Lecture #12

- Image Correlation (example)
- Color basics (Chapter 6)
- The Chromaticity Diagram
- Color Images
- RGB Color Cube
- Color spaces
- Pseudocolor
- Multispectral Imaging

White Light

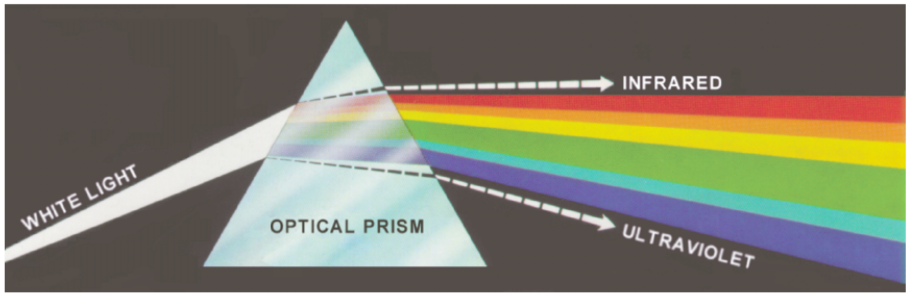


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

A prism splits white light into its component colors.

Optical Units

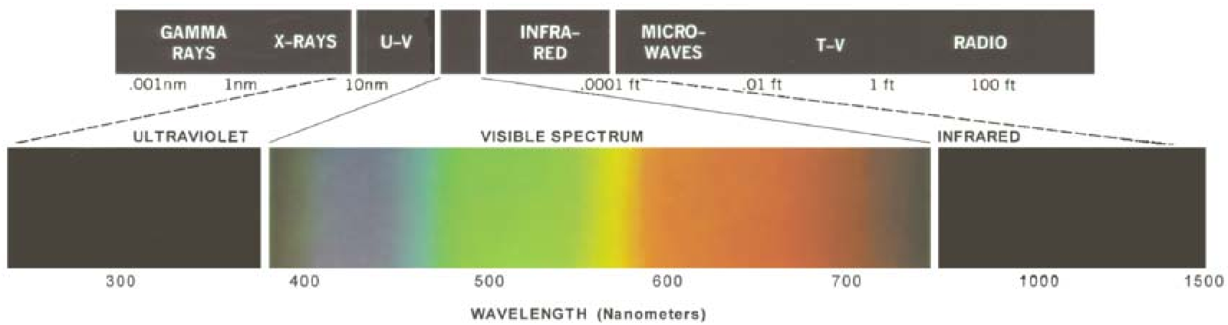
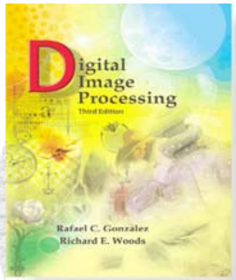


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

<u>Radiometric units:</u>
Radiance (watts/sr/m^2) — power per unit solid angle emitted by a light source
Irradiance (watts/m^2) — total power incident on a surface

<u>Photometric units (corrected for wavelength sensitivity of the human eye):</u>
Luminous intensity (candela) - "power" emitted by a source in a given direction
Luminance (candela/m^2) — total light passing through a given surface or emitted from a surface
Luminous flux (lumens) — luminous flux of light produced by a light source that emits one candela of luminous intensity over a solid angle of one steradian



Human Eye

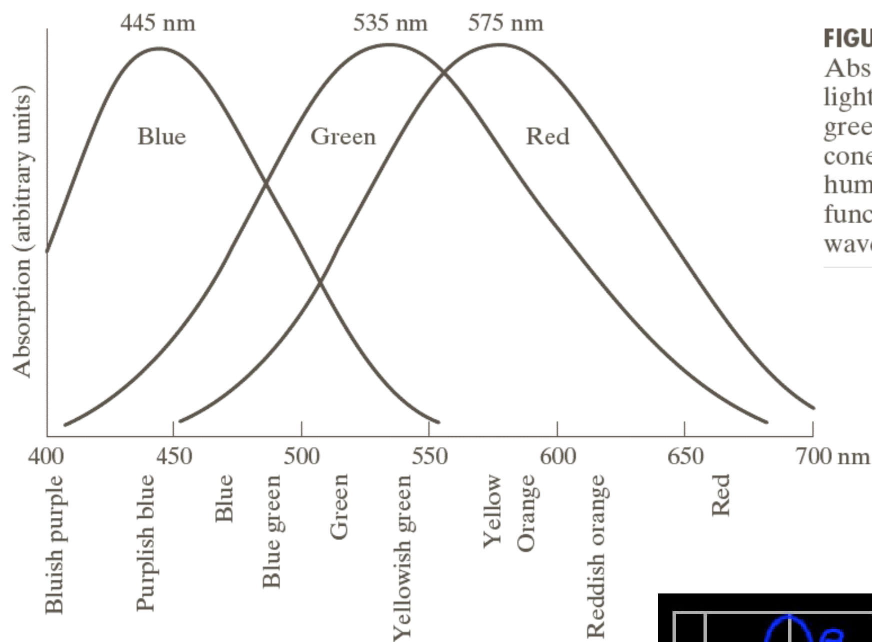
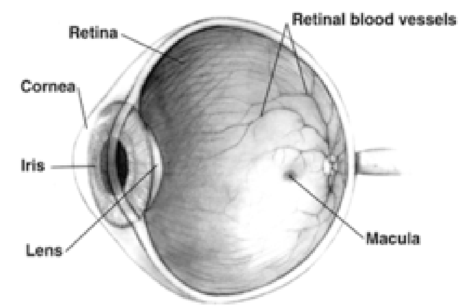


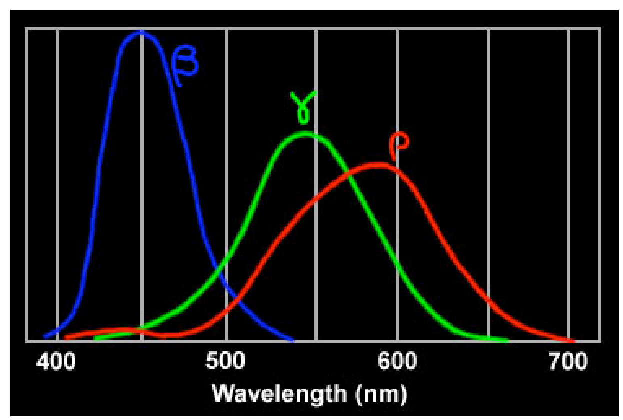
FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

The cones provide all the color sensitivity and are concentrated near the macula.



Relative color sensitivity of the cones.

65% of cones are red sensitive; 33% are green sensitive; 2% are blue sensitive.

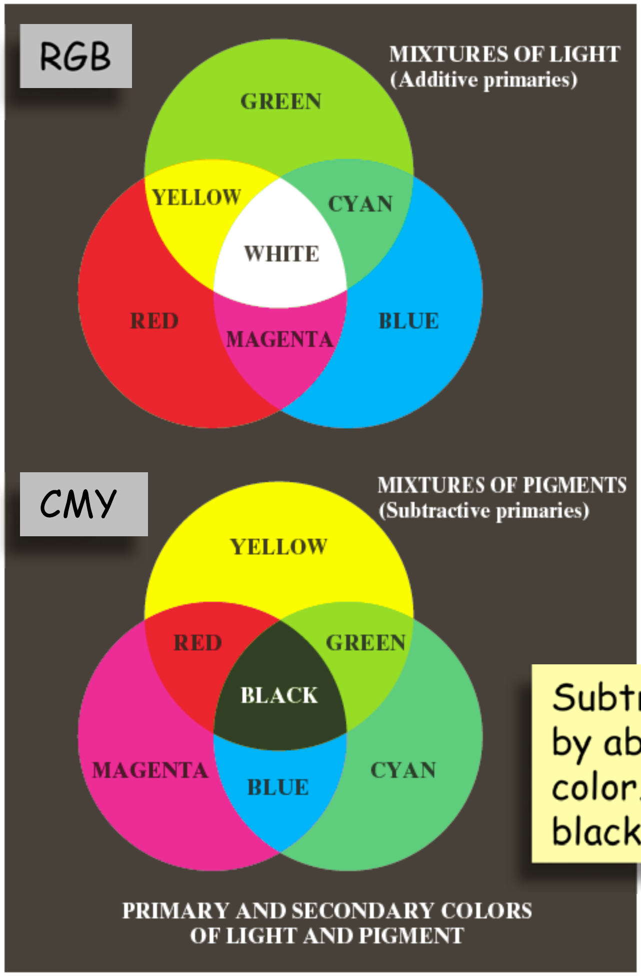


Primary/Secondary Colors

(Primary) additive colors operate in transmission such as found in televisions and computer monitors

(Secondary) subtractive colors operate in reflection such as found in printing

For example, yellow absorbs blue and reflects red+green=yellow



a
b

FIGURE 6.4 Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lamp Business Division.)

Subtractive colors operate by absorbing a primary color. They usually require black as an additional color.

Why K?

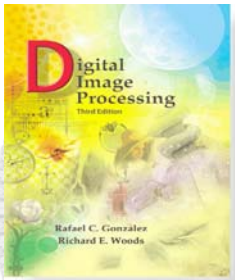
Common reasons for adding a K (black) ink include:

* Text is typically printed in black and includes fine detail (such as serifs), so to reproduce text or other finely detailed outlines using three inks without slight blurring would require impractically accurate registration (i.e. all three images would need to be aligned extremely precisely).

* A combination of 100% cyan, magenta, and yellow inks soaks the paper with ink, making it slower to dry, and sometimes impractically so.

* A combination of 100% cyan, magenta, and yellow inks often results in a muddy dark brown color that does not quite appear black. Adding black ink absorbs more light, and yields much “blacker” blacks.

* Using black ink is less expensive than using the corresponding amounts of colored inks.



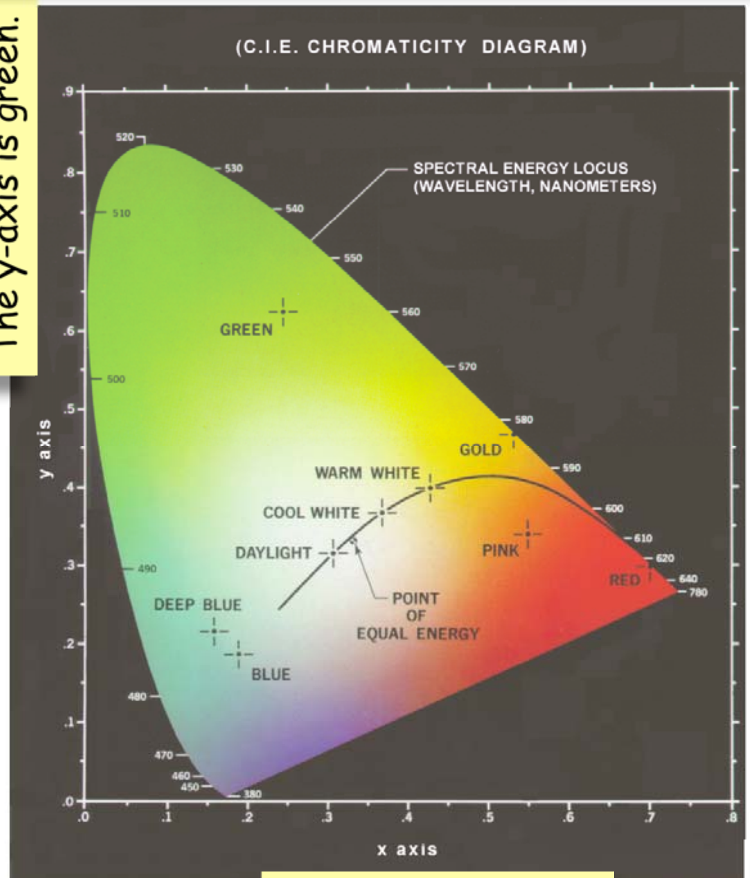
CIE Chromaticity Diagram

The diagram shows all colors perceivable by the human eye.

