

Module 4

4.1 Color Fundamentals :

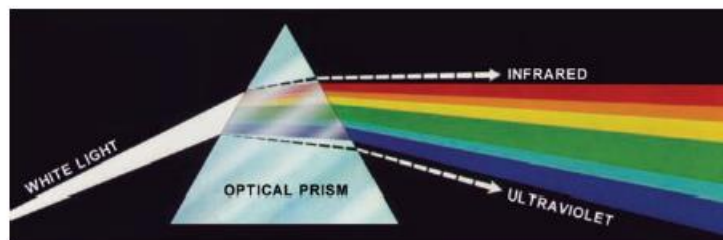
Although the process employed by the human brain in perceiving and interpreting color is a physiopsychological phenomenon that is not fully understood, the physical nature of color can be expressed on a formal basis supported by experimental and theoretical results.

In 1666, Sir Isaac Newton discovered that,

- **White light** through a **glass prism** separates into a **continuous spectrum** of colors: **Violet, Blue, Green, Yellow, Orange, Red**
 - Color transitions are **smooth**; no abrupt boundaries.

FIGURE 6.1

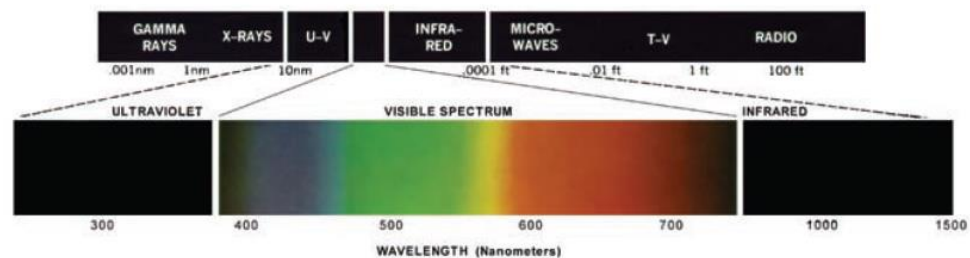
Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lighting Division.)



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. 6.2, 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 to 570 nm range, while absorbing most of the energy at other wavelengths.

FIGURE 6.2

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



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 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).

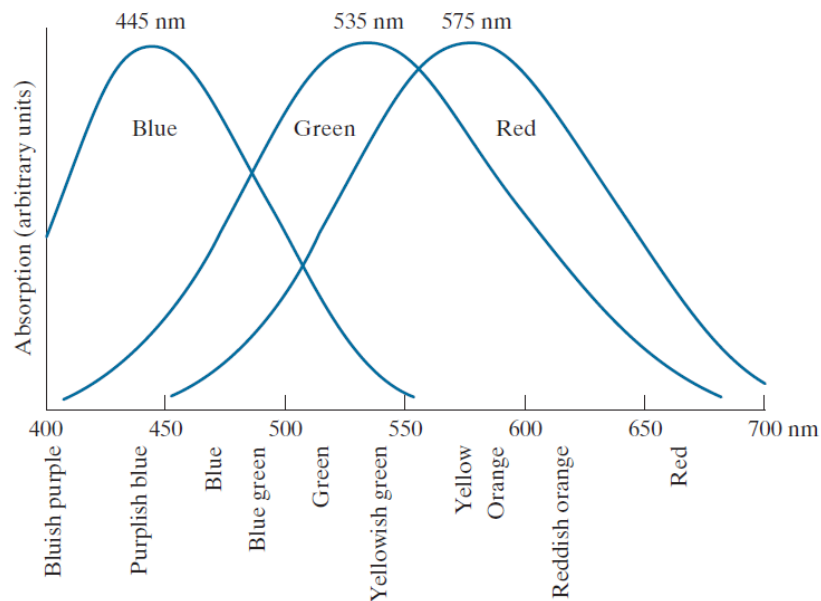
Luminance, measured in lumens (lm), is a measure of the amount of energy that an observer *perceives* from a light source. For example, light emitted from a source operating in the far infrared region of the spectrum could have significant energy (radiance), but an observer would hardly perceive it; its luminance would be almost zero.

Finally, *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 6.3 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 6.3

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:

blue = 435.8 nm,

green = 546.1 nm, and

red = 700 nm.

The CIE standards correspond only approximately with experimental data.

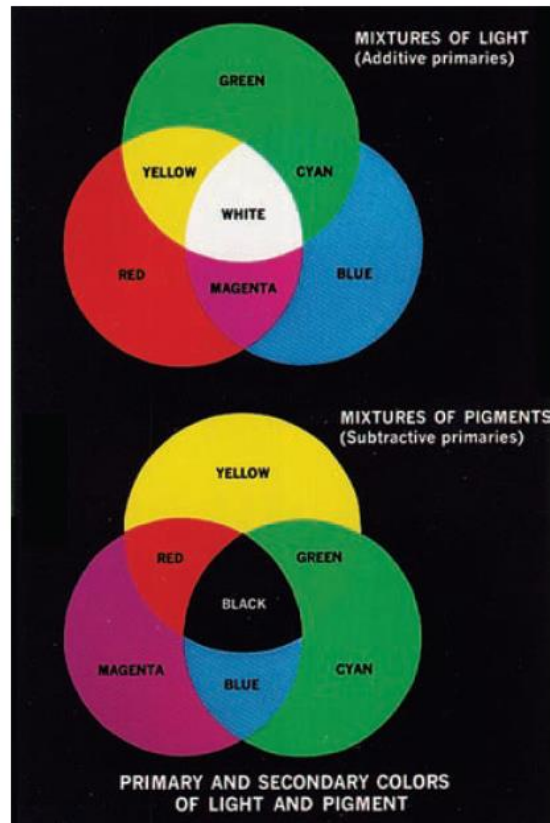
The primary colors can be added together to produce the *secondary* colors of light—*magenta* (red plus blue), *cyan* (green plus blue), and *yellow* (red plus green). Mixing the three primaries, or a secondary with its opposite primary color, in the right intensities produces white light. This result is illustrated in Fig. 6.4(a), which shows also the three primary colors and their combinations to produce the secondary colors of light.

