Set 6: Color Image Processing

Lecturer Arto Kaarna

Lappeenranta University of Technology (LUT)
School of Engineering Science (LENS)
Machine Vision and Pattern Recognition (MVPR)

Arto.Kaarna@lut.fi
http://www.lut.fi/web/en/school-of-engineering-science/research/machine-vision-and-pattern-recognition

Contents

- Color fundamentals
- Color models
- Pseudocolor image processing
- Full-color image processing
- Color transformations

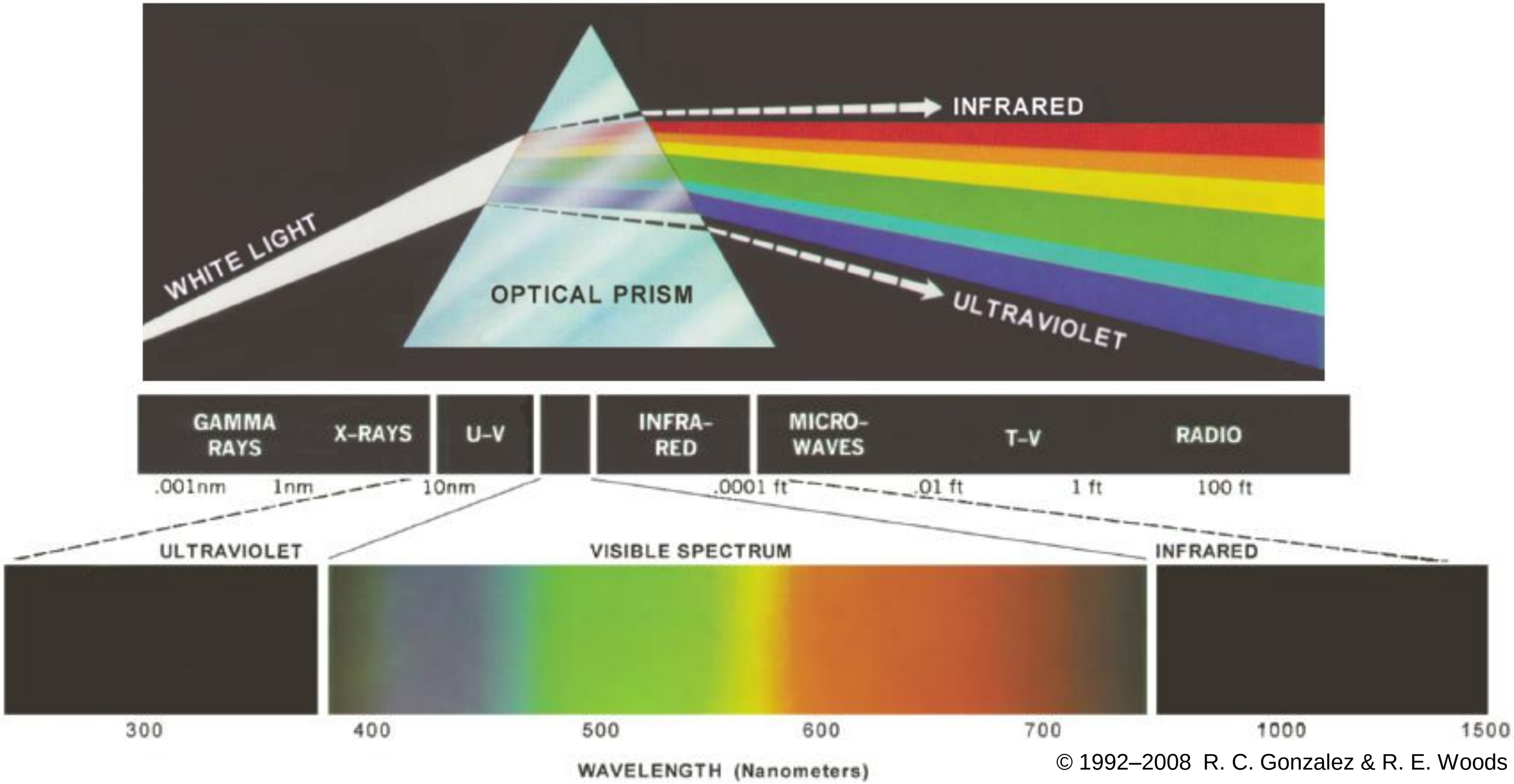
- Spectral images

Color fundamentals

- Color that humans (animals) perceive in an object are determined by the nature of light reflected from the object
- Visible light is composed of a relatively narrow band of frequencies in the electromagnetic spectrum
  - Lower wavelengths (higher frequencies): ultraviolet
  - Higher wavelengths (lower frequencies): infrared
  - Acromatic light has only intensity (no color, e.g. black and white TV)

Color fundamentals

- Electromagnetic spectrum



Color fundamentals

- Luminous intensity: intensity in a given direction, of a source that emits monochromatic radiation of frequency 540×1012 hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. A regular candle has intensity of one cd (*cd*).
- Illuminance: Luminous power incident on a surface (*lux*).
- Luminance: Luminous power per unit solid angle per unit projected source area. (cd/m^2)
- Luminous flux: Luminous energy per unit time (*lm, cd*sr*).

Color fundamentals

- Units related to human vision (photometry)
  - Wavelength
  - Brightness
    - a light source with a high luminous flux (lm),
    - a light source with a luminous flux concentrated into a very narrow beam (cd),
    - a light source against a dark background

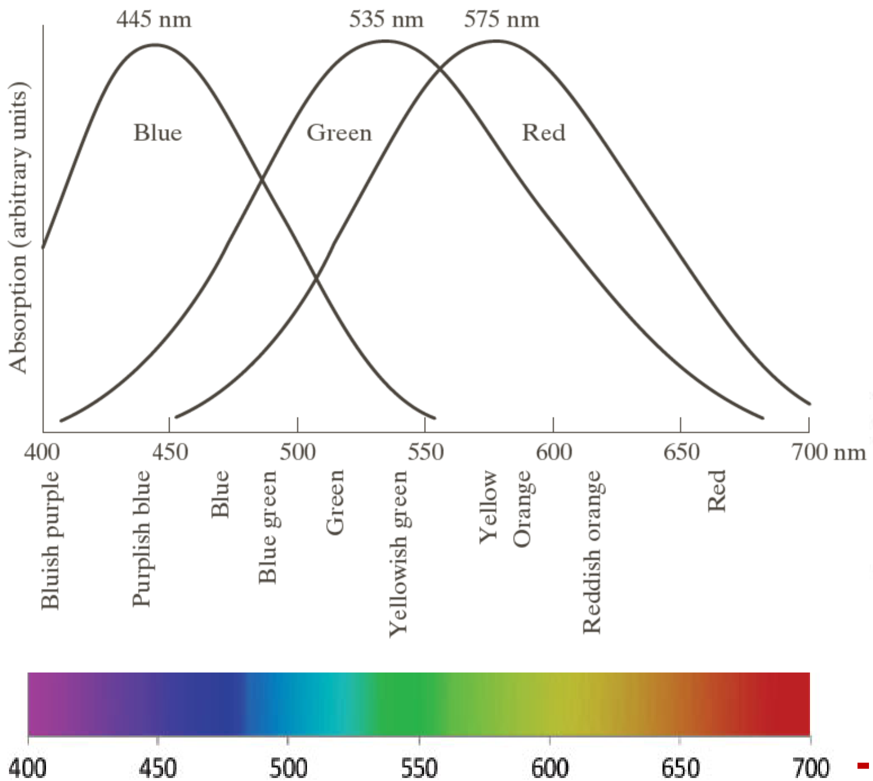
Photometric	**Radiometric**
Luminance (cd/m^{-2})	Radiance ($W \cdot sr^{-1} \cdot m^{-2}$)
Luminous flux (lm)	Radiant flux (w)
Luminous intensity (cd)	Radiant intensity (W/sr)

Color fundamentals

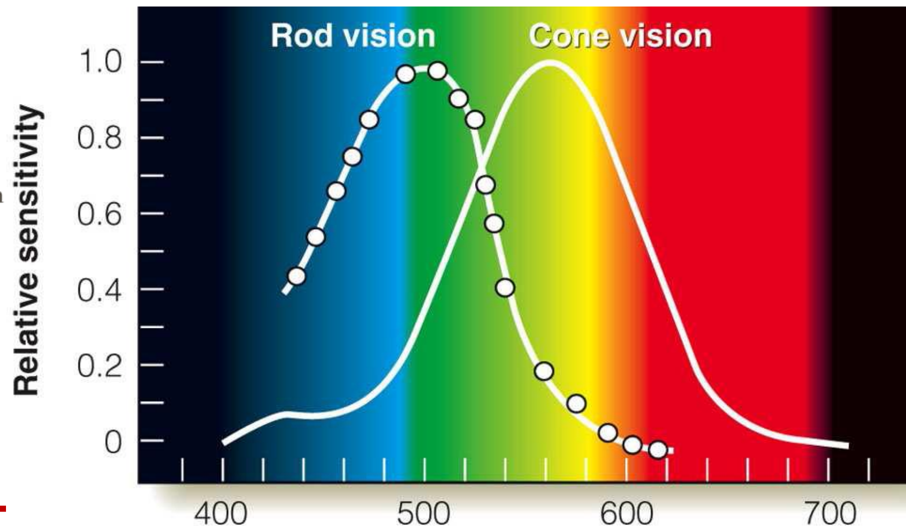
- Cones are the sensors in the human eye responsible for color vision
- 6-7 million cones divided into three principal sensing categories (R, G, B) -> primary colors (but no single color may be called red, green or blue)
  - Secondary colors: Magenta, Cyan and Yellow

Color fundamentals

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

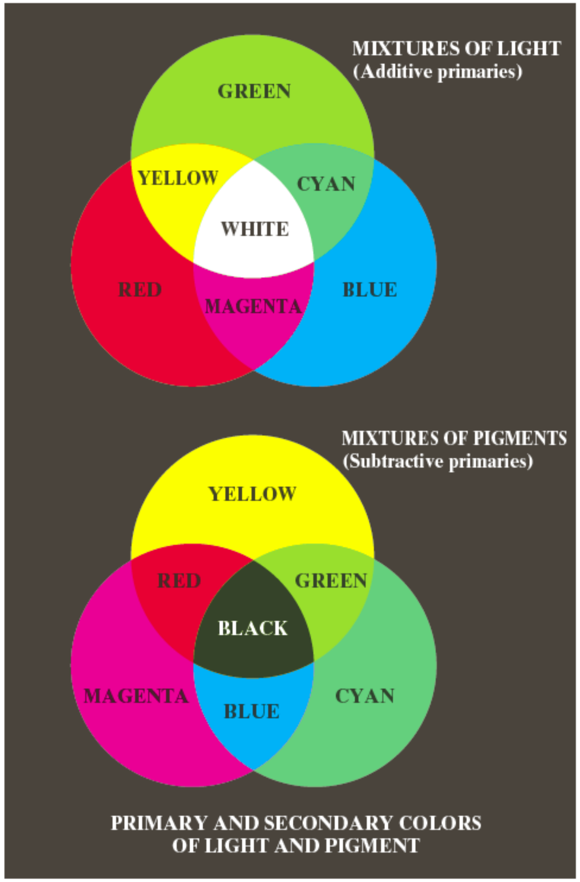


Rods: scotopic vision (low light)
mesopic vision
Cones: photopic vision (colors)



Color fundamentals

- ”A primary color of pigment is defined as the one that subtracts or absorbs a primary color of light and reflects or transmits the other two.”(Gonzalez-Woods)
- Primary colors of pigments are magenta, cyan and yellow (CMYK-printers)
  - Secondary colors R, G, B
- All pigment primaries -> black
- All light primaries -> white
- Additive vs. subtractive primaries



Color fundamentals

- Brightness
  - Subjective chromatic notion of intensity
- Hue
  - Represents dominant color (wavelength) as perceived by an observer
- Saturation
  - Relative purity or amount of white light mixed with a hue (pure spectrum colors are fully saturated, colors such as pink less saturated)

Color fundamentals

- Chromaticity: hue and saturation together
  - Color may be characterized by brightness and chromaticity
- Amounts of red, green and blue needed for any particular color are called tristimulus values and are denoted by *X*, *Y* and *Z*
- Trichromatic coefficients are then

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

Color fundamentals

- How are *X*, *Y*, and *Z* obtained?