Characteristics of color:
- Brightness
- Chromaticity:
  - Hue - dominant color seen by the observer
  - Saturation - amount of white light mixed with the color

A chromaticity diagram plots the tristimulus values x,y and z of a color. This is based upon X,Y and Z — the amounts of red, green and blue needed to represent a color.

The y-axis is green.



The x-axis is red.

FIGURE 6.5 Chromaticity diagram. (Courtesy of the General Electric Co., Lamp Business Division.)

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z}$$

where $x + y + z + 1$

Blue is not plotted since is is equal to 1-x-y

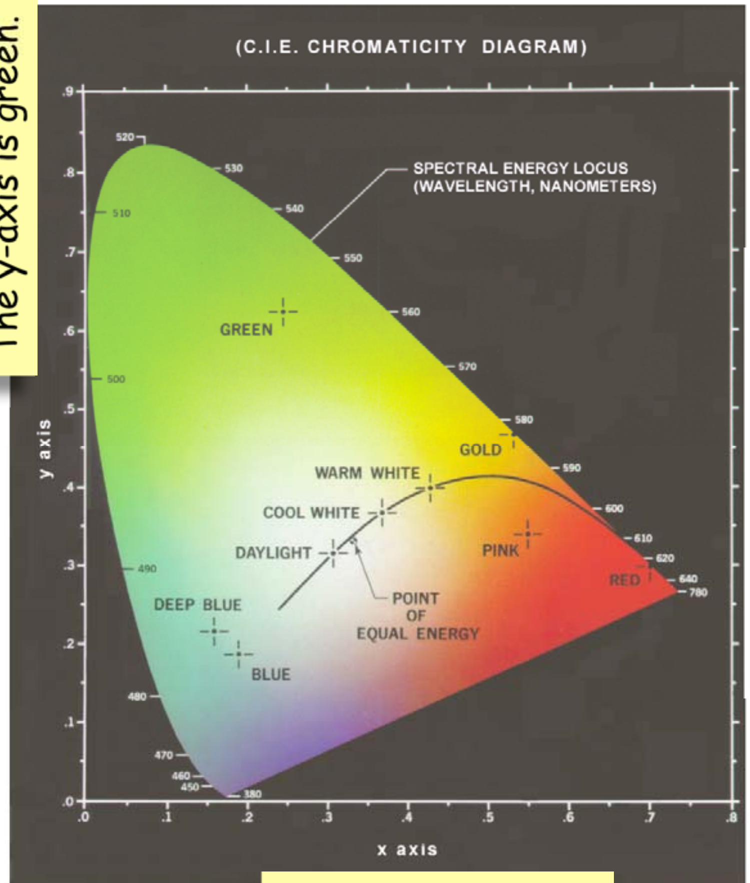
CIE Chromaticity Diagram

Characteristics of color:
- Brightness
- Chromaticity:
  - Hue - dominant color seen by the observer
  - Saturation - amount of white light mixed with the color

The point of equal energy (x=0.33,y=0.33, implied z=0.33) defines the CIE standard for white light

Any point on the boundary is fully saturated (saturation=1)

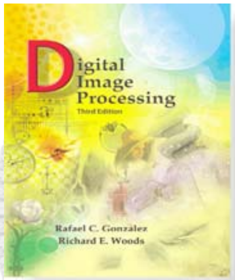
The y-axis is green.



The x-axis is red.

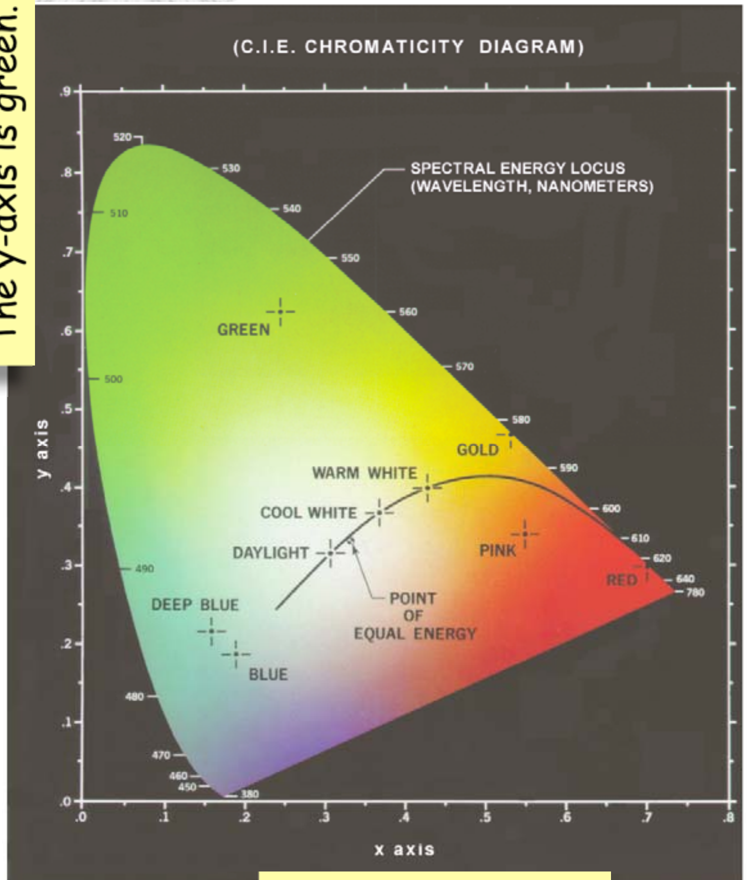
FIGURE 6.5 Chromaticity diagram. (Courtesy of the General Electric Co., Lamp Business Division.)

Note that we can define many kinds of white near the CIE standard for white. These include daylight (more blue), cool white (more red and green), and warm white (much more red)

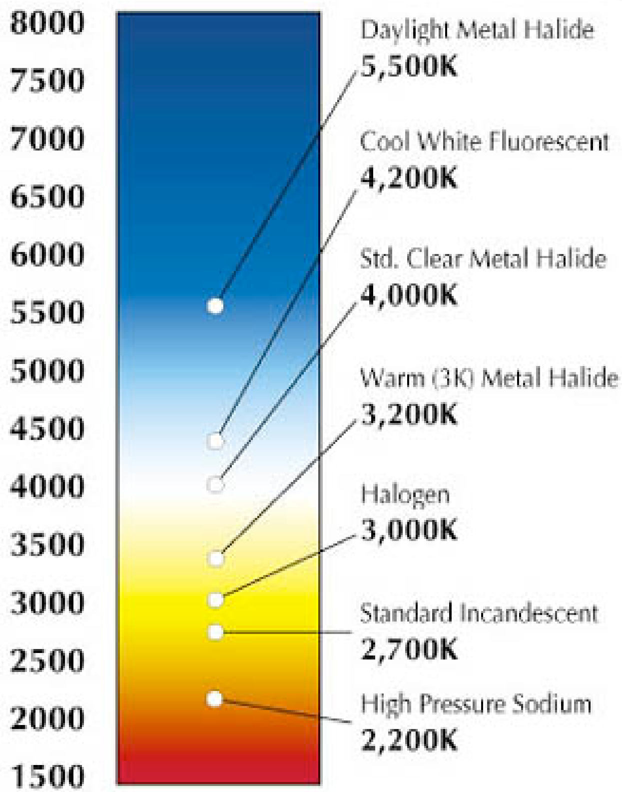


Color Temperature

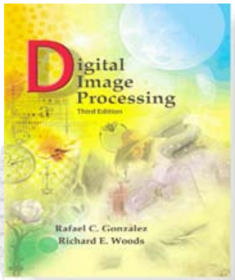
The y-axis is green.



The x-axis is red.



Color Temperature (measured in Kelvin) describes how "warm" or how "cool" the light source is. It is based on the color of light emitted by an incandescent source. As a piece of metal (a theoretical Blackbody) is heated, it changes color from reddish to orange to yellowish to white to bluish-white. The color of light emitted by an incandescent object depends only on the temperature. We can use this scale to describe the color of a light source by its "Color Temperature."



CIE Chromaticity Diagram

Color printers are capable of far less color rendition than a color monitor. The two regions define typical limits of printers and monitors.

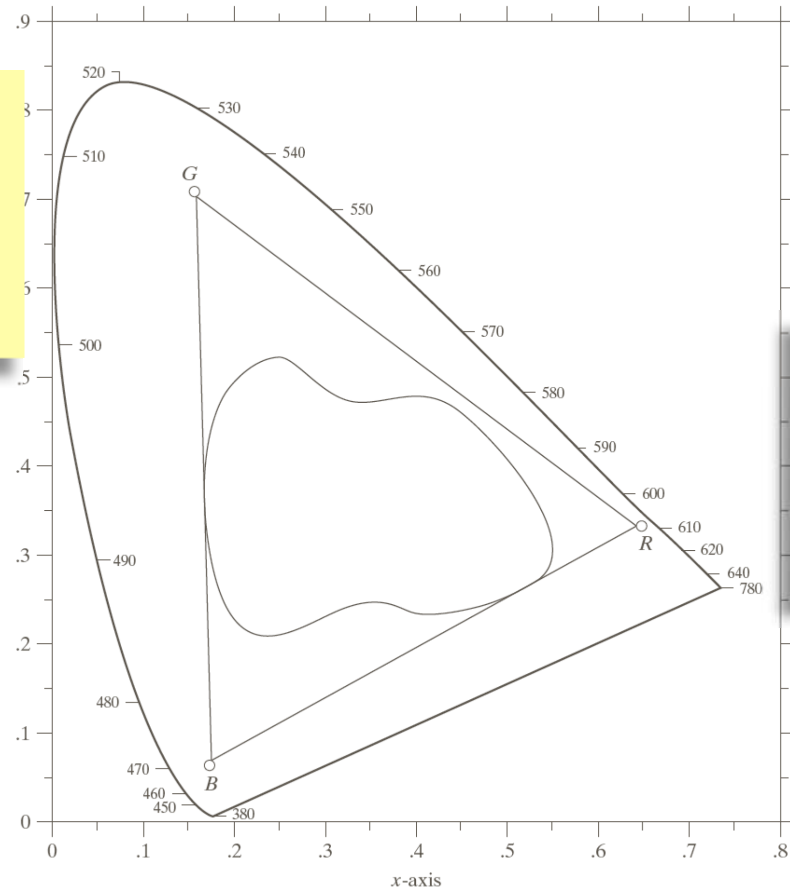
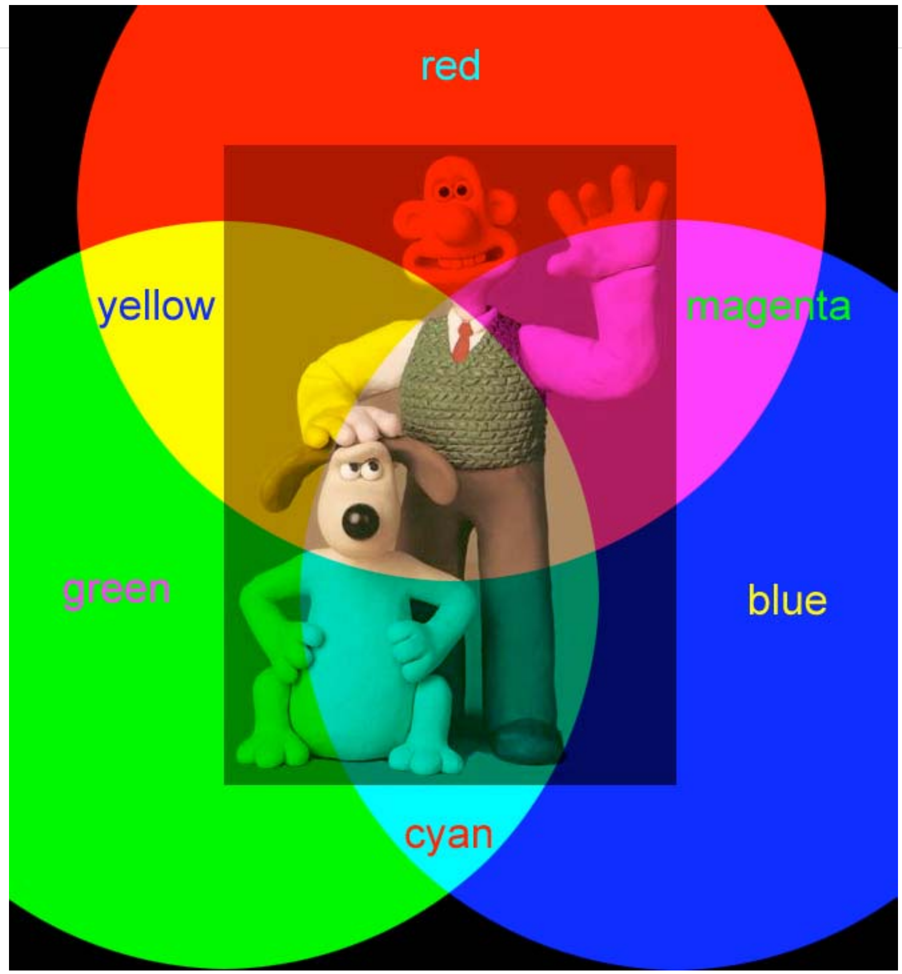


