Color Image Processing

Image Processing with Biomedical Applications
ELEG-475/675
Prof. Barner

Color Image Processing

- *Full-color* and *pseudo-color* processing
- Color vision
- Color space representations
- Color processing
  - Correction
  - Enhancement
  - Smoothing/sharpening
  - Segmentation

Color Fundamentals (I)

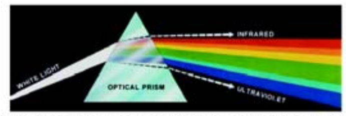


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

- The visible light spectrum is continuous
- Six Broad regions:
  - Violet, blue, green, yellow, orange, and red
- Object color depends on what wavelengths it reflects
- Achromatic light is void of color (flat spectrum)
  - Characterization: *intensity* (gray level)

Color Fundamentals (II)

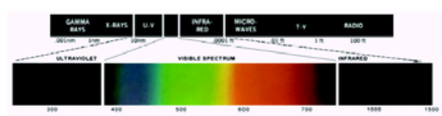
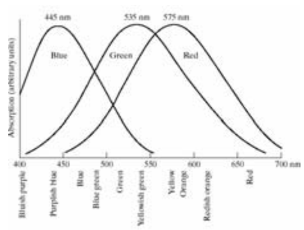


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

- Chromatic light spectrum: 400-700 nm
- Descriptive quantities:
  - *Radiance* – total energy that flows from a light source (Watts)
  - *Luminance* – amount of energy and observer perceives from a light source (lumens)
  - *Brightness* – subjected descriptor of intensity

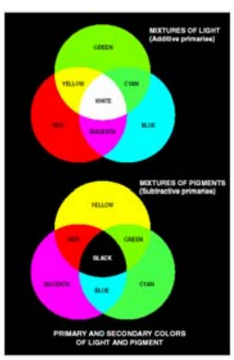
Vision Response



- Cone response:
  - 6-7 million receptors
  - Red sensitive: 65%
  - Green sensitive: 33%
  - Blue sensitive: 2%
    - Most sensitive receptors
- Primary colors: red (R), green (G), blue (B)
- International Commission on Illumination (CIE) standard definitions:
  - Blue (435.8 nm), Green (546.1 nm), Red (700 nm)
    - Defined in 1931 – doesn't exactly match human perception

Primary and Secondary Colors

- Add primary colors to obtain *secondary* colors of light:
  - Magenta, cyan, and yellow
- Primarily colors of:
  - Light – sources
    - Red, green, blue
  - Pigments – absorbs (subtracts) a primary color of light and reflects (transmits) the other two
    - Magenta (absorbs green), cyan (absorbs red), and yellow (absorbs blue)
    - Secondary pigments:
      - Red, green, and blue



Brightness and Chromaticity

- *Brightness* – notion of intensity
- *Hue* – an attribute associated with the dominant wavelength (color)
  - The color of an object determines its hue
- *Saturation* – relative purity, or the amount of white light mixed with a hue
  - Pure spectrum colors are fully saturated, e.g., red
  - Saturation is inversely proportional to the amount of white light in a color
- Chromaticity is hue and saturation together
  - A color may be characterized by its brightness and chromaticity

Tristimulus Representation

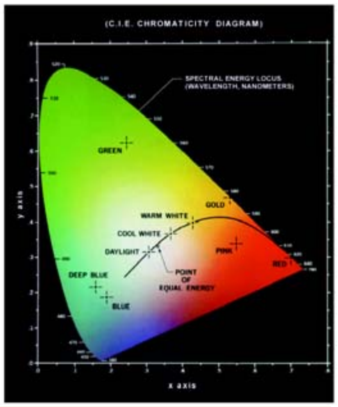
- Tristimulus values: *X* – red; Y – green; *Z* – blue
- Trichromatic coefficients:

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

- alternate approach: *chromaticity diagram*
  - Gives color composition as a function of red (x) and green (y)
    - Solve for blue (z) according to the above
  - Projects 3-D color space on to two dimensions

