CSL7320: Digital Image Analysis

Color Image Processing

Color Image Processing

Motivation:
- Powerful descriptor $\rightarrow$ Object identification
- Humans discern thousands of colour shades, intensities (only two dozen shades of gray)

Colour IP:
- Full-colour processing
  - Colour TV camera, scanner
  - Recent development
- Pseudo-colour processing
  - Assign colour to monochrome intensity
  - Used in the past

Some gray-scale methods directly applicable to colour images, others require reformulation...

Colour fundamentals

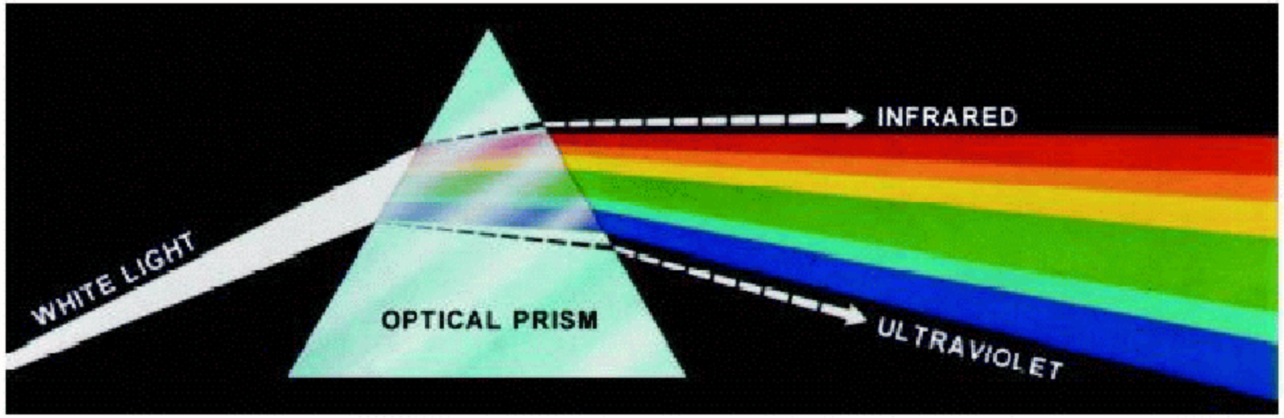

FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

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Color Images

Perceived colour determined by light reflected by object
For example, green objects reflect light with wavelengths primarily in the 500 to 570 nm range, while absorbing most of the energy at other wavelengths

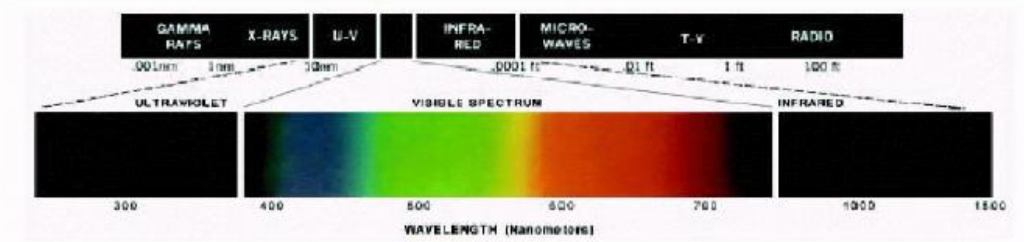

FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

Achromatic light:
- **1 attribute, intensity $\rightarrow$ gray level**

Chromatic light:
- **Radiance**
  - **Total energy from light source** ○ **Watts** (W)
- **Luminance**
  - **Amount of energy observer perceives** ○ **Lumens** (lm)
- **Brightness**
  - **Subjective: "achromatic intensity"** ○ **Can't measure**

Light emitted from source in far infrared region has significant energy (radiance), but luminance is almost zero

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Color Images

Sensors (cones) in human eye:
(R, G, and B: primary colours)

- **Red (R)**
  - **65 %**
- **Green (G)**
  - **33 %**
- **Blue (B)**
  - **2 %**
  - **Most sensitive**

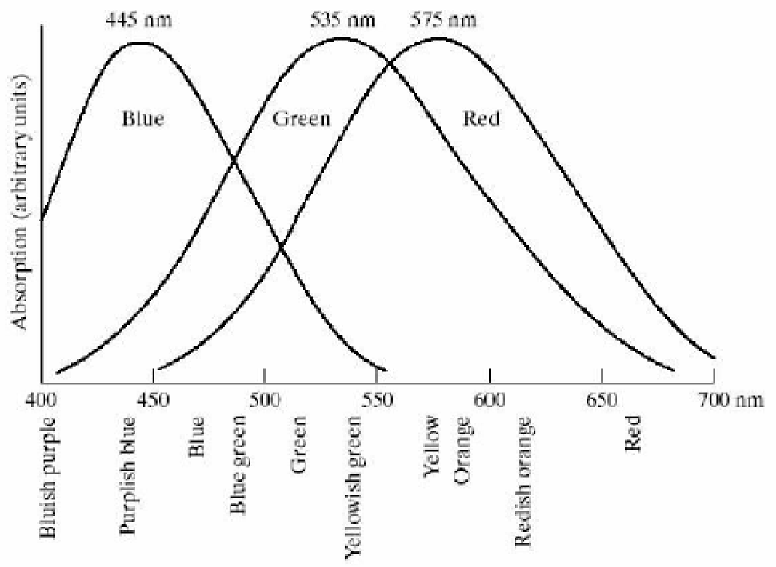

FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

Note: No single colour may be called R, G, or B. When mixed in various intensity proportions, the three standard primaries can not produce all visible colours. The wavelength must also be allowed to vary.

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Color Images

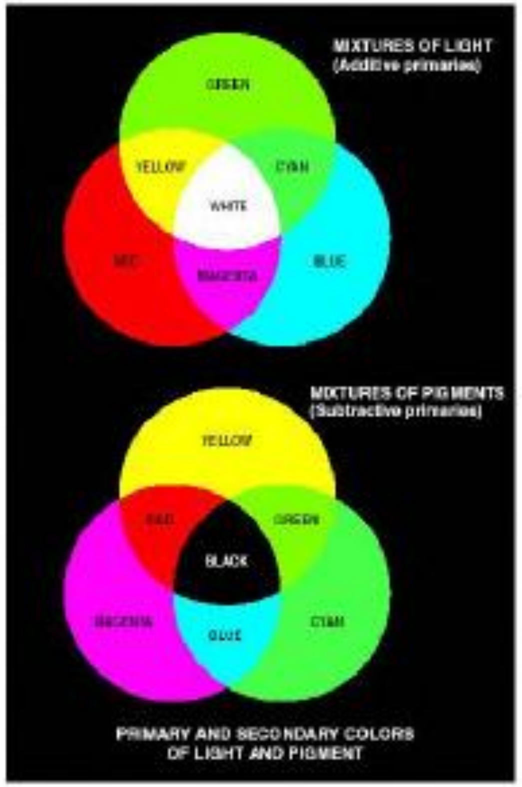
<u>Primary colours of light</u>

red + green + blue = white

<u>Secondary colours of light</u>

red	+	blue	=	magenta
green	+	blue	=	cyan
red	+	green	=	yellow

- Difference between primary colours of light and pigment
- Primary colour of pigment absorbs a primary colour of light and reflects the other two
- Primary colours of pigment: magenta, cyan and yellow
- Secondary colours of pigment: red, green and blue



a
b

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

Slide credit: TW793

Color Images

Additive nature of light colours: colour TV reception

Characteristics used to distinguish colours:

- Brightness
  - Chromatic notion of intensity
- Hue
  - Dominant wavelength
  - Dominant perceived colour
- Saturation
  - Relative purity
  - Pink is less saturated
  - $\downarrow$ Saturation $\Rightarrow \uparrow$ White light

Hue & Saturation $\equiv$ Chromaticity

Tristimulus values: amount of R, G and B needed to form a particular colour and is denoted by X, Y and Z, respectively

Trichromatic coefficients:

$$x = \frac{X}{X+Y+Z}, \; y = \frac{Y}{X+Y+Z}, \; z = \frac{Z}{X+Y+Z}, \; \boxed{x+y+z=1}$$

For a specified wavelength, the tristimulus values can be obtained from curves or tables (complied from experiments)

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Color Models

Colour model/space/system: coordinate system + subspace within it; each colour = single point

Models:
- RGB (red, green, blue)
  - Colour monitors ◦ Colour video cameras
- CMY (cyan, magenta, yellow)
  - Colour printing
- CMYK (cyan, magenta, yellow, black)
  - Colour printing
- HSI (hue, saturation, intensity)
  - Human description/interpretation of colour
  - Decouples colour and gray-scale information
  - Suitable for many gray-scale techniques

The RGB Colour Model

Based on Cartesian coordinate system

Pixel depth: # of bits used to represent a pixel in RGB space

Each R, G, & B image = 8-bit image ⇒ depth = 24 bits ⇒ "full-colour" image ⇒ total # of colours = $(2^8)^3 = 16777216$