FIGURE 6.6 Typical color gamut of color monitors (triangle) and color printing devices (irregular region).

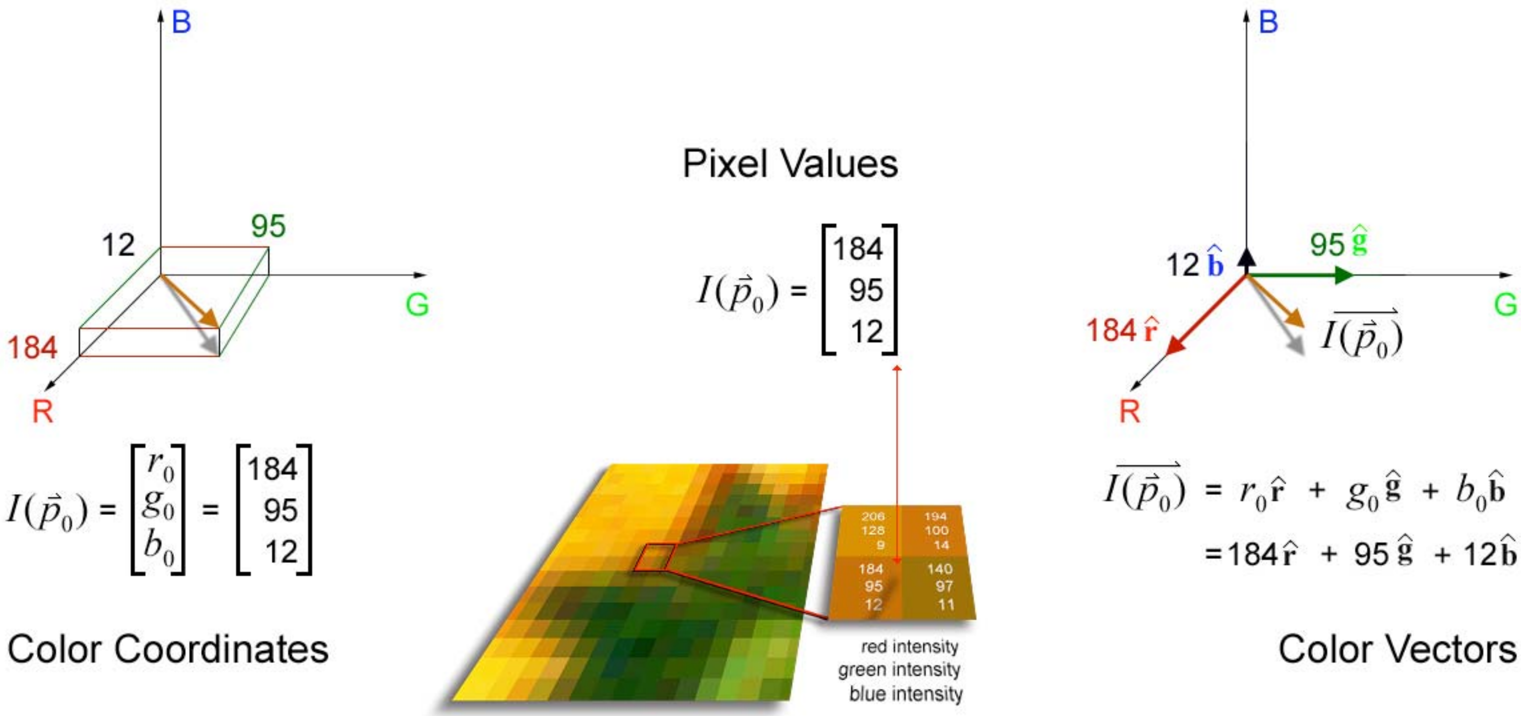
Note that a monitor (triangle) is incapable of displaying color temperatures below about 1900°K. A printer is even worse.

Color Images

- Are constructed from three overlaid intensity maps.
- Each map represents the intensity of a different “primary” color.
- The actual hues of the primaries do not matter as long as they are distinct.
- The primaries are 3 vectors (or axes) that form a “basis” of the color space.



Pixels — Coordinates or Vectors?



$$I(\vec{p}_0) = \begin{bmatrix} r_0 \\ g_0 \\ b_0 \end{bmatrix} = \begin{bmatrix} 184 \\ 95 \\ 12 \end{bmatrix}$$

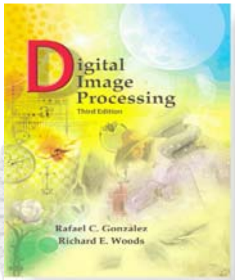
Color Coordinates

$$I(\vec{p}_0) = \begin{bmatrix} 184 \\ 95 \\ 12 \end{bmatrix}$$

$$\overrightarrow{I(\vec{p}_0)} = r_0\hat{\mathbf{r}} + g_0\hat{\mathbf{g}} + b_0\hat{\mathbf{b}}$$
$$= 184\hat{\mathbf{r}} + 95\hat{\mathbf{g}} + 12\hat{\mathbf{b}}$$

Color Vectors

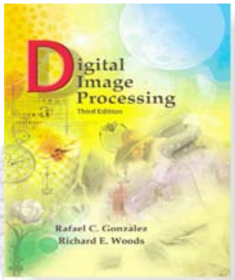
Each color corresponds to a point in a 3D vector space



Color Space

for standard digital images

- primary image colors red, green, and blue
  - correspond to R,G, and B axes in color space.
- 8-bits of intensity resolution per color
  - correspond to integers 0 through 255 on axes.
- no negative values
  - color "space" is a cube in the first octant of 3-space.
- color space is discrete
  - 256^3 possible colors = 16,777,216 elements in cube.



RGB Color Cube

The colors along the diagonal have equal amounts of red, green, and blue which defines gray. But their intensity given by I=(R+G+B)/3 varies from 0 (black) to 1 (white) along the cube's diagonal.

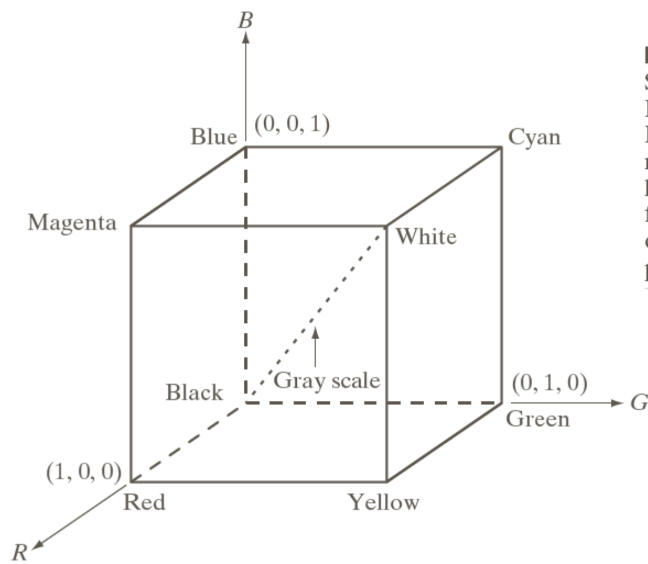


FIGURE 6.7 Schematic of the RGB color cube. Points along the main diagonal have gray values, from black at the origin to white at point (1, 1, 1).

RGB Color Cube

Typically each color is defined by three 8-bit numbers for 24-bit color. Some computer programs also support 48-bit color.

The top surface can be written as (R,G,255)

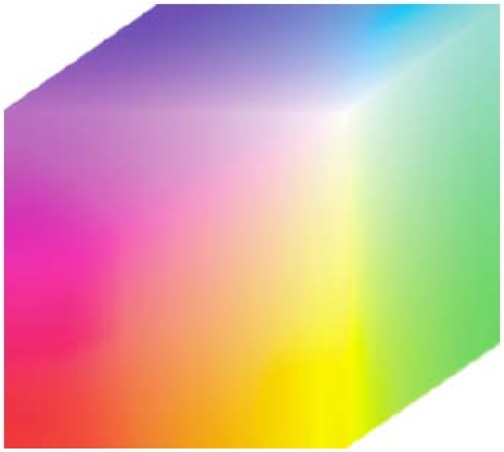
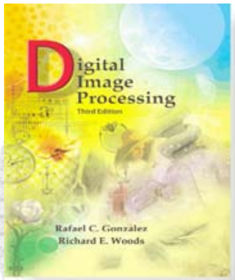


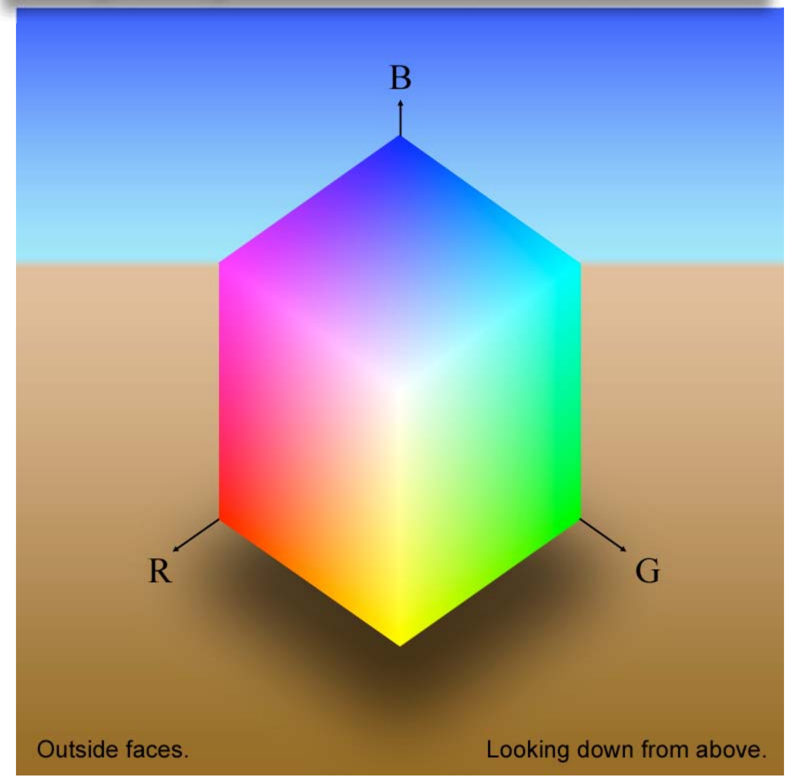
FIGURE 6.8 RGB 24-bit color cube.

