Digital Image Processing
Chapter 6:
Color Image Processing
1666 Sir Isaac Newton, 24 year old, discovered white light 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

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

**FIGURE 2.1**
Simplified diagram of a cross section of the human eye.

Figure is from slides at Gonzalez/ Woods DIP book website (Chapter 2)
Two Types of Photoreceptors at Retina

- **Rods**
  - Long and thin
  - Large quantity (~ 100 million)
  - Provide *scotopic* vision (i.e., dim light vision or at low illumination)
  - Only extract luminance information and provide a general overall picture

- **Cones**
  - Short and thick, densely packed in fovea (center of retina)
  - Much fewer (~ 6.5 million) and less sensitive to light than rods
  - Provide *photopic* vision (i.e., bright light vision or at high illumination)
  - Help resolve fine details as each cone is connected to its own nerve end
  - Responsible for color vision

**Mesopic vision**
- provided at intermediate illumination by both rod and cones
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 = 546.1 nm
Blue = 435.8 nm

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

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

- **Luminance** (or intensity)
  - Independent of the luminance of surroundings

  \[ L(x, y) = \int_{0}^{\infty} I(x, y, \lambda)V(\lambda)d\lambda \]

  - \( I(x,y,\lambda) \) -- spatial light distribution
  - \( V(\lambda) \) -- relative luminous efficiency func. of visual system ~ bell shape
    (different for scotopic vs. photopic vision; highest for green wavelength, second for red, and least for blue)

- **Brightness**
  - Perceived luminance
  - Depends on surrounding luminance
• Example: visible digital watermark
  – How to make the watermark appears the same graylevel all over the image?

from IBM Watson web page
“Vatican Digital Library”
Look into Simultaneous Contrast Phenomenon

• Human perception more sensitive to luminance contrast than absolute luminance

• Weber’s Law: \[ \frac{|L_s - L_0|}{L_0} = \text{const} \]
  – Luminance of an object \( L_0 \) is set to be just noticeable from luminance of surround \( L_s \)
  – For just-noticeable luminance difference \( \Delta L \):
    \[ \frac{\Delta L}{L} \approx d(\log L) \approx 0.02 \text{ (const)} \]
    • equal increments in log luminance are perceived as equally different

• Empirical luminance-to-contrast models
  – Assume \( L \in [1, 100] \), and \( c \in [0, 100] \)
  – \( c = 50 \log_{10} L \) (logarithmic law, widely used)
  – \( c = 21.9 L^{1/3} \) (cubic root law)
• Visual system tends to undershoot or overshoot around the boundary of regions of different intensities

Demonstrates the perceived brightness is not a simple function of light intensity
**Color of Light**

- Perceived color depends on spectral content (wavelength composition)
  - e.g., 700nm ~ red.
  - “spectral color”
    - A light with very narrow bandwidth

- A light with equal energy in all visible bands appears white

“Spectrum” from [http://www.physics.sfasu.edu/astro/color.html](http://www.physics.sfasu.edu/astro/color.html)
Primary and Secondary Colors

Primary colors

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

White subtracted by CMY to get Black
• Any color can be reproduced by mixing an appropriate set of three primary colors  (Thomas Young, 1802)

• Three types of cones in human retina
  – Absorption response $S_i(\lambda)$ has peaks around 450nm (blue), 550nm (green), 620nm (yellow-green)
  – Color sensation depends on the spectral response $\{\alpha_1(C), \alpha_2(C), \alpha_3(C)\}$ rather than the complete light spectrum $C(\lambda)$

\[
\int S_1(\lambda) \, C(\lambda) \, d\lambda \quad \alpha_1(C)
\]
\[
\int S_2(\lambda) \, C(\lambda) \, d\lambda \quad \alpha_2(C)
\]
\[
\int S_3(\lambda) \, C(\lambda) \, d\lambda \quad \alpha_3(C)
\]

Identically perceived colors if $\alpha_i(C_1) = \alpha_i(C_2)$
Example: Seeing Yellow Without Yellow

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

Mix green and red light to obtain perception of yellow, without shining a single yellow photon.

