Color Imaging

Delivered by

Dr. Subarna Chatterjee
subarna.cs.et@msruas.ac.in

CONTENTS

- Color Models
  - The RGB Color Model,
  - The CMY and
  - CMYK Color Models,
  - The HSI Color Model,
- Pseudocolor Image Processing,
- Intensity Slicing,
- Gray Level to Color Transformations,
- Basics of Full-Color Image Processing,
- Color Transformations.

Color Imaging

- Light

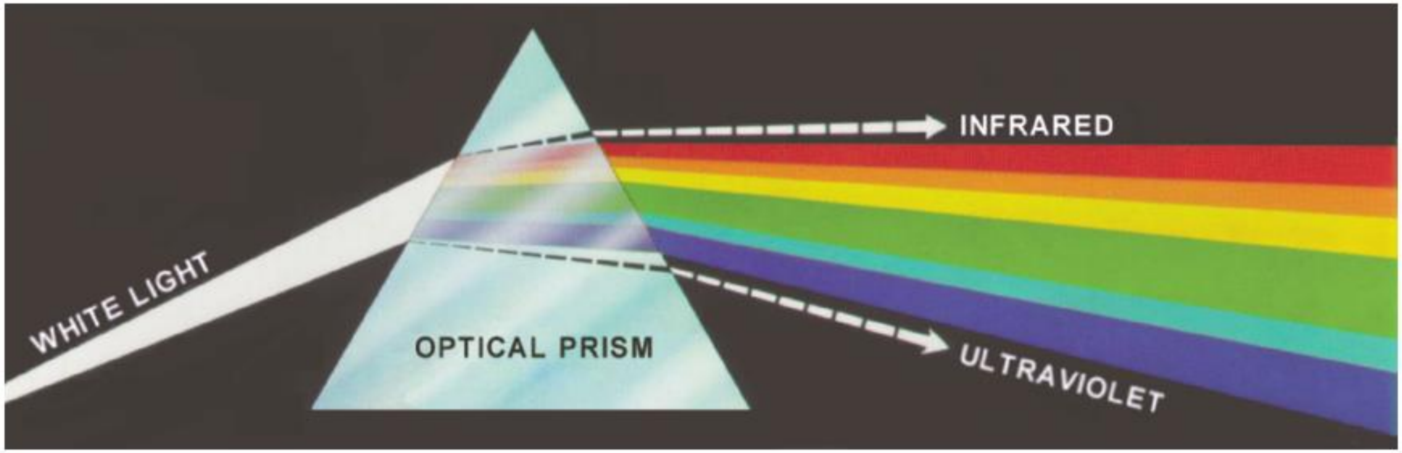
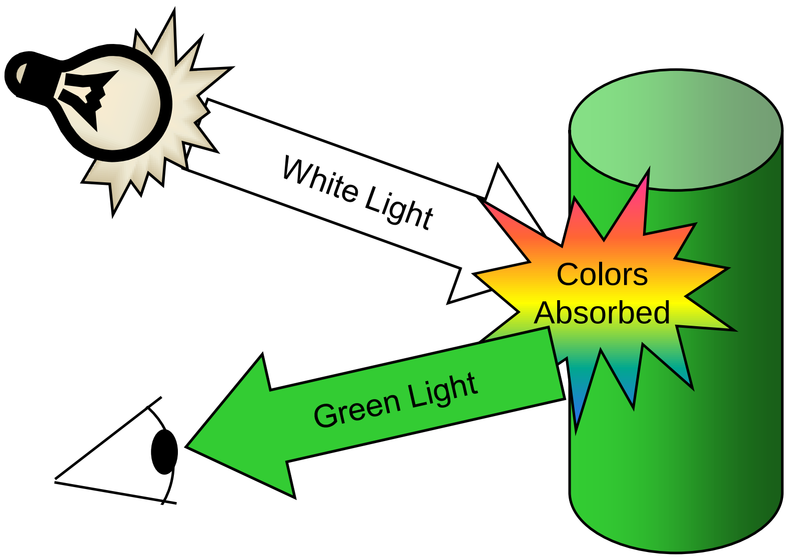


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

- In 1666 Sir Isaac Newton discovered that when a beam of sunlight passes through a glass prism, the emerging beam is split into a spectrum of colors

Color Fundamentals (cont...)

- The colors that humans and most animals perceive in an object are determined by the nature of the light reflected from the object
- For example, green objects reflect light with wave lengths primarily in the range of 500 – 570 nm while absorbing most of the energy at other wavelengths.



Color Fundamentals (cont…)

- 3 basic quantities are used to describe the quality of a chromatic light source:
  - **Radiance:** the total amount of energy that flows from the light source (measured in watts)
  - **Luminance:** the amount of energy an observer *perceives* from the light source (measured in lumens)
    - Note we can have high radiance, but low luminance
  - **Brightness:** a subjective (practically unmeasurable) notion that embodies the achromatic notion of intensity of light

Color Fundamentals (cont...)

- Chromatic light spans the electromagnetic spectrum from approximately 400 to 700 nm.
- Human color vision is achieved through 6 to 7 million cones in each eye.
- Visible light spectrum

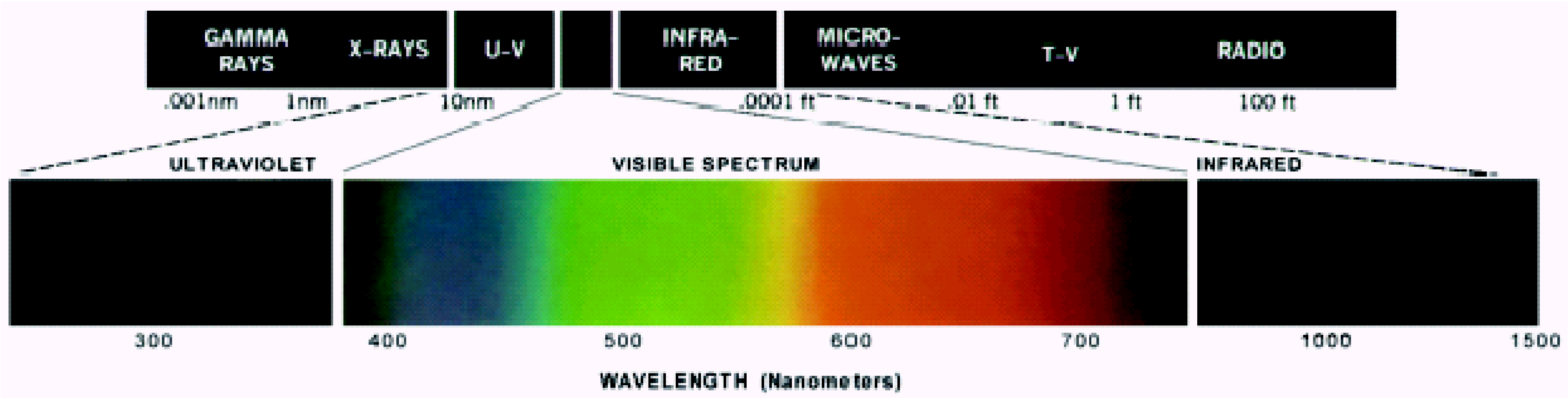


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

Cont..

- The actual color perceived by a human of an object depends on both the color of the illumination and the reflectivity of the object, as well as the sensitivity of human perception.
- Objects appear to be different colors because they absorb and reflect different colors of light. A blue object, for example, reflects blue light while absorbing other colors.
- Grey objects or grey images reflect and absorb all frequencies of light about equally, so they do not appear colored.

Cont..

- Color is sensed by the eye using three kinds of cones, each sensitive primarily to red, green or blue, though there is significant overlap.
- We refer to red, green and blue as the primary colors, and denote to set as RGB.

blue = 435.8nm

green = 546.1nm

red = 700nm

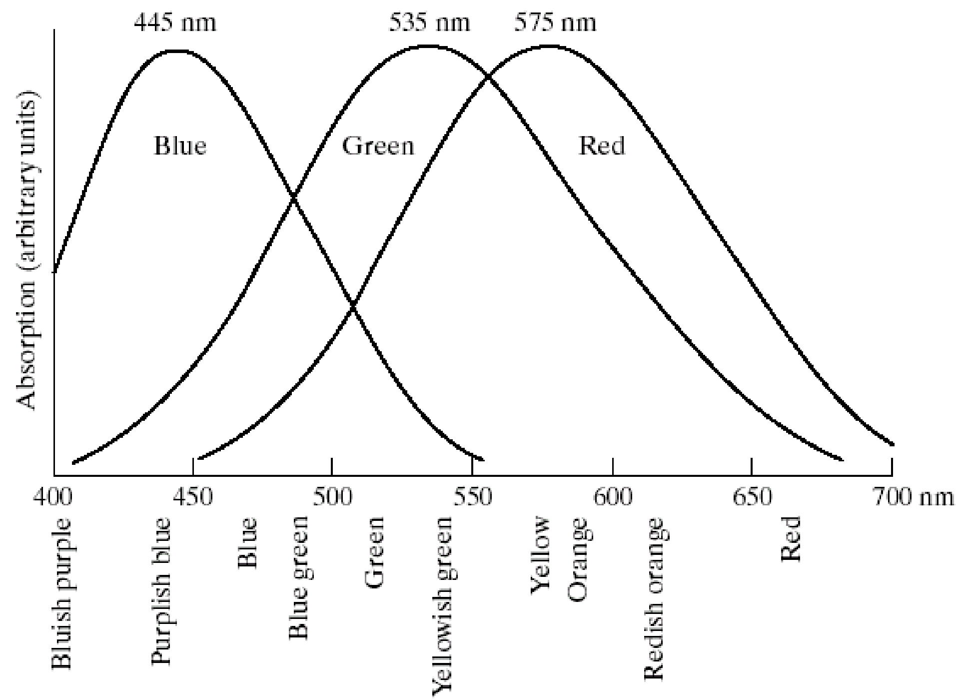


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

Color Fundamentals

- **Three principal sensing groups:**
  - 66% of these cones are sensitive to red light
  - 33% to green light
  - 2% to blue light.
- Absorption curves for the different cones have been determined experimentally.
- Strangely these do not match the CIE standards for red (700nm), green (546.1nm) and blue (435.8nm) light as the standards were developed before the experiments!

Color Imaging

- Trichromacy and human color vision

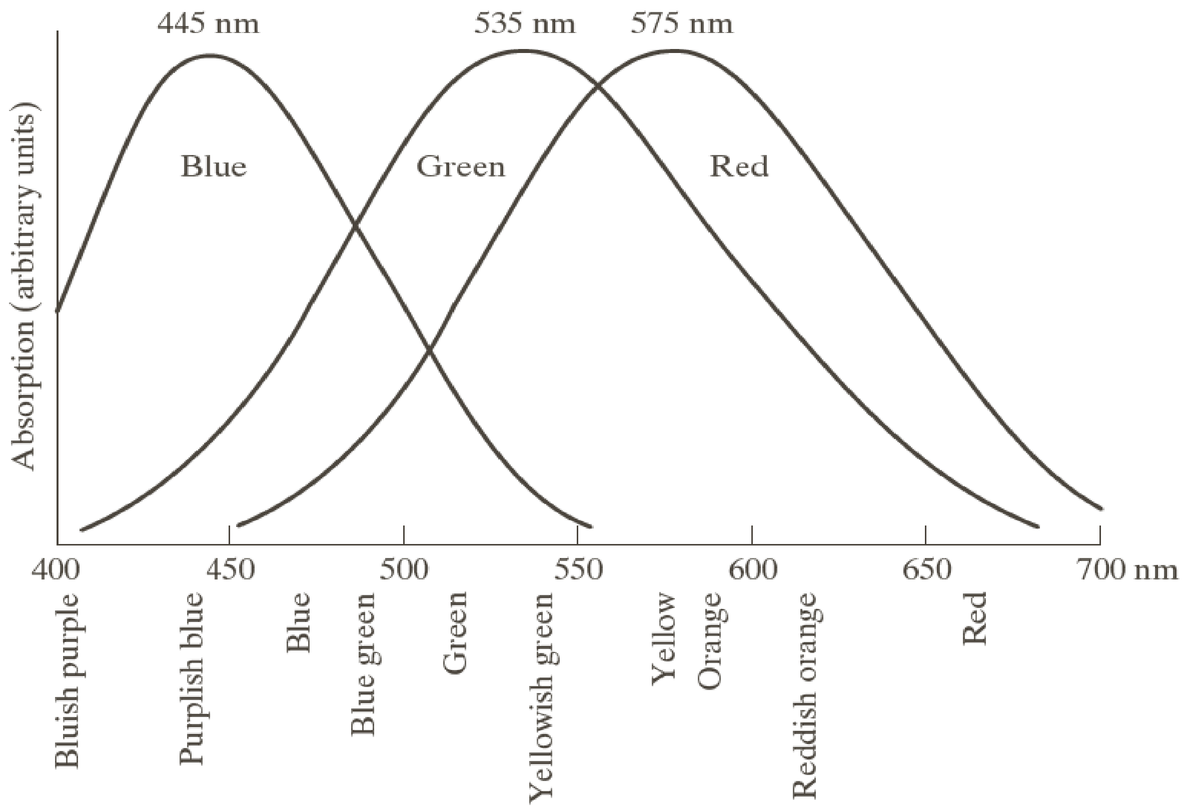
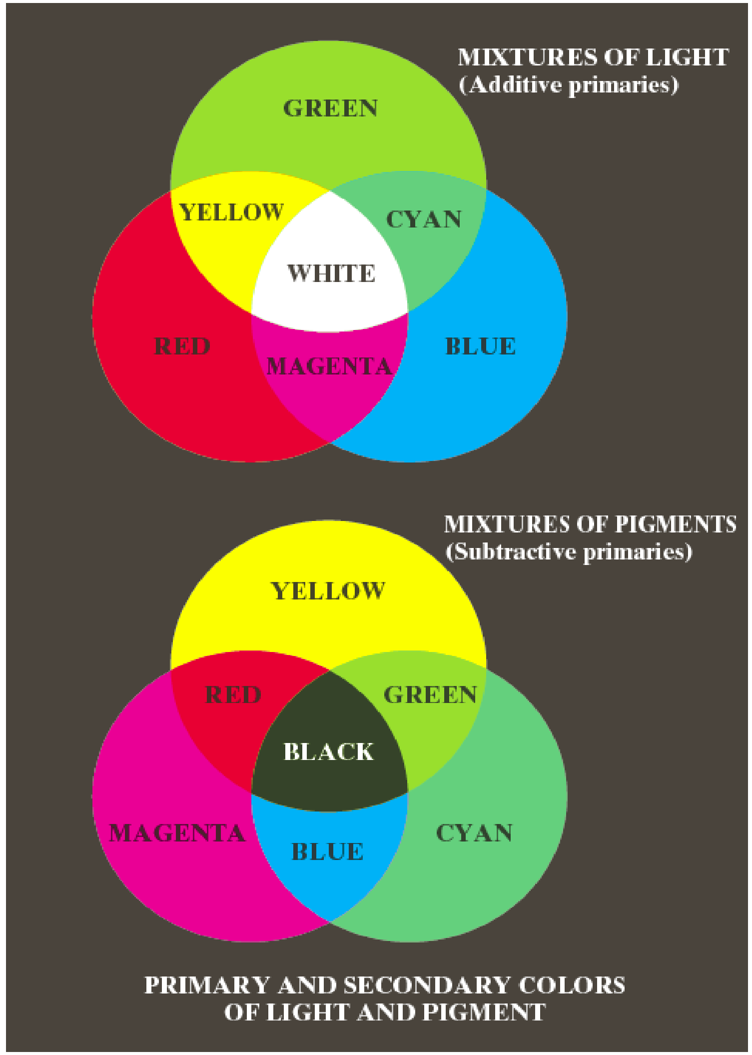


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

Notice that the curves centered at G and R are very close

Cont…

- The primary colors can be added to produce the secondary colors.
  - magenta (red + blue),
  - cyan (green + blue), and
  - yellow (red + green)
- Mixing the three primaries produces white.
- Mixing a secondary with its opposite primary produces white (e.g. red + cyan).



Cont..

- Important difference:
  – Primary colors of light (red, green, blue)
  – Primary colors of pigments (colorants)
    - A color that subtracts or absorbs a primary color of light and reflects the other two.
    - These are cyan, magenta and yellow (CMY).
    - A proper combination of pigment primaries produces black.

Cont..

- Distinguishing one color from another:
  - **Brightness:** the achromatic notion of intensity.
  - **Hue:** the dominant wavelength in a mixture of light waves (the dominant color perceived by an observer, e.g. when we call an object red or orange we refer to its hue).
  - **Saturation:** the amount of white light mixed with a hue. Pure colors are fully saturated. Pink (red+white) is less saturated.

Cont..

- Hue and saturation are called ***chromaticity***.
- Therefore, any color is characterized by its brightness and chromaticity.
- The amounts of red, green and blue needed to form a particular color are called *tri-stimulus* values and are denoted by X, Y, Z.

Cont..

- A color is then specified by its *tri-chromatic coefficients:*

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

$$x + y + z = 1$$

- For any visible wavelength, the tri-stimulus values needed to produce that wavelength are obtained by curves compiled by extensive experimentation.

- We will return to that point at the last part of the lecture.

