Color Image Processing

Spectrum of White Light

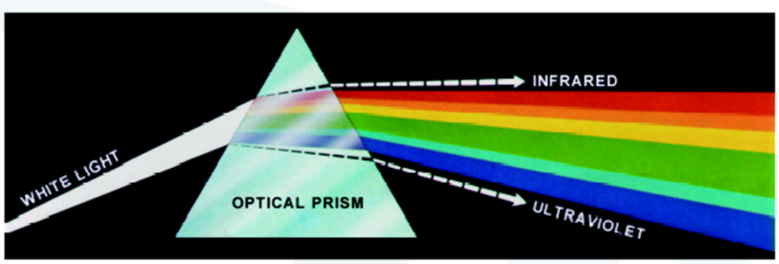
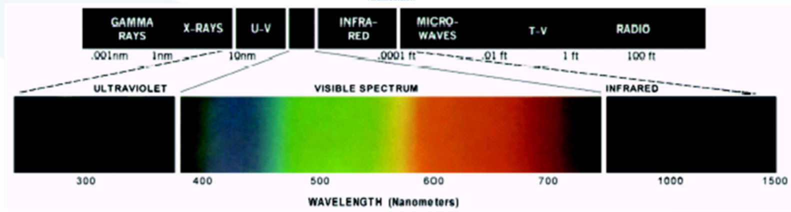


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

1666 Sir Isaac Newton, 24 year old, discovered white light spectrum.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Electromagnetic Spectrum



Visible light wavelength: from around 400 to 700 nm

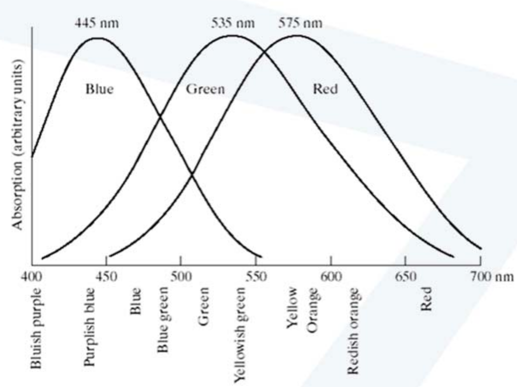
1. For an achromatic (monochrome) light source, there is only 1 attribute to describe the quality: intensity

2. For a chromatic light source, there are 3 attributes to describe the quality:
   Radiance = total amount of energy flow from a light source (Watts)
   Luminance = amount of energy received by an observer (lumens)
   Brightness = intensity

gsɒɒr9.1 'm'q' dct-ɪx.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Sensitivity of Cones in the Human Eye



6-7 millions cones in a human eye
- 65% sensitive to Red light
- 33% sensitive to Green light
- 2 % sensitive to Blue light

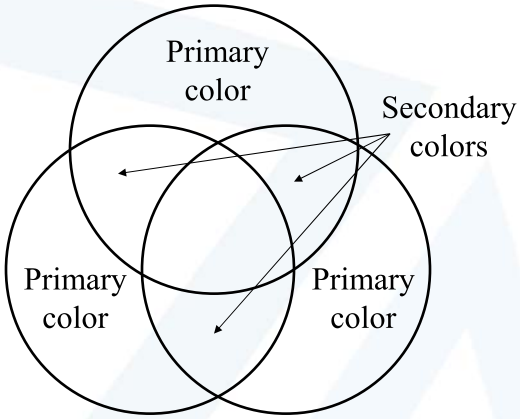
Primary colors:
Defined CIE in 1931
Red = 700 nm
Green = 546.1nm
Blue = 435.8 nm

CIE = Commission Internationale de l'Eclairage
(The International Commission on Illumination)

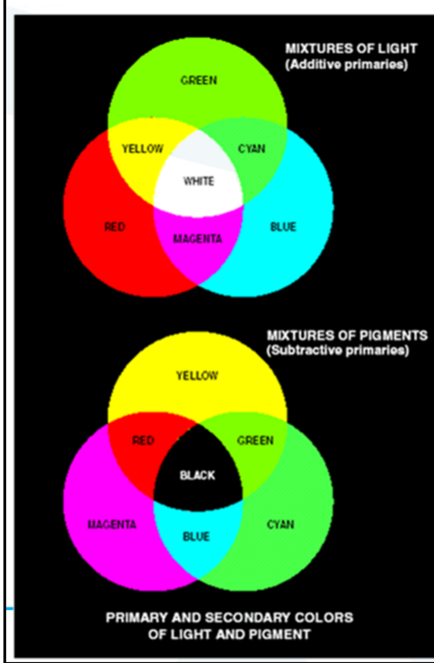
gsɒɒr9.1 'm'q' dct-ɪx.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Primary and Secondary Colors



Primary and Secondary Colors (cont.)



Additive primary colors: RGB use in the case of light sources such as color monitors

RGB add together to get white

Subtractive primary colors: CMY use in the case of pigments in printing devices

- yellow subtracts (absorbs) blue and transmits (reflects) other two primary color of light (green and red)

White subtracted by CMY to get Black

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Characterization

Hue: dominant color corresponding to a dominant wavelength of mixture light wave

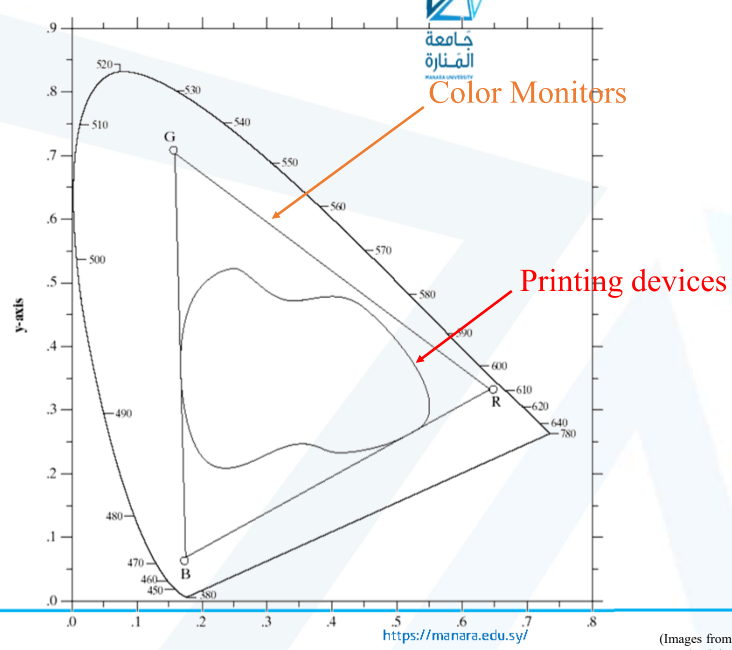
Saturation: Relative purity or amount of white light mixed with a hue (inversely proportional to amount of white light added)

Brightness: Intensity

Hue } Chromaticity
Saturation

amount of red (X), green (Y) and blue (Z) to form any particular color is called *tristimulus.*

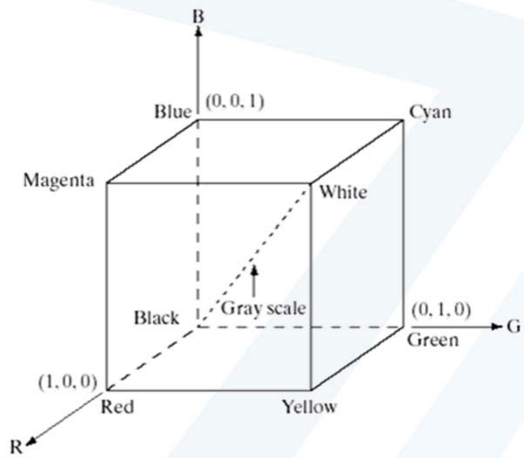
Color Gamut of Color Monitors and Printing Devices