Differentiating between the primary colors of light and the primary colors of pigments or colorants is important. In the latter, 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. 6.4(b). A proper combination of the three pigment primaries, or a secondary with its opposite primary, produces black.

a
b

FIGURE 6.4

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



Color television reception is an example of the additive nature of light colors.

- **CRT Displays:** Use **phosphor triads (R, G, B)** modulated by electron beams.
- **LCDs:** Use **polarized light, TFTs, and color filters.**
- **Plasma:** Use **gas cells** coated with RGB phosphors.

All use **additive RGB light mixing** to produce full-color images.

The characteristics generally used to distinguish one color from another are brightness, hue, and saturation. As indicated earlier in this section, 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

$$x = \frac{X}{X + Y + Z} \quad (6-1)$$

$$y = \frac{Y}{X + Y + Z} \quad (6-2)$$

and

$$z = \frac{Z}{X + Y + Z} \quad (6-3)$$

We see from these equations that

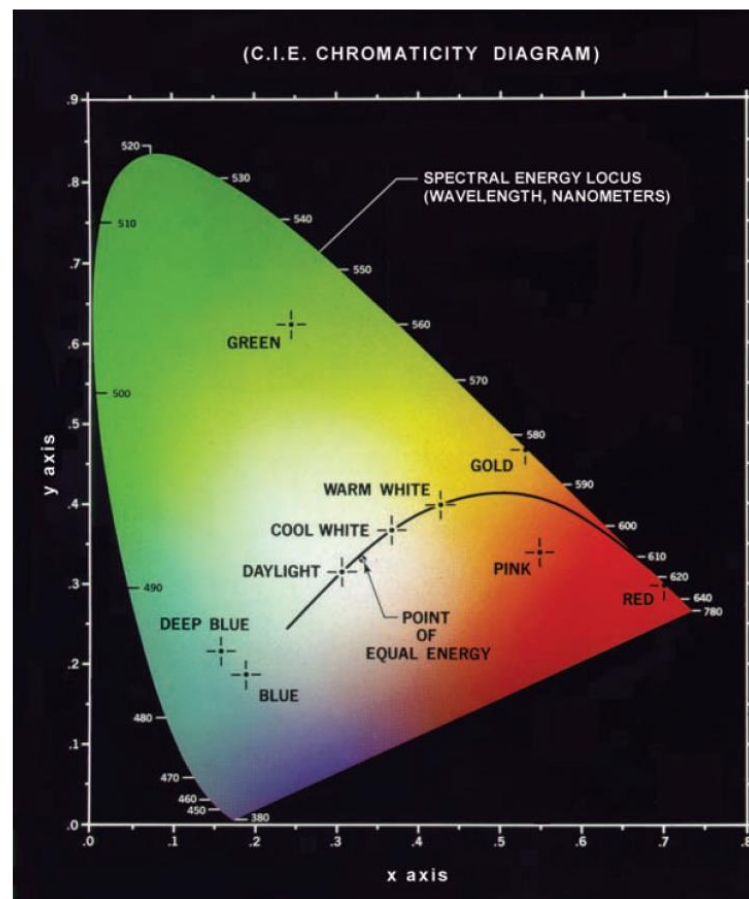
$$x + y + z = 1 \quad (6-4)$$

Another approach for specifying colors is to use the CIE *chromaticity diagram*.

The chromaticity diagram is useful for color mixing because a straight-line segment joining any two points in the diagram defines all the different color variations that can be obtained by combining these two colors additively. Consider, for example, a straight line drawn from the red to the green points shown in Fig. 6.5. If there is more red than green light, the exact point representing the new color will be on the line segment, but it will be closer to the red point than to the green point. Similarly, a line drawn from the point of equal energy to any point on the boundary of the chart will define all the shades of that particular spectrum color.

FIGURE 6.5

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



- Plots **x (red)** vs **y (green)**.
- **z (blue)** is computed as:

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

- The **boundary** of the diagram = **pure spectrum colors (fully saturated)**.
- **Interior points** = **mixtures**.
- **Point of equal energy** = white ($x \approx y \approx z \approx 1/3$).

A triangle connecting three RGB points = color gamut.
Not all visible colors can be reproduced by 3 fixed primaries.

4.2 Color Models

A color model is a specification of

- (1) a coordinate system, and
- (2) a subspace within that system, such that each color in the model is represented by a single point contained in that subspace.

The purpose of a *color model* (also called a *color space* or *color system*) is to facilitate the specification of colors in some standard way.

Most color models in use today are oriented either toward hardware (such as for color monitors and printers) or toward applications, where color manipulation is a goal (the creation of color graphics for animation is an example of the latter). In terms of digital image processing, the hardware-oriented models most commonly used in practice are the **RGB (red, green, blue) model** for color monitors and a broad class of color video cameras;

the **CMY (cyan, magenta, yellow)** and **CMYK (cyan, magenta, yellow, black) models** for color printing;

and the **HSI (hue, saturation, intensity) model**, which corresponds closely with the way humans describe and interpret color. The HSI model also has the advantage that it decouples the color and gray-scale information in an image, making it suitable for many of the gray-scale techniques.

