14

Color Models

14.1 INTRODUCTION

Color is a very important aspect of computer graphics. Color is the by-product of the spectrum of light, as it is reflected or absorbed, as received by the human eye and processed by the human brain.

14.1.1 Light and Color

Before starting about color models, it is important to know how the human eye and brain turn light into color. Fig. 14.2 depicts the position of visible light in narrow frequency band within the electromagnetic spectrum. A few other frequency bands within this spectrum are also shown.

Monochromatic light is made up of one single pure frequency. In general, we see light made up of multi frequency, is known as multichromatic. Monochromatic light looks to the eye as a pure color, and can never be white or magenta, since it contains only one frequency, the wave of monochromatic light can be *represented* as a **sine,** as shown in Fig. 14.1.

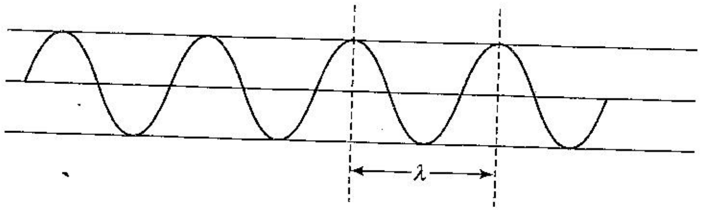


FIGURE 14.1

Brightness of light depends on the height (amplitude) of the sine wave. The width of one period (called lambda denoted as λ) is the wavelength of the light, and is inversely related to the frequency. As illustrated from Fig. 14.2 visible light has wavelengths from around 400 to 700 nm.(1 nm = 10^{-9} meter).

Light itself is an electromagnetic wave. Electromagnetic waves are thus a signal that is made out of one or more frequencies, for example the Electromagnetic waves used by a microwave oven are of very high frequency, while radio waves are very low frequency. The eye is only sensitive to a very narrow band of frequencies, namely, the frequencies between 429 THz and 750 THz (1 THz = 1 TeraHertz - 10^{12} Hz). All other electromagnetic waves can't be seen as shown in Fig. 14.3.

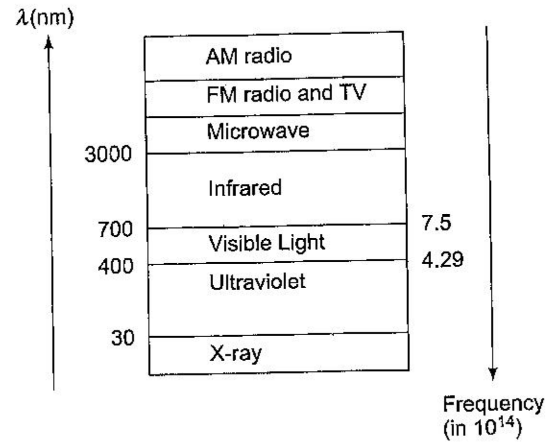


FIGURE 14.2 Electromagnetic Spectrum

Each frequency value within the visible band corresponds to a distinct color. At the low frequency end is a red color and the highest frequency end is a violet color as shown in Fig. 14.3

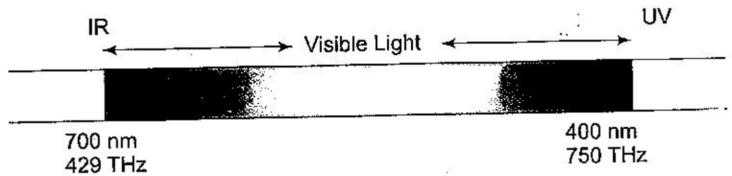


FIGURE 14.3 Color Pattern Corresponding to Electromagnetic Spectrum

This visible spectrum shows all the possible colors that can be made out of monochromatic light. Some light sources, such as lasers and Natrium lights, send out monochromatic light, but in general, light is multichromatic. For example, the sun sends out white light, which is light that contains ALL frequencies! That means the sum of red, yellow, green, blue and violet light looks like white! Physically speaking, it's not white at all, it's the sum of a lot of sine curves, but the human brain makes it look white. Color is thus something psychologically, and not something physical.

14.1.2 Characteristics of Light

Light can be characterized by three terms: saturation, hue and brightness.

Saturation (Purity)

It corresponds to physical property called excitation purity. It refers to how far a color is from white color. It is defined as percentage of luminance allocated to the pure color component i.e.,

$$\text{Saturation} = \frac{\text{Pure color}}{\text{Pure color} + \text{White}}$$

A completely pure color is 100 percent saturated, white light is 0 percent saturated, whereas mixture of pure color and white color have saturations between 0 and 100 percent.

Hue

It distinguishes white color from red, purple, yellow, green, etc. It is the term related to dominant wavelength (or dominant frequency). It is also called the color of the light.

Brightness

It corresponds to the physical property called ***luminance.*** Luminance measure the total energy in the light. It is proportional to the area bounded under the curve (Refer to Fig. 14.4).

$$\text{Luminance} = \text{Area under the curve} = \int_{\lambda} P(\lambda)d\lambda$$

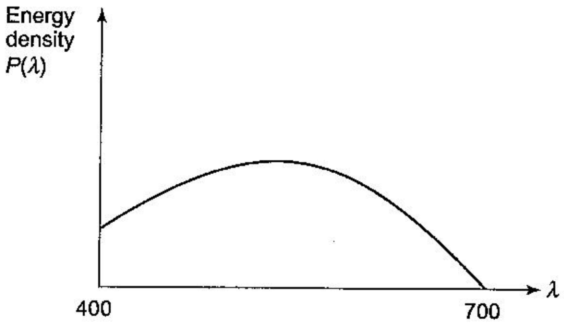


FIGURE 14.4

Higher the luminance, the brighter the light to be observes.
Color gamut determines the dominate wavelength and purity of color (See Section 14.3.2).

Light waves are a sum of many different frequencies, or the sum of many sine curves. Each of these sine curves has its own frequency, and can have its own amplitude. A **spectrum** shows for each frequency the amplitude. Here's an example of such a spectrum:

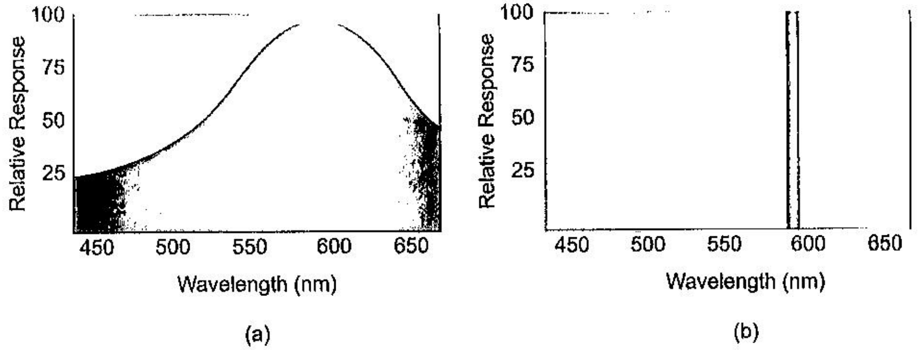


FIGURE 14.5

Fig 14.5(a) illustrates the spectrum of a yellow LED. The top of the spectrum is the Dominant Frequency, and that is the color our eyes will usually see if light with this spectrum shines on it. If this yellow LED would have been monochromatic, the spectrum would have looked like as shown in Fig. 14.5(b).

Fig 14.6 illustrate the spectrum of white light is as follows (the height of the curve doesn't really matter):

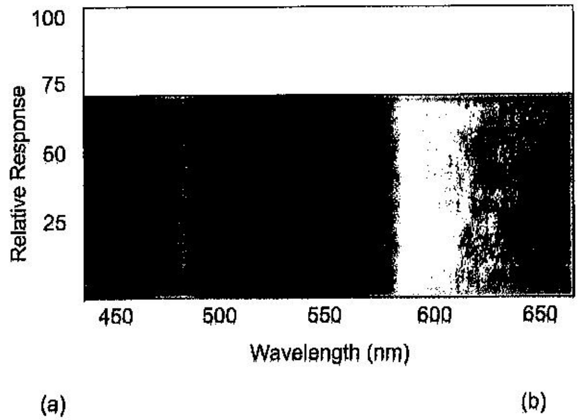


FIGURE 14.6

All frequencies are equally much in the light, only then it looks purely white to the brain. In all other cases, a certain frequency will be dominant and then that frequency will be the color the brain sees.

The spectrum of black light shown in Fig. 14.7.

Indeed, there's no light at all, the amplitude of every frequency is zero. Black is the color the brain gives to the absence of light.

14.1.3 The Eye and Color Perception

This section is about how the eye and the brain distinguish different colors.

