Color Image Processing

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Introduction

- In automated image analysis, color is a powerful descriptor, which simplifies object identification and extraction.
- The human eye can distinguish between thousands of color shades and intensities but only about 20-30 shades of gray. Hence, use of color in human image processing would be very effective.
- Color image processing consists of two parts: Pseudo-color processing and Full color processing.

Introduction (con'd)

- Pseudo-color processing:
  (false) colors are assigned to a monochrome image.
  - For example, objects with different intensity values maybe assigned different colors, which would enable easy identification/recognition by humans.
- Full-color processing:
  images are acquired with full color-sensors/cameras.
  - This has become common in the last decade or so,due to the easy and cheap availability of color sensors and hardware.

Color Fundamentals

- When a beam of sunlight is passed through a glass prism, the emerging beam of light is not white but consists of a continuous spectrum of colors (Sir Isaac Newton, 1666).
- The color spectrum can be divided into six broad regions:
  violet, blue, green, yellow, orange, and red.

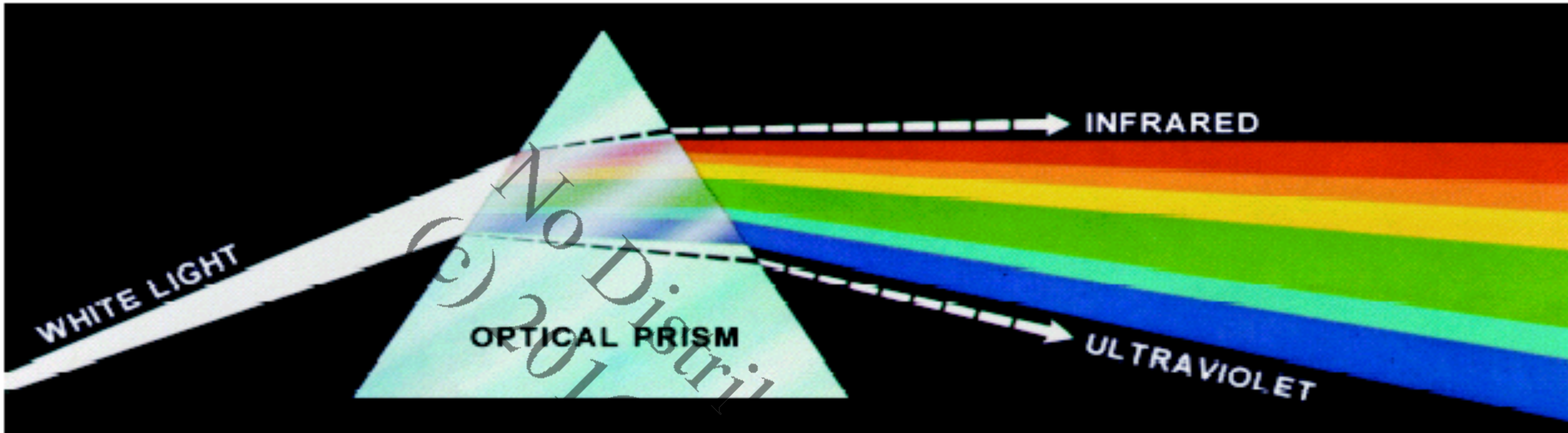


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

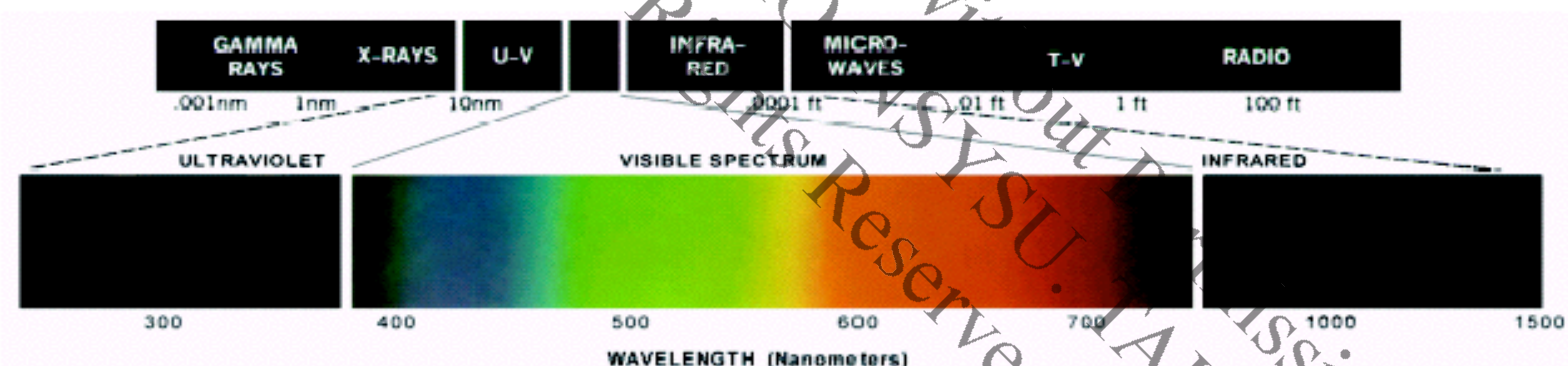


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

Color Fundamentals

- Color perceived by the human eye depends on the nature of light reflected by an object.
- Light that is relatively balanced in all visible wavelengths is perceived as white.
- Objects that appear green reflect more light in the 500-570 nm range (absorbing other wavelengths of light).

Color Fundamentals

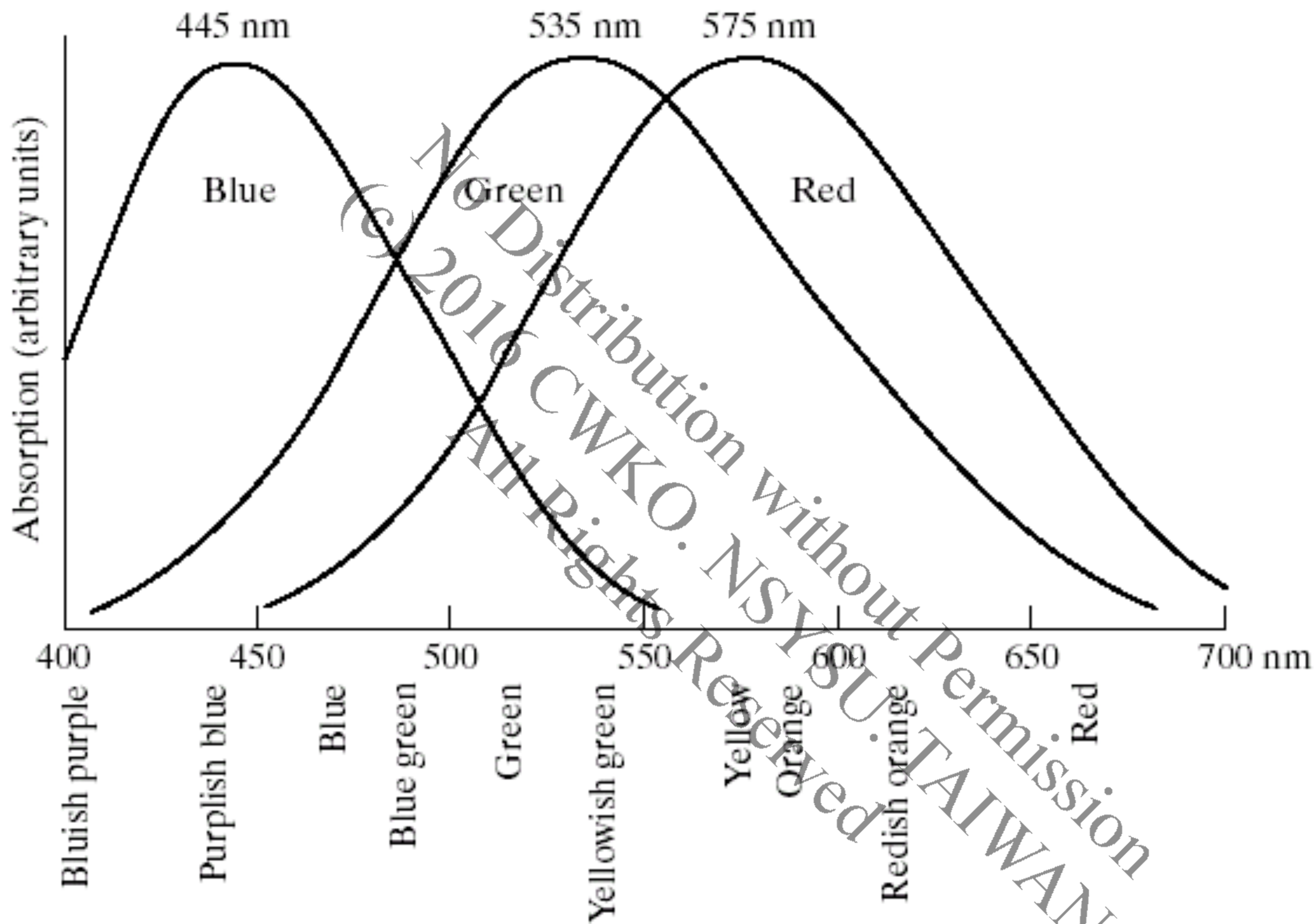
- Characterization of light is important for the understanding of color.
- If the light is achromatic (devoid of color), its only attribute is its intensity (amount of light).
  - This is what we have been dealing with so far.
  - The term gray-level refers to the scalar measure of the intensity of light -- black to grays to white.
- Chromatic light spans the electromagnetic (EM) spectrum from approximately 400 nm to 700 nm.

