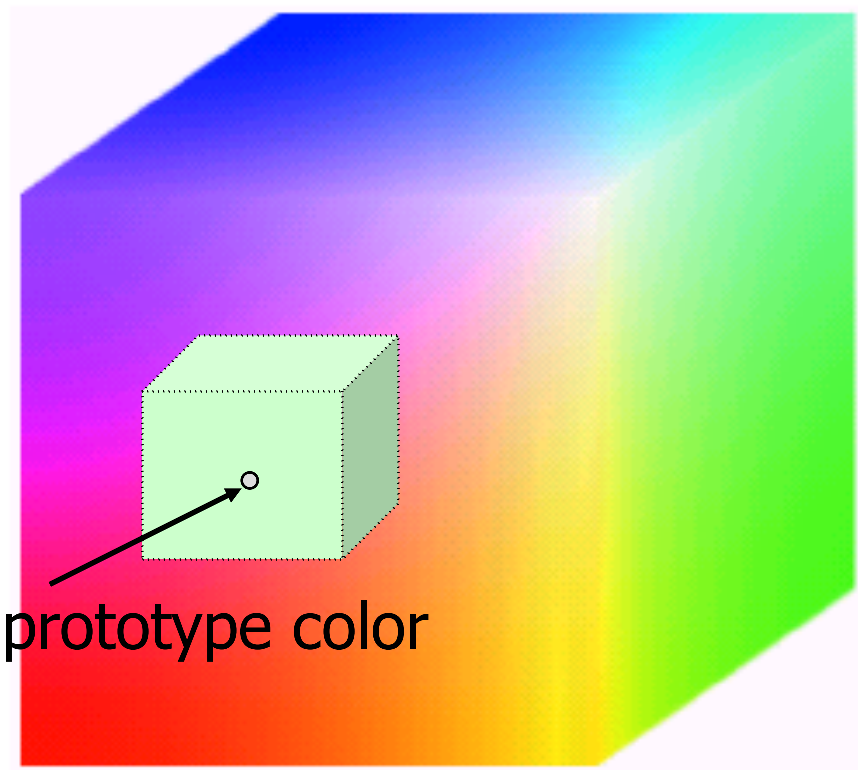
$$s_i = \begin{cases} 0.5 & if \sum_{j=1}^{n} (r_j - a_j)^2 > R_0^2 \\ r_i & otherwise \end{cases} , \qquad i = 1,2,\ldots,n$$

Implementation of color slicing

- How to take a region of colors of interest?



