Unit-7

Color Image Processing

Color fundamentals and Color Models (RGB, CMY, CMYK, HSI, YUV, HSV), model transformation, Colour Slicing, Histogram processing of Colour images.

INTRODUCTION

Colour is the perceptual sensation of light in the visible range incident upon the retina. Colour is the most visually striking feature of any image and it has a significant bearing on the scenic beauty of an image. To understand colour, it is necessary to understand the nature of light. Light exhibits a dual nature. It behaves both as a particle and as a wave. When photons hit the retina, they give rise to electric impulses, which on reaching the brain, are translated into colour. Different wavelengths of light are perceived as different colours. However, not every wavelength can be perceived by the human eye. The wavelengths between 380 nm and 780 nm form the visible spectrum.

Color Fundamentals

Although the process employed by the human brain in perceiving and interpreting color is a physio psychological phenomenon that is not fully understood, the physical nature of color can be expressed on a formal basis supported by experimental and theoretical results.

In 1666, Sir Isaac Newton discovered that when a beam of sunlight passes through a glass prism, the emerging light is not white, but consists instead of a continuous spectrum of colors ranging from violet at one end to red at the other. As Fig. 7.1 shows, the color spectrum may be divided into six broad regions: violet, blue, green, yellow, orange, and red. When viewed in full color (see Fig. 7.2), no color in the spectrum ends abruptly; rather, each color blends smoothly into the next.

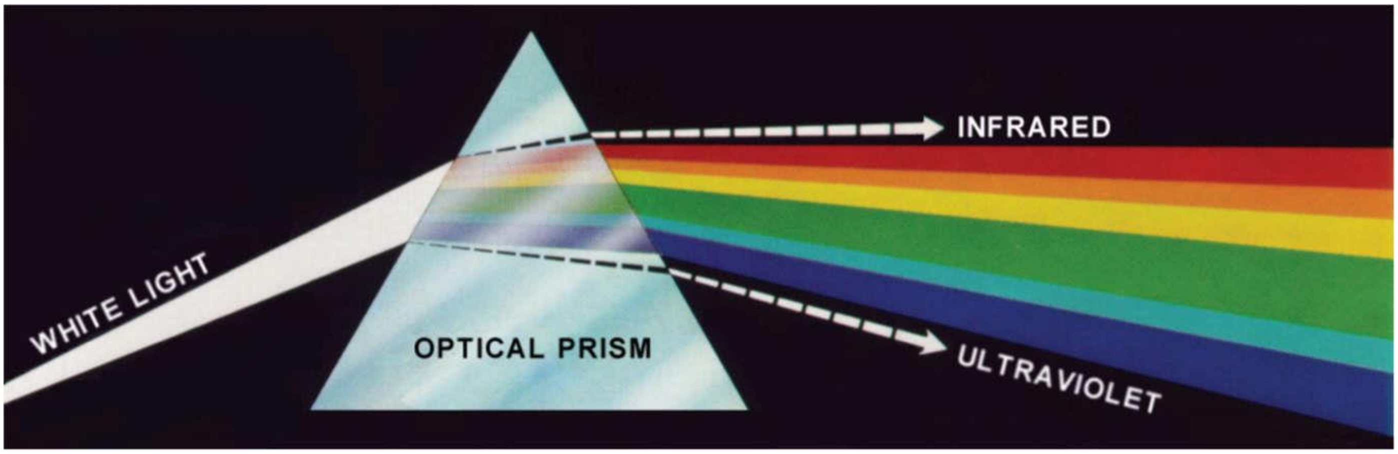

FIGURE 7.1
Color spectrum seen by passing white light through a prism.
(Courtesy of the General Electric Co., Lighting Division.)

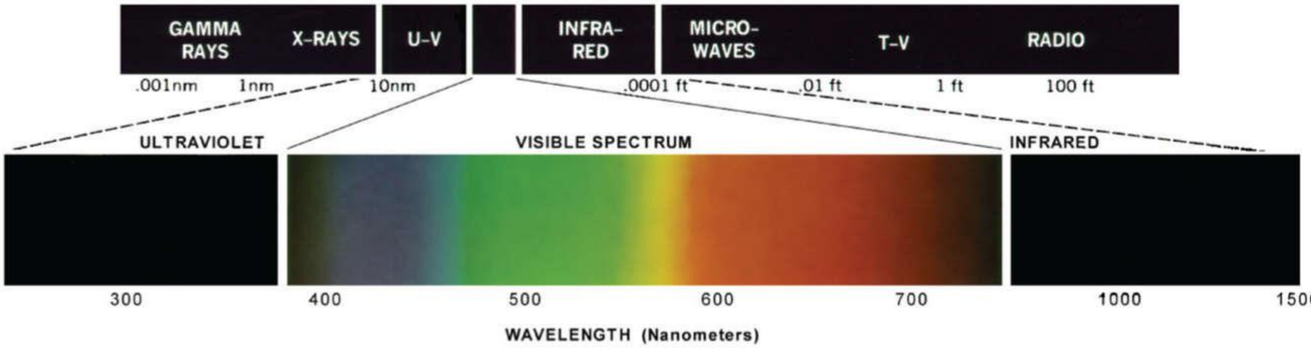

FIGURE 7.2
Wavelengths comprising the visible range of the electromagnetic spectrum.
(Courtesy of the General Electric Co., Lighting Division.)