Basic quantities to describe the quality of a chromatic source of light

- Radiance is the total amount of light that flows from a light source (measured in Watts).
- Luminance gives a measure of the amount of energy an observer perceives from a light source (measured in lumens).
- Brightness is a subjective descriptor that is impossible to measure.

Human eyes vs. color image

- Cones in the retina are responsible for color perception in the human eye.
- Six to seven million cones in the human eye can be divided into three categories:
  - red light sensitive cones (65%)
  - green light sensitive cones (33%)
  - blue light sensitive cones (2%).
  - The latter cones are the most sensitive ones.

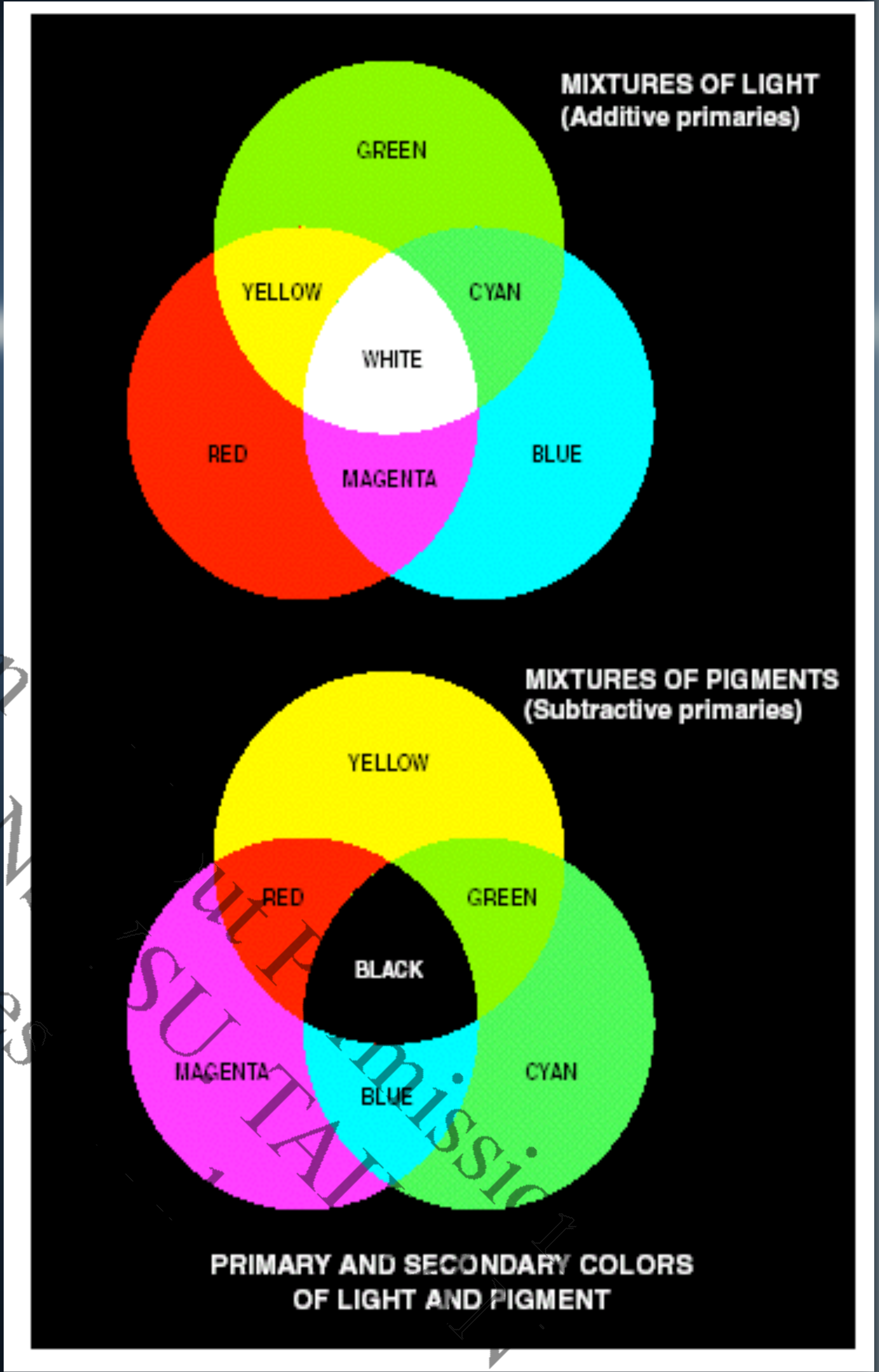

445 nm
535 nm
575 nm
Absorption (arbitrary units)
Blue
Green
Red
400
450
500
550
600
650
700 nm
Bluish purple
Purplish blue
Blue
Blue green
Green
Yellowish green
Yellow
Orange
Redish orange
Red

Primary Colors

- Red (R) (700 nm)
  Green (G) (546.1 nm)
  Blue (B) (435.8 nm)
- The wavelengths for the three primary colors are established by standardization by the CIE (International Commission on Illumination).
  - They correspond to the experimental curve only approximately.