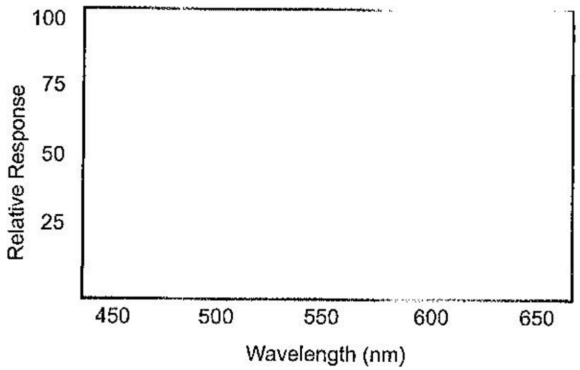


FIGURE 14.7

So light falls on the retina, and on the retina there are two types of cells viz., rods and cones. The rods only detect whether or not light is present, and are important at night. So rods are sensitive to the whole spectrum at once and can't tell what frequency the light has, and thus can't provide any color information. To detect color, you'd need photoreceptors that are sensitive to only a certain frequency. That's exactly what the cones do?

The eye has three classes of color-sensitive light receptors called *cones,* which respond roughly to red, blue and green light (around 650, 530 and 460 nm, respectively). Such a rod isn't sensitive to a single frequency, they overlap a bit, it's just sensitive mostly to a certain frequency (Refer to fig. 14.4).

For example, yellow has a frequency between red and green. This yellow frequency will excite both the red and green cones a bit, and the human brain converts the signal "both red and green cones are excited" to "yellow". Even the blue cones are still a bit excited by yellow light, but neglegible. If light falls on the eye that has two frequencies: red and green, it will also excite both the red and green cones, so this light will show up as yellow as well, even though it doesn't contain any yellow frequency at all. If blue light falls on the retina, the blue cones are excited very strongly, while the green and red ones will give only a neglectable signal. And the brain turns the signal "mainly the blue cone is excited" to "blue". White light contains **all** frequencies, so if white light falls on the retina, all 3 types of cones are excited, and the brain turns the signal "green, red and blue cones all excited" into "white".

Thanks to God for gifting us with 3 types of cones. Table 14.1 depicts the 8 (2^3) main colors.

TABLE 14.1

Cones			*Color*
Blue	*Green*	*Red*	
N	N	N	Black
N	N	Y	Red
N	Y	N	Green
N	Y	Y	Yellow
Y	N	N	Blue
Y	N	Y	Magenta
Y	N	Y	Cyan
Y	Y	N	White

Y: Cone excited
N: Cone not excited

You can, of course, distinguish much more colors than these 8 because each receptor type can have different levels of excitement.

The table explains how the brain creates different "hues" of colors out of the incoming signal, but it also gives a certain brightness to the light, based on how strong the incoming signal is: if it's very strong, the brain indicates it as a very bright red, white, ..., but if it's very weak, it'll be almost black. And then there's also the "saturation" of the color, this is based on the relative difference in strength each color type gives: if the red signal is very strong, but blue and green are also pretty strong, the color will have a low saturation, it's red-grayish or red whitish. If however the red signal would be very strong, and the blue and green signal very weak, a very red color shows up.

Since different spectra can look exactly the same for us, and some animals have different types of color receptors, it's possible that two colors that look same to us, may be two different colors for some animal.

The above process happens on every location of the retina separately, so that a complex two-dimensional image is formed where each location on the image can have it's own color.

Color blindness means one or more of the color types of cones are missing or less sensitive, for example if you miss the red one, you can only see the difference between light that has mainly green and light that has mainly blue. Light with mainly red, will show up as green for such a person, because the green receptors are still more sensitive to red than the blue ones. People who have 2 types of cones missing, and have thus only one type left, see in black and white, because only two main types of signals now exist: "the cone is excited" and "the cone is not excited". Imagine how much more colors a human would be able to see if he had 4 types of color receptors instead of only 3.

14.2 TWO BASIC COLOR APPROACHES

As we have already discussed, the human eye is sensitive to electromagnetic radiation with wavelengths between 400 and 700 nanometers. This radiation is known as ***light.*** The visible spectrum is illustrated in Fig. 14.3. A range of colors can be reproduced by one of two complimentary approaches:

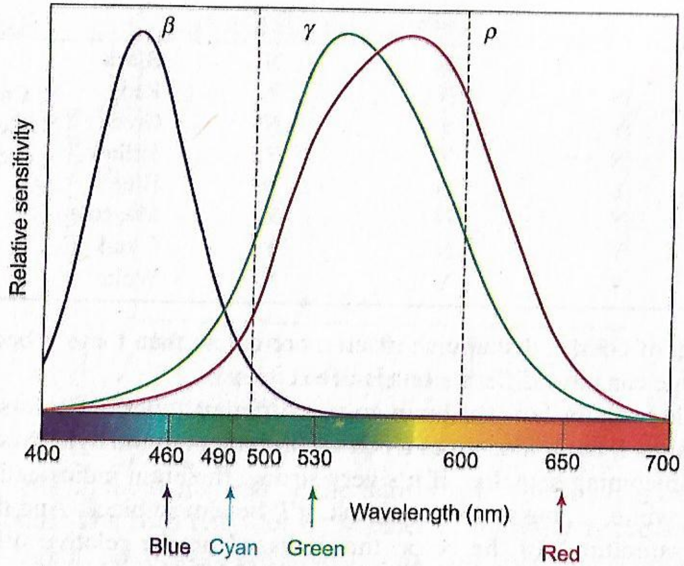


FIGURE 14.8 Human Spectral Sensitivity to Color (Three cones types (p,y,P) correspond to R,G,B)

14.2.1 Additive Colors

Additive colors are created by mixing spectral light in varying combinations. The most common examples of this are television screens and computer monitors, which produce color pixels by firing red, green and blue electron guns at phosphors on the television or monitor screen.

More precisely, additive color is produced by any combination of solid spectral colors that are optically mixed by being placed closely together, or by being presented in very rapid succession. Under these circumstances, two or more colors may be perceived as one color.

The ***additive primary*** colors are red (R), green (G), and blue (B). Adding R and G light makes yellow (Y). Similarly, G + B = cyan (C) and R + B = magenta (M). Combining all three additive primaries in equal amount makes white. Color plate 14.2 (p.323) more precisely defined the color combination of additive primary colors.

14.2.2 Subtractive Colors

Subtractive colors are seen when pigments in an object absorb certain wavelengths of white light while reflecting the rest. We see examples of this all around us. Any colored object, whether natural or man-made, absorbs some wavelengths of light and reflects or transmits others; the wavelengths left in the reflected/transmitted light make up the color we see.

This is the nature of color print production and cyan, magenta and yellow, as used in four-color process printing, are considered to be the subtractive primaries.

The objects may either transmit light (transparencies) or reflect light (paper, for example). The *subtractive primaries* are C, M and Y. Cyan absorbs red; hence C is sometimes called "minus red" (-R). Similarly, M is -G and Y is(-B). Color plate 14.2 more precisely defined the color combination of subtractive primary colors.

The subtractive color model in printing operates not only with CMY(K), but also with spot colors, that is, pre-mixed inks.

Unfortunately, ideal C, Y and M inks don't exist; the subtractive primaries don't entirely remove their compliments (R, B and G). This isn't a problem for film, where light is transmitted through three separate dye layers, but it has important consequences for prints made with ink on reflective media (i.e., paper). Combining C, Y and M usually produces a muddy brown. Black ink or key (K) must be added to the mix to obtain deep black tones. CMYK color is highly ***device dependent***— there are many algorithms for converting RGB to CMYK. Photographic editing should be done in RGB (or related) color spaces. Conversion to CMYK (usually with colors added to extend the printer color gamut) should be left to the printer driver software.

Additive Color vs Subtractive Color

(1) Additive color has primary colors red, green, blue. Subtractive color has primary color cyan, magenta, yellow.

(2) In case of additive color light from independent sources is added.
Whereas in case of subtractive color portion of visible light spectrum are absorbed.

(3) Adding all three additive primaries in equal amounts creates gray or white light. Combining all three subtractive primaries in equal amounts creates gray **or** black.

(4) Each subtractive primary colors removes one of the additive primary colors from the reflected **or** transmitted image. Cyan **(C) removes** red; hence it is known as minus red (-R), Similarly, M is –G and Y is –B.

(5) Additive colors are used to display color. For example, in television screen and color monitors use additive colors.
Subtractive colors are used to print color. For example, ink-jet printers, laser printers use subtractive colors.

(6) Colors perceived in additive colors are the result of **transmitted** light. Colors perceived in subtractive colors are the result of **reflected** light.

You can obtain a wide range of colors, but not *all* the colors the eye can see, by combining RGB light. The *gamut* of colors a device can reproduce depends on the spectrum of the primaries, which can be far from ideal. To complicate matters, the eye's response doesn't correspond *exactly* to R, G and B, as commonly defined (the description above is oversimplified).

14.3 COLOR MODELS

Color models are used to classify colors and to qualify them according to such attributes as hue, saturation, chroma, lightness or brightness. They are further used for matching colors and are valuable resources for anyone working with color in any medium: print, video, or Web.