(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

RGB Color Model

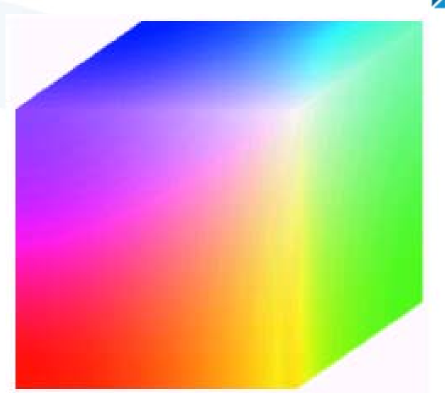
Purpose of color models: to facilitate the specification of colors in some standard



RGB color models:
- based on cartesian coordinate system

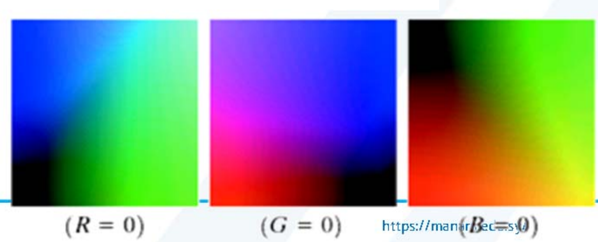
(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

RGB Color Cube



R = 8 bits
G = 8 bits
B = 8 bits

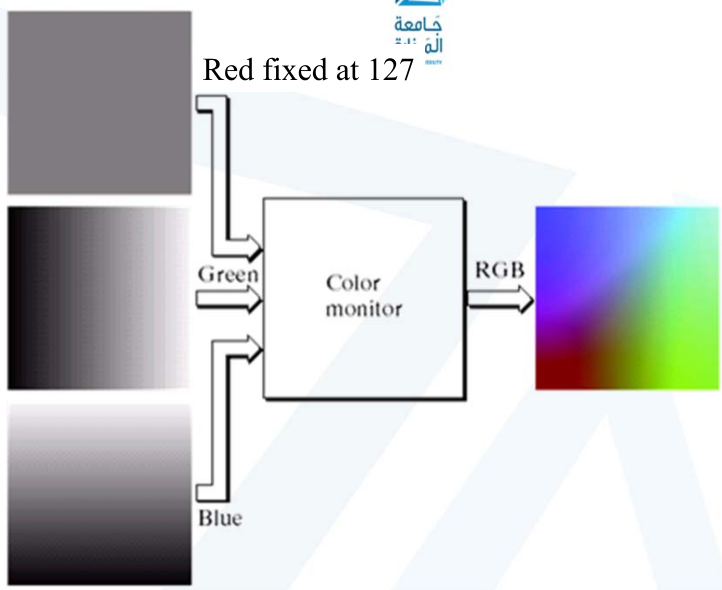
Color depth 24 bits = 16777216 colors



Hidden faces of the cube

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

RGB Color Model (cont.)

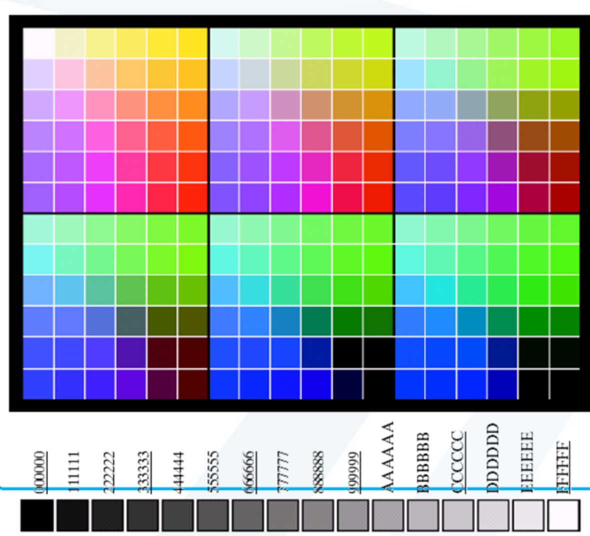


(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Safe RGB Colors

Safe RGB colors: a subset of RGB colors.

There are 216 colors common in most operating systems.



a
b

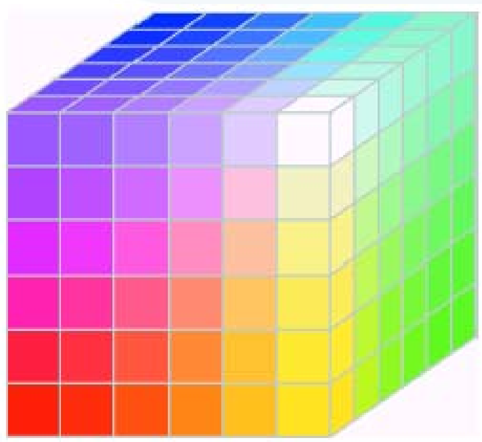
FIGURE 6.10 (a) The 216 safe RGB colors. (b) All the grays in the 256-color RGB system (grays that are part of the safe color group are shown underlined).

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

RGB Safe-color Cube

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.



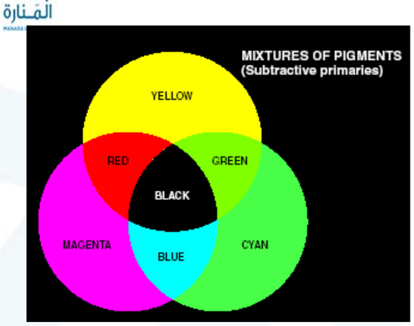
The RGB Cube is divided into 6 intervals on each axis to achieve the total $6^3 = 216$ common colors.

However, for 8 bit color representation, there are the total 256 colors. Therefore, the remaining 40 colors are left to OS.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

CMY and CMYK Color Models

C = Cyan
M = Magenta
Y = Yellow
K = Black



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

HSI Color Model

RGB, CMY models are not good for human interpreting

HSI Color model:

Hue: Dominant color

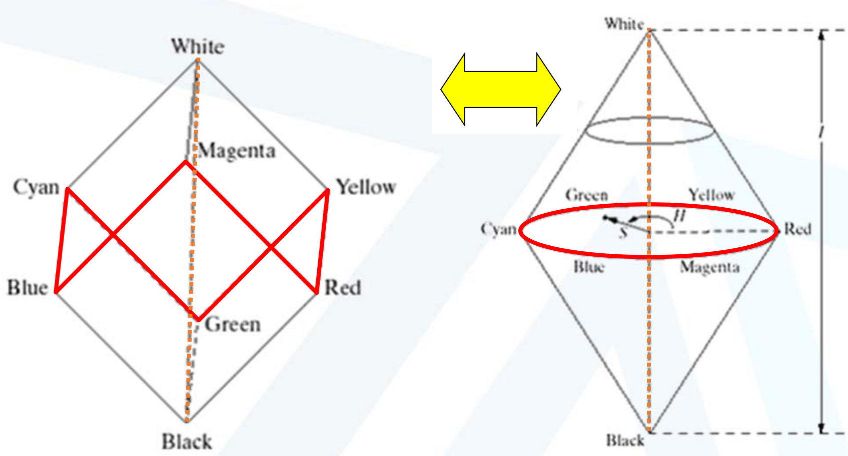
Saturation: Relative purity (inversely proportional to amount of white light added)

} Color carrying information

Intensity: Brightness

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

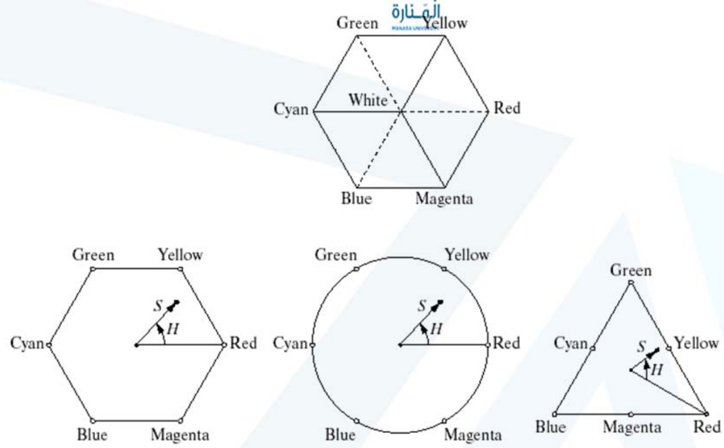
Relationship Between RGB and HSI Color Models



