Color Image Processing

Background

- Humans can perceive thousands of colors, and only about a couple of dozen gray shades (cones/rods)
- Divide into two major areas: full color and pseudo color processing
  - Full color – Image is acquired with a full-color sensor like TV camera or color scanner
  - Pseudo color – Assign a color to a range of monochrome intensities
  - The availability of inexpensive and powerful hardware has resulted in the proliferation of applications based on full color processing
- 8-bit color vs 24-bit color
  - Color quantization
- Some of the gray scale image processing methods are directly applicable to color processing but others will need reformulation

Color fundamentals

- Color spectrum/prism
  - Figure 6.1
  - White light divided into different colors
  - Colors blend into each other smoothly (Figure 6.2)
- Color – Perceptual result of light in the visible region of spectrum as incident on the retina
  - 400 nm to 700 nm
  - Visible light is a narrow band of frequencies in the electromagnetic spectrum (Figure 6.2)
  - White light is result of reflected light balanced across all visible wavelengths
  - Reflectance from a body in limited range of viible spectrum is perceived as color
    - Green objects reflect light with wavelength in the 500-570nm range while absorbing other wavelengths
- Characterization of light
  - Achromatic (no color) or monochromatic light characterized by intensity
  - Gray level as a scalar measure of intensity from black to white
- Chromatic light
  - Spans the electromagnetic spectrum from approximately 400–700nm
  - Light source characterized by three quantities

    Radiance Total amount of energy emitted by light source, measured in watts
      - Physical power of light energy
      - Measures the quantity of radiation that passes through or emitted from a surface and falls within a given solid anle in a specified direction
      - Expressed in a spectral power distribution, often in 31 components, each representing a 10 nm band

    Brightness Achromatic notion of intensity to describe color sensation
      - Attribute of a visual sensation according to which an area appears to emit more or less light
      - Cannot be measured quantitatively

Luminance Measure of amount of energy as perceived by an observer, measured in lumens or candelas per square meter
  * More tractable version of brightness, defined by CIE
  * Radiant power weighted by a spectral sensitivity function that is characteristic of vision
  * Luminous efficiency peaks at 555nm
  * CIE luminance, denoted by Y, is the integral of spectral power distribution, using spectral sensitivity curve as a weighting function
  * Magnitude of luminance is proportional to physical power, but spectral composition is related to brightness sensitivity of human vision
  * Units of measurement for image processing
    · Normalized to 1 or 100 with respect to a standard white reference
    · $Y = 1$ is the white reference of a studio broadcast monitor whose luminance is 80 cd/m^2

– Cones in the eye respond to three colors: red, green, blue
  * 6 to 7 million cones in human eye
  * 65% cones respond to red eye
  * 33% cones respond to green light
  * 2% cones respond to blue light, these being most sensitive
  * Figure 6-03
  * Red, green, and blue are known as primary colors
    · In 1931, CIE designated specific wavelengths for primary colors
    · Red – 700nm
    · Green – 546.1nm
    · Blue – 435.8nm
    · To generate all colors, we may have to vary the wavelengths of primary colors while mixing colors; so the three primary colors are neither fixed nor standard
    · The curves in Fig 6.3 indicate that a single color may be called red, green, or blue
– Secondary colors
  * Created by adding primary colors
  * Cyan = Green + Blue
  * Magenta = Red + Blue
  * Yellow = Red + Green
  * Mixing all three primary colors produces white
  * Fig 6-04
  * The secondary colors are primary colors of pigments, which have red, green, and blue as secondary colors
– How do we represent black? Absence of color.
  * While printing, we need to print black on white
  * Subtractive colors based on pigments
  * Primary color of a pigment is defined as one that absorbs a primary color of light and transmits the other two
  * Given by cyan, magenta, yellow (CMY)
  * A secondary combined with its opposite primary produces black
– Color TV reception
  * Characterized by additive nature of colors
  * Large array of triangular dot patterns of electron sensitive phosphor
  * Intensity of individual phosphors modulated by electron gun, one corresponding to each primary color
  * The same technolofy is used in the flat panel displays, usingd three subpixels to generate a color pixel
– Color characterized by three quantities

