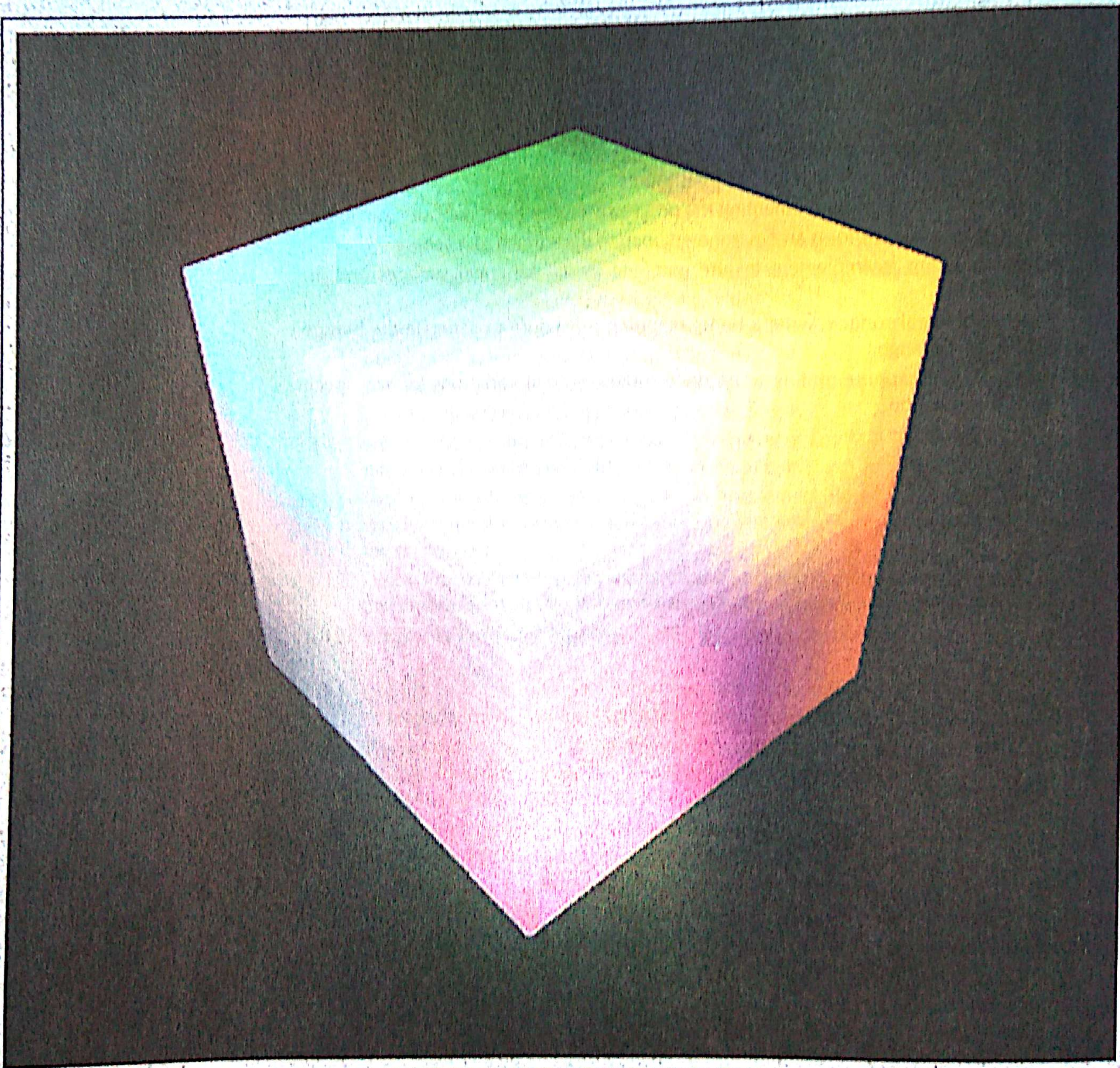
CHAPTER

15 Color Models and Color Applications



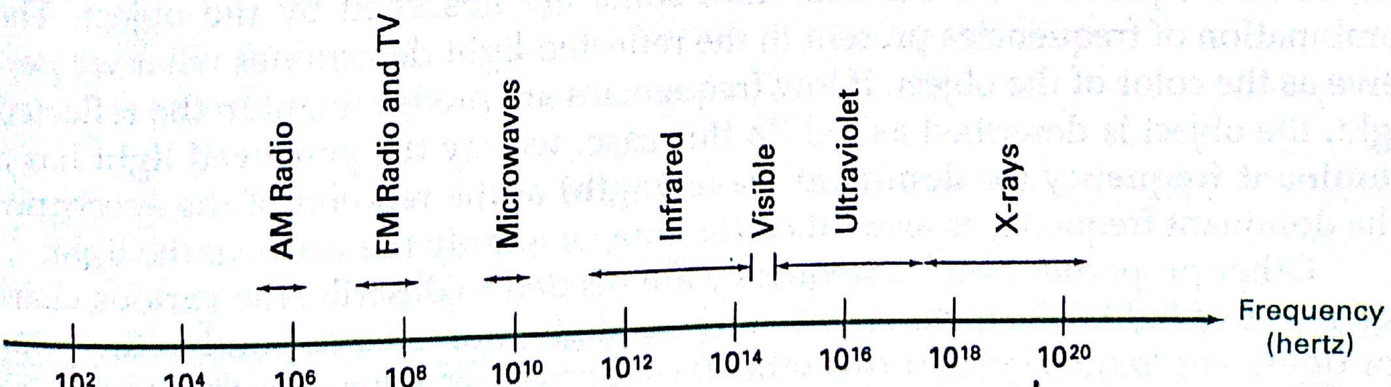
Our discussions of color up to this point have concentrated on the mechanisms for generating color displays with combinations of red, green, and blue light. This model is helpful in understanding how color is represented on a video monitor, but several other color models are useful as well in graphics applications. Some models are used to describe color output on printers and plotters, and other models provide a more intuitive color-parameter interface for the user.

A **color model** is a method for explaining the properties or behavior of color within some particular context. No single color model can explain all aspects of color, so we make use of different models to help describe the different perceived characteristics of color.

15-1 PROPERTIES OF LIGHT

What we perceive as "light", or different colors, is a narrow frequency band within the electromagnetic spectrum. A few of the other frequency bands within this spectrum are called radio waves, microwaves, infrared waves, and X-rays. Figure 15-1 shows the approximate frequency ranges for some of the electromagnetic bands.

Each frequency value within the visible band corresponds to a distinct color. At the low-frequency end is a red color (4.3×10^{14} hertz), and the highest frequency we can see is a violet color (7.5×10^{14} hertz). Spectral colors range from the reds through orange and yellow at the low-frequency end to greens, blues, and violet at the high end.



