CHAPTER 2

THEORETICAL CONSIDERATION

AND LITERATURE REVIEW

This chapter described about theoretical considerations such as the perceiving color, the XYZ tristimulus values and device independent color spaces, RGB color space and sRGB color space, the color display system, the color perception equation, and JAVA programming language and literature review.

2.1 Theoretical considerations

2.1.1 The perceiving color

Color results from the interaction of a light source, an object, and the eye and brain, or visual system. The visual system begins when light from the light source strikes the object and some of this energy is reflected and passes through in the eyes. Light entering our eyes is imaged onto the back of the eyeball, the retina, where light receptors absorb a portion of the incident light and generate a signal eventually interpreted by the brain. The quality of the retinal image depends on the absorption, scattering, and focusing properties of the cornea, lens, and fluids filling the eyeball. These optical elements influence the spectral and spatial properties of the light receptors.

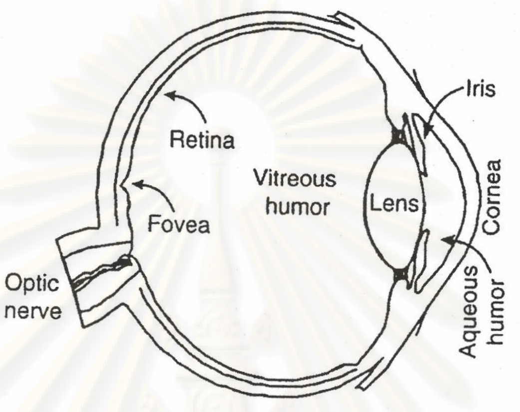

Figure 2-1 The cross section of the human eye.

There are two classes of receptors, rods and cones, named according to their shape. Rods are sensitive to brightness of light and detect very small amounts of light such as starlight. As the amount of light increases, the rods become desensitized and cease sending signals to the brain. During the day or in a well-lit room, the rod signals are inactive.

Cones, the second class of receptors, have much lower sensitivity to incident light. As the amount of light increases, the cones start sending neural signals. The cones are our color receptors. Our sensations of color are a result of having three types of cones responding differently to light of various wavelengths. Stimuli that cause different colors have different cone signals. The letters L, M, and S are used to represent the three cones with their peak sensitivities in the long, middle, and short wavelength regions, respectively.

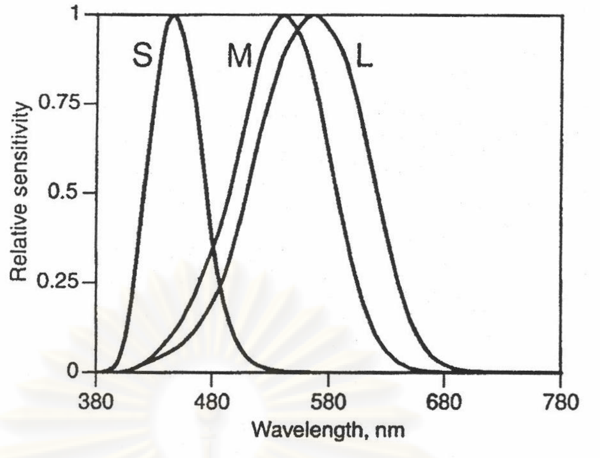

Figure 2-2 The relative spectral sensitivity of the L, M, and S cones.

The rods and cones in the eye form a retinal mosaic. The detectors are closely packed as in a mosaic with the pattern varying in its arrangement throughout the retina. In the center of the eye or fovea, only cones are present, about 50,000. Foveal vision is used for distinguishing very fine detail, such as reading and seeing objects at a distance. Outside the fovea, the number of cones is greatly reduced and they are situated quite apart from one another. The remainder of the mosaic consists of rods. Each individual receptor does not have a separate connection to the brain; rather, receptors interconnect within the retina, forming receptive fields. In forming receptive fields, the individual cone signals can either add together or be subtracted from one another. And the interaction of the three cone receptors can form the opponent signals. Finally, the opponent signals leave the retina via the optic nerve and eventually arrive at the back of the brain. The brain signals are interpreted through a cognitive process that results in color [5].

2.1.2 The Munsell Color System

Albert H.Munsell developed the Munsell Color System in 1905 as a teaching aid for art students [5]. The goal of Munsell was to have both a numerical system and a physical exemplification, achieved via the Atlas of the Munsell Colors.

Munsell color system was divided into three-dimensional color spaces of hue, lightness, and chroma, referred to as Munsell hue, Munsell value, and Munsell chroma, respectively.

2.1.2.1 Munsell Hue

Munsell desire for a numerical classification led to five principle hues, purple (P), blue (B), green (G), yellow (Y), and red (R), and five intermediate hues, purple-blue (PB), blue-green (BG), green-yellow (GY), yellow-red (YR), and red-purple (RP), as shown in Figure 2-3. The ten hues are arranged in a circle. Each ten hues can be further divided into ten subhues: 1R, 2R,…, 9R and 10R. Having hue divided into 100 steps leads to much greater visual equality between neighboring hues than systems based on the five principle hues.