Hue Dominant color as perceived by an observer (red, orange, or yellow)

Saturation Relative purity of color; pure spectrum colors are fully saturated

- Saturation is inversely proportional to the amount of white light added

Brightness Achromatic notion of intensity

- Chromaticity
  - Combination of hue and saturation
  - Allows a color to be expressed as its brightness and chromaticity
- Tristimulus values
  - Three types of cones in the eye require three components for each color, using appropriate spectral weighting functions
    - Based on standard curves/functions defined by CIE – Commission Internationale de L'Éclairage
    - Curves specify the transformation of spectral power distribution for each color into three numbers
  - Amount of red, green, and blue to express a color
  - Denoted by X, Y, and Z
  - Color specified by its tristimulus coefficients

$$\begin{aligned} x &= \frac{X}{X+Y+Z} \\ y &= \frac{Y}{X+Y+Z} \\ z &= \frac{Z}{X+Y+Z} \end{aligned}$$

  - Note that $x + y + z = 1$
- Chromaticity diagram
  - Figure 6-05
  - Color given as a function of x and y
  - The corresponding value of z is obtained by $1 - (x + y)$
  - Points on the boundary are fully saturated colors
  - Saturation at point of equal energy is 0
  - Mainly useful for color mixing
    - Any straight line joining two points defines all the color variations obtained by combining the two colors additively
    - Extension to three colors by using a triangle to connect three points
    - Supports the assertion that not all colors can be obtained with three single, fixed primaries as some of them are outside the triangle
    - Figure 6-06 – Color gamut

Color models

- Also called color space or color system
- Allow the specification of colors in some standard way
- Specification of a coordinate system and a subspace within that system
  - Each color represented by a single point
- Models oriented towards hardware (rendering and scanning) or software (reasoning and applications)
- RGB color model

- Figure 6-07
- Unit cube
  * Based on Cartesian coordinate system
  * All color values are assumed to be normalized to the range [0,1]
  * Colors defined by vectors extending from origin; origin represents black
  * RGB primaries are at the corners that are neighbors to the origin; other corners (at distance 2 from origin) represent secondary colors (CMY)
  * Corner opposite to origin, given by point (1,1,1), represents white
  * Different shades of gray are distributed along the cube diagonal from black to white corners
- Pixel depth – Number of bits used to represent each pixel in RGB space
  * Depth of 24-bits when each color represented by 8 bits in the triplet to represent pixel
  * Figure 6-08
- Rendering an image
  * Images consist of three component images, one for each primary color
  * Figure 6-09
  * Fuse the three color components together
- Acquiring an image
  * Figure 6-09, but in reverse
  * Acquire individual color planes and put them together
- Does not make sense to use all the possible 2^{24} colors in 24-bit space
  * Safe colors
    · Can be reproduced on a variety of devices
    · Likely to be reproduced faithfully, reasonably independent of hardware capabilities
  * Safe RGBcolors or safe browser colors
    · Number of colors that can be reproduced faithfully in any system – 256
    · 40 of these colors are known to be processed differently by different OSs
    · Number of colors common to most systems – 216
  * Safe RGB color values
    · Formed from 6 possible values of each component as follows

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

    · Each successive color is 51 (0x33) more than its predecessor
    · Triplets give $6^3 = 216$ possible values
    · Figure 6-10
    · Not all possible 8-bit gray colors are included in the set of 216 colors
    · RGB safe-color cube – Figure 6.11
    · Color safe cube has valid colors only on the surface

- CMY and CMYK color models
  - Primary colors of pigments
  - Pigments subtract light rather than radiate light
    * Illuminating a surface coated with cyan pigment absorbs red component of light
  - Devices that deposit color pigments on paper perform an RGB to CMY conversion internally by a simple operation