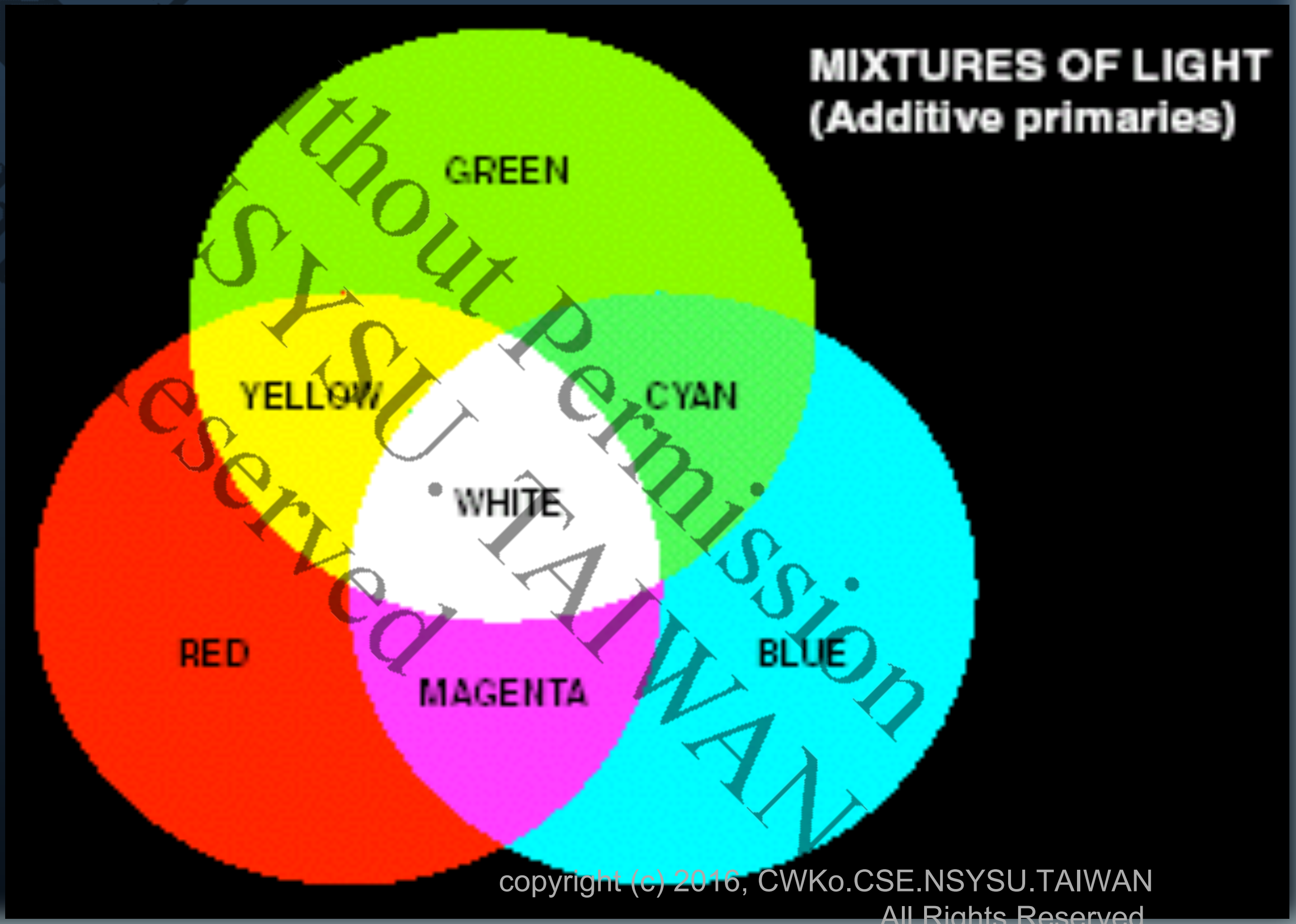
Primary and Secondary

- Primary colors when added produce secondary colors:
  - Magenta (red + blue)
  - Cyan (green + blue)
  - Yellow (red + green)



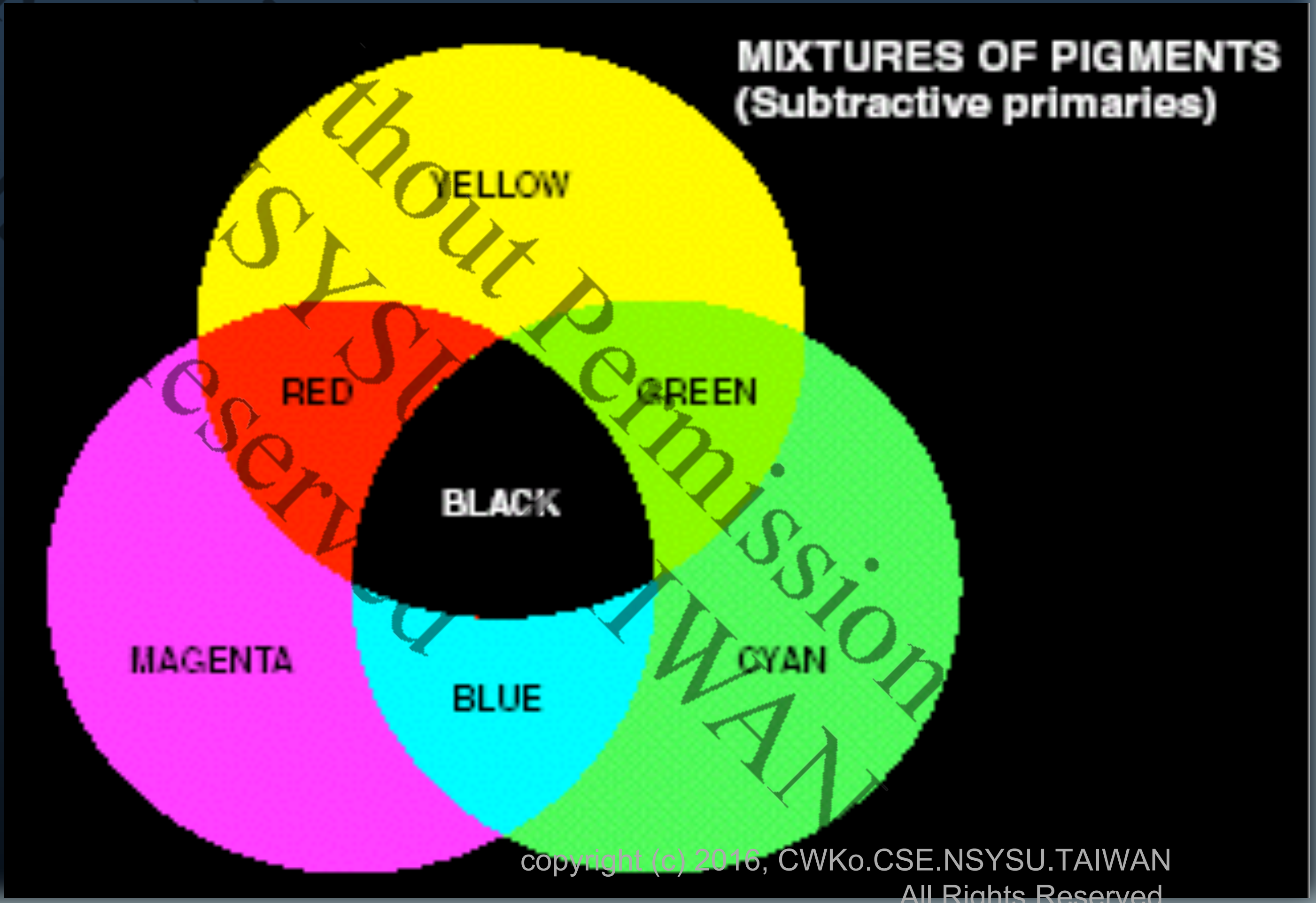
Primary and Secondary

- Mixing the three primaries, or a secondary with its opposite primary, in the right intensities produces white light.