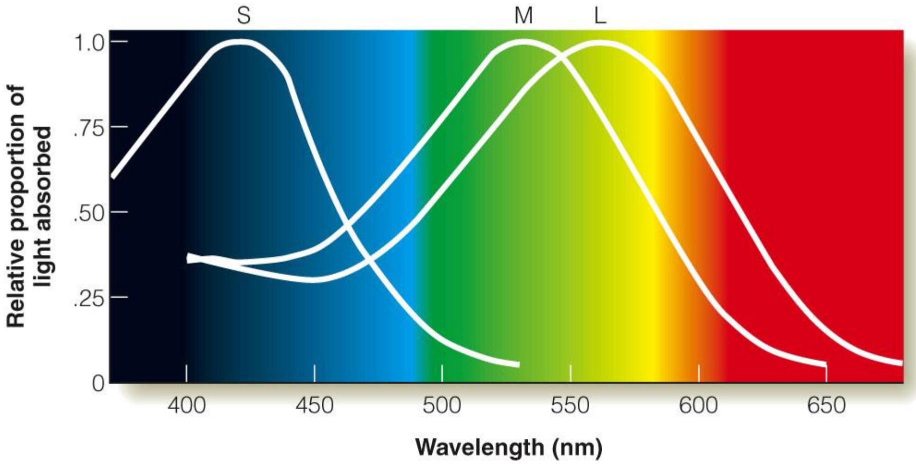
$$X = k \int_{\lambda} I(\lambda) O(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = k \int_{\lambda} I(\lambda) O(\lambda) \bar{y}(\lambda) d\lambda,$$

$$Z = k \int_{\lambda} I(\lambda) O(\lambda) \bar{z}(\lambda) d\lambda$$

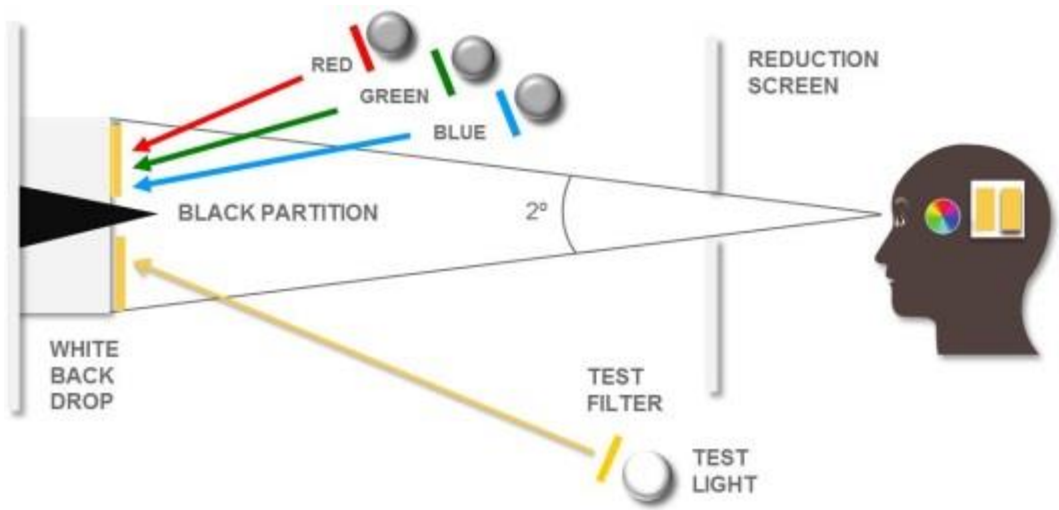
$$k = 100 / \int_{\lambda} I(\lambda) \bar{y}(\lambda) d\lambda$$

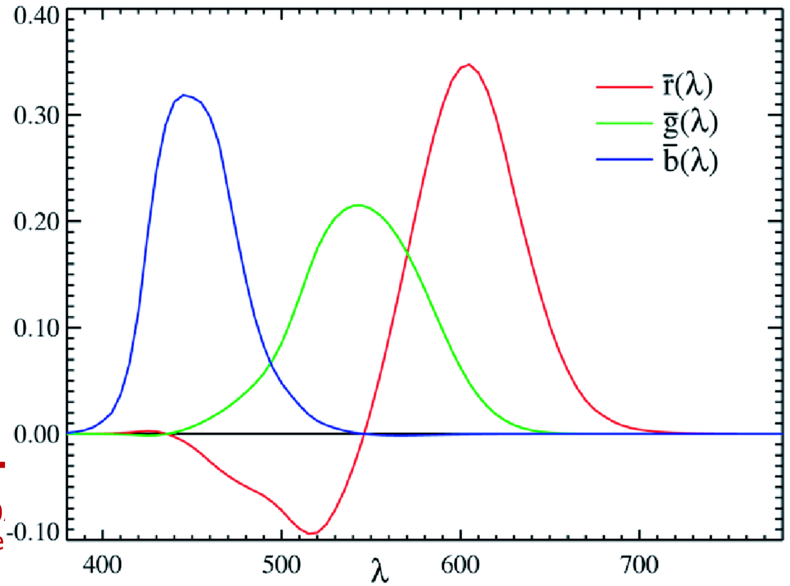
I: Illuminant
O: Object
k: Constant for scaling

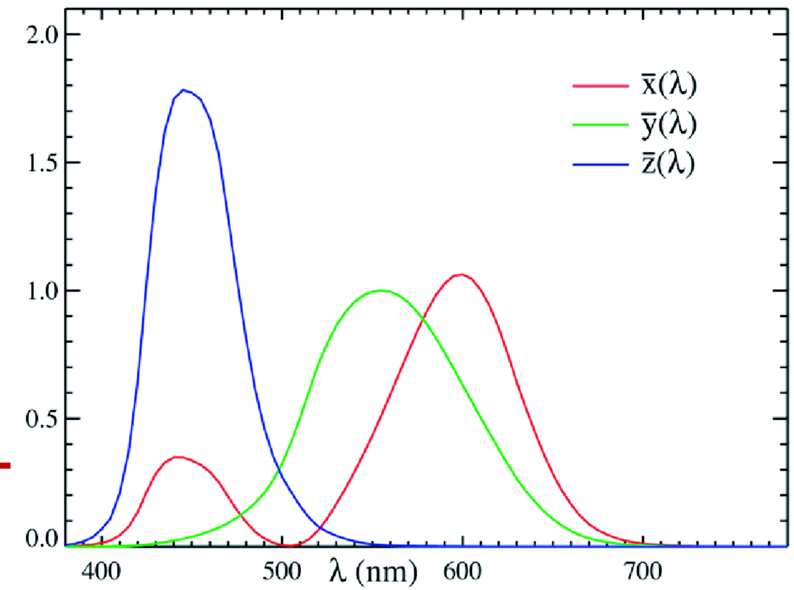


Color fundamentals

- Color matching functions

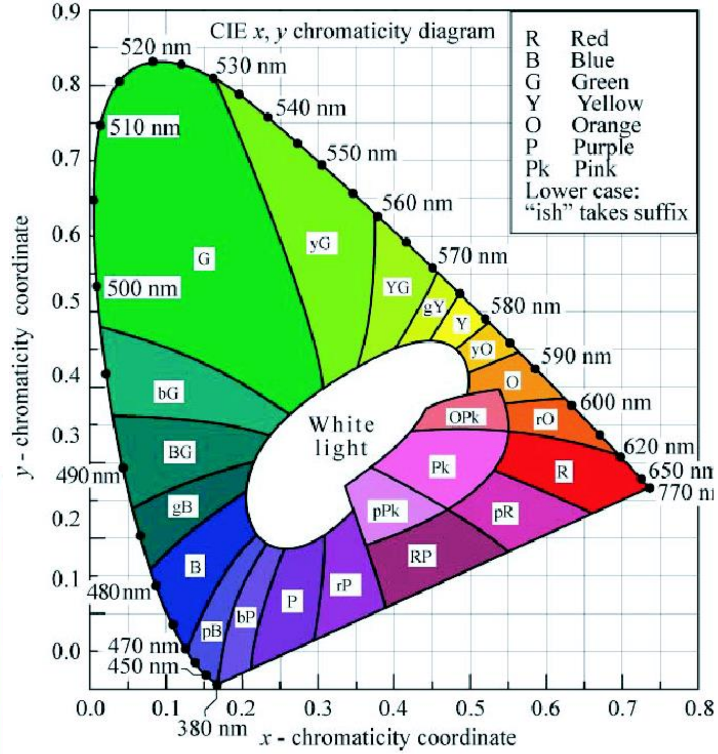




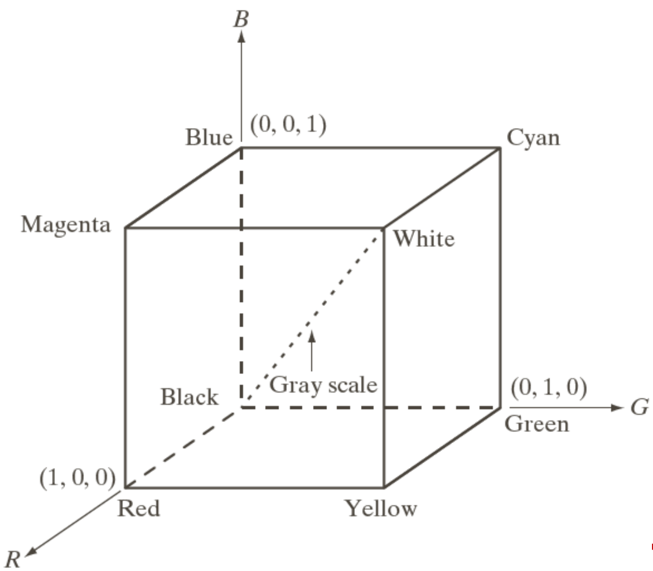


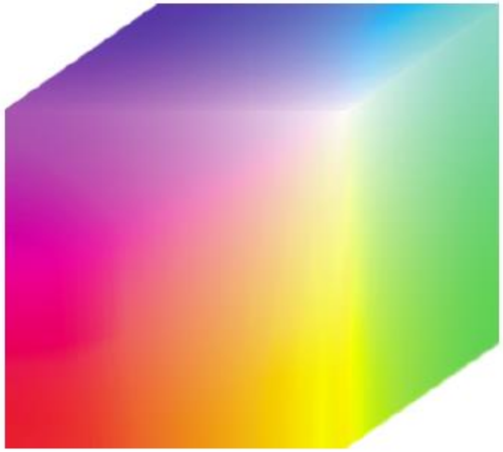
Color fundamentals

- As the results of modelling, there are various chromaticity (2D) and color (3D) spaces
- Some are suitable for devices, some are suitable for humans



xy chromaticity space





RGB solid color cube, composed of $(2^8)^3$=16 777 216 colors

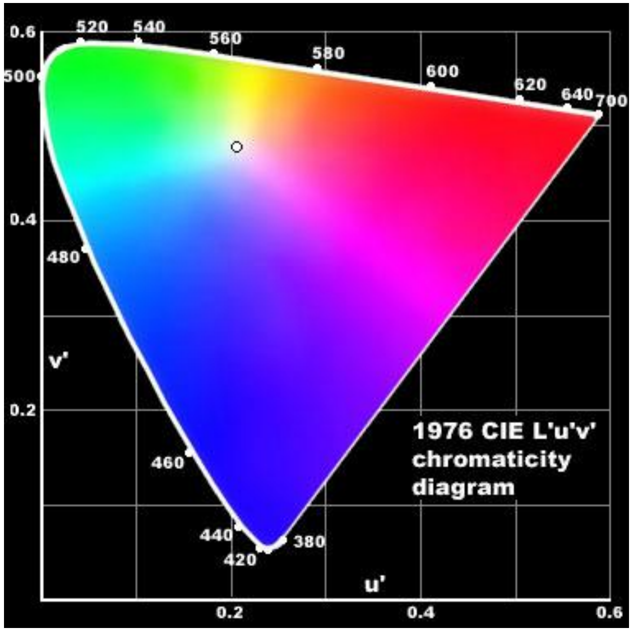
Color fundamentals

- Other color spaces

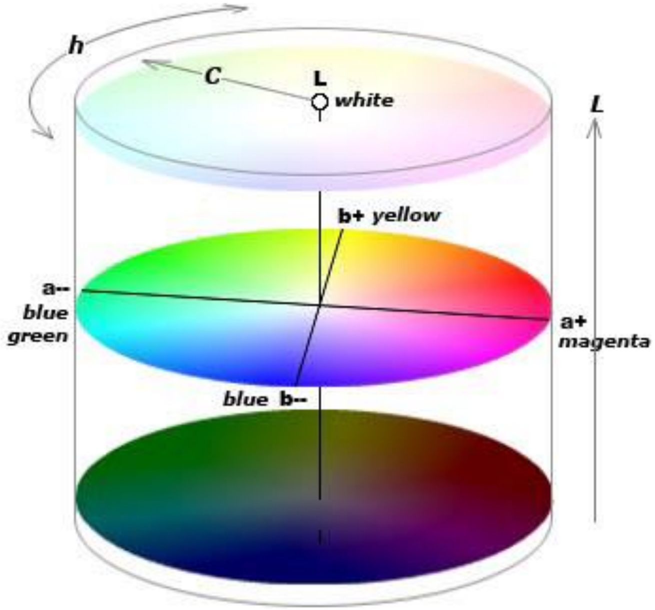
$$L^\star = 116 f(Y/Y_n) - 16$$
$$a^\star = 500\left[f(X/X_n) - f(Y/Y_n)\right]$$
$$b^\star = 200\left[f(Y/Y_n) - f(Z/Z_n)\right]$$

CMYK:

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



*Lu*v** rescales *xyY*



Lab color opponents

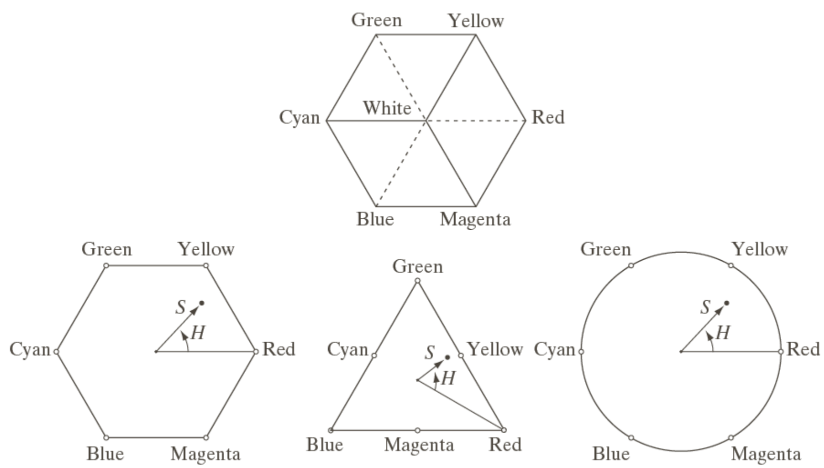
Color fundamentals

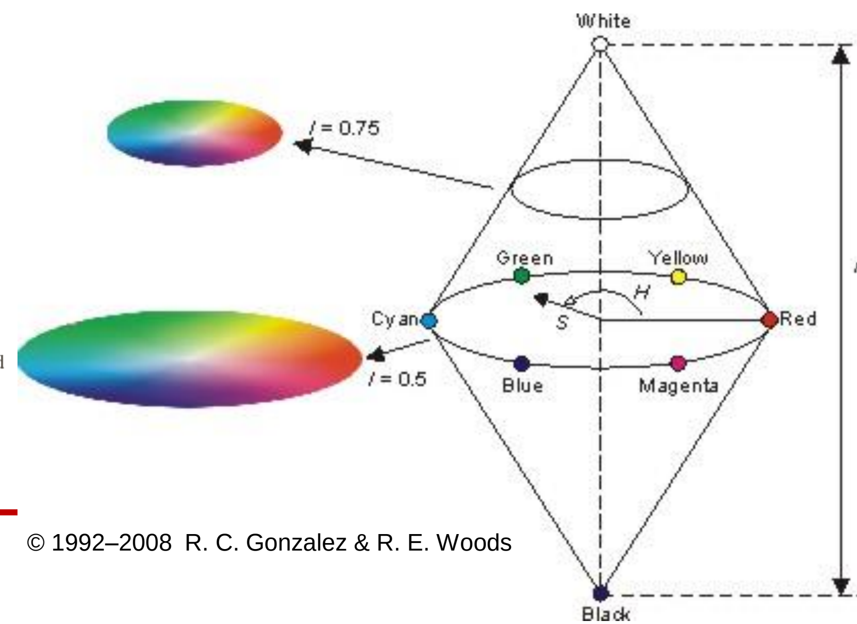
- HSI color space
  - Hue-Saturation planes, perpendicuar to the Intensity axis
  - Hue is defined by an angle from some reference point
  - Saturation is the length of the vector from the origin to a color point

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

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

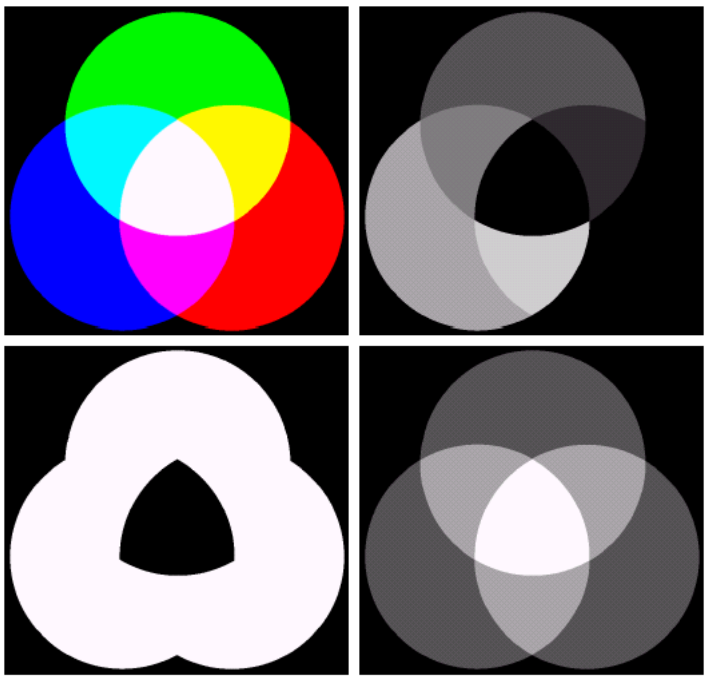
$$S = 1 - \frac{3}{(R+G+B)}\{\min(R,G,B)\}$$





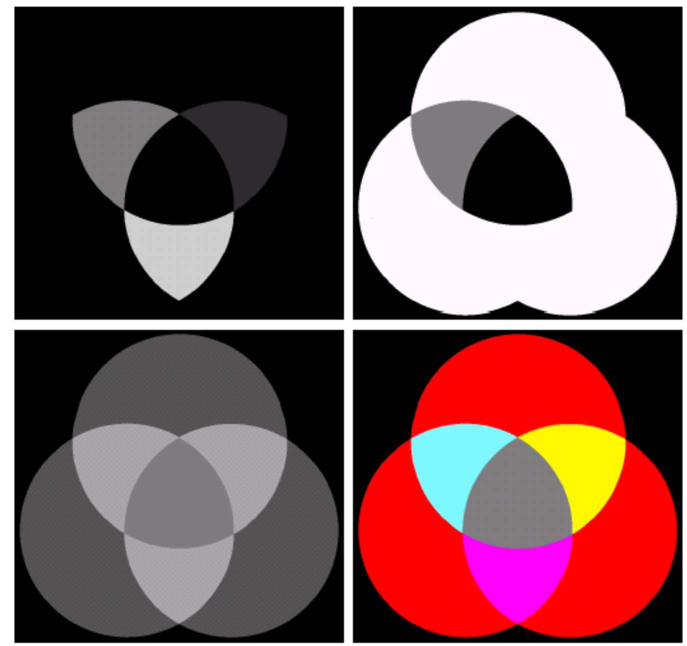
Color fundamentals

- RGB vs. HSI color spaces



a b
c d

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



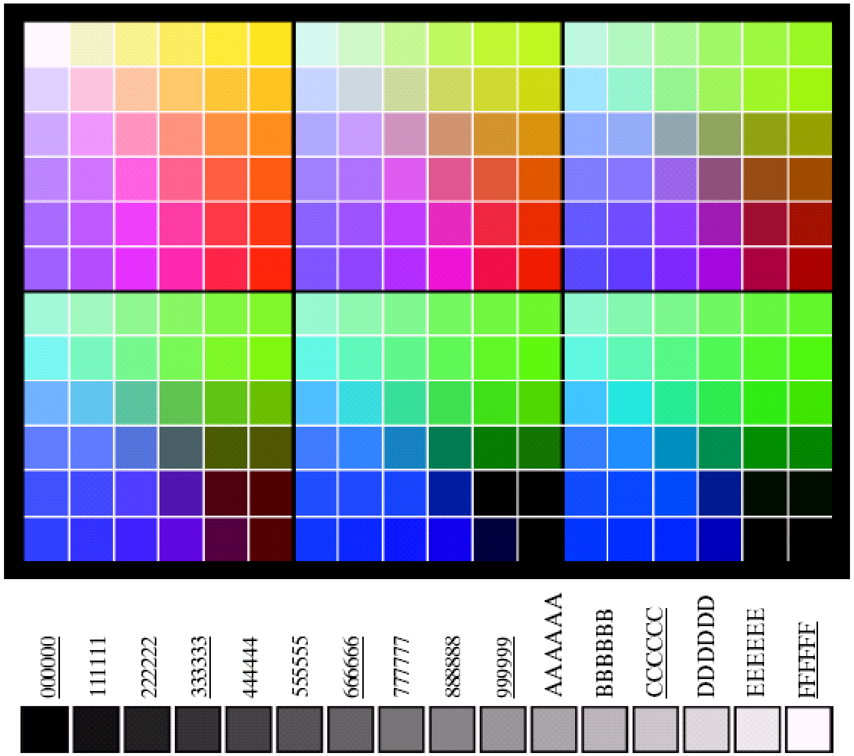
a b
c d

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

Color fundamentals

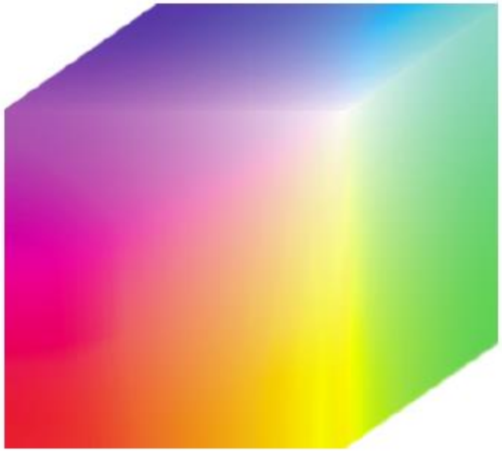
- Safe RGB colors
  - reproducing colors similarly with any device
  - only a limited set of all digital values are selected for presentation, totally 216 colors out of 256
  - FFFFFF -> FF0000
  - … 00FFFF -> 000000

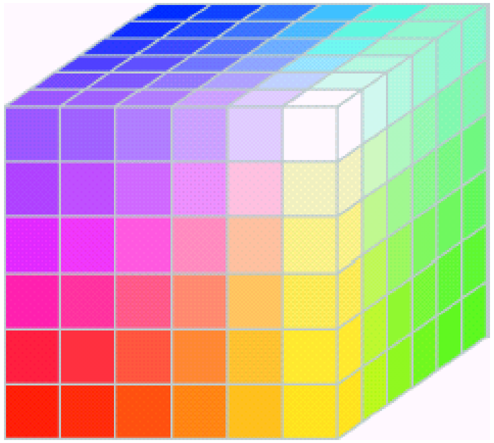
Number System	Color Equivalents					
Hex	00	33	66	99	CC	FF
Decimal	0	51	102	153	204	255