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

- Equal contribution of cyan, magenta, and yellow should produce black but in practice, it produces muddy-looking black
  - A fourth color is added, yielding CMYK system

- Indexed or palette image
  - Uses a fixed number of colors within the color or gray component of an image
  - Image values are just indices in a table of color values

- HSI color model
  - Hue, saturation, intensity
  - RGB and CMY models
    - Ideally suited for hardware implementation
    - RGB matches the human eye's perception for primary colors
    - RGB and CMY not suitable for describing colors for human interpretation
    - Dark or light or pastel colors
    - Humans do not think of color images as being composed of three primary images that form a single images
  - Human description of images/colors
    - In terms of hue, saturation, and brightness
  - HSI model decouples intensity component from the color-carrying components (hue and saturation)
    - Ideal tool for developing image processing algorithms
    - Natural and intuitive to humans
  - Intensity
    - Measure over some interval of the electromagnetic spectrum of the flow of power that is radiated from, or incident on, a surface
    - Linear light measure, expressed in units such as watts per square meter
    - Controlled on a CRT monitor by voltages presented, in a nonlinear manner for each color component
    - CRT voltages are not proportional to intensity
    - RGB color images can be viewed as three monochrome intensity images
    - Extracting intensity from RGB images
      - Stand the RGB color cube on the black vertex, with white vertex directly above it (Figure 6.12a)
      - Line joining the black and white vertices is now vertical
      - Intensity of any color given by intersection of intensity axis and a plane perpendicular to it and intersecting with the color point in cube
      - Saturation of color increases as a function of distance from intensity axis
      - Saturation of points along intensity axis is zero (all points on intensity axis are gray)
  - Hue
    - Color attribute that describes a pure color
    - Consider the plane defined by black, white, and cyan (Figure 6.12b)
    - Intensity axis is contained within this plane
    - All points contained in plane segment given by these three points have the same hue – cyan
    - Rotating the plane about the intensity axis gives us different hues
    - HSI space is represented by a vertical intensity axis and the locus of color points that lie on planes perpendicular to the axis
      - As planes move up and down on intensity axis, the boundaries of intersection of each plane with the faces of the cube have a triangular or hexagonal shape
  - Above discussion leads us to conclude that we can convert a color from the RGB values to HSI space by working out the geometrical formulas (Figure 6.13)

    * Primary colors are separated by $120°$
    * Secondary colors are $60°$ from the primaries
    * Hue of a point is determined by an angle from a reference point
      · By convention, reference point is taken as angle from red axis
      · Hue increases counterclockwise from red axis
    * Saturation is the length of vector from origin to the point
      · Origin is given by intensity axis
  – Figure 6.14 to describe HSI model

- Converting colors from RGB to HSI
  – Consider RGB values normalized to the range $[0, 1]$
  – Given an RGB value, H is obtained as follows:

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

    * It should be normalized to the range $[0, 1]$ by dividing the quantity computed above by 360
  – θ is given by

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

    * θ is measured with respect to red axis of HSI space
  – Saturation is given by

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

  – Intensity component is given by

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

- Converting colors from HSI to RGB
  – Consider the values of HSI in the interval $[0, 1]$
  – H should be multiplied by 360 (or 2π) to recover the angle; further computation is based on the value of H
  – RG sector – $0° \leq H < 120°$

$$\begin{aligned} B &= I(1-S) \\ R &= I\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \\ G &= 3I - (R+B) \end{aligned}$$

  – GB sector – $120° \leq H < 240°$

$$\begin{aligned} H' &= H - 120° \\ R &= I(1-S) \\ G &= I\left[1 + \frac{S\cos H'}{\cos(60° - H')}\right] \\ B &= 3I - (R+G) \end{aligned}$$