The bottom surface can be written as (R,G,0)

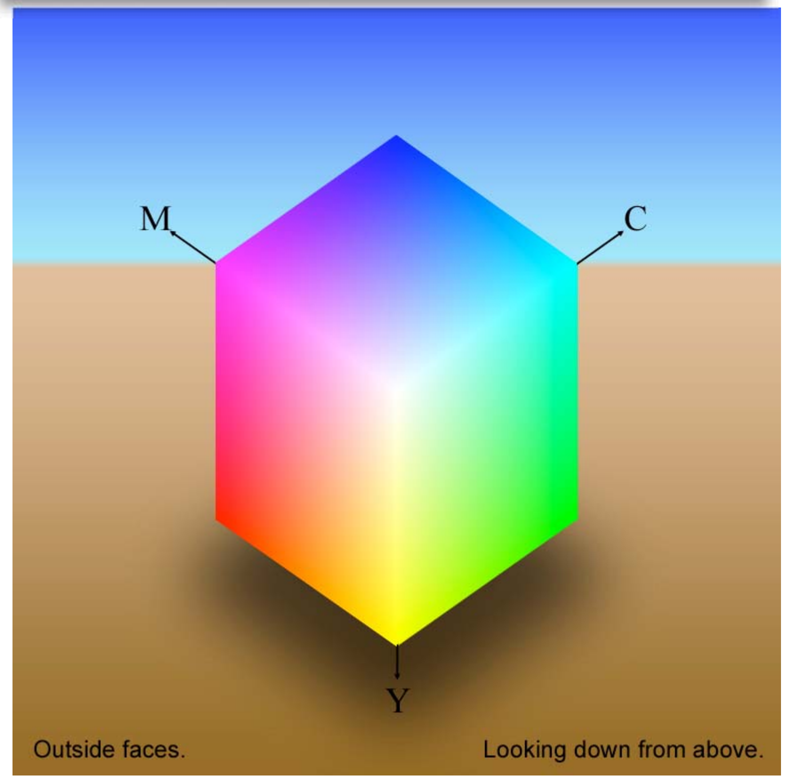


Color Cube: Faces (outer)

The primary colors are at three vertices.

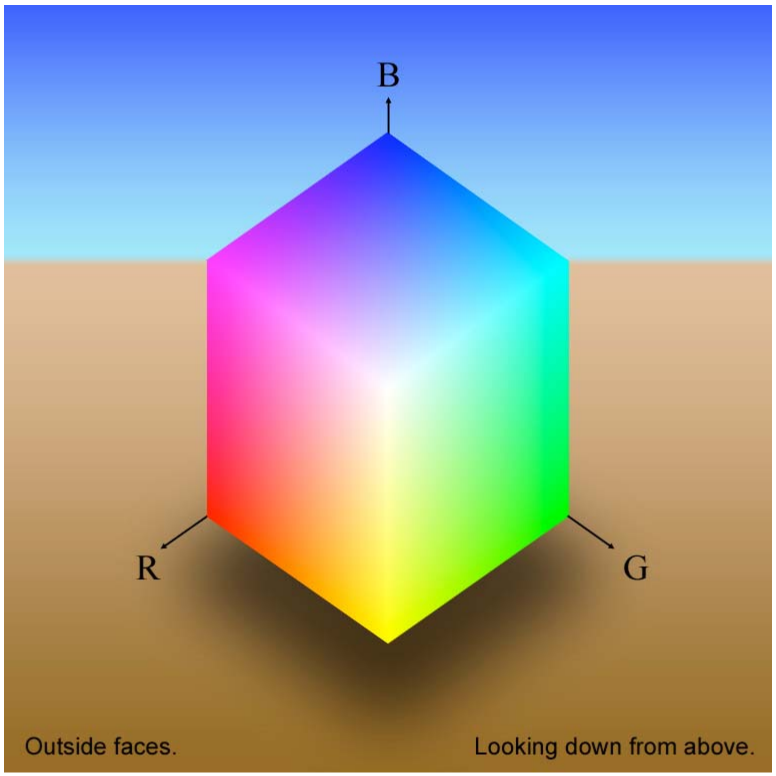


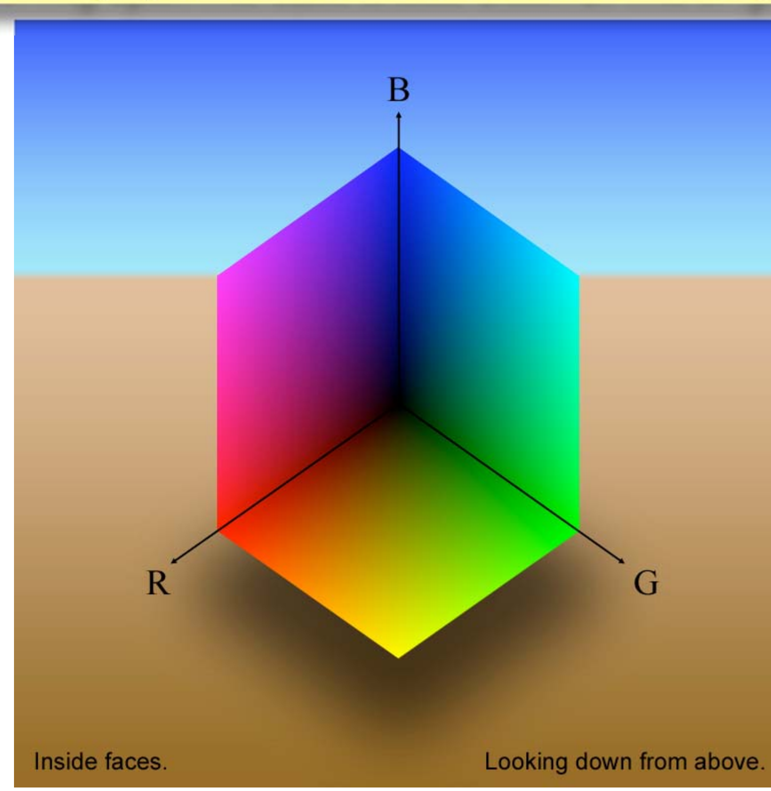
The secondary colors are at three different vertices



Color Cube: Faces (inner and outer)

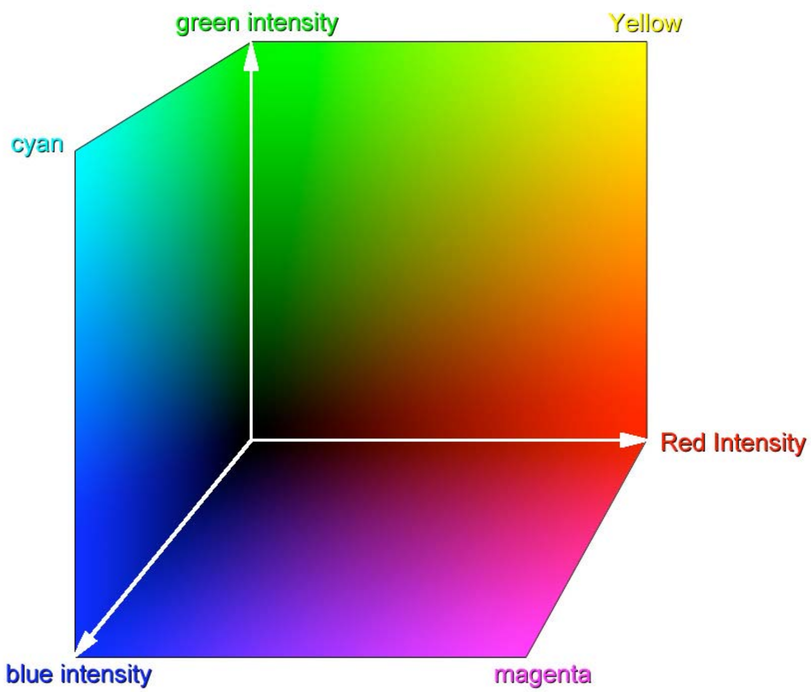
Cutting open the cube shows black at the origin.



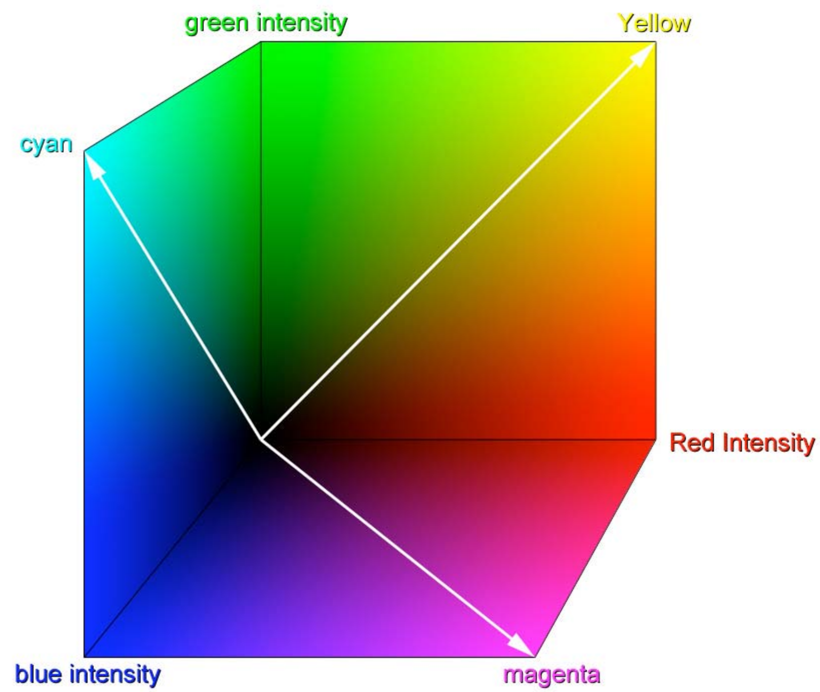


Black and white form the remaining two vertices.