Basically, the colors that humans and some other animals perceive in an object are determined by the nature of the light reflected from the object. As illustrated in Fig. 7.2, visible light is composed of a relatively narrow band of frequencies in the electromagnetic spectrum. A body that reflects light that is balanced in all visible wavelengths appears white to the observer. However, a body that favors reflectance in a limited range of the visible spectrum exhibits some shades of color. For example, green objects reflect light with wavelengths primarily in the 500 nm to 570 nm range, while absorbing most of the energy at other wavelengths.

Characterization of light is central to the science of color. If the light is *achromatic* (void of color), its only attribute is its *intensity*, or amount. Achromatic light is what you see on movie films made before the 1930s, the term *gray (*or *intensity) level* refers to a scalar measure of intensity that ranges from black, to grays, and finally to white.

Chromatic light spans the electromagnetic spectrum from approximately 400 nm to 700 nm. Three basic quantities used to describe the quality of a chromatic light source are: radiance, luminance, and brightness.

Radiance is the total amount of energy that flows from the light source, and it is usually measured in watts (W). *Luminance*, measured in lumens (lm), is a measure of the amount of energy that an observer *perceives* from a light source. For example, light emitted from a source operating in the far infrared region of the spectrum could have significant energy (radiance), but an observer would hardly perceive it; its luminance would be almost zero. *Brightness* is a subjective descriptor that is practically impossible to measure. It embodies the achromatic notion of intensity, and is one of the key factors in describing color sensation.

Cones are the sensors in the eye responsible for color vision. Detailed experimental evidence has established that the 6 to 7 million cones in the human eye can be divided into three principal sensing categories, corresponding roughly to red, green, and blue. Approximately 65% of all cones are sensitive to red light, 33% are sensitive to green light, and only about 2% are sensitive to blue. However, the blue cones are the most sensitive. **Figure 7.3** shows average experimental curves detailing the absorption of light by the red, green, and blue cones in the eye.

Because of these absorption characteristics, the human eye sees colors as variable combinations of the so-called *primary colors*: *red* (R), *green* (G), and *blue* (B).

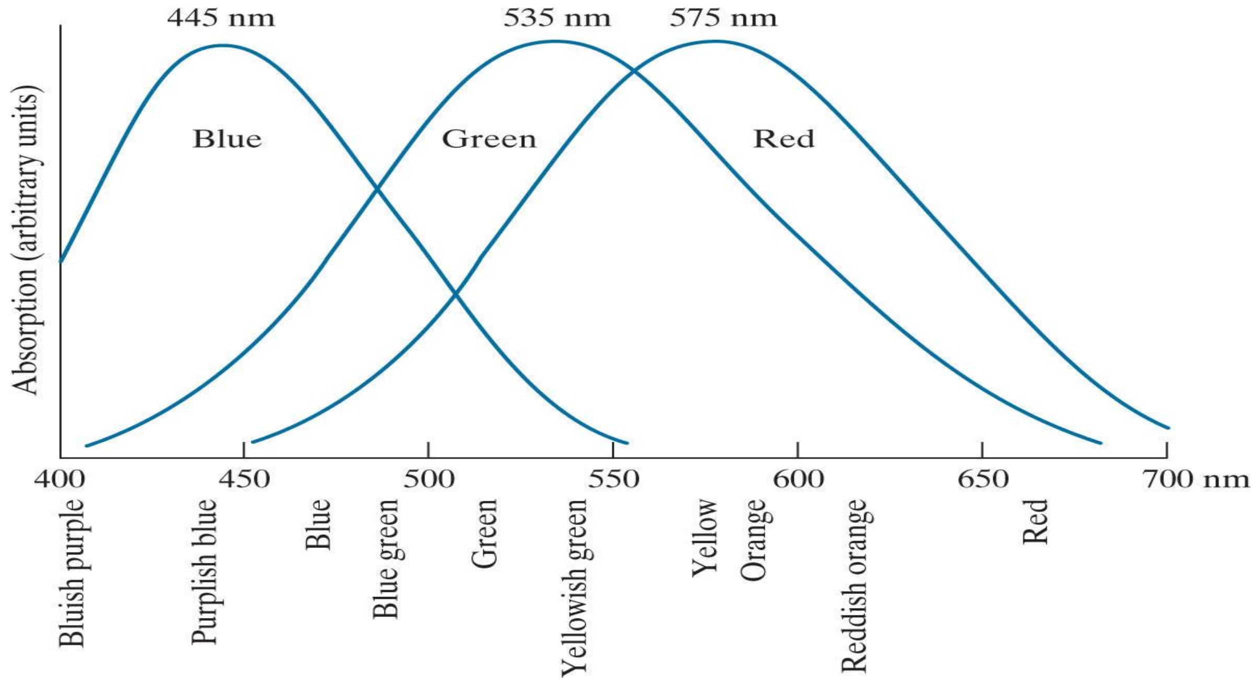

FIGURE 7.3
Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

For the purpose of standardization, the CIE (Commission Internationale del'Eclairage—the International Commission on Illumination) designated in 1931 the following specific wavelength values to the three primary colors: and this standard was set before results such as those in **Fig. 7.3** became available in 1965. Thus, the CIE standards correspond only approximately with experimental data. It is important to keep in mind that defining three specific primary color wavelengths for the purpose of standardization does *not* mean that these three fixed RGB components acting alone can generate all spectrum colors. Use of the word *primary* has been widely misinterpreted to mean that the three standard primaries, when mixed in various intensity proportions, can produce all visible colors.