A color model is an orderly system for creating a whole range of colors from a small set of primary colors. There are two basic types of color models:

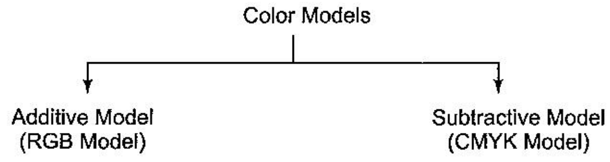


FIGURE 14.9

Additive color models use **light** to display color while subtractive models use printing **inks.** Colors perceived in additive models are the result of **transmitted** light. Colors perceived in subtractive models are the result of **reflected** light.

Additive vs. Subtractive Color Models

Since, additive color models display color as a result of light being transmitted (added) the total absence of light would be perceived as **black.** Subtractive color models display color as a result of light being absorbed (subtracted) by the printing inks. As more ink is added, less and less light is reflected. Where there is a total absence of ink the resulting light being reflected (from a white surface) would be perceived as **white** as illustrated in figure 14.10.

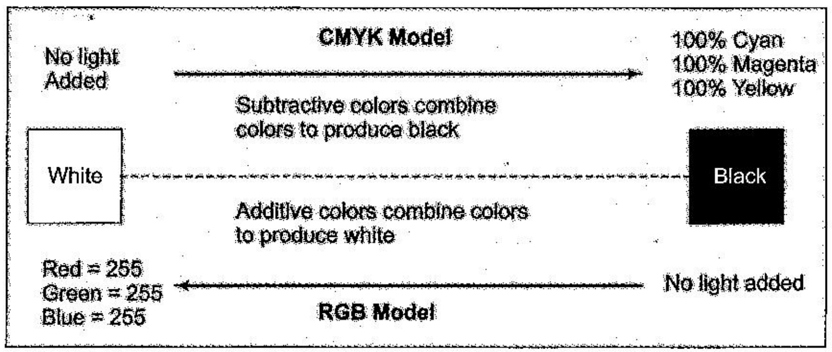


FIGURE 14.10 Comparative Structure of Additive and Subtractive Color Models

14.3.1 Color Gamut and Color "Space"

Each color model has is own gamut (range) of colors that can be displayed or printed. Each color model is limited to only a portion of the visible spectrum. Since a color model has a particular range of available color or gamut, it is referred to as using a "color space". An image or vector graphic is said to use either the RGB color space or the CMYK color space (or the color space of another color model). Some graphic applications present the user with more than one color model for image editing or illustration and it is important to choose the right one for the task.

14.3.2 CIE Chromaticity Diagram

When visible spectrum is plotted on *xy* plane, then we obtain a tongue-shaped curve as shown by color plate 14.1. This curve is called **CIE chromaticity diagram.**

The horseshoe line starting at 400 nm on the lower left and wrapping around the top to 700 nm on the right is called the *spectrum locus.* It represents the pure spectral colors— the beautiful, intense colors produced by a prism in clear sunlight. The screen image is but a pale approximation. The straight line connecting the endpoints of the horseshoe is called the *purple boundary.* The full gamut of human vision lies within this figure. The vertical axis gives an approximate indication of the proportion of green; the horizontal axis moves from blue on the left to red on the right.

Point C in the diagram corresponds to the white-light position. The location of white depends on the illuminant color temperature. Some typical values:

Incandescent lamp	2856°K	$x, y = 0.448, 0.407$
Direct sunlight	5335°K	$x, y = 0.336, 0.350$
Overcast sky, D65	6500°K	$x, y = 0.313, 0.329$

The chromaticity diagram is useful for the following:

(1) It helps us to compare color gamut of two different set of primaries.
(2) It helps to identify the complementary colors.
(3) It determines the dominant wavelength of a color. (Refer to fig. 14.11)
(4) It determines the saturation of a color. (Refer to fig. 14.7)

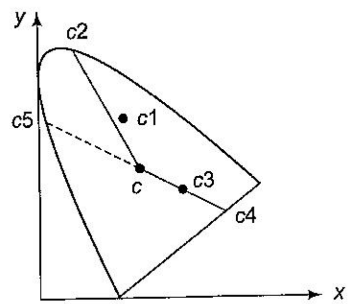


FIGURE 14.11

cc2 line passes through c1 and cc4 line passes through c3. Dominant wavelength of color c1 [illegible]

Dominant wavelength of color c3 = complement of c4 = c5 (because color point c3 lies below color point c)

$$\text{Purity of color } c1 = \frac{\text{Distance from c to c1 } (d_{c1})}{\text{Distance from c to c2} (d_{c2})}$$

14.3.3 The RGB Color Model

This color model based upon vision theory. Red, green, and blue are the primary stimuli for human color perception and are the primary additive colors. The RGB color model is the one you will mostly be dealing with in computer graphics. It is also called the ***additive color model,*** because you add three color components together to form any color. The relationship between the colors can be seen in this illustration:

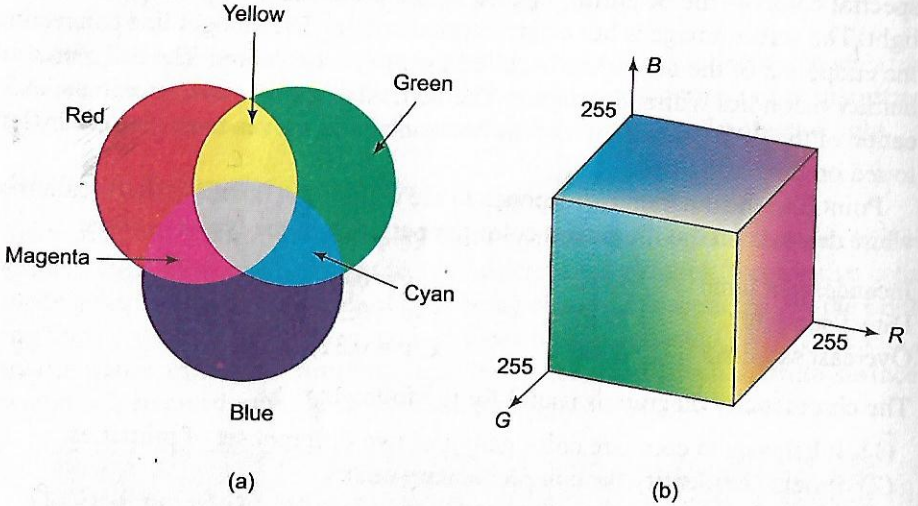


FIGURE 14.12

The RGB color model works exactly like those color receptors of the human eye work: ***the RGB color model describes a color by using three variables: red, green and blue. These variables can be compared to the strength of the signals from the three types of color receptors in the nerves.***

A computer or TV screen works this way too: it has 3 types of cells, red, green and blue, and can make each type brighter or darker independently, exciting the correct receptors of the eye to create the desired color.

If you look with a magnifying glass to a white area of your computer screen, you can see that the color white is actually made out of the three colors red, green and blue. This means the white emitted by a computer screen is different from white sunlight: while white sunlight contains photons of all frequencies (except a few), the computer screen only has three frequencies. The human eye can't see the difference between these two kinds of white.

The combination of red, green, and blue in full intensity makes white. White light is created when all colors of the EM spectrum converge in full intensity. The importance of RGB as a color model is that it relates very closely to the way we perceive color with the $\alpha\ \beta\ \gamma$ receptors in our retinas.

RGB is the basic color model used in television or any other medium that projects the color. It is the basic color model on computers and is used for Web graphics, but it cannot be used for print production.

The RGB model forms its gamut from the primary additive colors of red, green and blue, refer to color plate 14.4.

In RGB color, the higher the values of R, G and B, the brighter the color will be, and if R=G=B, the color will be a shade of gray.

RGB color model can represent this model with unit cube defined on R, G and B axes, as shown in Fig. 14.13. The origin represents the black and vertex with coordinates (1,1,1) is white. Vertices of the cube represent the primary colors.

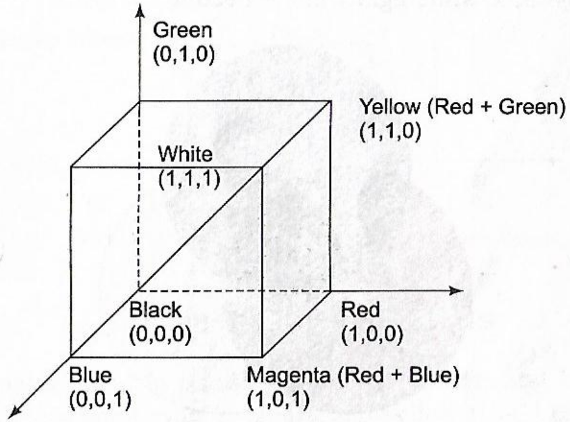


FIGURE 14.13 RGB Color Model

Each color in this model is represented as the triple (R, G, B), where the values of R, G and B lies in the range 0 to 1.