RGB HSI

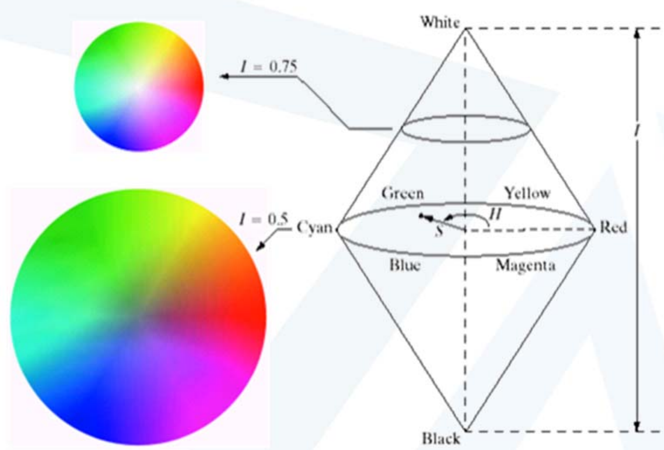
(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Hue and Saturation on Color Planes



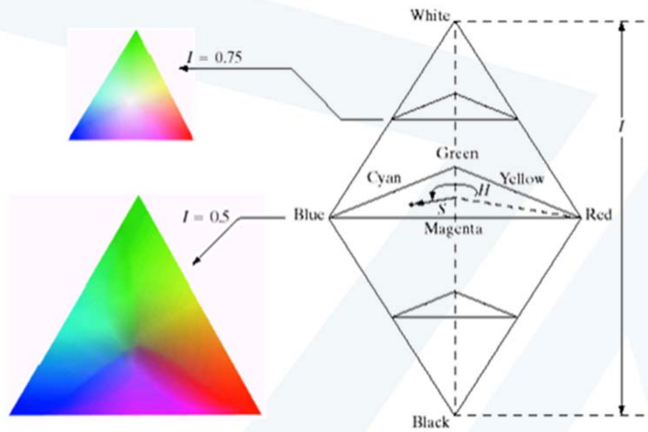
1. A dot is the plane is an arbitrary color
2. Hue is an angle from a red axis.
3. Saturation is a distance to the point.

HSI Color Model (cont.)



Intensity is given by a position on the vertical axis.

HSI Color Model

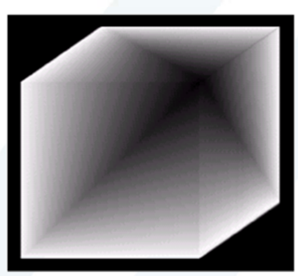


Intensity is given by a position on the vertical axis.

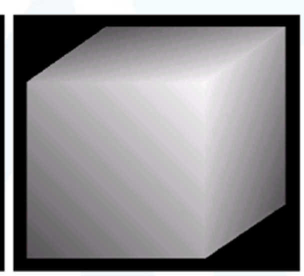
Example: HSI Components of RGB Cube

RGB Cube

Hue



Saturation



Intensity

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Converting Colors from RGB to HSI

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

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

$$S = 1 - \frac{3}{R+G+B}$$

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

Converting Colors from HSI to RGB

RG sector: $0 \le H < 120$

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

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

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

GB sector: $120 \le H < 240$

$$H = H - 120$$

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

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

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

BR sector: $240 \le H \le 360$

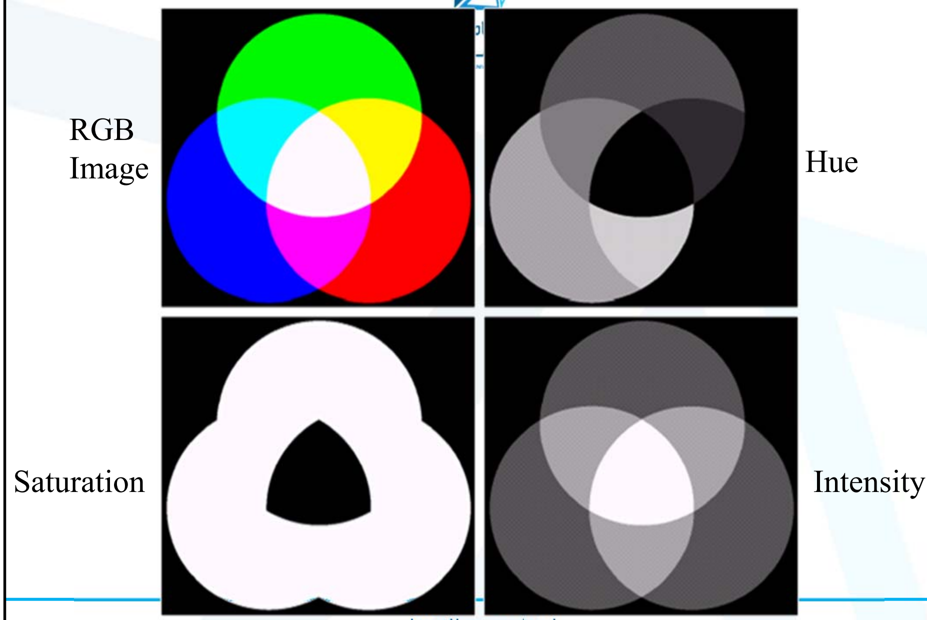
$$H = H - 240$$

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

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

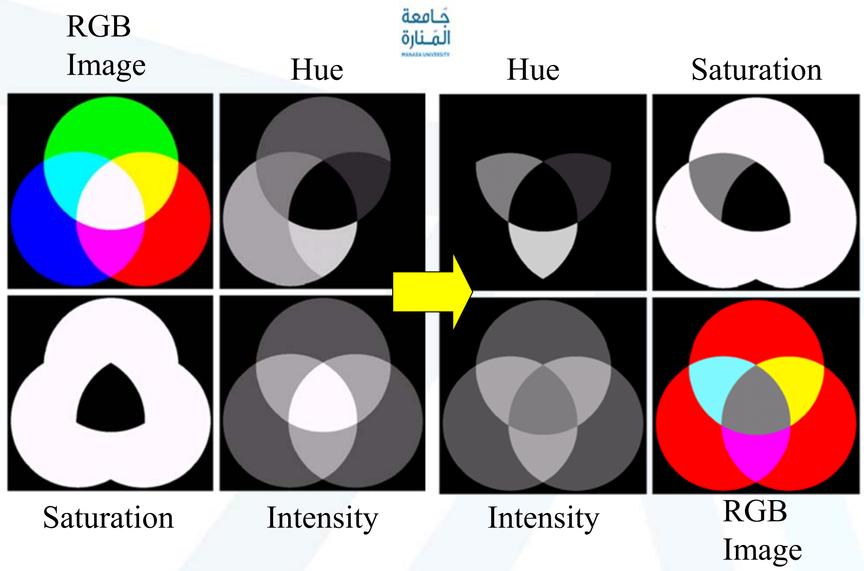
$$R = 1-(G+B)$$

Example: HSI Components of RGB Colors



(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Example: Manipulating HSI Components



(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Image Processing

There are 2 types of color image processes

1. **Pseudocolor image process**: Assigning colors to gray values based on a specific criterion. Gray scale images to be processed may be a single image or multiple images such as multispectral images

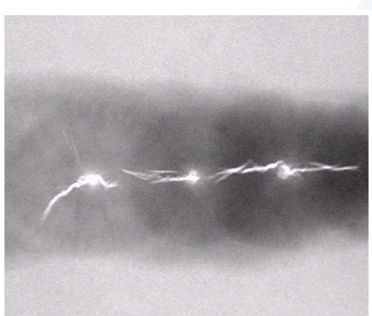
2. **Full color image process**: The process to manipulate real color images such as color photographs.

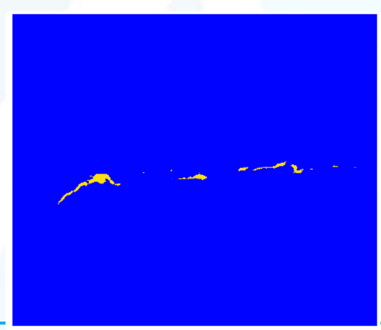
Pseudocolor Image Processing

Pseudo color = false color : In some case there is no "color" concept for a gray scale image but we can assign "false" colors to an image.