  – BR sector – $0° \leq H < 360°$

$$\begin{aligned} H' &= H - 240° \\ G &= I(1-S) \\ B &= I\left[1 + \frac{S\cos H'}{\cos(60° - H')}\right] \\ R &= 3I - (G+B) \end{aligned}$$

- Figure 6.15
  - HSI components of RGB cube, plotted separately
  - Discontinuity along the $45°$ line in the hue figure
    * See the reason by going around the middle in Figure 6.8
  - Saturation image shows progressively darker values close to the white vertex of RGB cube
  - Intensity is simply the average of RGB values at the corresponding pixel
- Manipulating HSI component images
  - Figure 6.16 – image composed of primary and secondary RGB colors and their HSI equivalents
    * In hue, red region maps to black as its angle is $0°$
    * In b, c, and d parts of the image, the pixels are scaled to the range [0,1]
  - Individual colors changed by changing the hue image
  - Purity of colors changed by varying the saturation
  - Figure 6.17a – Change blue and green pixels in Figure 6.16a to 0 (compare with Figure 6.16b)
  - Figure 6.17b – Change saturation of cyan component in Figure 6.16c to half
  - Figure 6.17c – Reduce the intensity of central white region in Figure 6.16d by half
  - Figure 6.17d – Combine the three HSI components back into RGB image

HSV color space

- Projects the RGB color cube onto a non-linear chroma angle (H), a radial saturation percentage (S), and a luminance-inspired value (V)
- Similar to HSI color space
- Used to compare the hue channel in OpenCV

Pseudocolor image processing

- Also known as *indexed color*
- Assign colors to gray values based on a fixed criteria
  - 216 index entries from 8-bit RGB color system as a $6 \times 6 \times 6$ cube in a direct color system
  - Gives an integer in the range 0 to 5 for each component of RGB
  - Requires less data to encode an image
  - Some graphics file formats, such as GIF and TIFF add an index colormap to the image with gamma-corrected RGB entries
- Used as an aid to human visualization and interpretation of gray-scale events in an image or sequence of images, such as visualizing population density in different areas on a map
- May have nothing to do with processing of true color images
- Intensity slicing
  - Also called density slicing or color coding
  - Slicing planes parallel to horizontal plane in 3D space, with the intensity of image providing the third dimension on image plane

    * Figure 6.18
    * Plane at $f(x,y) = l_i$ to slice the image function into two levels
    * Assign different colors to area on different sides of the slicing plane
    * Relative appearance of the resulting image manipulated by moving the slicing plane up and down the gray-level axis
  - Technique summary
    * Gray scale representation – $[0, L-1]$
    * Black represented by l_0, $[f(x,y) = 0]$
    * White represented by $[l_{L-1}]$, $[f(x,y) = L-1]$
    * Define P planes perpendicular to intensity axis at levels $l_1, l_2, \ldots, l_P$
    * $0 < P < L-1$
    * P planes partition the gray scale into $P+1$ intervals as $V_1, V_2, \ldots, V_{P+1}$
    * Make gray-level to color assignment as

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

      where c_k is the color associated with kth intensity interval V_k defined by partitioning planes at $l = k-1$ and $l = k$
  - Alternative mapping function to intensity slicing planes
    * Figure 6.19
    * Staircase form of mapping with multiple levels
  - Figure 6.20 – Picker Thyroid Phantom (radiation test pattern)
    * Intensity slicing image into eight color regions
    * Idea is to make it easy to distinguish between shades without assigning any semantic interpretation to the color
  - Figure 6.21 – Cracks in weld seen through X-ray image
    * Full strength of X-rays passing through is assigned one color; everything else a different color
  - Figure 6.22 – Measurement of rainfall levels