Color fundamentals

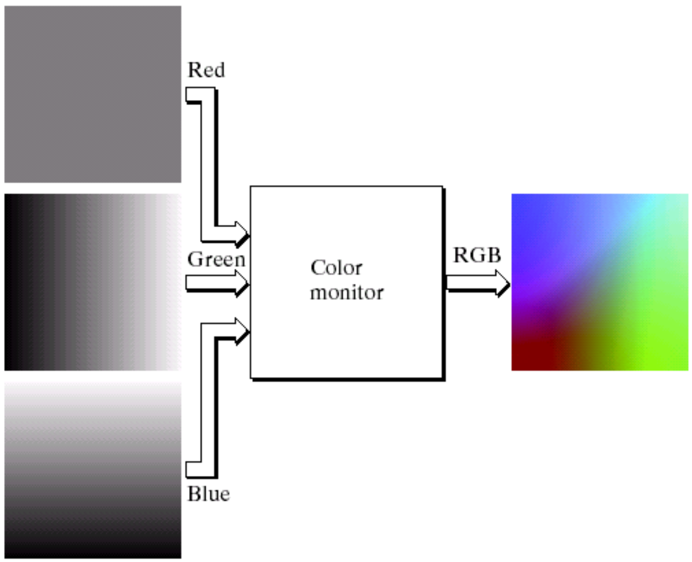
- RGB solid and safe RGB colors

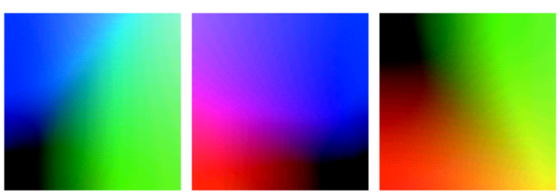




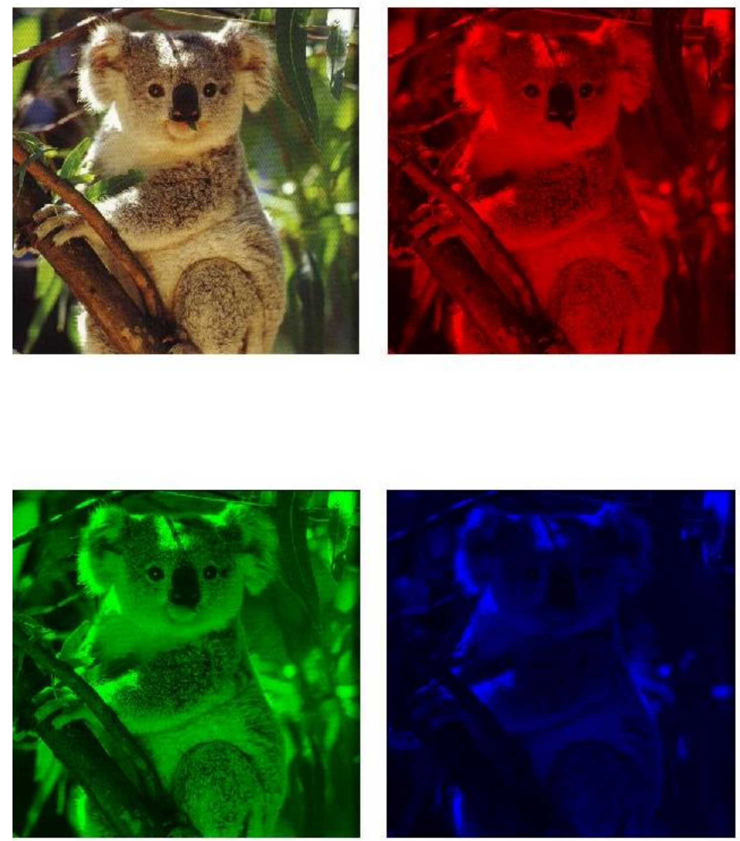
Color images

- Composing a RGB image





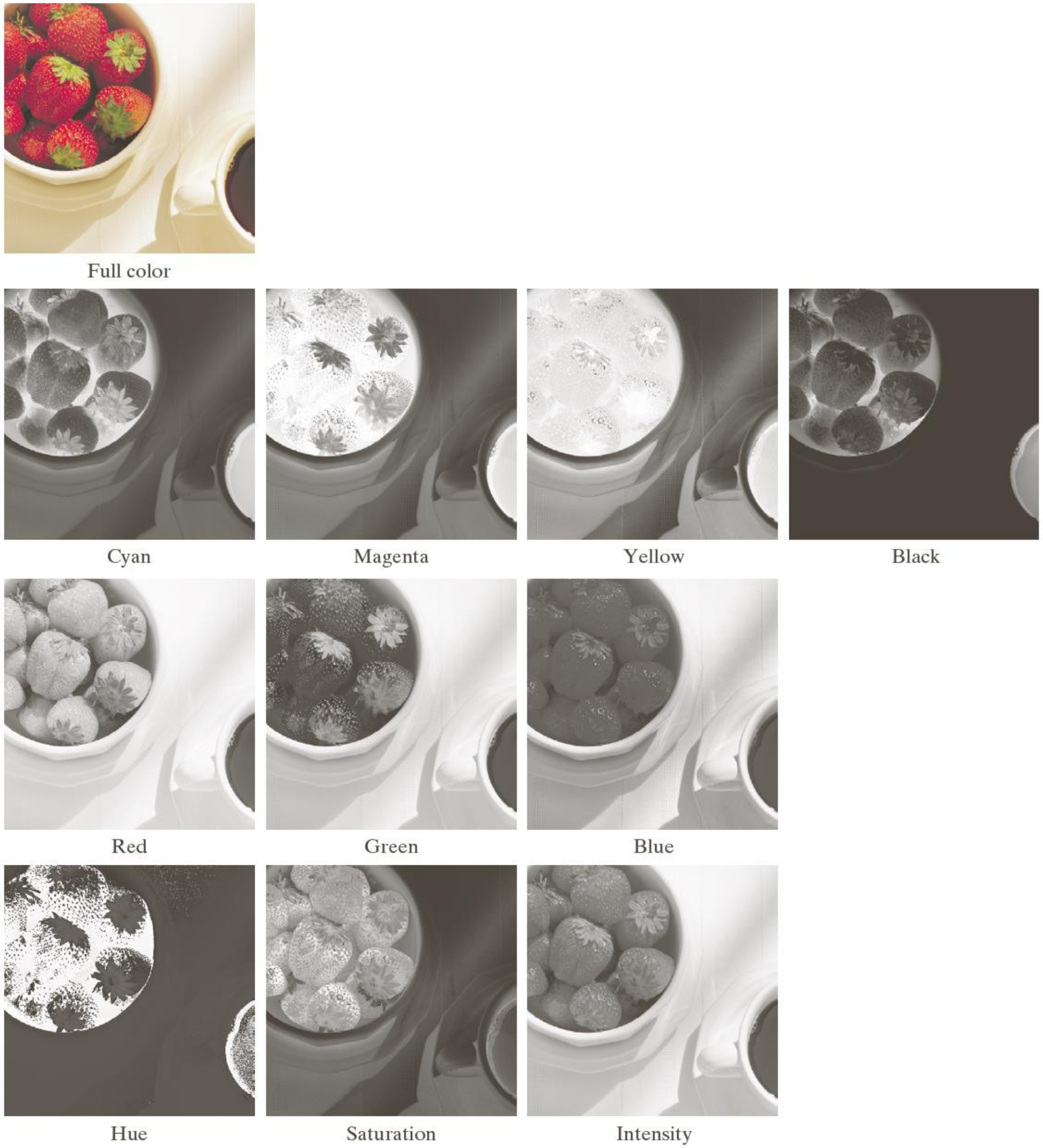
$(R = 0)$ $(G = 0)$ $(B = 0)$



Color images

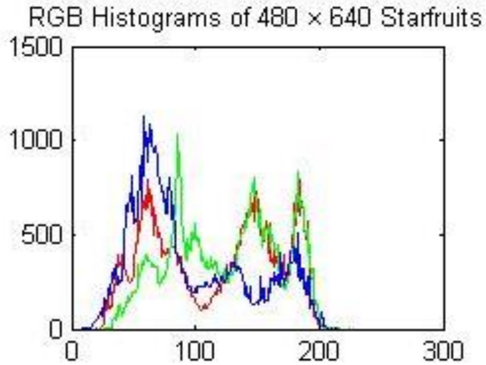
- Color components
- Full color vs.

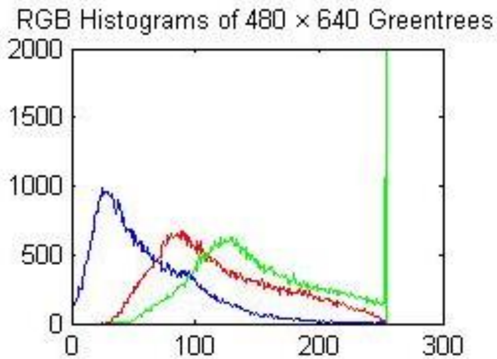
  CMYK, RGB, HSI

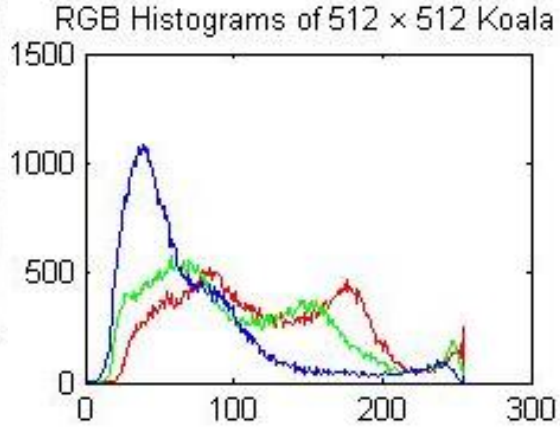


Color images

- Component-wise histograms







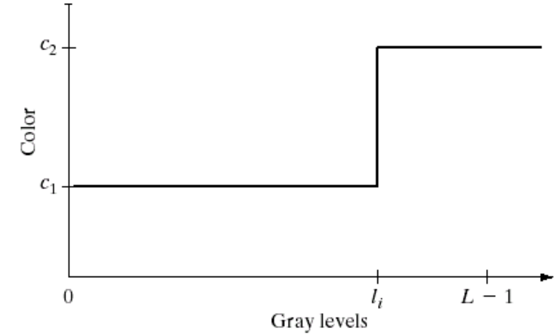
Color images

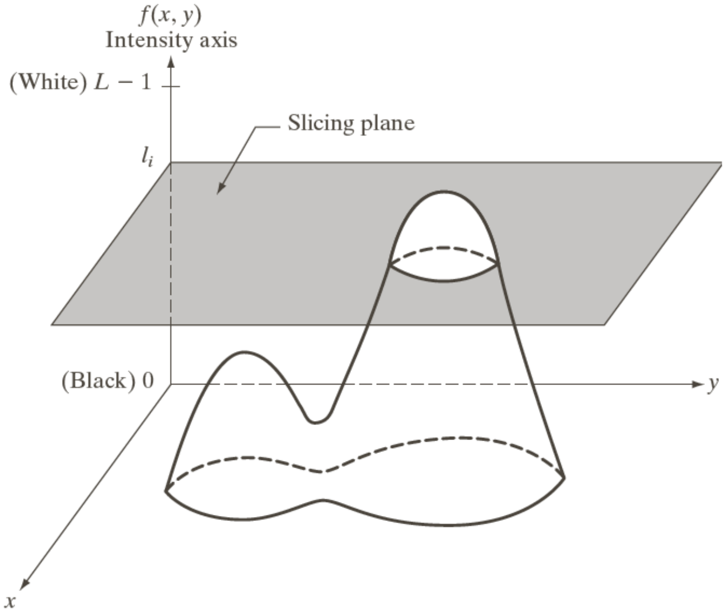
- Pseudocolor image processing
  - Assigning colors to gray values based on a specific criterion
  - The principal use is visualization and interpretation
    - Humans can discern thousands of color shades and intensities vs. about two dozen shades of gray
  - Intensity slicing
    - An image is interpreted as a 3D function
    - A plane slices the image function into two levels

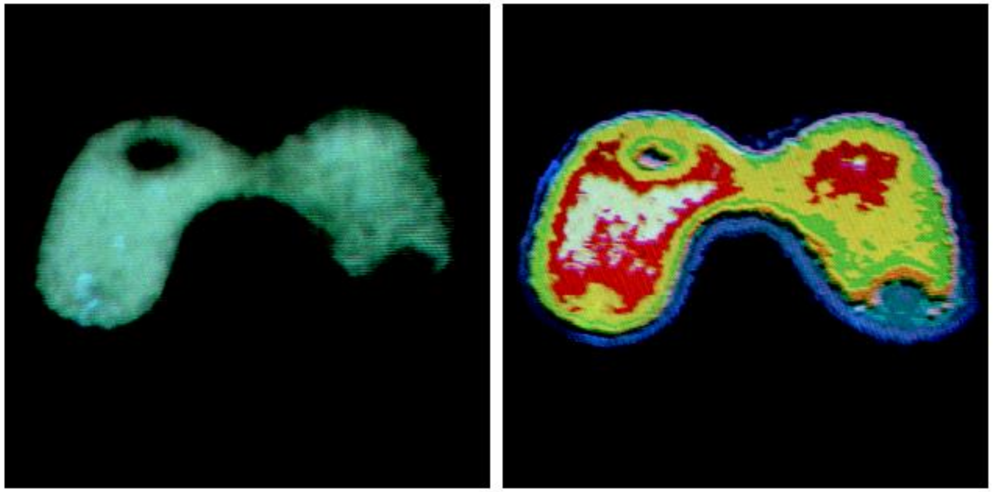
Color images

- Pseudocolor image processing: intensity slicing
- Multiple planes allow multiple colors

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



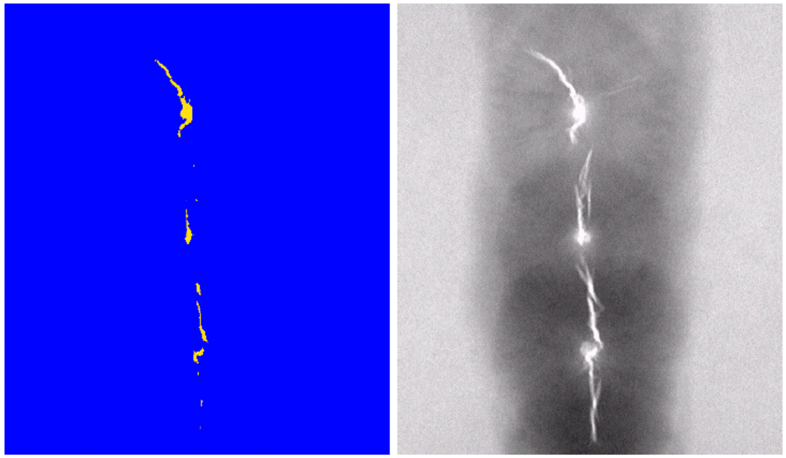


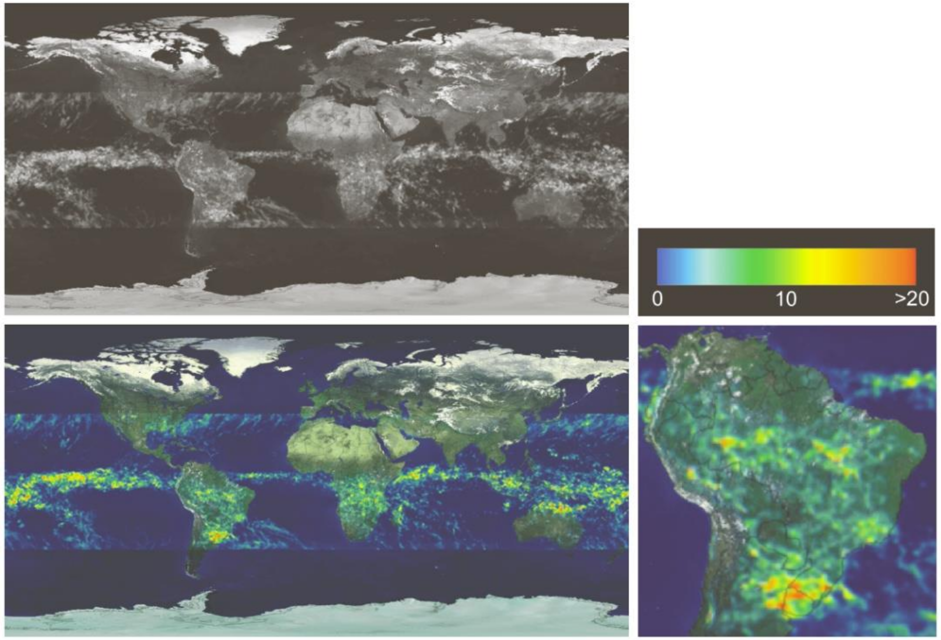


Color images

- Pseudocolor image processing: intensity slicing
  - One intensity only is of interest
  - Gray scale to color scale, e.g. annual rainfall