The primary colors can be added together to produce the *secondary* colors of light—*magenta* (red plus blue), *cyan* (green plus blue), and *yellow* (red plus green). Mixing the three primaries, or a secondary with its opposite primary color, in the right intensities produces white light. This result is illustrated in **Fig. 7.4(a)**, which shows also the three primary colors and their combinations to produce the secondary colors of light.

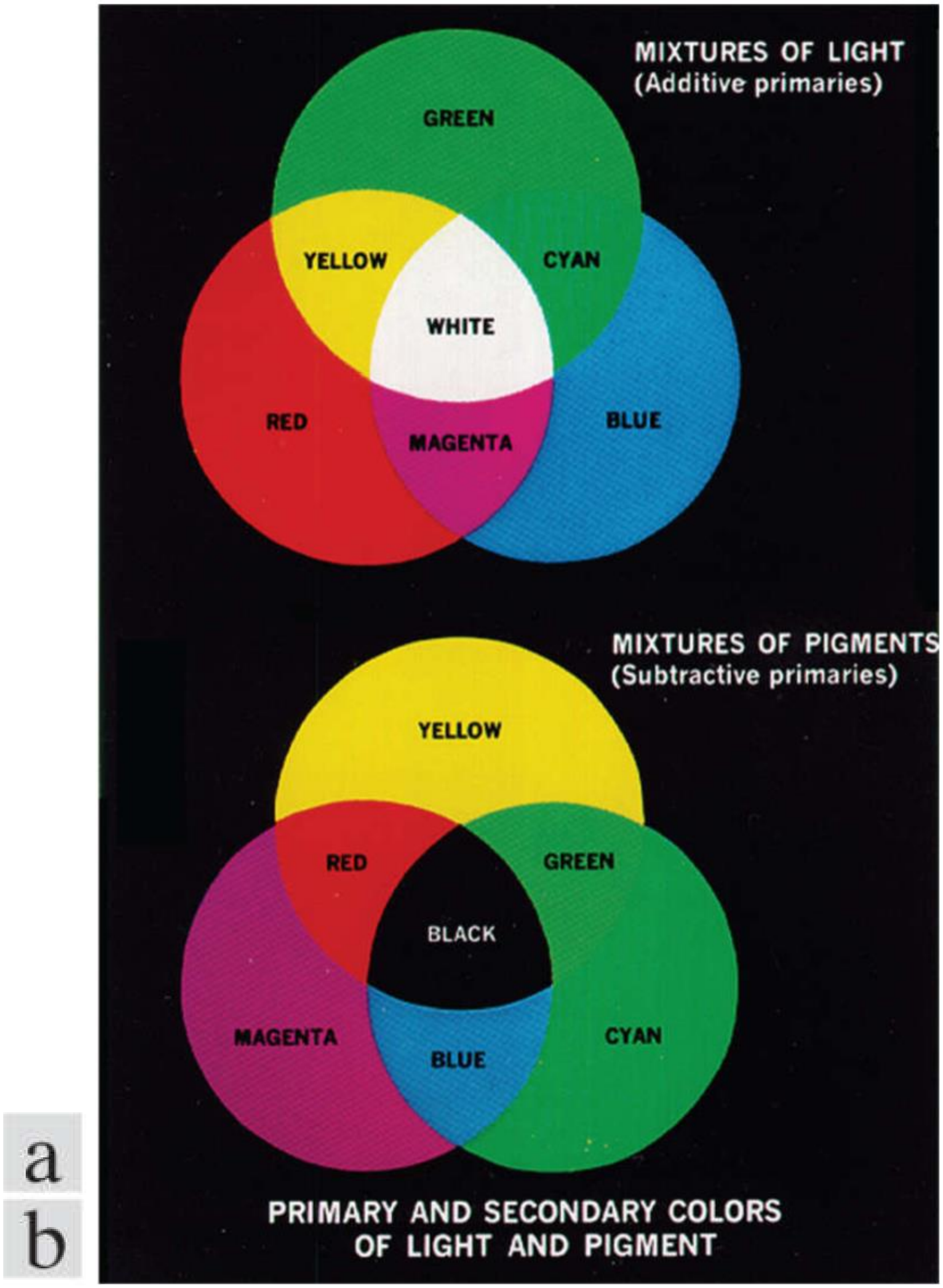

FIGURE 7.4
Primary and secondary colors of light and pigments.
(Courtesy of the General Electric Co., Lighting Division.)

Differentiating between the primary colors of light and the primary colors of pigments or colorants is important. A primary color is defined as one that subtracts or absorbs a primary color of light, and reflects or transmits the other two. Therefore, the primary colors of pigments are magenta, cyan, and yellow, and the secondary colors are red, green, and blue. These colors are shown in Fig. 7.4(b). **A proper combination of the three pigment primaries, or a secondary with its opposite primary, produces black.**

The characteristics generally used to distinguish one color from another are brightness, hue, and saturation.