- Gray level to color transformations
  - Separate independent transformation of gray level inputs to three colors
  - Figure 6.23
  - Composite image with color content modulated by nature of transformation function
  - Piecewise linear functions of gray levels
  - Figure 6.24 – Luggage through X-ray scanning system
    * Image on right contains a block of simulated plastic explosives
    * Figure 6.25 – Transformation functions used
    * Emphasize ranges in gray scale by changing sinusoidal frequencies

- Combining several monochrome images into a single color composite
  - Figure 6.26
  - Used in multispectral image processing, with different sensors producing individual monochrome images in different spectral bands
  - Figure 6.27
    * Images of Washington, DC, and Potomac river in red, green, blue, and near IR bands
    * Image f generated by replacing the red component of image e by NIR image
      · NIR strongly responsive to biomass component

    - Image f shows the difference between biomass (red) and man-made features such as concrete and asphalt (bluish green)
  - Figure 6.28
    - Jupiter moon Io, using images in several spectral regions by the spacecraft Galileo
    - Bright red depicts material recently ejected from an active volcano while surrounding yellow shows older sulfur deposits

Basics of full-color image processing

- Two major categories of processing
  1. Process each component of image (RGB or HSI) individually and then form a composite processed color image
     - Each component can be processed using gray-scale processing techniques
  2. Work with color pixels directly, treating each pixel as a vector

$$\mathbf{c} = \begin{bmatrix} c_R \\ c_G \\ c_B \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

     - Since each pixel is a function of coordinates (x, y), we have

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

     - Each component of the vector is a *spatial* variable in x and y
     - For an $M \times N$ image, there are MN vectors $\mathbf{c}(x, y)$ for $x = 0, 1, 2, \ldots, M-1$ and $y = 0, 1, 2, \ldots, N-1$
- The two methods may or may not produce equivalent results
  - Scalar versus vector operations
    - The process used should be applicable to both scalars and vectors
    - The operation on each component of the vector must be independent of the other components
  - Neighborhood processing will be an example where we get different results (Figure 6.29)
    - Averaging the images separately in individual planes and averaging the vectors will give different results

Color transformations

- Process the components of a color image within the context of a single color model, without converting components to different color space
- Think of an application that needs to brighten a picture
  - Can we achieve this by adding a constant quantity to each of the three RGB channels?
  - This will not only increase the intensity of each pixel but also hue and saturation
  - A better solution will be to manipulate the luminance I to recompute a valid RGB image with the same hue and saturation
- Formulation
  - Model color transformations using the expression

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

    T is the operator over a spatial neighborhood of (x, y)

- Each $f(x, y)$ component is a triplet in the chosen color space (Figure 6.29)
- Figure 6.30 – Various color components of an image
- Must consider the cost of converting from one color space to another when looking at the operations
- Modifying intensity of an image in different color spaces, using the transform

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

  * In HSI color space, converting a pixel h, s, i to h', s', i'

$$\begin{aligned} h' &= h \\ s' &= s \\ i' &= ki \end{aligned}$$

  * In RGB color space, converting a pixel r, g, b to r', g', b'

$$\begin{bmatrix} r' \\ g' \\ b' \end{bmatrix} = k \cdot \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

  * In CMY color space

$$\begin{aligned} c' &= kc + (1 - k) \\ m' &= km + (1 - k) \\ y' &= ky + (1 - k) \end{aligned}$$

- Simple operation in HSI but cost to convert to HSI may not be justifiable
  * Figure 6.31, using $k = 0.7$

- Color complements
  - Hues directly opposite one another on the color circle
    * Figure 6.32
  - Analogous to gray scale negatives
  - Can be used to enhance details buried in dark regions of an image
  - Figure 6.33
    * May not have the same saturation in negative image in HSI
    * Figure shows saturation component unaltered

- Color slicing
  - Used to highlight a specific range of colors in an image to separate objects from surroundings
  - Display just the colors of interest, or use the regions defined by specified colors for further processing
  - More complex than gray-level slicing, due to multiple dimensions for each pixel
  - Dependent on the color space chosen; I prefer HSI
  - Using a cube of width W to enclose the reference color with components $(a_1, a_2, \ldots, a_n)$, the transformation is given by