$4.3 - 7.5 \times 10^{14}$

Red violet

Figure 15-1
Electromagnetic spectrum.

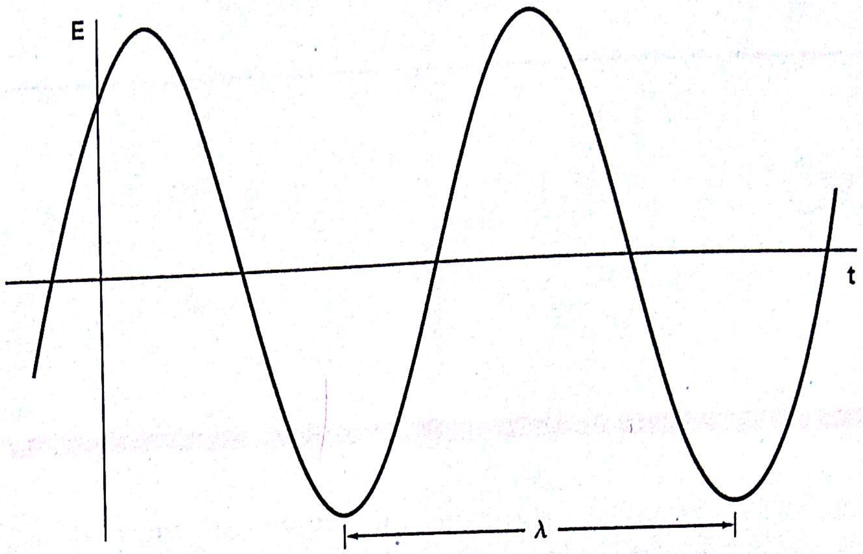


Figure 15-2
Time variations for one electric frequency component of a plane-polarized electromagnetic wave.

Since light is an electromagnetic wave, we can describe the various colors in terms of either the frequency f or the wavelength λ of the wave. In Fig. 15-2, we illustrate the oscillations present in a monochromatic electromagnetic wave, polarized so that the electric oscillations are in one plane. The wavelength and frequency of the monochromatic wave are inversely proportional to each other, with the proportionality constant as the speed of light c:

$$c = \lambda f \tag{15-1}$$

Frequency is constant for all materials, but the speed of light and the wavelength are material-dependent. In a vacuum, $c = 3 \times 10^{10}$ cm/sec. Light wavelengths are very small, so length units for designating spectral colors are usually either angstroms (1Å = 10^{-8} cm) or nanometers (1 nm = 10^{-7} cm). An equivalent term for nanometer is millimicron. Light at the red end of the spectrum has a wavelength of approximately 700 nanometers (nm), and the wavelength of the violet light at the other end of the spectrum is about 400 nm. Since wavelength units are somewhat more convenient to deal with than frequency units, spectral colors are typically specified in terms of wavelength.

A light source such as the sun or a light bulb emits all frequencies within the visible range to produce white light. When white light is incident upon an object, some frequencies are reflected and some are absorbed by the object. The combination of frequencies present in the reflected light determines what we perceive as the color of the object. If low frequencies are predominant in the reflected light, the object is described as red. In this case, we say the perceived light has a (1) **dominant frequency** (or **dominant wavelength**) at the red end of the spectrum. The dominant frequency is also called the **hue**, or simply the **color**, of the light.

Other properties besides frequency are needed to describe the various characteristics of light. When we view a source of light, our eyes respond to the color (or dominant frequency) and two other basic sensations. One of these we call the (2) **brightness**, which is the perceived intensity of the light. Intensity is the radiant energy emitted per unit time, per unit solid angle, and per unit projected area of the source. Radiant energy is related to the **luminance** of the source. The second

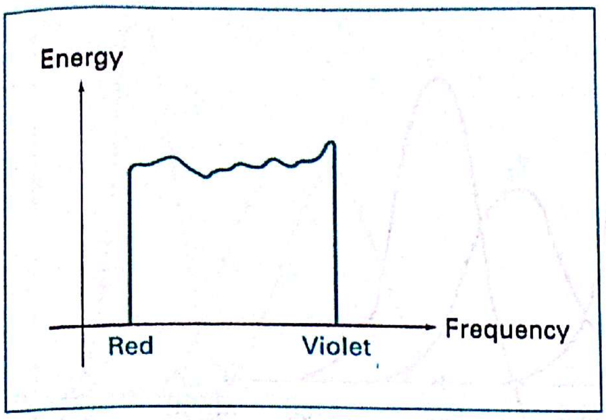


Figure 15-3
Energy distribution of a white-light source.

3 perceived characteristic is the **purity**, or **saturation**, of the light. Purity describes how washed out or how "pure" the color of the light appears. Pastels and pale colors are described as less pure. These three characteristics, dominant frequency, brightness, and purity, are commonly used to describe the different properties we perceive in a source of light. The term **chromaticity** is used to refer collectively to the two properties describing color characteristics: purity and dominant frequency.

Energy emitted by a white-light source has a distribution over the visible frequencies as shown in Fig. 15-3. Each frequency component within the range from red to violet contributes more or less equally to the total energy, and the color of the source is described as white. When a dominant frequency is present, the energy distribution for the source takes a form such as that in Fig. 15-4. We would now describe the light as having the color corresponding to the dominant frequency. The energy density of the dominant light component is labeled as E_D in this figure, and the contributions from the other frequencies produce white light of energy density E_W. We can calculate the brightness of the source as the area under the curve, which gives the total energy density emitted. Purity depends on the difference between E_D and E_W. The larger the energy E_D of the dominant frequency compared to the white-light component E_W, the more pure the light. We have a purity of 100 percent when $E_W = 0$ and a purity of 0 percent when $E_W = E_D$.

When we view light that has been formed by a combination of two or more sources, we see a resultant light with characteristics determined by the original sources. Two different-color light sources with suitably chosen intensities can be used to produce a range of other colors. If the two color sources combine to pro-

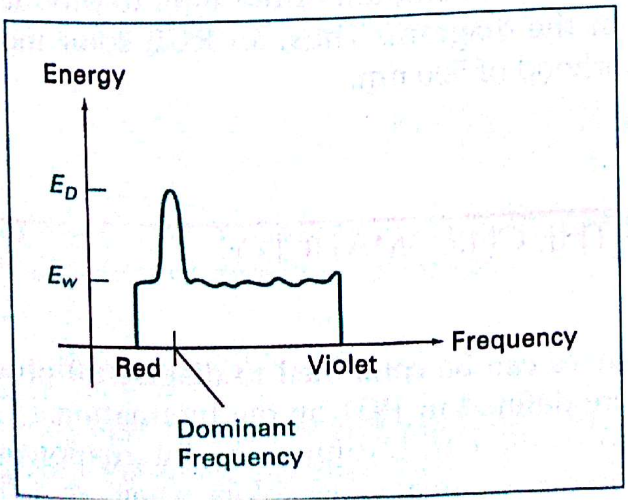


Figure 15-4
Energy distribution of a light source with a dominant frequency near the red end of the frequency range.