This is a reflection of the fact that color science is a broad field that encompasses many areas of application.

In summary :

The **RGB** model, comprising red, green, and blue components, is an **additive** model primarily used in **monitors and cameras**. It creates colors by combining light, where the mixture of all three at full intensity produces white. In contrast, the **CMY** model—made up of cyan, magenta, and yellow—is **subtractive** and commonly used in **color printers**. It operates by absorbing (subtracting) specific wavelengths of light. The **CMYK** model extends CMY by adding **black (K)** to enhance **depth and contrast** in **high-quality printing**. Lastly, the **HSI** model—composed of **hue, saturation, and intensity**—is a **perceptual** model designed to mirror the way humans perceive and describe color. It is widely used in **image analysis and enhancement** because it **decouples chromatic (color) and achromatic (intensity) information**, allowing separate processing of each. These models reflect the varied needs of visualization, printing, and image interpretation in digital imaging systems.

4.2.1 RGB Model

The **RGB color model** represents colors as combinations of the three **primary spectral components**:

- **R**: Red
- **G**: Green
- **B**: Blue

It is based on a **Cartesian coordinate system** forming a **3D color cube**:

- Axes: R, G, B
- Origin $[0, 0, 0]$ = **Black**
- Opposite corner $[1, 1, 1]$ (or $[255, 255, 255]$) = **White**
- **Secondary colors**:
 - Cyan ($G + B$)
 - Magenta ($R + B$)
 - Yellow ($R + G$)
- **Grayscale line**: Extends from black to white (points with equal $R = G = B$)

Normalization

- For theoretical analysis, RGB values are normalized to range **$[0, 1]$**
- In digital images, values are scaled to **$[0, 255]$** for 8-bit images

RGB in Digital Images

- Each color image in RGB is made up of **three component images** (Red, Green, Blue channels)
- These combine on an RGB display to produce the full color image

Pixel Depth

- The **pixel depth** refers to the total number of bits used to represent each pixel
 - Example: If each channel uses **8 bits**, then:
 - Total depth = $3 \times 8 = 24$ bits
 - Also called a **full-color image**
- **Total number of representable colors in 24-bit RGB =**

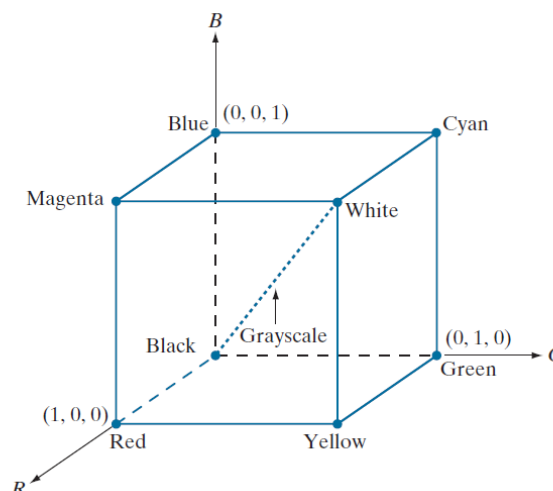
$$(2^8)^3 = 256^3 = \boxed{16,777,216}$$

Vector Representation

- RGB primaries can be treated as **unit vectors** from the origin
- Any color is represented by a **vector within or on the surface** of the RGB cube

FIGURE 6.7

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



4.2.2 THE CMY AND CMYK COLOR MODELS

CMY Color Model :

- **CMY** stands for **Cyan, Magenta, Yellow** – the **primary colors of pigments**.
- These are also the **secondary colors of light**:
 - Cyan = Green + Blue (removes red)
 - Magenta = Red + Blue (removes green)
 - Yellow = Red + Green (removes blue)
- Used in **color printing** and **photographic systems**.
- Operates on a **subtractive color principle**: pigments **absorb (subtract)** light rather than emit it.

Conversion from RGB to CMY

- Based on normalized values in range [0, 1]
- Equation:

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

- Example: If $R = 0.2$, then $C = 1 - 0.2 = 0.8$
- This implies:
 - $C = 1 - R$
 - $M = 1 - G$
 - $Y = 1 - B$

Conversion from CMY to RGB

- Simple inverse of above:

$$R = 1 - C, \quad G = 1 - M, \quad B = 1 - Y$$

CMYK Color Model :

In theory:

$$C + M + Y = \text{Black}$$

In practice: CMY inks **are not pure**, and combining them gives **muddy brown**.

Solution: **Add black (K)** to improve depth and sharpness – especially for text and dark areas.

It is Used in **high-quality color printing** (magazines, books, packaging).

Conversion from CMY to CMYK:

1. First compute:

$$K = \min(C, M, Y)$$

2. Then:

- If $K = 1$ (pure black):

$$C = M = Y = 0$$

- Else:

$$C = \frac{C - K}{1 - K}, \quad M = \frac{M - K}{1 - K}, \quad Y = \frac{Y - K}{1 - K}$$

Conversion from CMYK to CMY

$$C = C \cdot (1 - K) + K$$

$$M = M \cdot (1 - K) + K$$

$$Y = Y \cdot (1 - K) + K$$

It is important to keep in mind that all the conversions just presented to go between RGB, CMY, and CMYK are based on the preceding relationships as a group. There are many other ways to convert between these color models, so you cannot mix approaches and expect to get meaningful results. Also, colors seen on monitors generally appear much different when printed, unless these devices are calibrated. The same holds true in general for colors converted from one model to another.