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

  - If the color of interest is specified by a sphere of radius R_0, the transformation is

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

- Figure 6.34
- Color balancing
  - Process to compensate for incandescent lighting
  - You can perform color balancing by multiplying each channel with a different scale factor, or by mapping the pixels to XYZ color space, changing the nominal white point, and mapping back to RGB

Tone and color corrections

- Used for photo enhancement and color reproduction
- Device independent color model from CIE relating the color gamuts
- Use a color profile to map each device to color model
- CIE L*a*b* system
  - Most common model for color management systems
  - Components given by the following equations

$$\begin{aligned} L* &= 116 \cdot h\left(\frac{Y}{Y_W}\right) - 16 \\ a* &= 500\left[h\left(\frac{X}{X_W}\right) - h\left(\frac{Y}{Y_W}\right)\right] \\ b* &= 200\left[h\left(\frac{Y}{Y_W}\right) - h\left(\frac{Z}{Z_W}\right)\right] \end{aligned}$$

    where

$$h(q) = \begin{cases} q^{\frac{1}{3}} & \text{if } q > 0.008856 \\ 7.787q + \frac{16}{116} & \text{otherwise} \end{cases}$$

  - X_W, Y_W, and Z_W are values for refence white, called D_{65} which is defined by $x = 0.3127$ and $y = 0.3290$ in the CIE chromaticity diagram
  - X, Y, Z are computed from rgb values as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix}$$

    * Rec. 709 RGB corresponds to D_{65} white point
  - L*a*b* is calorimetric (colors perceived as matching are encoded identically), perceptually uniform (color differences among various hues are perceived uniformly), and device independent
  - Not directly displayable on any device but its gamut covers the entire visible spectrum
  - L*a*b* decouples intensity from color, making it useful for image manipulation (hue and contrast editing) and image compression applications
    * L* represents lightness or intensity
    * a* gives red minus green
    * b* gives green minus blue
  - Allows tonal and color imbalances to be corrected interactively and independently
    * Tonal range refers to general distribution of key intensities in an image
      · Adjust image brightness and contrast to provide maximum detail over a range of intensities
      · The colors themselves are not changed

- Figure 6.35 (RGB) and 6.36 (CMYK)
- Color balancing
  - Objectively performed using a color spectrometer
  - Can also be assessed visually using skin tones
  - Adjusting color components
    * Every action affects the overall color balance of the image
    * Perception of a color is affected by surrounding colors
    * Use color wheel (Figure 6.32) to increase the proportion of a color by decreasing the amount of complementary color
    * May also increase the proportion of a color by raising the contribution of its adjacent colors

Histogram processing

- Provides an automated way to perform enhancement
- Histogram equalization
  - Adapt the grayscale technique to multiple components
  - Applying grayscale techniques to different colors independently yields erroneous colors
  - Spread the intensities uniformly leaving the hues unchanged
  - Figure 6.37

Smoothing and sharpening

- Color image smoothing
  - Extend spatial filtering mask to color smoothing, dealing with component vectors
  - Let S_{xy} be the neighborhood centered at (x, y)
  - Average of RGB components in the neighborhood is given by

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

    which is the same as

    $$\bar{\mathbf{c}}(x, y) = \left[\begin{array}{c} \frac{1}{K} \sum_{(s,t) \in S_{xy}} R(s, t) \\ \frac{1}{K} \sum_{(s,t) \in S_{xy}} G(s, t) \\ \frac{1}{K} \sum_{(s,t) \in S_{xy}} B(s, t) \end{array} \right]$$
  - Same effect as smoothing each channel separately
  - Figure 6.38, Figure 6.40a
  - Figure 6.39 (HSI components)
    * Figure 6.40b – Smooth only the intensity component
    * Pixel colors do not change as they do with RGB smoothing
- Color image sharpening
  - Use Laplacian