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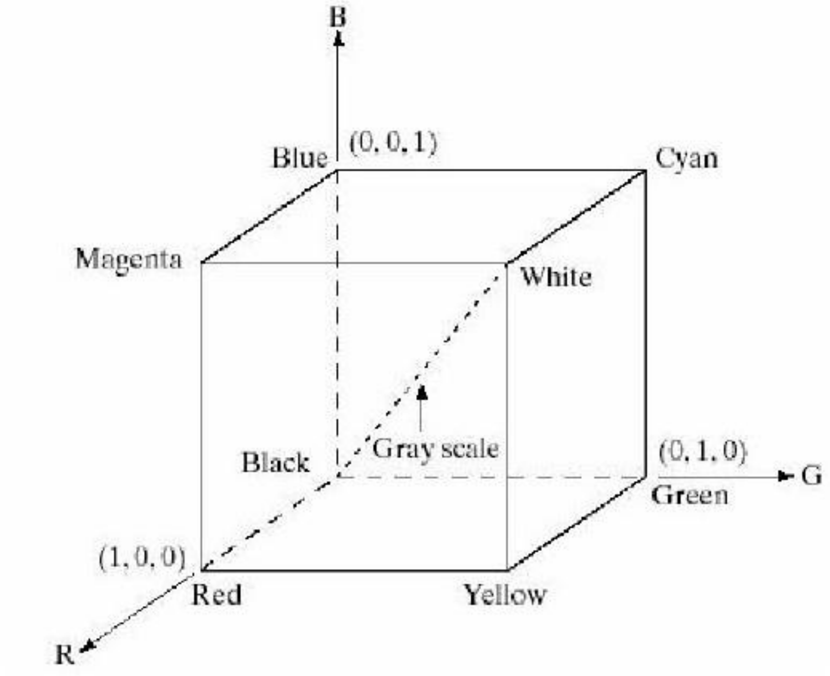
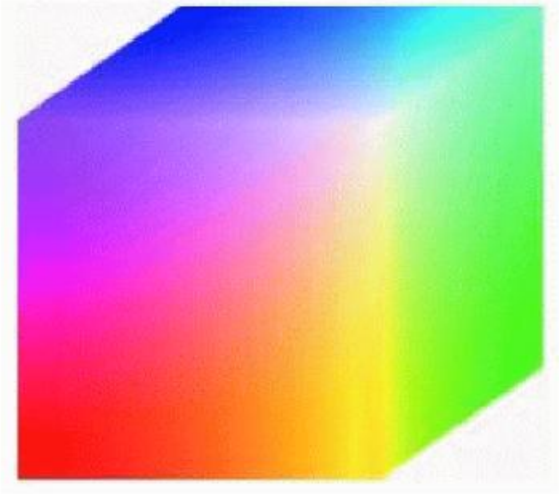
Color Models



Cube with all 16 777 216 colours:



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Color Models

Hidden face planes and cross section of cube

Mathematically normalized values: $[0, 1]$
Actual pixel values (computer): $0, 1, \ldots, 255$

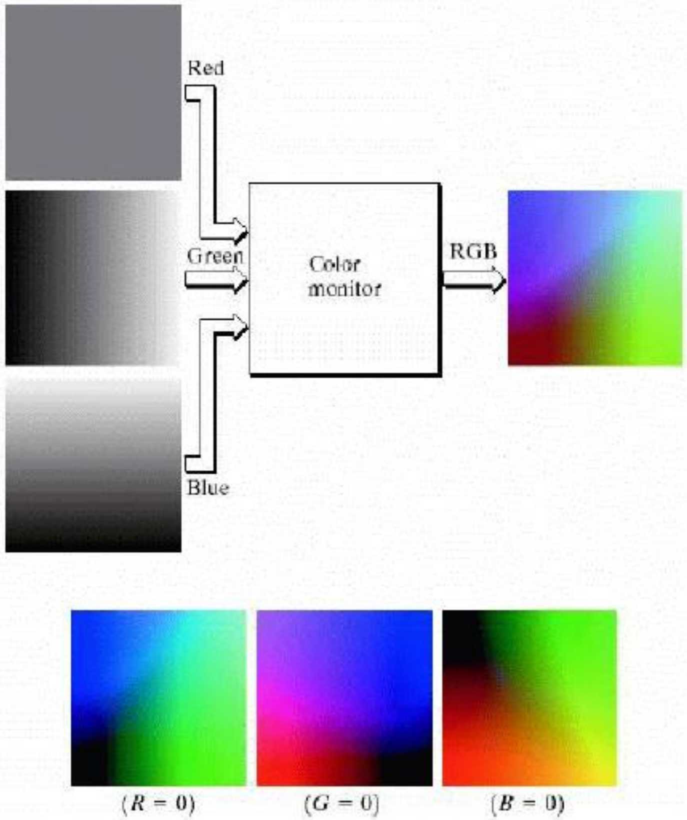

FIGURE 6.9 (a) Generating the RGB image of the cross-sectional color plane $(127, G, B)$. (b) The three hidden surface planes in the color cube of Fig. 6.8.

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Color Models

Many systems limited to 256 colours (or not necessary to use more)

Safe RGB colours: subset of colours likely to be produced faithfully, reasonable independently of hardware capabilities

Only 216 colours are common to most systems
$\Rightarrow$ **each RGB value can only be 0, 51, 102, 153, 204, or 255**
$\Rightarrow$ $(6)^3$ **= 216 possible value (all divisible by 3)**
$\Rightarrow$ **hexagonal number system:**

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.

Note: $(33)_{16} = 3 \times 16^1 + 3 \times 16^0 = 48 + 3 = (51)_{10}$
$(\mathrm{CC})_{16} = 12 \times 16^1 + 12 \times 16^0 = 192 + 12 = (204)_{10}$
$(\mathrm{FF})_{16} = (255)_{10} = (11111111)_2$
A grouping of two hex numbers forms an 8-bit byte

Purest red: FF0000
Black: 000000
White: FFFFFF

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Color Models

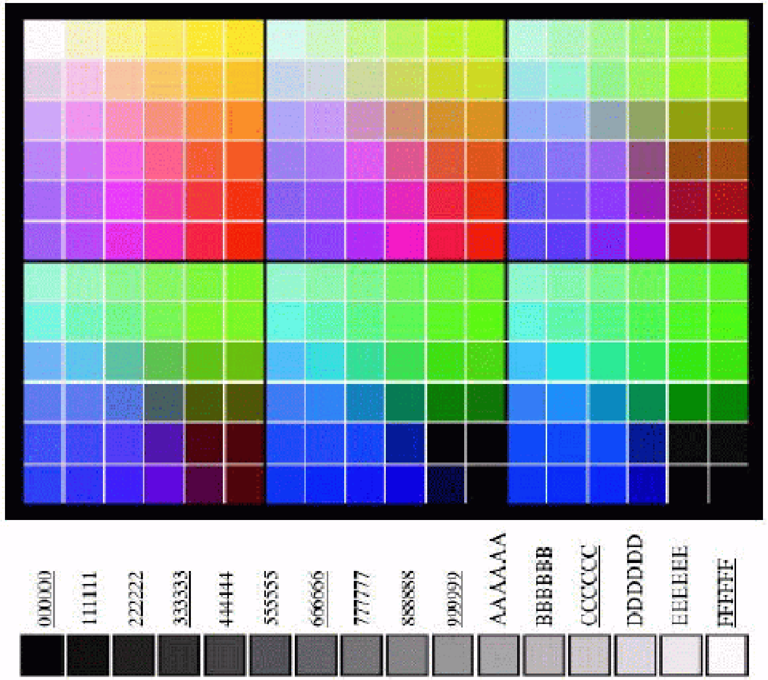

FIGURE 6.10 (a) The 216 safe RGB colors. (b) All the grays in the 256-color RGB system (grays that are part of the safe color group are shown underlined).

First array (block):

First row	FFFFFF **(white), FFFFCC, FFFF99, etc.**
Second row	FFCCFF, FFCCCC, FFCC99, **etc.**
Final square	FF0000 **(brightest possible red)**

Second array (block) starts with CCCCCC

Final square of last array: 000000 **(black)**

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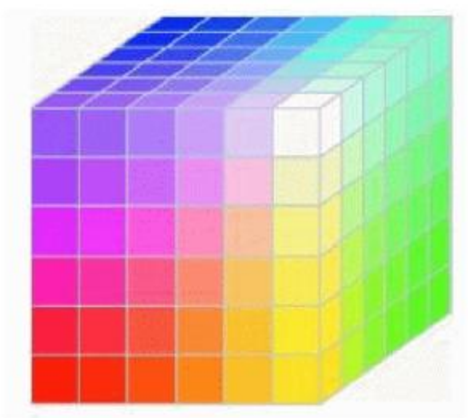
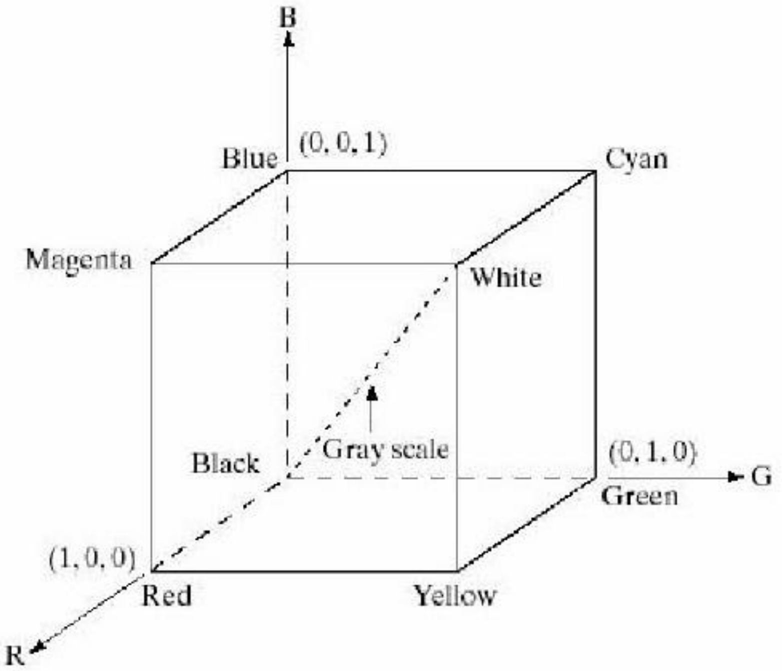
Color Models

The RGB safe-colour cube (colours only on surface planes)





The CMY and CMYK colour models

- **Cyan, magenta, yellow: sec. colours of light / prim. colours of pigment**
- **For example, when a surface coated with cyan pigment is illuminated with white light, no red light is reflected from the surface, that is, cyan subtracts red light from reflected white light**
- **Printers/copiers require CMY data input or do conversion:**

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

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Color Models

Theoretically equal amounts of the pigment primaries should produce black; in practice a muddy-looking black

To produce true black (predominant in printing), a fourth colour, black is added $\Rightarrow$ CMYK colour model