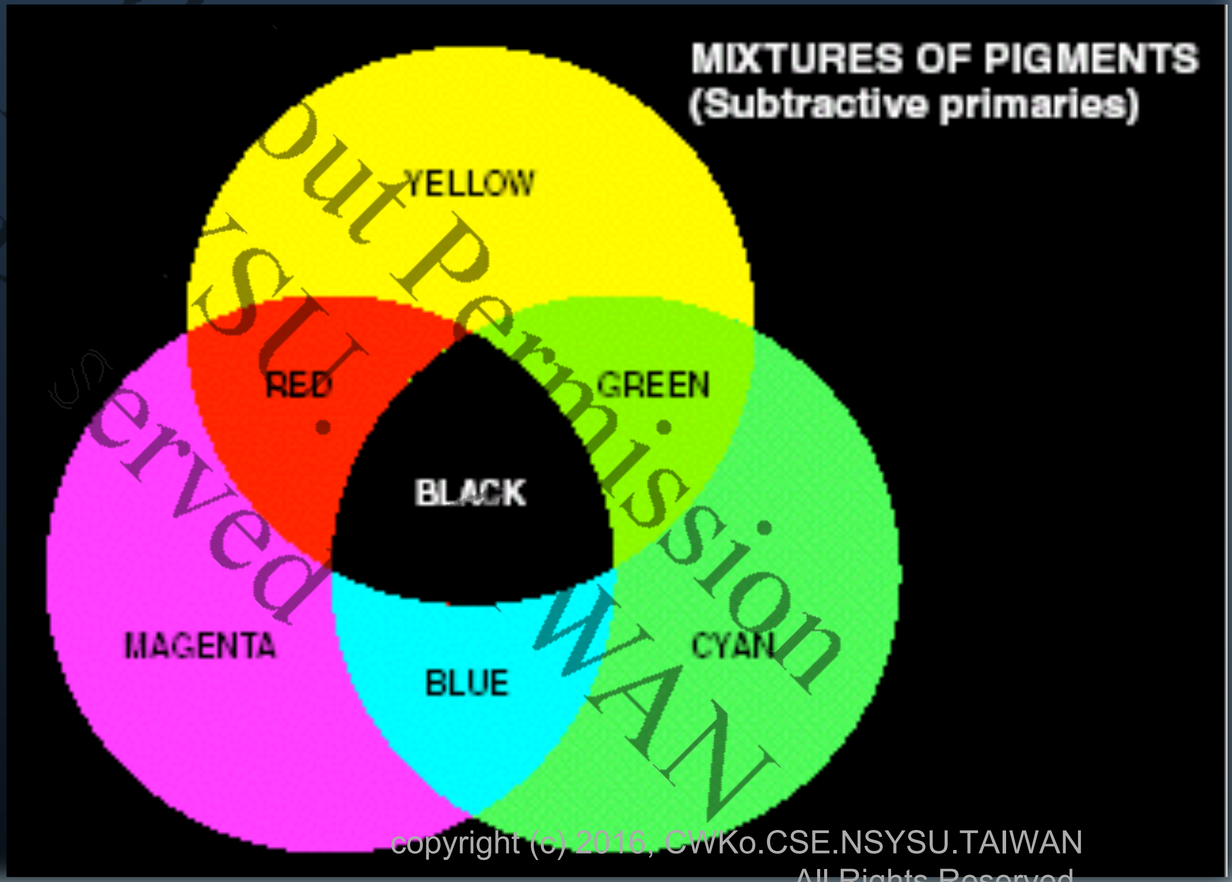
Primary and Secondary

- A primary color of pigment is defined as one that subtracts or absorbs a primary color of light and reflects or transmits the other two.



Primary and Secondary

- The primary colors of pigments are magenta, cyan, and yellow
- The secondary colors of pigment are red, green, and blue.



Primary and Secondary: Example

- Color television or a computer monitor is an example of additive nature of the color of light.
  - The inside of the screen is coated with dots of phosphor, each being capable of producing one of the three primary colors.
  - A combination of light of the three primary colors produces all the different colors we see.

Primary and Secondary: Example

- Printing is an example of the subtractive nature of color pigments.
  - For example, a pigment of red color actually absorbs light of all wavelengths, except that corresponding to red color.

Characteristics of Color

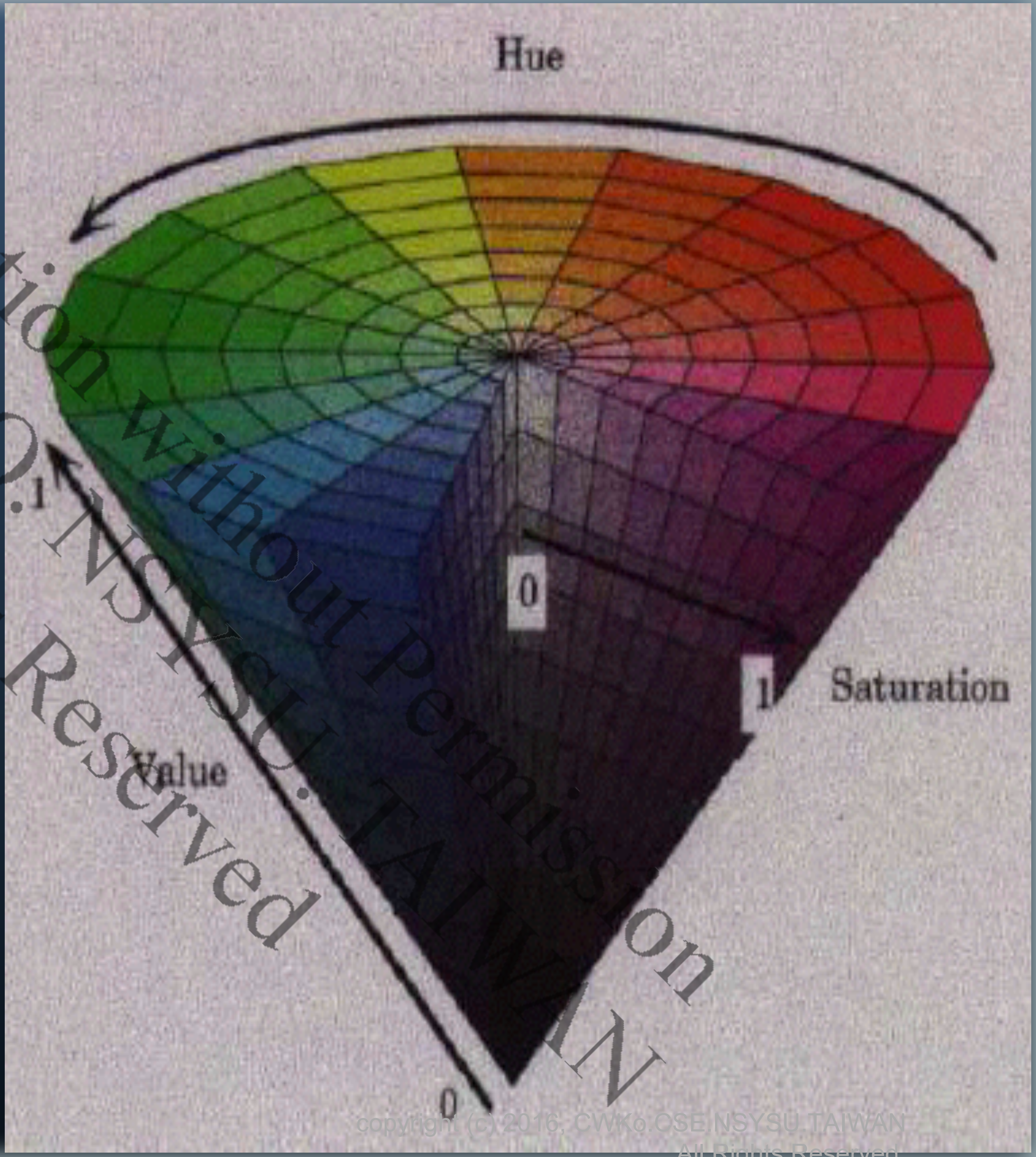
- Brightness (or value)
  - embodies the chromatic notion of intensity.
- Hue
  - associated with the dominant wavelength in a mixture of light waves.
  - It represents the dominant color as perceived by an observer (e.g. orange, red, violet).