CIE Chromaticity Diagram

- Specifying colors systematically can be achieved using the CIE **chromaticity diagram.**

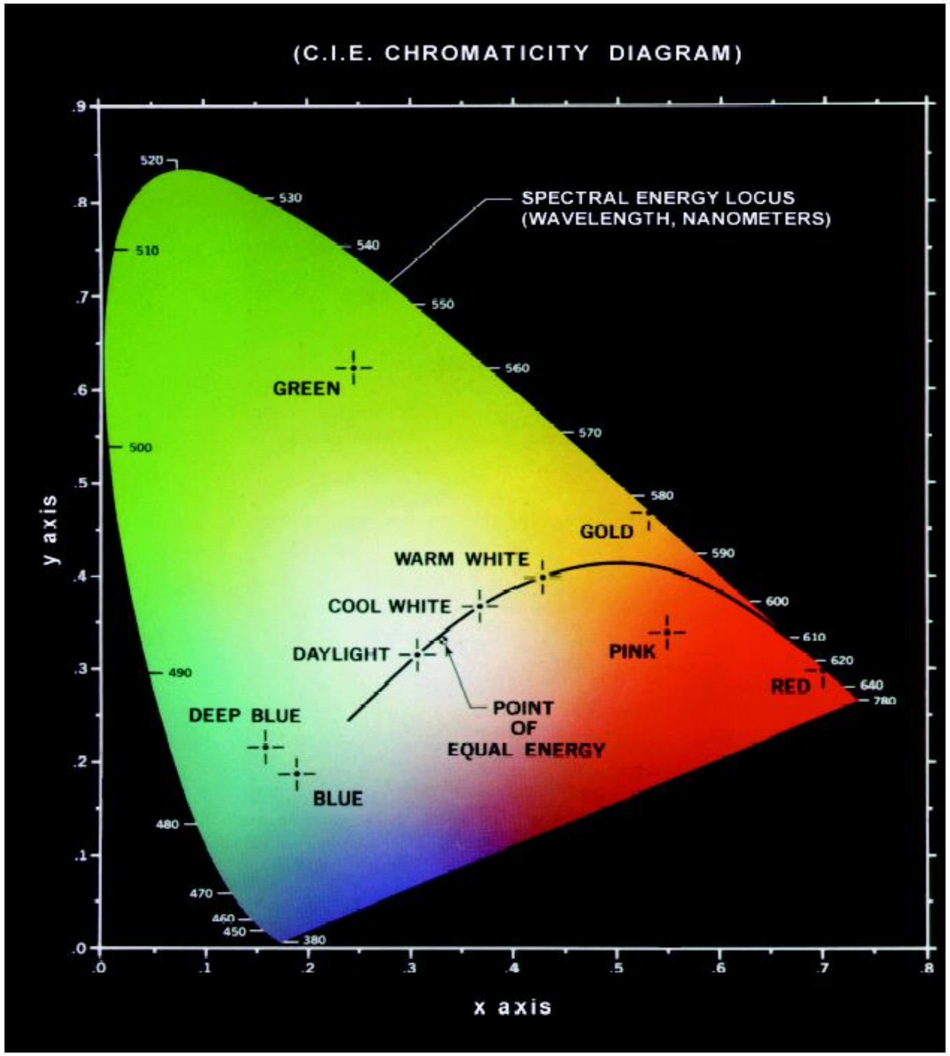
- On this diagram the *x*-axis represents the proportion of red and the *y*-axis represents the proportion of green used to produce a specific color.

- The proportion of blue used in a color is calculated as:

$$z = 1 - (x + y)$$

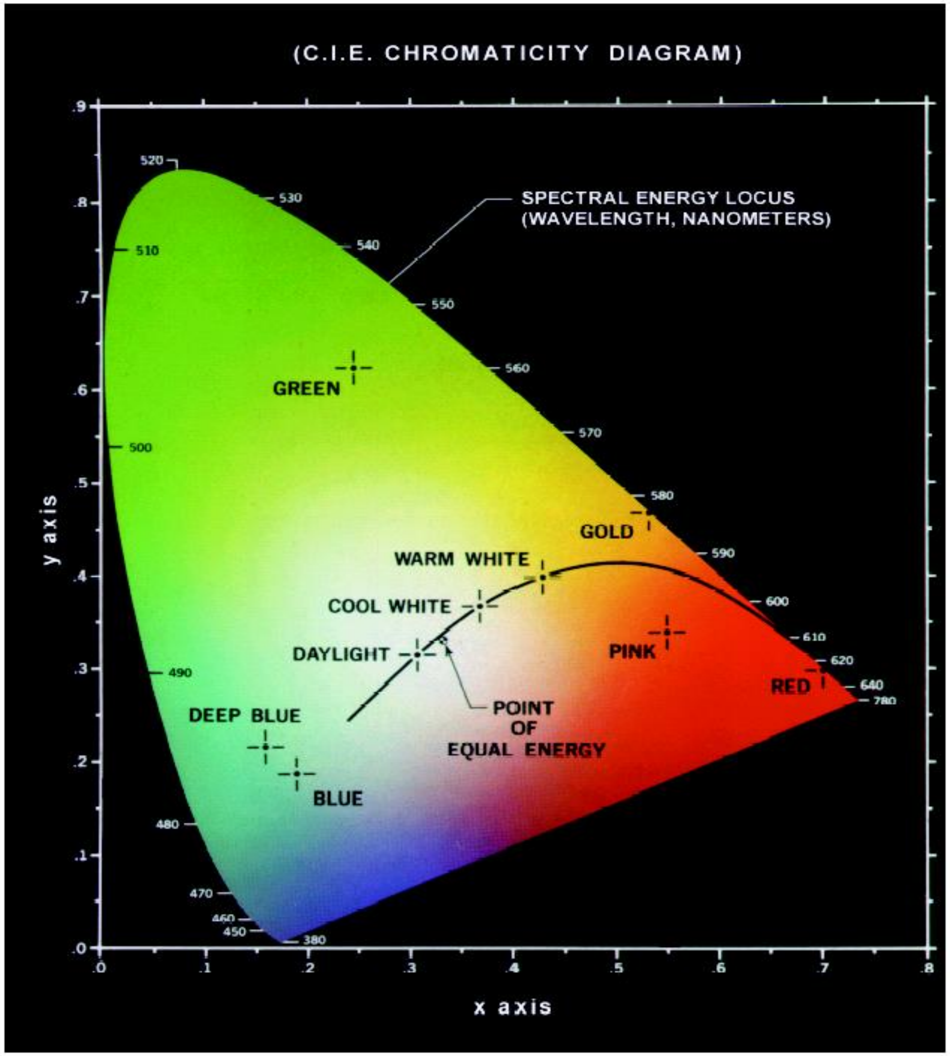
Cont..

- Point marked “Green”
  - 62% green, 25% red and 13% blue.
- Point marked “Red”
  - 32% green, 67% red and 1% blue.
- The diagram is usefull for color mixing.



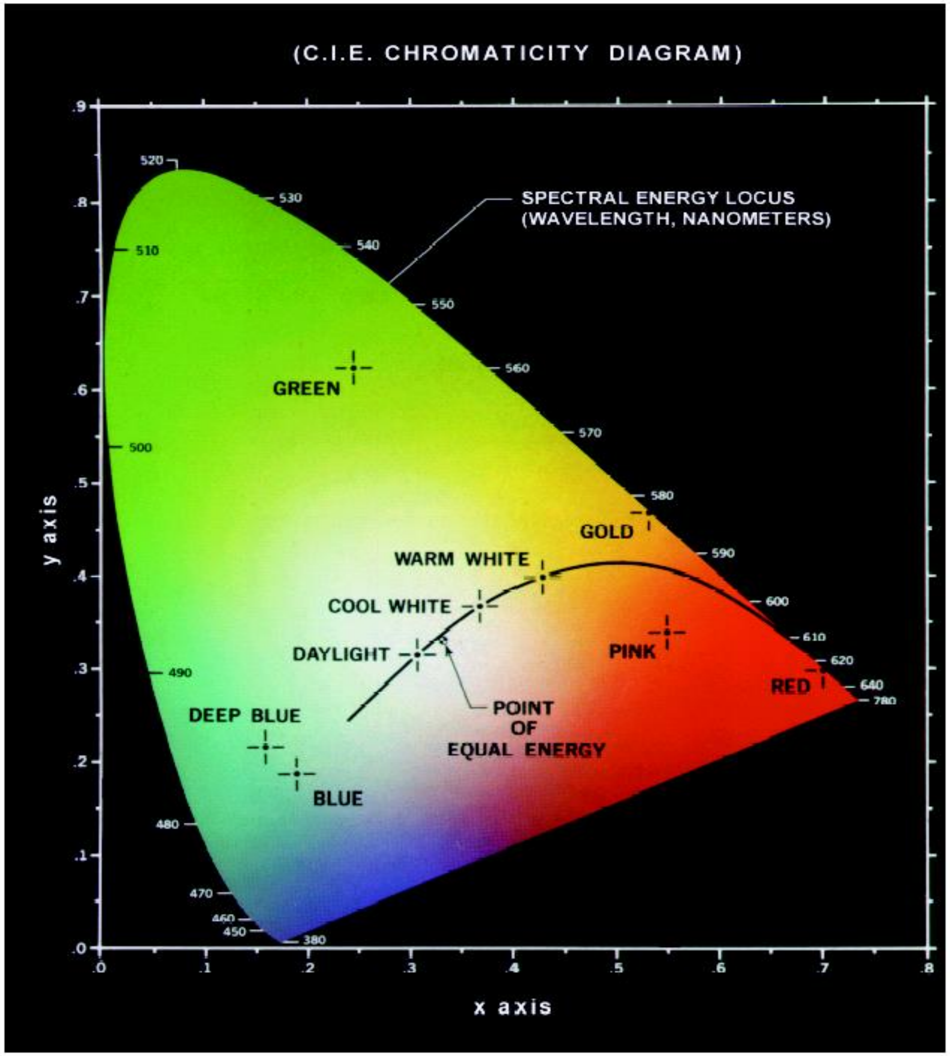
Cont..

- Any color located on the boundary of the chromaticity chart is fully saturated (*Pure colors*).
- The point of equal energy (PEE) has equal amounts of red, green and blue.
  – It is the CIE standard for pure white.



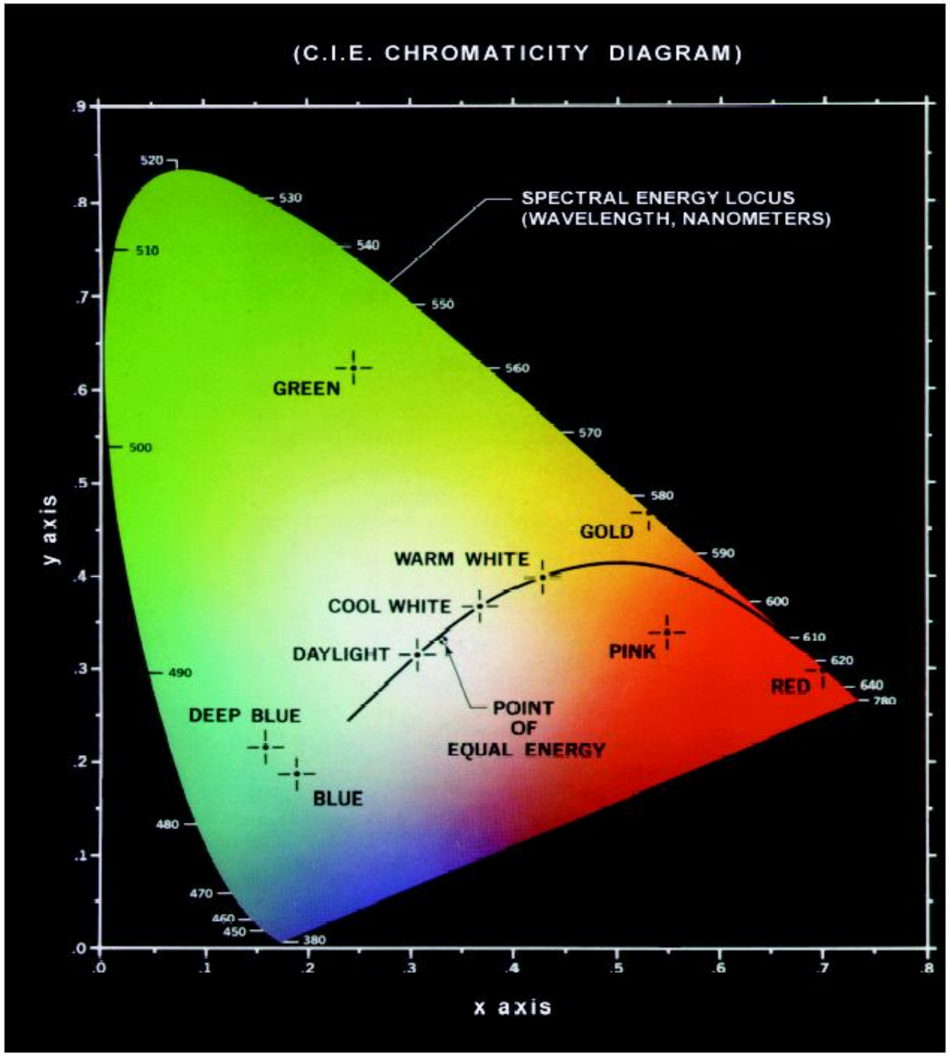
Cont..

- Any straight line joining 2 points in the diagram defines all the different colors that can be obtained by combining these two colors additively.
- A line drawn from the PEE to any point on the boundary defines all the shades of that particular color.



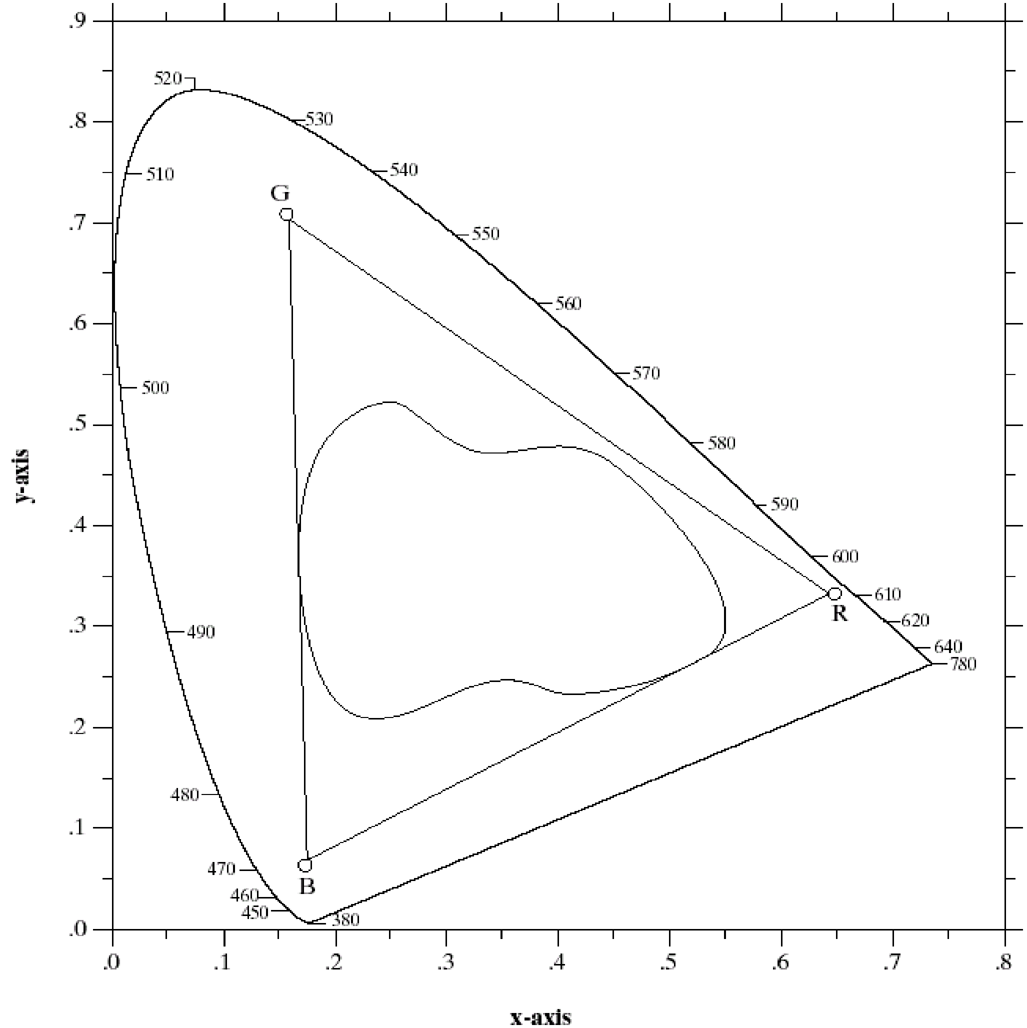
Cont..

- By combining any three given colors we may obtain the colors enclosed in the triangle defined by the three initial colors.