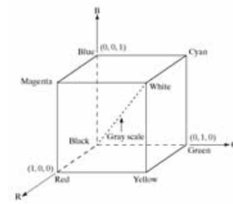
Chromaticity Diagram

- Pure colors are on the boundary
  - Fully saturated
- Interior points are mixtures
  - A line between two colors indicates all possible mixtures of the two colors
- *Color gamut* – triangle defined by three colors
  - Three color mixtures are restricted to the gamut
  - No three-color gamut completely encloses the chromaticity diagram



The RGB Color Model (Space)

- RGB is the most widely used hardware-oriented color space
  - Graphics boards, monitors, cameras, etc. testing
  - Normalized RGB values
  - Grayscale is a diagonal line through the cube
  - Quantization determines color *depth*
    - *Full-color*: 24-bit representations (16,777,216 colors)



Color Gamut Examples

- RGB monitor color gamut
  - Regular (triangular) shaped
  - Based on three highly controllable light primaries
- Printing device color gamut
  - Combination of additive and subtracted color mixing
  - Difficult control process
- Neither gamut includes *all* colors
  - Monitor is better

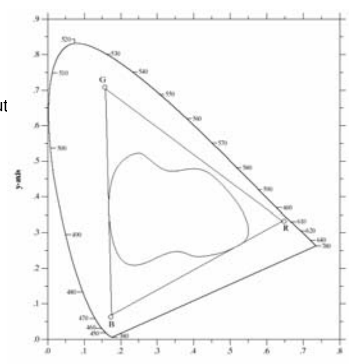
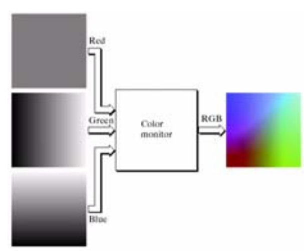
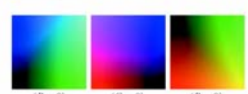


FIGURE 6.6 Typical color gamut of color monitors (triangle) and color printing devices (irregular region).

Color Image Generation

- Monochrome images represent each color component
  - Hyperplane examples:
    - Fix one dimension
    - Example shows three hidden sides of the color cube
- Acquisition process – reverse operations
  - Filter light to obtain RGB components





Safe RGB Colors (I)

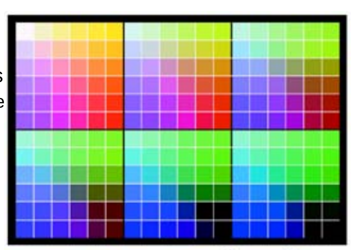
- Consistent color reproduction is problematic
  - Plethora of hardware from different manufacturers
- Define a subset of colors to be faithfully reproduced on all hardware
  - 256 colors
    - Sufficient number to produce good images
    - Small enough set to be accurately reproduced
    - 40 of these yield hardware specific results
  - De facto safe *RGB/Web/browser colors*: 216 colors
    - Formed as RGB triplets of values below

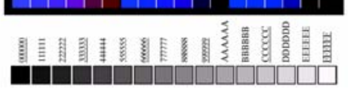
Number System	Color Equivalents					
Hex	00	33	66	99	CC	FF
Decimal	0	51	102	153	204	255

TABLE 6.1 Valid values of each RGB component in a safe color.

Safe RGB Colors (II)

- 216 safe RGB colors
- 256 color RGB system includes 16 gray levels
  - Six are in the 216 safe colors (underlined)
- RGB said-color cube



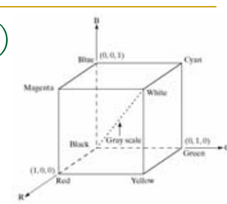


The CMY and CMYK Color Spaces

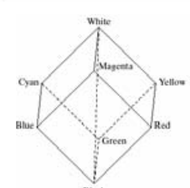
- CMY – cyan, magenta, and yellow
  - CMYK – adds black
    - Black is difficult (and costly) to produce with CMY
    - Four-color printing
  - Subtracted primaries – widely used in printing

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

The HSI Color Space (I)