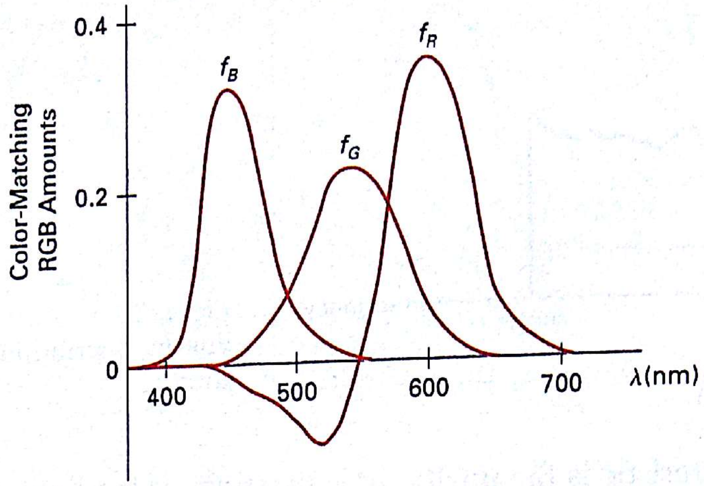


Figure 15-5
Amounts of RGB primaries needed to display spectral colors.

duce white light, they are referred to as **complementary colors.** Examples of complementary color pairs are red and cyan, green and magenta, and blue and yellow. With a judicious choice of two or more starting colors, we can form a wide range of other colors. Typically, color models that are used to describe combinations of light in terms of dominant frequency (hue) use three colors to obtain a reasonably wide range of colors, called the **color gamut** for that model. The two or three colors used to produce other colors in such a color model are referred to as **primary colors.**

No finite set of real primary colors can be combined to produce all possible visible colors. Nevertheless, three primaries are sufficient for most purposes, and colors not in the color gamut for a specified set of primaries can still be described by extended methods. If a certain color cannot be produced by combining the three primaries, we can mix one or two of the primaries with that color to obtain a match with the combination of remaining primaries. In this extended sense, a set of primary colors can be considered to describe all colors. Figure 15-5 shows the amounts of red, green, and blue needed to produce any spectral color. The curves plotted in Fig. 15-5, called *color-matching functions,* were obtained by averaging the judgments of a large number of observers. Colors in the vicinity of 500 nm can only be matched by "subtracting" an amount of red light from a combination of blue and green lights. This means that a color around 500 nm is described only by combining that color with an amount of red light to produce the blue–green combination specified in the diagram. Thus, an RGB color monitor cannot display colors in the neighborhood of 500 nm.

15-2 STANDARD PRIMARIES AND THE CHROMATICITY DIAGRAM

Since no finite set of color light sources can be combined to display all possible colors, three standard primaries were defined in 1931 by the International Commission on Illumination, referred to as the CIE (Commission Internationale de l'Éclairage). The three standard primaries are imaginary colors. They are defined mathematically with positive color-matching functions (Fig. 15-6) that specify the

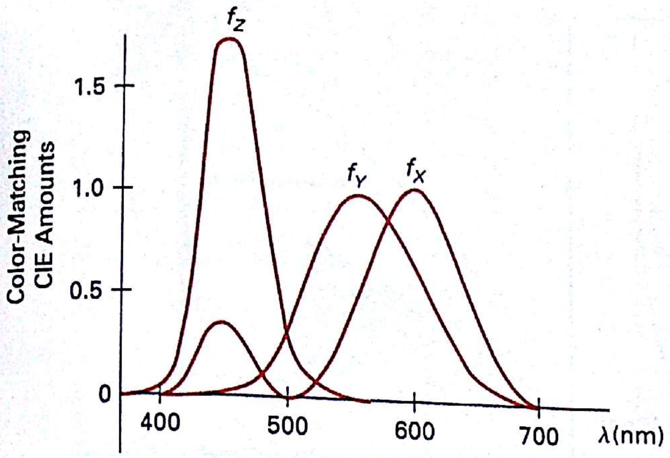


Figure 15-6
Amounts of CIE primaries needed to display spectral colors.

amount of each primary needed to describe any spectral color. This provides an international standard definition for all colors, and the CIE primaries eliminate negative-value color matching and other problems associated with selecting a set of real primaries.

XYZ Color Model

The set of CIE primaries is generally referred to as the XYZ, or (**X**, **Y**, **Z**), color model, where **X**, **Y**, and **Z** represent vectors in a three-dimensional, additive color space. Any color C_λ is then expressed as

$$C_\lambda = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z} \tag{15-2}$$

where X, Y, and Z designate the amounts of the standard primaries needed to match C_λ.

In discussing color properties, it is convenient to normalize the amounts in Eq. 15-2 against luminance $(X + Y + Z)$. Normalized amounts are thus calculated as

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z}, \qquad z = \frac{Z}{X+Y+Z} \tag{15-3}$$

with $x + y + z = 1$. Thus, any color can be represented with just the x and y amounts. Since we have normalized against luminance, parameters x and y are called the *chromaticity values* because they depend only on hue and purity. Also, if we specify colors only with x and y values, we cannot obtain the amounts X, Y, and Z. Therefore, a complete description of a color is typically given with the three values x, y, and Y. The remaining CIE amounts are then calculated as

$$X = \frac{x}{y}Y, \qquad Z = \frac{z}{y}Y \tag{15-4}$$

where $z = 1 - x - y$. Using chromaticity coordinates (x, y), we can represent all colors on a two-dimensional diagram.

CIE Chromaticity Diagram

When we plot the normalized amounts x and y for colors in the visible spectrum, we obtain the tongue-shaped curve shown in Fig. 15-7. This curve is called the **CIE chromaticity diagram**. Points along the curve are the "pure" colors in the

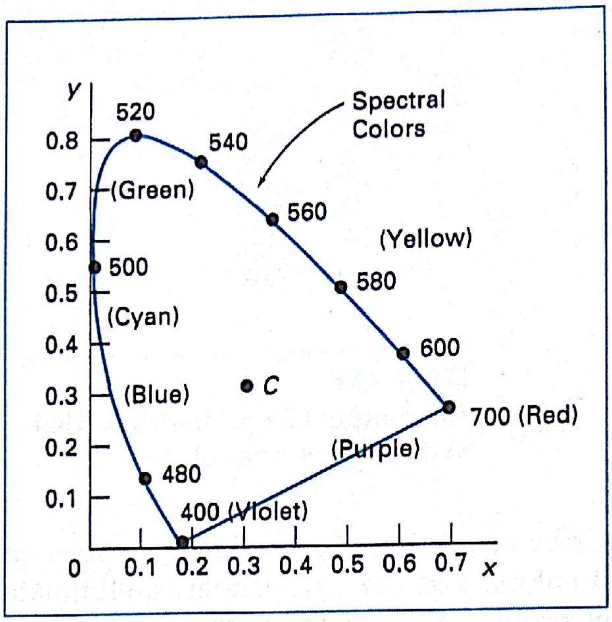


Figure 15-7
CIE chromaticity diagram. Spectral color positions along the curve are labeled in wavelength units (nm).

electromagnetic spectrum, labeled according to wavelength in nanometers from the red end to the violet end of the spectrum. The line joining the red and violet spectral points, called the *purple line,* is not part of the spectrum. Interior points represent all possible visible color combinations. Point C in the diagram corresponds to the white-light position. Actually, this point is plotted for a white-light source known as **illuminant** *C*, which is used as a standard approximation for "average" daylight.