Different Axis Sets in Color Space

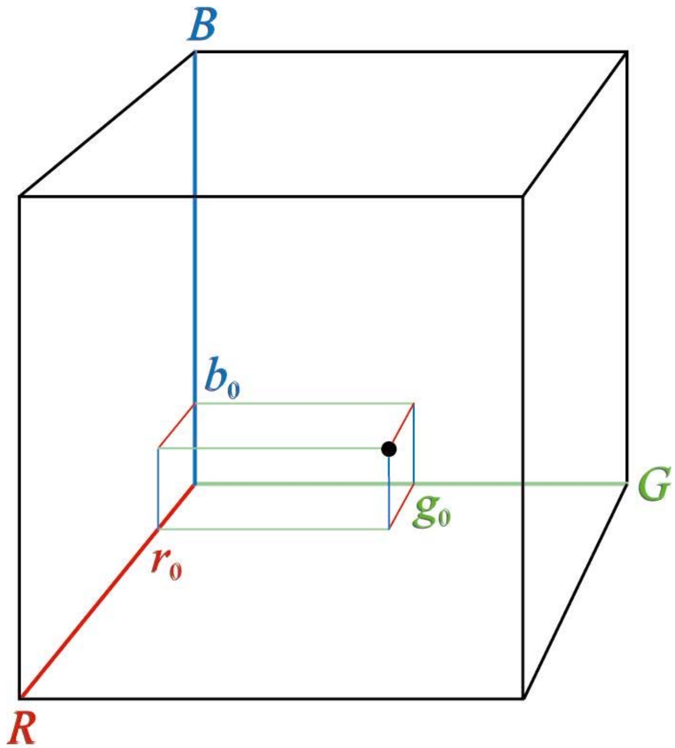


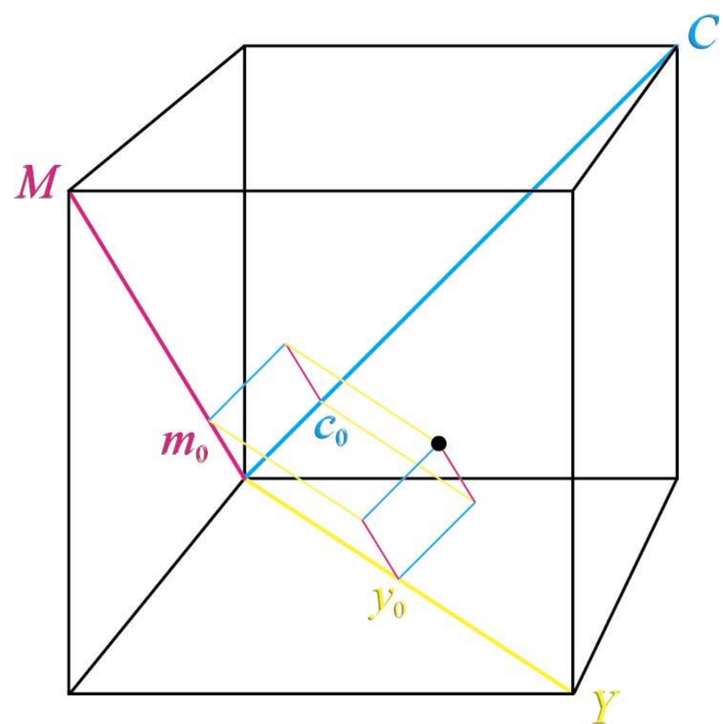
RGB axes



CMY axes

Color With Respect To Different Axes

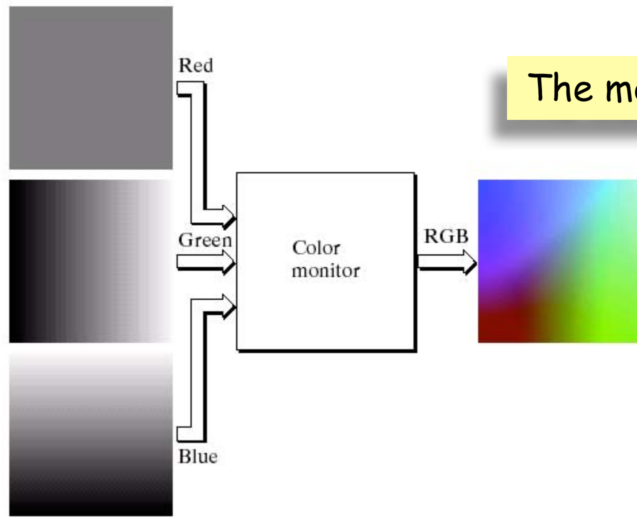




The same color has different RGB and CMY coordinates.

which may be related to each other.

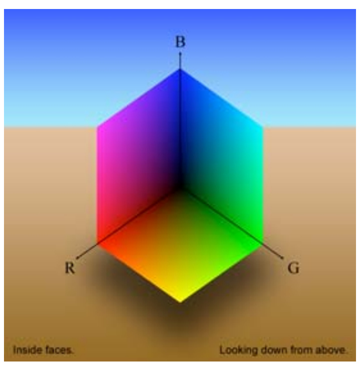
Color Monitors



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.

The monitor adds primary colors.



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

(0,G,B) (R,0,B) (R,G,0)

"safe" Colors

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.

Many systems restrict themselves to 256 Internet "safe" colors for simplicity and ease of generation.

Red coordinate values

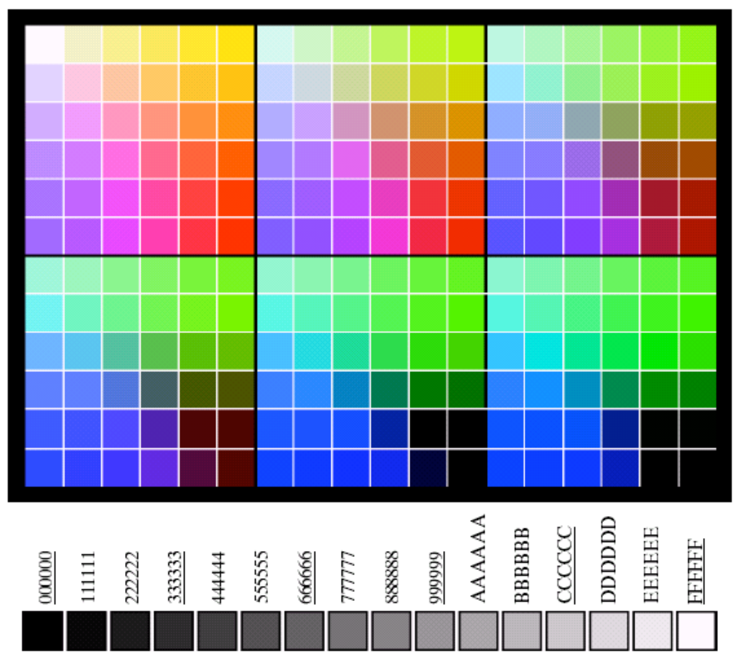
$FF	$CC	$99
$66	$33	$00

Decreasing blue

$FF → $00

Decreasing green

$FF ↓ $00



a
b

FIGURE 6.10 (a) The 216 safe RGB colors. (b) All the grays in the 256-color RGB system (grays that are part of the safe color group are shown underlined).

There are six safe grays.

"safe" colors

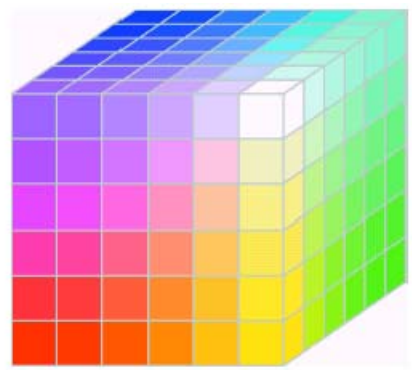
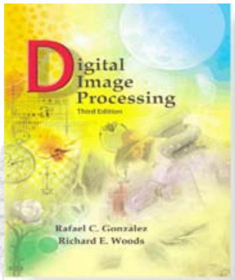


FIGURE 6.11 The RGB safe-color cube.

The Internet "safe" RGB color cube. All surface colors are "safe".

Color printers and copiers convert RGB to CMY. To get a good black on color printers a separate "black" is used.

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

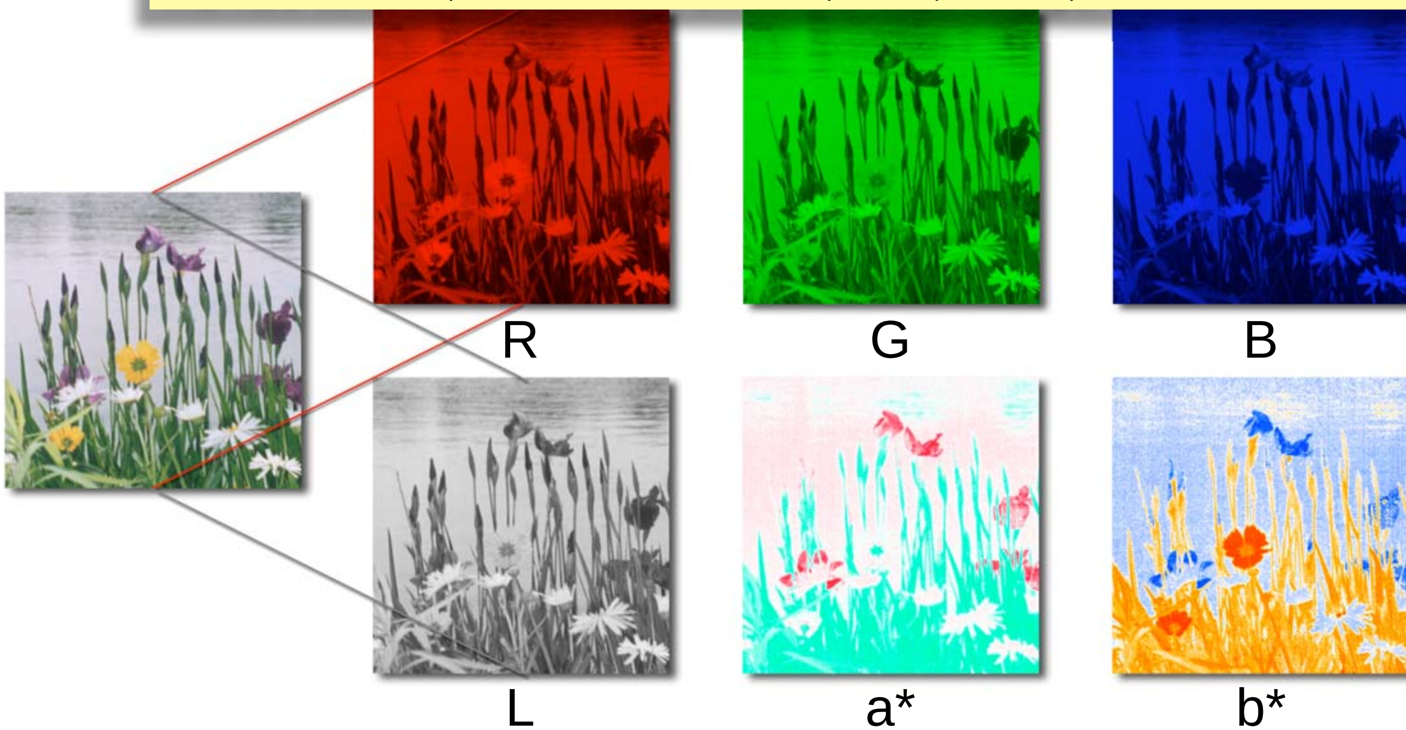


Color Images

are represented by three bands (not uniquely)

e.g., R, G, & B; L, a*, & b*; or HSI

The RGB color space results from simple ways to separate and combine color.