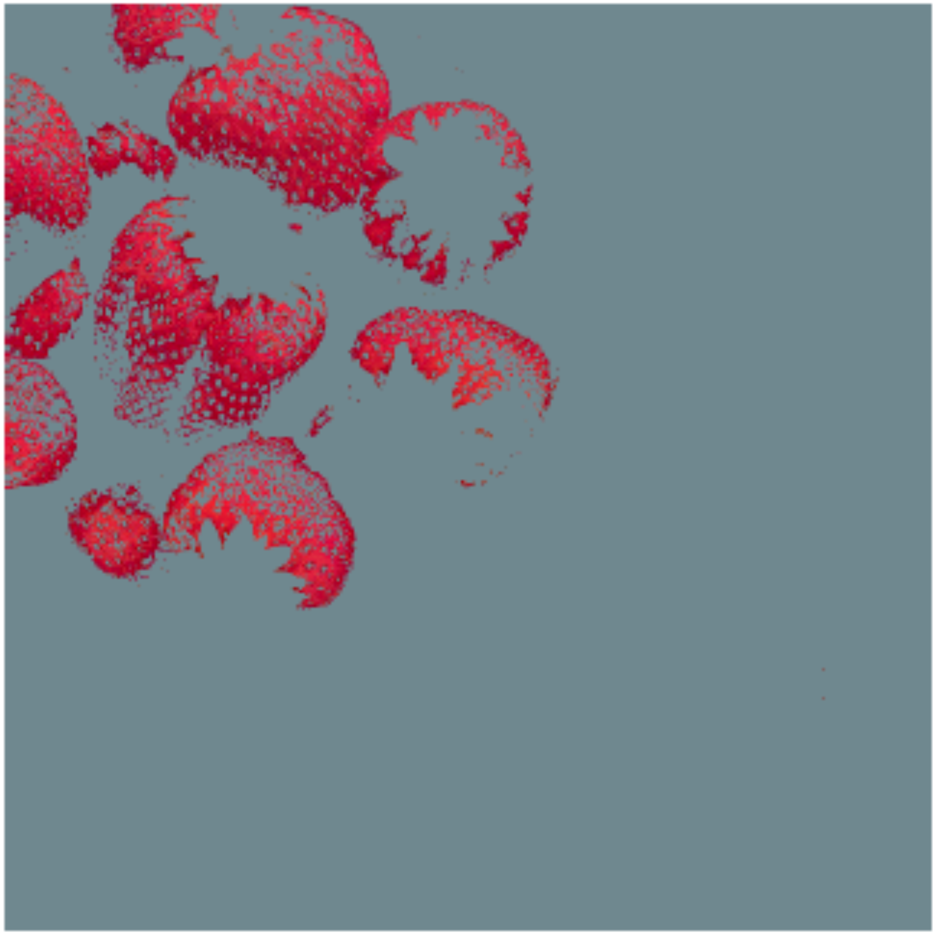
Sphere region



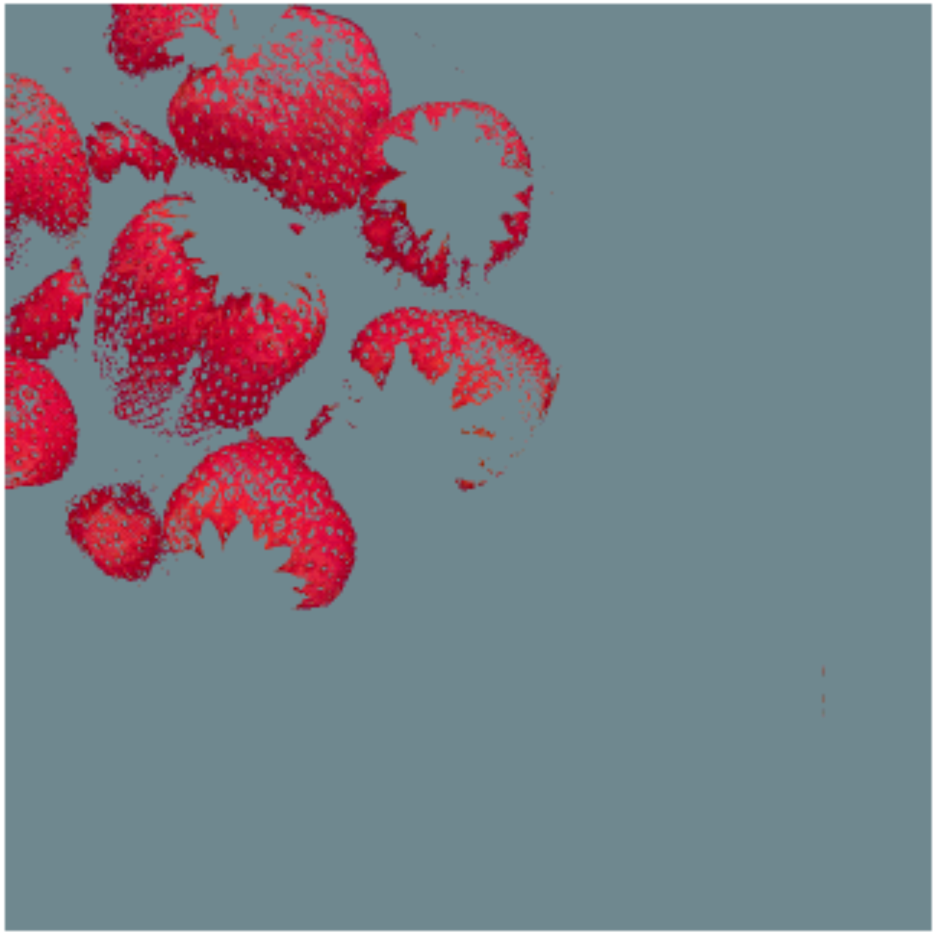
Cube region

Application

Full color



cube

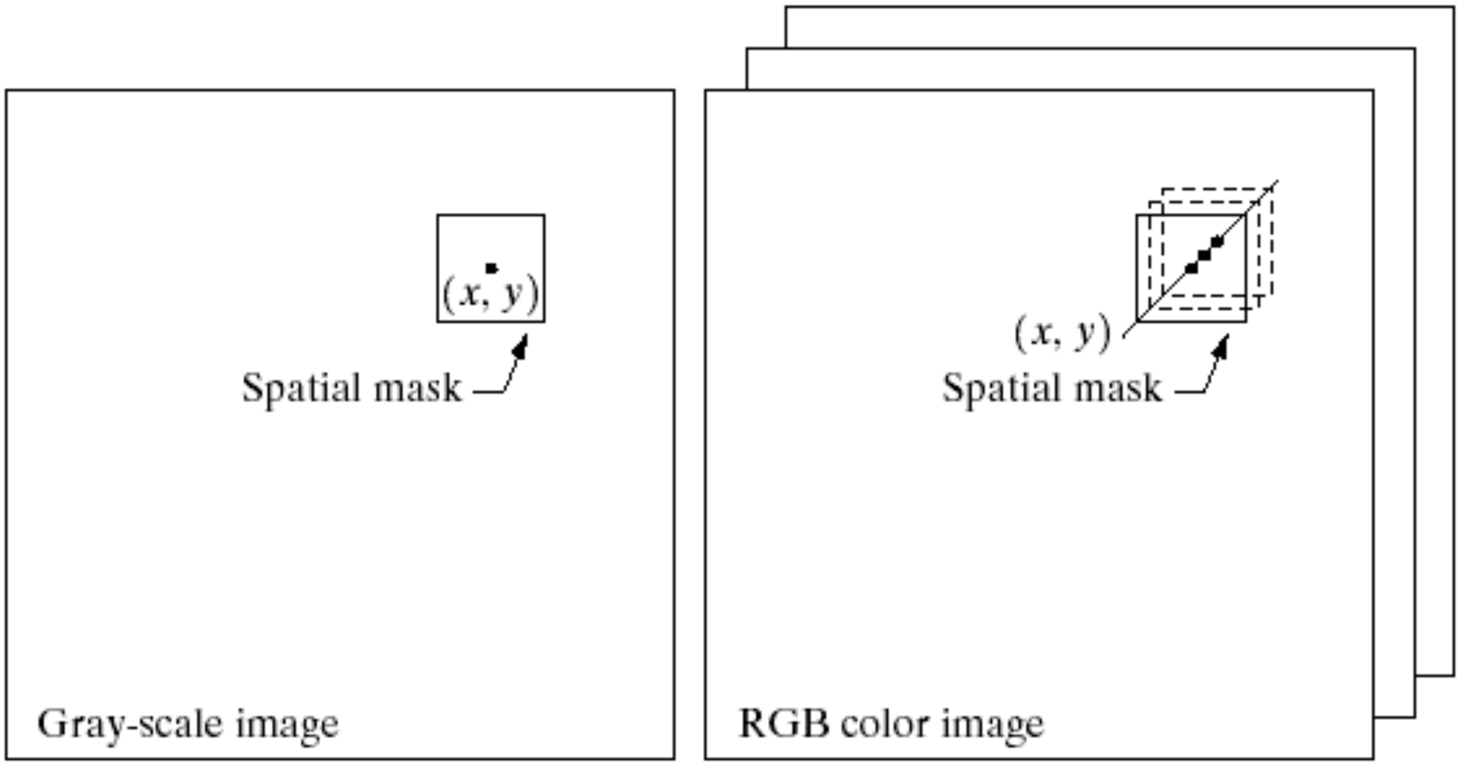


sphere

Color Smoothing and Sharpening

Color image smoothing

Neighborhood processing



Color image smoothing: averaging mask

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

vector processing

Neighborhood
Centered at (x,y)