Luminance values are not available in the chromaticity diagram because of normalization. Colors with different luminance but the same chromaticity map to the same point. The chromaticity diagram is useful for the following:

- Comparing color gamuts for different sets of primaries.
- Identifying complementary colors.
- Determining dominant wavelength and purity of a given color.

Color gamuts are represented on the chromaticity diagram as straight line segments or as polygons. All colors along the line joining points C_1 and C_2 in Fig. 15-8 can be obtained by mixing appropriate amounts of the colors C_1 and C_2. If a greater proportion of C_1 is used, the resultant color is closer to C_1 than to C_2. The color gamut for three points, such as C_3, C_4, and C_5 in Fig. 15-8, is a triangle with vertices at the three color positions. Three primaries can only generate colors inside or on the bounding edges of the triangle. Thus, the chromaticity diagram helps us understand why no set of three primaries can be additively combined to generate all colors, since no triangle within the diagram can encompass all colors. Color gamuts for video monitors and hard-copy devices are conveniently compared on the chromaticity diagram.

Since the color gamut for two points is a straight line, complementary colors must be represented on the chromaticity diagram as two points situated on opposite sides of C and connected with a straight line. When we mix proper amounts of the two colors C_1 and C_2 in Fig. 15-9, we can obtain white light.

We can also use the interpretation of color gamut for two primaries to determine the dominant wavelength of a color. For color point C_1 in Fig. 15-10, we can draw a straight line from C through C_1 to intersect the spectral curve at point

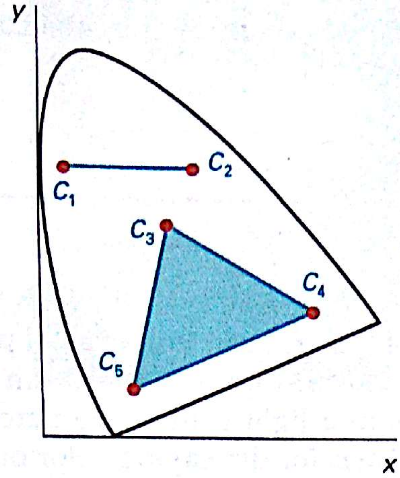


Figure 15-8
Color gamuts defined on the chromaticity diagram for a two-color and a three-color system of primaries.

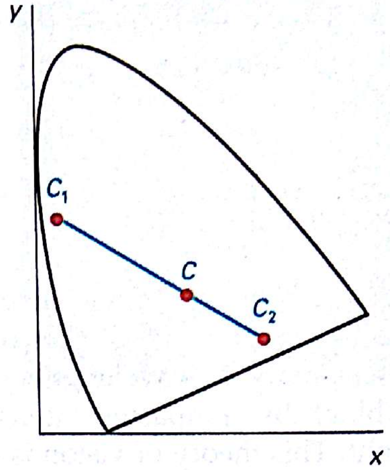


Figure 15-9
Representing complementary colors on the chromaticity diagram.

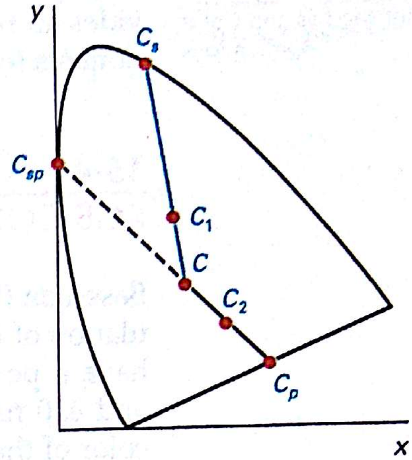


Figure 15-10
Determining dominant wavelength and purity with the chromaticity diagram.

C_s. Color C_1 can then be represented as a combination of white light C and the spectral color C_s. Thus, the dominant wavelength of C_1 is C_s. This method for determining dominant wavelength will not work for color points that are between C and the purple line. Drawing a line from C through point C_2 in Fig. 15-10 takes us to point C_p on the purple line, which is not in the visible spectrum. Point C_2 is referred to as a *nonspectral* color, and its dominant wavelength is taken as the compliment of C_p that lies on the spectral curve (point C_{sp}). Nonspectral colors are in the purple–magenta range and have spectral distributions with subtractive dominant wavelengths. They are generated by subtracting the spectral dominant wavelength (such as C_{sp}) from white light.

For any color point, such as C_1 in Fig. 15-10, we determine the purity as the relative distance of C_1 from C along the straight line joining C to C_s. If d_{c1} denotes the distance from C to C_1 and d_{cs} is the distance from C to C_s, we can calculate purity as the ratio d_{c1}/d_{cs}. Color C_1 in this figure is about 25 percent pure, since it is situated at about one-fourth the total distance from C to C_s. At position C_s, the color point would be 100 percent pure.

15-3 INTUITIVE COLOR CONCEPTS

An artist creates a color painting by mixing color pigments with white and black pigments to form the various shades, tints, and tones in the scene. Starting with the pigment for a "pure color" (or "pure hue"), the artist adds a black pigment to produce different **shades** of that color. The more black pigment, the darker the shade. Similarly, different **tints** of the color are obtained by adding a white pigment to the original color, making it lighter as more white is added. **Tones** of the color are produced by adding both black and white pigments.

To many, these color concepts are more intuitive than describing a color as a set of three numbers that give the relative proportions of the primary colors. It is generally much easier to think of making a color lighter by adding white and making a color darker by adding black. Therefore, graphics packages providing color palettes to a user often employ two or more color models. One model provides an intuitive color interface for the user, and others describe the color components for the output devices.

15-4 RGB COLOR MODEL

Based on the *tristimulus theory* of vision, our eyes perceive color through the stimulation of three visual pigments in the cones of the retina. These visual pigments have a peak sensitivity at wavelengths of about 630 nm (red), 530 nm (green), and 450 nm (blue). By comparing intensities in a light source, we perceive the color of the light. This theory of vision is the basis for displaying color output on a video monitor using the three color primaries, red, green, and blue, referred to as the RGB color model.