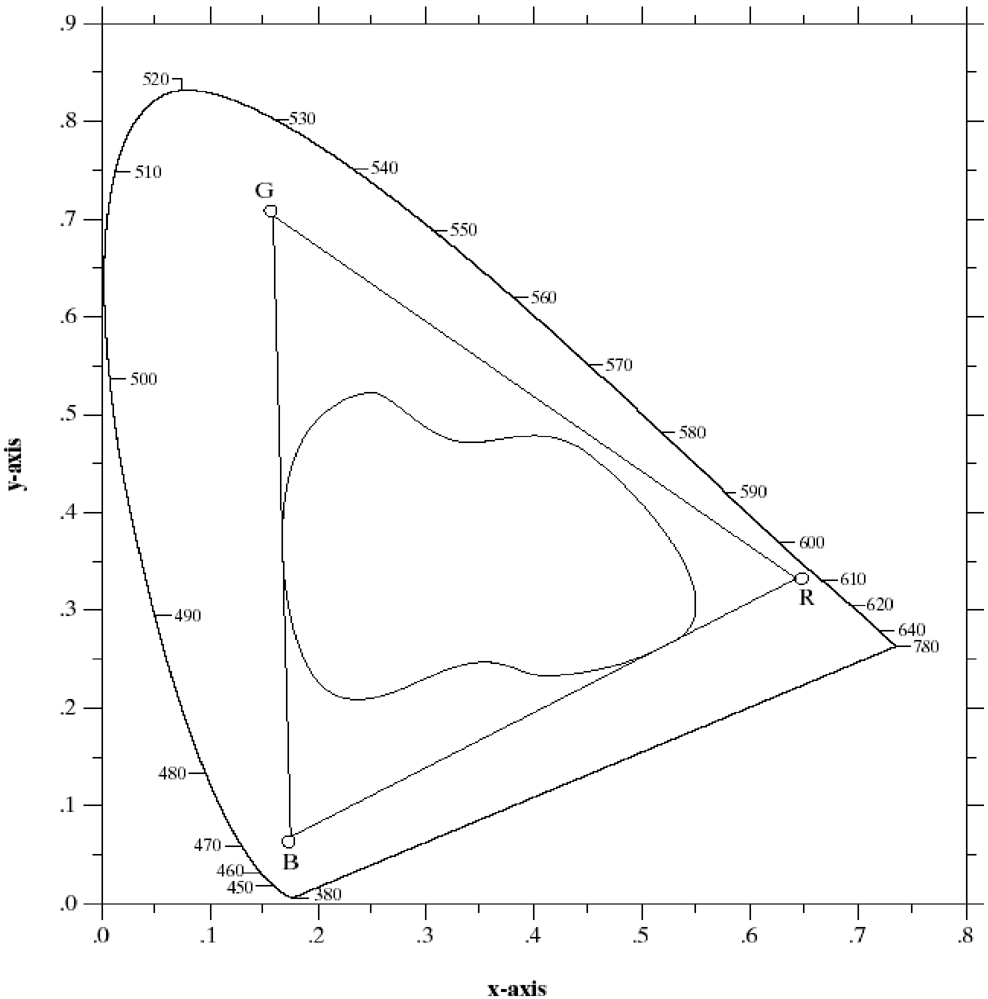
Cont..

- A triangle with vertices at any three *fixed pure colors* cannot enclose the entire color region.



Cont..

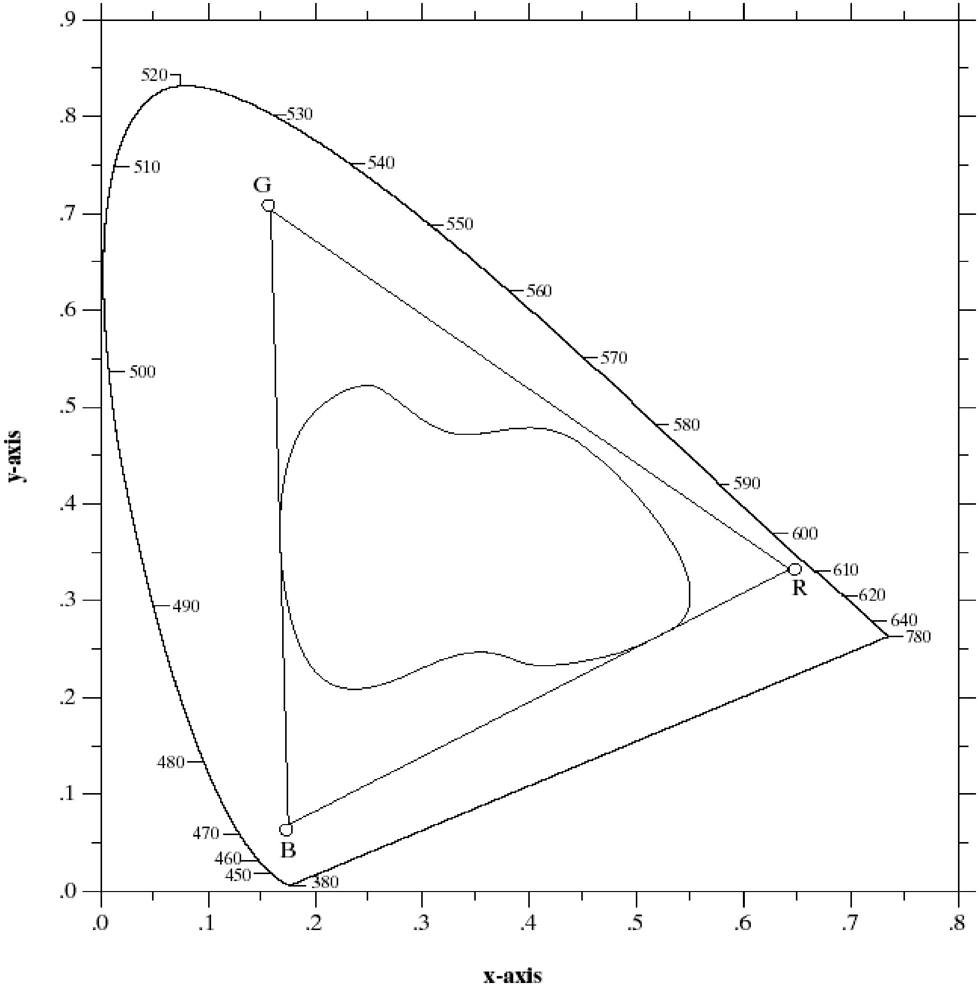
- The triangle shows the typical color gamut produced by RGB monitors.
- The entire color range cannot be displayed based on any three colors.
- The irregular shape is the gamut achieved by high quality color printers.



Cont..

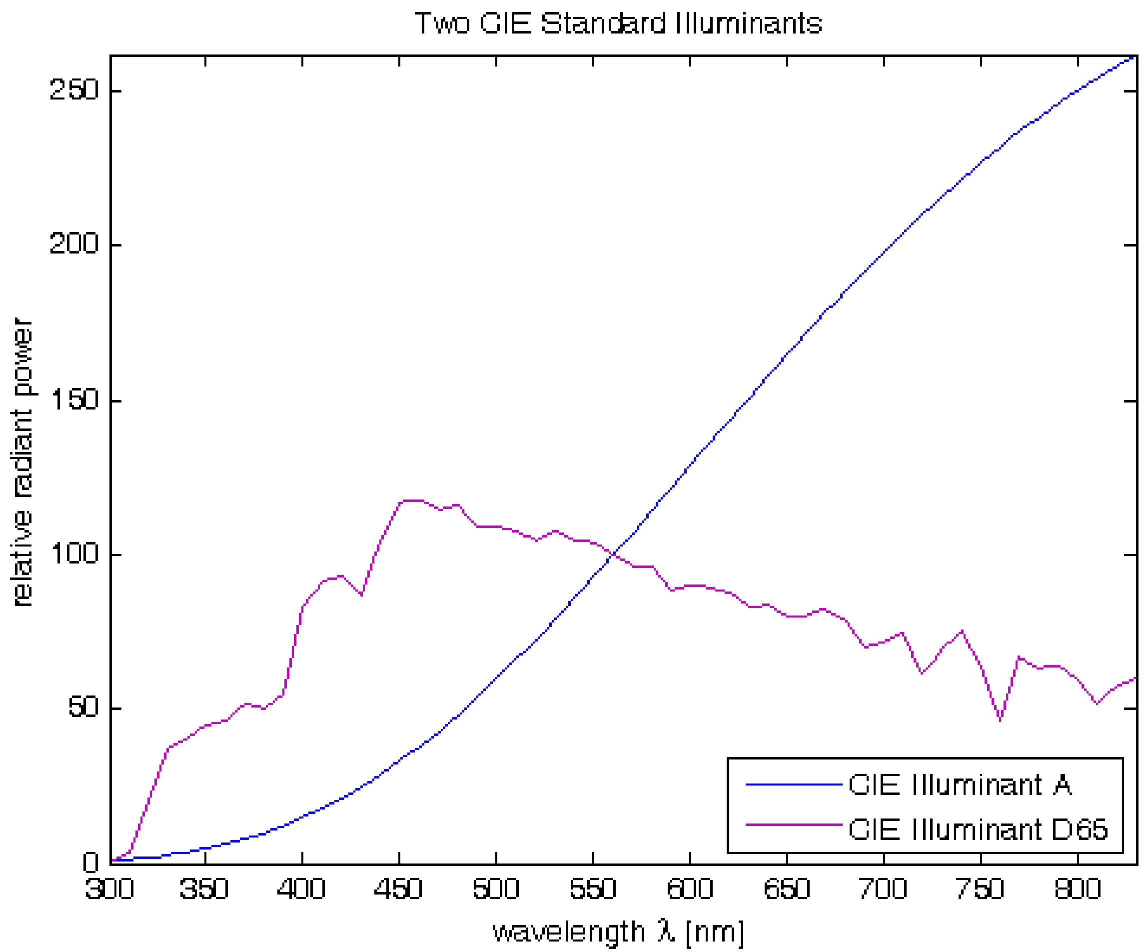
- The boundary of the printing gamut is irregular because printing is a combination of additive and subtractive color mixing.

- This is a more difficult process to control than that of displaying colors.



Color Imaging

- Power spectrum of standard illuminants



Color Models

- From the previous discussion it should be obvious that there are different ways to model color.

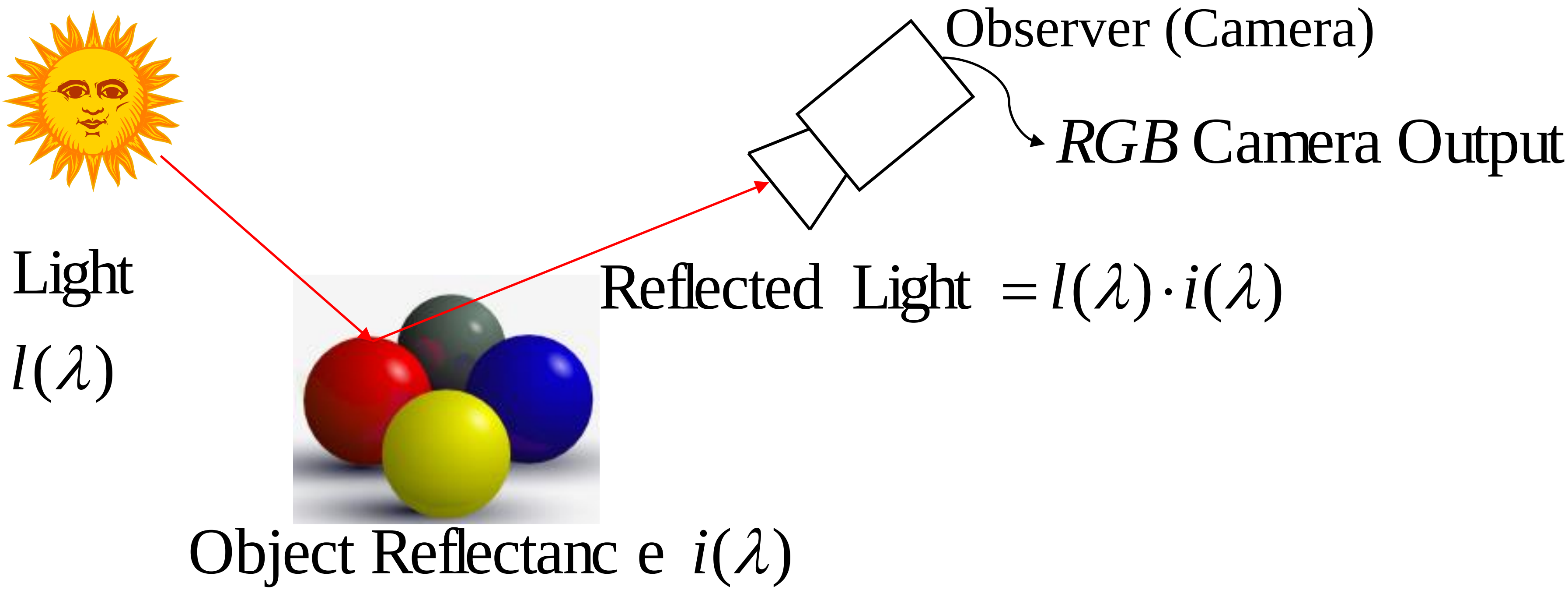
- We will consider two very popular models used in color image processing:
  - RGB (**R**ed **G**reen **B**lue) for computer display
  - CMYK model (Cyan-Magenta-Yellow-Black) for printing
  - HSI (**H**ue **S**aturation **I**ntensity)

RGB Color Model

- In the RGB model each color appears in its primary spectral components of red, green and blue.
- The model is based on a Cartesian coordinate system.
- RGB is an additive color model
- For computer displays uses light to display color, Colors result from transmitted light
- Red + Green + Blue = White

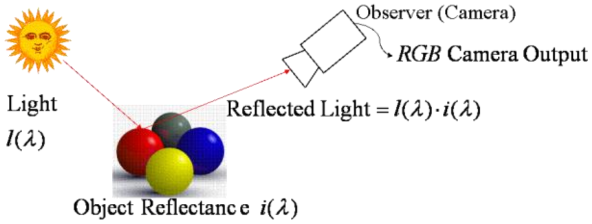
Cont..

- Color image formation (acquisition)



Cont..

- Color image formation (acquisition)



$$R(x,y)=\int l(\lambda)\cdot i(x,y,\lambda)\cdot F_R(\lambda)d\lambda$$

$$G(x,y)=\int l(\lambda)\cdot i(x,y,\lambda)\cdot F_G(\lambda)d\lambda$$

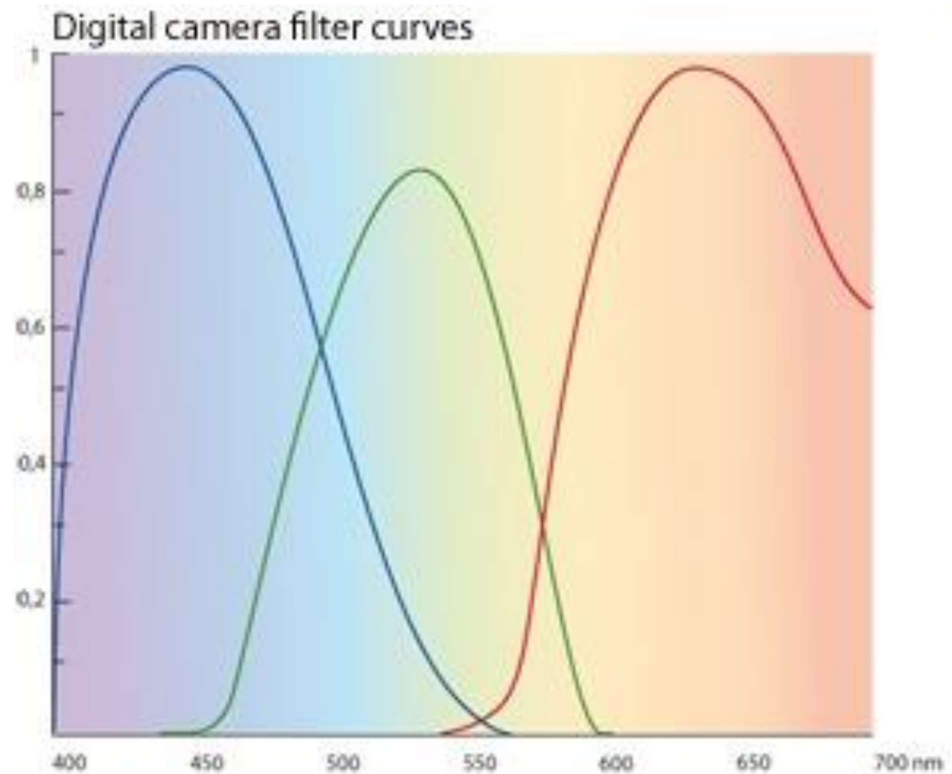
$$B(x,y)=\int l(\lambda)\cdot i(x,y,\lambda)\cdot F_B(\lambda)d\lambda$$

Color filters
Of the sensor

Cont..