Why we need to assign colors to gray scale image?

Answer: Human can distinguish different colors better than different shades of gray.





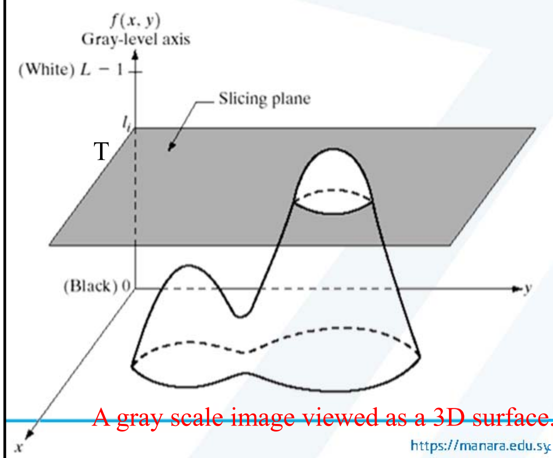
(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Intensity Slicing or Density Slicing

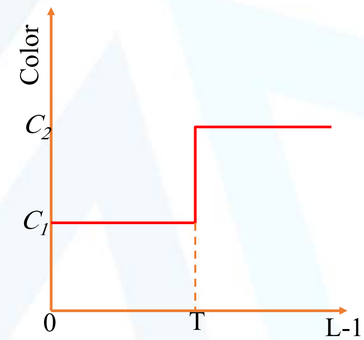
Formula:

$$g(x,y)=\begin{cases} C_1 & \text{if } f(x,y)\le T \\ C_2 & \text{if } f(x,y)>T \end{cases}$$

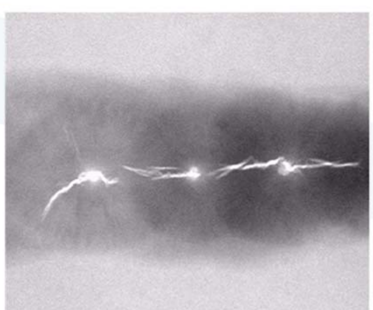
C_1 = Color No. 1
C_2 = Color No. 2



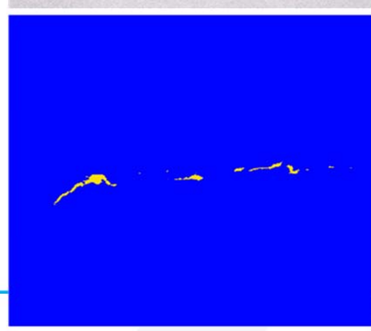
A gray scale image viewed as a 3D surface.



Intensity Slicing Example



An X-ray image of a weld with cracks



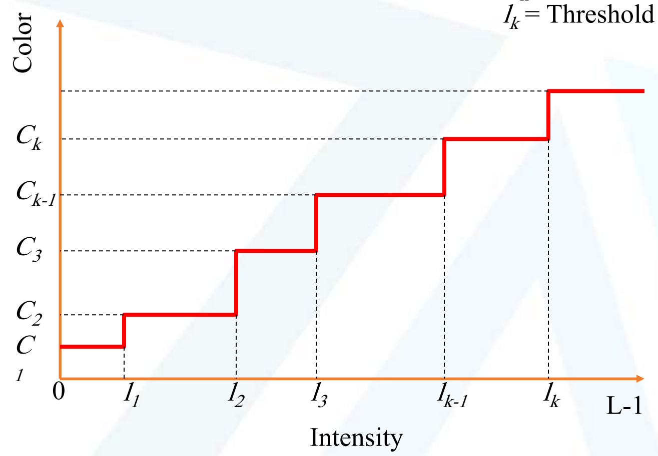
After assigning a yellow color to pixels with value 255 and a blue color to all other pixels.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Multi Level Intensity Slicing

$$g(x,y) = C_k \qquad \text{for } l_{k-1} < f(x,y) \le l_k$$

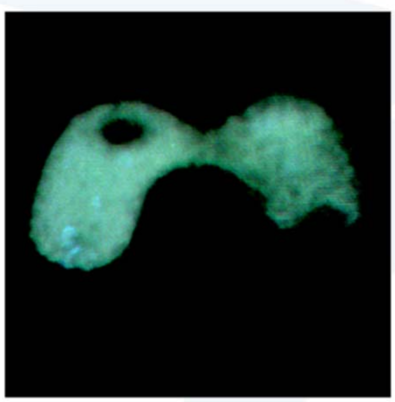
C_k = Color No. k
l_k = Threshold level k



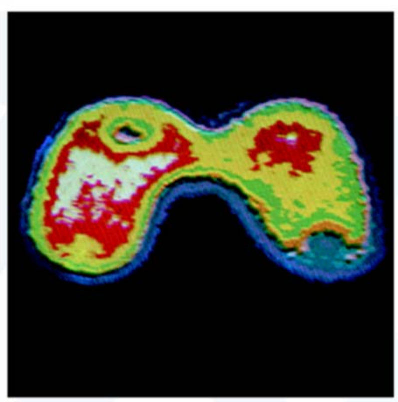
Multi Level Intensity Slicing Example

$$g(x,y) = C_k \qquad \text{for } l_{k-1} < f(x,y) \le l_k$$

C_k = Color No. k
l_k = Threshold level k



An X-ray image of the Picker Thyroid Phantom.

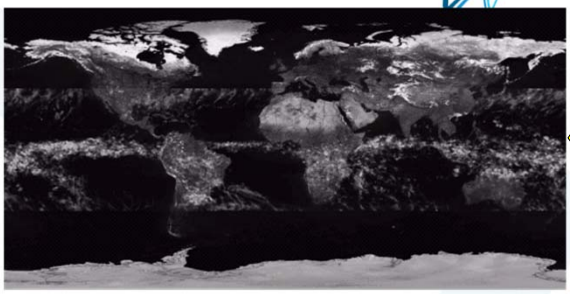


After density slicing into 8 colors

gsaor9.1 'm'q' dct-x.

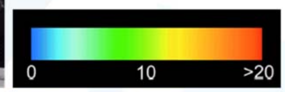
(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Coding Example

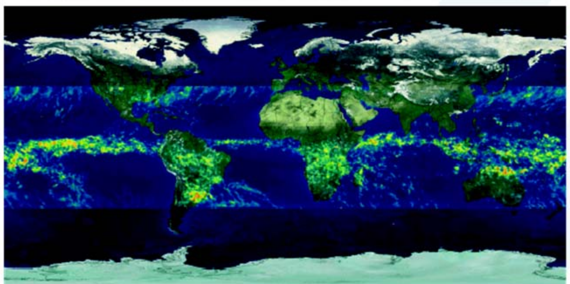


A unique color is assigned to each intensity value.

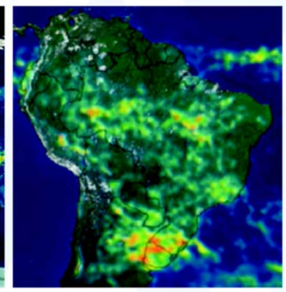
Gray-scale image of average monthly rainfall.