We can represent this model with the unit cube defined on R, G, and B axes, as shown in Fig. 15-11. The origin represents black, and the vertex with coordinates (1, 1, 1) is white. Vertices of the cube on the axes represent the primary colors, and the remaining vertices represent the complementary color for each of the primary colors.

As with the XYZ color system, the RGB color scheme is an additive model. Intensities of the primary colors are added to produce other colors. Each color point within the bounds of the cube can be represented as the triple (R, G, B), where values for R, G, and B are assigned in the range from 0 to 1. Thus, a color C_λ is expressed in RGB components as

$$C_\lambda = R\mathbf{R} + G\mathbf{G} + B\mathbf{B} \tag{15-5}$$

The magenta vertex is obtained by adding red and blue to produce the triple (1, 0, 1), and white at (1, 1, 1) is the sum of the red, green, and blue vertices. Shades of gray are represented along the main diagonal of the cube from the origin (black) to the white vertex. Each point along this diagonal has an equal contribution from each primary color, so that a gray shade halfway between black and

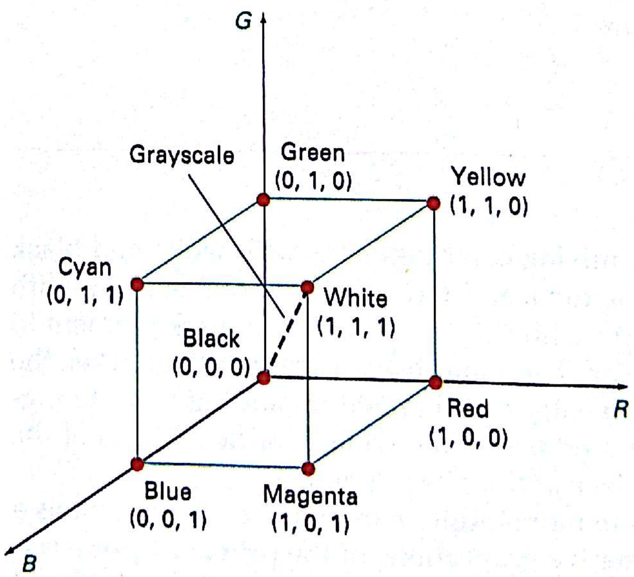


Figure 15-11
The RGB color model, defining colors with an additive process within the unit cube.

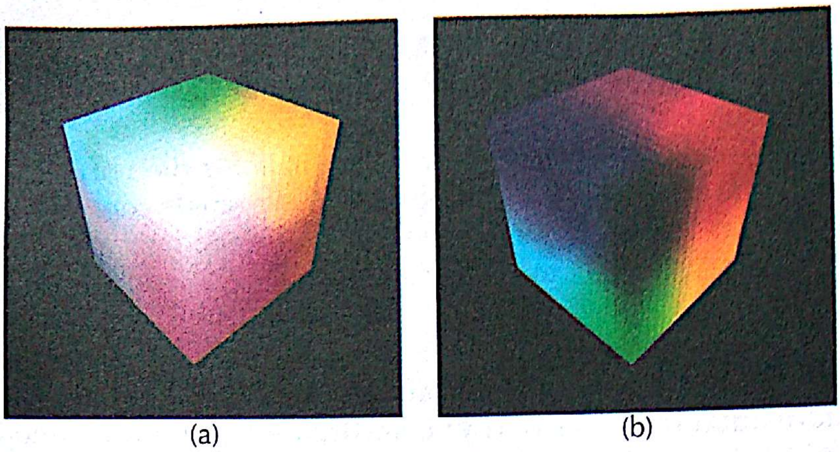


Figure 15-12
Two views of the RGB color cube: (a) along the grayscale diagonal from white to black and (b) along the grayscale diagonal from black to white.

TABLE 15-1
RGB (X, Y) CHROMACITY COORDINATES

	NTSC Standard	CIE Model	Approx. Color Monitor Values
R	(0.670,0.330)	(0.735, 0.265)	(0.628, 0.346)
G	(0.210, 0.710)	(0.274, 0.717)	(0.268, 0.588)
B	(0.140, 0.080)	(0.167, 0.009)	(0.150, 0.070)

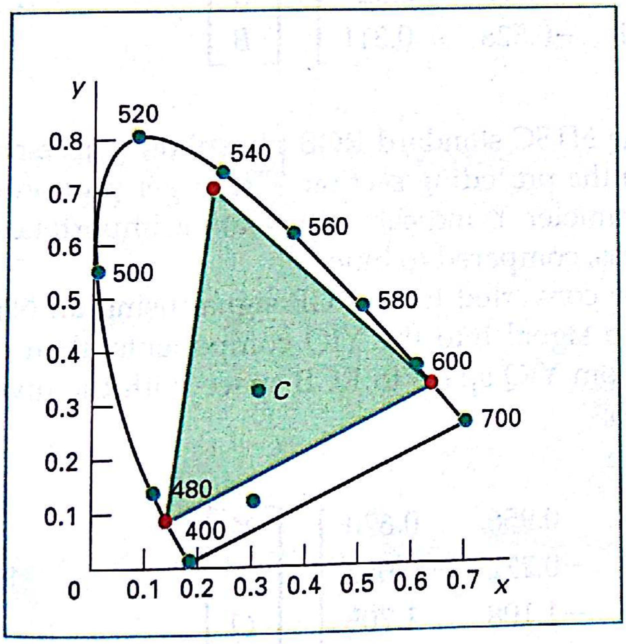


Figure 15-13
RGB color gamut.

white is represented as (0.5, 0.5, 0.5). The color graduations along the front and top planes of the RGB cube are illustrated in Fig. 15-12.

Chromaticity coordinates for an NTSC standard RGB phosphor are listed in Table 15-1. Also listed are the RGB chromaticity coordinates for the CIE RGB color model and the approximate values used for phosphors in color monitors. Figure 15-13 shows the color gamut for the NTSC standard RGB primaries.

15-5
YIQ COLOR MODEL

Whereas an RGB monitor requires separate signals for the red, green, and blue components of an image, a television monitor uses a single composite signal. The National Television System Committee (NTSC) color model for forming the composite video signal is the YIQ model, which is based on concepts in the CIE XYZ model.

In the YIQ color model, parameter Y is the same as in the XYZ model. Luminance (brightness) information is contained in the Y parameter, while chromaticity information (hue and purity) is incorporated into the I and Q parameters. A combination of red, green, and blue intensities are chosen for the Y parameter to yield the standard luminosity curve. Since Y contains the luminance information, black-and-white television monitors use only the Y signal. The largest bandwidth in the NTSC video signal (about 4 MHz) is assigned to the Y information. Parameter I contains orange–cyan hue information that provides the flesh-tone shading, and occupies a bandwidth of approximately 1.5 MHz. Parameter Q carries green–magenta hue information in a bandwidth of about 0.6 MHz.