Brightness embodies the achromatic notion of intensity.

Hue is an attribute associated with the dominant wavelength in a mixture of light waves. Hue represents dominant color as perceived by an observer. Thus, when we call an object red, orange, or yellow, we are referring to its hue.

Saturation refers to the relative purity or the amount of white light mixed with a hue. The pure spectrum colors are fully saturated.

Colors such as pink (red and white) and lavender (violet and white) are less saturated, with the degree of saturation being inversely proportional to the amount of white light added.

Hue and saturation taken together are called *chromaticity* and, therefore, a color may be characterized by its brightness and chromaticity.

The amounts of red, green, and blue needed to form any particular color are called the *tristimulus* values, and are denoted, X, Y, and Z, respectively.

A color is then specified by its *trichromatic coefficients*, defined as

$$x = \frac{X}{X+Y+Z} \tag{7-1}$$

$$y = \frac{Y}{X+Y+Z} \tag{7-2}$$

and

$$z = \frac{Z}{X+Y+Z} \tag{7-3}$$

We see from these equations that

$$x + y + z = 1 \tag{7-4}$$

Our use of x, y, and z in this context follows convention. These should not be confused with our use of (x, y) throughout the book to denote spatial coordinates.

For any wavelength of light in the visible spectrum, the tristimulus values needed to produce the color corresponding to that wavelength can be obtained directly from curves or tables that have been compiled from extensive experimental results (Poynton [1996, 2012]).

Another approach for specifying colors is to use the CIE *chromaticity diagram* (see Fig. 7.5), which shows color composition as a function of ***x* (red) and *y* (green)**. For any value of *x* and *y*, the corresponding value of ***z* (blue)** is obtained from Eq. (7-4) by noting that the point marked green in Fig. 7.5, for example, has approximately 62% green and 25% red content. It follows from Eq. (7-4) that the composition of blue is approximately 13%.

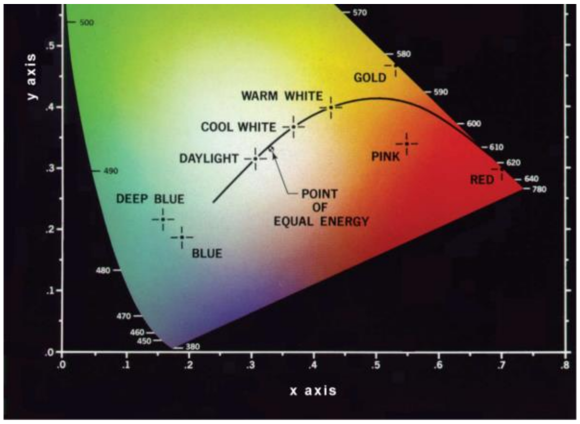

FIGURE 7.5
The CIE chromaticity diagram.
(Courtesy of the General Electric Co., Lighting Division.)

The positions of the various spectrum colors—from violet at 380 nm to red at 780 nm—are indicated around the boundary of the tongue-shaped chromaticity diagram. These are the pure colors shown in the spectrum of Fig. 7.2. Any point not actually on the boundary, but within the diagram, represents some mixture of the pure spectrum colors. The *point of equal energy* shown in Fig. 7.5 corresponds to equal fractions of the three primary colors; it represents the CIE standard for white light. Any point located on the boundary of the chromaticity chart is fully saturated. As a point leaves the boundary and approaches the point of equal energy, more white light is added to the color, and it becomes less saturated. The saturation at the point of equal energy is zero.

COLOUR MODEL

Colour models provide a standard way to specify a particular colour by defining a 3D coordinate system, and a subspace that contains all constructible colours within a particular model. *Any colour can be specified using a model*. Each colour model is oriented towards a specific software or image-processing application.

RGB Colour Model

In an RGB colour model, the three primary colours red, green and blue form the axis of the cube which is illustrated in Fig. 11.2. Each point in the cube represents a specific colour. This model is good for setting the electron gun for a CRT.

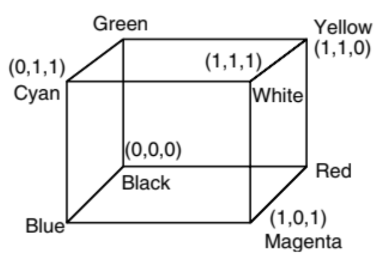

Fig. 11.2 *RGB colour cube*

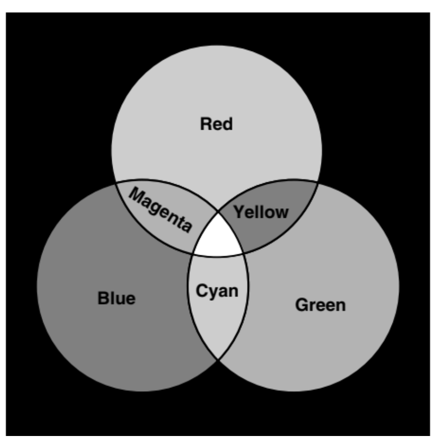

Fig. 11.3 RGB colour model

RGB is an additive colour model. From Fig. 11.3, it is obvious that

Magenta = Red + Blue

Yellow = Red + Green

Cyan = Blue + Green

Limitations of the RGB Model

The limitations of the RGB model are summarised below:

(i) The RGB colour coordinates are device dependent. This implies that the RGB model will not in general reproduce the same colour from one display to another.