- Color image formation (acquisition)

$$R(x,y)=\int l(\lambda)\cdot i(x,y,\lambda)\cdot F_R(\lambda)d\lambda$$
$$G(x,y)=\int l(\lambda)\cdot i(x,y,\lambda)\cdot F_G(\lambda)d\lambda$$
$$B(x,y)=\int l(\lambda)\cdot i(x,y,\lambda)\cdot F_B(\lambda)d\lambda$$

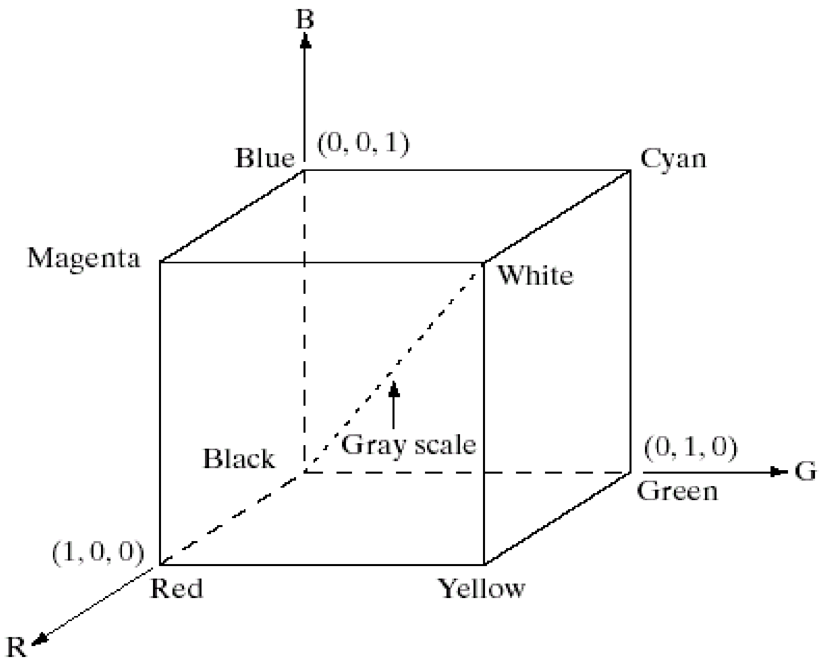


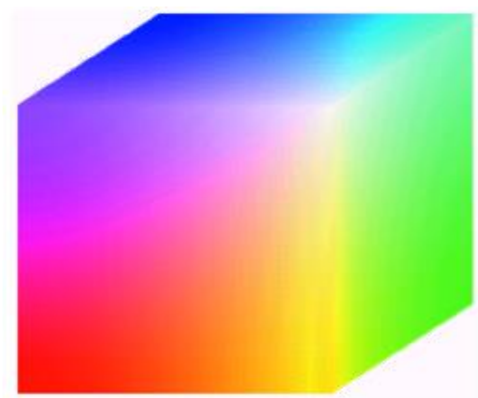
Cont..

- The RGB Color Model
  - R, G, B at 3 axis ranging in [0 1] each
  - Gray scale along the diagonal
  - If each component is quantized into 256 levels [0:255], the total number of different colors that can be produced is $(2^8)^3 = 2^{24}$ =16,777,216 colors.

Cont..

- RGB values are at 3 corners.
- Cyan magenta and yellow are at three other corners.
- Black is at the origin.
- White is the corner furthest from the origin.
- Different colors are points on or inside the cube represented by RGB vectors.





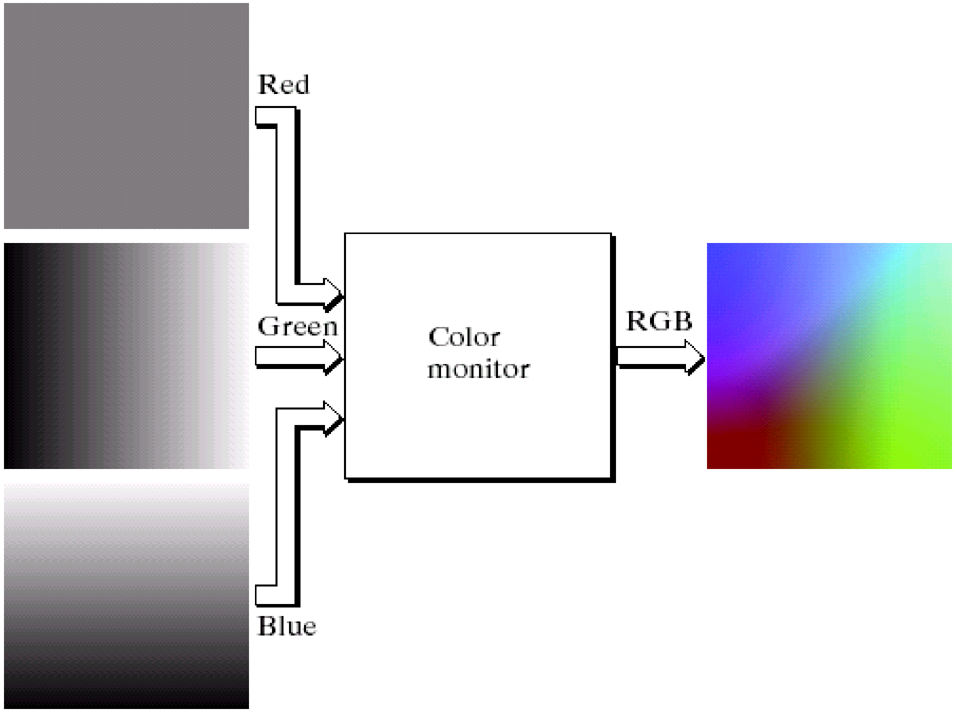
Cont..

- Images represented in the RGB color model consist of three component images – one for each primary color.
- When fed into a monitor these images are combined to create a composite color image.
- The number of bits used to represent each pixel is referred to as the color depth.
- A 24-bit image is often referred to as a full-color image as it allows $(2^8)^3$ = 16,777,216 colors.

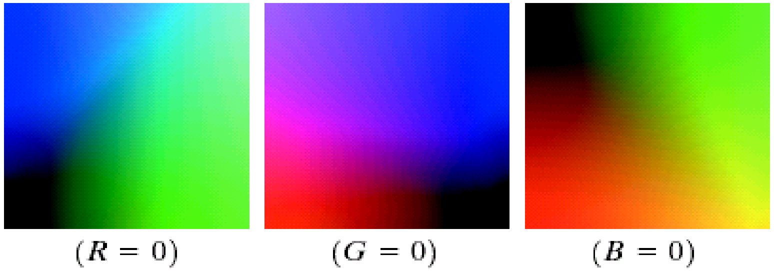
Cont..

a
b

FIGURE 6.9
(a) Generating the RGB image of the cross-sectional color plane (127, G, B).
(b) The three hidden surface planes in the color cube of Fig. 6.8.



These are scalar valued pixels



CMY/CMYK Color Model

- CMYK (subtractive color model) is the standard color model used in offset printing for full-color documents. Because such printing uses inks of these four basic colors, it is often called four-color printing.
- Where two colors of RGB overlaps, we see a new color formed by mixing of the two additive primaries. These new colors are:
  - A greenish blue called cyan.
  - A blushed red called magenta.
  - A bright yellow.
  - The key color , Black.

Cont..

- We can express this effect pseudo-algebraically. Writing R, G and B for red, green and blue, C, M and Y for cyan, magenta and yellow, and W for white, and using (+) to mean additive mixing of light, and (–) to mean subtraction of light, we have:
- C (cyan) = G + B = W - R
- M (magenta) = R + B = W - G
- Y (yellow) = R + G = W – B
- In each equation, the colour on the left is called the complementary colour of the one at the extreme right; for example, magenta is the complementary colour of green.

CMY Model

- RGB model asks what is added to black to get a particular color, the CMY (cyan-magenta-yellow) model asks what is subtracted from white.
- Appropriate to absorption of colors, used in printing devices and filters

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

CMY Model

CMY(K): printing

- Cyan, Magenta, Yellow (Black) – CMY(K)
- A subtractive color model

dye color	*absorbs*	*reflects*
cyan	red	blue and green
magenta	green	blue and red
yellow	blue	red and green
black	all	none

Color Imaging

- The YIQ Color Model
  - Video (NTSC) standard
  - Y encodes luminance; I and Q encode chrominance ("color")
  - Black and white TV shows only the Y channel
  - Backward compatibility; efficiency

$$\begin{cases} Y &= 0.299 \times R + 0.587 \times G + 0.114 \times B \\ I &= 0.596 \times R - 0.274 \times G - 0.322 \times B \\ Q &= 0.212 \times R - 0.523 \times G + 0.311 \times B \end{cases}$$

Color Imaging

- Color Models, YCbCr

$$\begin{cases} Y &= 0.2989 \times R + 0.5866 \times G + 0.1145 \times B \\ Cb &= -0.1688 \times R - 0.3312 \times G + 0.5000 \times B \\ Cr &= 0.5000 \times R - 0.4184 \times G - 0.0816 \times B \end{cases}$$

Color Imaging

- Color image representation (in RGB space)

Red Green Blue

Color Imaging

- Color image representation (in RGB space)

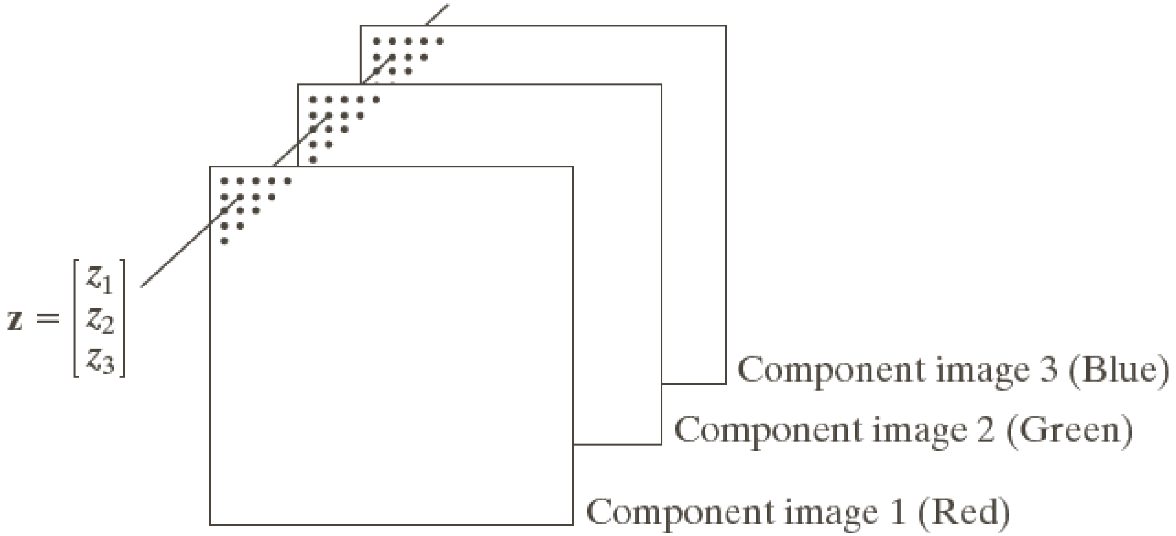


FIGURE 2.38 Formation of a vector from corresponding pixel values in three RGB component images.

HSI Color Model

- Hue, Saturation, Value or HSV is a color model that describes colors (hue or tint) in terms of their shade (saturation) and their brightness (value).

- HSV color model is based on polar coordinates; Developed in the 1970s for computer graphics applications, HSV is used today in **color pickers**, in **image editing software**, and less commonly in image analysis and computer vision.

Cont..

- **HSV** (hue-saturation-value), **HSI** (hue-saturation-intensity) and **HSL** (hue-saturation-lightness) are the three most common cylindrical-coordinate representations of points in an RGB color model.

- The HSV/HSI/HSL representations rearrange the geometry of RGB in an attempt to be more intuitive and perceptually relevant. The representations HSV, HSI and HSL are very similar, but not completely identical.

Cont..

- **Hue (H)**, in all 3 color spaces is an angular measurement, analogous to position around a color wheel. It ranges from 0 to 360 degree, with red at 0 degree, green at 120 degree, blue at 240 degree and so on.

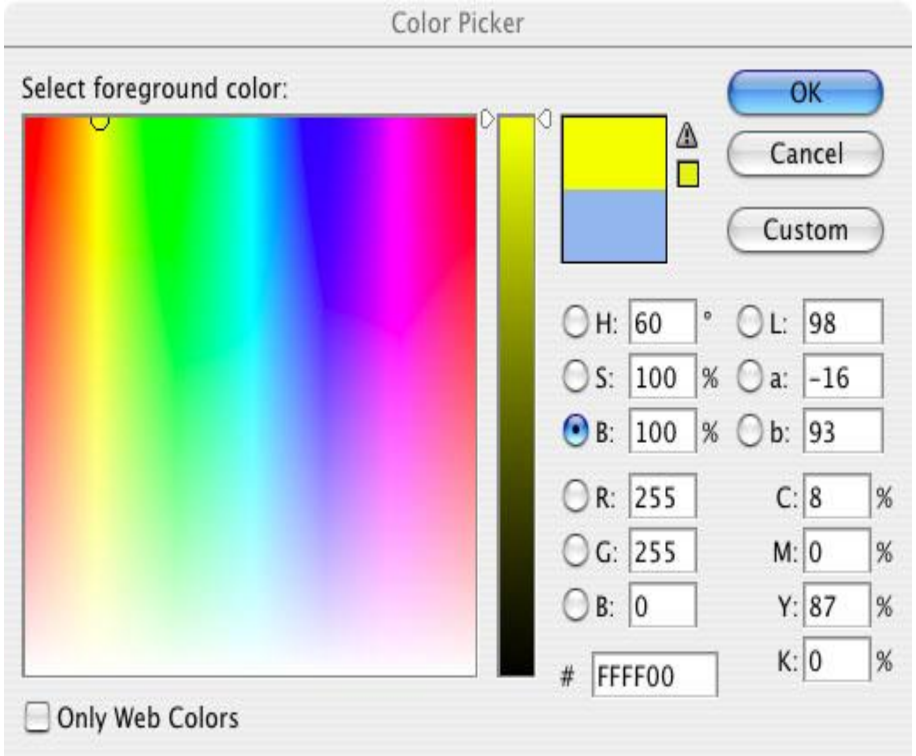
- The two representations rearrange the geometry of RGB in an attempt to be more intuitive and perceptually relevant, based on the color wheel.

Cont..

- **Saturation (S)** of the color ranges from 0 to 100%. Also sometimes, it called the "purity". The lower the saturation of a color, the more "grayness" is present and the more faded the color will appear.

- Value (V), the Brightness (V) of the color ranges from 0 to 100%. It is a nonlinear transformation of the RGB color space. Note that HSV and HSB are the same.

Cont..



- HSV colour picker HSV colour picker is used to control the V value, while the corresponding slices through the cylinder are displayed, and a colour is selected by clicking on a point in the disk. The RGB picker below simply uses sliders to control the three components, while the spectrum picker at the bottom lets you pick your colour directly by clicking.

HSI Color Model

- RGB is useful for hardware implementations and is related to the way in which the human visual system works.
- However, RGB is not a particularly intuitive way in which to describe colors.
- Rather when people describe colors they tend to use **hue**, **saturation** and **brightness.**
- RGB is great for color generation, but HSI is great for color description.

Cont..

Reminder:

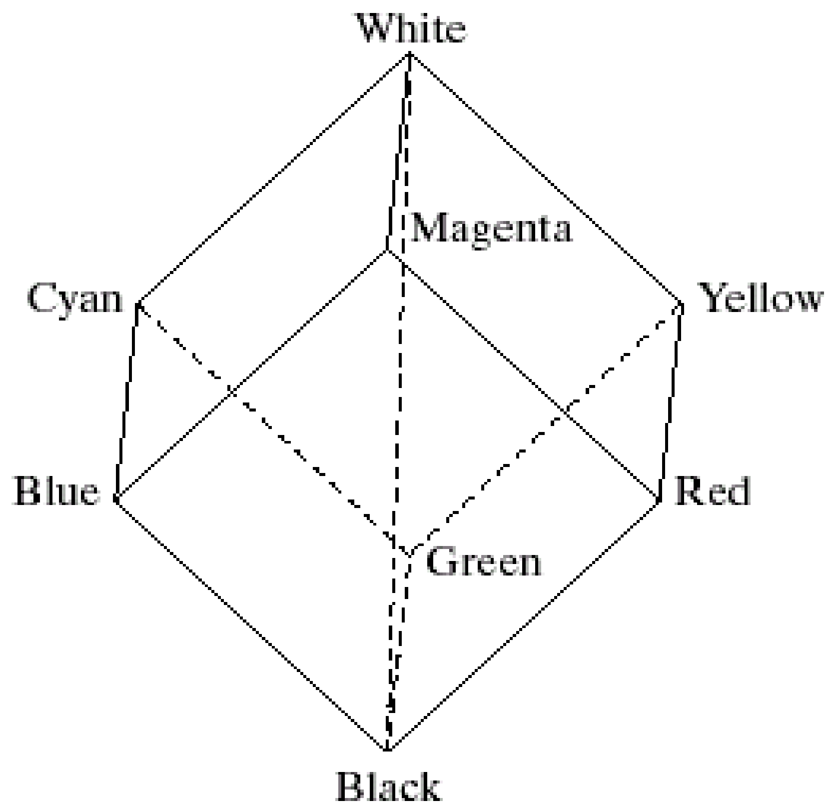
- **Hue:** A color attribute that describes a pure color (pure yellow, orange or red).
- **Saturation:** Gives a measure of how much a pure color is diluted with white light.
- **Intensity:** Brightness is nearly impossible to measure because it is so subjective. Instead we use intensity. Intensity is the same achromatic notion that we have seen in grey level images.