An RGB signal can be converted to a television signal using an NTSC encoder, which converts RGB values to YIQ values, then modulates and superimposes the I and Q information on the Y signal. The conversion from RGB values to YIQ values is accomplished with the transformation

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.144 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{15-6}$$

This transformation is based on the NTSC standard RGB phosphor, whose chromaticity coordinates were given in the preceding section. The larger proportions of red and green assigned to parameter Y indicate the relative importance of these hues in determining brightness, compared to blue.

An NTSC video signal can be converted to an RGB signal using an NTSC decoder, which separates the video signal into the YIQ components, then converts to RGB values. We convert from YIQ space to RGB space with the inverse matrix transformation from Eq. 15-6:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.000 & 0.956 & 0.620 \\ 1.000 & -0.272 & -0.647 \\ 1.000 & -1.108 & 1.705 \end{bmatrix} \cdot \begin{bmatrix} Y \\ I \\ Q \end{bmatrix} \tag{15-7}$$

15-6
CMY COLOR MODEL

A color model defined with the primary colors cyan, magenta, and yellow (CMY) is useful for describing color output to hard-copy devices. Unlike video monitors, which produce a color pattern by combining light from the screen phosphors, hard-copy devices such as plotters produce a color picture by coating a paper with color pigments. We see the colors by reflected light, a subtractive process.

As we have noted, cyan can be formed by adding green and blue light. Therefore, when white light is reflected from cyan-colored ink, the reflected light must have no red component. That is, red light is absorbed, or subtracted, by the ink. Similarly, magenta ink subtracts the green component from incident light, and yellow subtracts the blue component. A unit cube representation for the CMY model is illustrated in Fig. 15-14.

In the CMY model, point (1, 1, 1) represents black, because all components of the incident light are subtracted. The origin represents white light. Equal amounts of each of the primary colors produce grays, along the main diagonal of the cube. A combination of cyan and magenta ink produces blue light, because the red and green components of the incident light are absorbed. Other color combinations are obtained by a similar subtractive process.

The printing process often used with the CMY model generates a color point with a collection of four ink dots, somewhat as an RGB monitor uses a collection of three phosphor dots. One dot is used for each of the primary colors (cyan, magenta, and yellow), and one dot is black. A black dot is included because the combination of cyan, magenta, and yellow inks typically produce dark gray instead of black. Some plotters produce different color combinations by spraying the ink for the three primary colors over each other and allowing them to mix before they dry.

We can express the conversion from an RGB representation to a CMY representation with the matrix transformation

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{15-8}$$

where the white is represented in the RGB system as the unit column vector. Similarly, we convert from a CMY color representation to an RGB representation with the matrix transformation

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix} \tag{15-9}$$

where black is represented in the CMY system as the unit column vector.

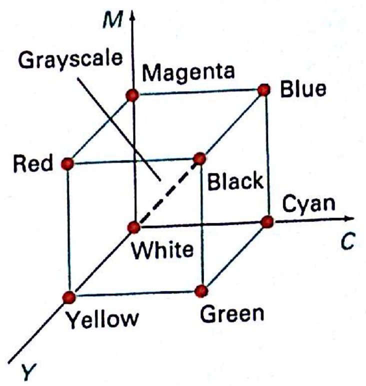


Figure 15-14
The CMY color model, defining colors with a subtractive process inside a unit cube.

15-7 HSV COLOR MODEL

Instead of a set of color primaries, the HSV model uses color descriptions that have a more intuitive appeal to a user. To give a color specification, a user selects a spectral color and the amounts of white and black that are to be added to obtain different shades, tints, and tones. Color parameters in this model are *hue* (*H*), *saturation* (*S*), and *value* (*V*).

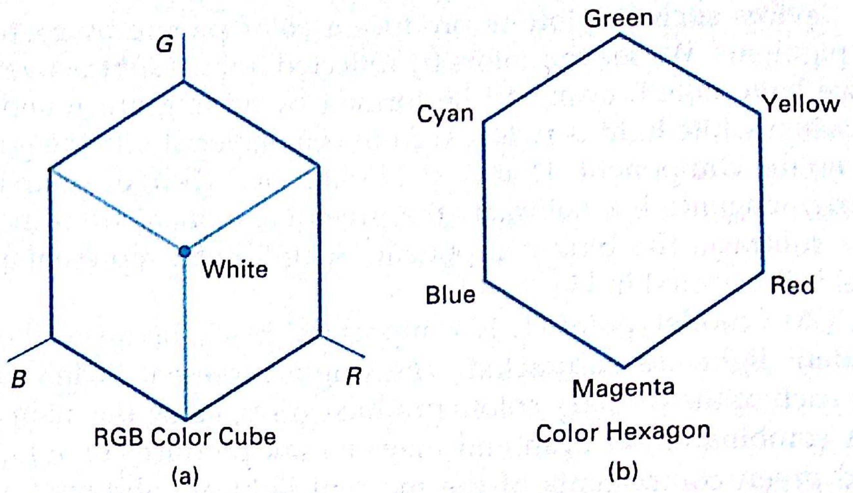


Figure 15-15
When the RGB color cube (a) is viewed along the diagonal from white to black, the color-cube outline is a hexagon (b).

The three-dimensional representation of the HSV model is derived from the RGB cube. If we imagine viewing the cube along the diagonal from the white vertex to the origin (black), we see an outline of the cube that has the hexagon shape shown in Fig. 15-15. The boundary of the hexagon represents the various hues, and it is used as the top of the HSV hexcone (Fig. 15-16). In the hexcone, saturation is measured along a horizontal axis, and value is along a vertical axis through the center of the hexcone.

Hue is represented as an angle about the vertical axis, ranging from 0° at red through 360°. Vertices of the hexagon are separated by 60° intervals. Yellow is at 60°, green at 120°, and cyan opposite red at $H = 180°$. Complementary colors are 180° apart.

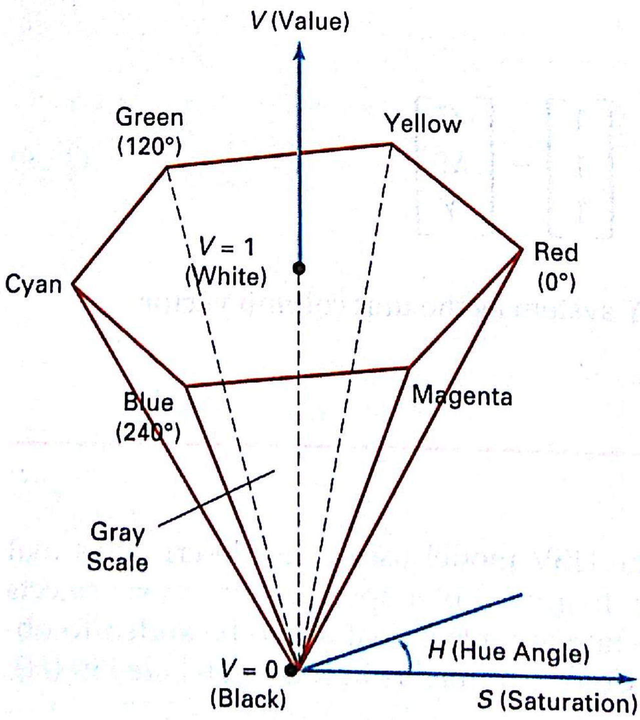


Figure 15-16
The HSV hexcone.