Characteristics of Color

- Saturation
  - refers to the relative purity or the amount of white light mixed with a hue.
  - Pure colors are fully saturated.
  - Colors such as pink (red + white) and lavender (violet + white) are less saturated, with the saturation being inversely proportional to the amount of white light added.

Characteristics of Color

- Hue and saturation together are called chromaticity.
- A color can be described in terms of its brightness and chromaticity.



Tristimulus Values

- The amounts of red, green, and blue needed to form any particular color are called the tristimulus values and are denoted by X, Y, and Z, respectively.
- In general, color is specified by its three trichromatic coefficients:

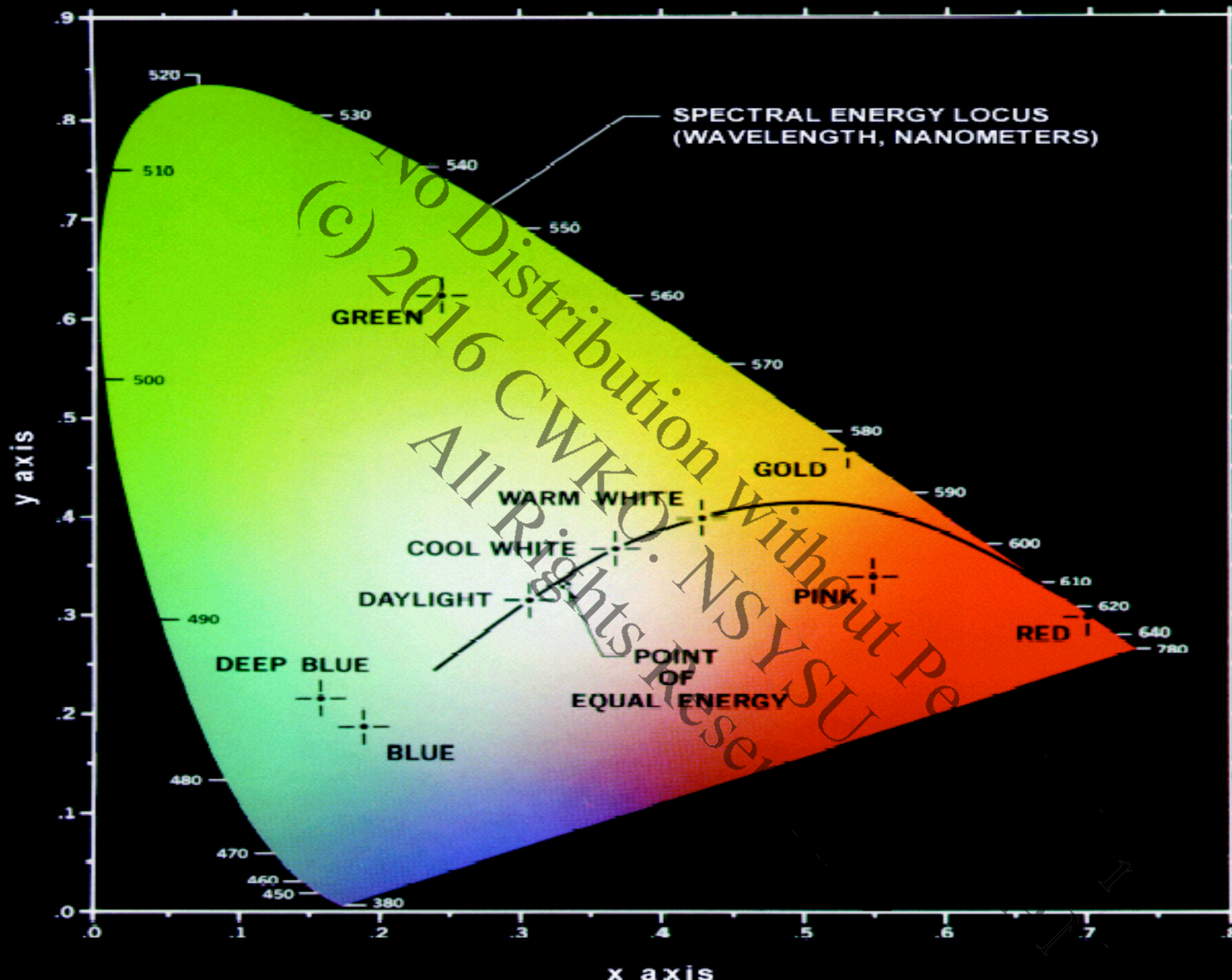
$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z}$$