The HSI colour model

Humans describe a colour object by its hue, saturation and brightness (see previous lecture for definitions)

HSI model decouples intensity component from colour-carrying information $\Rightarrow$ ideal tool for developing IP algorithms

RGB is ideal for colour image generation (camera, monitor)

Relationship between the RGB and HSI models

Figure 6.7:	**Colour cube on black vertex $(0,0,0)$, with white vertex $(1,1,1)$ directly above it Intensity axis (grays) joins white and black vertices**

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Color Models

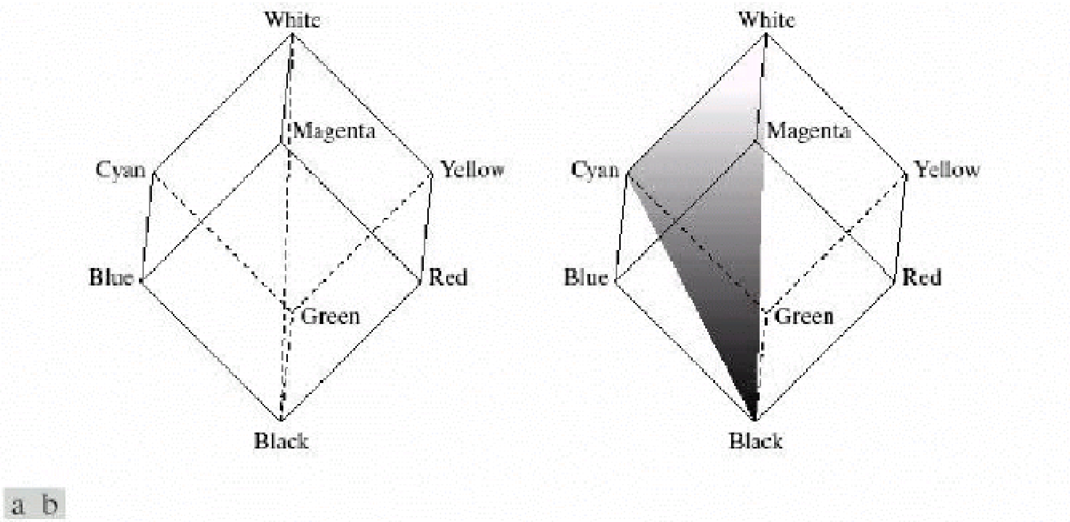

FIGURE 6.12 Conceptual relationships between the RGB and HSI color models.

Intensity:	**Plane perpendicular to intensity axis containing colour point** **Intensity: intersection of plane with intensity axis**
Saturation:	**Increases as a function of distance from intensity axis (saturation is zero on the axis)**
Hue:	**Consider plane defined by three points: black, white and cyan** **All points in this plane have the same hue, i.e. cyan** **(recall from section 6.1 that all colours generated by three colours lie in the triangle defined by those colours)**

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Color Models

Planes perpendicular to intensity axis...

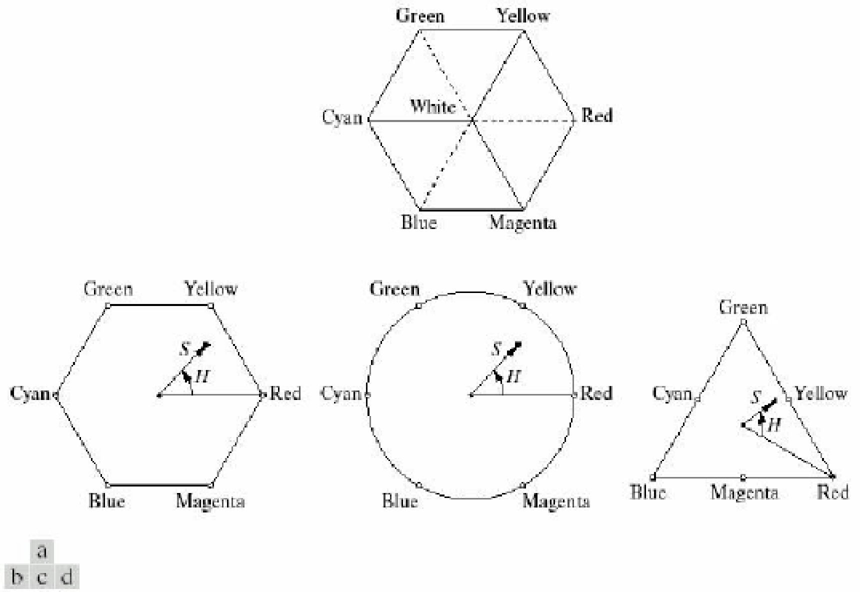

FIGURE 6.13 Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and the length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.

- **Angle between primary (or secondary) colours:** 120°
- **Angle between primary and secondary colours:** 60°
- **Hue determined by angle from reference point (usually red)**
- **Saturation is length of vector from origin to point**
- **Shape (hexagon, circle, triangle) does not matter**

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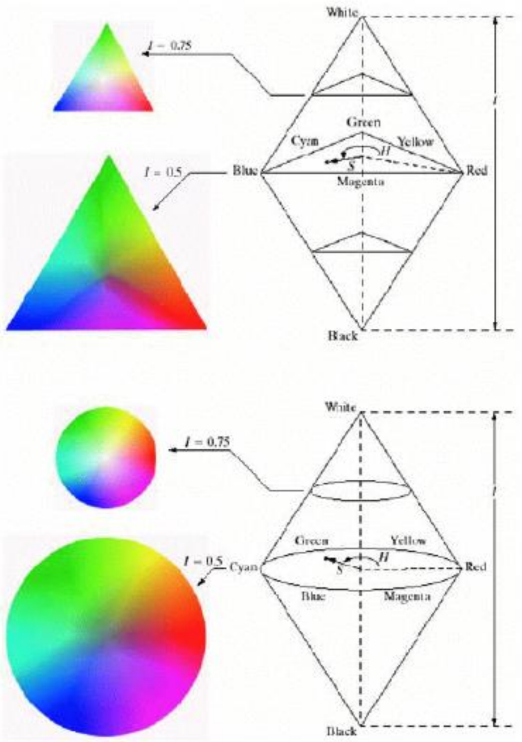
Color Models



Converting colours from RGB to HSI: $H = \begin{cases} \theta & \textbf{if } B \leq G \\ 360 - \theta & \textbf{if } B > G \end{cases}$

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

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Color Models

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

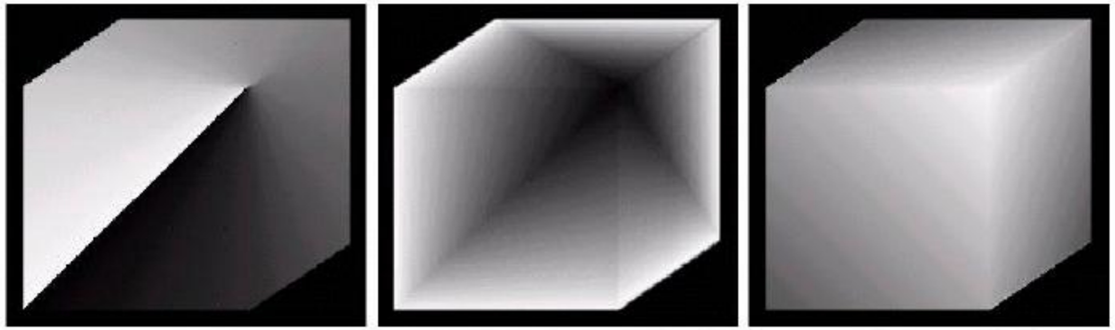
$$I = \frac{1}{3}(R+G+B)$$

Derivation of these formulas is tedious and is not discussed

Converting colours from HSI to RGB

See G&W: page 433/434

Example : **HSI values of RGB colour cube (figure 6.8)**



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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Color Models

Manipulating HSI component images

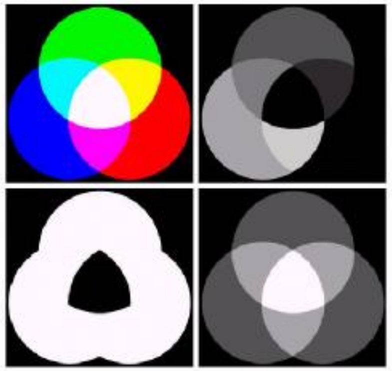

FIGURE 6.16 (a) RGB image and the components of its corresponding HSI image: (b) hue, (c) saturation, and (d) intensity.

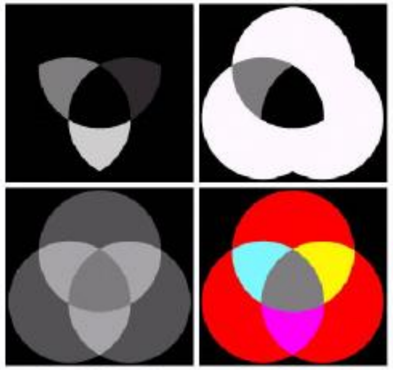

FIGURE 6.17 (a)–(c) Modified HSI component images. (d) Resulting RGB image. (See Fig. 6.16 for the original HSI images.)

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PseudoColor Image Processing

Assign colours to gray values based on specified criterion
Use: human visualization / interpretation of gray-scale events

Intensity Slicing

View image as 3D function and place planes parallel to coordinate plane; each plane slices the function in area of intersection
E.g., plane at $f(x, y) = l_i \Rightarrow$ 2 levels $\Rightarrow$ 2 different colours

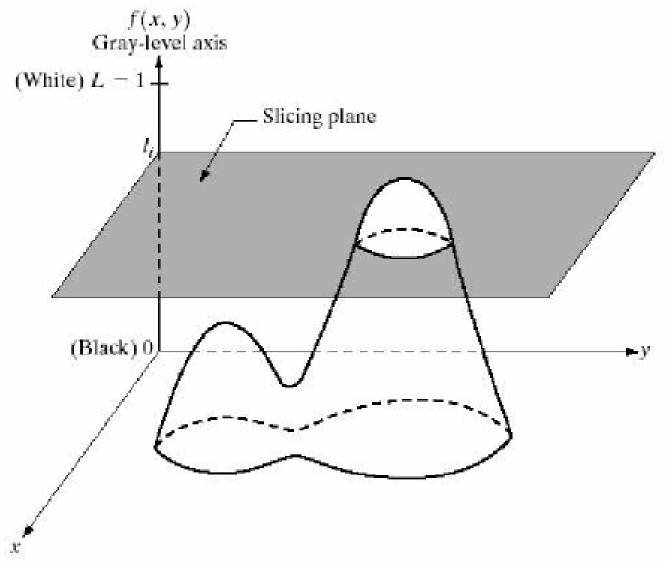

FIGURE 6.18 Geometric interpretation of the intensity-slicing technique.