4.2.3 HSI COLOR MODEL

RGB/CMY/CMYK models are good for hardware and image generation. the RGB system matches nicely with the fact that the human eye is strongly perceptive to red, green, and blue primaries.

Unfortunately, the RGB, CMY, and other similar color models are not well suited for describing colors in terms that are practical for human interpretation. For example, one does not refer to the color of an automobile by giving the percentage of each of the primaries composing its color. Furthermore, we do not think of color images as being composed of three primary images that combine to form a single image.

HSI is better for human perception:

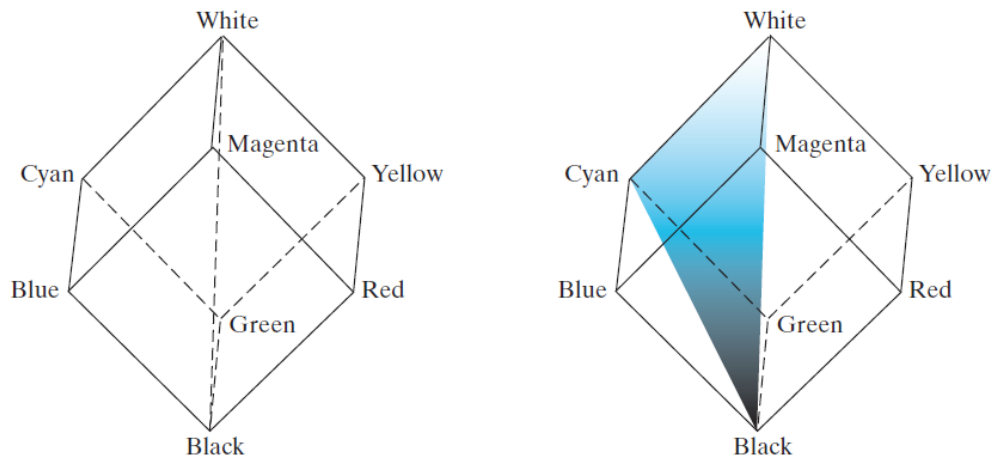
- Humans describe colors by **hue**, **saturation**, and **brightness**.

HSI **decouples intensity** from color, making it intuitive for tasks like **image segmentation**, **region detection**, and **color-based filtering**.

The HSI model is a useful tool for developing image processing algorithms based on color descriptions that are natural and intuitive to humans, who, after all, are the developers and users of these algorithms.

a b

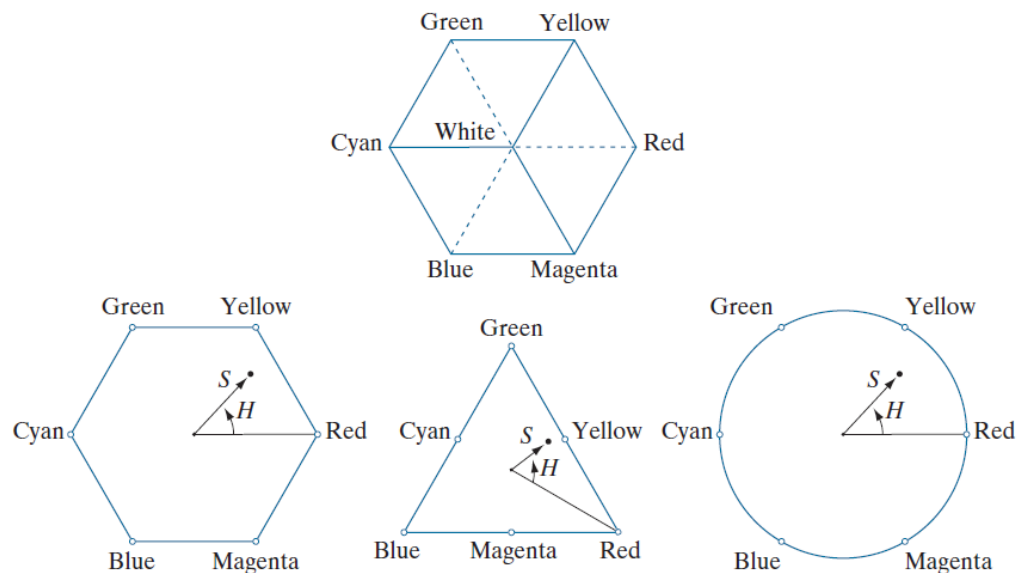
FIGURE 6.10
Conceptual relationships between the RGB and HSI color models.



The key point regarding the cube arrangement in Fig. 6.10, and its corresponding HSI color space, is that the HSI space is represented by a vertical intensity axis, and the locus of color points that lie on planes perpendicular to that axis. As the planes move up and down the intensity axis, the boundaries defined by the intersection of each plane with the faces of the cube have either a triangular or a hexagonal shape. This can be visualized much more readily by looking at the cube straight down its grayscale axis, as shown in Fig. 6.11(a). We see that the primary colors are separated by 120° . The secondary colors are 60° from the primaries, which means that the angle between secondaries is 120° also. Figure 6.11(b) shows the same hexagonal shape and an arbitrary color point (shown as a dot). The hue of the point is determined by an angle from some reference point. Usually (but not always) an angle of 0° from the red axis designates 0 hue, and the hue increases counterclockwise from there. The saturation (distance from the vertical axis) is the length of the vector from the origin to the point.

a
b c d

FIGURE 6.11
Hue and saturation in the HSI color model. The dot is any color point. The angle from the red axis gives the hue. The length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.