Color map



Color coded image



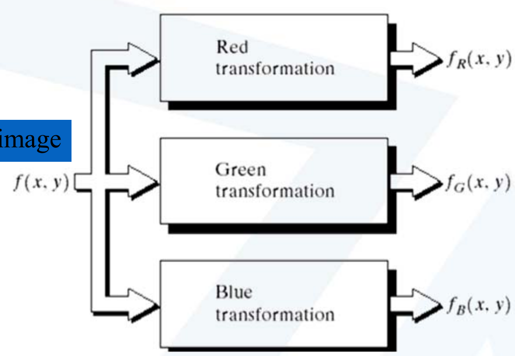
South America region

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Gray Level to Color Transformation

Assigning colors to gray levels based on specific mapping functions

Gray scale image



Red component

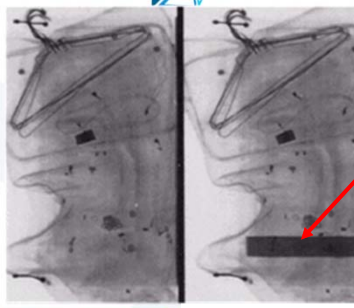
Green component

Blue component

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Gray Level to Color Transformation Example

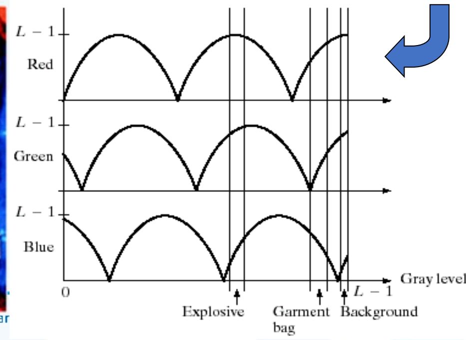
An X-ray image of a garment bag



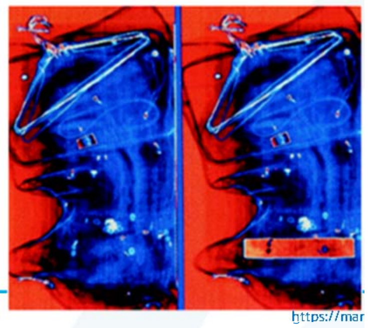
An X-ray image of a garment bag with a simulated explosive device

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Transformations

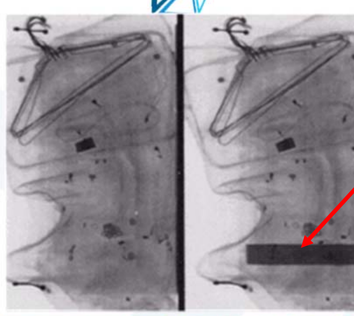


Color coded images



Gray Level to Color Transformation Example

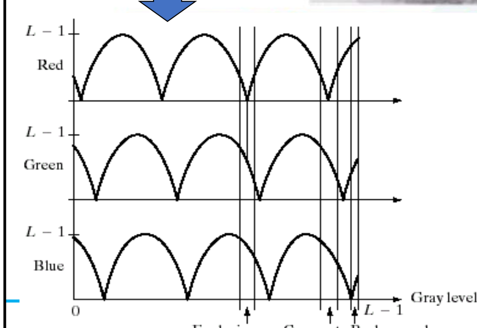
An X-ray image of a garment bag

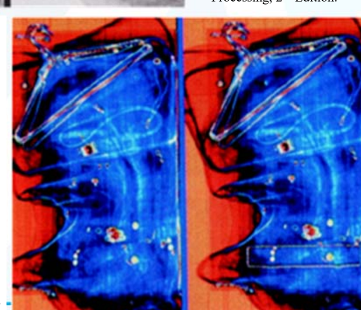


An X-ray image of a garment bag with a simulated explosive device

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Transformations

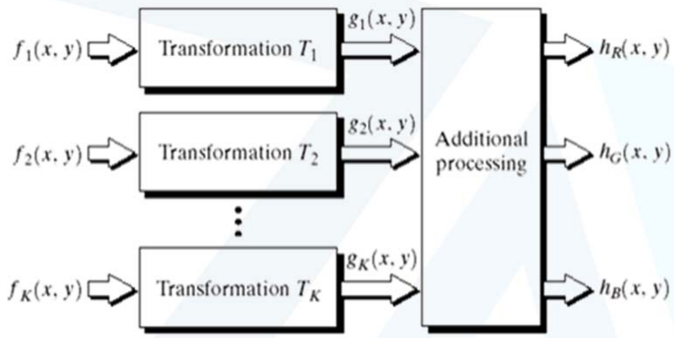




Color coded images

Pseudocolor Coding

Used in the case where there are many monochrome images such as multispectral satellite images.

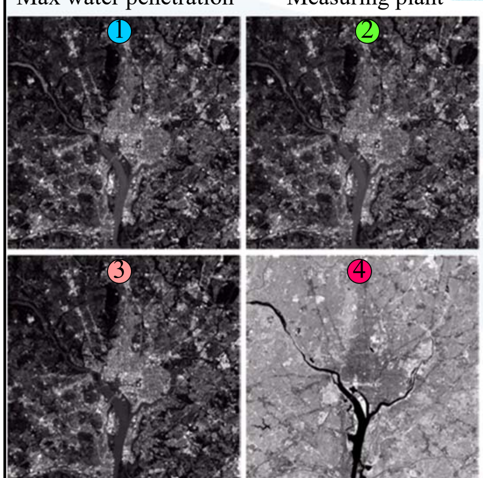


(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Pseudocolor Coding Example

Visible blue
λ= 0.45-0.52 µm
Max water penetration

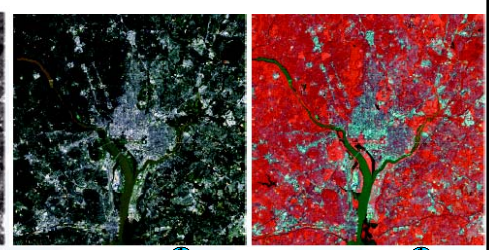
Visible green
λ= 0.52-0.60 µm
Measuring plant



Visible red
λ= 0.63-0.69 µm
Plant discrimination

Near infrared
λ= 0.76-0.90 µm
Biomass and shoreline mapping

Color composite images



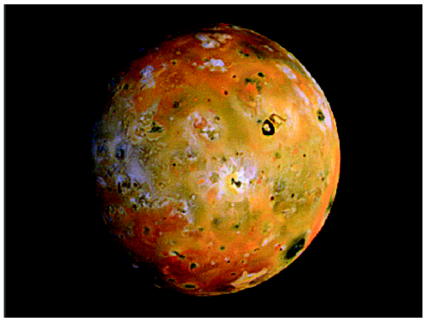
Red = 1
Green = 2
Blue = 3

Red = 1
Green = 2
Blue = 4

Washington D.C. area

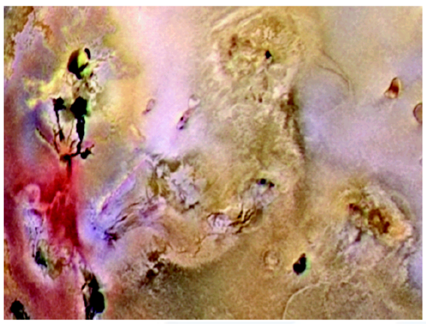
(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Pseudocolor Coding Example



Psuedocolor rendition of Jupiter moon Io

Yellow areas = older sulfur deposits.
Red areas = material ejected from active volcanoes.



A close-up

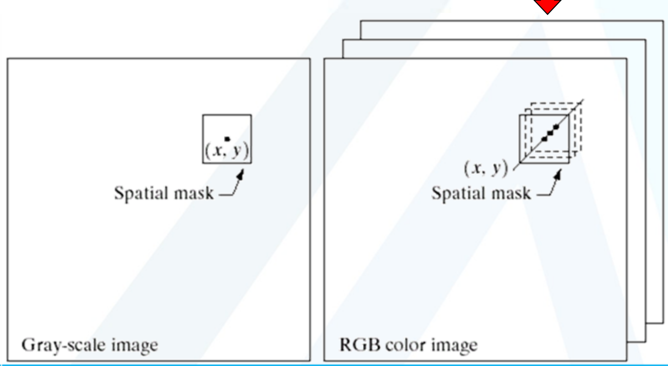
(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Basics of Full-Color Image Processing

2 Methods:

1. Per-color-component processing: process each component separately.
2. Vector processing: treat each pixel as a vector to be processed.

Example of per-color-component processing: smoothing an image
By smoothing each RGB component separately.



(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Example: *Full-Color Image and Variouis Color Space Components*

Color image

CMYK components

RGB components

HSI components

https://manara.edu.sy/

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Transformation

Use to transform colors to colors.