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

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PseudoColor Image Processing

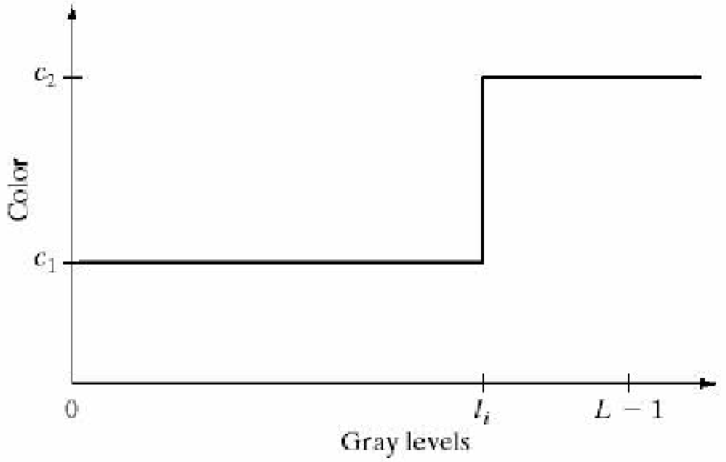

FIGURE 6.19 An alternative representation of the intensity-slicing technique.

In general:

Gray scale: $[0, L-1]$

Black $[f(x,y)=0]$**: level** l_0**; White** $[f(x,y)=L-1]$**:** l_{L-1}

Suppose P **planes perp. to intensity axis: levels** $l_1, l_2, \ldots, l_P$

Planes partition gray scale into $P+1$ **intervals** $V_1, V_2, \ldots, V_{P+1}$

Colour assignment: $f(x,y) = c_k$ **if** $f(x,y) \in V_k$

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PseudoColor Image Processing

Intensity slicing (human chest)

a b

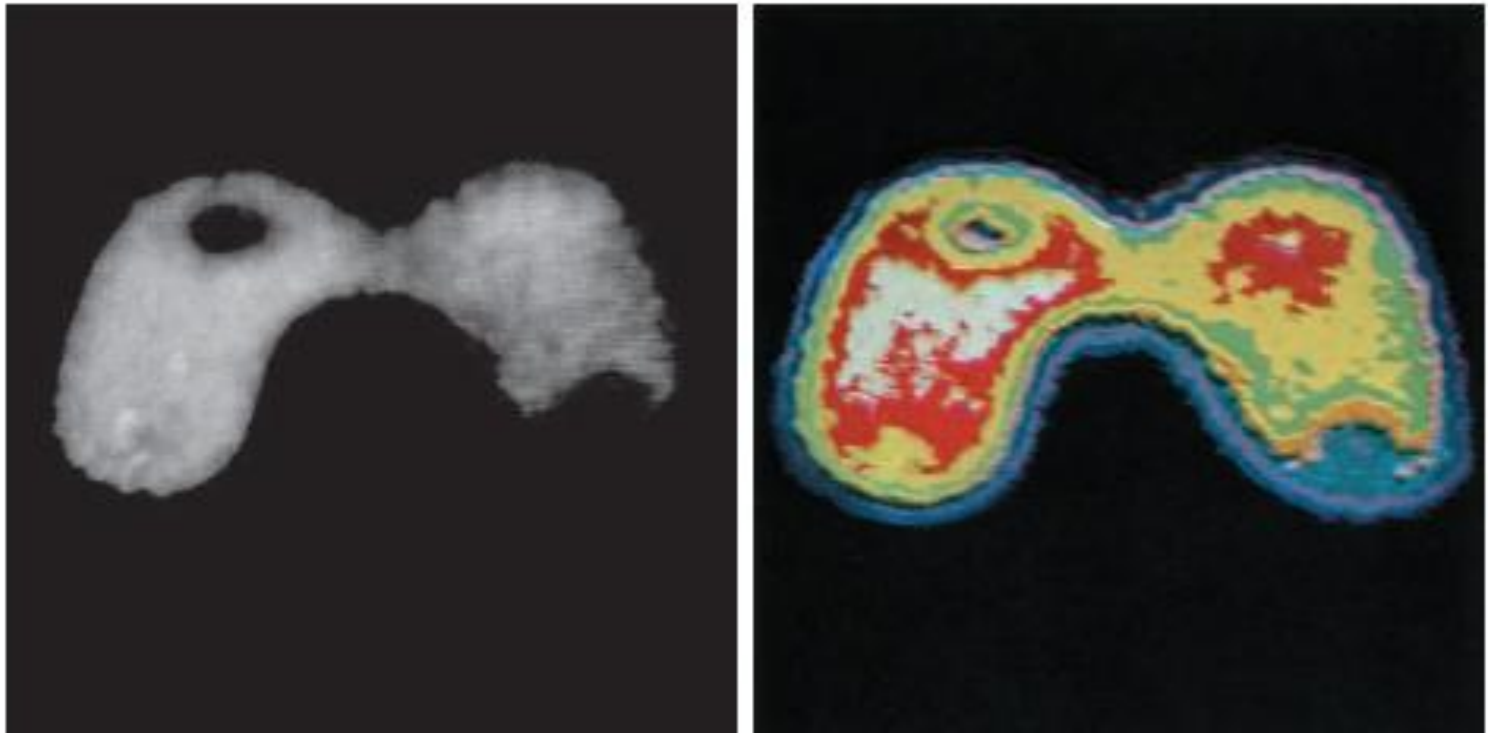

FIGURE 6.18 (a) Grayscale image of the Picker Thyroid Phantom. (b) Result of intensity slicing using eight colors. (Courtesy of Dr. J. L. Blankenship, Oak Ridge National Laboratory.)

Regions that appear of constant intensity in the monochrome image are actually quite variable!

Here the gray scale was divided into intervals, without regard of the meaning of the gray levels

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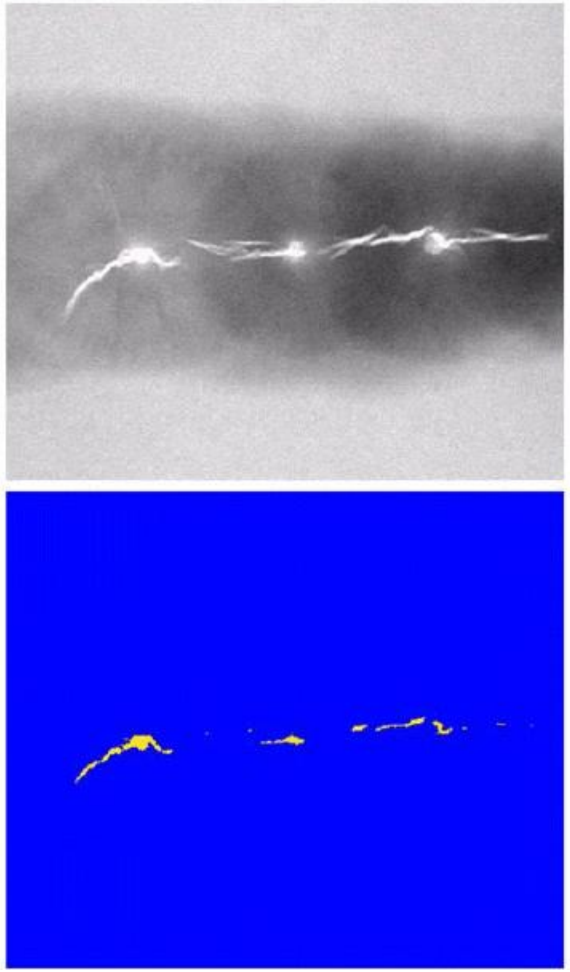
PseudoColor Image Processing

Another example: X-ray image of weld



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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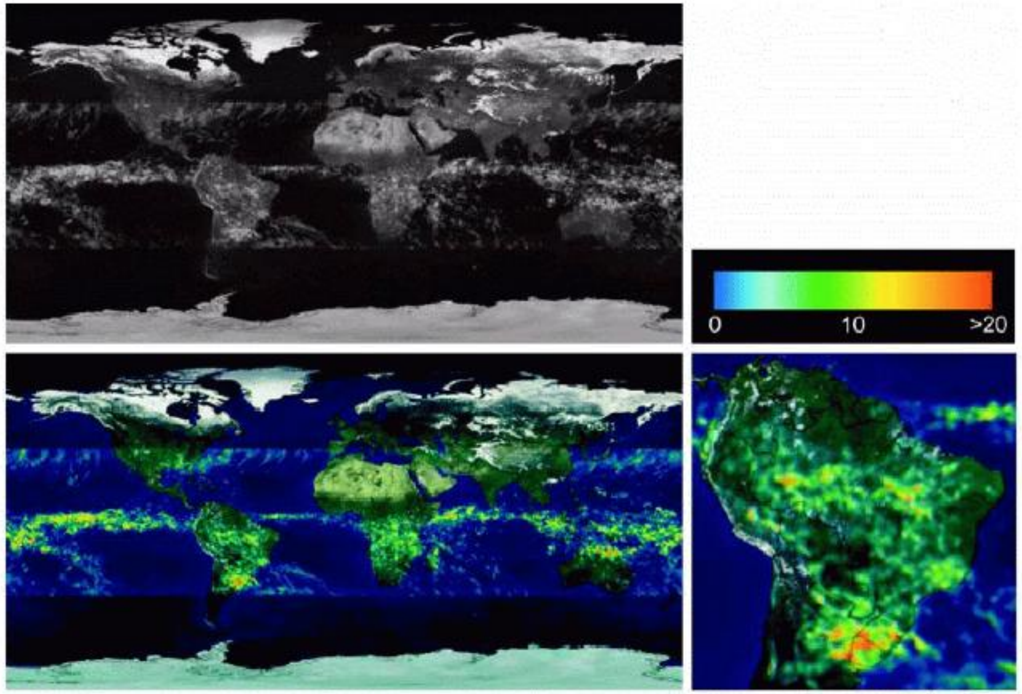
PseudoColor Image Processing

Use of colour to highlight rainfall levels



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 America region. (Courtesy of NASA.)