$$x + y + z = 1$$

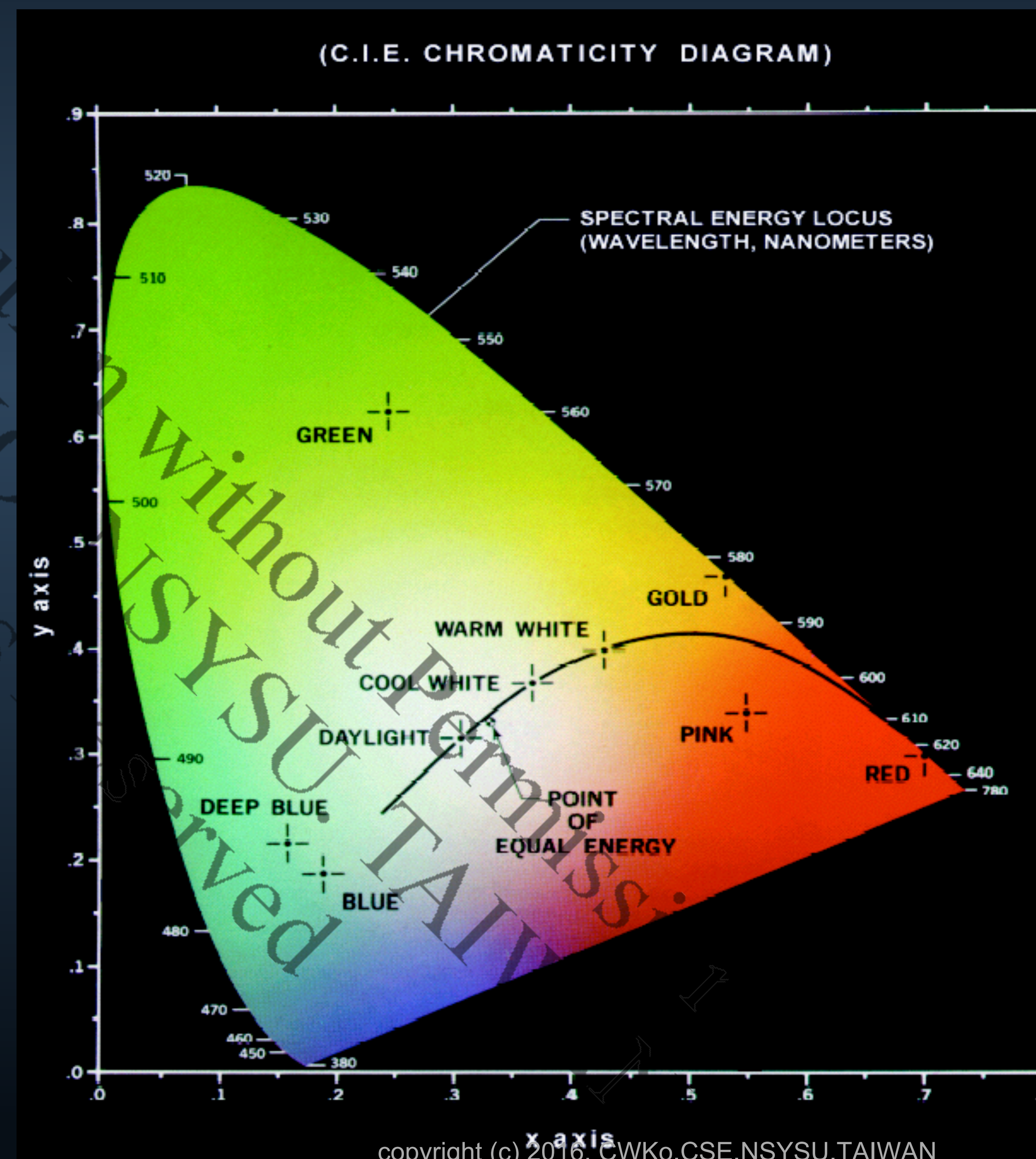
Chromaticity Diagram

- Another approach to specifying colors is via the CIE chromaticity diagram, which represents color composition by means of x (red) and y (green) values.
- For any value of x (red) and y (green), the corresponding value of z (blue) is given by $z=1-(x+y)$.

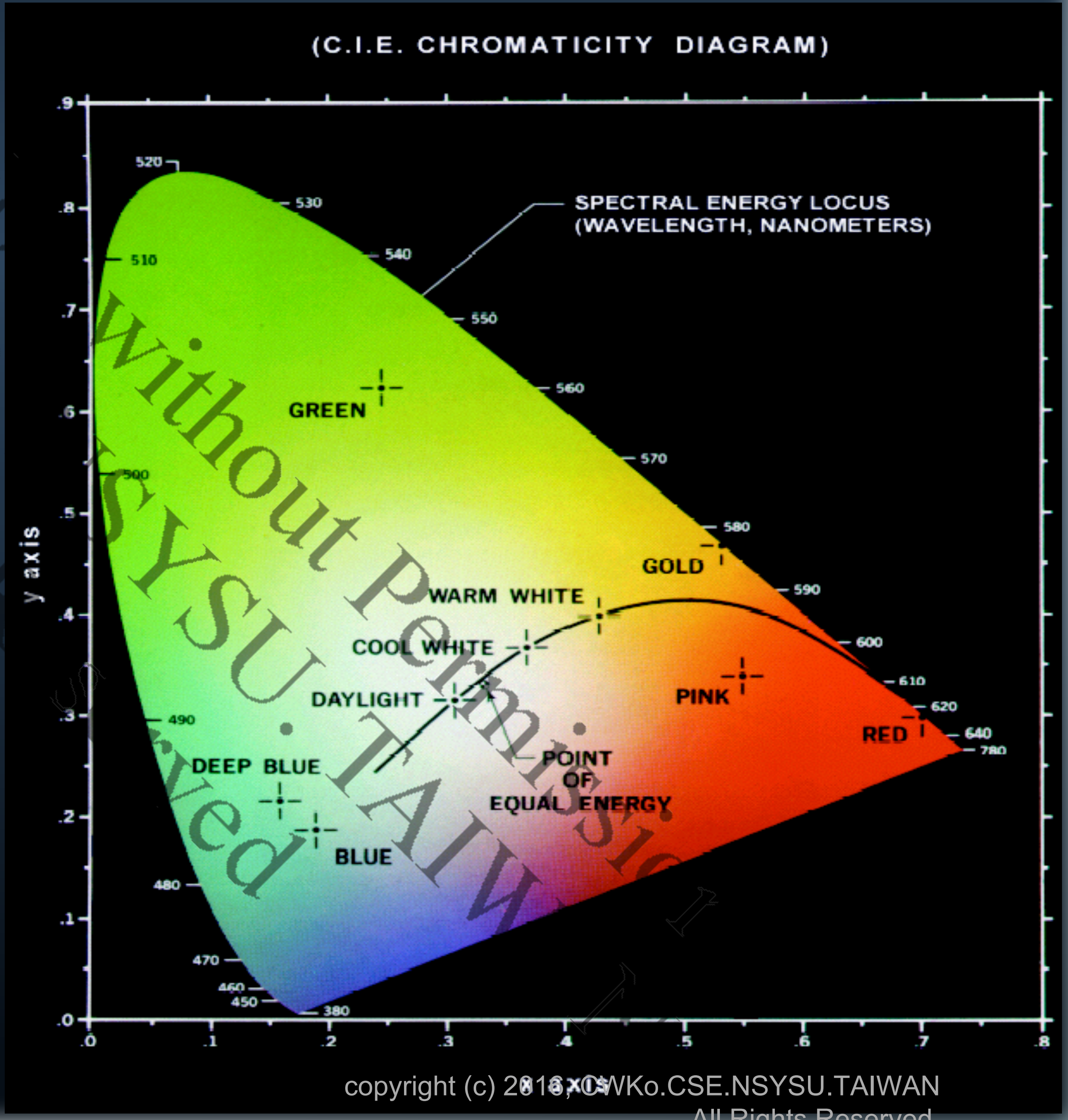
(C.I.E. CHROMATICITY DIAGRAM)



- The positions of various spectrum colors (completely saturated or "pure" colors) are indicated along the boundary of the tongue-shaped chromaticity diagram.
- Points inside this region represent some mixture of the pure colors.
- Point of equal energy corresponds to equal fractions of the three primary colors.



- As a point leaves the boundary and moves towards the center, more white light is added to the color and it becomes less saturated.
- The point of equal energy corresponds to zero saturation.
- The chromaticity diagram can be used for color mixing, since a line joining two points in the diagram represents all the colors that can be obtained by mixing the two colors additively.



- The triangular region enclosed by the line segments joining three points in the chromaticity diagram represents all the colors that can be obtained by combining the three colors.