(ii) The RGB model is not perceptually uniform. The meaning is that one unit of coordinate distance does not correspond to the same perceived colour difference in all regions of the colour space.

(iii) It is difficult to relate this model to colour appearance because its basis is to device signals and not display luminance values.

CMY Colour Model

CMY is a subtractive colour model. In subtractive color formation, the color is generated by light reflected from its surroundings and the color does not emit any light of its own. In the subtractive colour system, black color is produced by a combination of all the colors. **In subtractive color mixing, white means no color and black is a combination of all colors.** As more colors are added, the result becomes darker and tends towards black. Cyan, magenta and yellow (CMY) colors correspond to primary colors in subtractive color system. The primary colors are added to generate the secondary colors yellow (red + green), cyan (green + blue), magenta (red + blue).

Printers produce an image by reflective light, which is basically a subtractive process. Printers commonly employ the CMY model. In printing, black color is generated by mixing all colors, and, hence, subtractive color method is used. The CMY model cube is illustrated in Fig. 11.6.

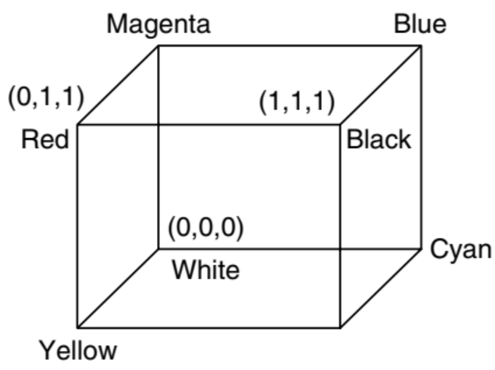

Fig. 11.6 *CMY colour cube*

The conversion between RGB and CMY is done as follows

$$C = 1 - R$$

$$M = 1 - G$$

$$Y = 1 - B$$

From Fig. 11.7, it is obvious that

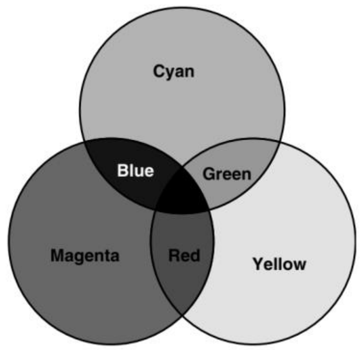

Fig. 11.7 *CMY colour model*

$$\text{Magenta} = \text{White} - \text{Green}$$
$$\text{Cyan} = \text{White} - \text{Red}$$
$$\text{Yellow} = \text{White} - \text{Blue}$$

In the CMY model, a pixel of color cyan, reflects all other RGB colors but red. A pixel with the color of magenta, reflects all other RGB colors but green. Now, if cyan and magenta colors are mixed, blue will be generated, rather than white as in the additive color system.

In the CMY model, the black color generated by combining cyan, magenta and yellow is not very impressive, therefore a new color, black, is added in CMY color model, generating CMYK model. In publishing industry this CMYK model is referred as four-color printing.

HSI Colour Model

HSI stands for Hue, Saturation and Intensity. Hue represents dominant colour as perceived by an observer. It is an attribute associated with the dominant wavelength. Saturation refers to the relative purity or the amount of white light mixed with a hue. Intensity reflects the brightness (or luminance).

HSI decouples the intensity information from the colour, while hue and saturation correspond to human perception, thus making this representation very useful for developing image-processing algorithms. HSI colour space is a popular colour space because it is based on human colour perception. whereas RGB can be described by a three-dimensional cube, the HSI model is represented as a color triangle, as shown in Fig. 2.9.

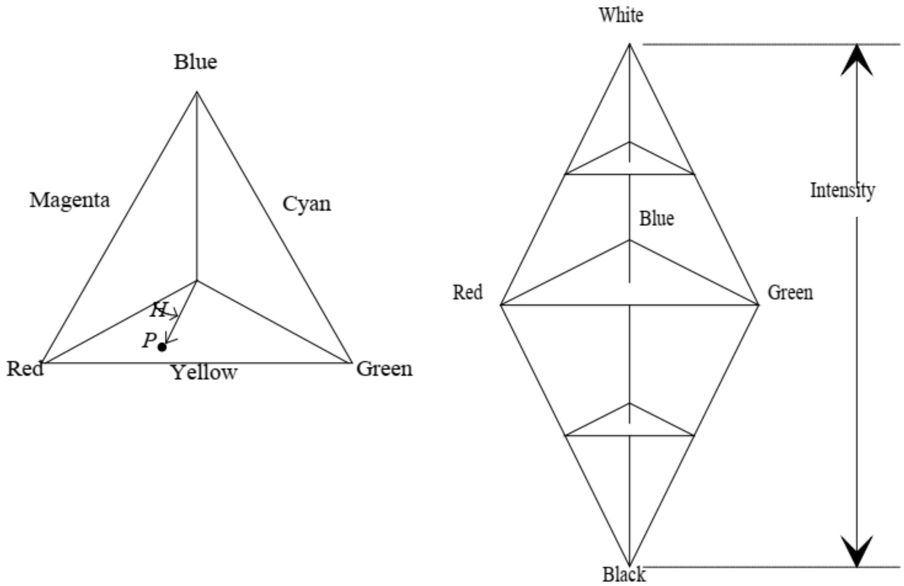

Fig. 2.9. HSI color triangle.