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

per-component processing

original R

G G

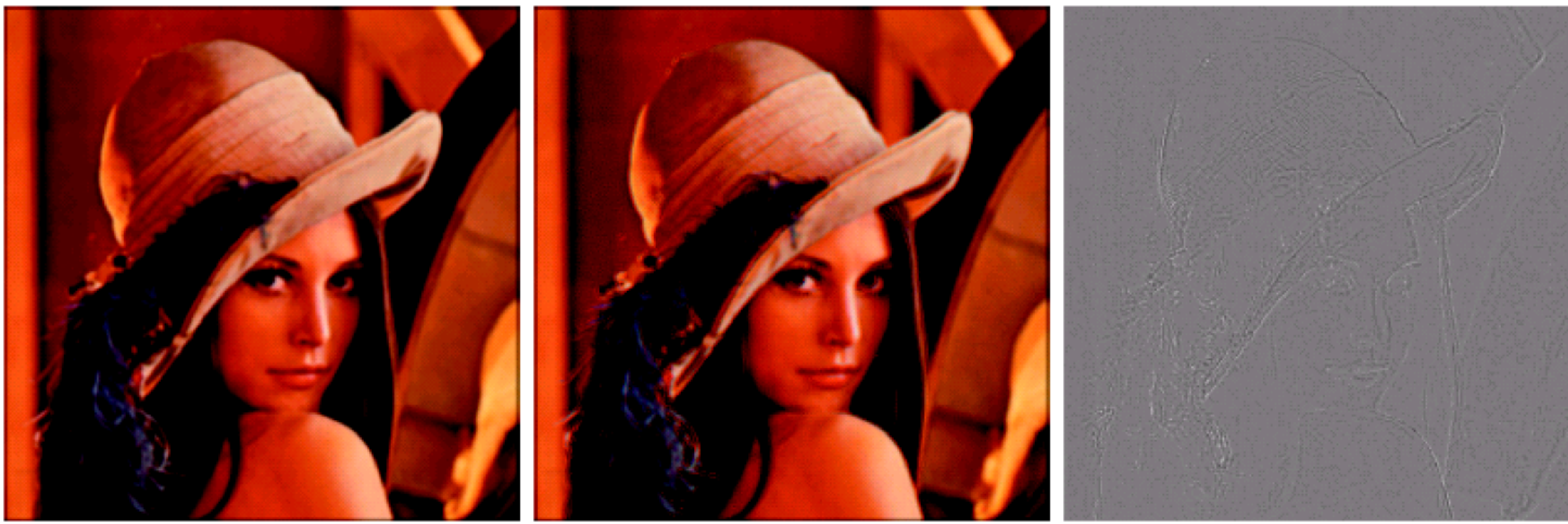
H S I

Example: 5x5 smoothing mask

RGB model

Smooth I
in HSI model

difference



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

As with intensity images, the Laplacian can be computed for each component images and applied for sharpening.

a b c

FIGURE 7.39 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.

Using Color in Image Segmentation

Color Segmentation in HSI Color Space

Segmentation is a process that partitions an image into regions.