"Seeing Yellow" figure is from B.Liu ELE330 S'01 lecture notes @ Princeton; R/G/B cone response is from slides at Gonzalez/ Woods DIP book website
• Mixture of three primaries:  \( C = \text{Sum}(\beta_k P_k(\lambda)) \)

• To match a given color \( C_1 \)
  – adjust \( \beta_k \) such that \( \alpha_i(C_1) = \alpha_i(C), \ i = 1,2,3. \)

• Tristimulus values \( T_k(C) \)
  – \( T_k(C) = \beta_k / w_k \)
  \[ w_k - \text{the amount of } k^{th} \text{ primary to match the reference white} \]

• Chromaticity \( t_k = T_k / (T_1+T_2+T_3) \)
  – \( t_1+t_2+t_3 = 1 \)
  – visualize \( (t_1, \ t_2) \) to obtain chromaticity diagram
**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

\[
\text{Hue} \quad \begin{array}{c}
\text{Saturation} \\
\text{Brightness}
\end{array} \quad \text{Chromaticity}
\]

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

- **Value of Brightness** (perceived luminance)
- **Chrominance**
  - **Hue**
    - specify color tone (redness, greenness, etc.)
    - depend on peak wavelength
  - **Saturation**
    - describe how pure the color is
    - depend on the spread (bandwidth) of light spectrum
    - reflect how much white light is added

- **RGB Û HSV Conversion ~ nonlinear**

HSV circular cone is from online documentation of Matlab image processing toolbox

Trichromatic coefficients:

\[ x = \frac{X}{X + Y + Z} \]

\[ y = \frac{Y}{X + Y + Z} \]

\[ z = \frac{Z}{X + Y + Z} \]

\[ x + y + z = 1 \]

Points on the boundary are fully saturated colors

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.)
Color Gamut of Color Monitors and Printing Devices

Color Monitors

Printing devices

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.)
CIE Color Coordinates (cont’d)

• CIE XYZ system

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
0.490 & 0.310 & 0.200 \\
0.177 & 0.813 & 0.011 \\
0.000 & 0.010 & 0.990
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

– hypothetical primary sources to yield all-positive spectral tristimulus values
– \(Y\) ~ luminance

• Color gamut of 3 primaries
  – Colors on line C1 and C2 can be produced by linear mixture of the two
  – Colors inside the triangle gamut can be reproduced by three primaries

From http://www.cs.rit.edu/~ncs/color/t_chroma.html
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.)

Red fixed at 127
Safe RGB Colors

Safe RGB colors: a subset of RGB colors.
There are 216 colors common in most operating systems.

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.)
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.
CMY and CMYK Color Models

- Primary colors for pigment
  - Defined as one that subtracts/absorbs a primary color of light & reflects the other two
- CMY – Cyan, Magenta, Yellow
  - Complementary to RGB
  - Proper mix of them produces black

$$C = \text{Cyan}$$
$$M = \text{Magenta}$$
$$Y = \text{Yellow}$$
$$K = \text{Black}$$
**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)

Intensity: Brightness

Color carrying information

(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.)
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.
Intensity is given by a position on the vertical axis.
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

\[
H = \begin{cases} 
\theta & \text{if } B \leq G \\
360 - \theta & \text{if } B > G 
\end{cases}
\]

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

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

\[
I = \frac{1}{3} (R + G + B)
\]
**Converting Colors from HSI to RGB**

**RG sector:** \( 0 \leq H < 120 \)

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

\[
B = I(1 - S)
\]

\[
G = 1 - (R + B)
\]

**GB sector:** \( 120 \leq H < 240 \)

\[
H = H - 120
\]

\[
R = I(1 - S)
\]

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

\[
B = 1 - (R + G)
\]

**BR sector:** \( 240 \leq H \leq 360 \)

\[
H = H - 240
\]

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

\[
G = I(1 - S)
\]

\[
R = 1 - (G + B)
\]
Example: HSI Components of RGB Colors

(Hues, Saturation, Intensities)

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing. 2nd Edition.)
Example: Manipulating HSI Components

RGB Image  Hue  Hue  Saturation
Saturation  Intensity  Intensity  RGB Image

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.)
**Color Coordinates Used in TV Transmission**

- Facilitate sending color video via 6MHz mono TV channel

- **YIQ for NTSC** (National Television Systems Committee) transmission system
  - Use receiver primary system \((R_N, G_N, B_N)\) as TV receivers standard
  - Transmission system use \((Y, I, Q)\) color coordinate
    - \(Y\) ~ luminance, \(I\) & \(Q\) ~ chrominance
    - \(I\) & \(Q\) are transmitted in through orthogonal carriers at the same freq.