HSI, Intensity & RGB

- Intensity can be extracted from RGB images.
- However, human perception of color does not refer to percentages of RGB.
- Remember the diagonal on the RGB color cube that we saw previously ran from black to white.
- Now consider if we stand this cube on the black vertex and position the white vertex directly above it.

Cont..

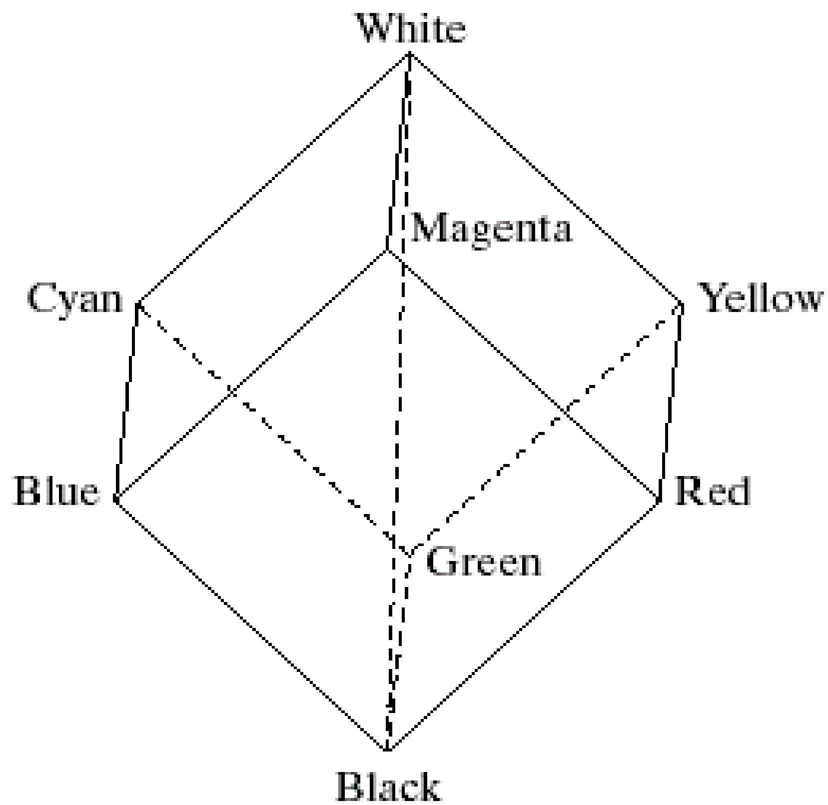
- The intensity component of any color can be determined by passing a plane *perpendicular* to the intensity axis and containing the color point.



- The intersection of the plane with the intensity axis gives us the intensity component of the color.

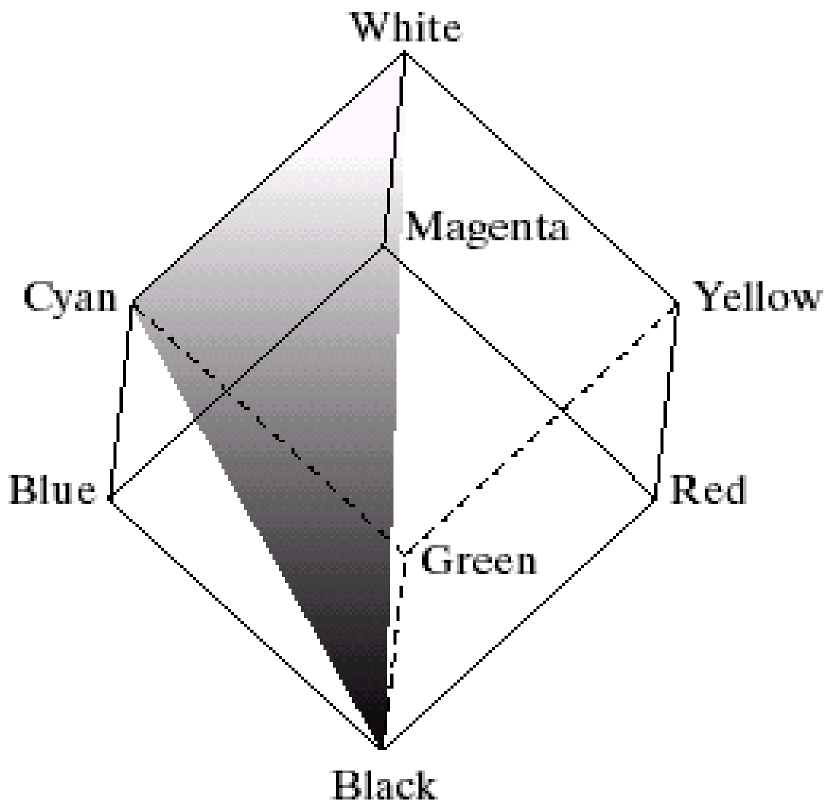
Cont..

- The saturation of a color (% of white missing from the color) increases as a function of distance from the intensity axis.



HSI, Hue & RGB

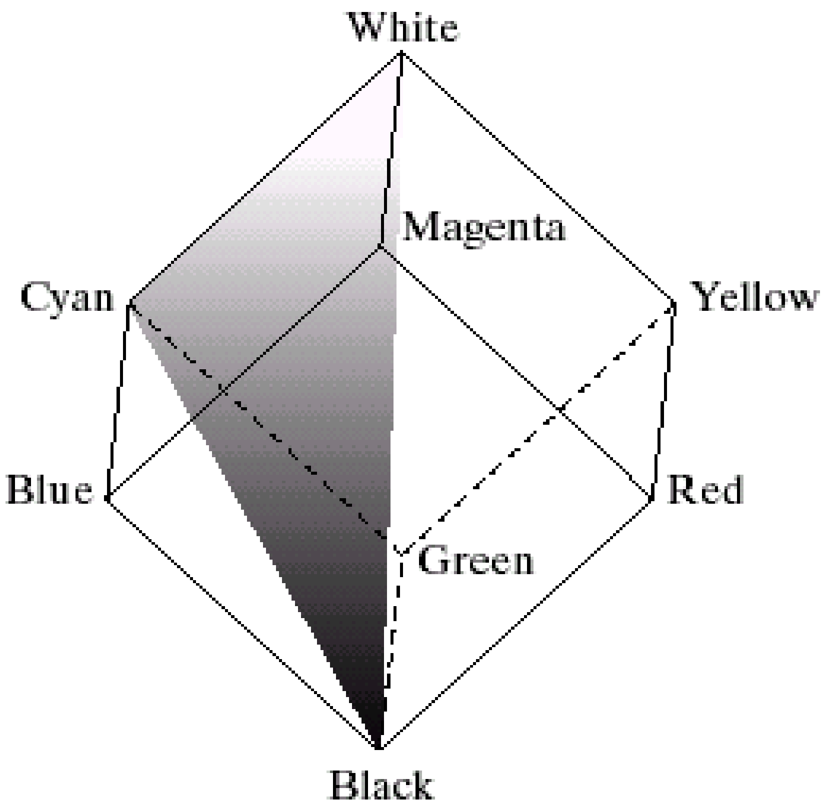
- In a similar way we can extract the hue from the RGB color cube.
- Consider a plane defined by the 3 points cyan, black and white.
- All points contained in this plane must have the same hue (cyan) as black and white cannot contribute hue information to a color.



Cont..

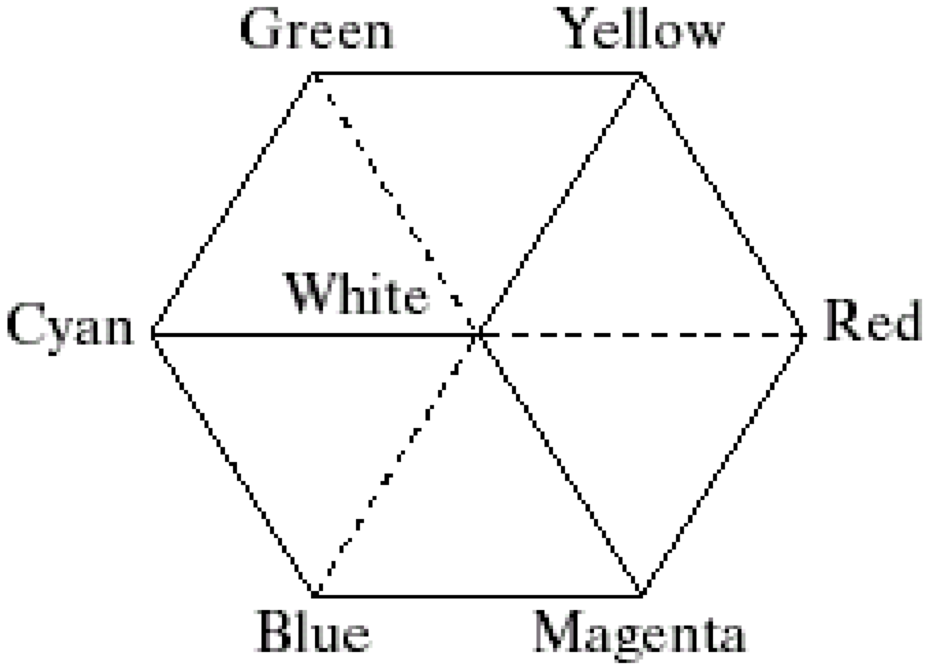
- By rotating the shaded plane around the intensity axis we obtain different hues.

- Conclusion:
  - The HSI values can be obtained from the RGB values.
  - We have to work the geometric formulas.



The HSI Color Model

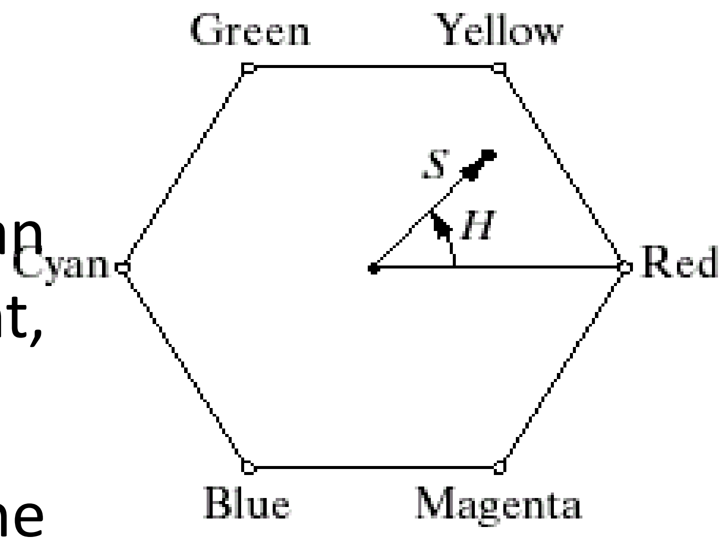
- If we look straight down at the RGB cube as it was arranged previously
- We would see a hexagonal shape with each primary color separated by 120° and secondary colors at 60° from the primaries.



- The HSI model is composed of a vertical intensity axis and the locus of color points that lie on planes perpendicular to that axis.

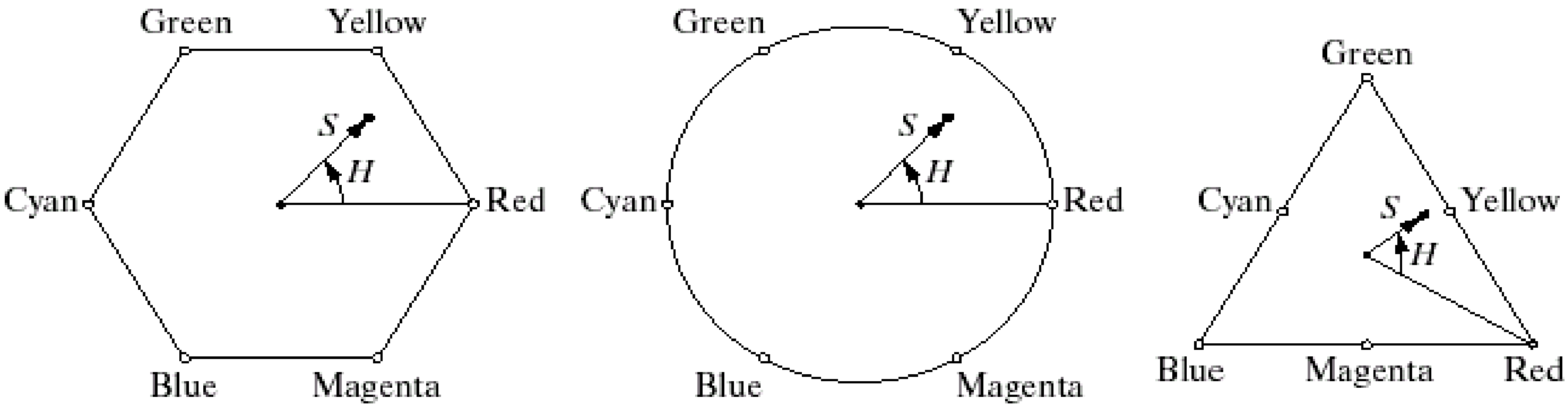
Cont..

- Hexagonal shape at an arbitrary color point
  - The **hue** is determined by an angle from a reference point, usually red.
  - The **saturation** is the distance from the origin to the point.
  - The **intensity** is determined by how far up the vertical intensity axis this hexagonal plane sits (not apparent from this diagram).

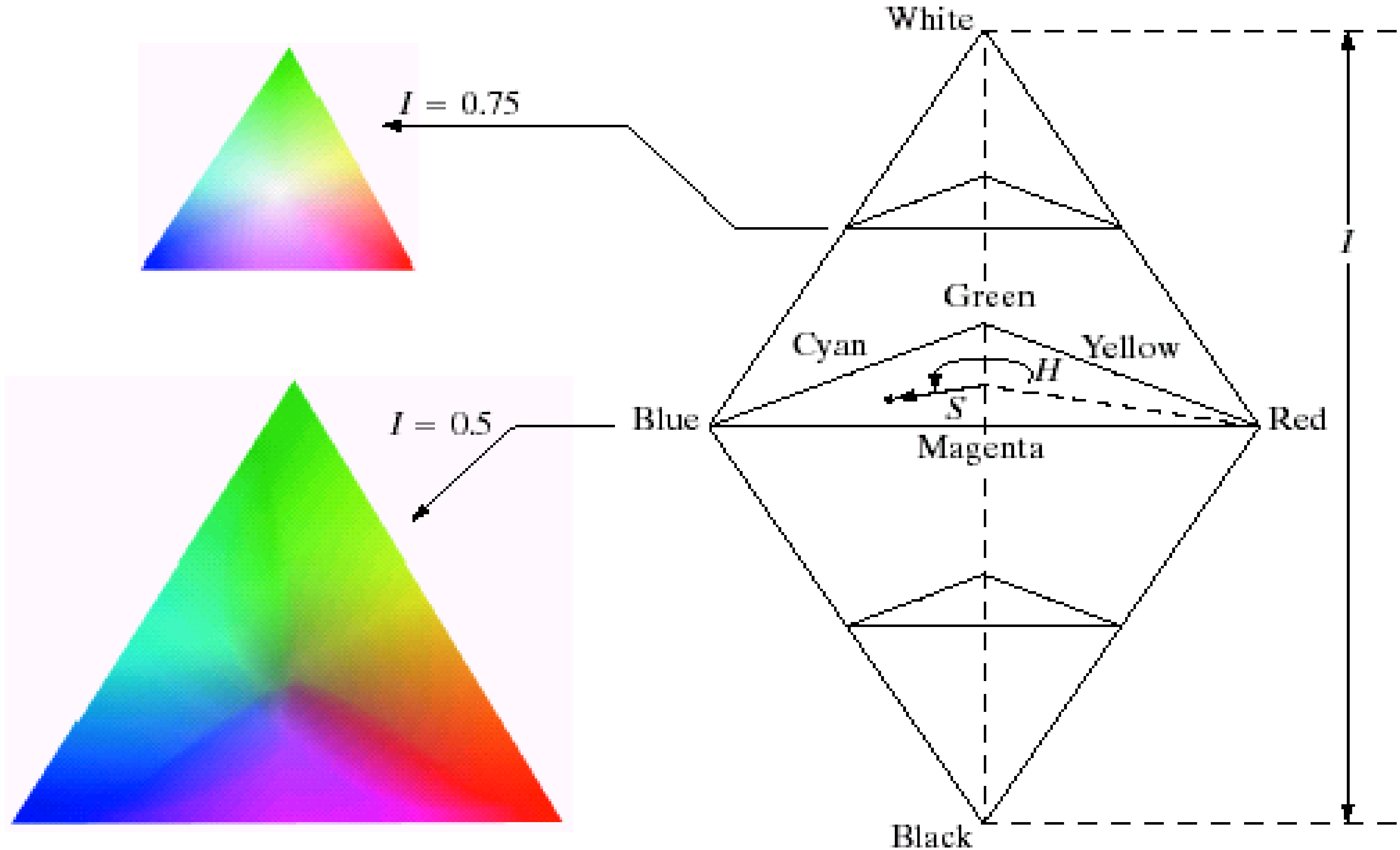


Cont..

- As the only important things are the **angle** and the **length** of the **saturation vector** this plane is also often represented as a **circle** or a **triangle**.