Formulation:

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

$f(x,y)$ = input color image, $g(x,y)$ = output color image
T = operation on f over a spatial neighborhood of (x,y)

When only data at one pixel is used in the transformation, we can express the transformation as:

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

Where r_i = color component of $f(x,y)$
s_i = color component of $g(x,y)$

For RGB images, $n = 3$

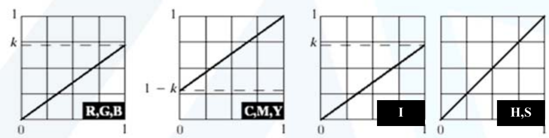
Example: Color Transformation

Formula for RGB:

$$s_R(x,y) = kr_R(x,y)$$
$$s_G(x,y) = kr_G(x,y)$$
$$s_B(x,y) = kr_B(x,y)$$

Formula for HSI:

$$s_I(x,y) = kr_I(x,y)$$



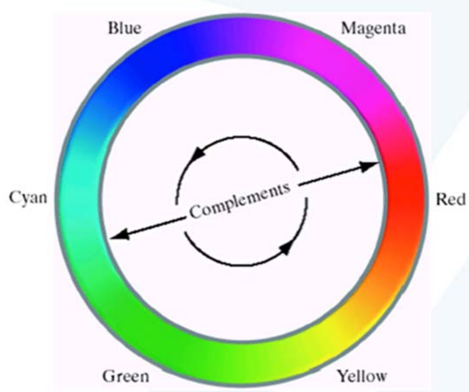
Formula for CMY:

$$s_C(x,y) = kr_C(x,y) + (1-k)$$
$$s_M(x,y) = kr_M(x,y) + (1-k)$$
$$s_Y(x,y) = kr_Y(x,y) + (1-k)$$

These 3 transformations give the same results.

Color Complements

Color complement replaces each color with its opposite color in the color circle of the Hue component. This operation is analogous to image negative in a gray scale image.



Color circle

Color Complement Transformation Example

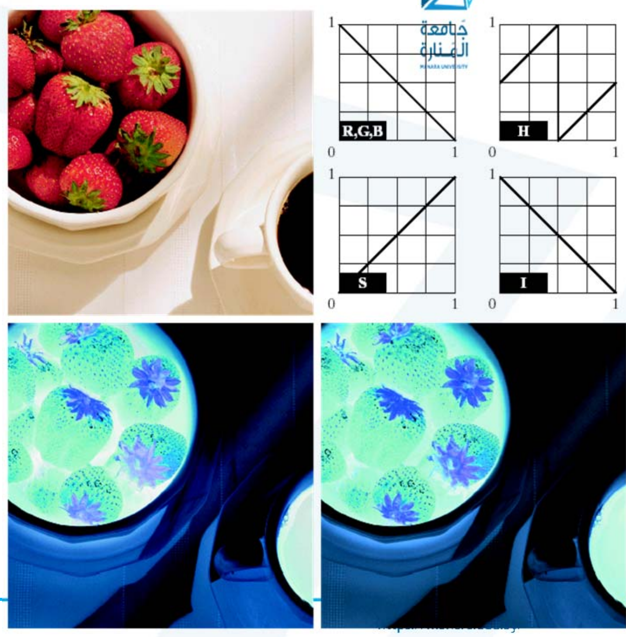


FIGURE 6.33 Color complement transformations. (a) Original image. (b) Complement transformation functions. (c) Complement of (a) based on the RGB mapping functions. (d) An approximation of the RGB complement using HSI transformations.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Slicing Transformation

We can perform "slicing" in color space: if the color of each pixel is far from a desired color more than threshold distance, we set that color to some specific color such as gray, otherwise we keep the original color unchanged.

$$s_i = \begin{cases} 0.5 & \text{if } \left[\left| r_j - a_j \right| > \frac{W}{2} \right]_{any\ 1 \le j \le n} \\ r_i & \text{otherwise} \end{cases}$$

$i = 1, 2, \ldots, n$

→ Set to gray

→ Keep the original color

or

$$s_i = \begin{cases} 0.5 & \text{if } \sum_{j=1}^{n} \left(r_j - a_j \right)^2 > R_0^2 \\ r_i & \text{otherwise} \end{cases}$$

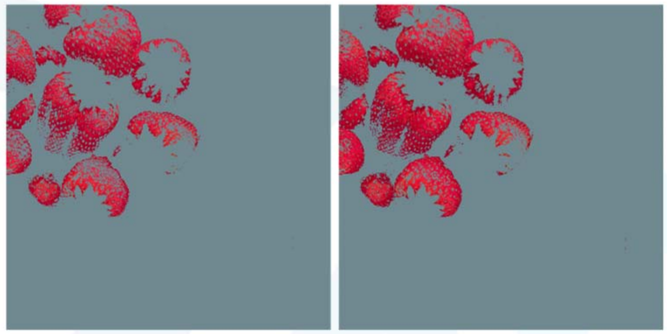
$i = 1, 2, \ldots, n$

→ Set to gray

→ Keep the original color

Color Slicing Transformation Example

After color slicing



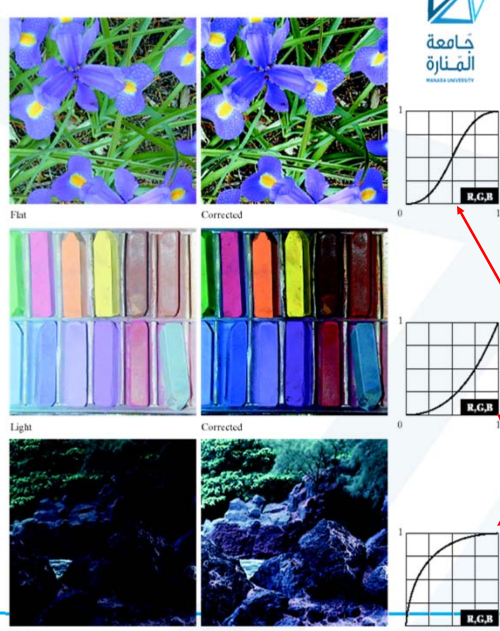
Original image

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).

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Tonal Correction Examples



In these examples, only brightness and contrast are adjusted while keeping color unchanged.

This can be done by using the same transformation for all RGB components.

Contrast enhancement

Power law transformations

https://manara.edu.sy

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Balancing Correction Examples

Color imbalance: primary color components in white area are not balance. We can measure these components by using a color spectrometer.

Color balancing can be performed by adjusting color components separately as seen in this slide.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Histogram Equalization of a Full-Color Image

❖ Histogram equalization of a color image can be performed by adjusting color intensity uniformly while leaving color unchanged.

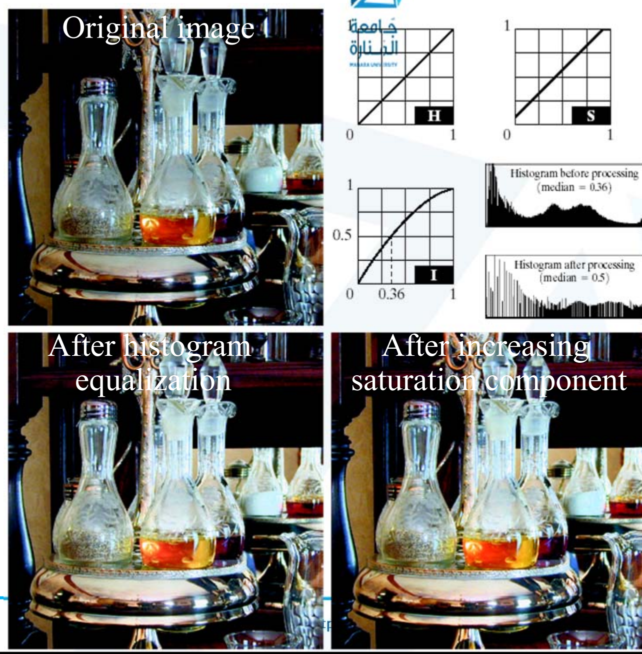
❖ The HSI model is suitable for histogram equalization where only Intensity (I) component is equalized.

$$s_k = T(r_k) = \sum_{j=0}^{k} p_r(r_j)$$

$$= \sum_{j=0}^{k} \frac{n_j}{N}$$

where r and s are intensity components of input and output color image.