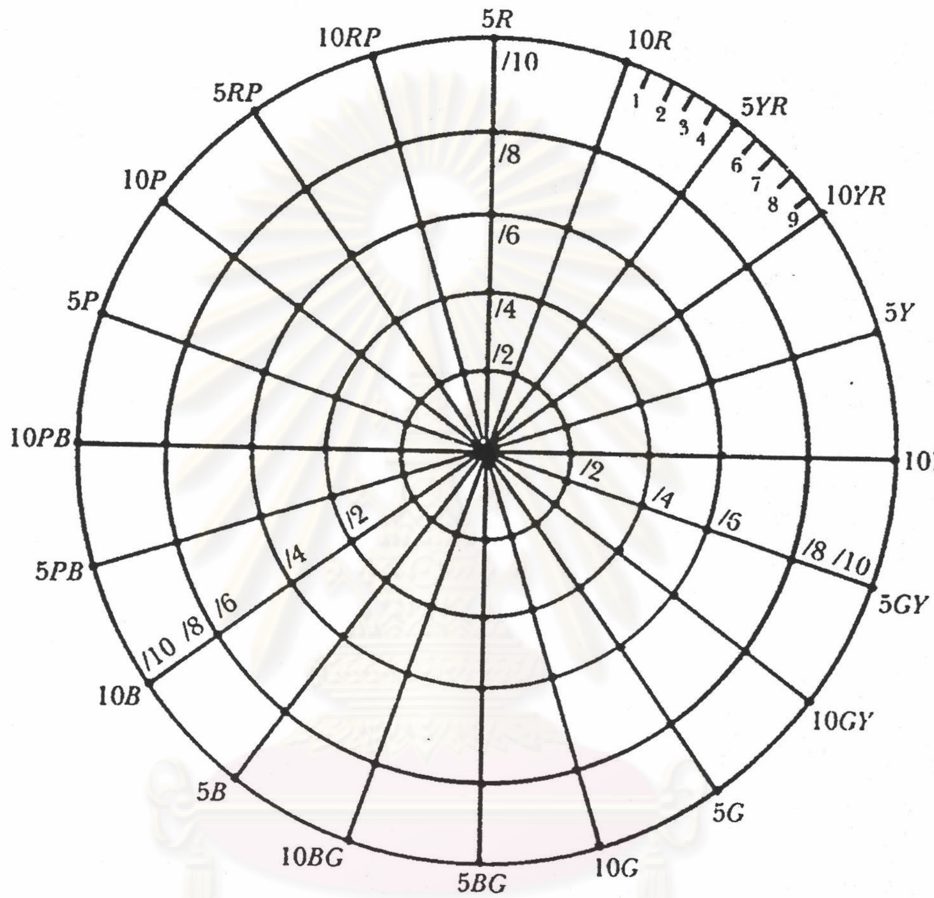

Figure 2-3 Arrangement of Hue circle in the Munsell System

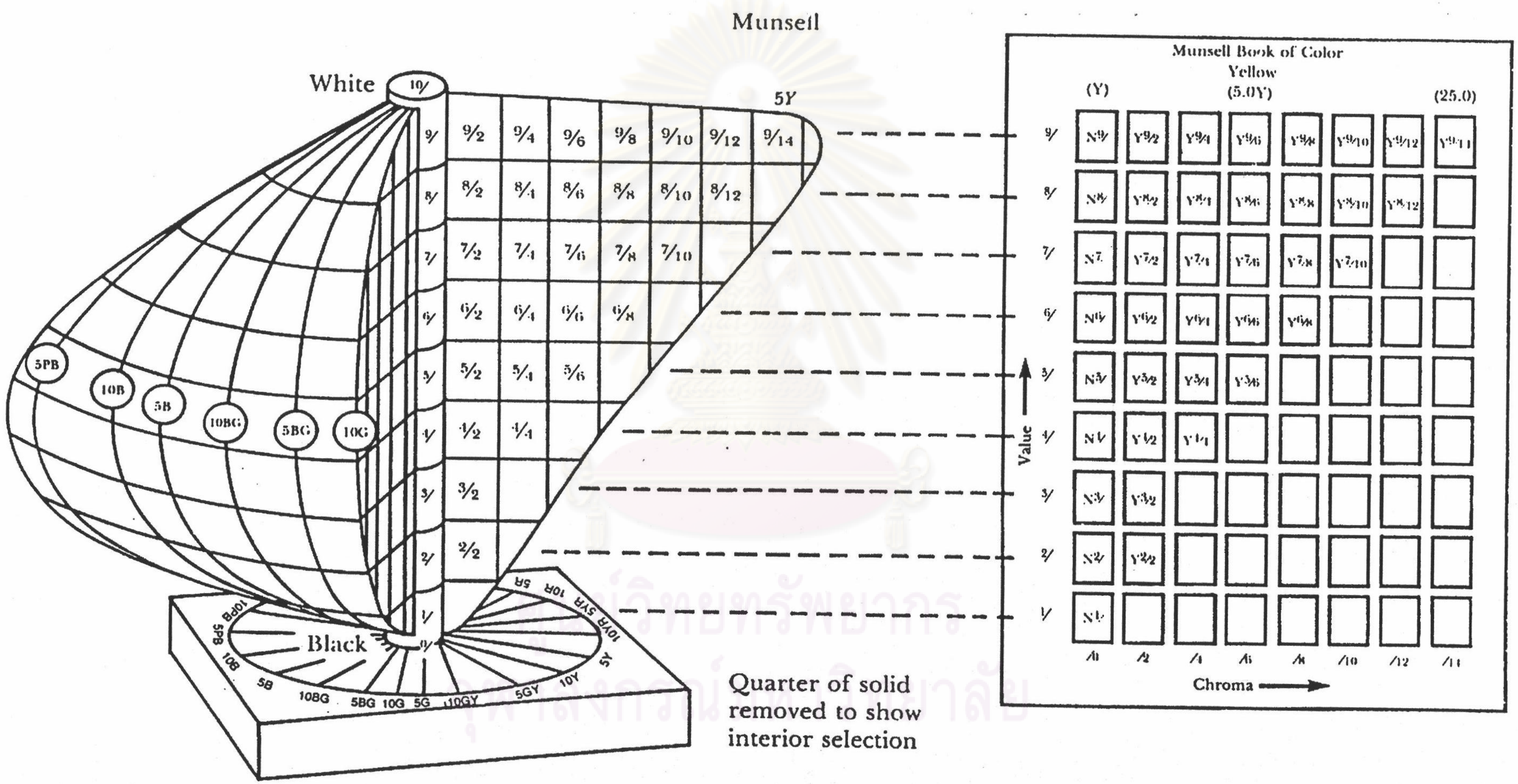

Figure 2-4 The Munsell color space

2.1.2.2 Munsell Values

Munsell values were divided into 10 steps based on the decimal system. And the value varies between black (0) and white (10), as shown in Figure 2-4 [6]. Achromatic colors found to be visually equally spaced were defined by their luminous reflectance based on a visual instrument built by Munsell. Achromatic colors are notated with the prefix “N”-for example, N0, N1,…, N10. The visual instrument was used to produce colors of various values for each hue.

2.1.2.3 Munsell Chroma

The distance of the sample from the value axis are intended to represent uniform differences in perceived chroma and are given numbers that are typically as small as 4 or less for weak colors, and 10 or more for strong colors. The scales of chroma extends from /0 for a neutral gray out to /10, /12, /14 or further [7].

For a defined hue and value, colors were formed into scales of increasing chroma with equal differences between neighboring sample.

Munsell planed on sampling three-dimensional color space with a sphere. This led to the Munsell color solid, in which each hue was extended to its maximum chroma at each value. The Atlas was produced using matte painted papers arranged to show both vertical and horizontal slices through the Munsell color solid [5].

2.1.3 XYZ tristimulus values and device independent color spaces

The concept for the XYZ stimulus values is based on the three-component theory of color vision, which states that the eyes possesses receptors for three primary colors (red, green and blue) and that all colors are seen as mixtures of these three primary colors. The CIE in 1931 defined the Standard Observer to have the color-matching function $\overline{x}(\lambda), \overline{y}(\lambda)$ and $\overline{z}(\lambda)$ by the following formulae [8]:

$$X = K \int_{380}^{780} S(\lambda)\overline{x}(\lambda)R(\lambda)d\lambda$$

$$Z = K \int_{380}^{780} S(\lambda)\overline{z}(\lambda)R(\lambda)d\lambda$$

$$Y = K \int_{380}^{780} S(\lambda)\overline{y}(\lambda)R(\lambda)d\lambda \qquad (2.1)$$

Where

$S(\lambda)$: Relative spectral power distribution of the illuminant.

$\overline{x}(\lambda), \overline{y}(\lambda)$ and $\overline{z}(\lambda)$: Color-matching functions.