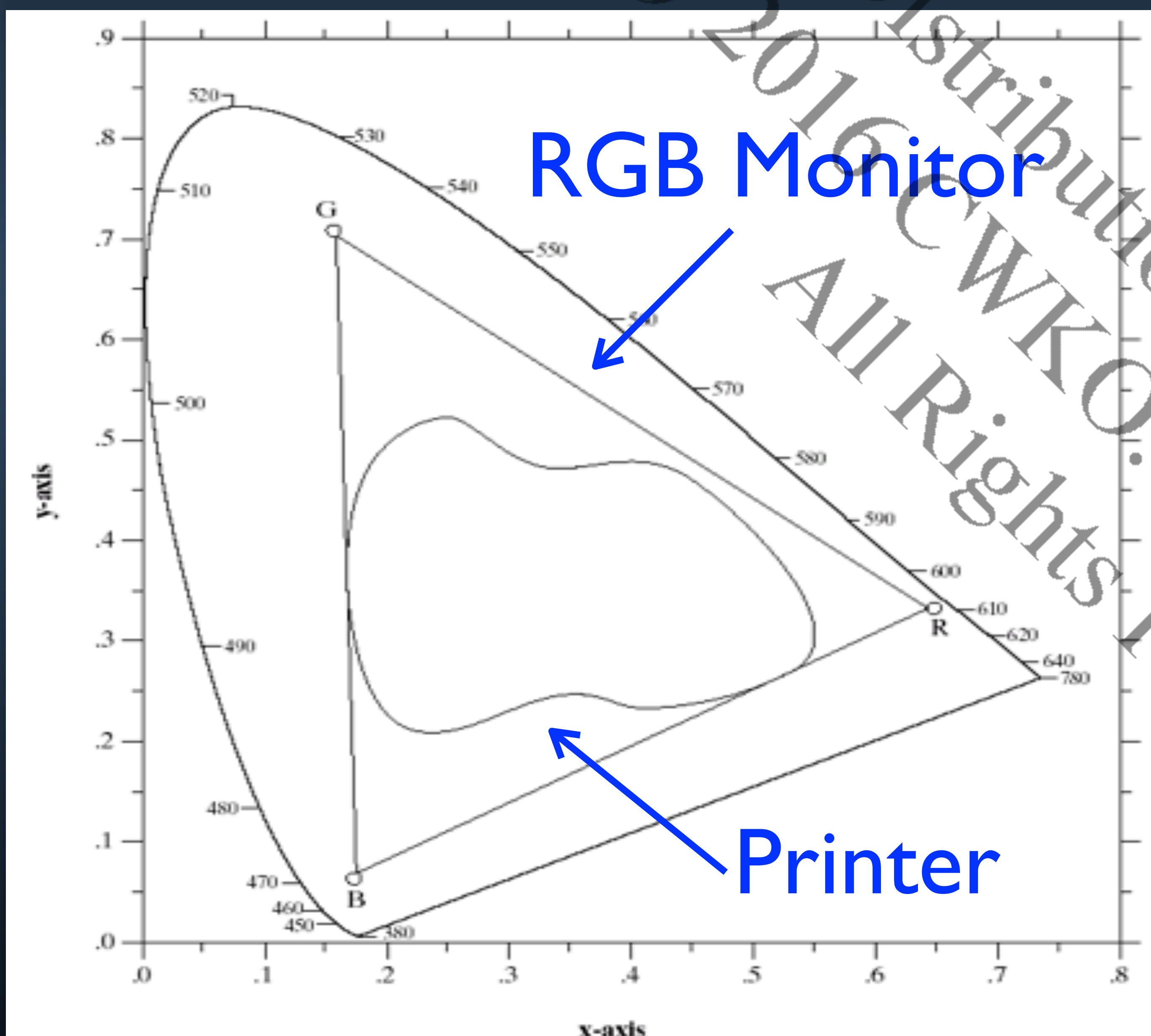
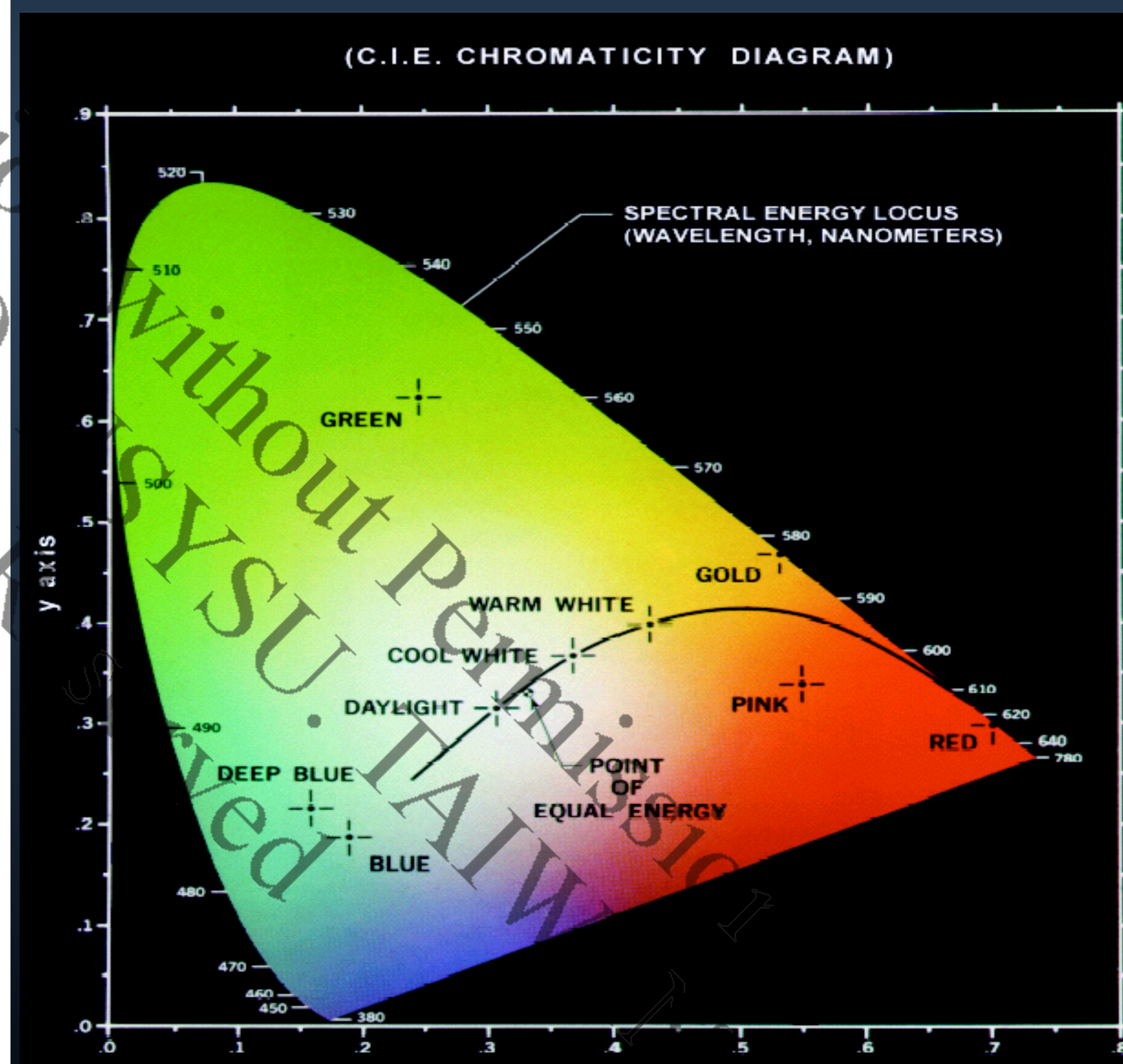