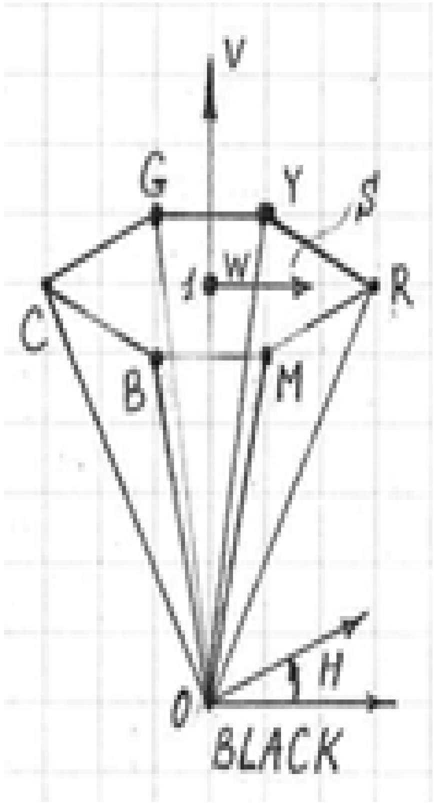


HSI Model Examples



Cont..

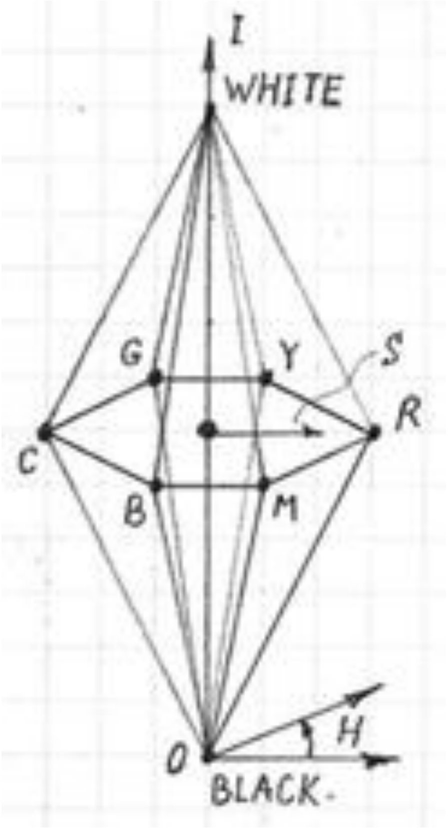
- **Saturation (S)** component in all 3 color spaces describes color intensity. A saturation value of 0 (in the middle of a hexagon) means that there is no color (gray).
- A saturation value at the **maximum** (at the outer edge of a hexagon) means that the colorfulness value is at maximum for the color defined by the hue.
- **HSV** model is called a **single hexagon model**. The top of the hexagon corresponds to maximum intensity V=1.
- The maximum saturation is available for maximum intensity. The bottom converges to one point that corresponds the color black.



HSV models (W-white, R-red, M-magenta, B-blue, C-cyan, G-green, Y-yellow)

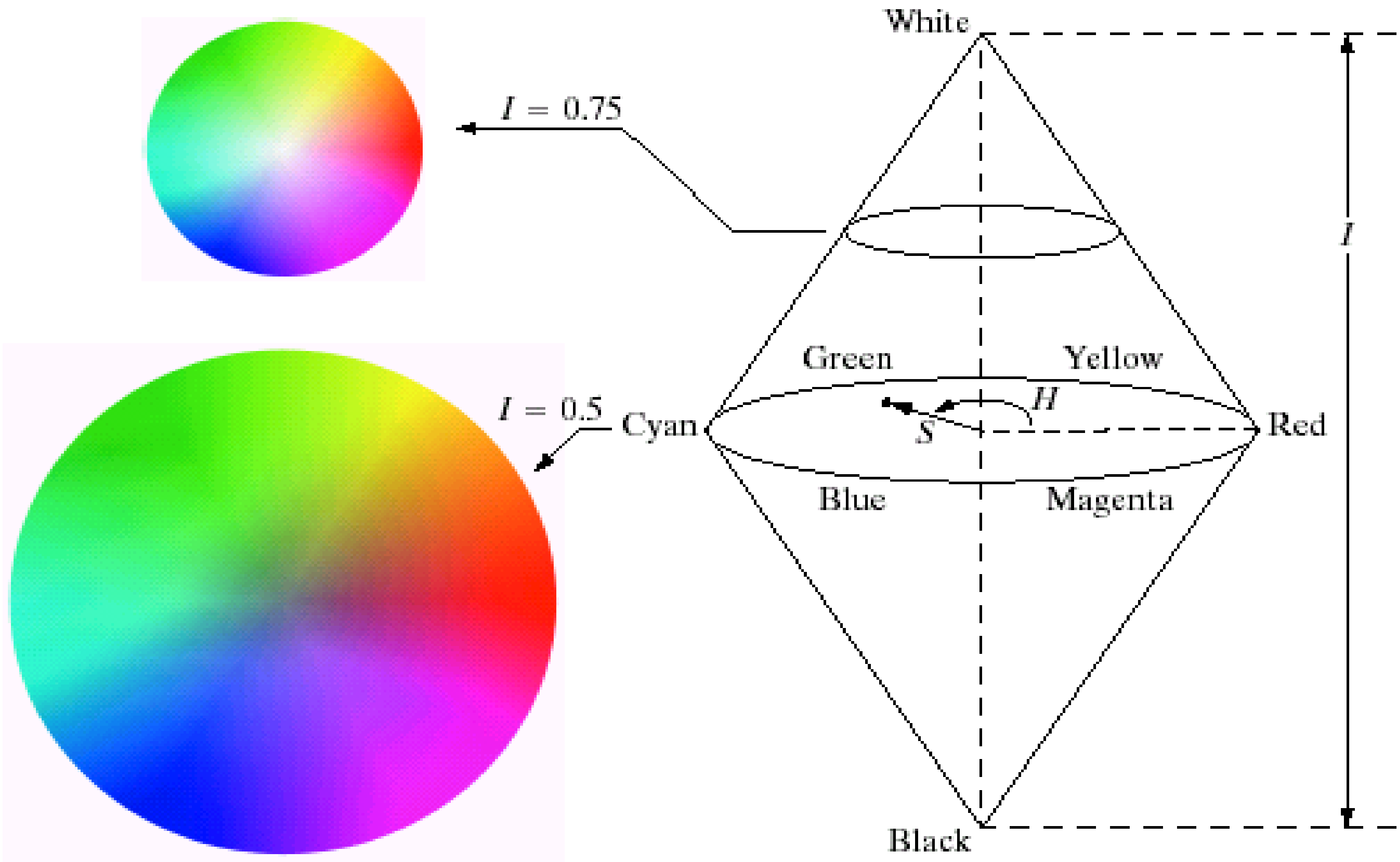
Cont..

- The **HSI** model is called a **double hexagon model**.
- The bottom is similar to HSV but the top also converges to one point that corresponds to the color white. The line between top point and bottom point corresponds to varying shades of gray.
- For the **HSI model**, the maximum saturation is available at a medium grey intensity. The **HSL** model is also a **double hexagon model**, where **lightness** is defined as the **average** of the **largest** and **smallest** color components.



HSI models (W-white, R-red, M-magenta, B-blue, C-cyan, G-green, Y-yellow)

Cont..



Converting From RGB To HSI

- Given a color as R, G, and B its H, S, and I values are calculated as follows:

$$H = \begin{cases} \theta & \text{if } B \le G \\ 360 - \theta & \text{if } B > G \end{cases} \qquad \theta = \cos^{-1}\left\{ \frac{\frac{1}{2}\left[(R-G)+(R-B)\right]}{\left[(R-G)^2+(R-B)(G-B)\right]^{\frac{1}{2}}} \right\}$$

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

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

Converting From HSI To RGB

- Given a color as H, S, and I it's R, G, and B values are calculated as follows:
  - RG sector ($0 <= H < 120°$)

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

$$G = 3I - (R + B),$$

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

Cont..

– GB sector ($120° <= H < 240°$)

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

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

$$B = 3I - (R + G)$$

Cont..

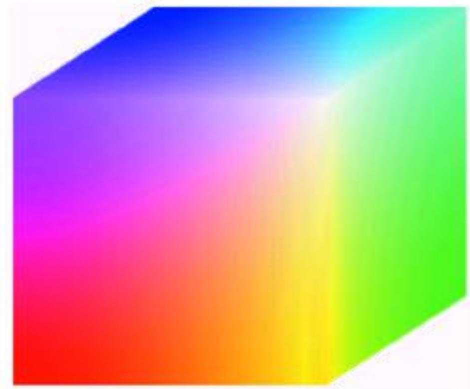
– BR sector ($240° <= H <= 360°$)

$$R = 3I - (G + B),$$

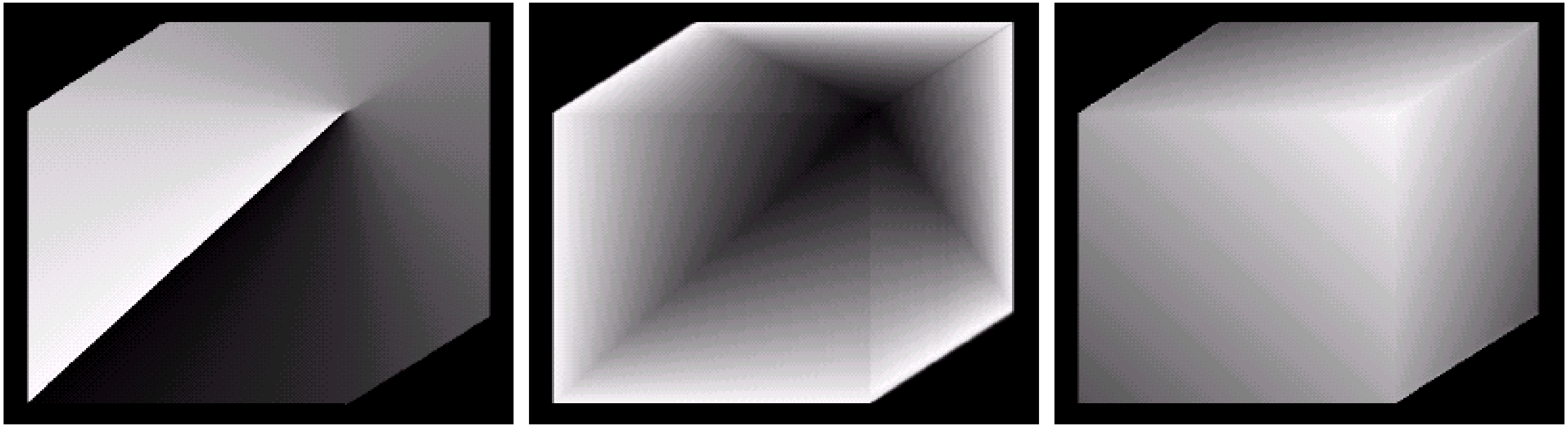
$$G = I(1 - S),$$

$$B = I\left[1 + \frac{S\cos(H - 240)}{\cos(H - 180)}\right]$$

HSI & RGB



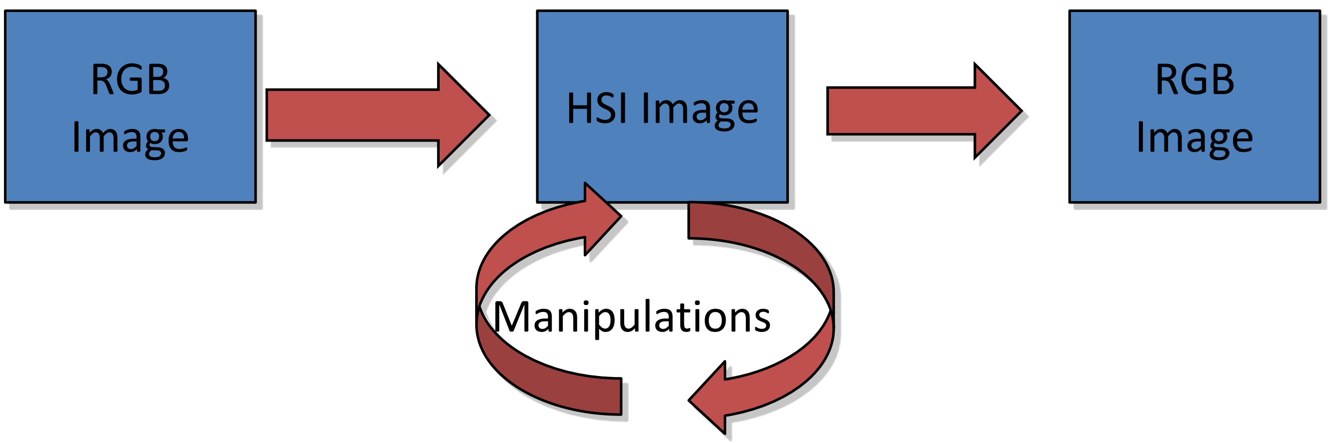
RGB Color Cube



H, S, and I Components of RGB Color Cube

Manipulating Images In The HSI Model

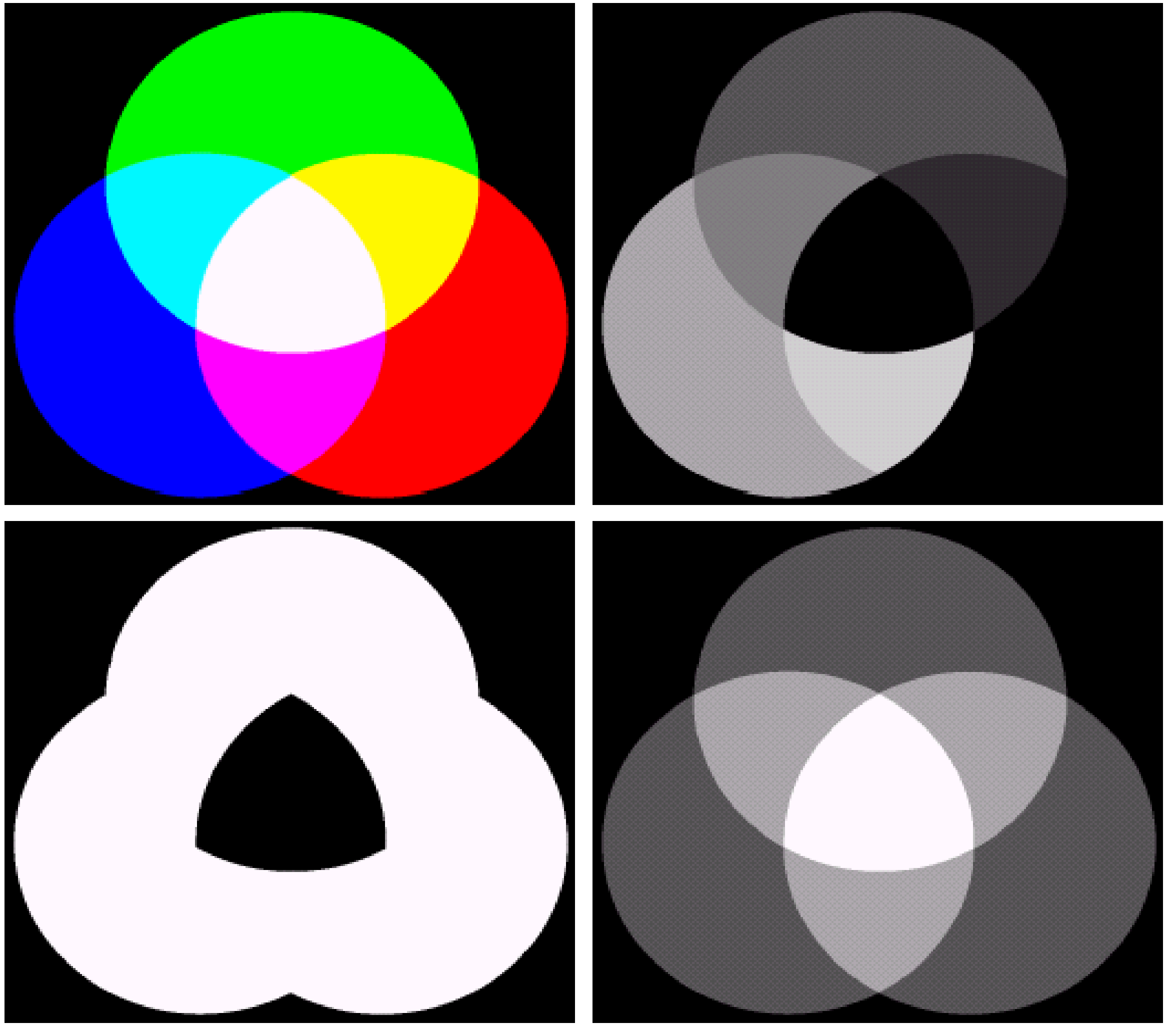
- In order to manipulate an image under the HSI model we:
  - First convert it from RGB to HSI
  - Perform our manipulations under HSI
  - Finally convert the image back from HSI to RGB