$R(\lambda)$: Spectral reflectance of specimen.

We have shown that calculating the tristimulus values of a color requires knowledge of the source, object, and observers. This is true for materials that reflect or transmit light interacting with them. There are many colors that are not materials, such as lights and displays. When calculating their tristimulus values, the spectral reflectance factor is not included in the tristimulus integration equation [5]. Furthermore, the convention of normalizing Y such that it equals 100 is generally not used. Instead, photometric units are used, for which the normalizing constant in the tristimulus equations, K, equals 683 lumens per watt, known as the maximum luminous efficacy with K_m replacing K. A lumen is a quantity that weights light by the photometric standard observer. There are the equations for calculating tristimulus values in luminance units (candelas per square meter), as shown in below formulae.

$$X=683\int_{380}^{780} L(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y=683\int_{380}^{780} L(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z=683\int_{380}^{780} L(\lambda)\bar{z}(\lambda)d\lambda \qquad (2.2)$$

Where $L(\lambda)$ is the lightness spectral radiation.

The xyz chromaticity coordinates, CIEL*a*b*, and CIEL*C*h$^\circ$ are the device independent color spaces which are calculated from the XYZ tristimulus values according to the following formulae:

xyz chromaticity coordinates:

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

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

$$z = \frac{Z}{X+Y+Z} = 1 - x - y \qquad (2.3)$$

CIEL*a*b* color space:

The values of L*,a* and b* are calculated according to the formulae below :

Lightness variable L*:

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16 \qquad (2.4)$$

Chromaticity coordinates a* and b*:

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right] \qquad (2.5)$$

X_n, Y_n, Z_n : Tristimulus values XYZ of a perfect reflecting diffuser.

CIE$L^*C^*h^\circ$ color space:

This color space values are defined by the following formulae:

$$\text{Chroma: } C^* = \sqrt{(a^*)^2 + (b^*)^2}$$

$$\text{Hue-Angle: } h^\circ = \tan^{-1}\left(\frac{b^*}{a^*}\right) \qquad (2.6)$$

where a^*, b^* : Chromaticity coordinates in the CIE$L^*a^*b^*$ color space.

CIE$L^*a^*b^*$ and CIE$L^*C^*h^\circ$ color spaces are the device independent color space but computer monitors use RGB space. Therefor, RGB study is necessary.

2.1.4 RGB color space and sRGB color space

2.1.4.1 RGB color space

The RGB color space is the device-dependent color space, which defines colors within a unit cube by the additive-color-mixing model. Red, green, and blue are additive primaries represented by the three axes of the cube as shown in Figure 1.2.1 ; all other colors within the cube can be represented as the triplet(R, G, B), where values R, G, and B are assigned in the range from 0 to 1. An important characteristic of the additive system is that the object itself is a light emitter such as a television. Scanners and computer monitors also use RGB space. And RGB values in one device will not look like RGB values in another device.

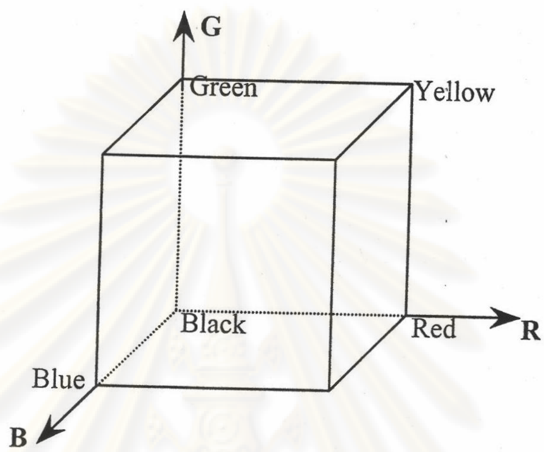

Figure 2-5 RGB color space

2.1.4.2 sRGB color space

sRGB is a standard color space, which decrease the problems in communicating color in open system since the ICC profiles have not provide a complete solution for all situations yet. This standard addresses these concerns, serves the needs of PC and Web based color imaging systems is based on the average performance of personal computer displays. There are two definitions to the proposed standard in this part; the viewing environment parameters with its dependencies on the human visual system and the standard device space colorimetric definitions and transformations. The viewing environment descriptions contain all the necessary information, when combined with most color appearance models, to provide conversions between the standard and target viewing environments. The colorimetric definitions provide the transforms necessary to convert between the sRGB color space and the CIEXYZ two degrees observer color space. The reference viewing environments are defined for standard RGB in Table 2-1 as follows :

2.1.4.2.1 sRGB Reference Viewing Environment

Table 2-1 The viewing environment parameters

sRGB Viewing Environment Parameters	
Conditions	**sRGB**
Luminance level	80 cd/m^2
Illuminant white	x = 0.3127, y = 0.3291 (D65)
Image surround	20% reflectance
Encoding ambient illuminant level	64 lux
Encoding ambient white point	x = 0.3457, y = 0.3585 (D50)
Encoding viewing flare	1.0%
Typical ambient illuminant level	200 lux
Typical ambient white point	x = 0.3457, y = 0.3585 (D50)
Typical viewing flare	5.0%

The sRGB reference viewing environment corresponds to conditions typical of monitor display viewing conditions.

The luminance level is representation of typical CRT display levels.

The chromaticities of the illuminant white are those of CIE D65.

The image surround is defined as "20%" of the maximum white luminance. This is close to a CIELAB L* value of 50.

The encoding viewing environment is consistent with recent discussions within the ISO JTAG2 committee for graphic arts and photographic viewing conditions for photographic images on monitor.

The typical viewing environment is representative of a typical office or home office viewing environment for personal computers.

The encoding ambient illuminance level is intended to be representative of a dim viewing environment. Note that the illuminance is at least an order of magnitude lower than average outdoor levels and approximately one-third of the typical ambient illuminance levels.

The chromaticities of the encoding ambient white are those of CIE D50.

Encoding viewing flare id specified to be 1.0% of the maximum white-luminance level.

The typical ambient illuminance level is intended to be representative of a typical office viewing environment. Note that the illuminance is at least an order of magnitude lower than average outdoor levels.

The chromaticities of the typical ambient white are those of CIE D50.

Typical viewing flare id specified to be 5.0% of the maximum white-luminance level.

2.1.4.2.2 Colorimetric Definitions and Digital Encoding

sRGB in combination with the reference viewing environment can be defined from standard CIE colorimetric values through simple mathematical transformations. CIE colorimetry provides the basic for sRGB encoding of the color. For the calculation of CIE colorimetric values, it is necessary to specify a viewing environment and a set of spectral sensitivities for a specific capture device. The definitions for RGB given in equation (2.7) to (2.9) are based on the colorspace's respective viewing environment. The CIE chromaticities for the red, green, and blue ITU-R BT.709 reference primaries, and for CIE Standard Illuminant D65, are given in Table 2-2.