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} =
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
0.596 & -0.275 & -0.321 \\
0.212 & -0.523 & 0.311
\end{bmatrix}
\begin{bmatrix}
R_N \\
G_N \\
B_N
\end{bmatrix}.
\]

\[
\begin{bmatrix}
Y \\
U \\
V
\end{bmatrix} =
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
-0.147 & -0.289 & 0.436 \\
0.615 & -0.515 & -0.100
\end{bmatrix}
\begin{bmatrix}
R_P \\
G_P \\
B_P
\end{bmatrix}.
\]

- **YUV** (YCbCr) for PAL and digital video
  - \(Y\) ~ luminance, \(Cb\) and \(Cr\) ~ chrominance
Color Coordinates

- RGB of CIE
- XYZ of CIE
- RGB of NTSC
- YIQ of NTSC
- YUV (YCbCr)
- CMY
Examples

RGB

HSV

YUV
Examples

A colour image

Red component
Green component
Blue component

RGB

Hue
Saturation
Value

HSV

Y
I
Q

YIQ
Summary

• Monochrome human vision
  – visual properties: luminance vs. brightness, etc.
  – image fidelity criteria
• Color
  – Color representations and three primary colors
  – Color coordinates
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.
**Intensity Slicing or Density Slicing**

Formula:

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

\( C_1 = \text{Color No. 1} \)

\( C_2 = \text{Color No. 2} \)

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

\[ g(x, y) = C_k \quad \text{for } l_{k-1} < f(x, y) \leq l_k \]

<table>
<thead>
<tr>
<th>grey level:</th>
<th>0–63</th>
<th>64–127</th>
<th>128–191</th>
<th>192–255</th>
</tr>
</thead>
<tbody>
<tr>
<td>colour:</td>
<td>blue</td>
<td>magenta</td>
<td>green</td>
<td>red</td>
</tr>
</tbody>
</table>

\[ C_k = \text{Color No. } k \]
\[ l_k = \text{Threshold level } k \]
Multi Level Intensity Slicing Example

\[ g(x, y) = C_k \quad \text{for} \quad l_{k-1} < f(x, y) \leq l_k \]

\( C_k = \text{Color No. } k \)

\( l_k = \text{Threshold level } k \)

An X-ray image of the Picker Thyroid Phantom.

After density slicing into 8 colors

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.)
Gray-scale image of average monthly rainfall.

Color coded image

South America region

Gray Level to Color Transformation

Assigning colors to gray levels based on specific mapping functions

Gray scale image $f(x, y)$

- **Red transformation** $f_R(x, y)$
  - Red component

- **Green transformation** $f_G(x, y)$
  - Green component

- **Blue transformation** $f_B(x, y)$
  - 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 with a simulated explosive device

Color coded images

Transformations

(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

Transformations

Color coded images

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

(Transformations from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.)
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.)
### Table 1.1
Thematic bands in NASA’s LANDSAT satellite.

<table>
<thead>
<tr>
<th>Band No.</th>
<th>Name</th>
<th>Wavelength (μm)</th>
<th>Characteristics and Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Visible blue</td>
<td>0.45–0.52</td>
<td>Maximum water penetration</td>
</tr>
<tr>
<td>2</td>
<td>Visible green</td>
<td>0.52–0.60</td>
<td>Good for measuring plant vigor</td>
</tr>
<tr>
<td>3</td>
<td>Visible red</td>
<td>0.63–0.69</td>
<td>Vegetation discrimination</td>
</tr>
<tr>
<td>4</td>
<td>Near infrared</td>
<td>0.76–0.90</td>
<td>Biomass and shoreline mapping</td>
</tr>
<tr>
<td>5</td>
<td>Middle infrared</td>
<td>1.55–1.75</td>
<td>Moisture content of soil and vegetation</td>
</tr>
<tr>
<td>6</td>
<td>Thermal infrared</td>
<td>10.4–12.5</td>
<td>Soil moisture; thermal mapping</td>
</tr>
<tr>
<td>7</td>
<td>Middle infrared</td>
<td>2.08–2.35</td>
<td>Mineral mapping</td>
</tr>
</tbody>
</table>
Pseudocolor Coding Example