Histogram Equalization of a Full-Color Image



a b
c d

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

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Image Smoothing

2 Methods:

1. Per-color-plane method: for RGB, CMY color models
   Smooth each color plane using moving averaging and then combine back to RGB

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

2. Smooth only Intensity component of a HSI image while leaving H and S unmodified.

Note: 2 methods are not equivalent.

Color Image Smoothing Example (cont.)

Color image

Red

Green

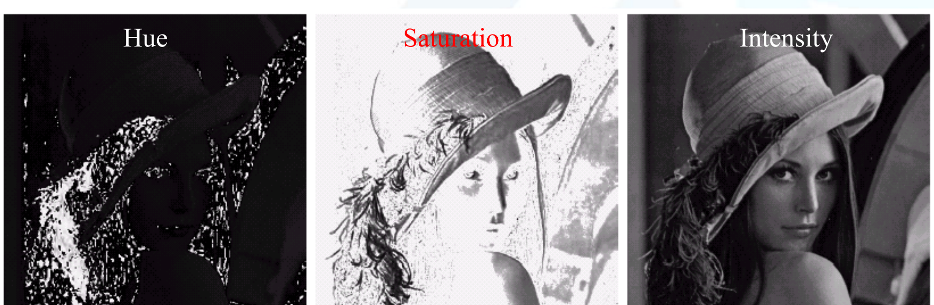
Blue

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Image Smoothing Example (cont.)

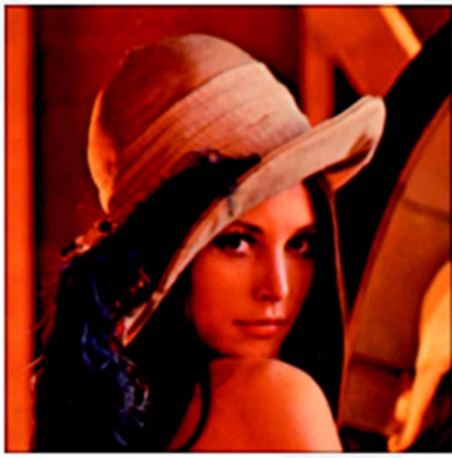
Color image

HSI Components



(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Image Smoothing Example (cont.)

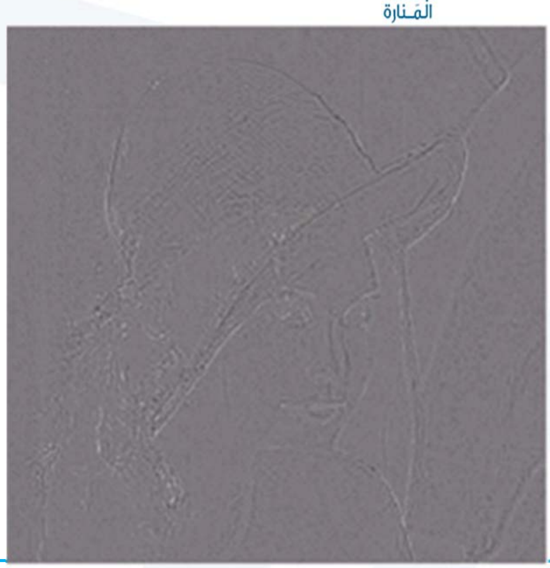


Smooth all RGB components

Smooth only I component of HSI (faster)

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Image Smoothing Example (cont.)



Difference between smoothed results from 2 methods in the previous slide.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Image Sharpening

We can do in the same manner as color image smoothing:

1. Per-color-plane method for RGB,CMY images
2. Sharpening only I component of a HSI image

Sharpening all RGB components　　Sharpening only I component of HSI

Color Image Sharpening Example (cont.)

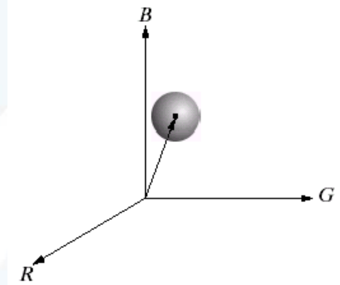
Difference between sharpened results from 2 methods in the previous slide.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Segmentation

2 Methods:

1. Segmented in HSI color space:
   A thresholding function based on color information in H and S Components. We rarely use I component for color image segmentation.



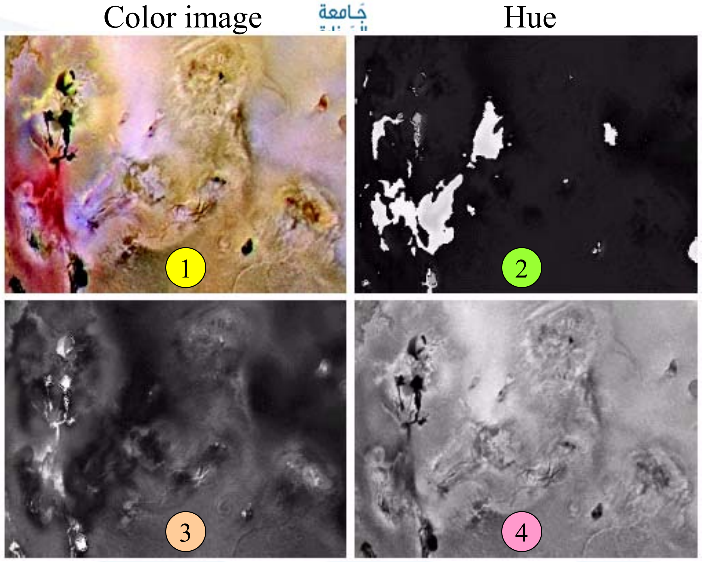
2. Segmentation in RGB vector space:
   A thresholding function based on distance in a color vector space.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Segmentation in HSI Color Space

Color image

Hue



Saturation

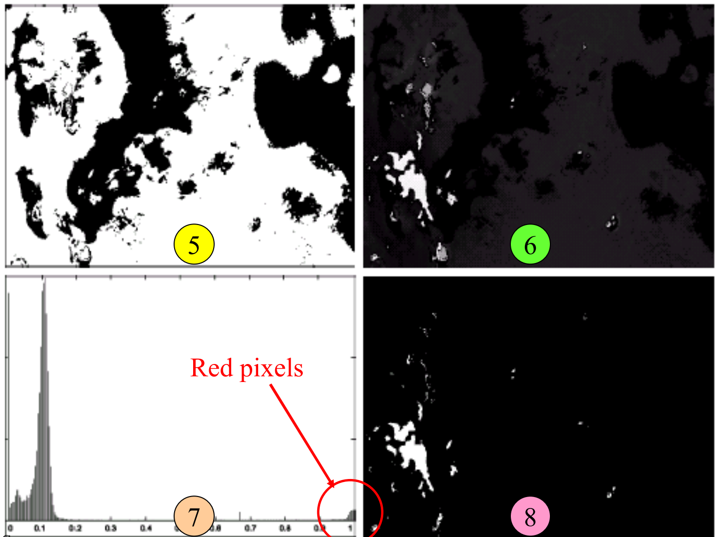
Intensity

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Segmentation in HSI Color Space (cont.)

Binary thresholding of S component with T = 10%

Product of (2) and (5)



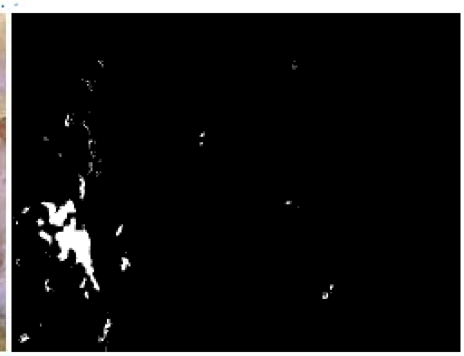
(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Histogram of (6)

Segmentation of red color pixels

Color Segmentation in HSI Color Space (cont.)