Table 2-2 CIE chromaticities for ITU-R BT.709 reference primaries and CIE standard illuminant

CIE chromaticities for ITU-R BT.709 reference primaries and CIE standard illuminant				
	Red	**Green**	**Blue**	**D65**
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
z	0.0300	0.1000	0.7900	0.3583

sRGB tristimulus values for the illuminated objects of the scene are simply linear combinations of the 1931 CIE XYZ values and these RGB tristimulus values can be computed using the following derived relationship :

$$\begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} = \begin{bmatrix} 0.03241 & -0.015374 & -0.004986 \\ -0.009692 & 0.01876 & 0.000416 \\ 0.000556 & -0.00204 & 0.01057 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{2.7}$$

The sRGB tristimulus values are next transformed to nonlinear sR'G'B' values as follows:

If $R_{sRGB}, G_{sRGB}, B_{sRGB} \leq 0.00304$

$$\begin{aligned} R'_{sRGB} &= 12.92 \times R_{sRGB} \\ G'_{sRGB} &= 12.92 \times G_{sRGB} \\ B'_{sRGB} &= 12.92 \times B_{sRGB} \end{aligned} \tag{2.8a}$$

else if $R_{sRGB}, G_{sRGB}, B_{sRGB} > 0.00304$

$$\begin{aligned} R'_{sRGB} &= 1.055 \times R_{sRGB}^{(1.0/2.4)} - 0.055 \\ G'_{sRGB} &= 1.055 \times G_{sRGB}^{(1.0/2.4)} - 0.055 \\ B'_{sRGB} &= 1.055 \times B_{sRGB}^{(1.0/2.4)} - 0.055 \end{aligned} \tag{2.8b}$$

Finally, the nonlinear sR'G'B' values are converted to digital code values. This conversion scales the above sR'G'B' values by using the equation below where WDC represents the white digital count and KDC represents the black digital count.

$$\begin{aligned} R_{8bit} &= \left[(WDC - KDC) \times R'_{sRGB}\right] + KDC \\ G_{8bit} &= \left[(WDC - KDC) \times G'_{sRGB}\right] + KDC \\ B_{8bit} &= \left[(WDC - KDC) \times B'_{sRGB}\right] + KDC \end{aligned} \tag{2.9}$$

This current specification propose using a black digital count of 0 and a white digital count of 255 for 24 bit(8 bit/channel) encoding. The resulting RGB values are formed according to the following equations:

$$\begin{aligned} R_{8bit} &= \left[(255 - 0.0) \times R'_{sRGB}\right] + 0.0 \\ G_{8bit} &= \left[(255 - 0.0) \times G'_{sRGB}\right] + 0.0 \\ B_{8bit} &= \left[(255 - 0.0) \times B'_{sRGB}\right] + 0.0 \end{aligned} \tag{2.10}$$

This obviously can be simplified as shown below.

$$\begin{aligned} R_{8bit} &= 255.0 \times R'_{sRGB} \\ G_{8bit} &= 255.0 \times G'_{sRGB} \\ B_{8bit} &= 255.0 \times B'_{sRGB} \end{aligned} \tag{2.11}$$

The reverse relationship is defined as follows:

$$R'_{sRGB} = R_{8bit} \div 255.0$$
$$G'_{sRGB} = G_{8bit} \div 255.0 \quad (2.12)$$
$$B'_{sRGB} = B_{8bit} \div 255.0$$

if $R'_{sRGB}, G'_{sRGB}, B'_{sRGB} \leq 0.03928$

$$R_{sRGB} = R'_{sRGB} \div 12.92$$
$$G_{sRGB} = G'_{sRGB} \div 12.92 \quad (2.13a)$$
$$B_{sRGB} = B'_{sRGB} \div 12.92$$

else if $R'_{sRGB}, G'_{sRGB}, B'_{sRGB} > 0.03928$

$$R_{sRGB} = \left[\left(R'_{sRGB} + 0.055 \right)/1.055\right]^{2.4}$$
$$G_{sRGB} = \left[\left(G'_{sRGB} + 0.055 \right)/1.055\right]^{2.4} \quad (2.13b)$$
$$B_{sRGB} = \left[\left(B'_{sRGB} + 0.055 \right)/1.055\right]^{2.4}$$

Finally, the sRGB values are transformed into XYZ by using the following derived relationship:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 41.24383 & 35.73945 & 18.01312 \\ 21.21564 & 71.35015 & 7.18721 \\ 1.91966 & 11.85690 & 94.77798 \end{bmatrix} \begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} \quad (2.14)$$

2.1.5 Color Display Systems

The color monitor is an additive color system having RGB primaries. A typical CRT display system is depicted in Figure 2-6. A display interface card connects the computer to the monitor. This card has three major components: bus interface, display memory, and digital-to-analog converters (DAC) [9].

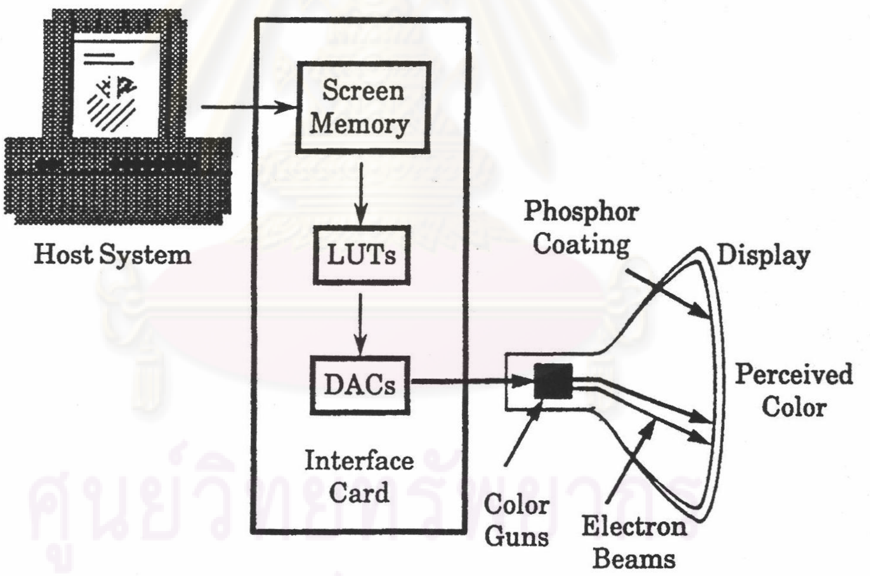

Figure 2-6 Schematic diagram of a typical CRT display system

Usually, the memory stores 24 bits per pixel or 8 bits per color. In principle, it can provide 16.8 million color (2^{24}); in reality, viewers would not be able to distinguish all of them. In this case, color lookup tables are included between the screen memory and the DACs.

The DACs provide voltage to the video amplifiers that, in turn, drive the RGB guns. The electronic beams generated from RGB guns are scanned across the CRT screen, causing their respective phosphors to fluoresce.