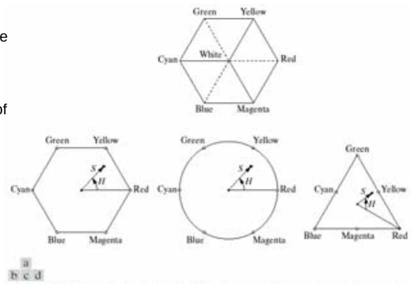


- Hue, saturation, intensity
  - human perceptual descriptions of color
  - Decouples intensity (gray level) from hue and saturation
  - Rotate RGB cube so intensity is the vertical axis
    - The intensity component of any color is its vertical component
    - Saturation – distance from vertical axis
      - Zero saturation: colors (gray values) on the vertical axis
      - Fully saturated: pure colors on the cube boundaries
    - Hue – primary color indicated as an angle of rotation



The HSI Color Space (II)

- View the HSI space from top down
  - Slicing plane perpendicular to intensity
- Intensity – height of slicing plane
- Saturation – distance from center (intensity axis)
- Hue – rotation angle from Red
- Natural shape: hexagon
  - Normalized to circle or triangle



a
b c d

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.

RGB to HSI Conversion

- Common HSI representations
- RGB to HSI conversion

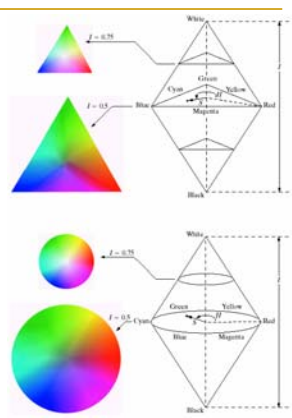
$$H = \begin{cases} \theta & \text{if } B \le G \\ 360-\theta & \text{if } B > G \end{cases}$$

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

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

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

  - Result for normalized (circular) HSI representation
  - Take care to note which HSI representation is being used!



HSI to RGB Conversion – Three Cases

- Case 1: RG sector (0° ≤H≤120°)

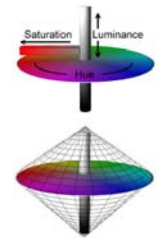
$$B = I(1-S)$$
$$R = I\left[1 + \frac{S\cos H}{\cos(60^\circ - H)}\right]$$
$$G = 1-(R+B)$$

- Case 2: GB sector (120° ≤H240°)

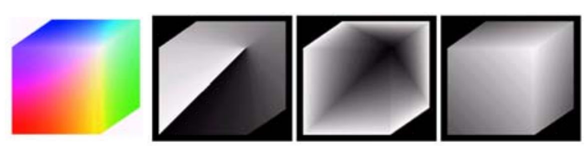
$$H = H - 120^\circ$$
$$R = I(1-S)$$
$$G = I\left[1 + \frac{S\cos H}{\cos(60^\circ - H)}\right]$$
$$B = 1-(R+G)$$

- Case 3: BR sector (240° ≤H≤360°)

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

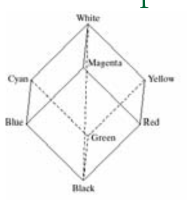


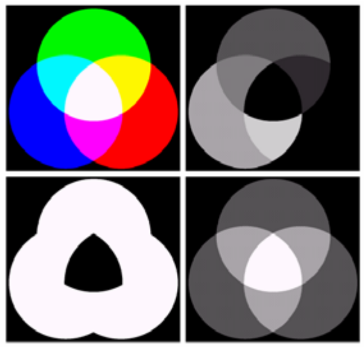
HSI Component Example (I)



- HSI representations of the color cube
  - Normalized values represented as gray values
  - Only values on surface of cube shown
- Explain:
  - Sharp transition in hue
  - Dark and light corners in saturation
  - Uniform intensity

HSI Component Example (II)





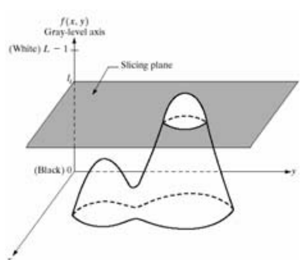
- Primary and secondary colors
  - HSI representation