Computers generally display RGB using 24-bit color. In the 24-bit RGB color model there are 256 variations for each of the additive colors of red, green and blue. Therefore, there are 16,777,216 possible colors (256 reds × 256 greens × 256 blues) in the 24-bit RGB color model. In the RGB color model, colors are represented by varying intensities of red, green and blue light. The intensity of each of the red, green and blue components are represented on a scale from 0 to 255 with 0 being the least intensity (no light emitted) to 255 (maximum intensity). 127 is half intensity. This means color 0,0,0 is the darkest black, color 255,0,0 is the brightest red, color 0,255,0 is the brightest green and color 0,0,255 is the brightest blue. 255,255,255 is the brightest white and 127,127,127 is gray. The RGB color model is not very intuitive.

TABLE 14.2 Depicts with Common RGB color Values

R	*G*	*B*	*Hex Value*	*Color*
0	0	0	000000	Black
255	0	0	FF0000	Red
0	255	0	00FF00	Green
0	0	255	0000FF	Blue
255	255	0	FFFF00	Yellow
255	0	255	FF00FF	Magenta

14.3.4 CMY(K) Model or Process Model

CMYK (Cyan, Magenta, Yellow, Key or Ink) is subtractive color model. It based on the theory that colors of an object are seen when pigments in the object absorb certain wavelengths of white light while reflecting the rest.

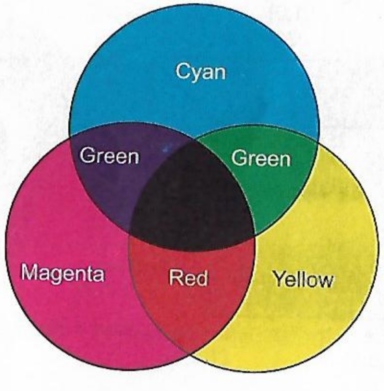


FIGURE 14.14 CMYK Color Model

Just as the primary colors of CMY are the secondary colors of RGB, the primary colors of RGB are the secondary colors of CMY. But as the illustrations show, the colors created by the subtractive model of CMY don't look exactly like the colors created in the additive model of RGB. Particularly, CMY cannot reproduce the brightness of RGB colors. In addition, the CMY gamut is much smaller than the RGB gamut (Refer to color plate 14.4).

In theory, the combination of cyan, magenta and yellow at 100%, create black (all light being absorbed). In practice, however, CMY usually cannot be used alone. Due to imperfections in the inks and other limitations of the process, full and equal absorption of the light isn't possible; thus true black or true grays cannot be created by mixing the inks in equal proportions. When cyan, magenta and yellow inks are combined it forms black—in theory. However, because of the impurities in ink, when cyan, magenta and yellow inks are combined it produces a muddy brown color. Black ink is added to this system to compensate for these impurities. In order to boost grays and shadows, and provide a genuine black, printers resort to adding black ink, indicated as K. Thus the practical application of the CMY color model is the ***four color*** CMYK process.

The CMYK printing method is also known as "four-color process" or simply "process" color. All the colors in the printable portion of the color spectrum can be achieved by overlapping "tints" of cyan, magenta, yellow and black inks. A tint is a screen of tiny dots appearing as a percentage of a solid color. When various tints of the four colors are printed in overlapping patterns it gives the illusion of continuous tones.

Cyan, magenta and yellow correspond roughly to the primary colors in art production: red, blue, and yellow. In the illustration below, you can see the CMY counterpart to the RGB model shown above:

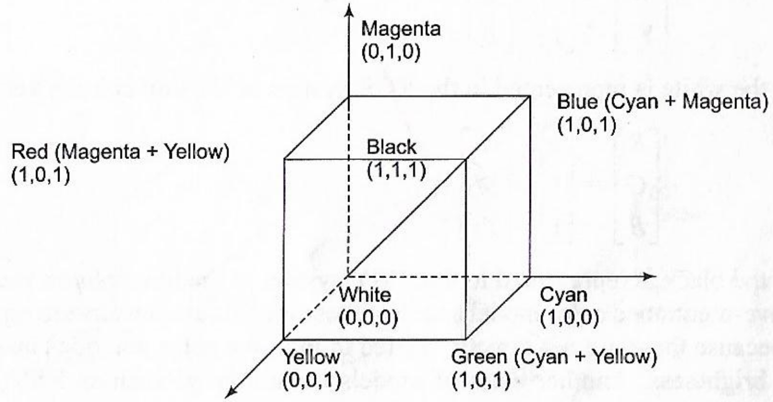


FIGURE 14.15 CMYK Color Model

The CMY model used in printing lays down overlapping layers of varying percentages of transparent cyan, magenta, and yellow inks. Light is transmitted through the inks and reflects off the surface below them (called the substrate). The percentages of CMY ink (which are applied as screens of halftone dots), subtract inverse percentages of RGB from the reflected light so that we see a particular color. This model is sometimes also known as ***process model*** or ***substrate model.***

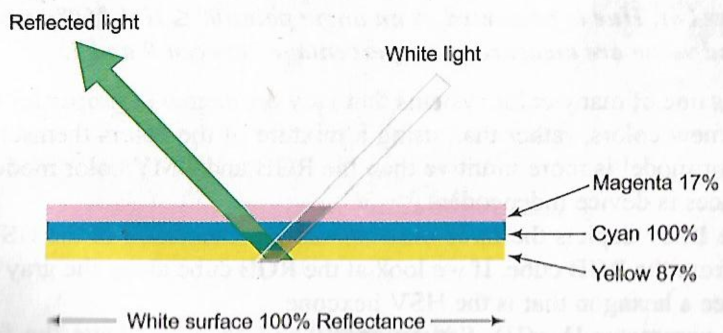


FIGURE 14.16

In the illustration above, a white substrate that reflects 100% of the light is printed with a 17% screen of magenta, a 100% screen of cyan, and an 87% screen of yellow. Magenta subtracts green wavelengths, cyan subtracts red wavelengths, and yellow subtracts blue wavelengths from the light. The reflected light, then, is made up of 0% of the red wavelengths, 44% of the green wavelengths, and 29% of the blue wavelengths.

Relationship between RGB Color Model and CMY Color Model

RGB color model and CMY color model are complement to each other.

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

where, the white is represented in the RGB system as the unit column vector.

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

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

Above-mentioned color models none of these models are sensitive to represent color because these are not directly related to intuitive color notations hue, saturation, brightness. Another class of models is introduced such as HSV(HSB), HLS, HVC models.

14.3.5 HSV Color Model

HSV(Hue, Saturation, Value) color model was created in 1978 by Alvy Ray Smith. It is non-linear reformation of RGB color. HSV is the color selection model used most often in illustration and image programs, like Fireworks and Freehand. Color selection is based on these criteria:

With hues along the outer edge at full saturation, and with saturation decreasing as you move to the center of the circle. Value or intensity is adjusted with a brightness bar. Hue is presented as an angle point($0° \le H \le 360°$), while saturation and value are measured as a percentage between 0 and 1.

HSV is one of many color systems that vary the degree of properties of colors to create new colors, rather than using a mixture of the colors themselves. The HSV color model is more intuitive than the RGB and CMY color models. HSV color spaces is device independent.

Figure 14.17 depicts the three-dimensional representation of the HSV model derived from the RGB cube. If we look at the RGB cube along the gray diagonal we can see a hexagon that is the HSV hexcone.

Three parameter Hue(H), Saturation(S), and Value(V) have the following range of values:

(a) The hue(H) is given by the angle about the vertical axis with red at 0°, yellow at 60°, green at 120°, cyan at 180°, blue at 240° and magenta at 300°. Note that the complementary colors are 180° apart. The complementary colors (red + cyan, blue + yellow, green + magenta) are diagonally opposite.

(b) The vertical axis is called value (V)($0.0 < V < 1.0$). At V=0, we have black, and at V = 1, we have white.

(c) The horizontal axis represents saturation(S) ($0.0 \le S \le 1.0$). It specifies purity of color and is the ratio of purity of a related hue to its maximum purity at S = "1" and V = 1. At S = 0 is the gray scale, that is the diagonal of the RGB cube corresponds to V of the HSV hexcone.

At S = 1 AND V = 1, we have pure hue. As S decreases hues are said to be less pure.