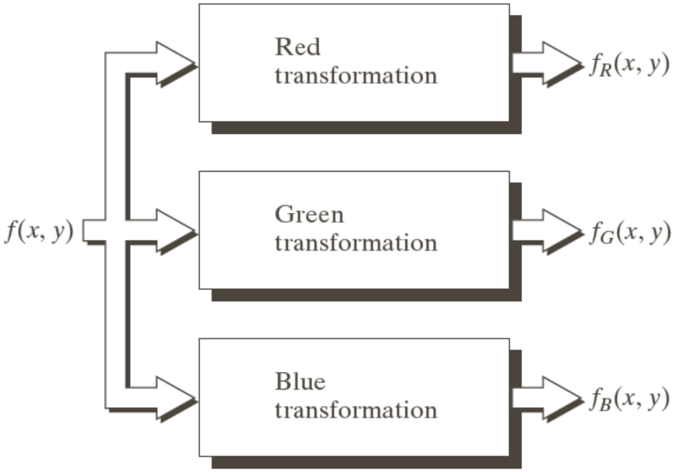
In X-ray of welded joints the defects are seen with a high intensity.

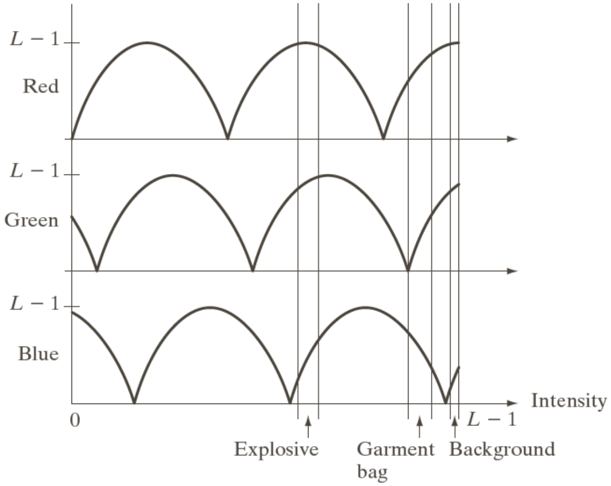




Color images

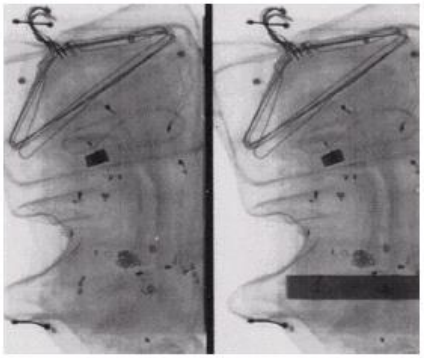
- Pseudocolor image processing
  - Intensity to color transformation: three independent transformations for intensity of each pixel

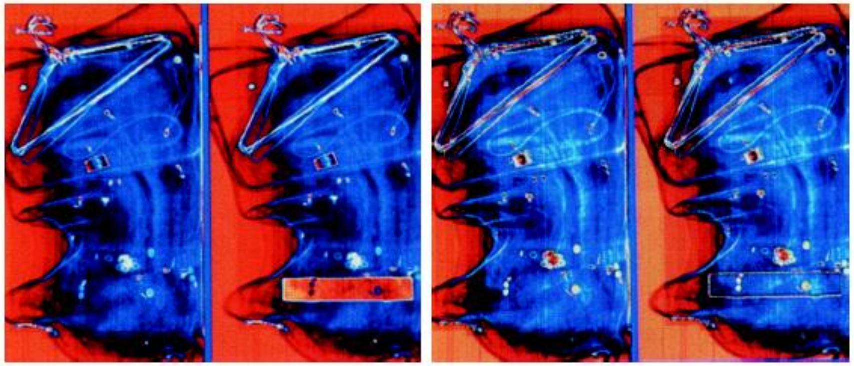


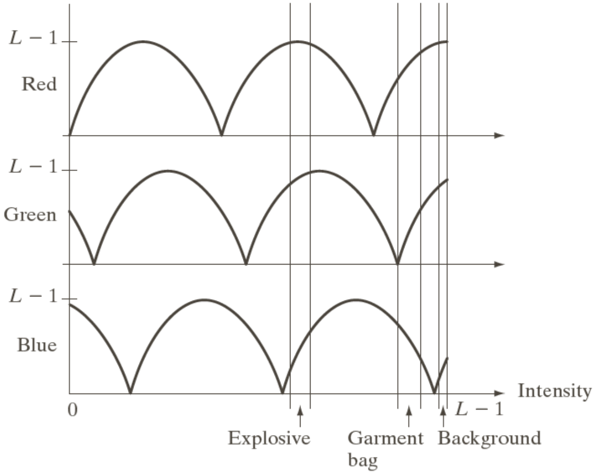


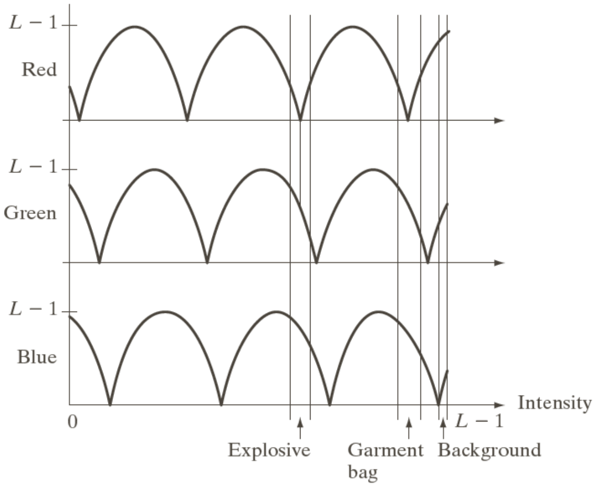
Color images

- X-ray imaging of baggage
  - Left: safe, right: plastic explosives
  - Left: explosives detected; right: ... missed
  - Up: better transformation, down: worse …



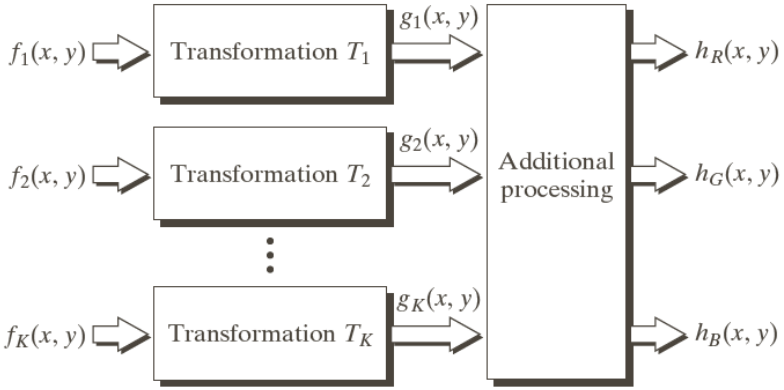


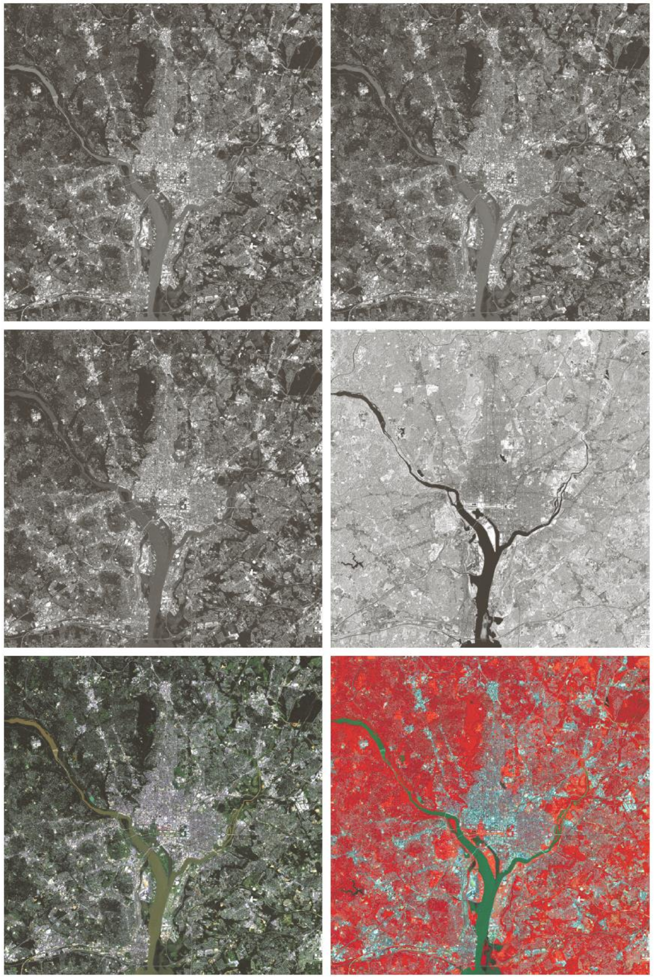




Color images

- Many times there are multiple intensity images which are composed into one color image, e.g. spectral images
  - multiple measurements (like bands) from a single target area

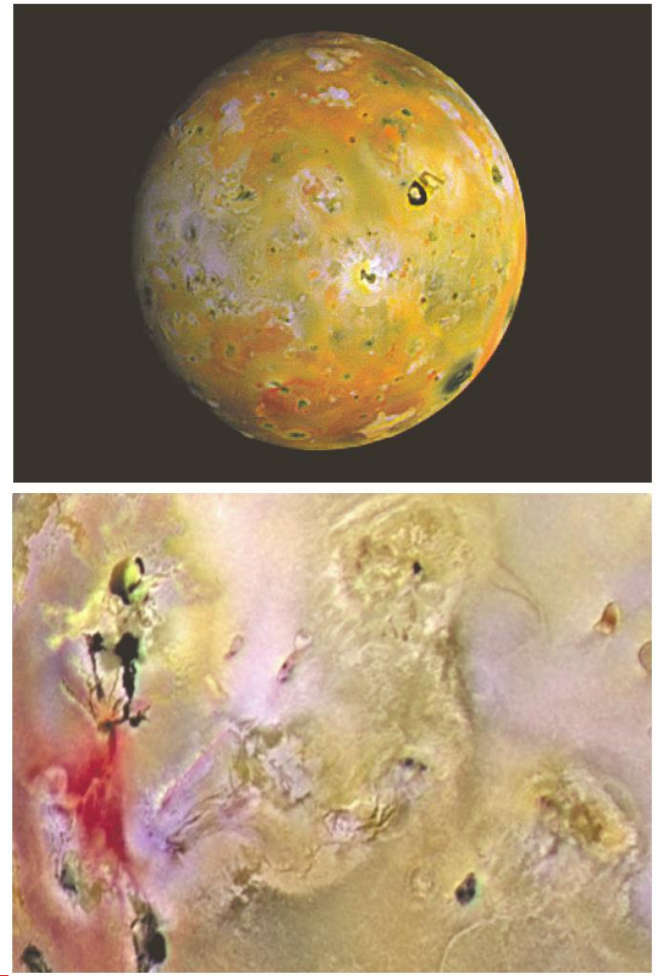




Bands 1,2,3,4 (NIR); 1,2,3; 1,2,4

Color images

- Another example for pseudo-color imaging
- From the moon of Jupiter, Io
  - Red: new material from an active volcano
  - Yellow: older sulfur deposits