All colors lie inside the triangle whose vertices are defined by the three basic colors, red, green and blue. If a vector is drawn from the central point of the triangle to the color point *P*, then hue (*H*) is the angle of the vector with respect to the red axis. For example, 0º indicates red color, 60º yellow, 120º green, and so on. Saturation (*S*) is the degree to which the color is undiluted by white and is proportional to the distance to the center of the triangle. The RGB to HSI conversion can be performed as follows:

$$H = \frac{1}{360^{o}} \cdot \cos^{-1}\left[\frac{\frac{1}{2}\cdot\left[(R-G)+(R-B)\right]}{\sqrt{(R-G)^{2}+(R-B)(G-B)}}\right], \text{ if } B \le G$$

$$H = 1-\frac{1}{360^{o}} \cdot \cos^{-1}\left[\frac{\frac{1}{2}\cdot\left[(R-G)+(R-B)\right]}{\sqrt{(R-G)^{2}+(R-B)(G-B)}}\right], \text{ otherwise}$$

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

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

The advantages of HSI are:

• The intensity is separated from the color information (similar to YUV and YIQ models).

• The hue and saturation components are intimately related to the way in which human beings perceive color.

The HSV (Hue– Saturation–Value) Color Model

Color models such as the *RGB* and *CMYK* described previously are very convenient to specify color coordinates for display or printing, respectively. They are not, however, useful to capture a typical human description of color. After all, none of us goes to a store looking for a FFFFCC shirt to go with the FFCC33 jacket we got for our birthday. Rather, the human perception of color is best described in terms of hue, saturation, and lightness.

Hue describes the color type, or tone, of the color (and very often is expressed by the "color name"). It can be signified as a point in a 360-degree color circle.

Saturation provides a measure of its purity (or how much it has been diluted in white). This is directly connected to the intensity of the color (range of gray in the color space). It is normally represented in terms of percentage ranging from 0% to 100%. If it is100%, it signifies an intense color presence.

Value also be called brightness and just like saturation it is represented as percentage. The range is from 0% to 100%. Zero represents black and 100 represents the brightest.

For representing colors in a way that is closer to the human description, a family of color models have been proposed. The common aspect among these models is their ability to dissociate the dimension of *intensity* (also called *brightness* or *value*) from the *chromaticity*—expressed as a combination of *hue* and *saturation*—of a color. We will look at a representative example from this family: the *HSV* (hue– saturation–value) color model.

The *HSV* (sometimes called *HSB*) color model can be obtained by looking at the *RGB* color cube along its main diagonal (or *gray axis*), which results in a hexagon shaped color palette. As we move along the main axis in the pyramid in Figure 16.10, the hexagon gets smaller, corresponding to decreasing values of *V*, from 1 (white) to 0 (black).

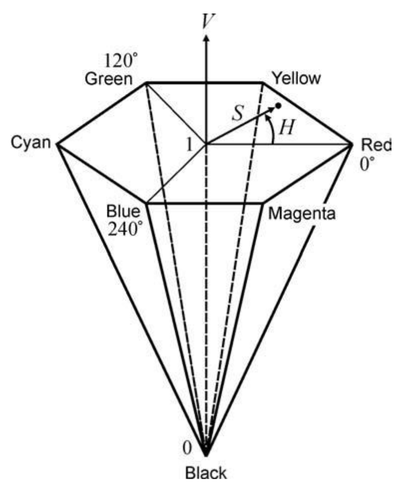

FIGURE 16.10 The HSV color model as a hexagonal cone.

For any hexagon, the three primary and the three secondary colors of light are represented in its vertices. Hue, therefore, is specified as an angle relative to the origin (the red axis by convention). Finally, saturation is specified by the distance to the axis: the longer the distance, the more saturated the color.

YUV model

In the YUV color model, Y is luminance and U and V represent chrominance or color information. The YUV color model is based on color information along with brightness information.

Thus, people also refer to this color model as the luminance/chrominance color system. In this model, the luminosity of the given color is detached and the hue (color) is determined. The luminosity data goes into the Y channel, whereas U and V carries different content. The U channel is created after subtracting the Y from the amount of blue in the given image. Concerning V, this channel is created by subtracting the amount of red from Y.

YUV is one of the color encoding systems and is mostly used in the color image pipeline (i.e., components used between an image source [for example, a camera] and image renderer [any display device]). YUV is an alternate option for the traditional RGB in display systems and is one of the efficient options in an image processing application where displays are involved.

In this color encoding scheme, the transmission errors are said to be reduced compared to the traditional RGB scheme. YUV standards have been globally accepted and products in the market almost are mostly in favor of YUV standards. Hence, this color model overtakes the rest of the schemes.

The standard formula to derive the YUV from RGB is:

$Y = 0.299R + 0.587G + 0.114B$, where R is red, G is green, B is blue.

$U = 0.492\ (B - Y)$, where B is blue, Y is yellow.

$V = 0.877\ (R - Y)$, where R is red, Y is yellow.