Generally, the monitor characterization consists of two parts. The first stage is a nonlinear transformation relating normalized DAC values to luminance Y. The second stage is a multiple linear transformation where the device-dependent monitor values are transformed to device-independent CIE tristimulus values.

2.1.5.1 Relationship between DAC and Luminance Y.

Many nonlinear functions have been proposed for relating DAC and Y. Notable ones are listed below [9] :

1. Second-order polynomial:

$$Y = q_1 + q_2 d_p + q_3 d_p^{2} \quad , \qquad (2.15)$$

Where d_p is the gun's DAC value, and q_i , I = 1, 2, 3 are coefficients obtained from regression.

2. Linear to logarithmatic:

$$\log Y = q_1 + q_2 d_p + q_3 d_p^2 \quad , \tag{2.16}$$

3. Second-order polynomial to logarithmatic:

$$\log Y = q_1 + q_2 d_p + q_3 d_p^2 \quad , \tag{2.17}$$

4. Logarithmatic to logarithmatic:

$$\log Y = q_1 + q_2 \log d_p \quad , \tag{2.18}$$

5. Second-order logarithmatic:

$$\log Y = q_1 + q_2 \log d_p + q_3 (\log d_p)^2 \quad . \tag{2.19}$$

In addition to these nonlinear functions, there are various piecewise linear interpolation methods.

2.1.5.2 Theoretical Monitor Model

Berns, Motta, and Gorzynski developed a model based on the signal processing and colorimetry appropriate to computer-controlled CRT displays [10]. The relationship between spectral radiant existence emitted and digital counts are derived as follows:

1. The digital information is quantized linearly to video voltage V_p in the DAC. The DAC determines the number of quantization levels and ranges from 0 to the maximum values, 2^n-1, where n is the number of DAC bits. The DAC values d_p is linearly proportional to the video voltage V_p as shown in Eq. (2.20).

$$V_p = (V_{max} - V_{min})[d_p / (2^n-1)] + V_{min} \quad , \qquad (2.20)$$

where the subscript p represents one of the CRT primary colors, p ∋ (R,G,B). constants V_{max} and V_{min} are the maximum and minimum video voltages, respectively.

2. The video amplifiers transform the positive V_p into negative voltages $V_{g,p}$:

$$V_{g,p} = \alpha_p V_p + \beta_p \quad , \qquad (2.21)$$

where α_p is the video amplifier gain of a component and β_p is the video amplifier offset of a component p.

3. The relationship between the current of the electron beam, I_p, and the amplified video voltage, $V_{g,p}$ is nonlinear:

$$i_p = (V_{g,p} - V_{c,p})^{\gamma_p} \quad ; \qquad V_{c,p} < V_{g,p} \tag{2.22}$$

$$= 0; \qquad V_{c,p} < V_{g,p}$$

where γ_p is an exponent commonly referred to as gamma, and $V_{c,p}$ is the cut-off voltage of a component p.

4. It is assumed that the amount of phosphor emission measured in radiometric terms is linearly related to the beam current.

$$M_{\lambda,p} = k_{\lambda,p}\, i_p \qquad , \tag{2.23}$$

where $M_{\lambda,p}$ is the spectral radiant exitance and $k_{\lambda,p}$ is a spectral constant accounting for the particular CRT phosphor and faceplate combination.

Combining Eqs.(2.20), (2.21), and (2.22) into (2.23), we obtain

$$M_{\lambda,p} = k_{\lambda,p} \left(\alpha_p[(V_{max} - V_{min})[d_p / (2^n-1)] + V_{min}] + \beta_p - V_{c,p} \right)^{\gamma_p} \tag{2.24}$$

From Eq.(2.24) would be difficult to apply to the task of predicting spectral radiant exitance (dependent variable) from DAC values (independent variable). Therefore it is useful to define the maximum spectral radiant exitance $M_{\lambda,p}$:

$$\frac{M_{g,p}}{M_{\lambda,p,max}} = \left[\left(\frac{\alpha_p (V_{max} - V_{min})}{\alpha_p V_{max} + \beta_p - V_{c,p}}\right)\left(\frac{d_p}{2^n - 1}\right) + \left(\frac{\alpha_p V_{min} + \beta_p - V_{c,p}}{\alpha_p V_{max} + \beta_p - V_{c,p}}\right)\right]^{\gamma_p} \quad (2.25)$$

It is convenient to define monitor gain and offset terms $k_{g,p}$ and $k_{o,p}$:

$$k_{g,p} = \left(\frac{\alpha_p (V_{max} - V_{min})}{\alpha_p V_{max} + \beta_p - V_{c,p}}\right)$$
$$k_{o,p} = \left(\frac{\alpha_p V_{min} + \beta_p - V_{c,p}}{\alpha_p V_{max} + \beta_p - V_{c,p}}\right) \quad (2.26)$$

Note that $k_g + k_o = 1$ and Goniophotometric measurements indicate that many CRTs are isotropic radiators within typical viewing angles [11,12]. Therefore, we can relate the spectral radiance L_λ to DAC values $L_\lambda = M_\lambda / \pi$

The resulting equation relating d_p to the spectral radiance

$$L_{\lambda,p} = L_{\lambda,p,max}\left(k_{g,p}\left[d_p / \left(2^n - 1\right)\right] + k_{o,p}\right)^{\gamma_p}$$

if $\left(k_{g,p}\left[d_p / \left(2^n - 1\right)\right] + k_{o,p}\right) \geq 0$

$$= 0 \qquad \text{if } \left(k_{g,p}\left[d_p / \left(2^n - 1\right)\right] + k_{o,p}\right) < 0 \quad (2.27)$$

For example, the red scalar R can be introduced.

$$L_{\lambda,p} = R L_{\lambda,p,max}. \tag{2.28}$$

Then R can be rewritten as

$$R = \left(k_{g,p}\left[d_p / \left(2^n - 1\right)\right] + k_{o,p}\right)^{\gamma_r} \quad \text{if } \left(k_{g,p}\left[d_p / \left(2^n - 1\right)\right] + k_{o,p}\right) \geq 0$$

$$= 0 \quad \text{if } \left(k_{g,p}\left[d_p / \left(2^n - 1\right)\right] + k_{o,p}\right) < 0 \tag{2.29}$$

This equation, known as tone reproduction characteristics, has been represented by the gain, offset, and gamma model (GOG model). From a colorimetric perspective, the R scalar is a tristimulus value. The red channel has the following set of CIE tristimulus values when measured in luminance units:

$$\begin{aligned} X_r &= 683\int L_{\lambda,r} x_\lambda d\lambda \\ Y_r &= 683\int L_{\lambda,r} y_\lambda d\lambda \\ Z_r &= 683\int L_{\lambda,r} z_\lambda d\lambda. \end{aligned} \tag{2.30}$$