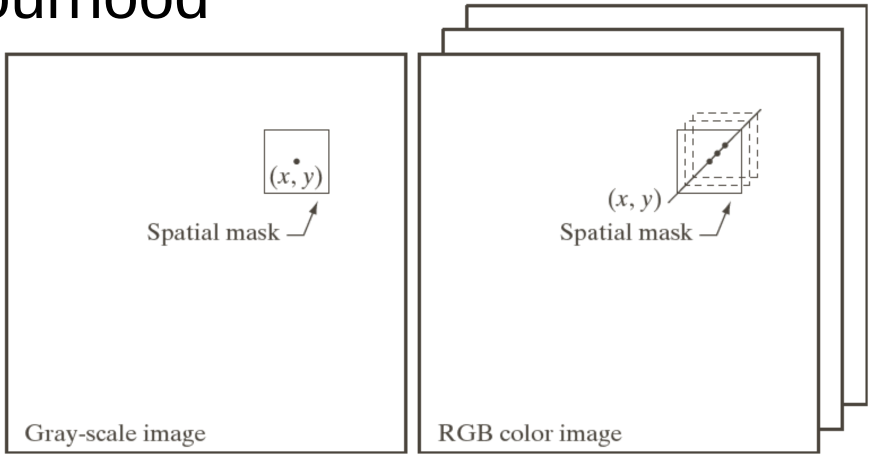


Color Image Processing

- In principle, there are two approaches
  - Process each component image separately
    - Processing similar to gray-scale images
    - Each component image may contain different type of information depending on the color space used
  - Working with pixel values directly (3-component vectors)
  - The two approaches produce similar results if
    - The process is applicable to scalars and vectors
    - Operation on each component of a vector is independent of the other components

Color Image Processing

- E.g. averaging operation, spatial masking of a gray-scale and of a color image
  - Left: summing and dividing by the number of pixels
  - Right: summing all the vectors and dividing each component by the number of vectors in the neighbourhood

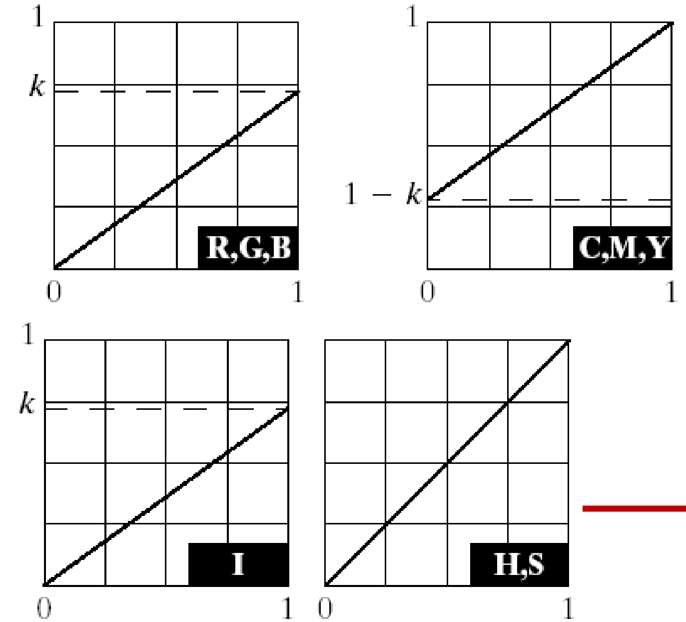


Color Image Processing

- Color transformations

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

- E.g. RGB, *n=3;* CMYK, *n=4*
- E.g. modifying the intensity of a
  - HSI-image: $s_1 = r_1, s_2 = r_2, s_3 = kr_3,\ \ \text{e.g. } k = 0.7$
  - RGB-image: $s_i = kr_i, i = 1,2,3$

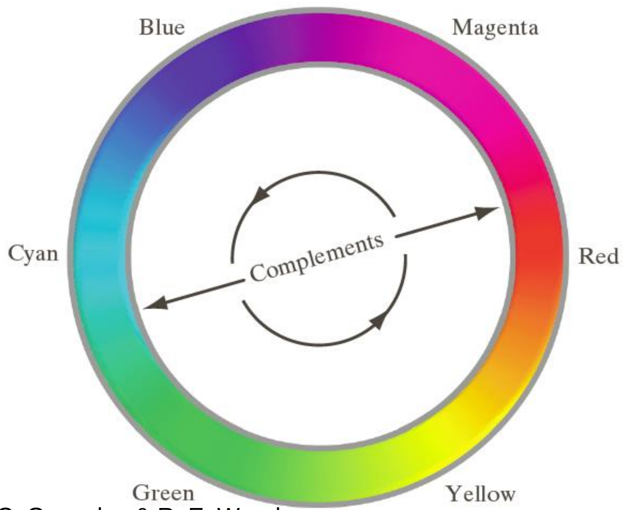


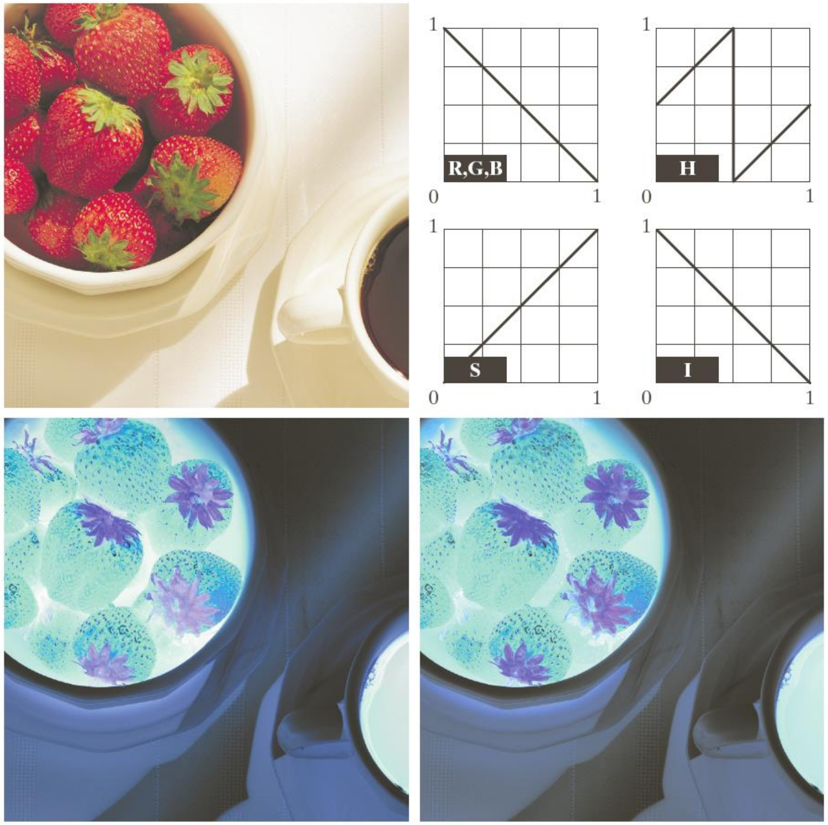
Color Image Processing

- Color complements: analogous to gray-scale negatives
- E.g. hue circle, and

  RGB and HSI complements,

  now S unaltered





Color Image Processing

- Color slicing to
  - Make the colors of interest separate better
  - Use a region of colors for masking in later processing
- More complicated than in the case of gray-scale values
- E.g. a neutral color replacing the original when the original is out of range

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

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

Color Image Processing

- Color slicing

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 $(0.5, 0.5, 0.5)$.

Color Image Processing

- Tone and color corrections
  - To maintain the color consistency between the various display devices
  - Device independent color space
    - Each device has its own color gamut
    - There should be a mapping between the color gamut of the device and the standard color gamut

$$L^* = 116 * h\left(\frac{Y}{Y_W}\right) - 16, \qquad h(q) = \begin{cases} \sqrt[3]{q}, & q > 0.008856 \\ 7.787q + \frac{16}{116}, & q \le 0.008856 \end{cases}$$

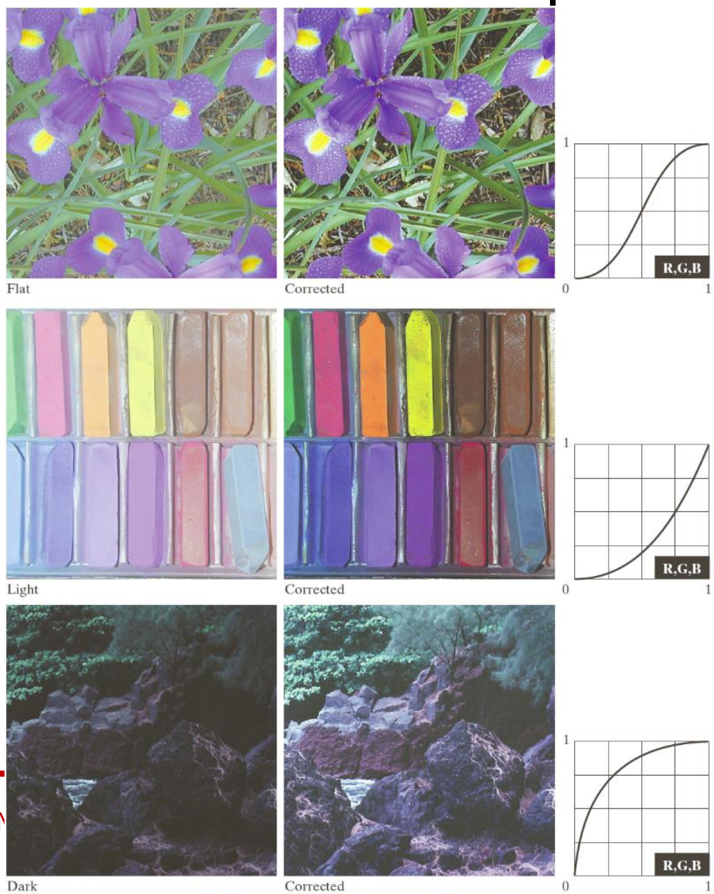
$$a^* = 500 * \left[h\left(\frac{X}{X_W}\right) - h\left(\frac{Y}{Y_W}\right)\right], \; b^* = 200 * \left[h\left(\frac{Y}{Y_W}\right) - h\left(\frac{Z}{Z_W}\right)\right]$$

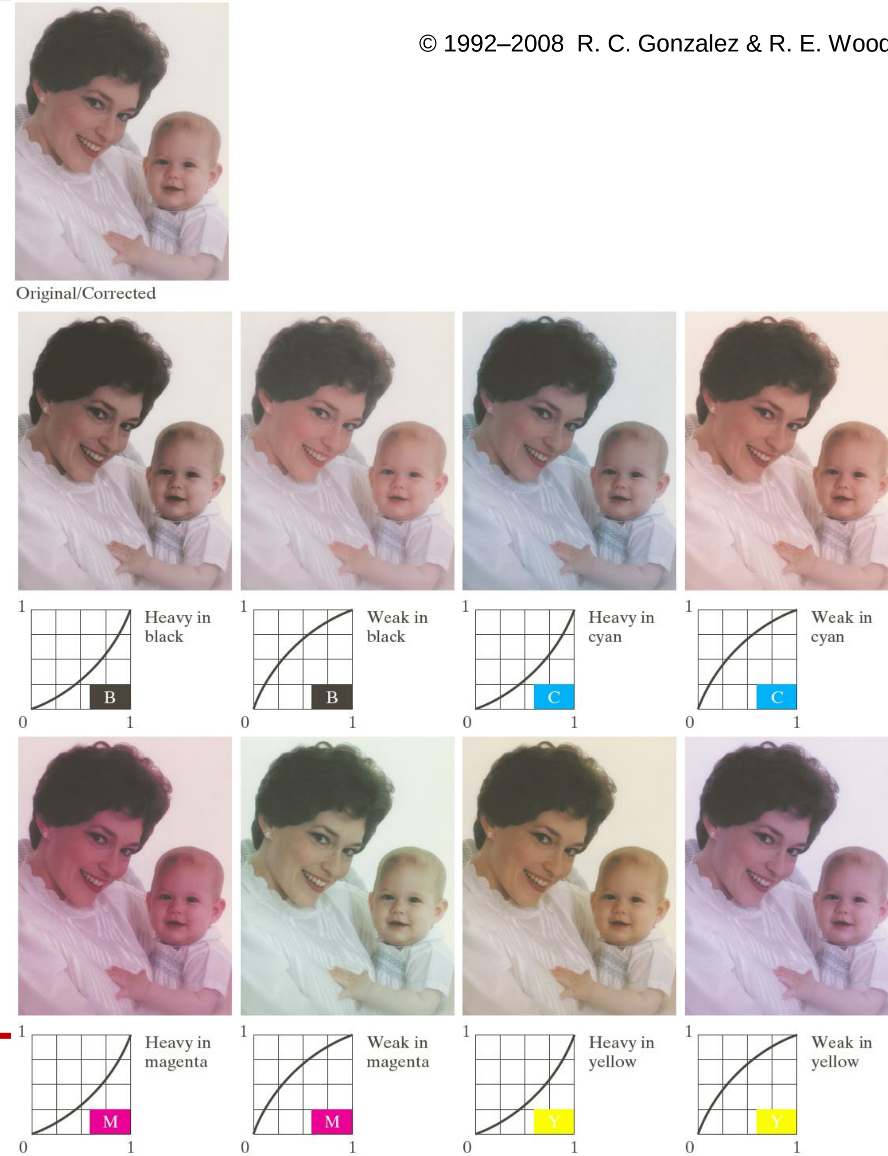
Color Image Processing

- $L^*a^*b^*$ is called
  - Colorimetric (matching colors are encoded similarly)
  - Perceptually uniform (which it is not)
  - Device independent
  - a^*b^* correspond to the two chromaticities
- Tonal range
  - High-key: colors with high intensities
  - Middle-key: between high and low
  - Low-key: colors in low intensities