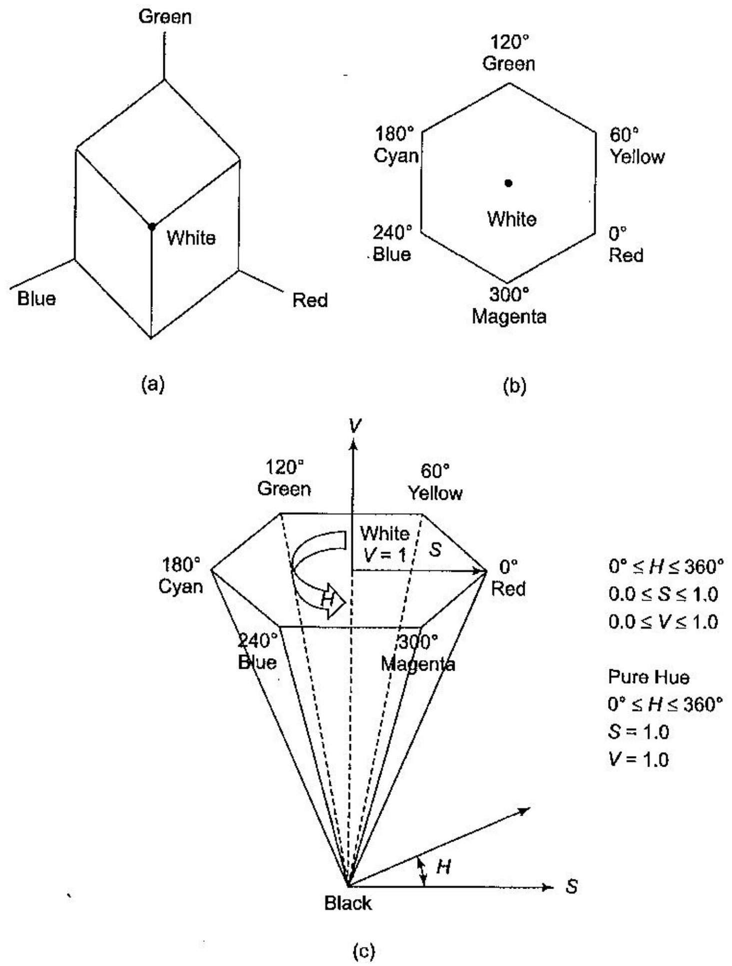


FIGURE 14.17

The user specifies a color (hue) and then adds white or black. Changing the **saturation** parameter corresponds to adding or subtracting white and changing the **value** parameter corresponds to adding or subtracting black.

Artists start with a "pure color or hue", then add black pigment to produce different *shades*. The more black pigment the darker the *shade*. They add white pigment and get different *tints*. Adding both black and white pigments gives different *tones*. (Refer to fig. 14.18). If we look at the cross-section of the hexcone we can see the analogy with the artists model.

So to choose a color we do the following:

1. Select pure hue (specifies H and sets S = V = 1)
2. To add black decrease V
3. To add white decrease S.
4. To add black and white decrease V and S.

For example: pure blue H = 240°, S = V – 1, dark blue H = 240°, S = 1, V = 0.40, light blue H = 240°, S = .3, V = 1.0

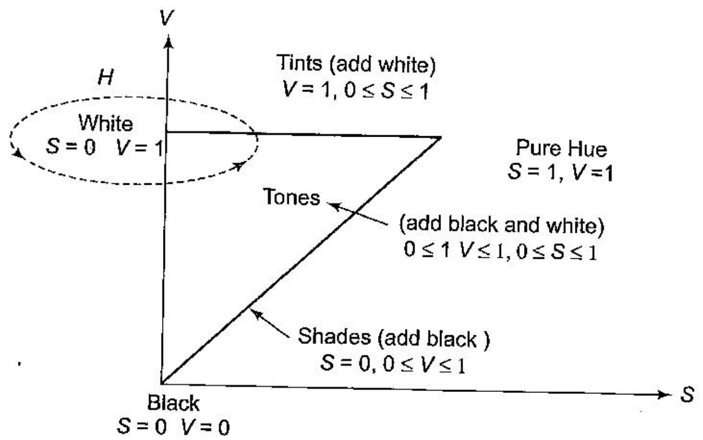


FIGURE 14.18 Cross-section of HSV Hexcone

The human eye can distinguish about 128 different hues, 130 different tints (saturation levels), and from 16 (blue part of spectrum) to 23 (yellow part of spectrum) different shades. So we can distinguish about $128 \times 130 \times 23 = 380{,}000$ colors.

14.3.6 HLS Color Model

HLS(Hue, Lightness, Saturation) is another way to describe intuitive color with 3 parameters. Three colors parameters in this model are called hue(H), (lightness) (L), and saturation(S). HSL is also known by the abbreviations of HLS and HIS, while the L can often refer to luminosity or luminance rather than light. HLS is more intuitive than RGB and CMY color models.

Figure 14.19 depicts the HLS color model. The HLS color model is graphically represented by a double cone or hexcone, this shape resembles a spinning top. The top and bottom ends of the cone, also called apexes, are the colors black and white. In this model, the hue is represented by the angular perimeter. The S part of HSL is graphically viewed by varying distances from the axis, which is the line that is located in the center of the graph in the vertical direction. And finally the distance between the two apexes is what represents the light of the color model. To put this graph, and the one for the similar HSV graph (which is a single cone representation of color model), into perspective both are variations of the well-know RGB color model. HLS color spaces can be device dependent or device independent.

Range of parameters and their effect on color specifications is as follows:

(a) Hue specifies the angle about vertical axis($0° \le H \le 360°$). In this model blue at H=0°, magenta at H=60°, red at H=120°, yellow at H=180°, green at H=240°, and cyan at H=300°. Note that the complementary colors are 180° apart. The complementary colors(red + cyan, blue + yellow, green + magenta) are diagonally opposite.

(b) The vertical axis is called lightness (L)($0.0 \le L \le 1$ ()). At L=0, we have black , at L=0.5 plane, we have pure hue, and at L=1.0, we have white. Along vertical axis(S=0) we have gray scale.

(c) The horizontal axis represents saturation(S) ($0.0 \le S \le 1.0$). It is the measure of the "purity" of a hue. As saturation is decreased, the hue becomes more gray. A saturation value of zero results in a gray-scale value i.e., at S= 0, we have gray scale. It specifies purity of color and is the ratio of purity of a related hue to its maximum purity at S = "1" and L = 0.5.

At S = 1 and L = 0.5 , we have pure hue. As S decreases hues are said to be less pure.

Likewise HSV model HLS model allows us to change shades, tints, tones in selected color. Thus, lightness is the amount of black or white in a color. Increasing lightness adds white to the hue, decreasing lightness adds black to the hue. Suppose artists start with a "pure color or hue", then add black pigment to produce different *shades*. The more black pigment, the darker the *shade*. Colors are made lighter if we increase the value of L and made darker if we decrease the value of L. They add white pigment and get different *tints*.

Comparison between HSV and HSL Color Models

(a) HSV represents the color model as a single-cone, while the HSL represents color model as a double-cone. Because the HSL model keeps the light and saturation aspects of the color model unique from each other, it tends to be more useful for those wishing to take advantage of these attributes in their work.

(b) The HSV goes all the way down to a white, which is not useful to many users of the color model. The HSL color model allows the color to range

(c) HSV color model can only range from the desired color to black. On the other hand, light can range from white to black in a HSL model (with the desired color in between). It is obvious that the HSL color model does indeed offer more freedom.

Computer programs that use color model are known to use either the HSL or HSV color models. Some programs will even use both. The most frequently used color model is the HSV. For example, **Apple computers uses** the HSV color model for their color picker, while **Microsoft** uses HSL. And while the simple Paint program provided by Microsoft only uses the HSL color model, more advanced photo editing software such as Adobe Photoshop benefits from using, both color models.