Tropical rainfall measuring mission (TRMM): a satellite uses a precipitation radar, a microwave imager, and a visible and infrared scanner to detect rain (also over ocean)

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Gray level to colour transformations

Perform three independent transformations on gray level of input pixel

Three results are fed separately into R, G and B channels of colour TV monitor $\Rightarrow$ composite image whose colour content is modulated by nature of transformation functions

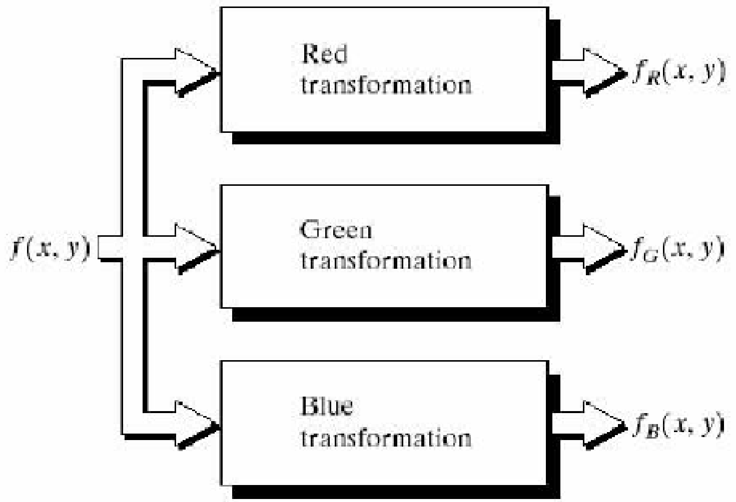
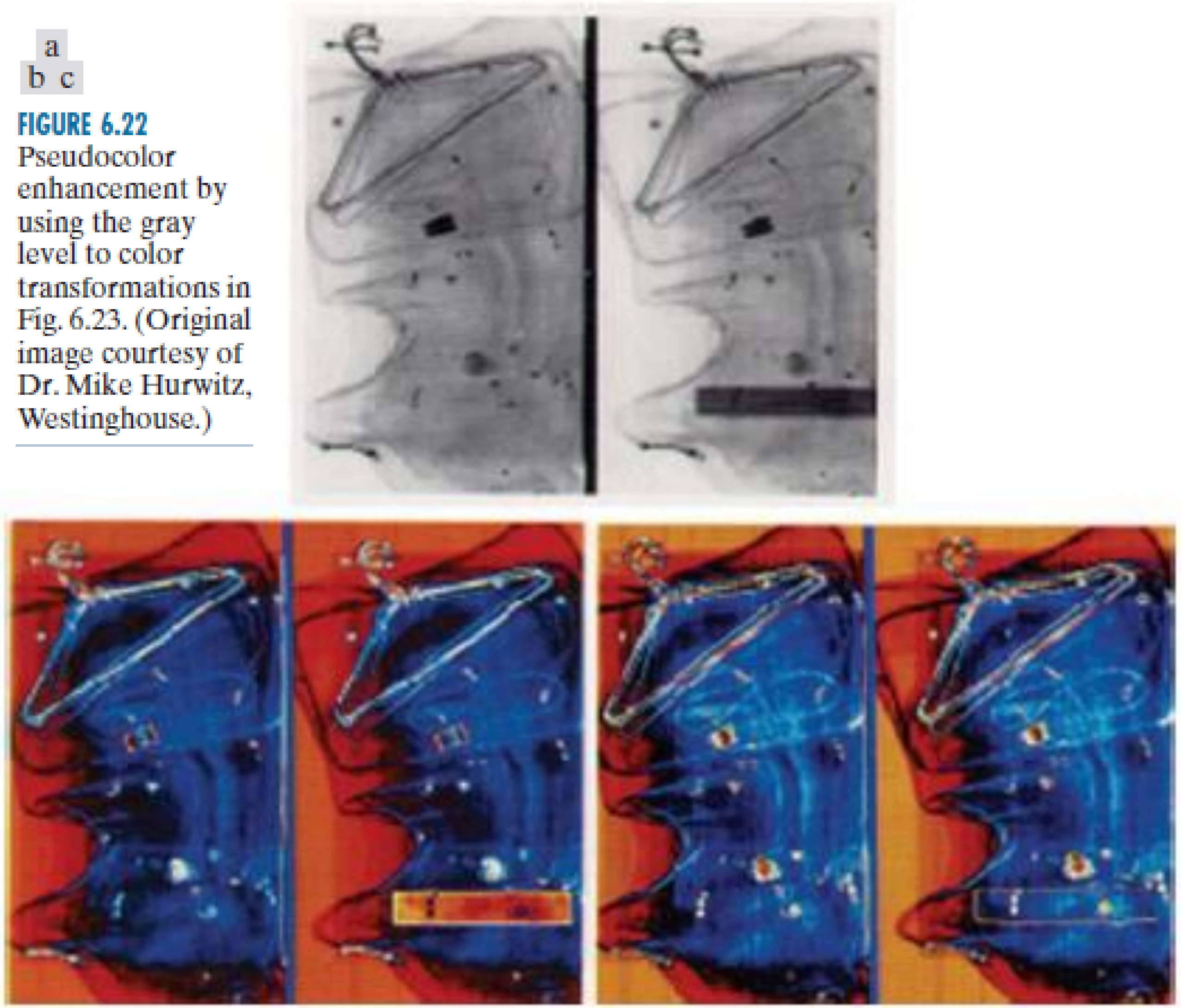


FIGURE 6.23 Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

Gray level to colour transformations

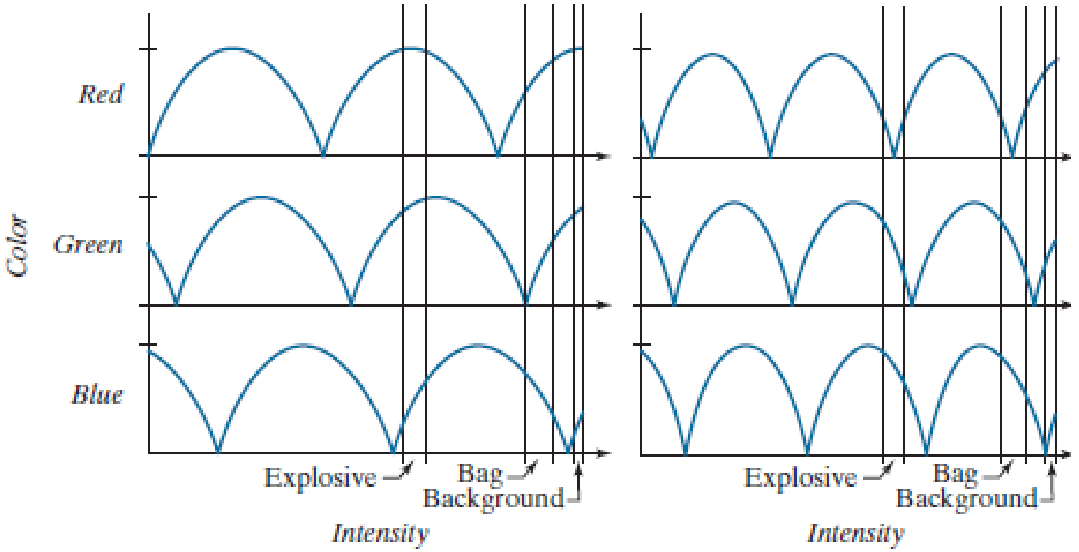
a
b c

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



a b

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



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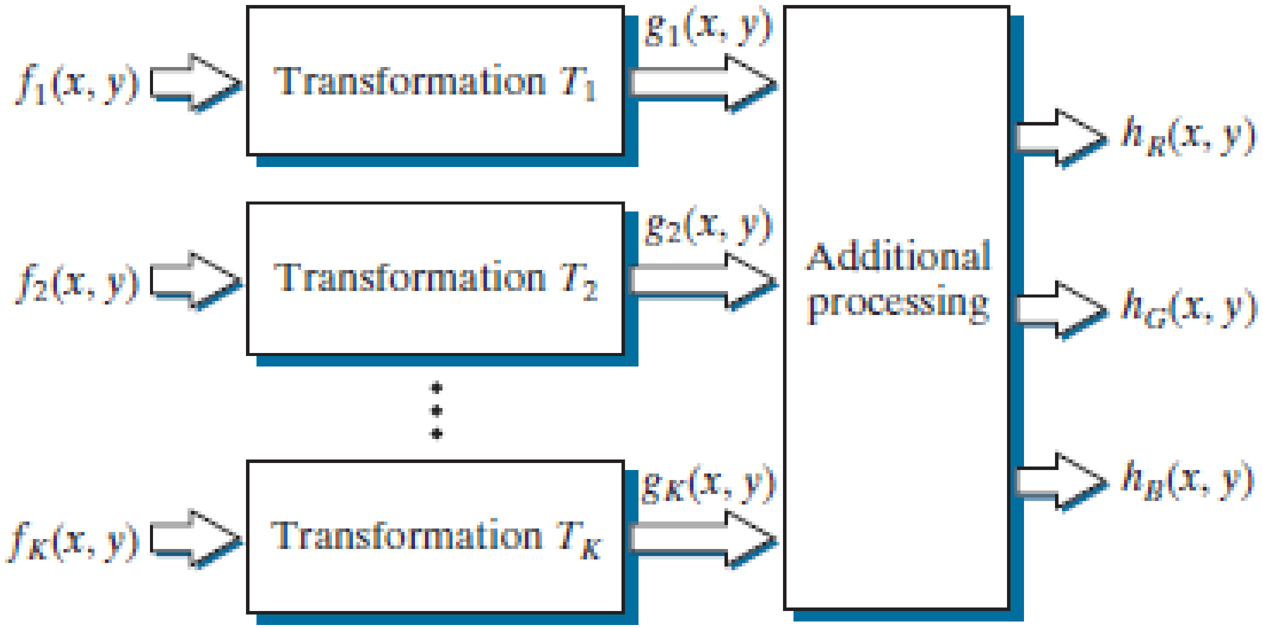
Gray level to colour transformations