Red

Green

Blue

Luminance

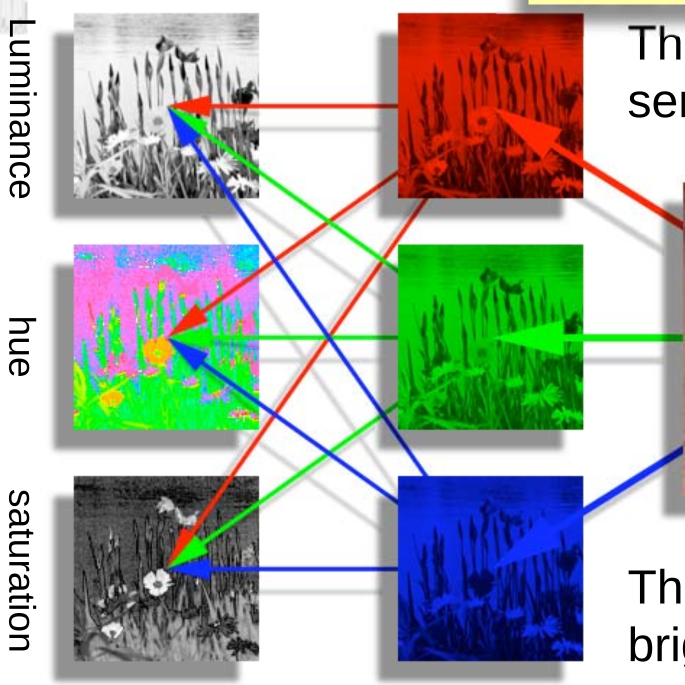
a*-chroma

b*-chroma

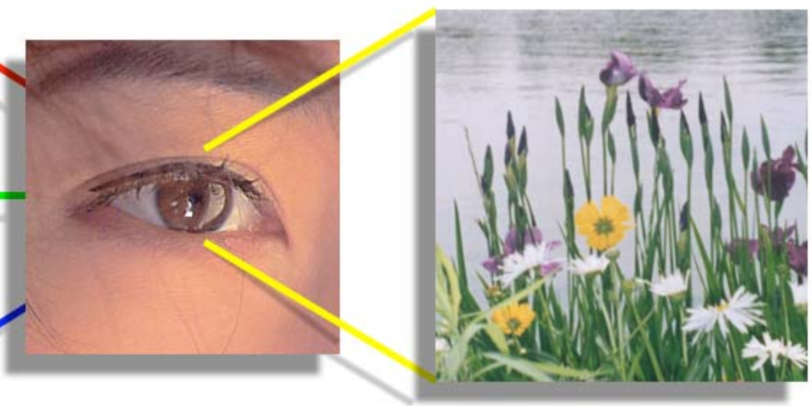
La*b* is a CIE color space designed to approximate human vision. L approximates the human perception of brightness. a* and b* are color opponents. There is no direct, simple conversion from RGB to La*b* since it requires a reference white (specifically a diffuse CIE D65 light source).

RGB to HSI: A Perceptual Transformation

How do humans perceive color?



The eye has 3 types of photoreceptors: sensitive to red, green, or blue light.

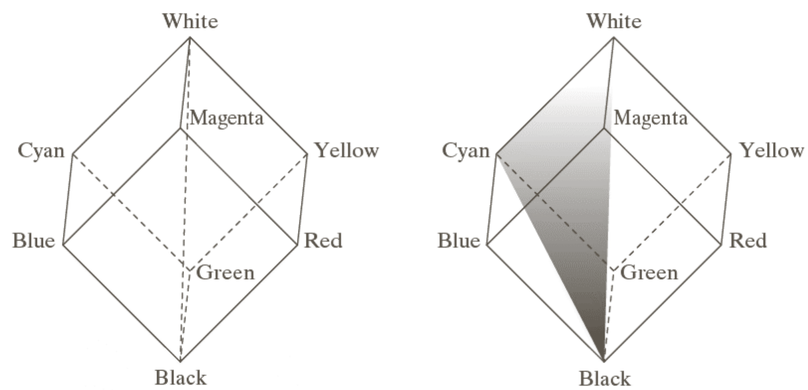


The brain transforms RGB into separate brightness and color channels (*e.g.*, HSI).

HSV Hue-Saturation-Value (also called HSB) is a perceptual system also called the Munsell color system. I ranges from black to a saturated color or white. There is a separate hue and Saturation.

HSL Hue-Saturation Luminance (also called HLS or HSI) defines luminance as the "lightness". L ranges from black to white. The half-way point is always a 50% gray.

HSI Color Space



a b

FIGURE 6.12 Conceptual relationships between the RGB and HSI color models.

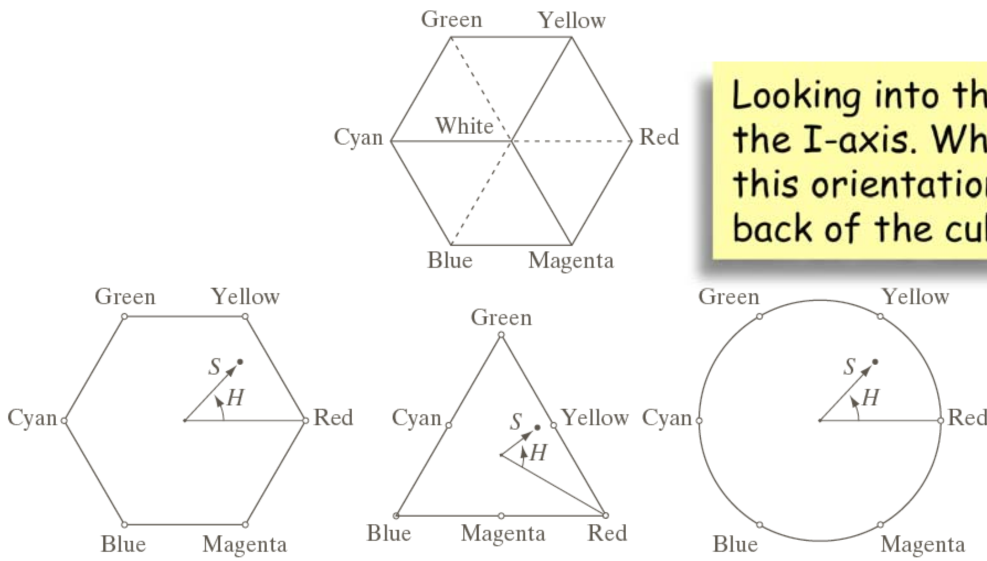
1. The black-white line defines the I-axis for the HSI color space.

2. Each plane ⊥ to the I-axis contains all colors of the same saturation, i.e., with the same amount of white.

3. The plane ⊥ to both the I-axis and the saturation plane will contain all colors of the same hue.

NOTE:GW uses the HSI color space

HSI Color Space



Looking into the RGB color cube along the I-axis. White is closest to you in this orientation. Dashed lines are the back of the cube.

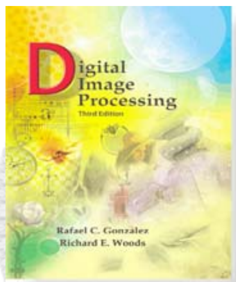
The saturation plane as bounded by the RGB cube is a hexagon.

The hexagonal saturation plane is usually more simply modeled as a triangle or circle.

S (radius) and H (angle) are usually expressed in polar coordinates with red=0°.

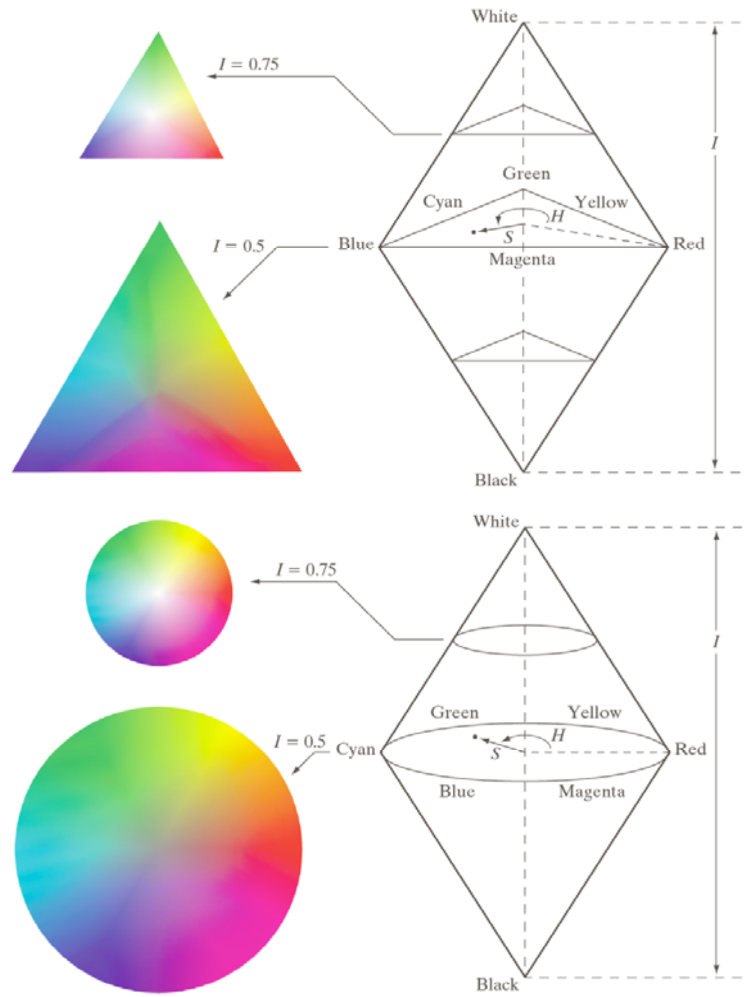
a
b c d

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.



HSI Color Space

The triangular and circular approximations to the RGB cube plotted in 3-D.



a
b

FIGURE 6.14 The HSI color model based on (a) triangular and (b) circular color planes. The triangles and circles are perpendicular to the vertical intensity axis.

White Light

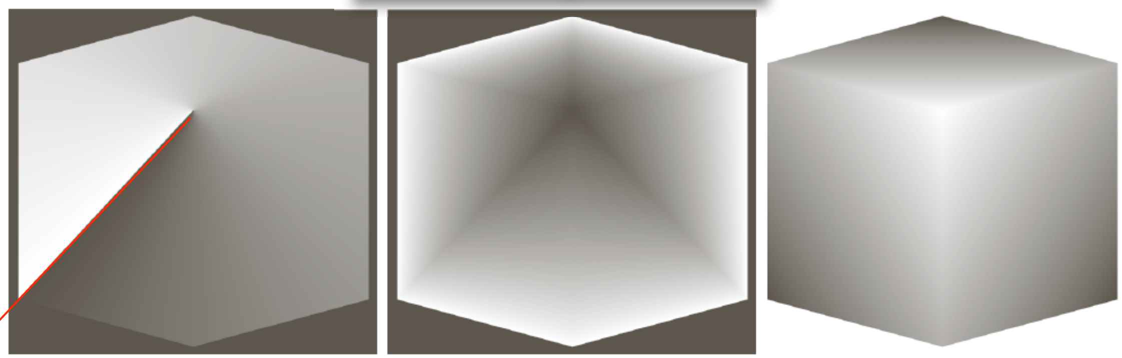


FIGURE 6.15 HSI components of the image in Fig. 6.8. (a) Hue, (b) saturation, and (c) intensity images.

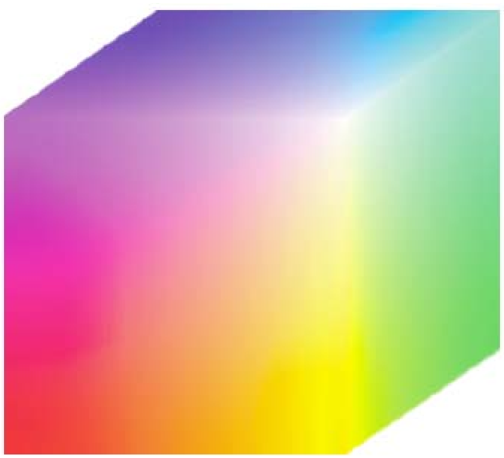
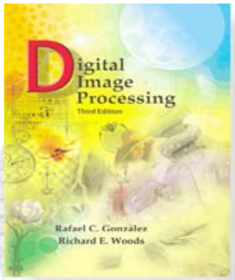


FIGURE 6.8 RGB 24-bit color cube.