RGB -> HSI -> RGB

RGB Image

Hue



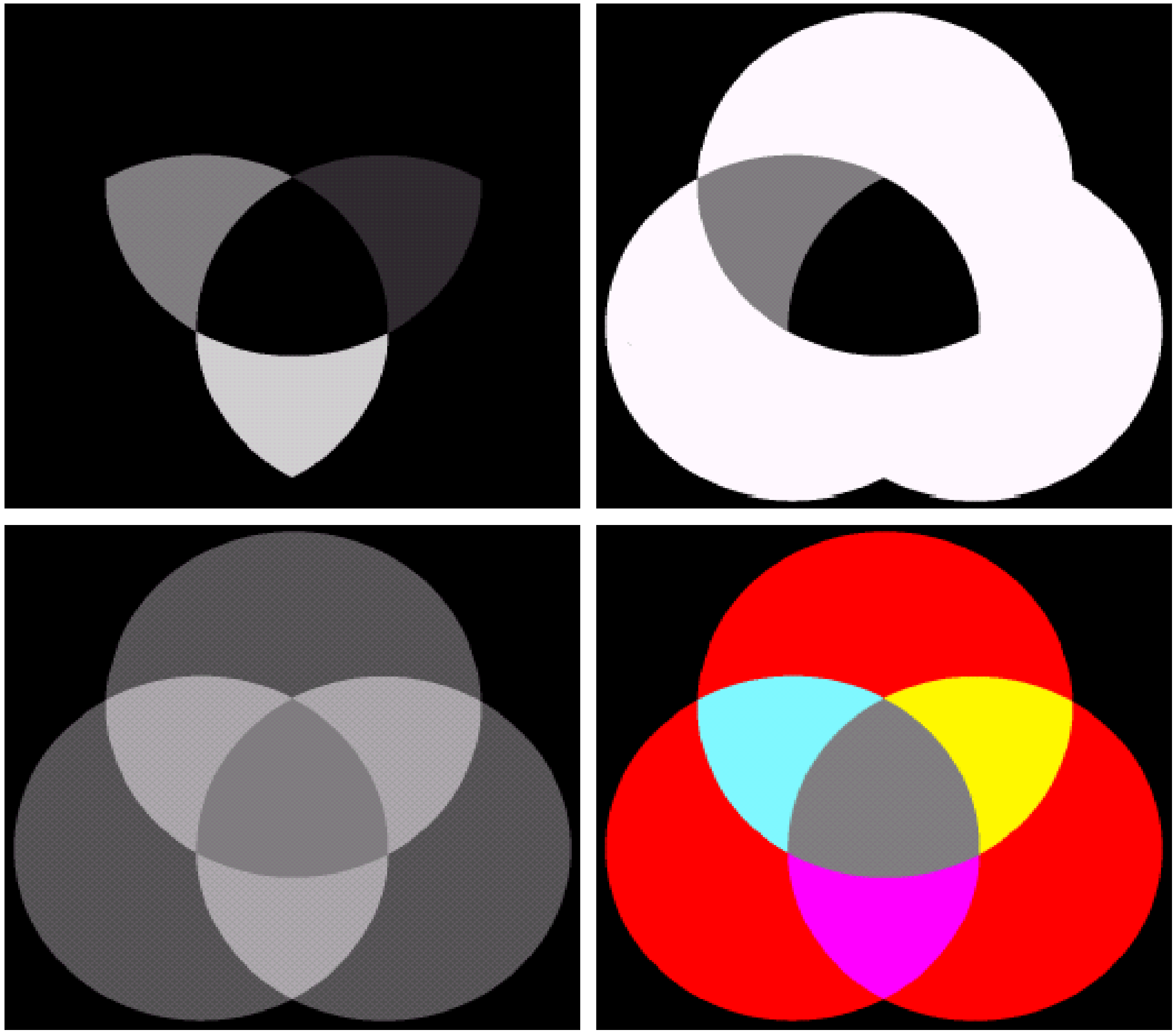
Saturation

Intensity

Cont..

Hue

Saturation



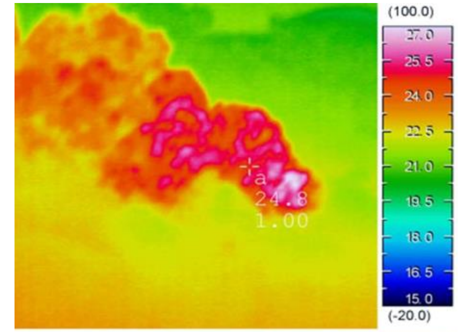
Intensity

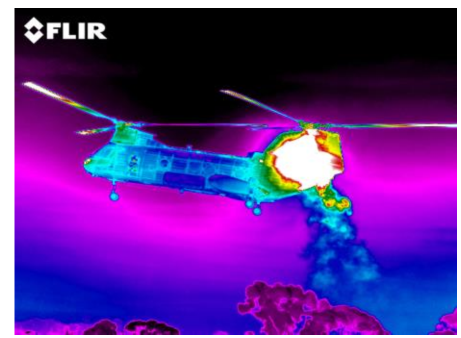
RGB Image

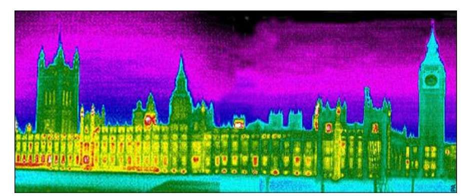
Pseudo-color Image Processing

- Pseudo-color (also called false color) image processing consists of assigning colors to grey values based on a specific criterion.

- The principle use of pseudo-color image processing is for human visualisation.
  – Humans can discern between thousands of color shades and intensities, compared to only about two dozen or so shades of grey.







Pseudo Color Image Processing – Intensity Slicing

- Intensity slicing and color coding is one of the simplest kinds of pseudo-color image processing.
- First we consider an image as a 3D function mapping spatial coordinates to intensities (that we can consider heights).
- Now consider placing planes at certain levels parallel to the coordinate plane.
- If a value is one side of such a plane it is rendered in one color, and a different color if on the other side.

Cont..

- The pseudo-colors used to colorize a gray level image do not represent the original, true colors if there were originally a color image.

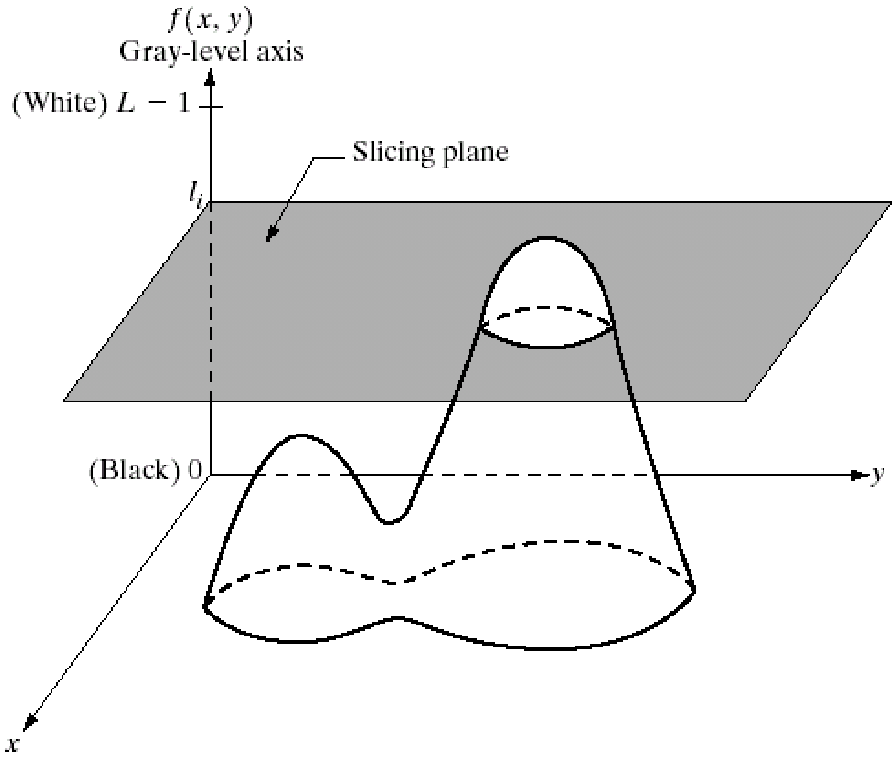


FIGURE 6.18 Geometric interpretation of the intensity-slicing technique.

Cont..

In general intensity slicing can be summarised as:

- Let $[0, L\text{-}1]$ represent the grey scale
- Let l_0 represent black $[f\,(x, y) = 0]$ and let $l_{L\text{-}1}$ represent white $[f\,(x, y) = L\text{-}1]$
- Suppose P planes perpendicular to the intensity axis are defined at levels $l_1, l_2, \ldots, l_p$
- Assuming that $0 < P < L\text{-}1$ then the P planes partition the grey scale into $P + 1$ intervals $V_1, V_2, \ldots, V_{P+1}$

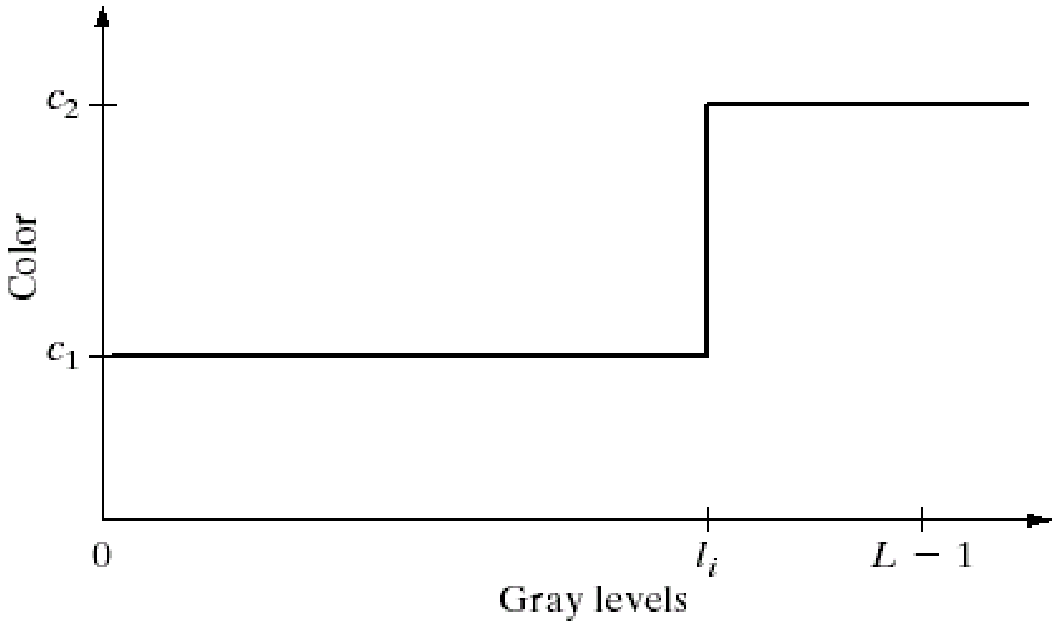
Cont..

– Grey level color assignments can then be made according to the relation:

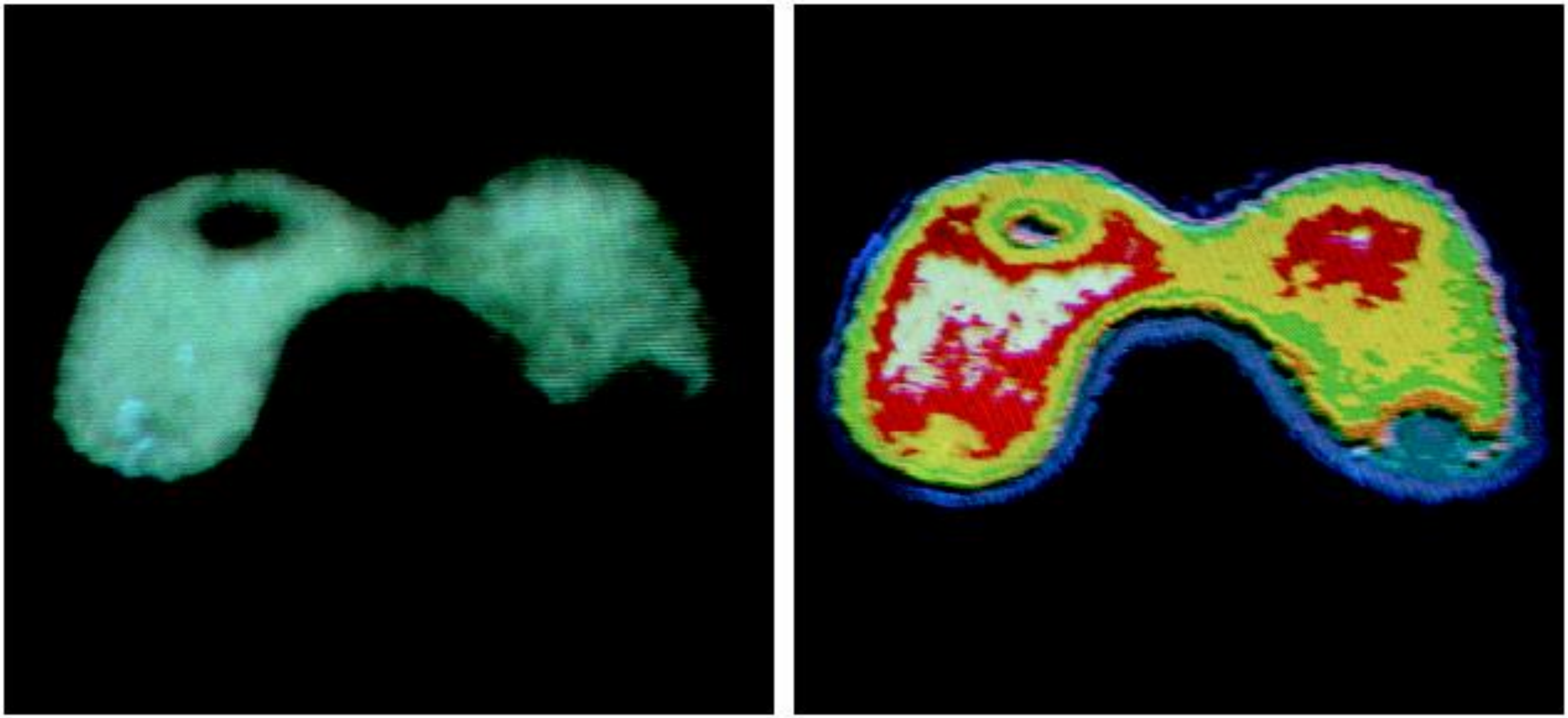
$$f(x,y) = c_k \qquad \text{if } f(x,y) \in V_k$$

– where c_k is the color associated with the k^{th} intensity level V_k defined by the partitioning planes at $l = k-1$ and $l = k$

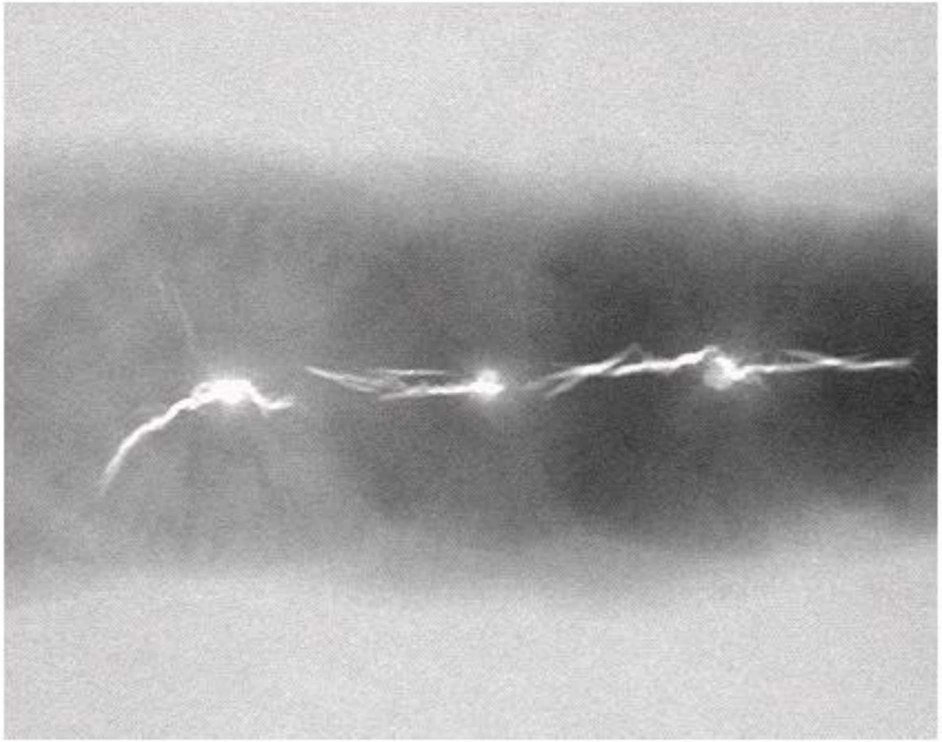
Cont..