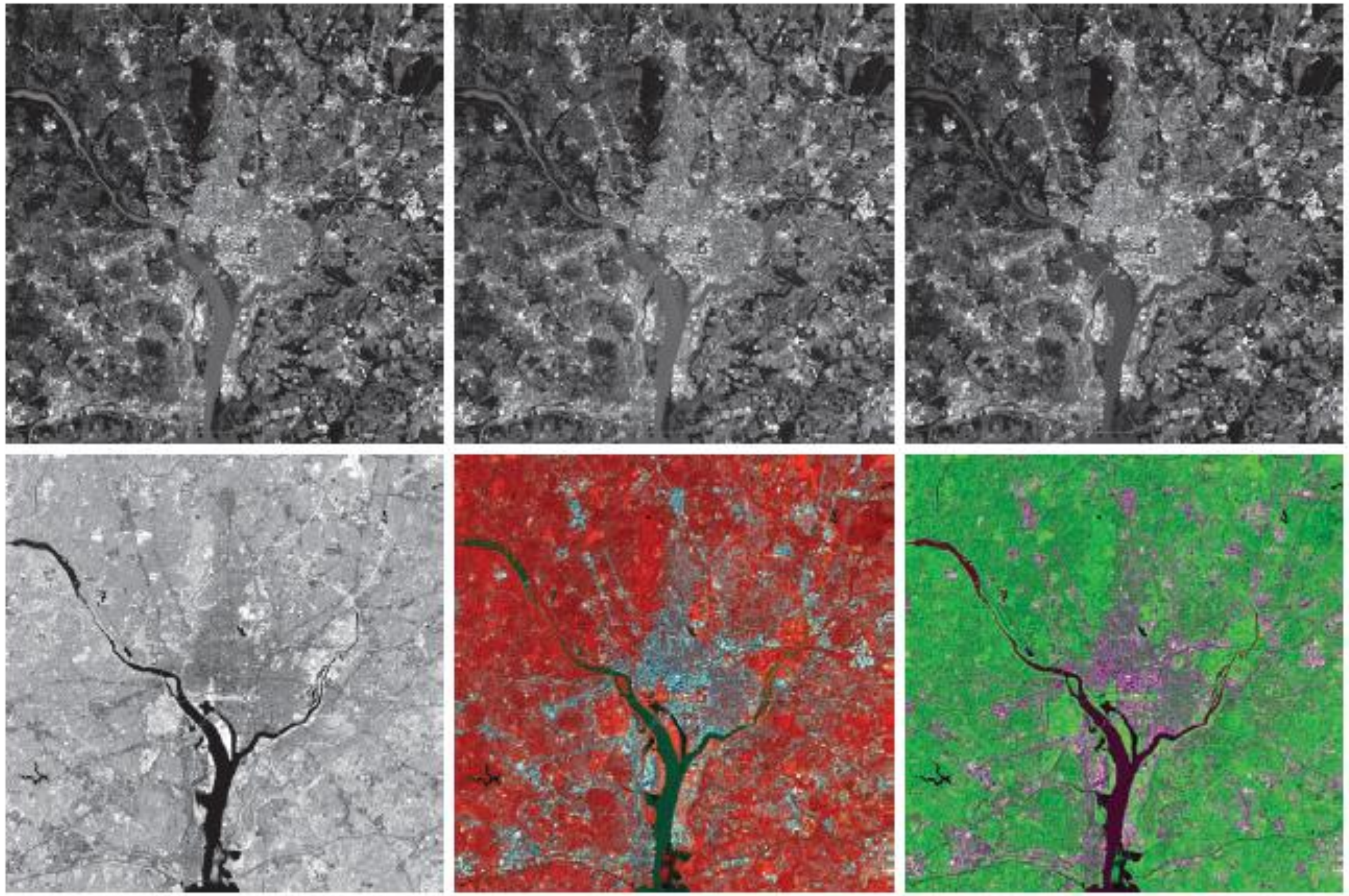
Combine several grayscale images into a single color composite

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



Gray level to colour transformations

Combine several grayscale images into a single color composite



a b c
d e f

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

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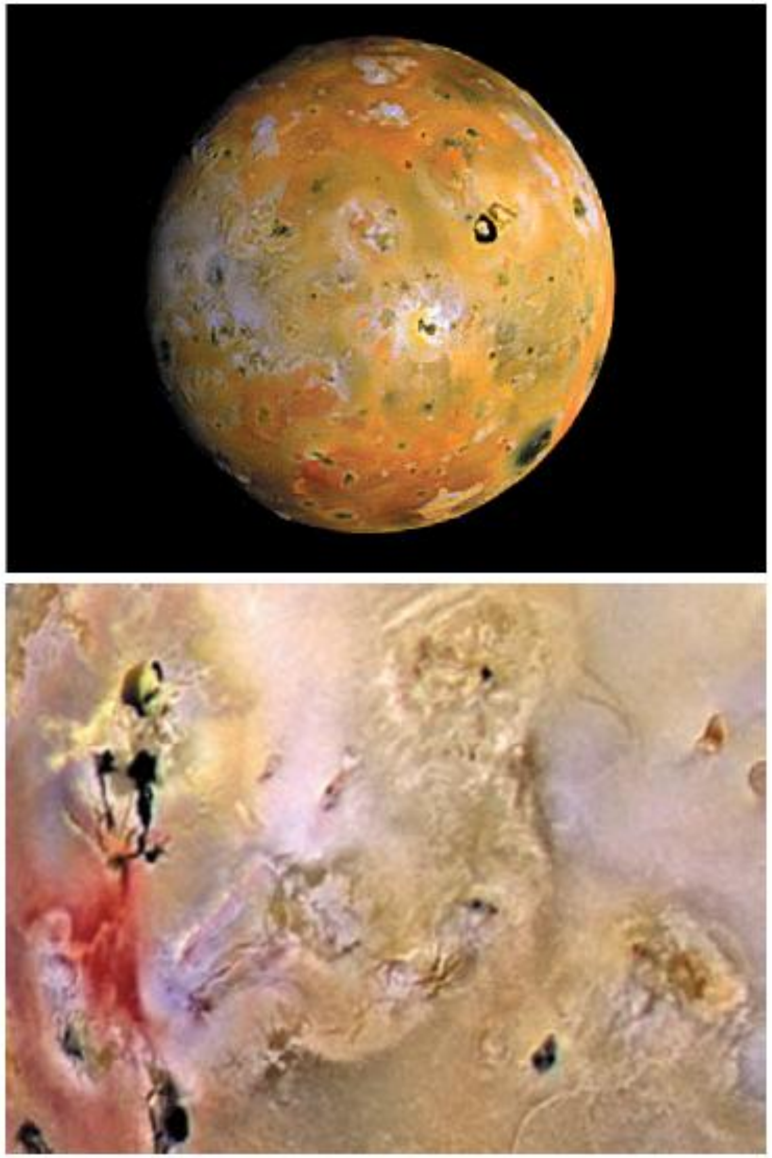
Gray level to colour transformations

The type of processing just illustrated uses the physical characteristics of a single band in a multispectral image to emphasize areas of interest. The same approach can help visualize events of interest in complex images in which the events are beyond human visual sensing capabilities



a
b

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

Several sensor images from the Galileo spacecraft (some in a spectral region not visible to human eye) were combined

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Full-Color Image Processing

Basics of full-colour image processing

Two categories:

(1) Process each component image individually and form composite processed colour image from the individually processed components

(2) Work with colour pixels directly; colour pixels really are vectors:

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

Note: the results of individual colour component processing are not always equivalent to direct processing in colour vector space

Processing is equivalent if:

(1) the process is applicable to both scalars and vectors;

(2) the operation on each component of a vector is independent of the other components