RGB to HSI Conversion :

Hue (H):

- Angle on a hexagonal color wheel (typically from red axis).
- Defined in degrees $[0^\circ, 360^\circ]$, but normalized to $[0, 1]$ for digital use.
- Equation:

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

Then:

$$H = \begin{cases} u, & \text{if } B \leq G \\ 360^\circ - u, & \text{if } B > G \end{cases}$$

Normalize by dividing by 360° .

Saturation (S):

- Purity of the color.
- Equation:

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

(if $R + G + B = 0$, set $S = 0$)

Intensity (I):

- Average brightness.
- Equation:

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

Assumptions:

- R, G, B must be **normalized to [0, 1]**.

HSI to RGB Conversion

Divide hue range into 3 sectors:

1. RG sector ($0^\circ \leq H < 120^\circ$):

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

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

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

2. **GB sector** ($120^\circ \leq H < 240^\circ$): Subtract 120° from H :

$$H = H - 120^\circ$$

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

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

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

3. **BR sector** ($240^\circ \leq H \leq 360^\circ$): Subtract 240° from H :

$$H = H - 240^\circ$$

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

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

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

Manipulating HSI Components

Changes are done **independently** in HSI space and then converted back to RGB.

- **Modify hue:** changes color tone (e.g., red to blue).
- **Modify saturation:** affects purity; reduces color vividness.
- **Modify intensity:** affects brightness; controls shading.

This independent control is useful in tasks like:

- **Highlighting specific regions**
- **Color correction**
- **Filtering based on hue or brightness**

Visualization & Geometry

- **Intensity axis** = vertical from black (0,0,0) to white (1,1,1).
- **Hue:** determined by angle from red axis in the color hexagon.
- **Saturation:** radial distance from intensity axis.
- Planes perpendicular to the intensity axis define constant intensity.

4.2.4 Device-Independent Color Model

Humans are capable of perceiving a wide spectrum of colors and subtle color variations. However, color perception varies from person to person, making it inherently subjective. Additionally, devices such as monitors, printers, scanners, and cameras often produce colors differently unless they are properly calibrated. These inconsistencies create a need for a device-independent approach to color representation.

Today's digital imaging systems, which include personal computers equipped with software, digital cameras, flatbed scanners, and inkjet printers, can act as a "digital darkroom." These systems allow users to perform color transformations and image enhancements directly. Commercial calibration tools—using spectrometers and specialized software—can measure and generate device-specific color profiles. These profiles help calibrate monitors and printers to achieve more accurate color reproduction.

For consistent color representation across different devices, it is essential to maintain color fidelity from one device to another, especially when transformations are created on screens and then printed. A device-independent color model ensures uniformity by relating the color gamuts of different devices to one another. The **CIE L*a*b*** model (also known as **CIELAB**) is widely used for this purpose. Its success relies on both the quality of the model and the accuracy of the color profiles used.

The CIE L*a*b* color model was introduced by the Commission Internationale de l'Éclairage (CIE) and has become a standard in many color management systems. It is designed to be **colorimetric**, meaning it represents colors in a way that matches human visual perception. It is also **perceptually uniform**, meaning that the perceived difference between colors is consistent across the spectrum. Most importantly, it is **device-independent**, meaning it provides a universal standard not tied to any specific hardware.

In the CIELAB model, the color components are represented by L^* , a^* , and b^* . The L^* component corresponds to **lightness** (intensity), the a^* component represents the **red–green axis**, and the b^* component represents the **yellow–blue axis**. These components are calculated using specific equations that normalize the tristimulus values (X , Y , Z) with respect to a reference white point (usually under CIE standard D65 illumination).

The formulas are as follows:

- $L^* = 116 \cdot h(Y/Y_W) - 16$
- $a^* = 500 \cdot [h(X/X_W) - h(Y/Y_W)]$
- $b^* = 200 \cdot [h(Y/Y_W) - h(Z/Z_W)]$

The function $h(q)$ is defined piecewise:

- If $q > 0.008856$, then $h(q) = q^{1/3}$
- If $q \leq 0.008856$, then $h(q) = 7.787 \cdot q + \frac{16}{116}$

The reference white values X_W , Y_W , Z_W typically represent the white point of a perfectly reflecting diffuser under standard illumination. These values are used to normalize the XYZ inputs and convert them into L*a*b* space.

Although the $L^*a^*b^*$ color space is not directly displayable on monitors or printers, it includes the **entire visible color spectrum**. Thus, any color from any input or output device can be represented within it. For practical use, the colors must be converted into displayable spaces like RGB or CMYK. Despite this, $L^*a^*b^*$ remains one of the most powerful models for **color correction, manipulation, and analysis**.

A significant advantage of the $L^*a^*b^*$ model is its ability to **separate lightness from color information**, a feature it shares with the HSI model. However, studies show that $L^*a^*b^*$ provides a **greater separation between lightness and chromaticity** than other models. This makes it particularly valuable for tasks like **image compression, tone correction, and color editing**, where manipulating intensity independently from color is beneficial.

Calibrated imaging systems based on $L^*a^*b^*$ allow for sequential correction of images. First, the **tonal range or key type** (distribution of intensities) is adjusted. Then, color imbalances, such as under- or over-saturation, are corrected. The key types are categorized as follows: **high-key images** have most information in the light intensity range; **low-key images** concentrate in dark tones; **middle-key images** are balanced across the range. Adjusting tonal range is a common preprocessing step before refining color balance.

In summary, the CIE $L^*a^*b^*$ model provides a comprehensive and perceptually meaningful method to describe color. Its independence from devices and close alignment with human vision make it ideal for applications requiring precise and consistent color reproduction.