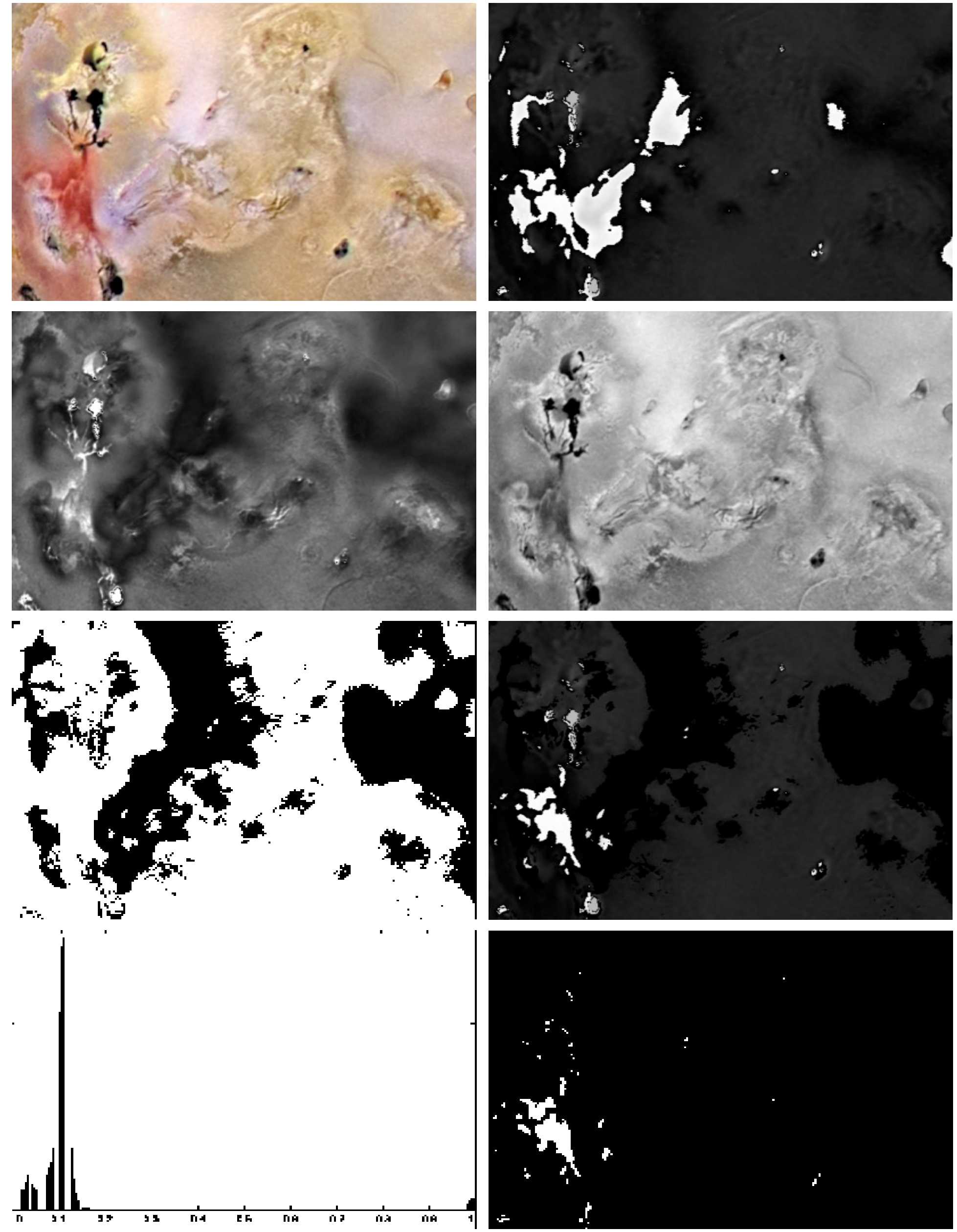


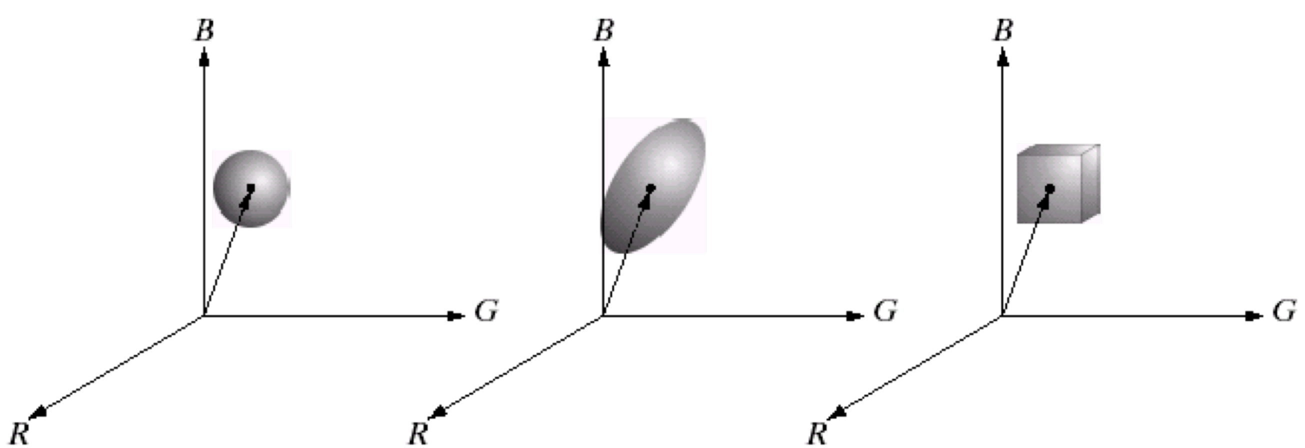
FIGURE 7.40 Image segmentation in HSI space. (a) Original. (b) Hue. (c) Saturation. (d) Intensity. (e) Binary saturation mask (black = 0). (f) Product of (b) and (e). (g) Histogram of (f). (h) Segmentation of red components from (a).

Color Image Segmentation

z is similar to **a** if the distance between them is less than a specified threshold.