Pseudocolor Image Processing

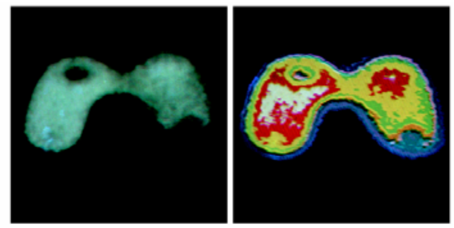
- Assigning colors to gray values yields *Pseudocolor* (*false color*) images
  - assignment criteria is application-specific
- *Intensity* (*density*) slicing
  - Assign colors based on gray value relation to slicing plane

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

    - Special case: Thresholding



Density Slicing Example (I)

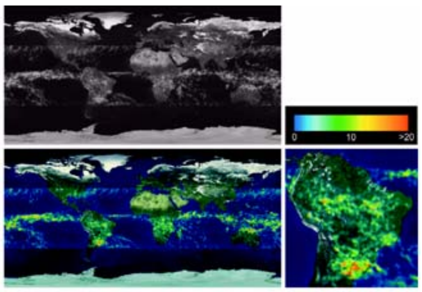


- Eight color density slicing of thyroid Phantom
  - Density slicing enables visualization of variations and details

Density Slicing Example (II)

- X-ray image of a weld
  - Density slicing to help visualize cracks

Density Slicing Example (III)

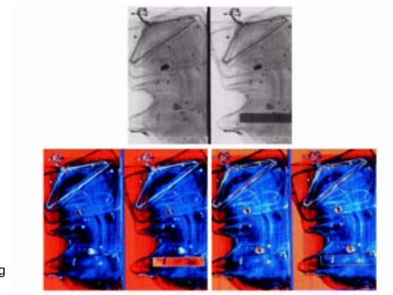


a b
c d

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.)

Example: Airport x-ray Scanning System

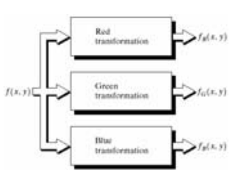
- Sinusoidal color mappings
  - Phase changes between components yield different results
  - Greatest color changes at sinusoidal troughs
    - Largest derivative
- First mapping:
  - Highlights explosives
- Second mapping:
  - Explosives and bag have similar mappings
    - Explosive is "transparent"

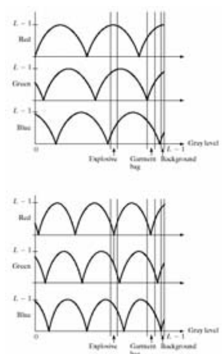


a
b c

FIGURE 6.24 Pseudocolor enhancement by using the gray-level to color transformations in Fig. 6.25. (Original image courtesy of Dr. Mike Hurwitz, Westinghouse.)

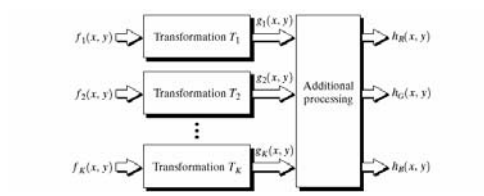
Gray Level to Color Transformations





- Each color can be a dependent/independent function of gray level
  - Example: RGB processing
  - Goal: highlight (color) objects or features of interest

Multispectral Extensions

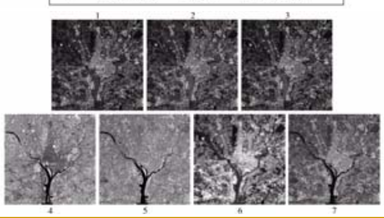


- Pseudo coloring is often used in the visualization of multispectral images
  - Examples: Satellite and astronomy images
    - Visible spectrum, infrared, radio waves, etc.
  - Transformations are applications and spectral band dependent

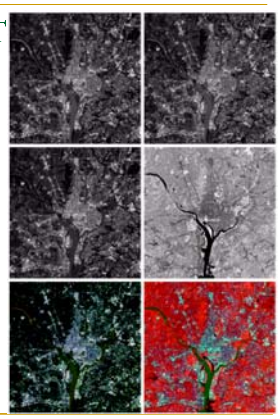
Wash. DC LANDSAT Example (I)

TABLE 1.1 Thematic bands in NASA's LANDSAT satellite.