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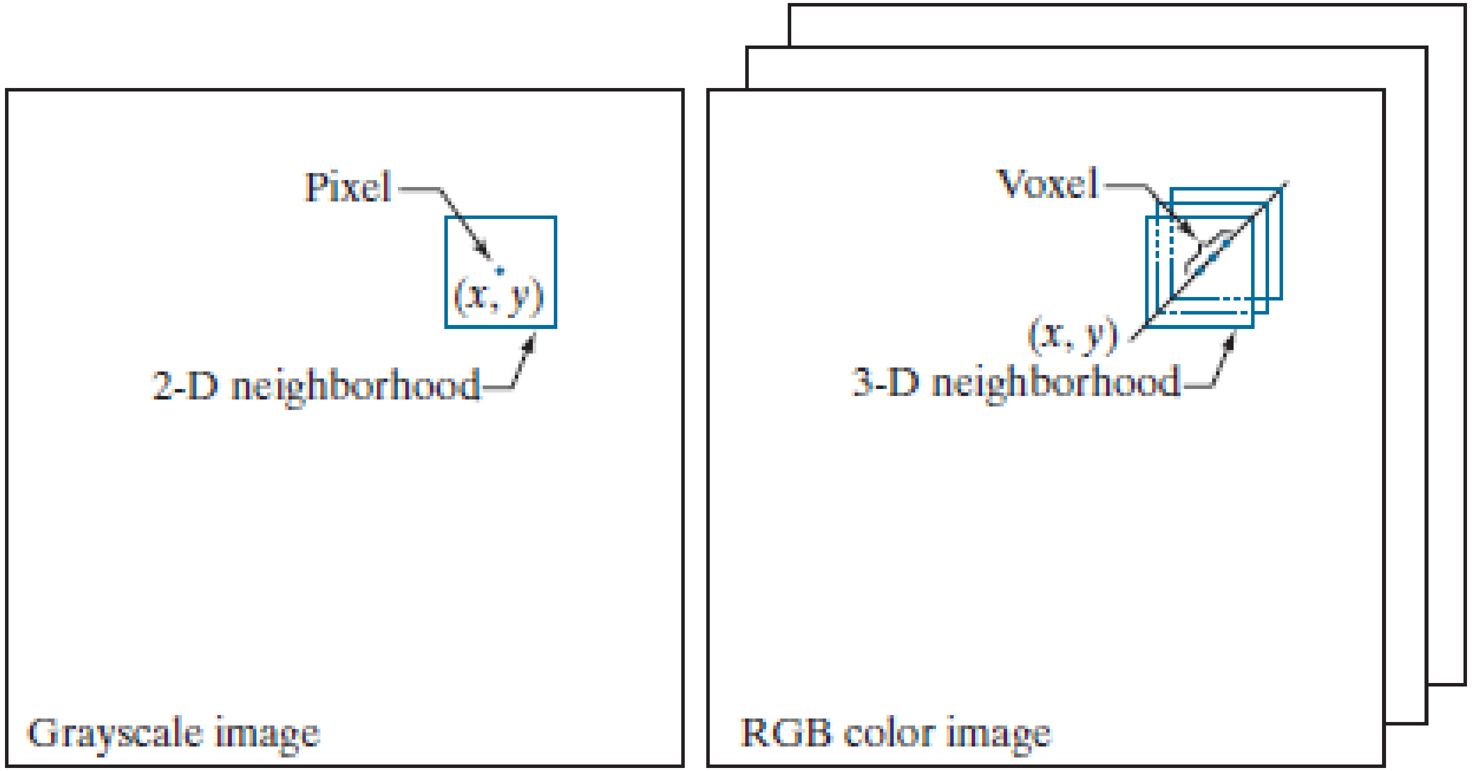
Full-Color Image Processing

Illustration: Neighbourhood averaging

a b

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



Result for per-colour-component and vector-based processing is equivalent.

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Full-Color Image Processing

Colour Transformations (Consider single model)

Formulation

Model colour transformations with $g(x, y) = T\,[\,f(x, y)\,]$

Pixel values here are triplets or quartets

Analogous to section 3.2 (gray-level), we now consider

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

Full-Color Image Processing

Some operations are better suited to specific models, but cost of converting between representations has to be considered as well! Example follows...

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Full-Color Image Processing

Suppose that we wish to modify the intensity of the image on previous page using

$g(x, y) = kf(x, y)$, **where** $0 < k < 1$

HSI colour space: $s_1 = r_1$, $s_2 = r_2$, $s_3 = kr_3$

RGB colour space: $s_i = kr_i, \ i = 1, 2, 3$

CMY colour space: $s_i = kr_i + (1 - k), \ i = 1, 2, 3$

Although the HSI transformation involves the fewest number of operations, the computations required to convert an RGB or CMY(K) image to the HSI space more than offsets the advantages of the simpler transformation

a b
c d e

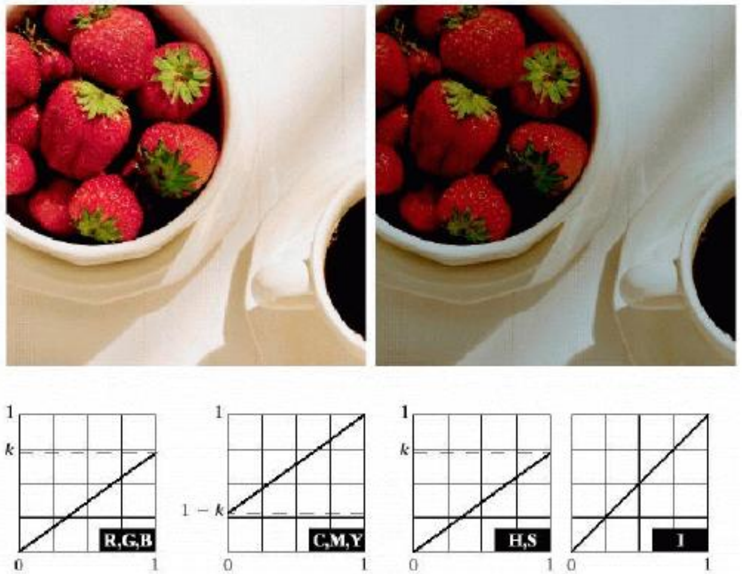

FIGURE 6.31 Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c)–(e) The required RGB, CMY, and HSI transformation functions. (Original image courtesy of MedData Interactive.)

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Full-Color Image Processing

Colour complements Complements: hues opposite one another on colour circle

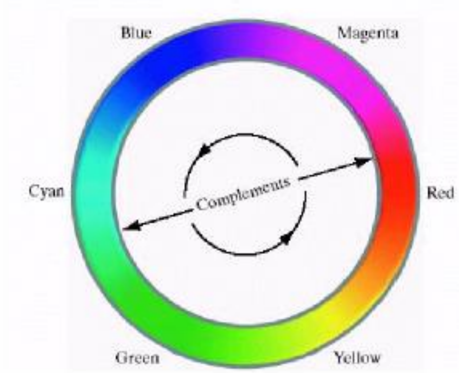
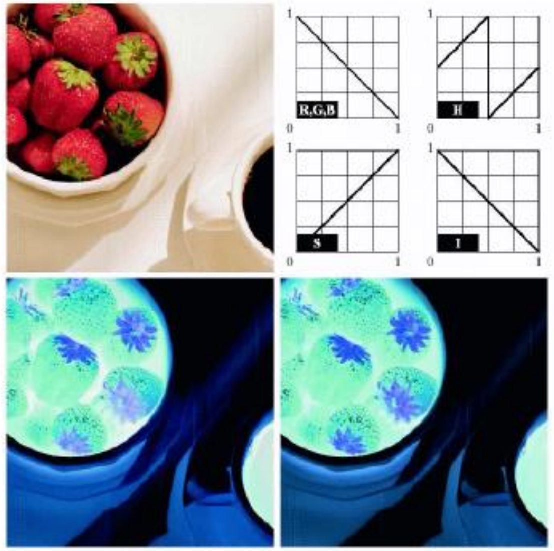


FIGURE 6.32 Complements on the color circle.

Useful for enhancing detail embedded in dark regions

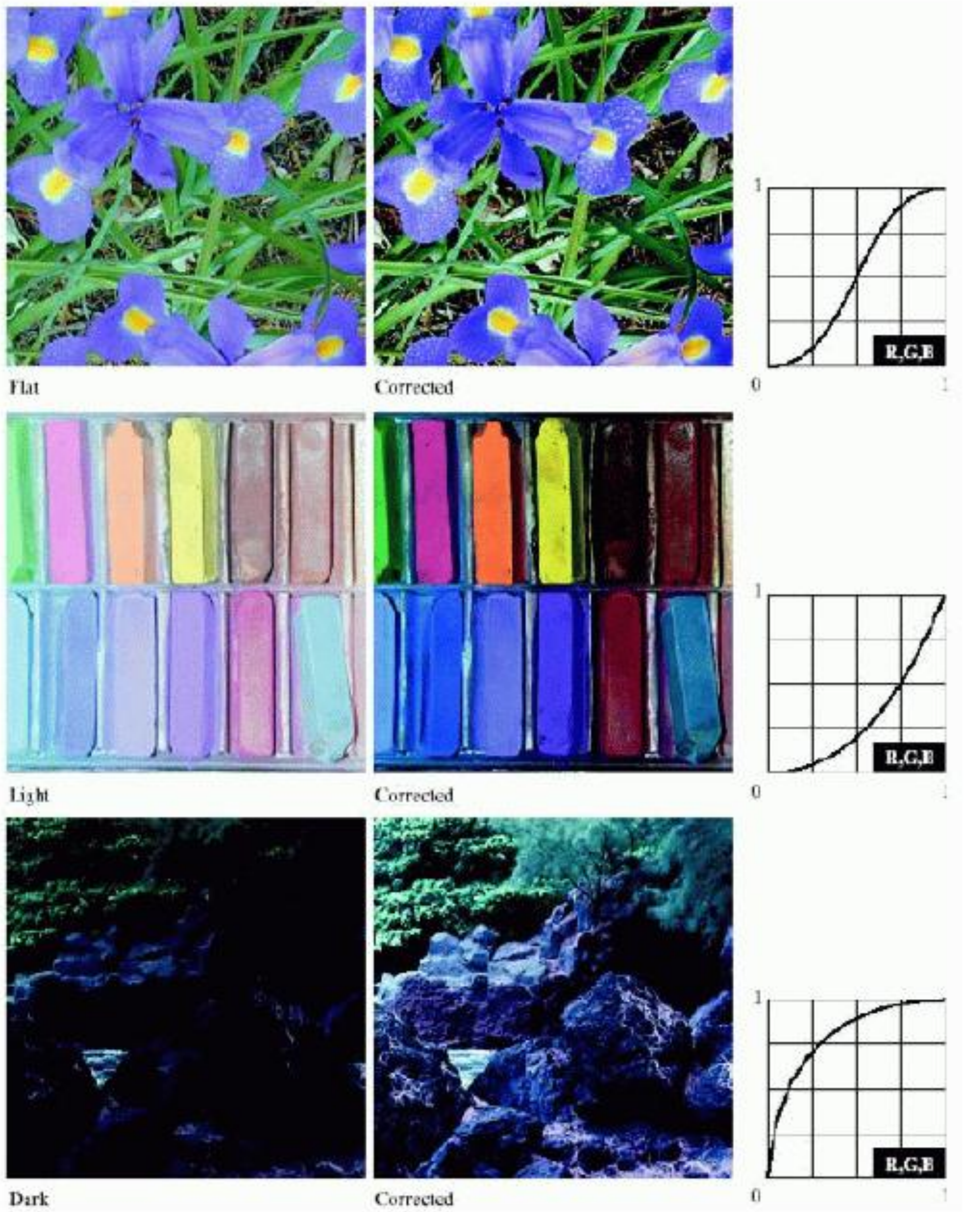


a b
c d

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.