RGB to HSI Conversion

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

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

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

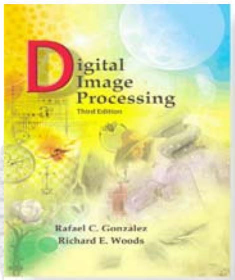
$$\theta = \cos^{-1}\left\{ \frac{\frac{1}{2}\left[\left(R - G\right) + \left(R - B\right)\right]}{\sqrt{\left(R - G\right)^2 + \left(R - B\right)\left(G - B\right)}} \right\}$$

HSI to RGB Conversion

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

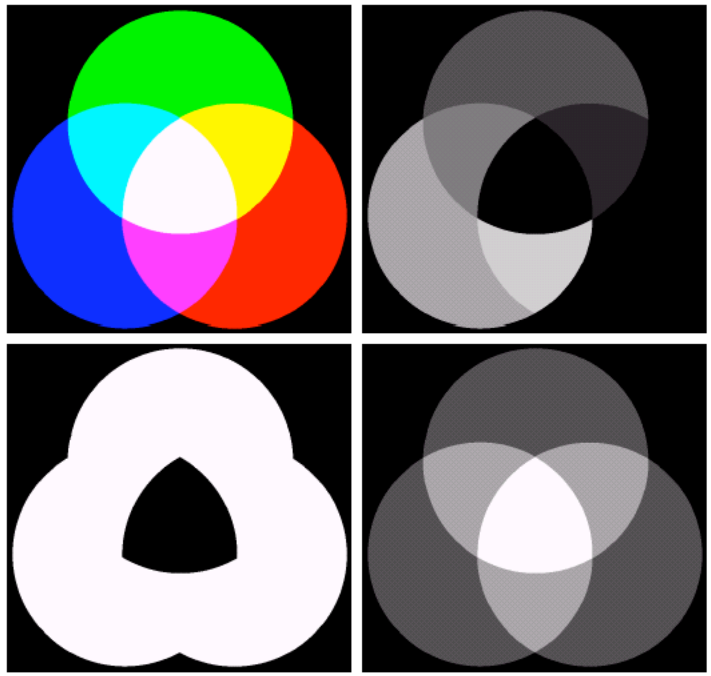
$$R = I\left[1 + \frac{S\cos H}{\cos(60^\circ - H)}\right]$$

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



RGB ↔ HSI

Primary/secondary colors



H component (angles):
B/W are zero hue
Red is 0° or black

S component [0:255]:
These colors are fully saturated (they are all on surface of RGB cube)

I component:
Average intensities

a b
c d

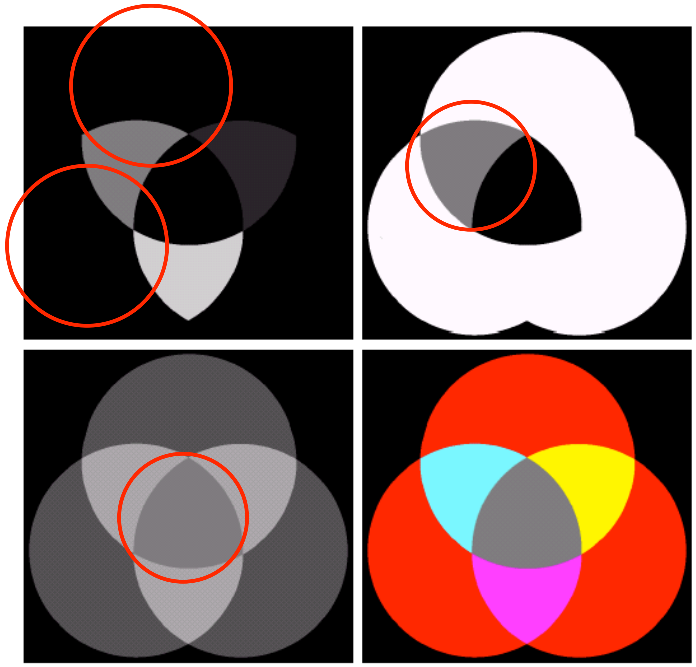
FIGURE 6.16 (a) RGB image and the components of its corresponding HSI image: (b) hue, (c) saturation, and (d) intensity.

Gray axis has zero hue and zero saturation.

HSI Color Processing

H component:
Change blue and green to zero,i.e., this makes them red.

I component:
Reduce intensity of white by 50%



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.)

S component:
Reduce cyan saturation by 50%

Transform back to RGB:
B & G become red
Cyan looks washed out
White is now 50% gray

Pseudocolor

If gray>l_i then color A

If gray<l_i then color B

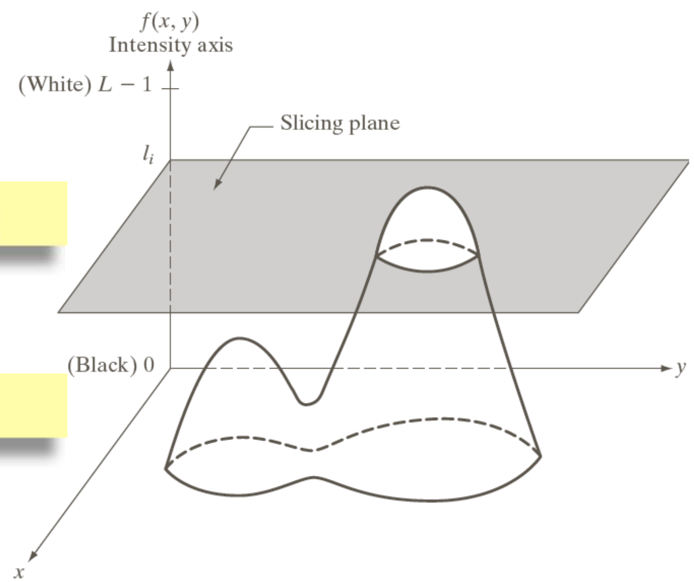


FIGURE 6.18 Geometric interpretation of the intensity-slicing technique.

Assign colors to grayscale values using some criterion. This technique is used a lot in data visualization.

Pseudocolor

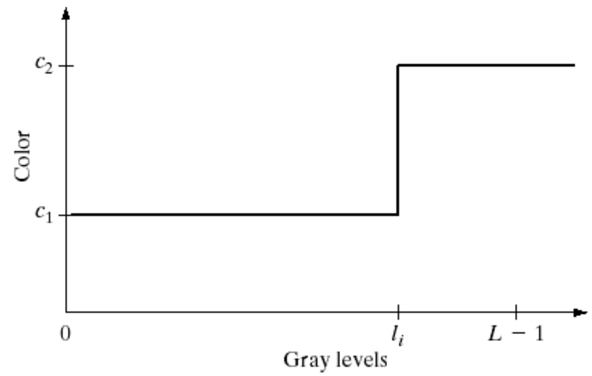
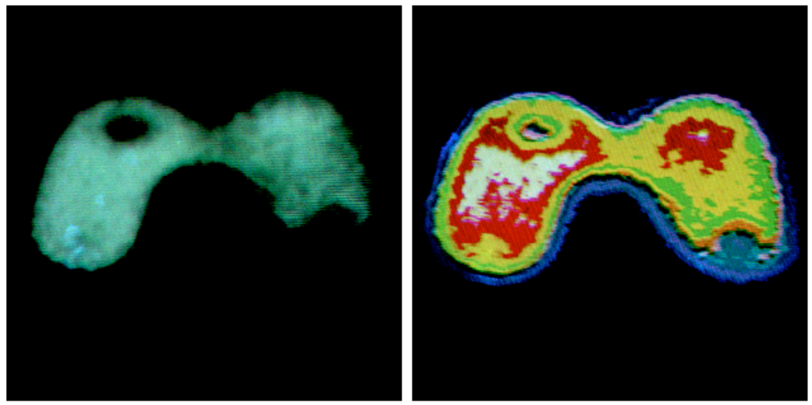


FIGURE 6.19 An alternative representation of the intensity-slicing technique.

Intensity slicing can also be described as an intensity transformation similar to those found in Chapter 2.

Pseucocolor



a b

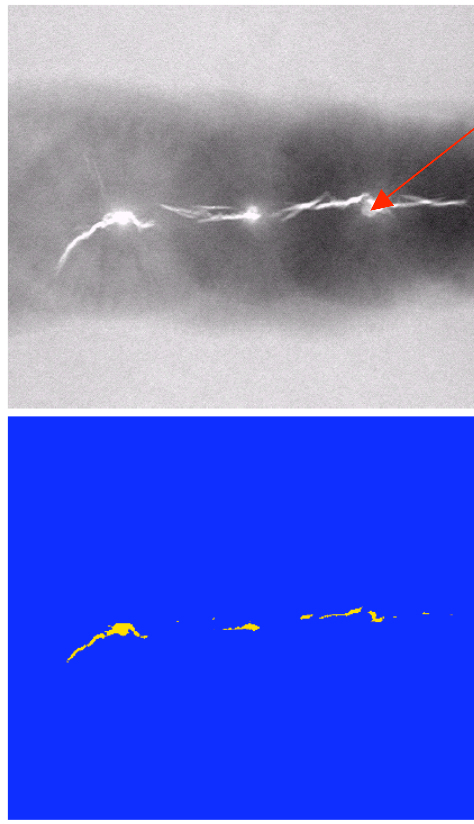
FIGURE 6.20 (a) Monochrome image of the Picker Thyroid Phantom. (b) Result of density slicing into eight colors. (Courtesy of Dr. J. L. Blankenship, Instrumentation and Controls Division, Oak Ridge National Laboratory.)

In this example we map gray scales to multiple colors (eight in this case).

Pseudocolor

a
b

FIGURE 6.21 (a) Monochrome X-ray image of a weld. (b) Result of color coding. (Original image courtesy of X-TEK Systems, Ltd.)

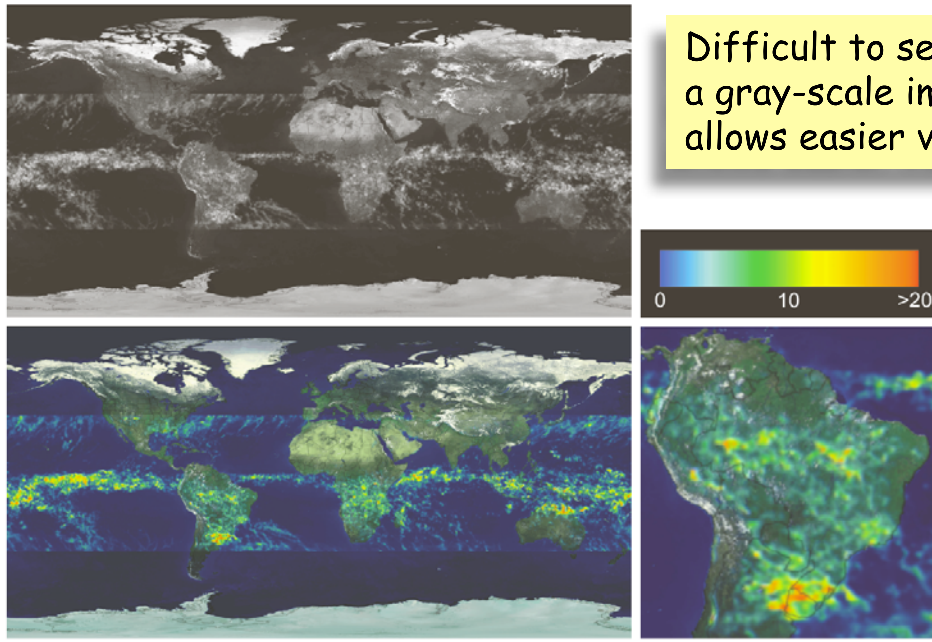


Cracks in a weld allow high-intensity x-ray exposure.

If gray=255 then yellow else blue.