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

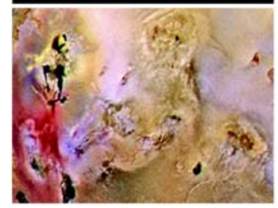


Wash. DC LANDSAT Example (II)



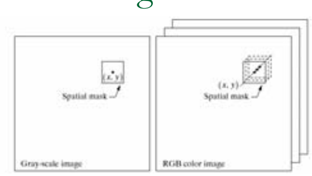
- Images in bands 1-4
- Color composite image using
  - Band 1 (visible blue) as blue
  - Band 2 (visible green) as green
  - Band 3 (visible red) as red
  - Result is difficult to analyze
- Color composite image using
  - Bands 1 and 2 as above
  - Band 4 (near infrared) as red
  - Better distinguishes between biomass (red dominated) and man-made structures

Galileo Spacecraft Example



- Multispectral image of
  - Jupiter's moon: Ito
  - Multispectral bands are chemical composition sensitive
- Pseudocolor image
  - Highlights volcanic activity
    - New deposits: red
    - Old deposits: yellow

Full-Color Image Processing



- Samples in observation window
  - Vectors

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

- General transformation:

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

- Restrict transformation to be a set $\{T_1, T_2, \ldots, T_n\}$ of *transformations* or *color mappings*

$$s_i = T_i(r_1, r_2, \ldots, r_n)$$

  - RGB: n=3; HSI: n=3; CMYK: n=4

Image & Components

- Image and CMYK, RGB, and HSI components
- Simple application:
  - Intensity scaling
  - HSI space:

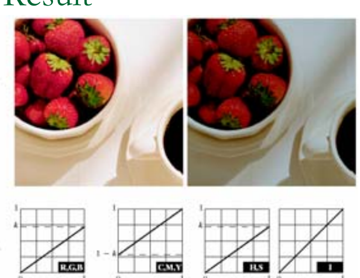
    $s_3 = kr_3$
  - RGB space:

    $s_i = kr_i \quad i=1,2,3$
  - CMY space:

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

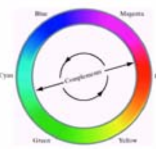
Scaling Result

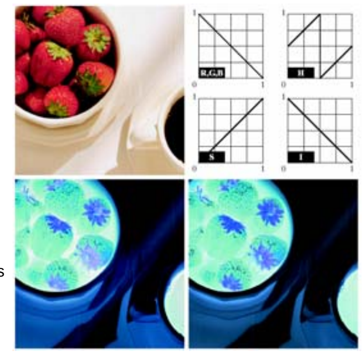
FIGURE 6.31 Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c)–(e) The required RGB, CMY, and HSI transformation functions. (Original image courtesy of MedData Interactive.)



- Scaling result for k=0.7
  - Shown: RGB, CMY, and HSI transformations
    - (HS and I transformations swapped)

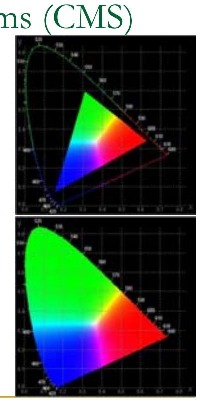
Color Complements





- Color circle
  - Circular connection of visible spectrum
- Color complementation
  - Color negatives
  - Shown transformations
    - RGB: exact
    - HSI: approximation
      - S component not independent of H&I

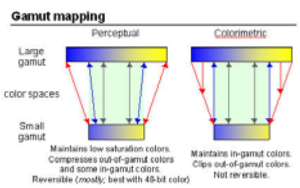
Color Management Systems (CMS)



- All devices have their own profile
- Goal: *device independent color model*
  - Must be able to represent the entire color gamut
  - Shown:
    - RGB monitor gamut
    - Full gamut