4.3 PSEUDOCOLOR IMAGE PROCESSING

Pseudocolor (sometimes called *false color*) image processing consists of assigning colors to gray values based on a specified criterion. The term pseudo or false color is used to differentiate the process of assigning colors to achromatic images from the processes associated with true color images. The principal use of pseudocolor is for human visualization and interpretation of grayscale events in an image or sequence of images.

4.3.1 INTENSITY SLICING AND COLOR CODING

Intensity slicing (also referred to as density slicing) and color coding are techniques in **pseudocolor processing** of digital images. These methods are particularly useful for highlighting different intensity ranges in an image, making it easier to visualize variations within the image data.

Conceptual Framework:

1. 3-D Function Representation:

- A digital image can be interpreted as a 3D function where the image's coordinates x and y correspond to pixel positions, and the intensity $f(x, y)$ represents the pixel value or brightness.
- The goal of intensity slicing is to divide the intensity range of an image into intervals and assign different colors to each interval.

2. Slicing the Intensity Function:

- A **plane** is placed parallel to the coordinate plane of the image. This plane "slices" through the intensity function at specific levels of intensity.

- The image intensity function can be visualized as a 3D surface, and each **slice** or **plane** is essentially a threshold that divides the intensity levels into different ranges.
 - The pixels above and below the plane are assigned distinct colors based on which interval they belong to.
3. **Simple Two-Color Slicing (Fig. 6.16):**
- Consider an intensity slicing method where a single plane is placed at intensity level l_i and divides the image into two parts:
 - **Pixels above the plane** are assigned one color.
 - **Pixels below the plane** are assigned another color.
 - Pixels at the **plane level** can be assigned a third color (for emphasis) or be treated as one of the two existing colors.
 - Moving the slicing plane up or down will change the relative appearance of the image by adjusting which intensity levels are highlighted.
4. **Multiple Color Slicing:**
- When there are more intensity planes, multiple intervals are created.
 - **General Process for Multiple Colors:**
 - Let the grayscale range be from 0 to $L - 1$, where 0 represents black and $L - 1$ represents white.
 - Define **P planes** at intensity levels $l_1, l_2, \dots, l_P$ (where $0 < P < L - 1$). These planes partition the grayscale into **P+1 intervals**.
 - Each interval I_k (for $k = 1, 2, \dots, P + 1$) is assigned a specific color, based on its corresponding intensity range.
 - The assignment is based on the pixel intensity $f(x,y)$, which determines the color assigned to each pixel.

Equation for Color Assignment:

- For a given pixel at position (x, y) , if its intensity $f(x, y)$ falls within the interval I_k defined by the planes at l_{k-1} and l_k , then the color associated with that interval c_k is assigned to the pixel.
- This mapping process can be represented by:

$$c_k = \text{Color associated with intensity interval } I_k$$

where I_k corresponds to the intensity range $[l_{k-1}, l_k]$.

5. **Staircase Mapping:**
- As more planes are added, the mapping between intensity and color forms a **staircase function** where each step corresponds to a different intensity interval.
 - The staircase form creates a more distinct separation between intensity ranges, highlighting variations in a more granular manner

Figure 6.16 (Slicing Example): Shows an intensity slicing example using a plane at $f(x,y) = l_i$, which divides the intensity values of the image into two regions, each assigned a different color.

FIGURE 6.16
Graphical
interpretation of
the intensity-
slicing technique.

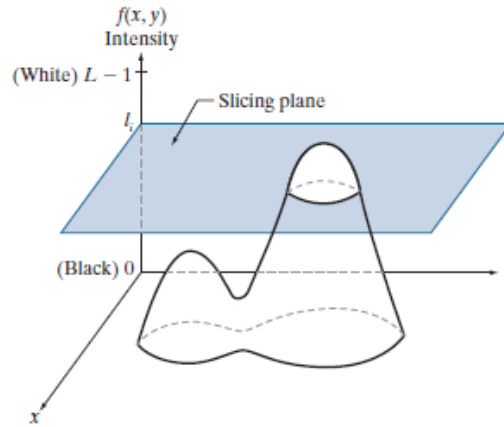
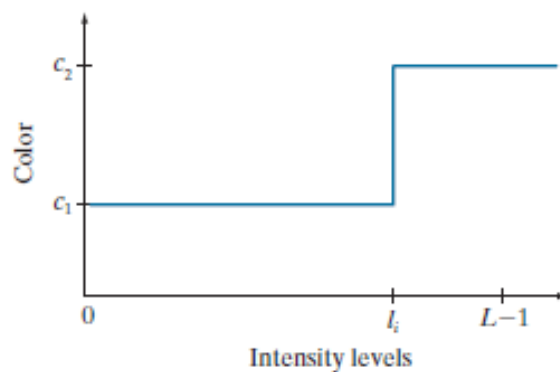


Figure 6.17 (Equivalent Approach): An alternative representation where each intensity level is mapped to a distinct color. When more planes are added, the mapping function takes a staircase form, effectively partitioning the intensity range into multiple segments, each with its own color.

FIGURE 6.17
An alternative
representation of
the intensity-
slicing technique.



Applications of Intensity Slicing and Color Coding:

1. **Medical Imaging:** In medical images like CT scans or MRIs, intensity slicing can highlight regions of interest based on specific intensity ranges (e.g., tissue types).
2. **Remote Sensing:** In satellite or aerial images, intensity slicing can differentiate between various land types or environmental conditions based on the intensity of the reflected light.
3. **Image Analysis:** Helps to isolate features that may be difficult to identify in grayscale, such as edges, structures, or other significant image features, making it easier for algorithms to process and analyze images.