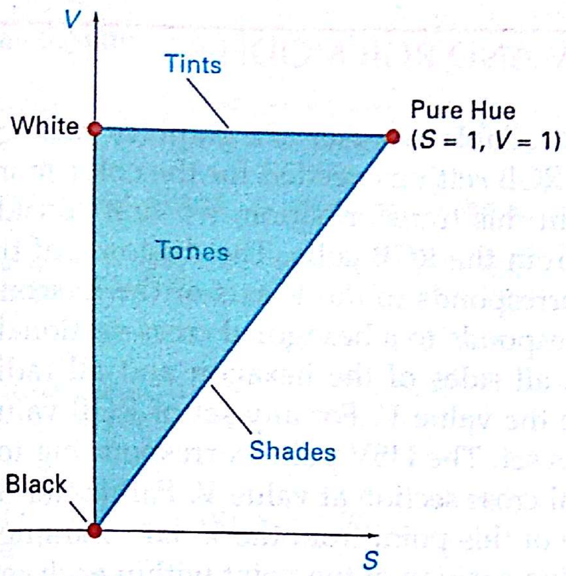


Figure 15-17
Cross section of the HSV hexcone, showing regions for shades, tints, and tones.

Saturation S varies from 0 to 1. It is represented in this model as the ratio of the purity of a selected hue to its maximum purity at $S = 1$. A selected hue is said to be one-quarter pure at the value $S = 0.25$. At $S = 0$, we have the gray scale.

Value V varies from 0 at the apex of the hexcone to 1 at the top. The apex represents black. At the top of the hexcone, colors have their maximum intensity. When $V = 1$ and $S = 1$, we have the "pure" hues. White is the point at $V = 1$ and $S = 0$.

This is a more intuitive model for most users. Starting with a selection for a pure hue, which specifies the hue angle H and sets $V = S = 1$, we describe the color we want in terms of adding either white or black to the pure hue. Adding black decreases the setting for V while S is held constant. To get a dark blue, V could be set to 0.4 with $S = 1$ and $H = 240°$. Similarly, when white is to be added to the hue selected, parameter S is decreased while keeping V constant. A light blue could be designated with $S = 0.3$ while $V = 1$ and $H = 240°$. By adding some black and some white, we decrease both V and S. An interface for this model typically presents the HSV parameter choices in a color palette.

Color concepts associated with the terms shades, tints, and tones are represented in a cross-sectional plane of the HSV hexcone (Fig. 15-17). Adding black to a pure hue decreases V down the side of the hexcone. Thus, various shades are represented with values $S = 1$ and $0 \leq V \leq 1$. Adding white to a pure tone produces different tints across the top plane of the hexcone, where parameter values are $V = 1$ and $0 \leq S \leq 1$. Various tones are specified by adding both black and white, producing color points within the triangular cross-sectional area of the hexcone.

The human eye can distinguish about 128 different hues and about 130 different tints (saturation levels). For each of these, a number of shades (value settings) can be detected, depending on the hue selected. About 23 shades are discernible with yellow colors, and about 16 different shades can be seen at the blue end of the spectrum. This means that we can distinguish about $128 \times 130 \times 23 = 82{,}720$ different colors. For most graphics applications, 128 hues, 8 saturation levels, and 15 value settings are sufficient. With this range of parameters in the HSV color model, 16,384 colors would be available to a user, and the system would need 14 bits of color storage per pixel. Color lookup tables could be used to reduce the storage requirements per pixel and to increase the number of available colors.

15-8 CONVERSION BETWEEN HSV AND RGB MODELS

If HSV color parameters are made available to a user of a graphics package, these parameters are transformed to the RGB settings needed for the color monitor. To determine the operations needed in this transformation, we first consider how the HSV hexcone can be derived from the RGB cube. The diagonal of this cube from black (the origin) to white corresponds to the V axis of the hexcone. Also, each subcube of the RGB cube corresponds to a hexagonal cross-sectional area of the hexcone. At any cross section, all sides of the hexagon and all radial lines from the V axis to any vertex have the value V. For any set of RGB values, V is equal to the maximum value in this set. The HSV point corresponding to the set of RGB values lies on the hexagonal cross section at value V. Parameter S is then determined as the relative distance of this point from the V axis. Parameter H is determined by calculating the relative position of the point within each sextant of the hexagon. An algorithm for mapping any set of RGB values into the corresponding HSV values is given in the following procedure:

```
#include <math.h>

/* Input:   h, s, v in range [0..1]
   Outputs: r, g, b in range [0..1] */
void hsvToRgb(float h, float s, float v, float * r, float * g, float * b)
{
  int i;
  float aa, bb, cc, f;

  if (s == 0) /* Grayscale */
    *r = *g = *b = v;
  else {
    if (h == 1.0) h = 0;
    h *= 6.0;
    i = ffloor (h);
    f = h - i;
    aa = v * (1 - s);
    bb = v * (1 - (s * f));
    cc = v * (1 - (s * (1 - f)));
    switch (i) {
    case 0: *r = v;  *g = cc; *b = aa; break;
    case 1: *r = bb; *g = v;  *b = aa; break;
    case 2: *r = aa; *g = v;  *b = cc; break;
    case 3: *r = aa; *g = bb; *b = v;  break;
    case 4: *r = cc; *g = aa; *b = v;  break;
    case 5: *r = v;  *g = aa; *b = bb; break;
    }
  }
}
```

We obtain the transformation from HSV parameters to RGB parameters by determining the inverse of the equations in `rgbToHsv procedure`. These inverse operations are carried out for each sextant of the hexcone. The resulting transformation equations are summarized in the following algorithm:

```
#include <math.h>

#define MIN(a,b) (a<b?a:b)
#define MAX(a,b) (a>b?a:b)
```

```
#define NO_HUE    -1

/* Input:   r, g, b in range [0..1]
   Outputs: h, s, v in range [0..1]
*/
void rgbToHsv (float r, float g, float b, float * h, float * s, float * v)
{
  float max = MAX (r, MAX (g, b)), min = MIN (r, MIN (g, b));
  float delta = max - min;

  *v = max;
  if (max != 0.0)
    *s = delta / max;
  else
    *s = 0.0;
  if (*s == 0.0) *h = NO_HUE;
  else {
    if (r == max)
      *h = (g - b) / delta;
    else if (g == max)
      *h = 2 + (b - r) / delta;
    else if (b == max)
      *h = 4 + (r - g) / delta;
    *h *= 60.0;
    if (*h < 0) *h += 360.0;
    *h /= 360.0;
  }
}
```

15-9 HLS COLOR MODEL

Another model based on intuitive color parameters is the HLS system used by Tektronix. This model has the double-cone representation shown in Fig. 15-18. The three color parameters in this model are called *hue* (H), *lightness* (L), and *saturation* (S).