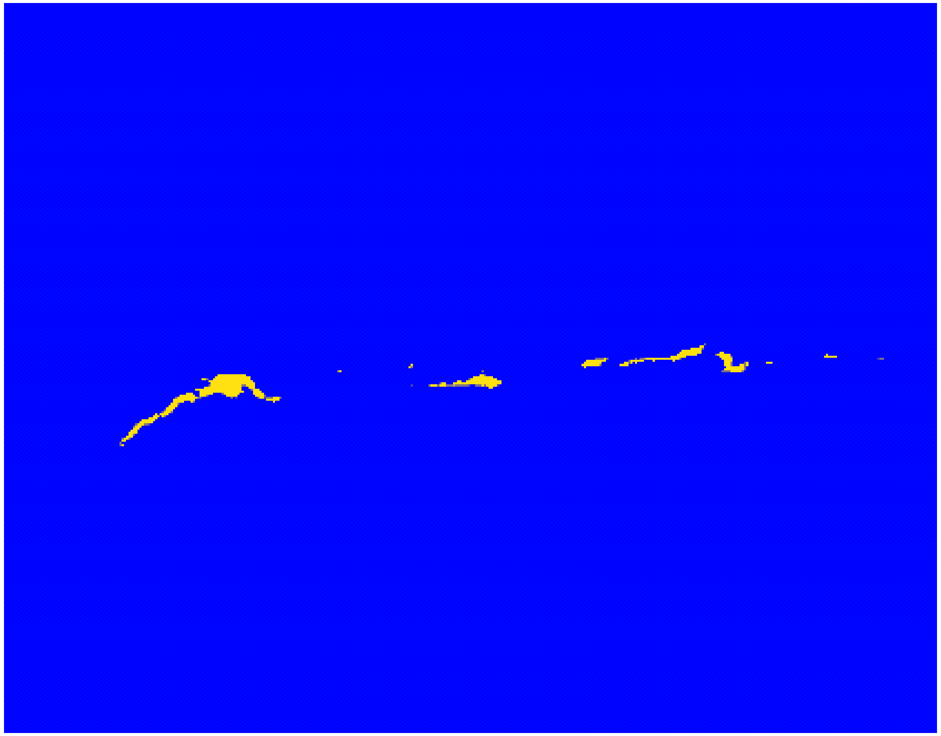


Cont..



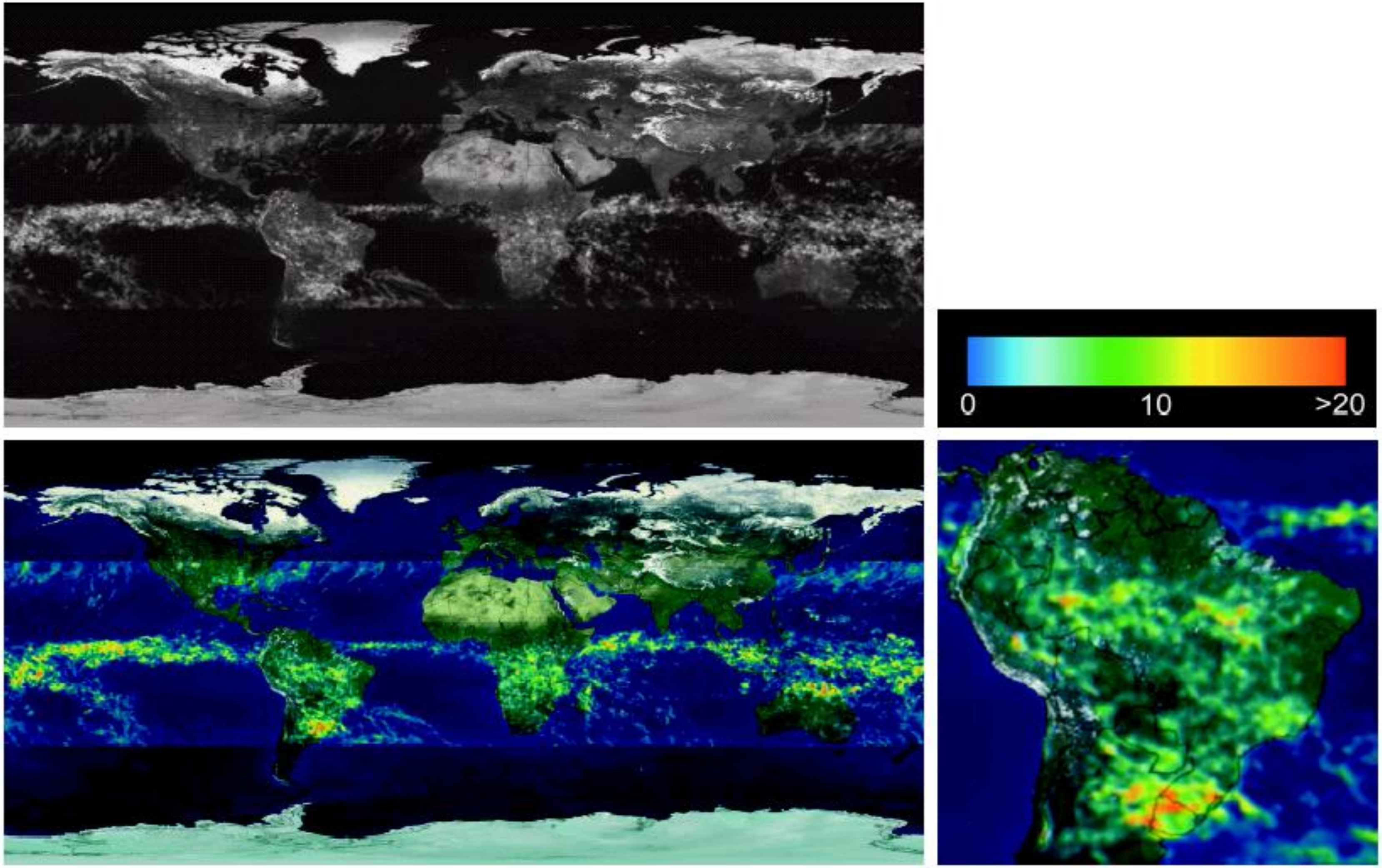
Cont..



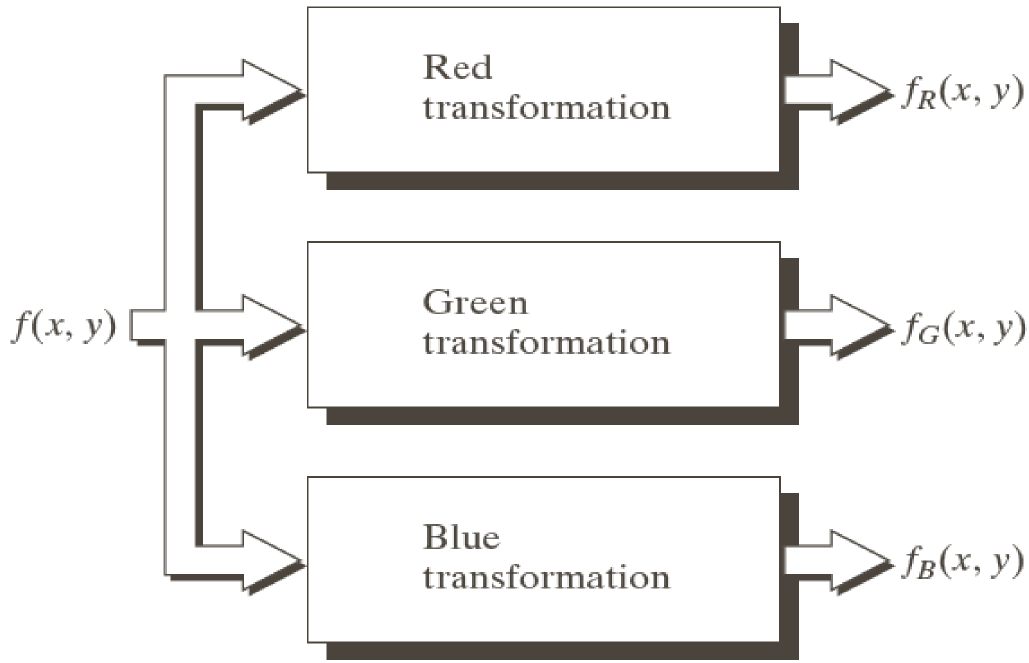


- Assigning the yellow color to intensity 255 and the blue color to the rest of the intensities may help a human inspector to rapidly evaluate a crack in an image of a weld.

Cont..

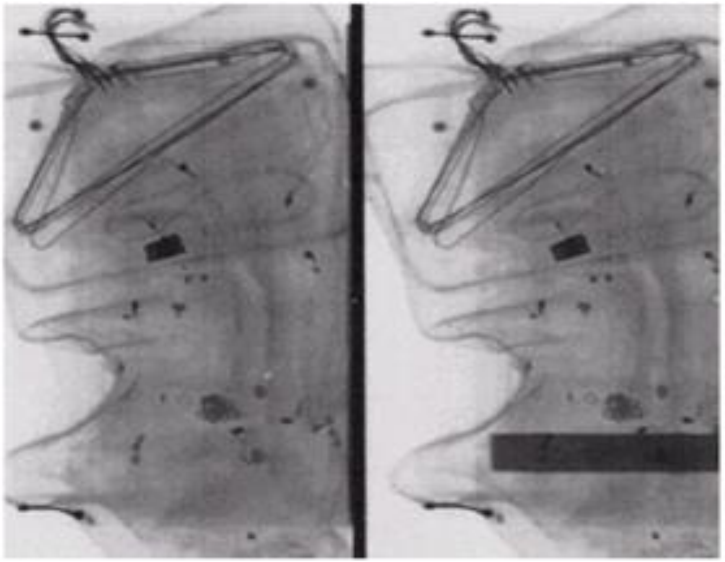


Cont..



- Three independent transformations of the intensity.
- The results are fed into the R, G, B channels.
- The resulting composite image highlights certain image parts.

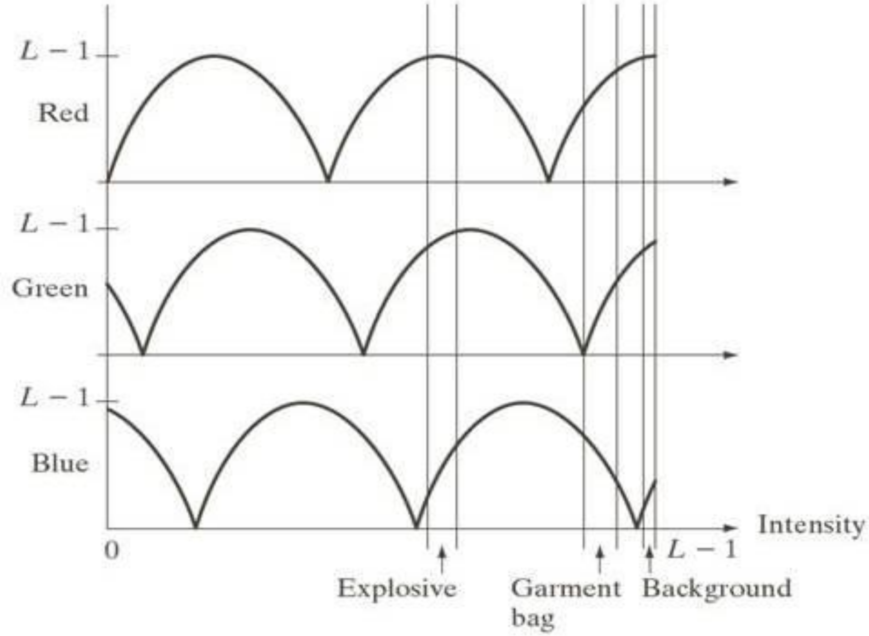
Cont..



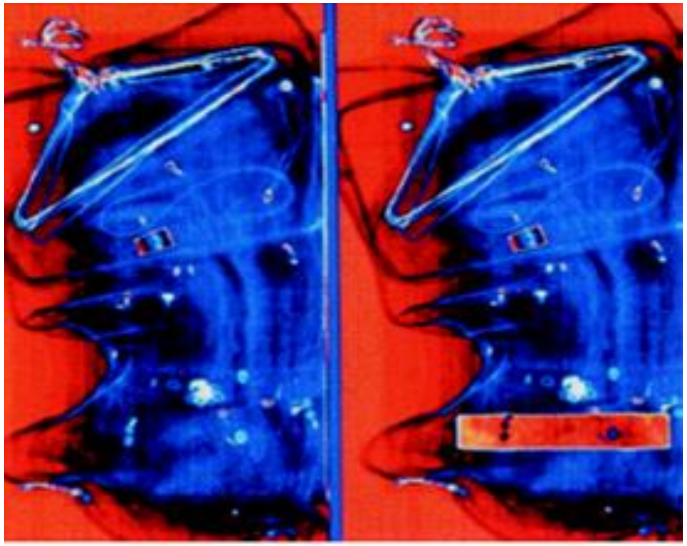
- X-ray images from airport scanning system.
- The image on the right contains plastic explosives.

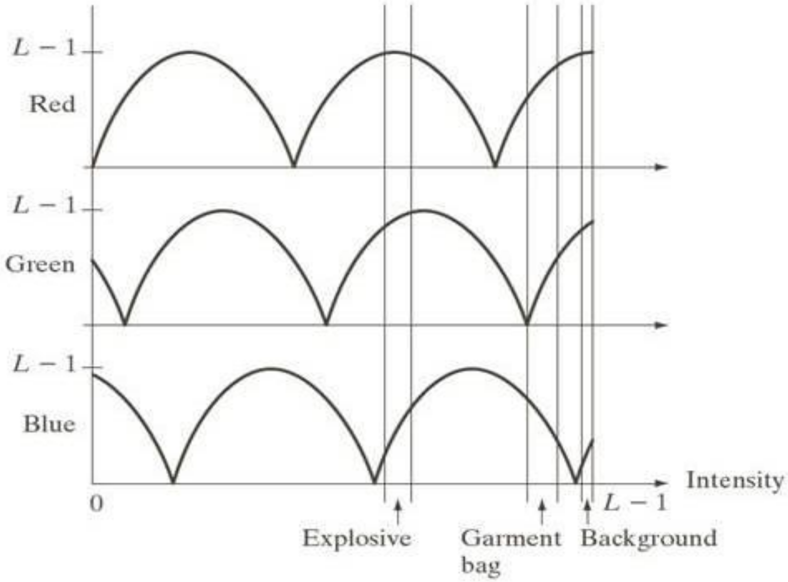
Cont..

- Sinusoidal transformation functions.
- Changing the phase or the frequency of the transformation functions can emphasize ranges in the gray scale.
  - A small change in the phase between the transformations assigns a strong color to the pixels with intensities in the valleys.



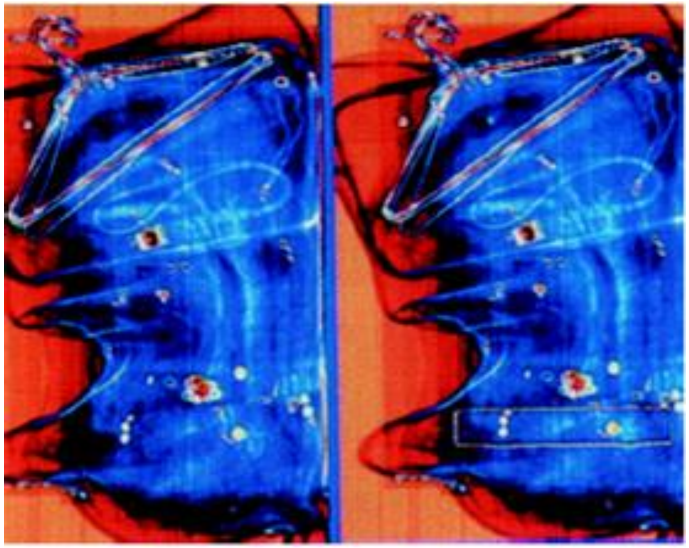
Cont..

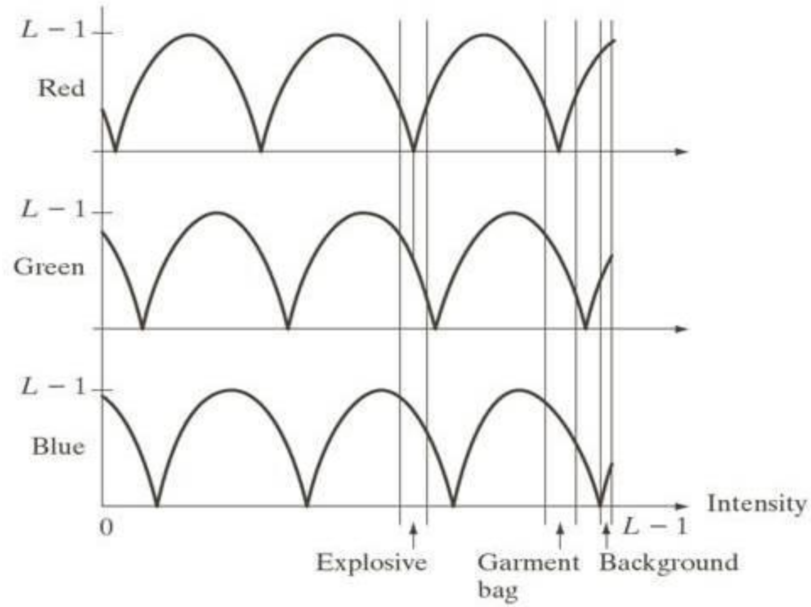




- Background and explosives are coded with approximately the same color although they differ.
- This is due to the periodicity of the sine waves.

Cont..





- Explosives and bag content are mapped by similar transformations and were assigned to the same color.
- The observer may "see" through the explosives and not mistake them for the background.

Full Color Image Processing

- Two processing methods:
  - (1) process each channel (or color component) separately, as if the color image were three gray scale images;
  - (2) process all channels with each pixel represented as a vector.