Substituting Eq.(2.28) into Eq.(2.30), we obtain

$$
\begin{aligned}
X_r &= R683\int L_{\lambda,r,max}\, x_\lambda\, d\lambda = RX_{r,max}\\
Y_r &= R683\int L_{\lambda,r,max}\, y_\lambda\, d\lambda = RY_{r,max}\\
Z_r &= R683\int L_{\lambda,r,max}\, z_\lambda\, d\lambda = RZ_{r,max}\,.
\end{aligned} \tag{2.31}
$$

Thus far, each channel has been considered separately. For a given pixel, the spectral radiance is a linear combination of three independent channels, assuming the detector area integrates the three emissions within the pixel. This is represented by Eq.(2.32):

$$
\begin{aligned}
X &= X_r + X_g + X_b\\
Y &= Y_r + Y_g + Y_b\\
Z &= Z_r + Z_g + Z_b
\end{aligned} \tag{2.32}
$$

Substituting Eq.(2.31) into Eq.(2.32), we obtain

$$
\begin{aligned}
X &= RX_{r,max} + GX_{g,max} + BX_{b,max}\\
Y &= RY_{r,max} + GY_{g,max} + BY_{b,max}\\
Z &= RZ_{r,max} + GZ_{g,max} + BZ_{b,max}
\end{aligned} \tag{2.33}
$$

The final set of equations relating DAC values to CIE tristimulus values is

$$
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{2.34}
$$

Equation (2.34) is used to describe the colorimetry of computer-controlled CRT displays. It consists of two stages: a nonlinear stage, where DAC values are converted to scalars, and a linear stage, where the scalars are transformed to CIE tristimulus values. For many applications, one knows the tristimulus values and wants to determine the appropriate digital values. In this case, inverse equation is required:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}.$$

$$\begin{aligned} d_r &= \left[\left(2^n - 1 \right) / k_{g,r} \right] \left(R^{1/\gamma_r} - k_{o,r} \right) \text{ if } 0 \le R \le 1 \\ d_g &= \left[\left(2^n - 1 \right) / k_{g,g} \right] \left(G^{1/\gamma_g} - k_{o,g} \right) \text{ if } 0 \le G \le 1 \\ d_b &= \left[\left(2^n - 1 \right) / k_{g,b} \right] \left(B^{1/\gamma_b} - k_{o,b} \right) \text{ if } 0 \le B \le 1 . \end{aligned} \tag{2.35}$$

Displaying a series of DAC values and measuring their tristimulus values developed a data set for estimating the necessary model parameters and testing model performance. The monitor was first warmed up overnight. All the measurements were made in a darkened laboratory. The required image was displayed for 90 seconds followed by three successive measurements of the tristimulus values. The average tristimulus values of the three measurements were recorded [9].

When a color system is described by Eq.(2.34) and (2.35), the system has stable primaries. That is, the chromaticity coordinates of each primary do not change with the level of output. This is clarified by expanding the primary tristimulus matrix into a product of a chromaticity matrix and a luminance matrix, shown in Eq.(2.36) [5] :

$$\begin{bmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{bmatrix} = \begin{bmatrix} (x_{r,max}/y_{r,max}) & (x_{g,max}/y_{g,max}) & (x_{b,max}/y_{b,max}) \\ 1 & 1 & 1 \\ (z_{r,max}/y_{r,max}) & (z_{g,max}/y_{g,max}) & (z_{b,max}/y_{b,max}) \end{bmatrix} \begin{bmatrix} L_{r,max} & 0 & 0 \\ 0 & L_{g,max} & 0 \\ 0 & 0 & L_{b,max} \end{bmatrix} \quad (2.36)$$

where x_r, x_g, …, z_g, z_b are chromaticities for each primary and $L_{r,max}$, $L_{g,max}$, and $L_{b,max}$ are the maximum luminances of each primary. (Recall that $z = 1\text{-}x\text{-}y$ and $Y = L = L_{r,max} + L_{g,max} + L_{b,max}$)

2.1.5.3 Color Mixing System

A color mixing system exemplifies relationships between color primaries and their intermixtures. For CRT (cathode ray tube) monitor, color are displayed by using three phosphors: red, green, blue. A paint dispensing system will use several highly chromatic colorants (usually more than three) and black. Although many processes and color system rely on three primaries, this is not a requirement. In face, there is a growing trend to increase the number of primaries in many color processes in order to increase the total number of producible colors, or color gamut, and improve color-matching capabilities [5].

The mixing of CRT displays is called "Additive Mixing" , as shown in Figure 2-5. When the amounts of the three primaries are at their minimum, black result; when the amounts of the three are at their maximum, white results. Increasing or decreasing amounts of individual primaries or their various combinations between the minimum and maximum in even increment produces a systematic arrangement of colors. Color CRT displays consist of three different types of phosphors coated onto the inside of the glass faceplate. Because each colored is forming a picture element, or pixel, is smaller than the eye's maximum resolution at typical viewing distances, the light is averaged by our receptors.

2.1.6 Color Perception Equation

From the previous studies, there are many researches about the quantifying color perception. They described the human perceptions by using 12 pairs of opponent words such as warm-cool, light-dark, deep-pale, heavy-light, vivid-sombre, soft-hard, and strong-week in the questionnaire under illuminant D65 in the light cabinet. Each observer was asked to fill in the questionnaire during visual assessment. After receiving the response of the observers from the visual assessment, the seven-point method was used to quantify the color perception of each color. For example, the calculation of " Warm-Cool" percentage (WC%) is as following:

$$WC\% = \frac{a\,(-3)+b\,(-2)+c\,(-1)+d\,(0)+e\,(1)+f\,(2)+g\,(3)}{3\,(\,a+b+c+d+e+f+g\,)}\times 100 \qquad (2.37)$$

where a, b, c, d, e, f, and g are the number of observers who choose –3, -2, -1, 0, 1, 2, and 3 respectively.

Table 2-3 The opponent word pairs

Symbol	Thai	English	Japanese	Chinese(Cantonese)
DP	Khem - Jang	Deep - Pale	Koi - Awai	Sem - Tsin
DYP	Kloenwai - Sangobning	Dynamic - Passive	Doutekina - Seitekina	Dung - Zing
DV	Dodden - Seed	Distinct - Vague	Hakkirishita - Bonyarishita	Tsing sik - Mou wu
GP	Choodchad - Reab	Gaudy - Plain	Hadena - Jimina	Zuk Jim - Pok sou
HL	Nuck - Bow	Heavy - Light	Omoi - Karui	Zung - Hing
LD	Sawang - Mued	Light - Dark	Akarui - Kurai	Gwong - Em
SF	Numnual - Kangkradang	Soft - Hard	Yawarakai - Katai	Jau jyn - Gin ngang
SS	Chadjan - Kamukkamoe	Striking - Subdued	Medatsu - Medatanai	Dyt muk - Jau wo
SW	Khemkang - Oanaer	Strong - Weak	Tsuyoi - Yowai	Koeng - Joek
TT	Prongsai - Tueb	Transparent - turbid	Sunda - Nigotta	Tung tau - Wen zuk
VS	Sodsai - Mon	Vivid - Dull	Azayakana - Kusunda	Sin ming - Em tam
WC	Ron - Yen	Warm - Cool	Atatakai - Tsumetai	Nyn - Lang