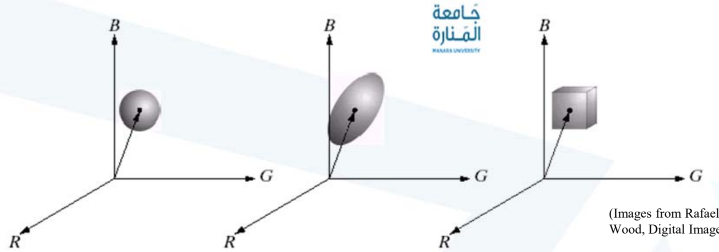
Color image



Segmented results of red pixels

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Segmentation in RGB Vector Space



a b c

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

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

1. Each point with (R,G,B) coordinate in the vector space represents one color.
2. Segmentation is based on distance thresholding in a vector space

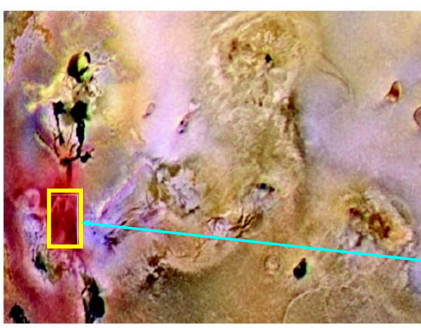
$$g(x,y) = \begin{cases} 1 & \text{if } D(\mathbf{c}(x,y),\mathbf{c}_T) \le T \\ 0 & \text{if } D(\mathbf{c}(x,y),\mathbf{c}_T) > T \end{cases}$$

$D(\mathbf{u},\mathbf{v})$ = distance function

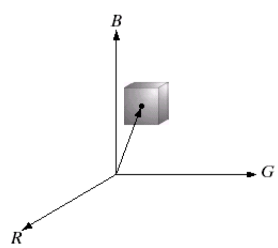
$\mathbf{c}_T$ = color to be segmented.

$\mathbf{c}(x,y)$ = RGB vector at pixel (x,y).

Example: Segmentation in RGB Vector Space

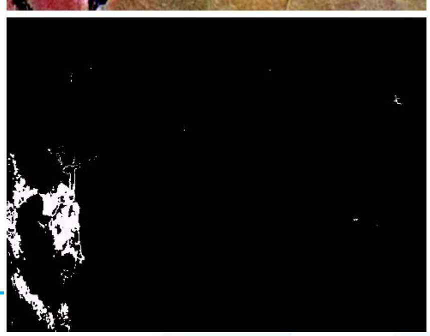


Color image



Reference color $\mathbf{c}_T$ to be segmented

$\mathbf{c}_T$ = average color of pixel in the box



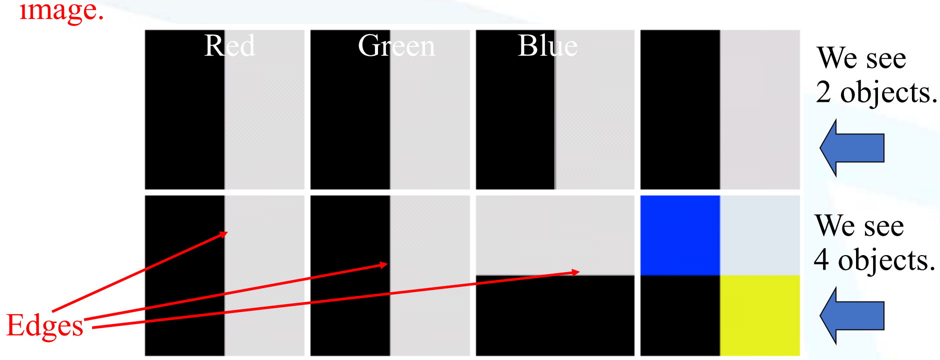
Results of segmentation in RGB vector space with Threshold value

T = 1.25 times the SD of R,G,B values In the box

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Gradient of a Color Image

Since gradient is define only for a scalar image, there is no concept of gradient for a color image. We can't compute gradient of each color component and combine the results to get the gradient of a color image.



(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Gradient of a Color Image (cont.)

One way to compute the maximum rate of change of a color image which is close to the meaning of gradient is to use the following formula: Gradient computed in RGB color space:

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

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

$$g_{xx}=\left|\frac{\partial R}{\partial x}\right|^2+\left|\frac{\partial G}{\partial x}\right|^2+\left|\frac{\partial B}{\partial x}\right|^2 \qquad g_{yy}=\left|\frac{\partial R}{\partial y}\right|^2+\left|\frac{\partial G}{\partial y}\right|^2+\left|\frac{\partial B}{\partial y}\right|^2$$

$$g_{xy}=\frac{\partial R}{\partial x}\frac{\partial R}{\partial y}+\frac{\partial G}{\partial x}\frac{\partial G}{\partial y}+\frac{\partial B}{\partial x}\frac{\partial B}{\partial y}$$

Gradient of a Color Image Example

Original image

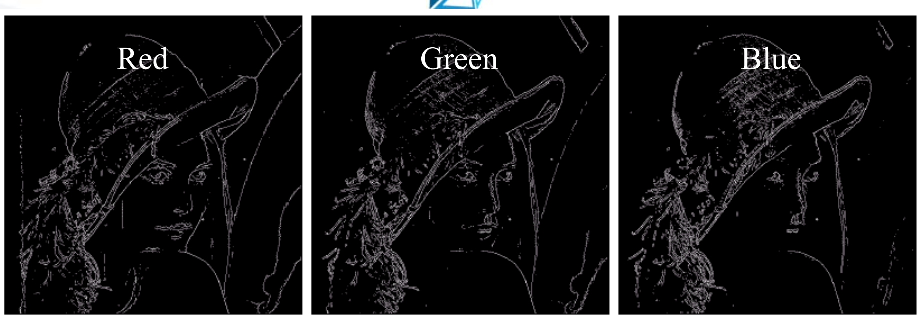
Obtained using the formula in the previous slide

Sum of gradients of each color component

Difference between 2 and 3

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Gradient of a Color Image Example

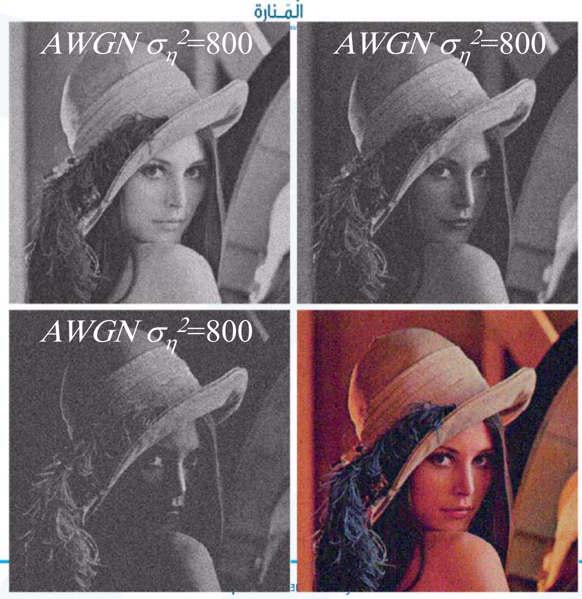


Gradients of each color component

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Noise in Color Images

Noise can corrupt each color component independently.



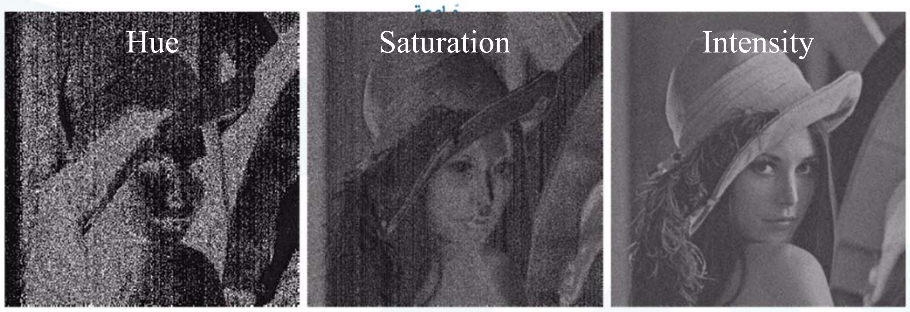
a b
c d

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).]

Noise is less noticeable in a color image

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Noise in Color Images



a b c

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

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Noise in Color Images

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.

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.

Color Image Compression

Original image

JPEG2000 File

After lossy compression with ratio 230:1

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.