Advantages and Limitations:

Advantages:

- **Improved Visibility:** Intensity slicing improves visibility by adding color to grayscale images, which can make it easier to interpret and analyze.
- **Simplicity:** The technique is simple to implement and can be very effective for specific applications where different intensity ranges correspond to distinct features or areas of interest.

Limitations:

- **Loss of Detail:** Intensity slicing may obscure subtle variations in intensity, as the image is being compressed into a limited number of color ranges.
- **Arbitrary Color Assignment:** The colors assigned to different intensity ranges are arbitrary, and the method does not convey information about the actual intensity values directly.
- **Overlapping Ranges:** In cases where intensity ranges overlap with important features, color coding may introduce visual artifacts that could make interpretation more difficult.

Intensity slicing and color coding are powerful tools in image processing, especially for highlighting certain intensity ranges and enhancing the visualization of features that might otherwise be difficult to distinguish in grayscale images. However, the method's effectiveness depends on careful selection of the intensity intervals and the number of colors used to represent them.

4.3.2 Intensity to Color Transformations in Image Processing

Intensity to color transformations go beyond the simpler intensity slicing technique. They offer more flexibility and allow for enhanced visualization of image data by applying independent transformations on the intensity values of pixels, and mapping the results to the red, green, and blue (RGB) channels of a color image. These transformations can utilize smooth, nonlinear functions, offering a wider range of pseudocolor enhancements.

FIGURE 6.21
Functional block diagram for pseudocolor image processing. Images f_R , f_G , and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

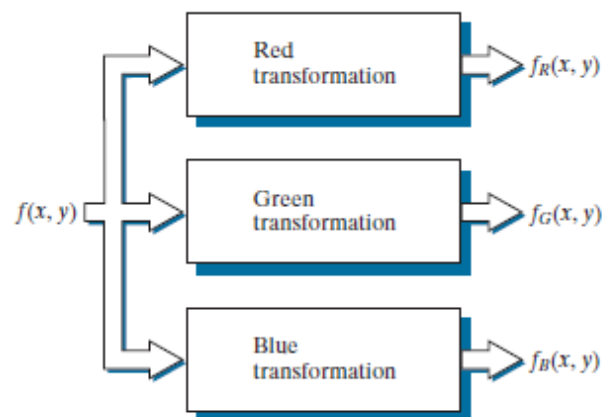


FIGURE 6.23
Transformation functions used to obtain the pseudocolor images in Fig. 6.22.

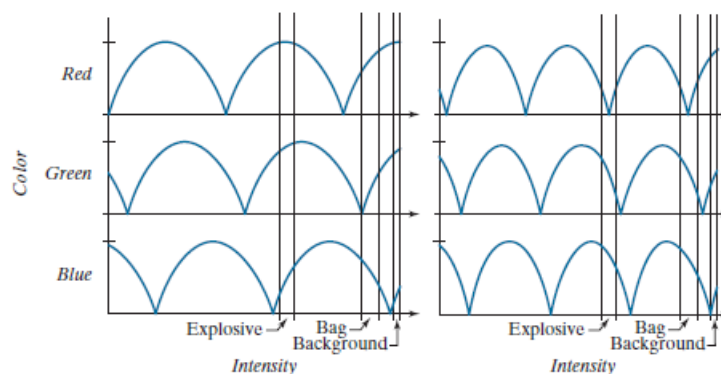
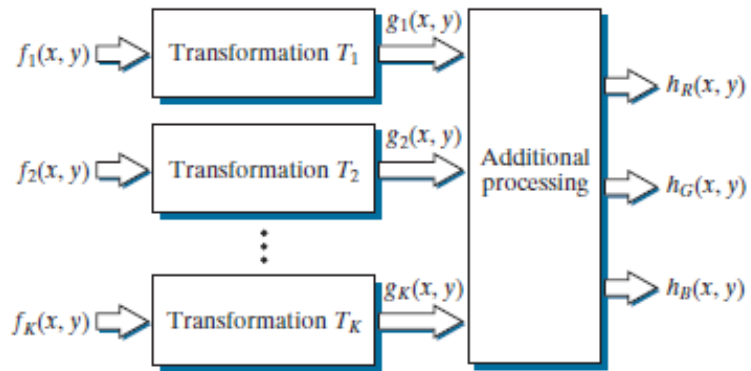


FIGURE 6.24

A pseudocolor coding approach using multiple grayscale images. The inputs are grayscale images. The outputs are the three components of an RGB composite image.



Key Concepts:

1. Basic Approach:

- Instead of just applying a simple intensity slicing technique, which divides the grayscale image into a few discrete intervals, intensity to color transformations use **nonlinear functions** to map intensity values to the RGB channels.
- The technique involves applying three independent transformation functions to the image intensity values:
 - One function for the **red** channel
 - One function for the **green** channel
 - One function for the **blue** channel
- These results are then combined to create a **color composite** image.

2. Comparison with Intensity Slicing:

- **Intensity Slicing:** Uses **piecewise linear functions** to map intensity levels to color intervals (as discussed in the earlier section). This technique often leads to sharp boundaries between colors and is a more rigid method of pseudocolor transformation.
- **Intensity to Color Transformation:** This method is more **flexible**, as it can involve **smooth, nonlinear transformations** that provide a more subtle and continuous range of color mapping.

3. Flexibility of Nonlinear Transformations:

- Nonlinear functions provide greater flexibility, as they can emphasize specific intensity ranges in ways that piecewise linear functions cannot. This makes the transformation suitable for a wider range of applications and image types, where nuanced color assignments are necessary.