Hue has the same meaning as in the HSV model. It specifies an angle about the vertical axis that locates a chosen hue. In this model, $H = 0°$ corresponds to blue. The remaining colors are specified around the perimeter of the cone in the same order as in the HSV model. Magenta is at 60°, red is at 120°, and cyan is located at $H = 180°$. Again, complementary colors are 180° apart on the double cone.

The vertical axis in this model is called lightness, L. At $L = 0$, we have black, and white is at $L = 1$. Gray scale is along the L axis, and the "pure hues" lie on the $L = 0.5$ plane.

Saturation parameter S again specifies relative purity of a color. This parameter varies from 0 to 1, and pure hues are those for which $S = 1$ and $L = 0.5$. As S decreases, the hues are said to be less pure. At $S = 0$, we have the gray scale.

As in the HSV model, the HLS system allows a user to think in terms of making a selected hue darker or lighter. A hue is selected with hue angle H, and the desired shade, tint, or tone is obtained by adjusting L and S. Colors are made lighter by increasing L and made darker by decreasing L. When S is decreased, the colors move toward gray.

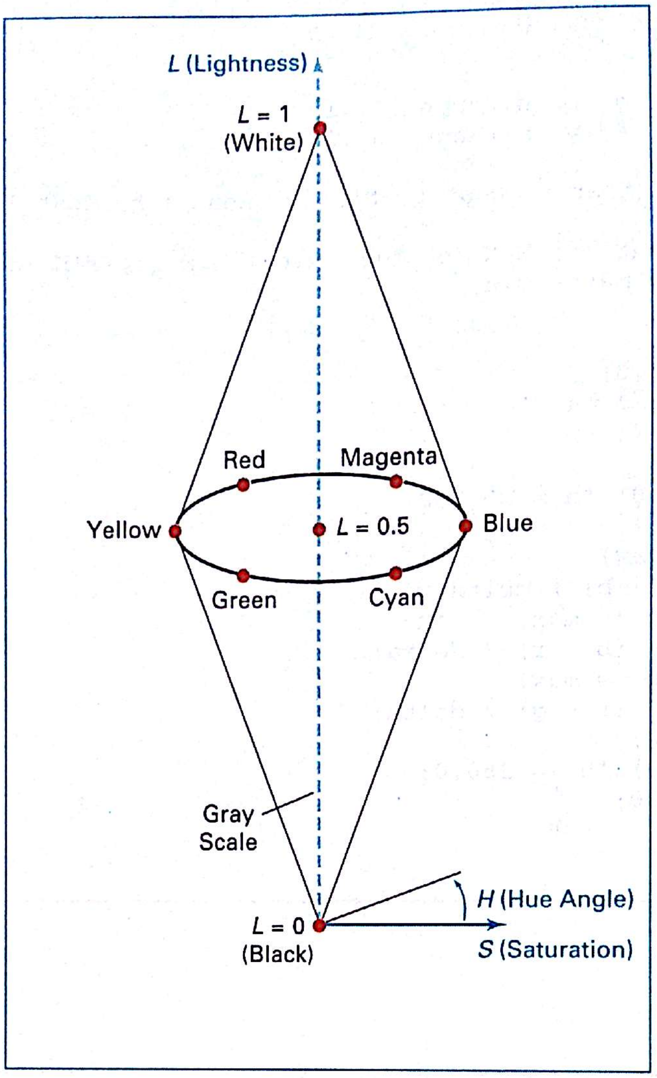


Figure 15-18
The HLS double cone.

15-10 COLOR SELECTION AND APPLICATIONS

A graphics package can provide color capabilities in a way that aids us in making color selections. Various combinations of colors can be selected using sliders and color wheels, and the system can also be designed to aid in the selection of harmonizing colors. In addition, the designer of a package can follow some basic color rules when designing the color displays that are to be presented to a user.

One method for obtaining a set of coordinating colors is to generate the set from some subspace of a color model. If colors are selected at regular intervals along any straight line within the RGB or CMY cube, for example, we can expect to obtain a set of well-matched colors. Randomly selected hues can be expected to produce harsh and clashing color combinations. Another consideration in the selection of color combinations is that different colors are perceived at different depths. This occurs because our eyes focus on colors according to their frequency. Blues, in particular, tend to recede. Displaying a blue pattern next to a red pattern can cause eye fatigue, because we continually need to refocus when our attention is switched from one area to the other. This problem can be reduced by separating these colors or by using colors from one-half or less of the color hexagon in the HSV model. With this technique, a display contains either blues and greens or reds and yellows.

As a general rule, the use of a smaller number of colors produces a more pleasing display than a large number of colors, and tints and shades blend better than pure hues. For a background, gray or the complement of one of the foreground colors is usually best.

SUMMARY

In this chapter, we have discussed the basic properties of light and the concept of a color model. Visible light can be characterized as a narrow frequency distribution within the electromagnetic spectrum. Light sources are described in terms of their dominant frequency (or hue), luminance (or brightness), and purity (or saturation). Complementary color sources are those that combine to produce white light.

One method for defining a color model is to specify a set of two or more primary colors that are combined to produce various other colors. Common color models defined with three primary colors are the RGB and CMY models. Video monitor displays use the RGB model, while hardcopy devices produce color output using the CMY model. Other color models, based on specification of luminance and purity values, include the YIQ, HSV, and HLS color models. Intuitive color models, such as the HSV and HLS models, allow colors to be specified by selecting a value for hue and the amounts of white and black to be added to the selected hue.

Since no model specified with a finite set of color parameters is capable of describing all possible colors, a set of three hypothetical colors, called the CIE primaries, has been adopted as the standard for defining all color combinations. The set of CIE primaries is commonly referred to as the XYZ color model. Plotting normalized values for the X and Y standards produces the CIE chromaticity diagram, which gives a representation for any color in terms of hue and purity. We can use this diagram to compare color gamuts for different color models, to identify complementary colors, and to determine dominant frequency and purity for a given color.

An important consideration in the generation of a color display is the selection of harmonious color combinations. We can do this by following a few simple rules. Coordinating colors usually can be selected from within a small subspace of a color model. Also, we should avoid displaying adjacent colors that differ widely in dominant frequency. And we should limit displays to a small number of color combinations formed with tints and shades, rather than with pure hues.