Full-Color Image Processing

Example 6.9: Tonal corrections



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Full-Color Image Processing

Example 6.10: Colour balancing (CMYK images)

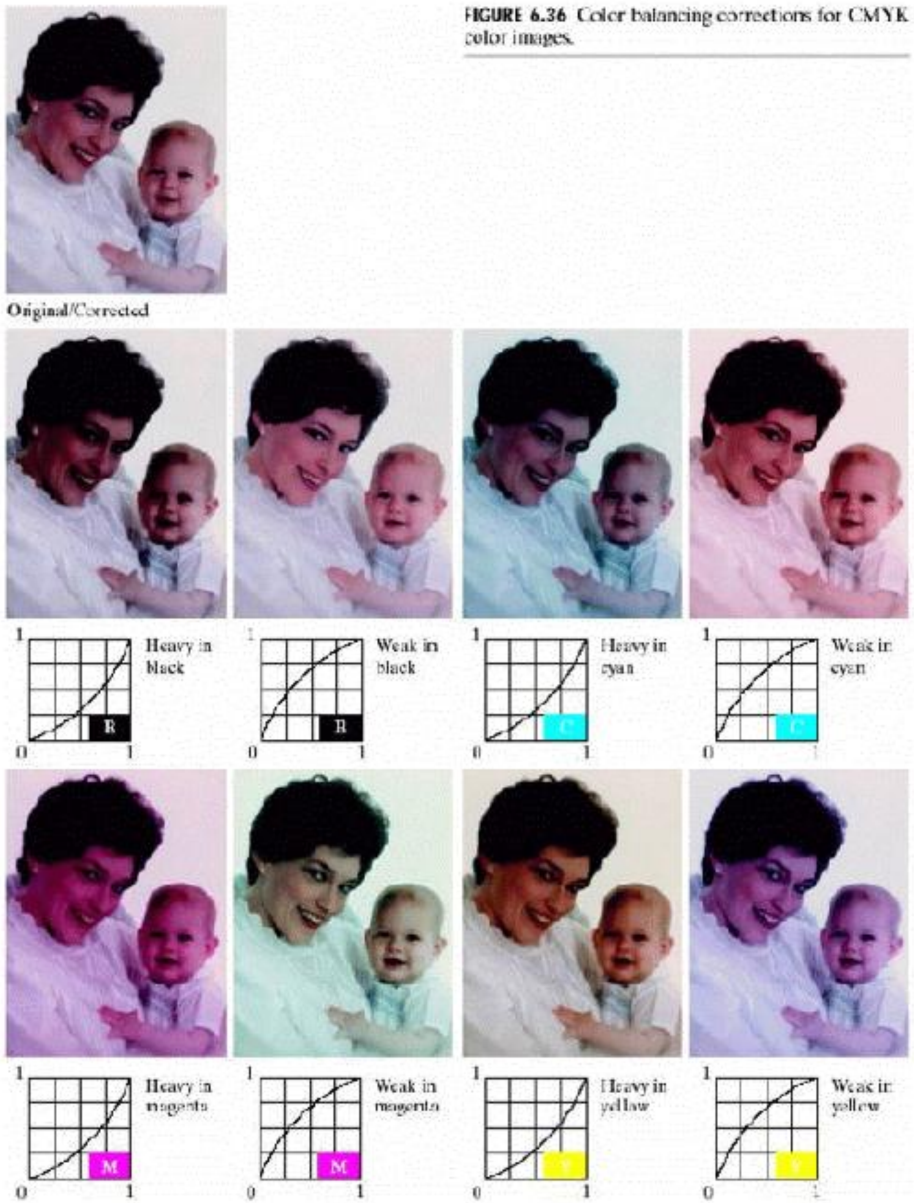

FIGURE 6.36 Color balancing corrections for CMYK color images.

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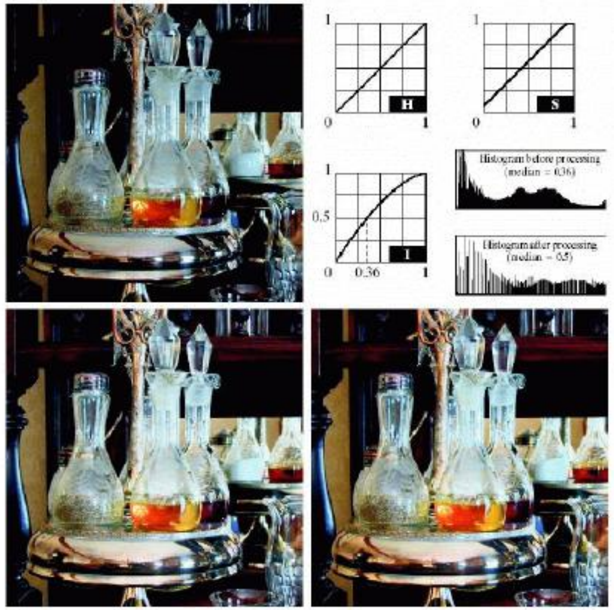
Full-Color Image Processing

Histogram processing

• Generally unwise to equalize colour components independently: results in erroneous colour • Rather spread colour intensities uniformly and leave the hues unchanged: HSI colour space well-suited for this approach

Example 6.11: Histogram equalization (HSI space)



a b
c d

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

(a) Original image (b)intensity transformation & histograms (c) image after histogram equalization (d) ↑ saturation after histogram equalization

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Full-Color Image Processing

Colour image smoothing: • **Smoothing by neigbourhood averaging can be performed using RGB colour vectors,** $\overline{\mathbf{c}}(x,y) = (1/K)\sum_{(x,y)\in S_{xy}} \mathbf{c}(x,y)$ **or can be carried out on a per-colour-plane basis**

$$\overline{\mathbf{c}}(x,y) = \begin{pmatrix} (1/K)\sum_{(x,y)\in S_{xy}} R(x,y) \\ (1/K)\sum_{(x,y)\in S_{xy}} G(x,y) \\ (1/K)\sum_{(x,y)\in S_{xy}} B(x,y) \end{pmatrix}$$

Example 6.12:

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.

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Full-Color Image Processing

Colour image sharpening

Similar to image smoothing, image sharpening can also be performed on a per-colour-plane basis (using the Laplacian),

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

Example 6.13:

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.

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Full-Color Image Processing

Colour segmentation Segmentation in RGB vector space

Given a set of representative colour points, calculate average colour ($\mathbf{a}$) and (if necessary) covariance matrix ($\mathbf{C}$)

Let $\mathbf{z}$ denote an arbitrary point in RGB space

Three similarity measures:

(1) Euclidean distance

$$\begin{aligned} D(\mathbf{z}, \mathbf{a}) &= ||\mathbf{z} - \mathbf{a}|| \\ &= \left[(\mathbf{z} - \mathbf{a})^T (\mathbf{z} - \mathbf{a}) \right]^{\frac{1}{2}} \\ &= \left[(z_R - a_R)^2 + (z_G - a_G)^2 + (z_B - a_B)^2 \right]^{\frac{1}{2}} \end{aligned}$$

$D(\mathbf{z}, \mathbf{a}) \leq D_0 \Rightarrow$ points within solid spherical region

(2) "Mahalanobis"-like distance

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

$D(\mathbf{z}, \mathbf{a}) \leq D_0 \Rightarrow$ points within solid ellipsoidal region

(3) Bounding box (computationally less expensive)
Centered at $\mathbf{a}$, dimensions proportional to standard deviations (σ_R, σ_G, σ_B) along colour axes

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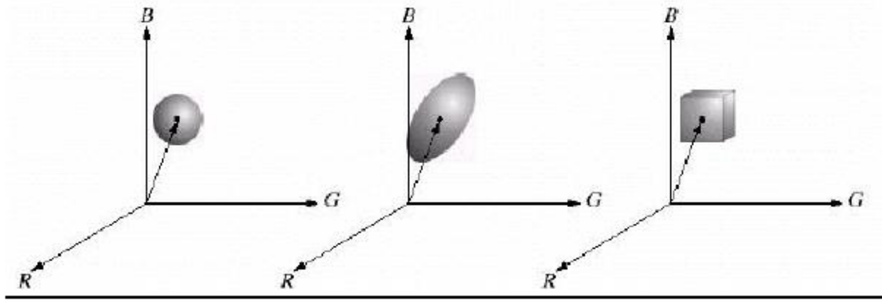
Full-Color Image Processing

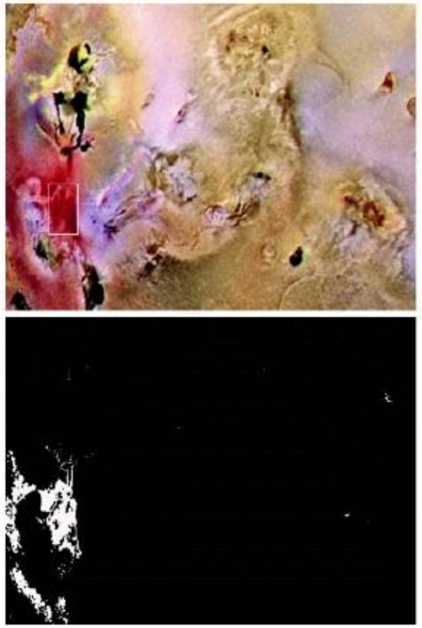
Colour segmentation Segmentation in RGB vector space



a b c

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

Example 6.15: Colour image segmentation in RGB 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).

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