CIE L*a*b* Color Space (I)

- Desired color space attributes
  - *Color metric* – colors perceived as matching are identically coded
  - *Perceptually uniform* – color differences among various hues are perceived uniformly
    - Distance in color space matches perceived difference in colors
  - *Device independent* – independent of specific device display characteristics
    - Gamut encompasses entire visible spectrum



CIE L*a*b* Color Space (II)

- Tristimulus to L*a*b* conversion:

$$L^* = 116 \cdot h\left(\frac{Y}{Y_W}\right) - 16$$

$$a^* = 500\left[h\left(\frac{X}{X_W}\right) - h\left(\frac{Y}{Y_W}\right)\right]$$

$$b^* = 200\left[h\left(\frac{Y}{Y_W}\right) - h\left(\frac{Z}{Z_W}\right)\right]$$

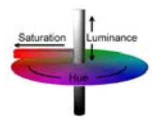
where

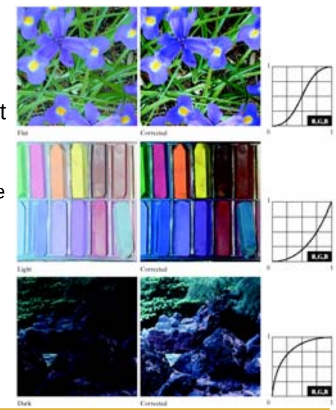
$$h(q) = \begin{cases} \sqrt[3]{q} & q > 0.008856 \\ 7.787q + 16/116 & q \le 0.008856 \end{cases}$$

- Reference white tristimulus values:
  - X_W=0.3127, Y_W=0.3290, and Z_W=1-X_W-Y_W
- Components:
  - Intensity (lightness): *L**
  - Color:
    - Red minus green: *a**
    - Green minus blue: *b**
- Appropriate for applications that require:
  - Full color space representation
  - Color space distance and perceptual difference matching
  - Drawbacks: computational cost

Tone Corrections

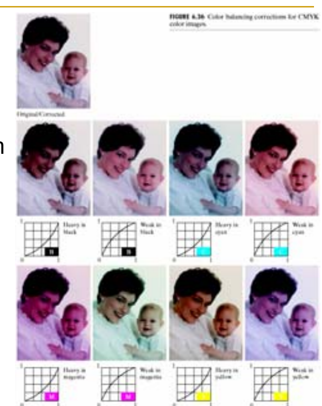
- Change intensity, not color
  - RGB and CMYK space: uniformly scale components
  - HSI space: scale intensity (luminance)





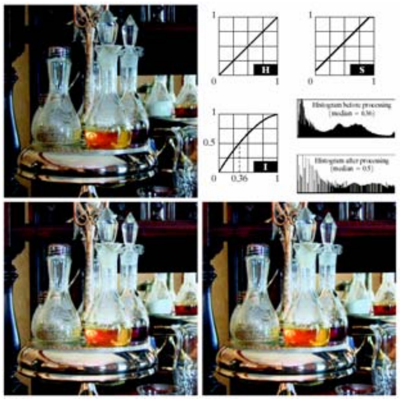
Color Imbalances

- Color in balances are normally addressed in the RGB or CMYK spaces
  - Corrective mappings shown



Histogram Processing

- Perform histogram equalization on Intensity
  - Avoids generation of new colors
    - Independent component processing is undesirable
  - Improves statistics of intensity
  - Does impact vibrancy of colors
    - Solution: increase saturation



Separable Functions

- Simple separable linear functions can be applied to components independently
  - Example: spatial averaging

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

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

  - Apply on RGB components

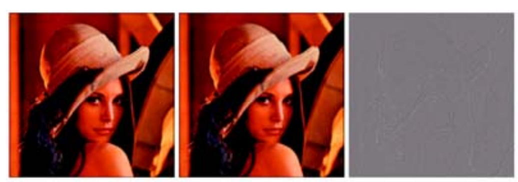
HSI Processing

a b c

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

- Alternative approach: process Intensity
  - Useful for extending grayscale procedures to color

RGB HSI Smoothing Comparison



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.