The relationship between the results obtained from the visual assessments and the colorimetric values were used to set empirical color perception equation by the mathematical multiple linear regression. The CIE colorimetric attributes, L*, C* and h^{o} were the independent variables whereas each color perception percentage was the dependent variable in the mathematical model. From the results of the color perception values (CP) were derived as a general equation base on CIEL*C*h^{o} as following

$$CP = \left[\left\{ k_1 \left(L^* - L^*_0 \right) \right\}^2 + \left\{ k_2 \left(C^* - C^*_0 \right) \right\}^2 \right]^{1/2} + k_3 \quad (2.38)$$

where CP: Color perception value

L^*: CIE $L^*C^*h^o$ metric lightness

L_0^*: CIE $L^*C^*h^o$ metric lightness when visual assessment has the minimum value

C^*: CIE $L^*C^*h^o$ metric chroma

C_0^*: CIE $L^*C^*h^o$ metric chroma when visual assessment has the minimum value

k_1 : Constant of the contribution of CIE$L^*C^*h^o$ of lightness for color perception

k_2 : Constant of the contribution of CIE$L^*C^*h^o$ of chroma for color perception

k_3 : Color perception value when visual assessment has the minimum value

Therefore, the empirical color perception equations, showed the relationship between color perceptions and the CIE colorimetric attributes, were derived and are illustrated below [13]

"Light-Dark"

$$LD = \left[\left\{ 3.4 \left(L^* - 10 \right) \right\}^2 + \left\{ 4.5 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 184 \qquad (2.39)$$

"Soft-Hard"

$$SH = -\left[\left\{ 2.2 \left(L^* - 90 \right) \right\}^2 + \left\{ 0.9 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} + 79 \qquad (2.40)$$

"Warm-Cool"

$$WC = \left[\left\{ 0.27 \left(L^* - 100 \right) \right\}^2 + \left\{ 1.48 \left(1 + \cos \left(\Delta h^\circ_{40} \right) \right) \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 58 \qquad (2.41)$$

"Transparent-Turbid"

$$TT = \left[\left\{ 3.1 \left(L^* - 30 \right) \right\}^2 + \left\{ 2.7 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 122 \tag{2.42}$$

"Deep-Pale"

$$DP = \left[\left\{ 2.6 \left(L^* - 100 \right) \right\}^2 + \left\{ 1.8 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 90 \tag{2.43}$$

"Distinct-Vague"

$$DV = \left[\left\{ 1.9 \left(L^* - 60 \right) \right\}^2 + \left\{ 3.3 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 62 \tag{2.44}$$

"Heavy-Light"

$$HL = \left[\left\{ 2.6 \left(L^* - 100 \right) \right\}^2 + \left\{ 0.6 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 96 \tag{2.45}$$

"Vivid-Sombre"

$$VS = \left[\left\{ 2.2 \left(L^* - 10 \right) \right\}^2 + \left\{ 5.0 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 157 \tag{2.46}$$

"Strong-Weak"

$$SW = \left[\left\{ 2.1 \left(L^* - 90 \right) \right\}^2 + \left\{ 0.6 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 52 \tag{2.47}$$

"Dynamic-Passive"

$$DYP = \left[\left\{ 1.1 \left(L^* - 20 \right) \right\}^2 + \left\{ 3.8 \left(1 - \Delta h^\circ_{290} / 360 \right) C^* \right\}^2 \right]^{1/2} - 100 \tag{2.48}$$

"Gaudy-Plain"

$$GP = \left[\left\{ 0.4 \left(L^{*} - 10 \right) \right\}^{2} + \left\{ 3.8 \left(1 - \Delta h^{\circ}_{290} / 360 \right) C^{*} \right\}^{2} \right]^{1/2} - 95 \qquad (2.49)$$

"Striking-Subdued"

$$SS = \left[\left\{ 1.6 \left(L^{*} - 90 \right) \right\}^{2} + \left\{ 3.1 \left(1 - \Delta h^{\circ}_{290} / 360 \right) C^{*} \right\}^{2} \right]^{1/2} - 65 \qquad (2.50)$$

Where

$$\Delta h^{\circ}_{40} = \begin{cases} 40 - h^{\circ} \; ; \; 0 < h^{\circ} \leq 40 \\ h^{\circ} - 40 \; ; \; 40 < h^{\circ} \leq 220 \\ 400 - h^{\circ} \; ; \; 220 < h^{\circ} \leq 360 \end{cases} \qquad (2.51a)$$

and

$$\Delta h^{\circ}_{290} = \begin{cases} h^{\circ} + 70 \; ; \; 0 < h^{\circ} \leq 110 \\ 290 - h^{\circ} \; ; \; 110 < h^{\circ} \leq 290 \\ h^{\circ} - 290 \; ; \; 290 < h^{\circ} \leq 360 \end{cases} \qquad (2.51b)$$

2.1.7 Java programming language

2.1.7.1 Programming language

Programming languages are broadly classified into three levels: machine languages, assembly languages, and high-level languages. Machine language is the only programming language the CPU understands. Each type of CPU has its own machine language. For example, the

Intel Pentium and Motorola PowerPC understand different machine languages. Machine-language instructions are binary coded and very low level [14].

One level above machine language is assembly language, which allows "high level" symbolic programming. Instead of writing programs as a sequence of bits, assembly language allows programmers to write programs using symbolic operation codes. Since the CPU does not recognize programs written in assembly language, we use an assembler to translate programs written in assembly language into machine-language equivalents. Compared to writing programs in machine language, writing programs in assembly language is much faster, but not fast enough for writing complex programs.

High-level languages were developed to enable programmers to write programs faster than when using assembly languages. These language are FORTRAN (FORmula TRANslator), a programming language intended for mathematical computation, allows programmers to express numerical equations directly as

$$X = (Y + Z) / 2$$

COBOL (Common Business Oriented Language) is a programming language intended for business data processing applications. FORTRAN and COBOL were developed in the late 1905s and early 1960s and are still in use [14]. BASIC (Beginners All-purpose Symbolic Instructional Code) was developed specifical-level as an easy language for students to learn and use. BASIC was the first high-level language available for microcomputers. Another famous high-level language is Pascal, which was designed as an academic language. Since the CPU does not recognize programs written in a high-level language, we must use a compiler to translate them into assembly language equivalents.

The programming language C was developed in the early 1970s at AT&T Bell Labs [14]. The C++ programming language was developed as a successor of C in the early 1980s to add support for object-oriented programming. Object-oriented programming is a style of programming gaining wider acceptance today. Although the concept of object-oriented programming is old (the first object-oriented programming language, Simula, was developed in the late 1960s), its significance wasn't realized until the early 1980s [14].