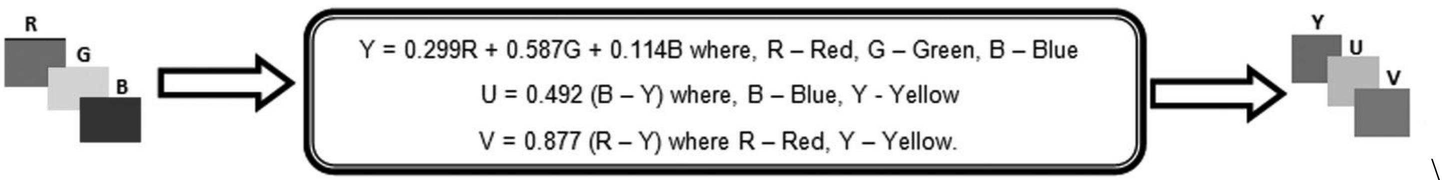

FIGURE: RGB to YUV conversion.

The luminance component can be considered as a grayscale version of the RGB image. There are certain advantages of YUV compared to RGB, which are:

• The brightness information is separated from the color information.

• The correlations between the color components are reduced.

• Most of the information is in the *Y* component, while the information content in the *U* and *V* is less.

The latter two properties are very useful in various applications, such as image compression. This is because the correlations between the different color components are reduced, thus, each of the components can be compressed separately. Besides that, more bits can be allocated to the *Y* component than to *U* and *V*. The YUV color system is adopted in the JPEG image compression standard.

Model Transformation

The techniques described in this section, collectively called *color transformations*, deal with processing the components of a color image within the context of a *single* color model, as opposed to color transformations *between* color models.

Formulation

Color transformations for multispectral images using the general expression

$$s_i = T_i(r_i) \qquad i = 1, 2, \ldots, n \tag{7.38}$$

where n is the total number of component images, r_i are the intensity values of the input component images, s_i are the spatially corresponding intensities in the output component images, and T_i are a set of *transformation* or *color mapping functions* that operate on r_i to produce s_i. Equation (7-38) is applied individually to all pixels in the input image. For example, in the case of RGB color images, $n = 3, r_1, r_2, r_3$ are the intensities values at a point in the input components images, and s_1, s_2, s_3 are the corresponding transformed pixels in the output image. The fact that *i* is also a subscript on *T* means that, in principle, we can implement a different transformation for each input component image.

As an illustration, the first row of Fig. 7.28 shows a full color CMYK image of a simple scene, and the second row shows its four component images, all normalized to the range [0, 1]. We see that the strawberries are composed of large amounts of magenta and yellow because the images corresponding to these two CMYK components are the brightest. Black is used sparingly and is generally confined to the coffee and shadows within the bowl of strawberries. The fourth row shows the equivalent RGB images obtained from the CMYK images using Eqs. (7-13) -(7-15) . Here we see that the strawberries contain a large amount of red and very little (although some) green and blue. From the RGB images, we obtained the CMY images in the third row using Eq. (7-5) . Note that these CMY images are slightly different from the CMY images in the row above them. This is because the CMY images in these two systems are different as a result of using K in one of them. The last row of Fig. 7.28 shows the HSI components, obtained from the RGB images using Eqs. (7-16) -(7-19) . As expected, the intensity (I) component is a grayscale rendition of the full-color original. The saturation image (S) is as expected also. The strawberries are relatively pure in color; as a result, they show the highest saturation (least dilution by white light) values of any of the other elements of the image. Finally, we note some difficulty in interpreting the values of the hue (H) component image. The problem is that (1) there is a discontinuity in the HSI model where $0°$ and $360°$ meet [see Fig. 7.13(a)], and (2) hue is undefined for a saturation of 0 (i.e., for white, black, and pure grays). The discontinuity of the model is most apparent around the strawberries, which are depicted in gray level values near both black (0) and white (1). The result is an unexpected mixture of highly contrasting gray levels to represent a single color—red.

FIGURE 7.28

A full-color image and its various color-space components.

(Original image courtesy of MedData Interactive.)

We can apply Eq. (7-38) to any of the color-space component images in Fig. 7.28 . In theory, any transformation can be performed in any color model. In practice, however, some operations are better suited to specific models. For a given transformation, the effects of converting between representations must be factored into the decision regarding the color space in which to implement it. For example, suppose that we wish to modify the intensity of the full-color image in the first row of Fig. 7.28 by a constant value, k in the range [0, 1]. In the HSI color space we need to modify only the intensity component image:

$$s_3 = kr_3 \tag{7-39}$$

and we let $s_1 = r_1$ and $s_2 = r_2$. In terms of our earlier discussion note that we are using two different transformation functions: T_1 and T_2 are identity transformations, and T_3 is a constant transformation.

In the RGB color space we need to modify all three components by the same constant transformation:

$$s_i = kr_i \qquad i = 1, 2, 3 \tag{7-40}$$

The CMY space requires a similar set of linear transformations (see Problem 7.16):

$$s_i = kr_i + (1 - k) \qquad i = 1, 2, 3 \tag{7-41}$$

Similarly, the transformations required to change the intensity of the CMYK image is given by

$$s_i = \begin{cases} r_i & i = 1, 2, 3 \\ kr_i + (1 - k) & i = 4 \end{cases} \tag{7-42}$$

This equation tells us that to change the intensity of a CMYK image, we only change the fourth (K) component.