Euclidian Distance: $$D(\mathrm{z},\mathrm{a}) = \|\mathrm{z}-\mathrm{a}\|$$
$$= \left[(\mathrm{z}-\mathrm{a})^T(\mathrm{z}-\mathrm{a})\right]^{1/2}$$
$$= \left[(z_R-a_R)^2+(z_G-a_G)^2+(z_B-a_B)^2\right]^{1/2}$$

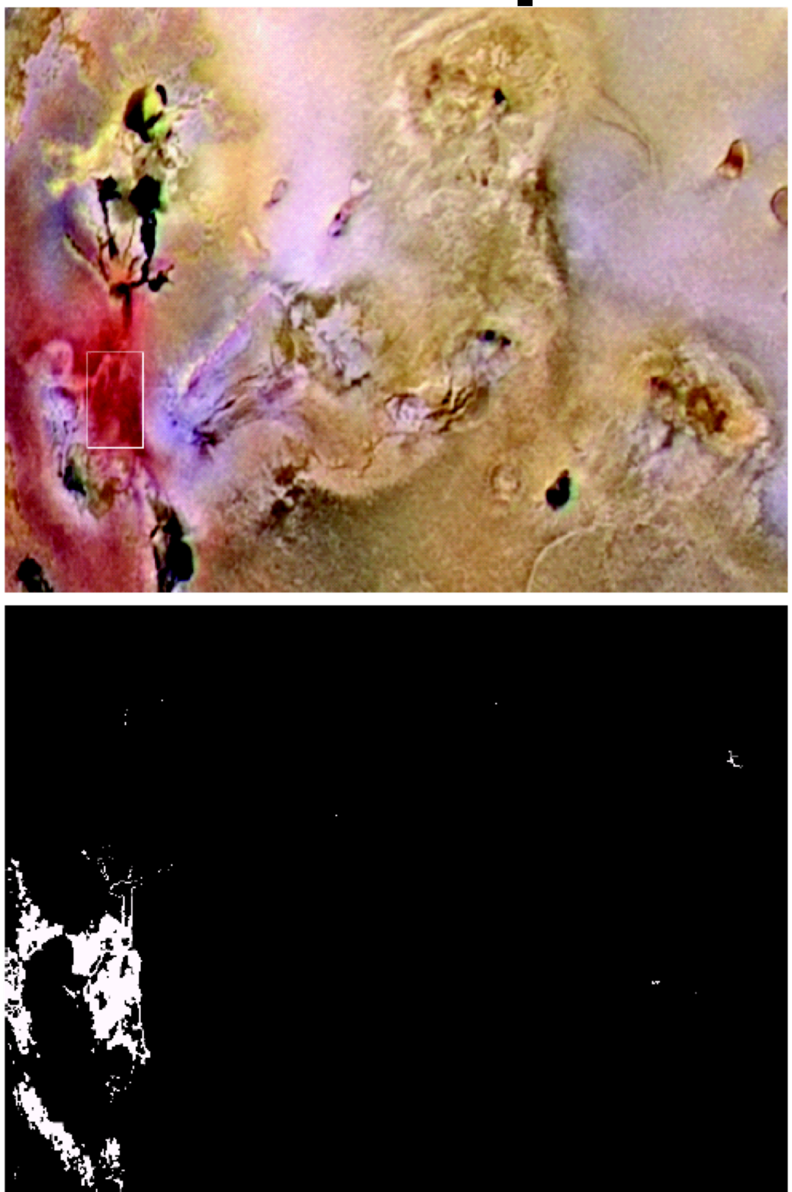
Generalized form: $$D(\mathrm{z},\mathrm{a}) = \left[(\mathrm{z}-\mathrm{a})^T\mathrm{C}^{-1}(\mathrm{z}-\mathrm{a})\right]^{1/2}$$



a b c

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

Color Segmentation in RGB Color Space



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).

Summary

- Color is a powerful description for computer vision tasks
- Humans can discern many more different colors than shades of gray
- Pseudo-color image processing allows the conversion of grayscale images into color images
- Color space transformation are useful for particular tasks of image enhancement
- Similar operations of smooth and sharpening performed on grayscale images can be performed on color images as well.
- Although any color space can be used for image segmentation, RGB typically obtains better result compared to HSI.

Next Time: Chapter 9 Morphological Image Processing

Questions?

Slide Credits

Images taken from Digital Image Processing by Gonzalez and Woods Text.

Material taken from Jen-Chang Liu lecture slides

Material taken from Allan Hanbury lecture slides

Material taken from Hamidreza Pourreza lecture slides