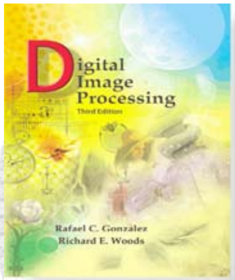
Pseudocolor

Difficult to see the patterns in a gray-scale image. Color allows easier visualization.



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 American region. (Courtesy of NASA.)



Color Transformations

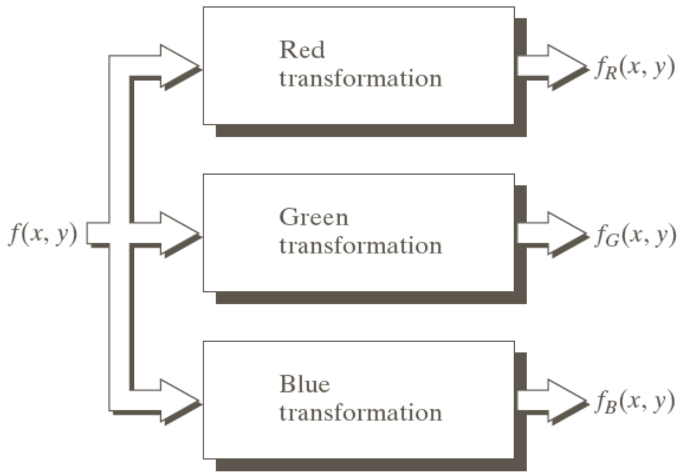
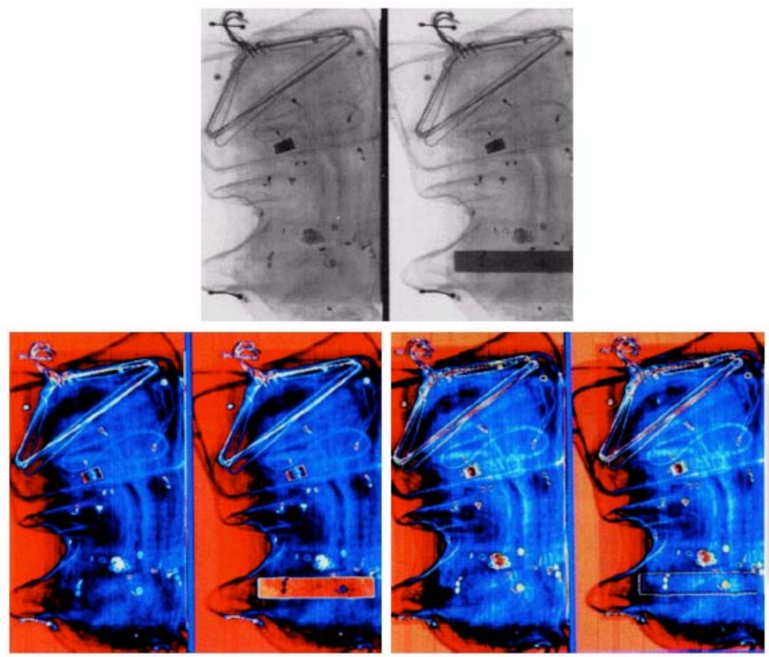


FIGURE 6.23 Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

We can perform simultaneous color transformations and combine the result on an RGB monitor.

Color Transformations



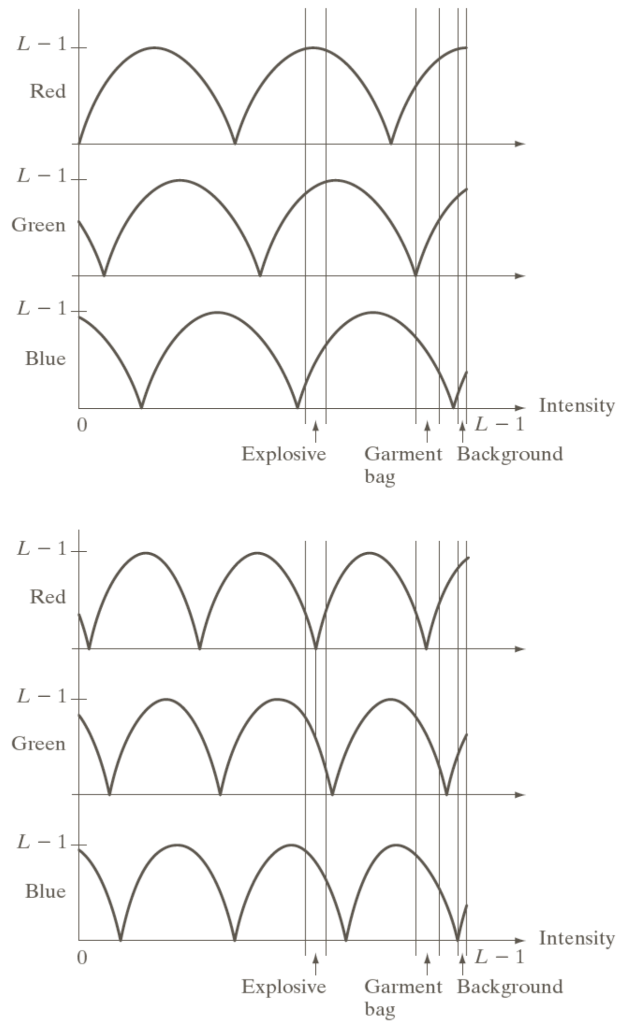
These are periodic transformations designed to map intensities into specific colors.

a
b c

Transform 6.25(a) Transform 6.25(b)

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.)

Color Transformations



a
b

FIGURE 6.25 Transformation functions used to obtain the images in Fig. 6.24.

Color Transformations

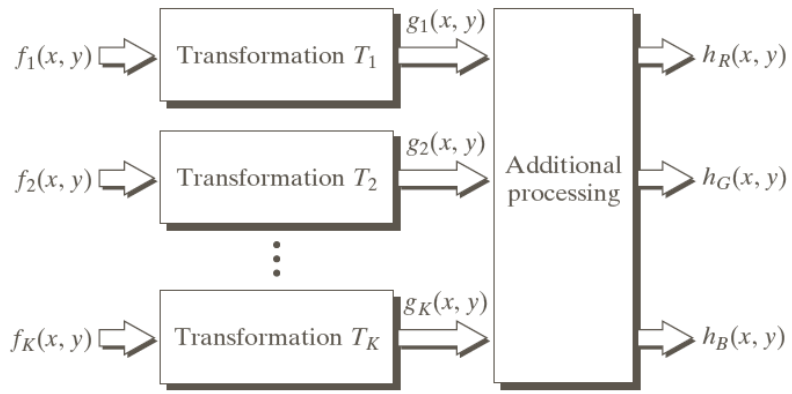


FIGURE 6.26 A pseudocolor coding approach used when several monochrome images are available.

More sophisticated color transformations can be used to, for example, combine grayscale images from different sensors.

Multi-Spectral Imaging

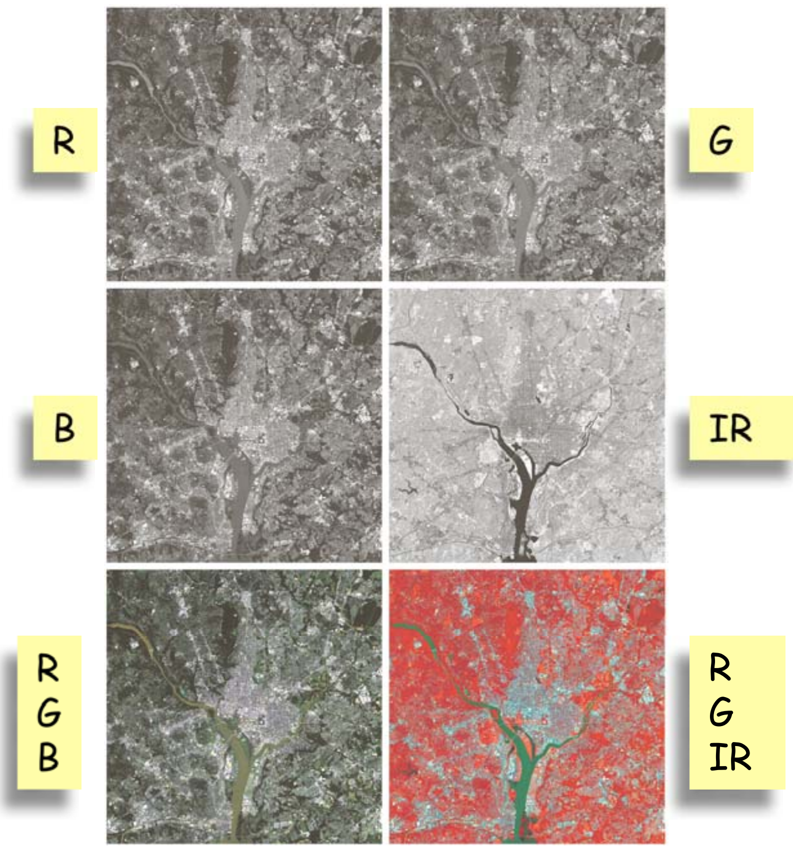
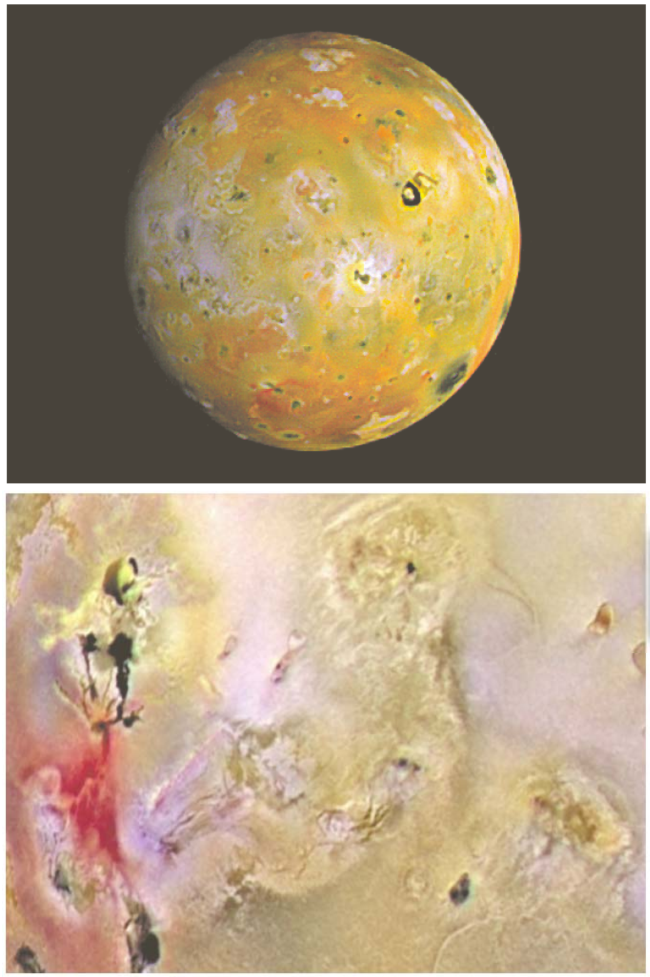


FIGURE 6.27 (a)–(d) Images in bands 1–4 in Fig. 1.10 (see Table 1.1). (e) Color composite image obtained by treating (a), (b), and (c) as the red, green, blue components of an RGB image. (f) Image obtained in the same manner, but using in the red channel the near-infrared image in (d). (Original multispectral images courtesy of NASA.)

a b
c d
e f

Multi-Spectral Imaging

Color encoding of a variety of different sensor inputs.



a
b

FIGURE 6.28 (a) Pseudocolor rendition of Jupiter Moon Io. (b) A close-up. (Courtesy of NASA.)

Older ejected material (sulfur) is yellow.

Red material was recently ejected from a volcano.