- Similar, but not identical results
  - RGB processing introduces new colors

RGB HSI Sharpening Comparison

a b c

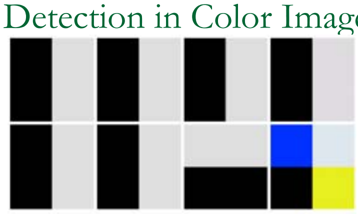
FIGURE 6.41 Image sharpening with the Laplacian. (a) Result of processing each RGB channel. (b) Result of processing the intensity component and converting to RGB. (c) Difference between the two results.

- Laplacian reduces to component-wise application

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

- Application on Intensity yields similar results

Edge Detection in Color Images

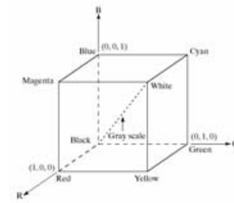


a b c d
e f g h

FIGURE 6.45 (a)–(c) *R*, *G*, and *B* component images and (d) resulting RGB color image. (f)–(g) *R*, *G*, and *B* component images and (h) resulting RGB color image.

- Gradient operators applied independently to color components yields poor results
- RGB example: step edges in individual color planes
  - Case 1: aligned edges
  - Case 2: two aligned edges, one orthogonal edge
  - Both cases yield identical gradients at image center
    - Color change more significant in Case 1

Vector Gradient



- RGB unit vectors: **r, g**, **b**
- Directional derivatives:

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

- Dot products:

$$g_{xx}=\mathbf{u}\cdot\mathbf{u}=\mathbf{u}^T\mathbf{u}=\left|\frac{\partial R}{\partial x}\right|^2+\left|\frac{\partial G}{\partial x}\right|^2+\left|\frac{\partial B}{\partial x}\right|^2$$
$$g_{yy}=\mathbf{v}\cdot\mathbf{v}=\mathbf{v}^T\mathbf{v}=\left|\frac{\partial R}{\partial y}\right|^2+\left|\frac{\partial G}{\partial y}\right|^2+\left|\frac{\partial B}{\partial y}\right|^2$$
$$g_{xy}=\mathbf{u}\cdot\mathbf{v}=\mathbf{u}^T\mathbf{v}=\frac{\partial R}{\partial x}\frac{\partial R}{\partial y}+\frac{\partial G}{\partial x}\frac{\partial G}{\partial y}+\frac{\partial B}{\partial x}\frac{\partial B}{\partial y}$$

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

- Magnitude of maximum change:

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

Gradient Example

- Shown
  - Input image
  - RGB space vector gradient
  - RGB space independent component gradient
    - Results summed
  - Difference image

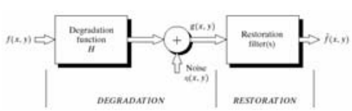
Component Gradients

a b c

FIGURE 6.47 Component gradient images of the color image in Fig. 6.46. (a) Red component, (b) green component, and (c) blue component. These three images were added and scaled to produce the image in Fig. 6.46(c).

- RGB component gradients
  - Note broken edges in individual components

Noise in Color Images



- The general degradation model holds in the color case
- Noise affecting individual color planes usually has the same characteristics
  - Usually modeled as independent
- Possible differences:
  - Differences in channel illumination levels
    - Red (filtered) channel in a CCD camera tends to have lower illumination (higher noise)
  - Bad sensors in an individual channel

Noise and Color Space Conversion

- Independent Gaussian noise in the RGB channels
  - Resulting color image
  - Note introduced colors

HSI Representation of Noisy Image

a b c

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

- Hue and saturation are severely degraded
  - Nonlinear transformations from the RGB space
    - Involves cosine and minimum operators
- Intensity component is smoothed
  - Average of RGB components

Single Channel Corruption

- Single channel corruption
  - Salt and pepper noise in the green channel
  - p=0.05
- Color space conversion
  - Spreads noise
  - Changes statistics
  - Shown: HSI components