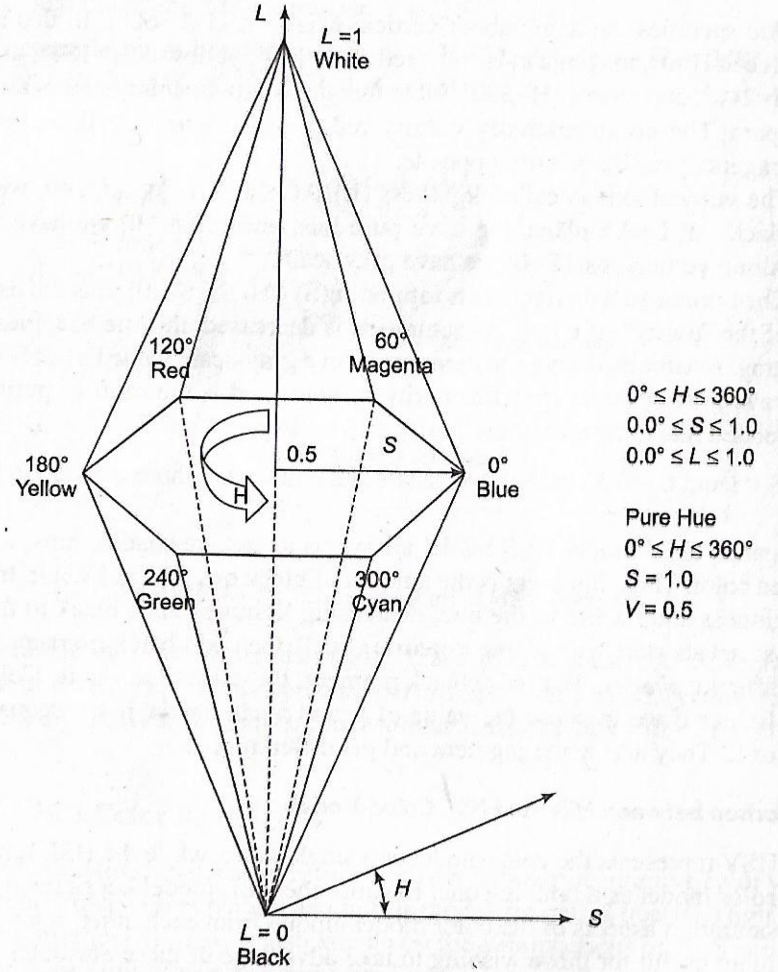
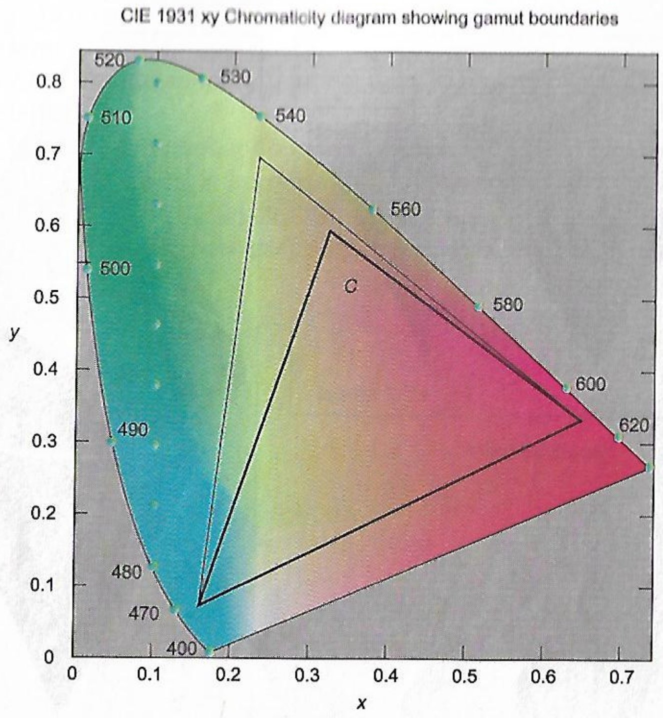
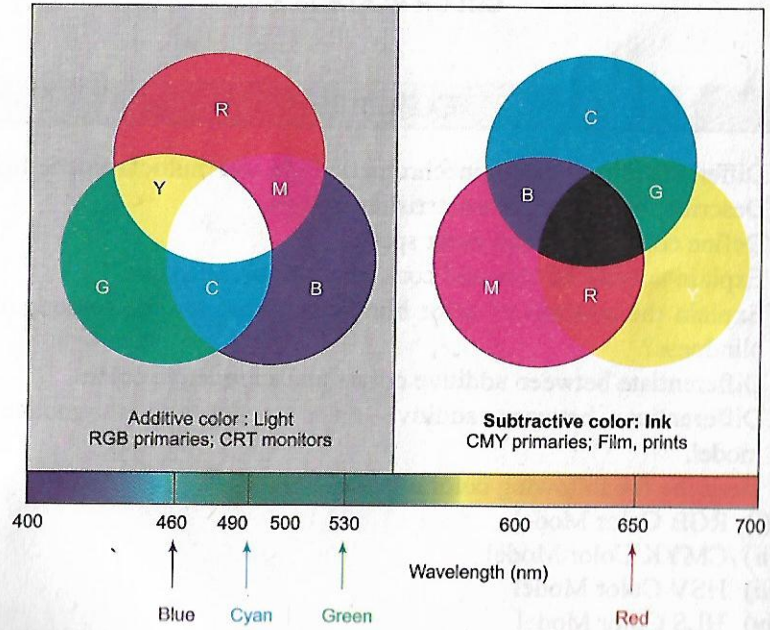


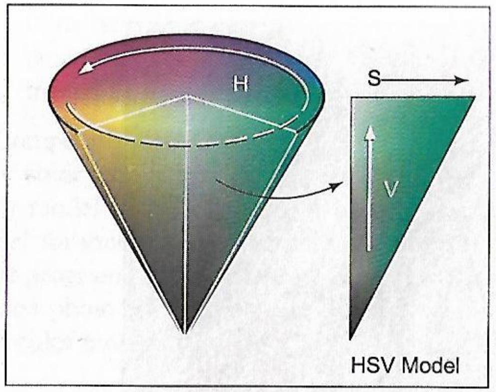
FIGURE 14.19



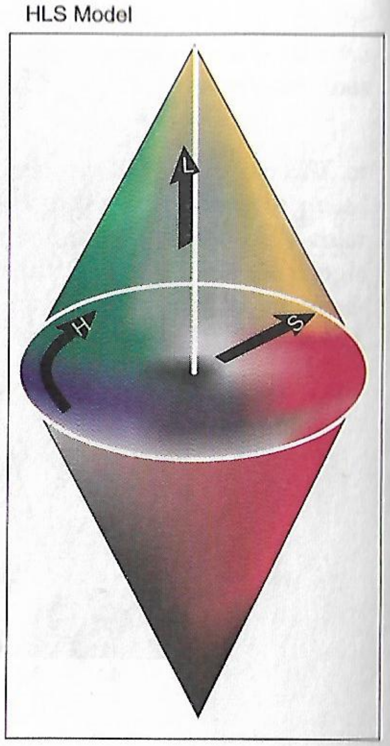
COLOR PLATE 14.1



COLOR PLATE 14.2



(a) HSV Model



(b) HLS Model

COLOR PLATE 14.3

EXERCISES

1. Differentiate between monochromatic light and multichromatic light.
2. Describe the various characteristics of light.
3. Define color gamut and color space.
4. Explain the role of rods and cons for color prescription.
5. Explain the concept of color blindness. What are the reasons of color blindness?
6. Differentiate between additive colors and subtractive colors.
7. Differentiate between additive color model and subtractive color model.
8. Describe the following color models
   (i) RGB Color Model
   (ii) CMYK Color Model
   (iii) HSV Color Model
   (iv) HLS Color Model

9. Why HSV model is more intuitive than RGB model and CMYK model? Explain.
10. Why HLS model is more intuitive than RGB model and CMYK model? Explain.
11. Explain CIE chromaticity diagram. Hence, specify its importance.
12. Why CMYK model is known as device-dependent? Explain.
13. What is the role of K' in CMYK model?
14. Derive relationship between RGB model and CMYK model.

octree list, each pixel area is assigned some color value. But Color value is assigned only if no values have previously been stored on this area. Thus front colors are loaded for pixels in the frame buffer & obscured or invisible areas are eliminated and not processed further. Octree method is an extension of the quadtree method

8.2.8 Ray Casting

Ray casting is a common hidden surface removal method. It tries to mimic actual physical effects associated with the propagation of light. Ray tracing is an extension of ray casting. Ray tracing is an illumination based rendering method for producing views of virtual 3D scene on screen. Ray casting mostly uses image space approach.

This ray tracing approach we will discuss in detail when we look at illumination and shading models.

8.3 Illumination and Shading

In the last section we studied few visible surface detection methods which display the objects visible from the viewing position. But to be displayed, the prerequisite is the presence of light (illumination). Thus illumination is the exposure of an object to the light Illumination and shading is the last important step in 3D graphics pipeline.

Light leaves the light source eg., a bulb or a sum, and is reflected from many surfaces and then finally reflected to our eyes, or through an image plane of a camera. In the overall process of reflection, scattering from the objects in the path of light rays there is always production of shadows and shades with varying levels of intensities. Shading also contributes to the realism of the scene under preparation.

An illumination which is also called lighting model or shading model, is used to calculate the intensity of the light that is reflected at a given point on the surface of the object. This illumination model is further used by rendering process to determine the light intensity of each projected pixel position in a scene.

Creating a virtual reality of a real scene (say a class room) involves:

- Modeling and positioning of several complex objects,
- Determine the visible surface and project the view w.r.t. the viewer,
- Obtain shading using surface normal, surface properties and light sources,
- Obtain shadows from occlusions

In a real world environment, light rays flow in almost infinite directions, some direct from the source and some reflected from shiny surfaces of the objects. But a real world image taken using a digital camera will only capture a small subset of the light rays passing through small area.

To accurately construct a picture of the room via computer graphics, we have to simulate the illumination process and be able to calculate the shading at each point of each surface in our scene. Often an approximated view is generated using many complex formulations and algorithms.

Process of illumination involves surface normal, source of light and viewer directions. It is shown in fig. 8.25. S is the source of light direction, V is viewer direction and N is surface normal. θ is the angle between surface normal and source. And ϕ is the angle between surface normal and viewer direction.