Color Image Processing

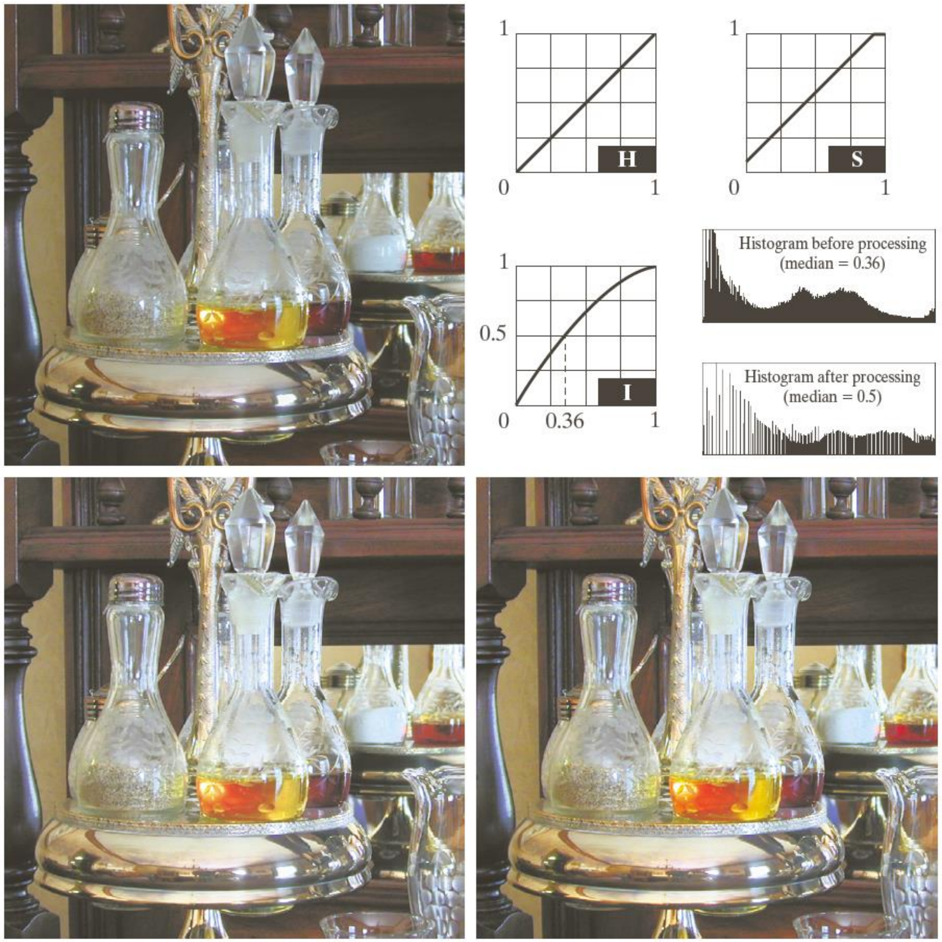
- Tuning image tones,
  RGB and CMYK spaces





Color Image Processing

- Histogram processing
  - Histogram equalization on the intensity channel only
  - The color channels (chromaticities) are not modified
- An example on HSI space (hue and saturation untouched) and also saturation tuned



Color Image Processing

- Image smoothing
- For a RGB image, the average of the RGB component vectors in the neighbourhood is

$$\bar{\boldsymbol{c}}(x,y) = \frac{1}{K}\sum_{(s,t)\in S_{xy}} \boldsymbol{c}(s,t)\,,\boldsymbol{c}(x,y) = \begin{bmatrix} c_R(x,y) \\ c_G(x,y) \\ c_B(x,y) \end{bmatrix} = \begin{bmatrix} R(x,y) \\ R(x,y) \\ R(x,y) \end{bmatrix}$$

and then

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

which means that smoothing of an RGB image it equal to the smoothing of each R,G, and B plane separately.

Color Image Processing

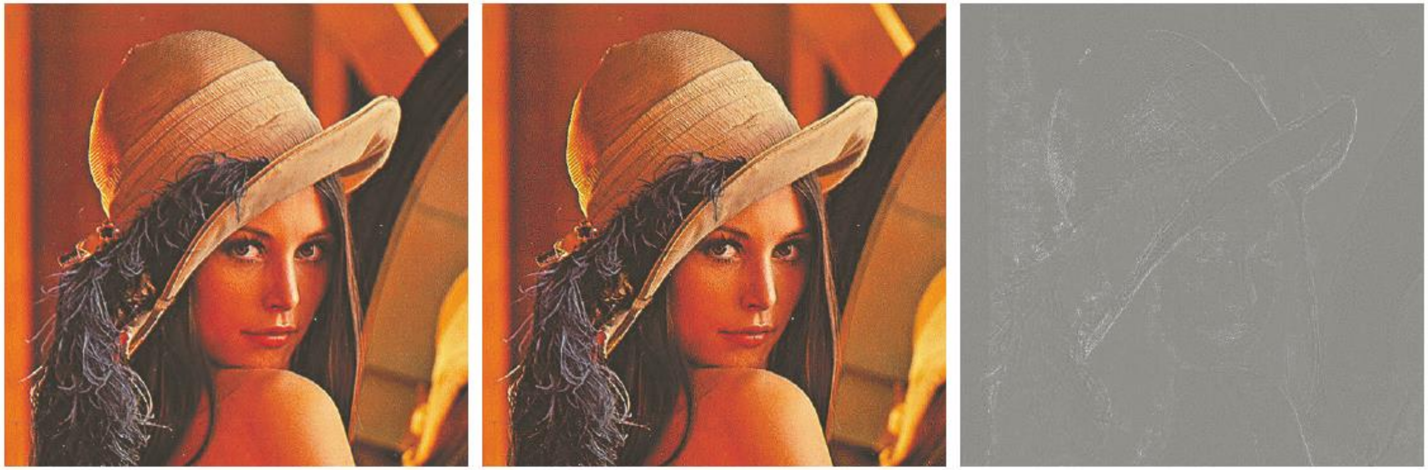
- RGB image and R, G, and B components
- After plane–wise smoothing (5x5), after smoothing I-component of the HSI-image, difference between the two

Color Image Processing

- Image sharpening: for the Laplacian filter in vector form

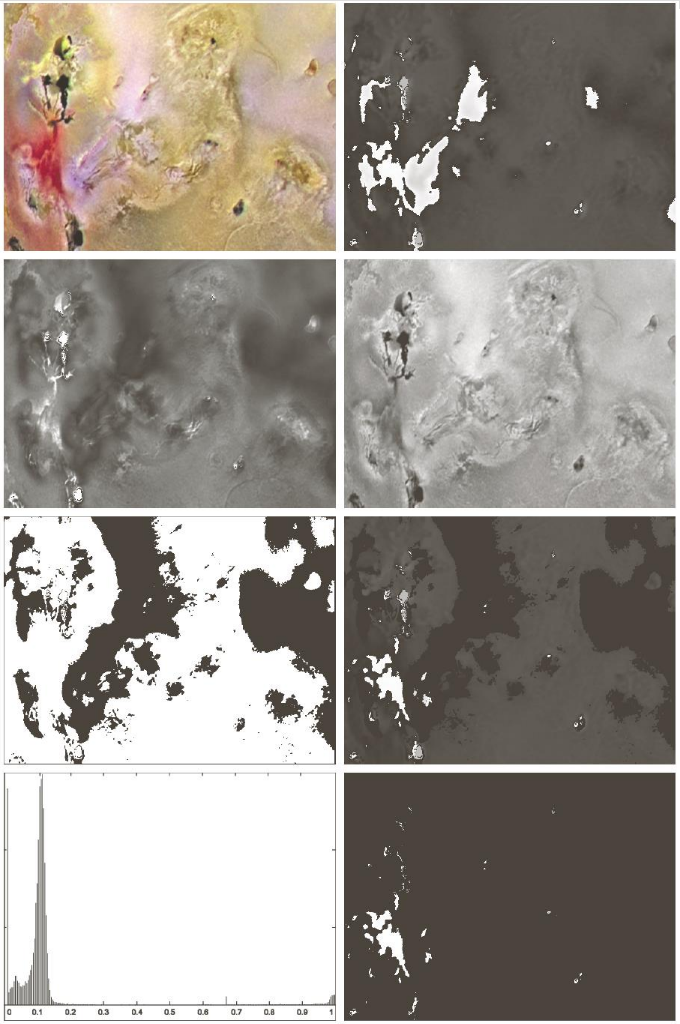
$$\nabla^2[\mathbf{c}(x,y)] = \begin{bmatrix} \nabla^2 R(x,y) \\ \nabla^2 G(x,y) \\ \nabla^2 B(x,y) \end{bmatrix}$$ which enables plane-wise processing

- Plane-wise sharpening an RGB image
- Sharpening the intensity plane of an HSI image



Color Image Processing

- Image segmentation
  - In HSI color space
    - H caarries the color information
    - S may be used for masking
  - In RGB space, a vector space is used in segmentation
  - The color of interest is $\boldsymbol{a}$
  - Color of the current pixel is $\boldsymbol{z}$
  - The distance metric D is needed



a b
c d
e f
g h

FIGURE 6.42 Image segmentation in HSI space. (a) Original. (b) Hue. (c) Saturation. (d) Intensity. (e) Binary saturation mask (black = 0). (f) Product of (b) and (e). (g) Histogram of (f). (h) Segmentation of red components in (a).

Color Image Processing

- Now the segmentation becomes

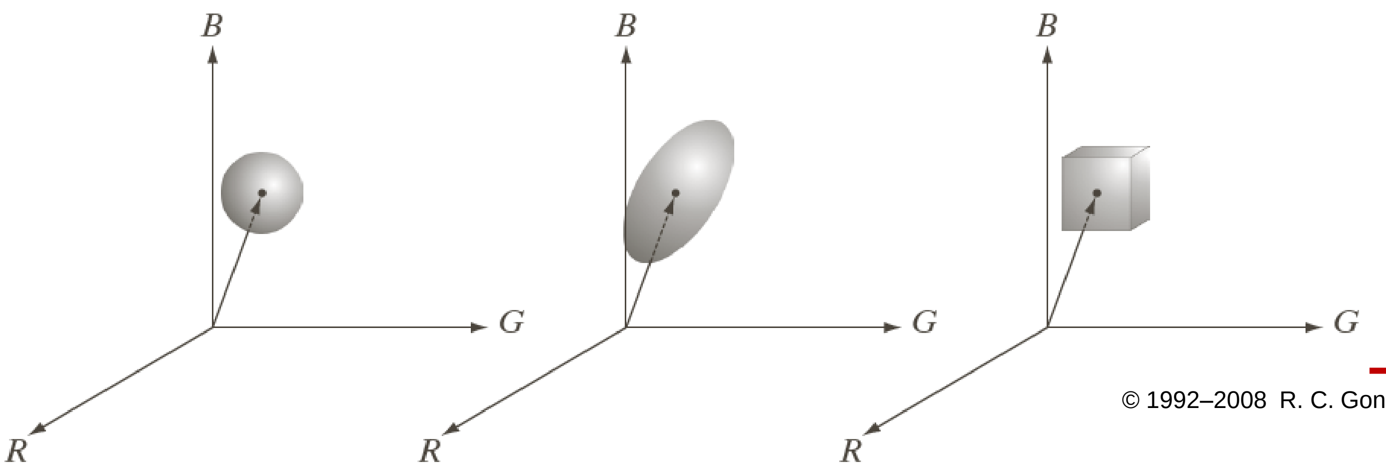
$$D(\boldsymbol{z},\boldsymbol{a}) = \|\boldsymbol{z}-\boldsymbol{a}\| = [(\boldsymbol{z}-\boldsymbol{a})^T(\boldsymbol{z}-\boldsymbol{a})]^{1/2}$$

$$= [(z_R-a_R)^2+(z_G-a_G)^2+(z_B-a_B)^2]^{1/2}$$

$$D(\boldsymbol{z},\boldsymbol{a}) \le D_0$$

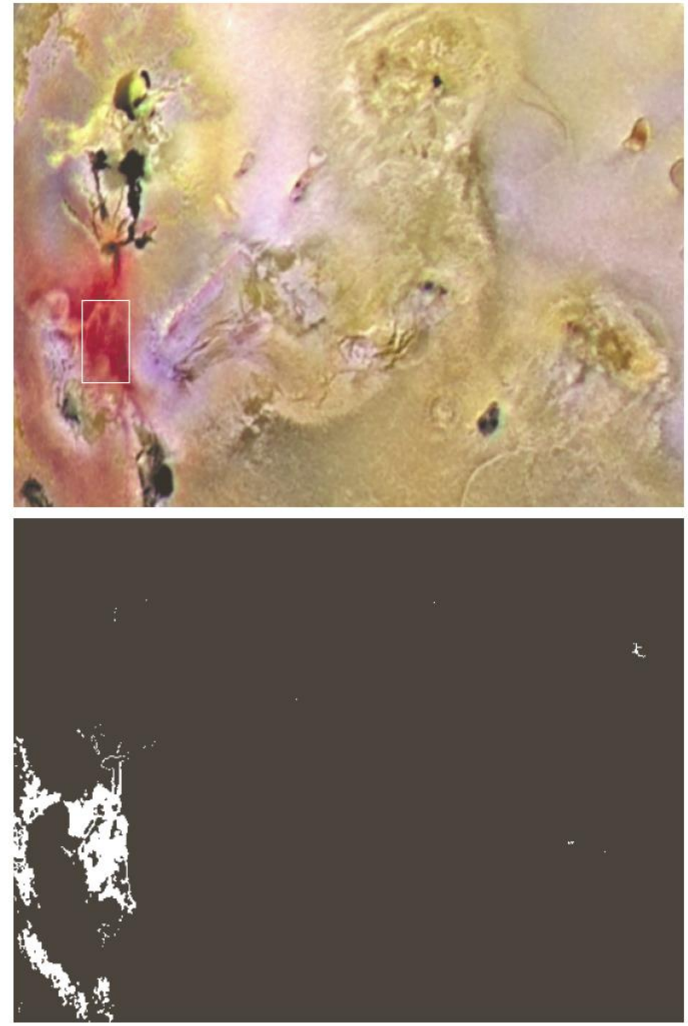
- In general,

$$D(\boldsymbol{z},\boldsymbol{a}) = [(\boldsymbol{z}-\boldsymbol{a})^T\boldsymbol{C}^{-1}(\boldsymbol{z}-\boldsymbol{a})]^{1/2}$$