Figure 7.29(b) shows the result of applying the transformations in Eqs. (7-39) through (7-42) to the full-color image of Fig. 7.28 , using $k = 0.7$. The mapping functions themselves are shown graphically in Figs. 7.29(c) through (h). Note that the mapping function for CMYK consist of two parts, as do the functions for HSI; one of the transformations handles one component, and the other does the rest. Although we used several different transformations, the net result of changing the intensity of the color by a constant value was the same for all.

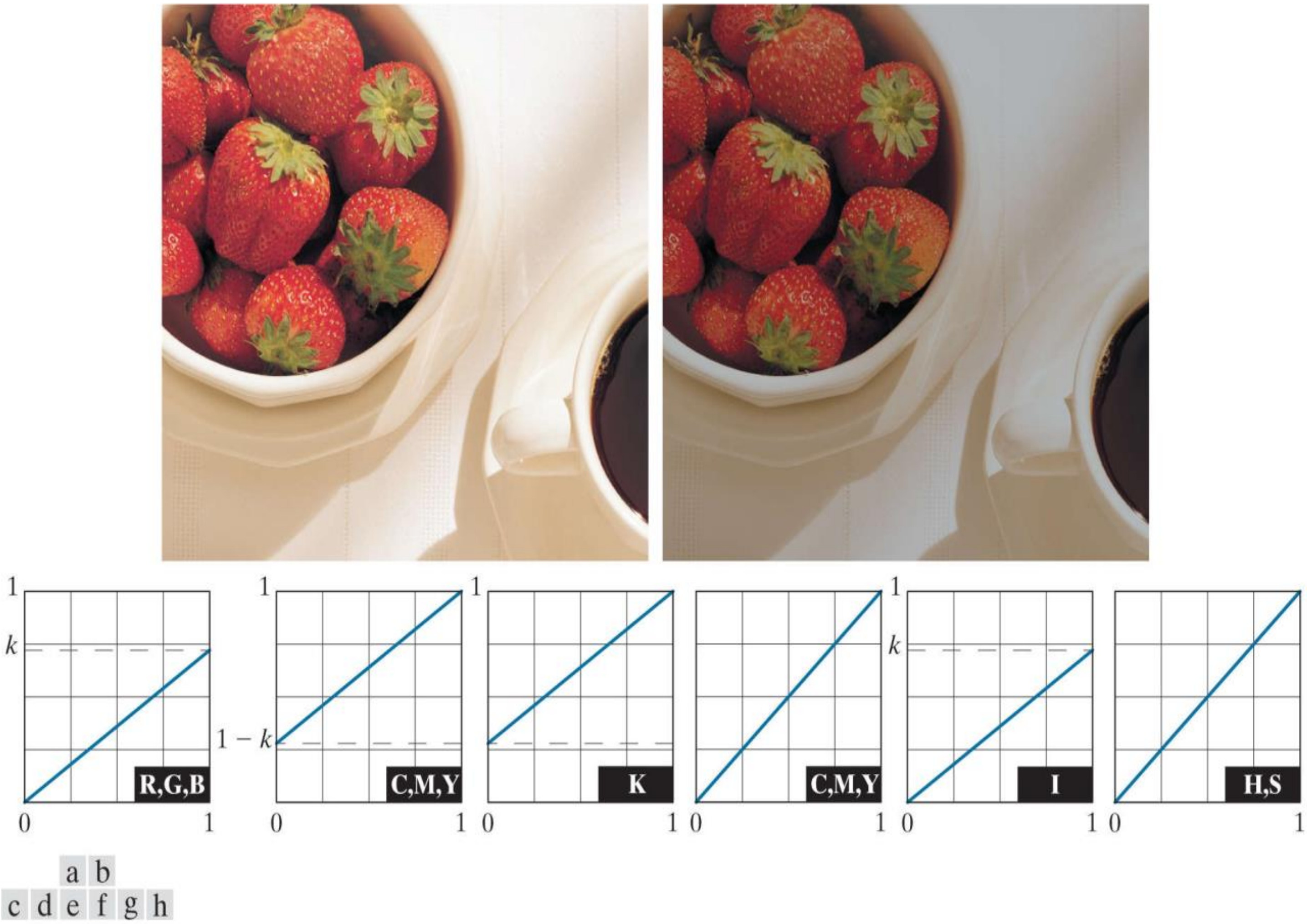

FIGURE 7.29

Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c) The required RGB mapping function. (d)–(e) The required CMYK mapping functions. (f) The required CMY mapping function. (g)–(h) The required HSI mapping functions.

(Original image courtesy of MedData Interactive.)

It is important to note that each transformation defined in **Eqs. (7-39)** through **(7-42)** depends only on one component within its color space. For example, the red output component, s_1, in **Eq. (7-40)** is independent of the green (r_2) and blue (r_3) inputs; it depends only on the red (r_1) input. Transformations of this type are among the simplest and most frequently used color processing tools. They can be carried out on a per-color-component basis, as mentioned at the beginning of our discussion. In the remainder of this section, we will examine several such transformations and discuss a case in which the component transformation functions are dependent on all the color components of the input image and, therefore, cannot be done on an individual color-component basis.

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