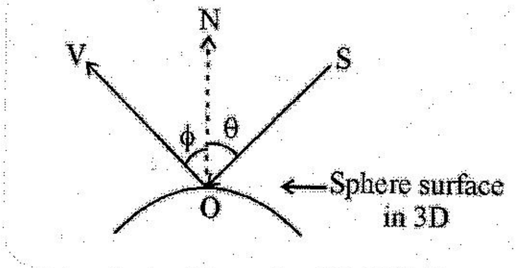


Fig. 8.25

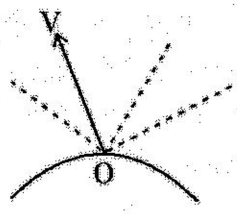


Fig. 8.26

Light rays from S hitting at point O and viewer is looking from viewing direction V. V may be in different plane than N and S.

Thus viewing direction can be anyone as shown in Fig. 8.26. Similarly, light rays could also come from various directions. There can be more than one light sources illuminating an environment thus affecting the objects present in the environment. Other sources of light can be inter reflection (reflection from shiny objects). Some objects in a scene may not have rays coming from the principle source directly, even then they illuminate. It is because of inter reflection. There are infinite rays, but we model only finite rays.

Before we start with certain illumination models, we make few compromises and simplifications. These are :

- Uniform media between the plane of projection and objects in 3D space.
- Consider only opaque objects. When light is incident on an opaque surface, part of it is reflected and part of it is absorbed. The amount of light reflected depends on the type of material (shiny surface reflects more light and dull surface absorbs more light).

- We assume that there is no inter reflections (approximated by ambient light).
- To simplify use point light sources. Light rays originate at a point and radially diverge. Distributed light rays originate at a finite area in space. Both types are shown in fig 8.27.

(a) Point source **(b) distributed source**

Fig. 8.27

- To simplify, assume simple color model.

Illumination at point (*x*, *y*) or intensity at viewer direction at point (*x*, *y*) is given by

$$I(V_{x,y}) = F(\phi, \theta, \rho, S_L) + A(V)$$

Here, ϕ is the angle between vectors V and N as given in fig. 8.25.

θ is the angle between vectors N and S.

ρ(*rho*) is the reflection coefficient at point O on object surface,

S_L is the intensity of the light source.

A is the ambient term.

Illumination consists of three parts:

- Ambient reflection
- Diffuse reflection
- Specular reflection

Thus three types of reflections which occur due to interaction of light and surface, is needed to be implemented by ray tracing techniques and other models, in order to attain realism.

8.3.1 Ambient Reflection

Few object surfaces in a scene are not illuminated by direct light sources but they are still visible. This is due to nearby illuminating objects (shiny objects) which reflect the light rays. These light rays in the environment is categorized as ambient light. This is a case of diffuse, non-directional source of light. This results from the effect of multiple reflections of light from many surfaces present in the environment

Ambient light is assumed to impinge equally on all surfaces from all directions. Thus we can write the illumination equation as :

$$I = I_a K_a$$

where, I_a is the intensity of ambient light assumed to be constant for all objects and K_a is the ambient reflection coefficient ($0 \le K_a \le 1$), a property of the surface material.

Though reflected light is constant for each surface, which is independent of the viewing direction and orientation of the surface, but it definitely depends on optical properties of the surface, i.e. how much a surface reflects and absorbs the light rays.

8.3.2 Diffuse Reflection

Diffuse reflection is characteristic of light reflected from a dull, non shiny surface. Diffuse reflections are constant over each surface in a scene, independent of the viewing direction. The object's brightness varies from one place to another depending on the direction of the light source (and also on the distance to some extent). Diffuse reflection models the light reflecting properties of matt surfaces, i.e. the surfaces that are rough or grainy which tend to scatter the reflected light in all directions. This scattered light is called diffuse reflection.

We are assuming here that diffuse reflection from the surface are scattered with equal intensity in all directions independent of the viewing direction. Such surfaces are ideal diffuse reflectors or Lambertian reflectors. Lambert's cosine law states that in diffuse reflection, intensity of reflected light is proportional to cos θ.

i.e. $I \propto \cos\theta$

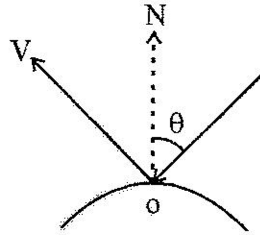


Fig. 8.28 diffuse reflection independent of viewing direction. Angle ϕ is ignored

Thus, diffuse illumination equation is :

$$I = I_d K_d \cos(\theta)$$

where I_d is the point light source's intensity

and, K_d($0 \le K_d \le 1$)is material's diffuse reflection coefficient, also, $0 \le \theta \le 90°$

Thus the amount of illumination depends on cos θ. As the angle between the surface normal and light source increases, illumination decreases at the point.

Thus when θ = 90° we have least illumination.

The above illumination equation can be rewritten as :

$$I = I_d K_d (\vec{N}.\vec{S})$$

where $\vec{N}$ and $\vec{S}$ are scalar quantities

So, $\vec{N}.\vec{S}$ = cos θ (dot product of $\vec{N}$ and $\vec{S}$)

Unless you are in a perfect dark room, a more realistic illumination equation is :

$$I = I_a K_a + I_d K_d (\vec{N} \vec{S})$$

This is the total diffuse reflection equation for illumination.

K_d = 1 for highly reflective surfaces reflecting whole light.

K_d = 0 for surfaces that absorb light completely.

8.3.3 Specular Reflection and the Phong Model

Specular reflection is observed on a shiny surface. Specular reflection is when the reflection is stronger in one viewing direction, in a concentrated region around specular reflection angle, i.e., there is a bright spot. fig. 8.29 observes the specular reflection.

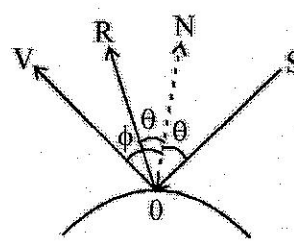


Fig. 8.29

R is the reflection vector. Angle of incidence equals the angle of specular reflection.

Shiny surface reflects light unequally in different direction. For an ideal reflector, specular reflection is visible only when V(Viewer direction) coincides with R. This is the case of perfect reflector example of which is mirror. For other real objects, specular reflection can be seen also when V and R don't coincide. This is the case of imperfect, non mirror type reflector, example is shiny plastics, gold and silver coated metal surfaces.

Intensity is the maximum along R, which decreases as α increases. α is the angle between reflection vector R and viewer direction V as shown in fig 8.30.

Thus α is the viewing angle relative to R.

If $\alpha = 0$, viewer will see light of more intensity.

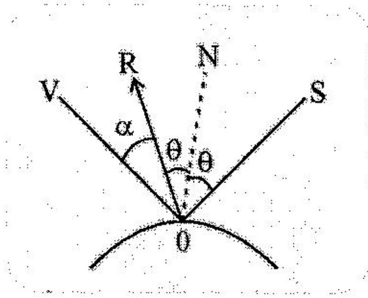


Fig. 8.30

The local illumination model generally used is

illumination = Ambient + Diffuse + specular.

It is also called phong specular reflection model. Phong observed that for very shiny surfaces the specular highlight was small and the intensity fell off rapidly, while for duller surfaces it was larger and fell off more slowly. So phong decided to let the reflected intensity be a function of $(\cos \alpha)^n$, where 'n' is specular reflection parameter dependent on the type of surface. $0 \leq \alpha \leq 90°$ and $n >= 200$ for shiny surface and n is small for dull surface.

For a perfect reflector (say mirror) n equals infinity and for a piece of card board n equals 0 or 1.

Thus, the illumination equation for phong specular reflection is :

$$I = I_s K_s \cos^n \alpha$$

where I_s is the intensity of light source

K_s is specular reflection coefficient.

Now, the total intensity when all ambient |diffuse| specular reflection occurs is :

$$I = I_a K_a + I_d K_d \cos\ \theta + I_s K_s \cos^n \alpha$$

since α is the angle between vectors V and R which are scalar vectors, so,

$$\cos^n \alpha = (\vec{V}.\vec{R})^n$$

here, $\vec{R}$ is the unit vector in specular reflection direction and $\vec{V}$ is the unit vector in viewer direction

11.2 THE PHONG MODEL

This is a widely used and highly effective way to mimic the reflection of light from object surfaces to the viewer's eye. It is considered an empirical approach because, although it is consistent with some basic principles of physics, it is largely based on our observation of the phenomenon. It is also referred to as a *local illumination model* because its main focus is on the direct impact of the light coming from the light source. On the other hand, a *global illumination model* attempts to include such secondary effects as light going through transparent/translucent material and light bouncing from one object surface to another.

Now consider a point light source [see Fig. 11.7(a)], which is an idealized light with all its energy coming out from a single point in space (a reasonable approximation to a bulb). Our eye is at the viewpoint looking at point Q on the surface of an object. What should be the color of Q? In other words, what should be the color of the light reflected into our eye from Q (in the direction of vector $\mathbf{V}$)?