Applications:

1. Multispectral Image Processing:

- **Multispectral images** contain multiple grayscale images taken from different spectral bands (e.g., visible light, infrared, etc.). Each band represents a different

aspect of the scene, and intensity to color transformations can be used to combine these grayscale images into a single **color composite**.

- **Example:** A multispectral image could combine the visible light bands (red, green, and blue) with the near-infrared band, where vegetation can be highlighted using a specific color transformation.
- **Example (Vegetation Highlighting):** In Figure 6.25(e) from the reference, the **infrared** band is used to replace the red channel in the RGB composite. This highlights **vegetation** in **bright red**, while the remaining components of the scene are shown in muted tones, making the vegetation stand out more clearly.

2. Emphasizing Areas of Interest:

- The technique is particularly useful for emphasizing **areas of interest** in an image based on specific intensity characteristics. In the case of vegetation in a multispectral image, the near-infrared band typically responds strongly to vegetation, making it an ideal candidate for emphasizing green spaces in color composites.

3. Remote Sensing:

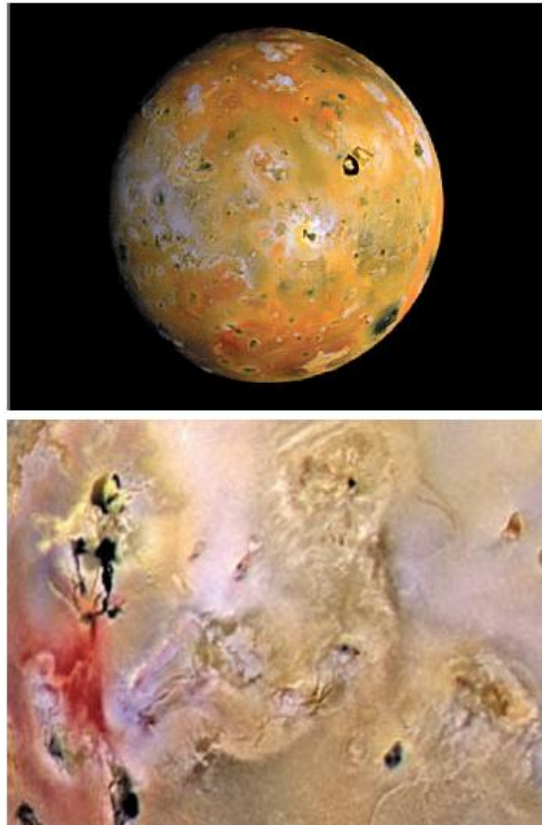
- In **remote sensing** and **satellite imagery**, multiple spectral bands are captured, often beyond the visible light spectrum (such as infrared or thermal). Intensity to color transformations can combine these bands into a single image that makes **interpretation** easier.

4. Jupiter's Moon Io (Fig. 6.26):

- Using data from the Galileo spacecraft, scientists can combine multiple sensor images of **Jupiter's moon Io**. These sensor images may be from different spectral regions, some of which are invisible to the human eye. The transformation into pseudocolor makes it easier to visualize phenomena such as **volcanic eruptions** or chemical compositions.
- For instance, in Figure 6.26(b), **bright red** color indicates **newly ejected material** from an active volcano on Io, while surrounding **yellow** areas show older sulfur deposits. This pseudocolor map makes it much easier to interpret the surface properties and geological activities of Io compared to examining the individual grayscale images.

a
b

FIGURE 6.26
(a) Pseudocolor
rendition of
Jupiter Moon Io.
(b) A close-up.
(Courtesy of
NASA.)



Detailed Steps for Intensity to Color Transformation:

1. Transformations on Each Intensity Channel:

- For each pixel, three independent transformations are applied:
 1. **Red Channel:** A transformation function is applied to the intensity values to map them to a red color range.
 2. **Green Channel:** A transformation function is applied to the intensity values to map them to a green color range.
 3. **Blue Channel:** A transformation function is applied to the intensity values to map them to a blue color range.

2. Creation of the Color Composite:

- After the transformations are performed, the three color channels (red, green, and blue) are combined to create a **composite RGB color image**.
- The resulting image uses the modulated intensity values to represent **different aspects** of the scene based on the properties of each channel.

3. Nonlinear vs Linear Transformations:

- While the earlier discussed **intensity slicing** often uses **piecewise linear** transformations (with sharp color boundaries), **nonlinear transformations** provide

gradual color transitions, enhancing the visual interpretation of complex image features.

Advantages of Intensity to Color Transformations:

1. **Flexibility:** Nonlinear transformations offer the ability to map intensity levels in a more flexible manner, leading to smoother and more expressive color representations.
2. **Improved Visualization:** This technique enhances the visualization of specific features that might not be visible or easily interpretable in grayscale images.
3. **Integration of Multiple Spectral Bands:** The ability to combine **multispectral data** into a single color image aids in the interpretation of complex data, especially when dealing with remote sensing or multispectral satellite imagery.
4. **Emphasis on Specific Features:** The technique can emphasize certain regions based on their spectral characteristics, such as highlighting vegetation, identifying geological features, or focusing on specific chemical compositions.

Intensity to color transformations provide a powerful method for enhancing the visualization of digital images by applying nonlinear transformations to intensity values, resulting in a richer and more detailed color map. This technique is particularly useful in applications like **multispectral image processing**, **remote sensing**, and **geological analysis**, where different spectral bands are combined to reveal specific features that are not immediately apparent in grayscale images.