2.1.7.2 Java programming language

Java is a new object-oriented language that is receiving a wide attention from both industry and academia. Java was developed by James Gosling and his team at Sun Microsystems in California. The language was based on C and C++ and was originally intended for writing programs that control consumer appliances such as toasters, microwave ovens, and others. The language was called Oak, named after the oak tree outside of Gosling's office, but the name was already taken, so the team renamed it Java.

Java is often described as a Web programming language because of its use in writing programs called applets that run within a web browser. That is, you need a web browser to execute

Java applets. Java is receiving phenomenal attention today because of applets, a feature unique to Java. Applets allow more dynamic and flexible dissemination of information on the Internet, and this feature alone makes Java an attractive language to learn. However, we are not limited to writing applets in Java. We can write Java application also. A Java application is a complete stand-alone program that does not require a web browser. A Java application is analogous to a program we write in other programming languages.

The usefulness of Java programming language:

1. JAVA is a program, which is simple for study.
2. It is a robust program.
3. It is a secure program for transfer one to the other computers.
4. It is a platform independent program.

2.1.7.3 Classes and Objects

The two most important concepts in object-oriented programming are the class and the object. In the broadest term, an object is a thing, both tangible and intangible, that we can imagine. A program written in object-oriented style will consist of interacting objects. An object is comprised of data and operations that manipulate these data. Almost all nontrivial programs will have many objects of the same type. Inside a program we write instructions to create objects. For the computer to be able to create an object, we must provide a definition, called a class. A class is a kind of mold or template that the computer used to create object. An object is called an instance of a class. An object is an instance of exactly one class. An instance of a class belongs to the class [15].

2.2 Literature Review

Nakamura et al. [15] derived the color image formulae and expressed the visual assessment against twele color image word pairs of "Vivid-Sombre", "Deep-Pale", "Warm-Cool", "Light-Dark", "Heavy-Light", Gaudy-Plain", "Striking-Subdued", "Dynamic-Passive", "Distinct-Vague", "Transparent-Turbid", "Soft-Hard" and "Strong-Weak" in order to perform the numerical expression of human color image perception. The visual assessment, which computed from colorimetric values, was compared with the MUNSELL and CIELAB values. Each value from the empirical formulae was represent the color image to make the color image diagram and also projected the MUNSELL and CIELAB color order system on the diagrams.

Ho [16] researched about the relationship between colorimetric values and each opponent pair of the color images, "Warm-Cool", "Dynamic-Passive", "Light-Dark" and "Soft-Hard". The difference of the color images between the Japanese and British observers were also examined.

"Warm-Cool" color image was influenced by hue and chroma. "Dynamic-Passive" color image was dominated by chroma. "Light-Dark" color image was directly proportional to the lightness. "Soft-Hard" color image was determined by lightness and chroma. The difference between the British observer in "Soft-Hard" color image was found that Chroma C* more than 65 gave the British observers a Hard image while these color gave the Japanese observers a Soft image. The "Light-Dark" color image for British observers had a higher correlation with the lightness than Japanese observers.

Ngampatipatpong [17] attempts to link the gap between physical and perceptual colors parameter by deriving the quantitative visual scale of the word which express human color perception which using the twelve opponent word pair and relevant to calorimetric values. The derivation of the visual assessment and calorimetric values establishes the color perception equation. It can analyze the calorimetric characteristic of the visual scale in CIEL*,C*, h^{o} color space and then obtain the color perception map. This diagram determines the relationship between the twelve opponent word pairs into three groups, which are dominated by chroma, lightness and hue, respectively.

Sato et al. [18] presented the affective tone of color that was quantitatively analyzed from psychological viewpoints. The fundamental factors were "Light-Dark", "Deep-Pale" and "Heavy-Light" feeling. The feeling of various colors was verified with the above factors in term of correlated colorimetric values that related to the affective tone. The visual assessment was compared with lightness, color depth and the other parameter that computed from the colorimetric values in order to set of empirical formulae. The affective tone of color indicated that the feeling is mainly affected by lightness and color depth.

Sato et al. [19] performed a visual experiment to analyze quantitatively the feeling of color in terms of colorimetric values. The visual experiment confirmed that the feeling were mainly affected by Munsell chroma and Munsell value. Finally, the empirical formulae were established to represent the feeling as follow.

$$CI = \left[\{ k_v (V - V_0) \}^2 + \{ k_c (C - C_0) \}^2 \right]^{1/2} + k_s \qquad (2.52)$$

where, CI is color image value

V is Munsell value

C is Munsell chroma

V_0 is Munsell value when the color image percent is minimum

C_0 is Munsell chroma when the color image percent is minimum

k_v is constant of the contribution of Munsell value for the color image

k_c is constant of the contribution of Munsell chroma for the color image

k_s is constant for the scaling of the color image

Ngampatipatpong et al. [20] derived the quantitative visual scale of the word which express human emotion by using the opponent word pair and relevant to calorimetric values. The experiment establishes color emotion scale of Thai observers, which relates to its lightness and chroma.

Sato et al. [21] used the numerical expression of color emotion to find the instrumentally assessment. The twenty-four color emotion formulae based on the Munsell and CIELAB color systems were derived. The characteristic of color emotion simulated through the above fprmulae was indicated as color emotion lines in Munsell color system and the color emotion map was developed.

Xin et al. [22] investigated the twelve color emotion pairs and quantifying them with standard color specifications. The mathematical models were derived using the obtained visual assessment result from Hong Kong Chinese. Chroma of a color was found to be the dominant parameter affecting the "Warm-Cool", "Vivid-Sombre", "Gaudy-Plain", "Striking-Subdued" and "Dynamic-Passive" color emotions. Lightness of color was found to be the dominant parameter affecting the "Deep-Pale", "Heavy-Light", "Transparent-Turbid", "Soft-Hard" and "Strong-Weak" color emotions. For the "Light-Dark" and "Distinct-Vague" color emotion were influenced by both the chroma and lightness of colors. The obtained visual assessment results from the Japanese, Thai and Hong Kong people were compared and very good correlation in the "Transparent-Turbid" was found among these countries.

Bangchokdee [13] studied further the numerical expression of the color perception corresponding to twelve opponent word pairs through seven-point assessments carried out by Thai observers. The twelve color perception equations were derived from the relationship between the colorimetric values and visual assessments. The obtained visual results between methods and countries were compared by correlation and paired t-test in terms of hue and tone at a significant level of 0.05. High relationships based on correlation coefficients between methods were found. Then all twelve word pairs and hue differences were found in "Warm-Cool" and in "Gaudy-Pain" of achromatic color, while tone comparisons were different at all twelve tones. There was a significant relationship between countries, with the exception of the "Deep-Pale". Hue differences tended to occur in all twelve tones. Visual results occurred with Japanese test subjects that were translated to Thai though color perception equations, showing high correlation with Thai data. There was an exception with "Soft-Hard". It was particularly interesting to examine the obtained colorimetric properties of the color perception between Japanese and Thai persons. A color perception map used in this study can directly translate the magnitude of the color perception.