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

- Figure 6.41

Image segmentation based on color

- Segmentation in HSI color space
  - Color is conveniently represented in hue image
  - Saturation is used as a masking image to isolate regions of interest in the hue image
  - Intensity image used less frequently as it has no color information
  - Example 6.14
    * Segment the reddish region in lower left of Figure 6.42a
    * Figure 6.42e: Binary mask by thresholding the saturation image with 10% of the maximum value in the image
    * Figure 6.42f: Product of hue and thresholded saturation
    * Fugire 6.42g: Histogram of Figure 6.42f
- Segmentation in RGB vector space
  - Create an estimate of the average color to be segmented as vector **a**
  - Let **z** be an arbitrary point in the RGB color space
  - **z** is similar to **a** if the Euclidean distance between them is less than specified threshold D_0

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

  - Figure 6.43
  - Example 6.15: Figure 6.44

Image File Formats

- Files used to store, archive, and exchange image data
  - Standardized file formats facilitate the exchange of images and allow different applications to read those images
- Criteria to select appropriate file format
  - Image type
    * Binary, grayscale, or color images
    * Document scans, floating point images
    * Maximum image size for satellite images
  - Storage size and compression
    * Lossy or lossless compression
  - Compatibility
    * Exchange of image data with others and across applications
    * Long-term machine readability of data
  - Application domain
    * Print, web, film, graphics, medicine, astronomy
- Raster vs vector data

  - All images considered thus far have been raster images
  - Vector graphics represent geometric objects using continuous coordinates
    * The objects are rasterized when they need to be displayed on a physical device
  - Used to encode geodata for navigation systems
- Tagged Image File Format (TIFF)
  - Supports grayscale, indexed, and true color images
  - A single file may contain a number of images with different properties
  - Provides a range of different compression methods (LZW, ZIP, CCITT, and JPEG), and color spaces
  - You can create new image types and information blocks by defining new *tags*
    * Proprietary tags may not be always supported leading to "unsupported tag" error
    * Web browsers do not natively support TIFF
- Graphics Interchange Format (GIF)
  - Originally designed by CompuServe in 1986
  - Provided early support for indexed color at various bit depths
  - Provided LZW compression, interlaced image loading, and ability to encode simple animations by storing a number of images in a single file for sequential display
  - Does not support true color images
  - Allows pixels to be encoded using fewer bits
  - Uses lossless color quantization and lossless LZW compression
- Portable Network Graphics (PNG)
  - Developed as a replacement for GIF because of licensing issues
  - Supports three different types of images
    1. True color, with up to 3×16 bpp
    2. Grayscale, with up to 16 bpp
    3. Indexed, with up to 256 colors
  - Also may include an α-channel for transparency with a maximum width of 16 bits
    * α-channel of a GIF image is only 1 bit
  - Supports only one image per file, with maximum size as $2^{30} \times 2^{30}$ pixels
    * Cannot support animation like GIF
  - Supports lossless compression by a variation of PKZIP but no lossy compression
- Joint Photographic Experts Group (JPEG)
  - Goal to achieve average data reduction of 1:16
  - Supports images with up to 256 color components
  - Three steps in the core algorithm for RGB images
    1. Color conversion and down sampling
       * Transform from RGB to YC_bC_r space; Y is brightness while the other two components are color
       * Human visual system is less sensitive to rapid color change; compress color components more to achieve significant data reduction without a perceptive change in image quality
    2. Cosine transform and quantization in frequency space
       * Image is divided into a regular grid of 8×8 blocks
       * Compute frequency spectrum of each block using discrete cosine transform

    * The 64 spectral components of each block are quantized into a quantization table
    * Reduce high frequency compnents and recompute them during decompression
  3. Lossless compression
    * Compress quantized spectral component data stream using arithmetic or Huffman encoding
- Not a good choice for images such as line drawings