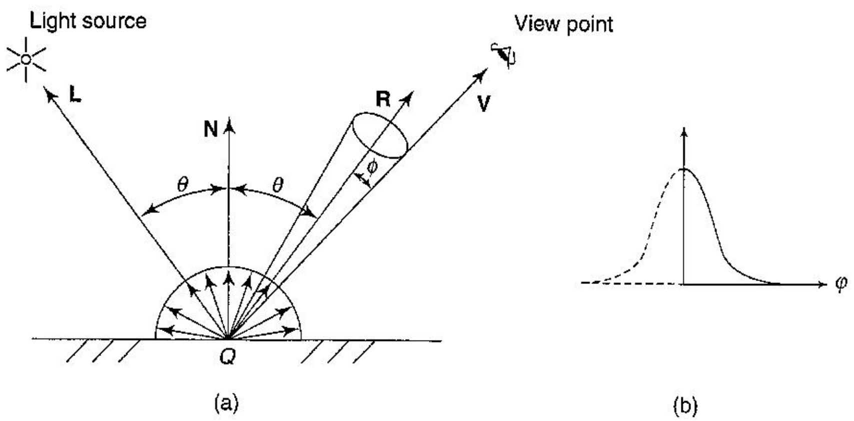


Fig. 11.7

There are two extreme cases of light reflection. The first is called *diffuse reflection.* In this case light energy from the light source (in the direction of $-\mathbf{L}$) gets reflected/bounced off equally in all directions (see the small arrows forming a half-circle/hemisphere). We also want the energy level of the reflection to be a function of the incident angle θ (between $\mathbf{L}$ and surface normal $\mathbf{N}$). The smaller the angle, the higher the reflection (kind of like bouncing a ball off a wall). The mathematical tool we use to achieve these is to have the reflection proportional to $\cos(\theta)$.

The second case is called *specular reflection.* It attempts to capture the characteristic of a shiny or mirror-like surface. Were the surface in Fig. 11.7(a) a perfect mirror, energy from the light source would be reflected in exactly one direction (the direction of vector $\mathbf{R}$). Since a perfect mirror is nonexistent we want to distribute reflected energy across a small cone-shaped space centered around $\mathbf{R}$, with the reflection being the strongest along the direction of $\mathbf{R}$ (i.e. $\varphi = 0$) and decreasing quickly as φ increases [see the bell-shaped curve in Fig. 11.7(b)]. The mathematical means for modeling this effect is $\cos^k(\varphi)$, where the parameter k provides for a convenient way to vary the degree of shininess ($k = 1$ for a dull surface and $k = 100$ for a mirror-like surface). For a

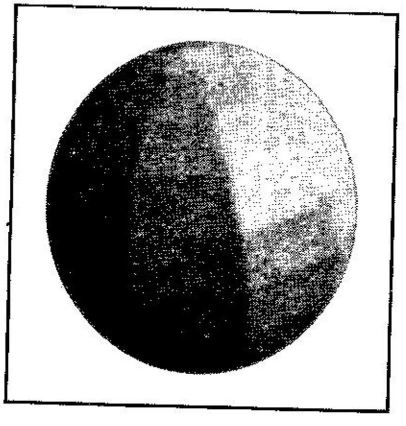
8.4 Shading

Illumination methods we studied in the last section would be used know for rendering process to produce views of virtual 3D scene on 2D screen. Objects in the scene can be curved surface objects or can be polygon surfaces. Each polygon surface can be rendered with a single intensity. The other way can be to obtain intensity at each point of the surface using interpolation scheme. The first way is used mostly for polygons called constant intensity shading or faceted shading or flat shading.

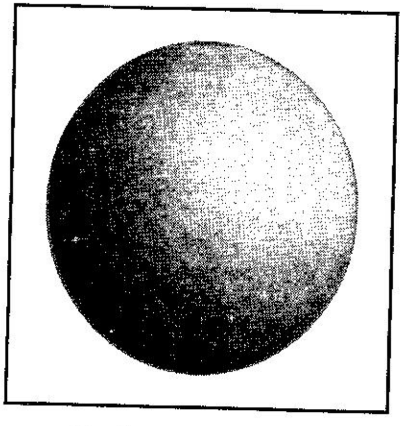
Flat shading determines a single intensity value and use it to shade an entire polygon. This approach is valid provided :

- The light source is at infinity such that N.S is constant over entire face.
- The viewer is at infinity such that N.V is constant over entire face.
- Polygon is not an approximation of a curved surface.

Surface we get after rendering with constant shading is not a smooth surface, infact its a flat surface. So we use Gouraud shading using interpolation scheme. Approximation of an object is rendered with Flat shading and Gouraud shading in fig. 8.31.



(a) Flat shading



(b) Gouraud shading

Fig. 8.31

8.4.1 Gouraud Shading

In this shading method, we calculate intensity value at each point on the polygon surface using interpolation scheme. Then we match these intensity values with intensity values of adjacent polygons along common edges, thus eliminating the intensity discontinuity which we faced in flat shading.

We following the given steps for Gouraud shading :

- First determine the average unit normal vector at each polygon vertex. Average is calculated because the vertex may be shared by other polygons also. So, the unit normal vector at vertex V is given by:

$$\vec{N_V} = \frac{\sum_{K=1}^{n} N_k}{\left|\sum_{K=1}^{n} N_k\right|}$$

where value of $K = 1$ to n (n is the number of surfaces which are in contact with vertex V.)

- Then we use illumination models to calculate intensity at each vertex normal.
- The last step is to interpolate the calculated vertex intensities over the surface of the polygon. For this purpose, scanline algorithm is used. For each scanline, we calculate the intensities at the intersection of scanline with the edges of polygon, through interpolation from intensities at vertex points. This is shown in fig. 8.32. N_1, N_2, N_3 are unit normal vectors at the three vertices of the polygon. I_1, I_2, I_3 are the corresponding calculated intensities.

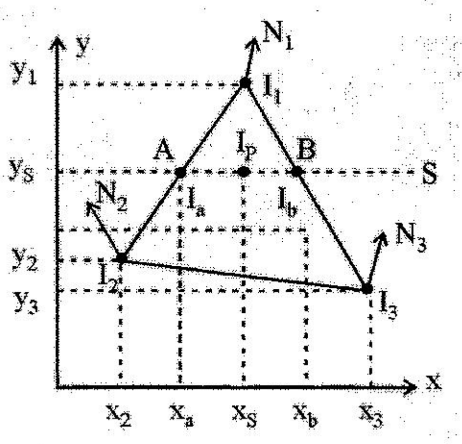


Fig. 8.32

Scanline S intersects the edges of the polygon. To calculate the intensity at A, interpolate the intensities I_1 and I_2.

Thus, $$I_a = I_1 + (I_2 - I_1)\frac{(y_1 - y_s)}{y_1 - y_2}$$

Similarly, intensity at point B can be calculated using intensities I_1 and I_3 as :

$$I_b = I_1 + (I_3 - I_1)\frac{(y_1 - y_s)}{y_1 - y_3}$$

Through the same linear interpolation process, calculate intensity at point P on the scan line S as :

$$I_p = I_b + (I_a - I_b)\frac{(x_b - x_s)}{x_b - x_a}$$

The same way we can calculate intensities for other scan lines over the polygon surface.

Though Gauraud shading removes the discontinuities that were with constant shading method, but it does have disadvantages. We use linear intensity interpolation scheme which causes bright and dark streaks called mach bands to appear on the surface. So we use phong shading in which we divide the surface into number of polygon faces.

8.4.2 Phong Shading

The steps for phong shading are :

- Determine the average unit normal vector at each polygon vertex. This is done in the same way as for Gouraud shading.
- Then instead of interpolation intensities as in Gouraud shading, we interpolate the unit normal vectors at the vertices. This is shown in fig. 8.32.

N_1, N_2, N_3 are the unit normal vectors at the three vertices of the surface.

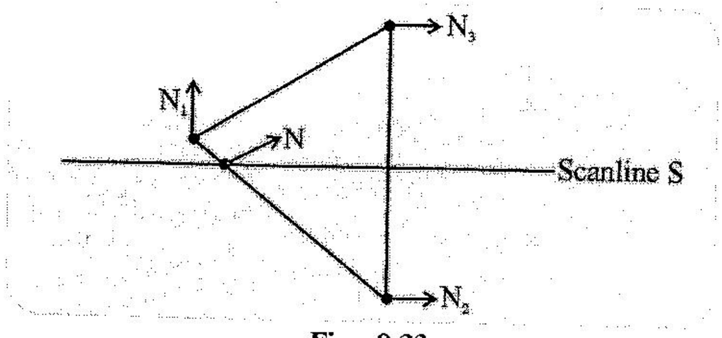


Fig. 8.33

Along the scanline S, we Compute normal vector N through the interpolation of normal vectors N_1 and N_2. The vector N is given by:

$$\vec{N} = \vec{N_1} + (\vec{N_2} - \vec{N_1})\frac{(y_1 - y)}{y_1 - y_2}$$