Visible blue
\( \lambda = 0.45-0.52 \, \mu m \)
Max water penetration

Visible green
\( \lambda = 0.52-0.60 \, \mu m \)
Measuring plant

Visible red
\( \lambda = 0.63-0.69 \, \mu m \)
Plant discrimination

Near infrared
\( \lambda = 0.76-0.90 \, \mu m \)
Biomass and shoreline mapping

Color composite images

1 2 3 4 Red = 1 Green = 2 Blue = 3

Better visualization: Show quite clearly the difference between biomass (red) and human-made features.

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.
Example: Full-Color Image and Various Color Space Components

Color image

CMYK components

RGB components

HSI components

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

Use to transform colors to colors.

Formulation:

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

\[ f(x,y) = \text{input color image}, \quad g(x,y) = \text{output color image} \]
\[ T = \text{operation on } f \text{ over a spatial neighborhood of } (x,y) \]

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

\[ s_i = T_i(r_1, r_2, \ldots, r_n) \quad i = 1, 2, \ldots, n \]

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:

\[ s_R(x, y) = k r_R(x, y) \]
\[ s_G(x, y) = k r_G(x, y) \]
\[ s_B(x, y) = k r_B(x, y) \]

Formula for HSI:

\[ s_I(x, y) = k r_I(x, y) \]

Formula for CMY:

\[ s_C(x, y) = k r_C(x, y) + (1 - k) \]
\[ s_M(x, y) = k r_M(x, y) + (1 - k) \]
\[ s_Y(x, y) = k r_Y(x, y) + (1 - k) \]

These 3 transformations give the same results.

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

(Images from Rafael C. Gonzalez and Richard E. Wood, Digital Image Processing, 2nd Edition.)
**Color Complement Transformation Example**

![Image of berries and coffee](image1)

**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.

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

Set to gray

or

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

Set to gray

Keep the original color

Keep the original color

\[ i = 1, 2, \ldots, n \]
Color Slicing Transformation Example

After color slicing

Original image

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

(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.

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

FIGURE 6.37
Histogram equalization (followed by saturation adjustment) in the HS1 color space.
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

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

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

Hue

Saturation

Intensity

(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 examples](image)

- Sharpening all RGB components
- Sharpening only I component of HSI
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.
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

Histogram of 6

Red pixels

Segmentation of red color pixels

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

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

\[
g(x, y) = \begin{cases} 
1 & \text{if } D(c(x, y), c_T) \leq T \\
0 & \text{if } D(c(x, y), c_T) > T 
\end{cases}
\]

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

\(c_T = \text{color to be segmented.}\)

\(c(x,y) = \text{RGB vector at pixel (x,y).}\)
Example: Segmentation in RGB Vector Space

Color image

Reference color $c_T$ to be segmented

$c_T = \text{average color of pixel in the box}$

Results of segmentation in RGB vector space with Threshold value

$T = 1.25 \times \text{SD of R,G,B values}$

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 defined 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.

We see 2 objects.

We see 4 objects.

Edges
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:

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

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

\[
g_{xx} = \left| \frac{\partial R}{\partial x} \right|^2 + \left| \frac{\partial G}{\partial x} \right|^2 + \left| \frac{\partial B}{\partial x} \right|^2
\]

\[
g_{yy} = \left| \frac{\partial R}{\partial y} \right|^2 + \left| \frac{\partial G}{\partial y} \right|^2 + \left| \frac{\partial B}{\partial y} \right|^2
\]

\[
g_{xy} = \frac{\partial R}{\partial x} \frac{\partial R}{\partial y} + \frac{\partial G}{\partial x} \frac{\partial G}{\partial y} + \frac{\partial B}{\partial x} \frac{\partial B}{\partial y}
\]
Gradient of a Color Image Example

Original image

Sum of gradients of each color component

Obtained using the formula in the previous slide

Difference between 2 and 3

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

**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).]

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

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

Salt & pepper noise in Green component

Hue

Saturation

Intensity

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.
Color Image Compression

Original image

After lossy compression with ratio 230:1

JPEG2000 File

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