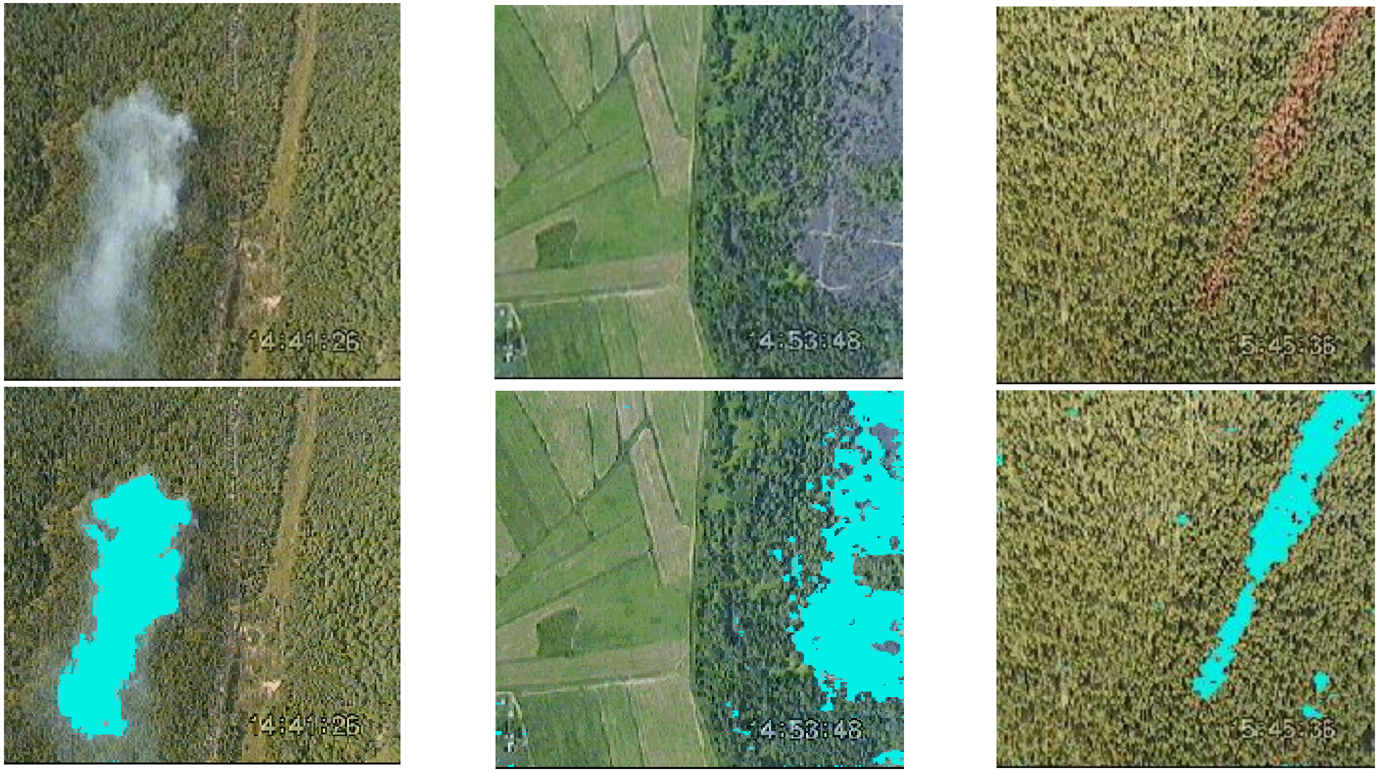
Color Image Processing

- Color image segmentation
  - Reddish colors of interest (rectangle on right)
  - The 3D box for distances is of size $(a_R \pm 1.25\sigma_R)$
  - The segmentation is more precise as that from the HSI color space



Color Image Processing

- Image segmentation based on color feature: burnt forest area, forest fire, dead forest (brown)



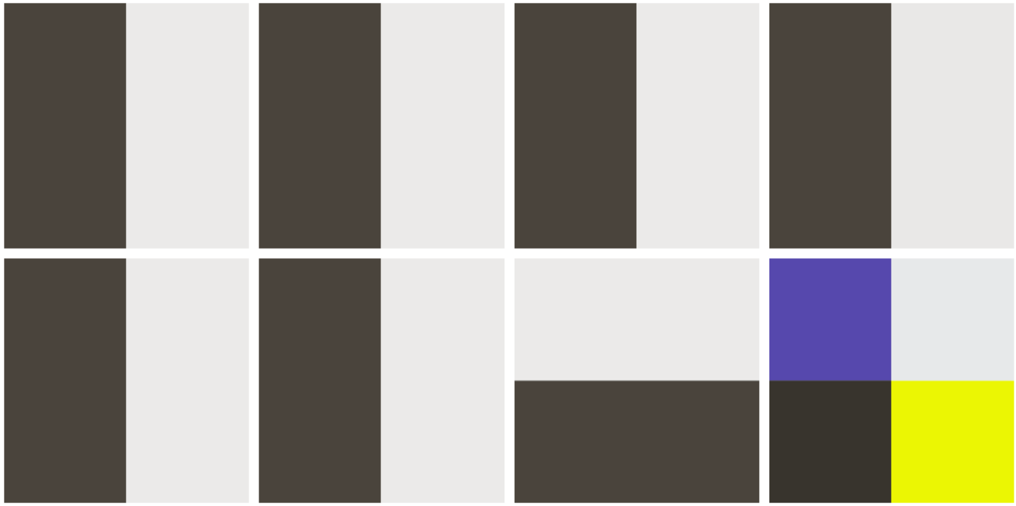
Color Image Processing

- Edge detection
  - The edges can be found separately from each plane
    - In most cases the results are satisfactory
  - Anyhow, the combination may be problematic

    E.g. R,G,B, RGB;

    and the center

    point of the image



Color Image Processing

- It can be shown than for a vectorized values, the direction of maximum rate of change of ***c****(x,y)* is in direction

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

and the rate of change is

$$F_\theta(x,y) = \left\{\frac{1}{2}\left[\left(g_{xx} + g_{yy}\right) + \left(g_{xx} - g_{yy}\right)cos2\theta(x,y) + 2g_{xy}sin2\theta(x,y)\right]\right\}^{1/2}$$

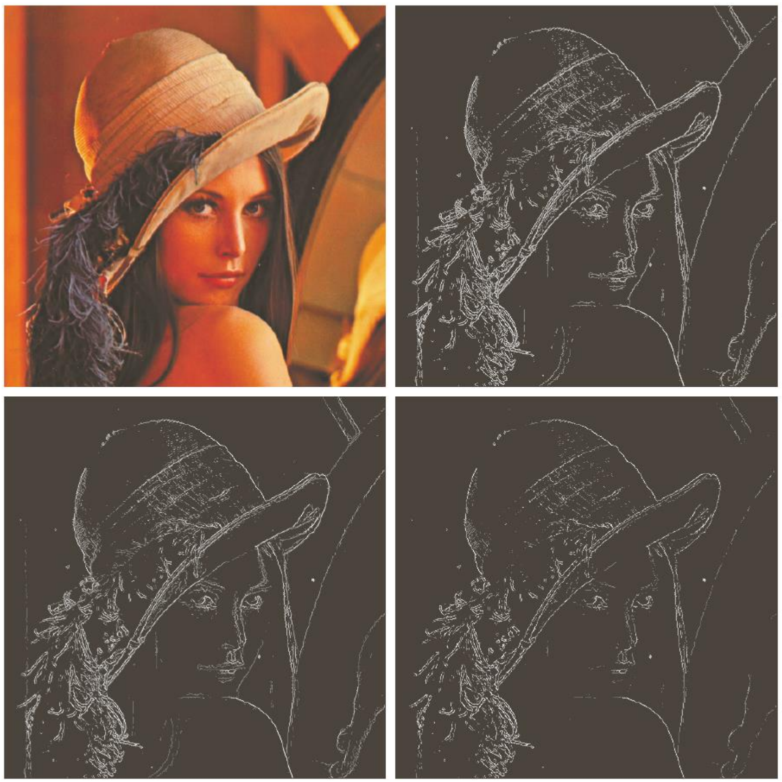
where e.g.

$$g_{xx} = \boldsymbol{u} \cdot \boldsymbol{u} = \boldsymbol{u}^T\boldsymbol{u}, \qquad \boldsymbol{u} = \frac{\partial R}{\partial x}\boldsymbol{r} + \frac{\partial G}{\partial x}\boldsymbol{g} + \frac{\partial B}{\partial x}\boldsymbol{b}$$

$\boldsymbol{r}$ is a unit vector along R axis (etc.)

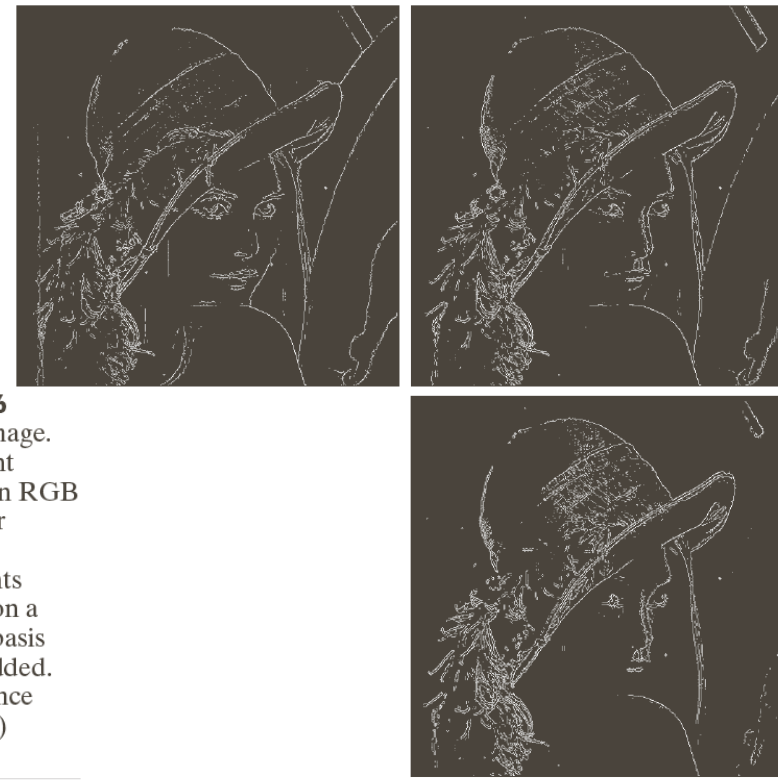
Color Image Processing

- Example on edge detection, gradient images



a b
c d

FIGURE 6.46
(a) RGB image.
(b) Gradient computed in RGB color vector space.
(c) Gradients computed on a per-image basis and then added.
(d) Difference between (b) and (c).



Color Image Processing

- Noise in color image
  - In principle, the noise content is similar in all channels
  - Exceptions: color filtering affects one channel only; electronics malfunctioning in one channel; various illumination conditions for various channels
  - Noise can be removed from eacg color component separately
    - Averaging filters operate similarly with scalars and vectors
    - How to find a medium from a set of vectors?

Color Image Processing

- Noise in color images
- Example: Gaussian noise in each channel; R,G,B and RGB;

  HSI

Color Image Processing

- Salt-and-pepper noise in G channel
- Noisy RGB image
- The corresponding H, S, and I components

Summary