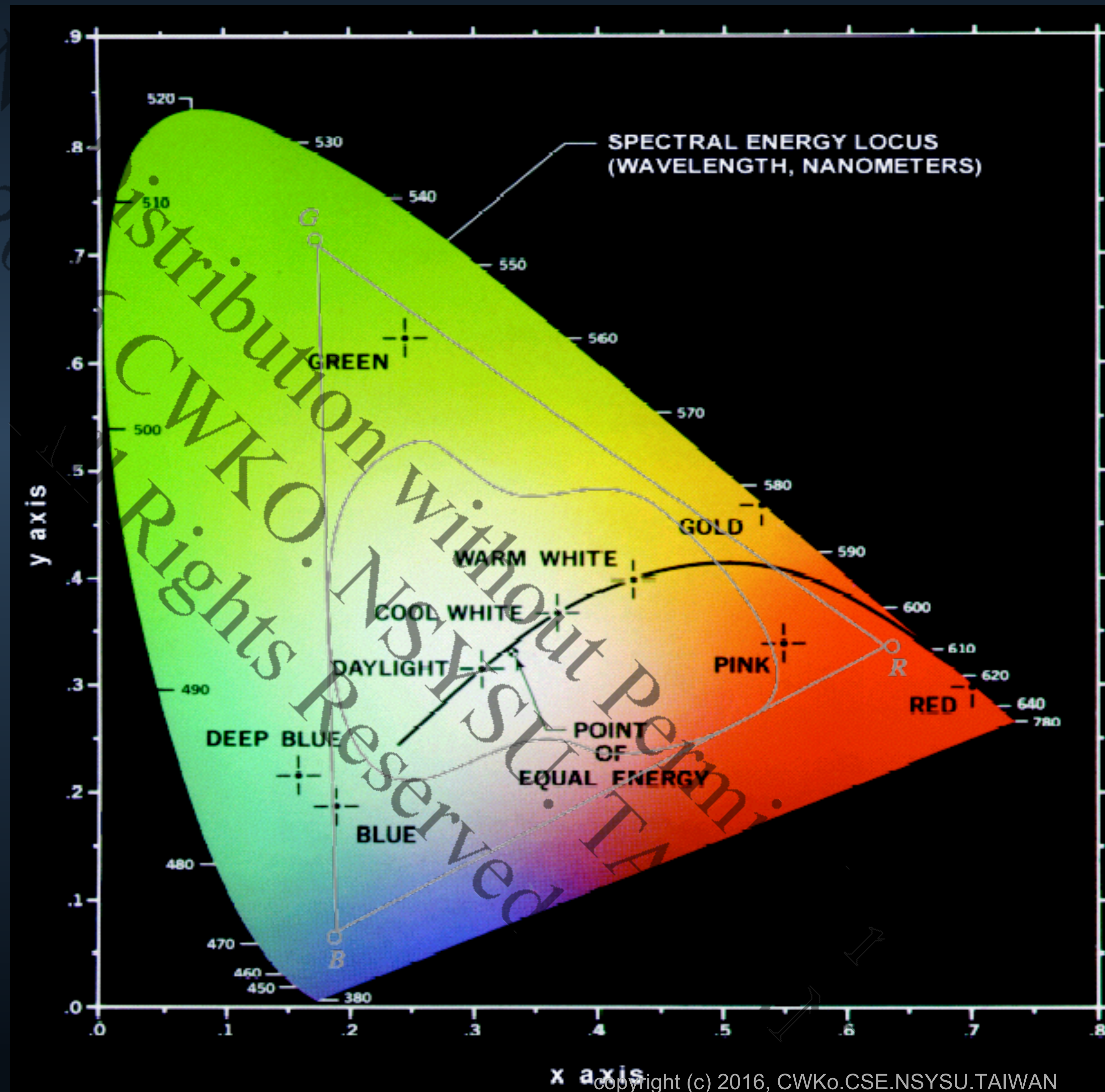
FIGURE 6.6 Typical color gamut of color monitors (triangle) and color printing devices (irregular region).



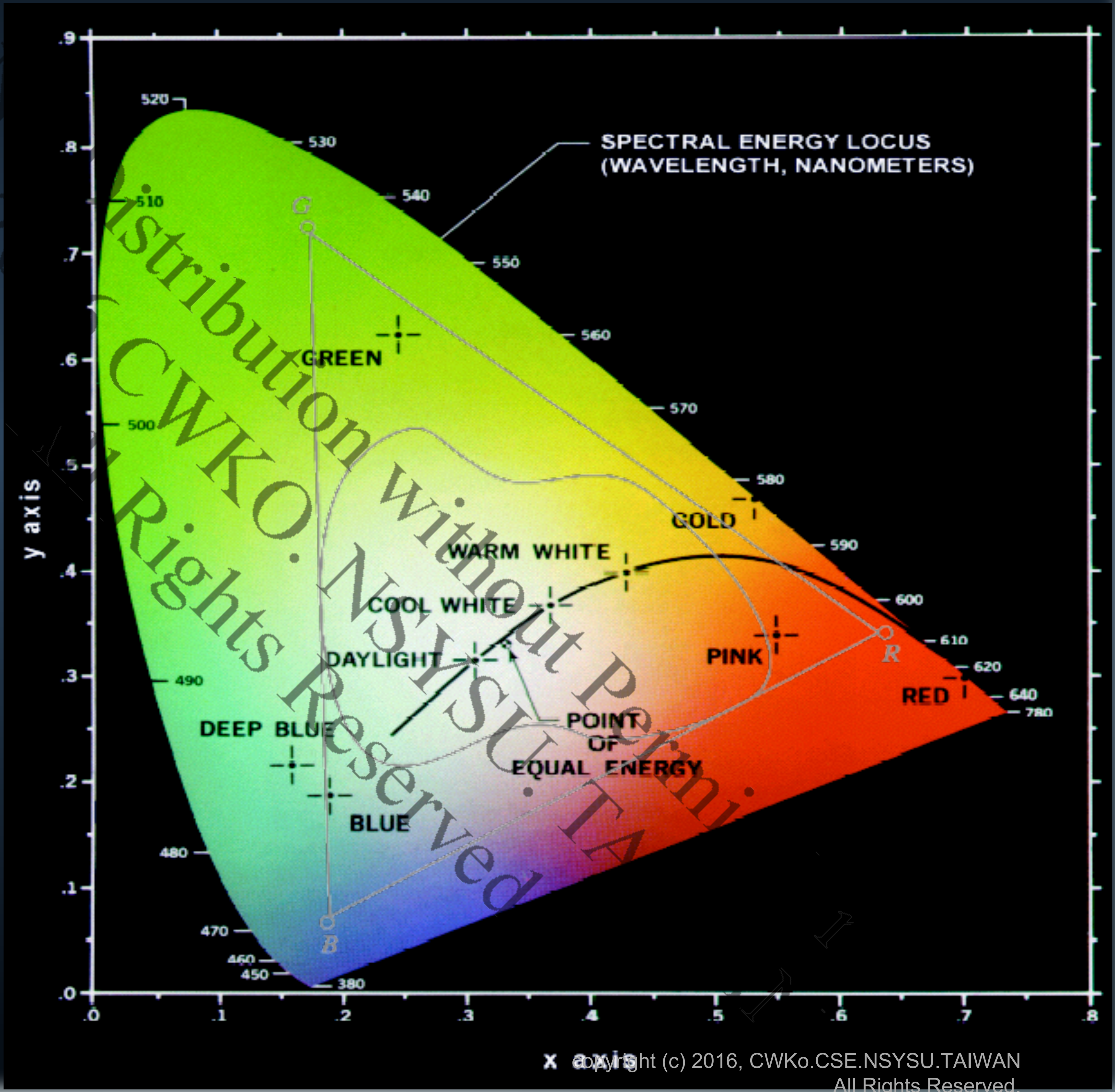
Chromaticity Diagram

- This is consistent with the remark made earlier that the three pure primary colors by themselves cannot produce all the colors (unless we change the wavelengths as well).

- The triangular region represents the typical range of colors (gamut of colors) produced by RGB monitors.



- The irregular region inside the triangular region represents the color gamut of modern high-quality color printers.



Color Models

- The purpose of a color model (or color space or color system) is to facilitate the specification of color in some standard fashion.
- A color model is a specification of a 3-D coordinate system and a subspace within that system where each color is represented by a single point.
- Most color models in use today are either based on hardware (color camera, printer) or on applications involving color manipulation (computer graphics, animation).

Color Models

- In image processing, the hardware based color models mainly used are: RGB, CMYK, and HSI.

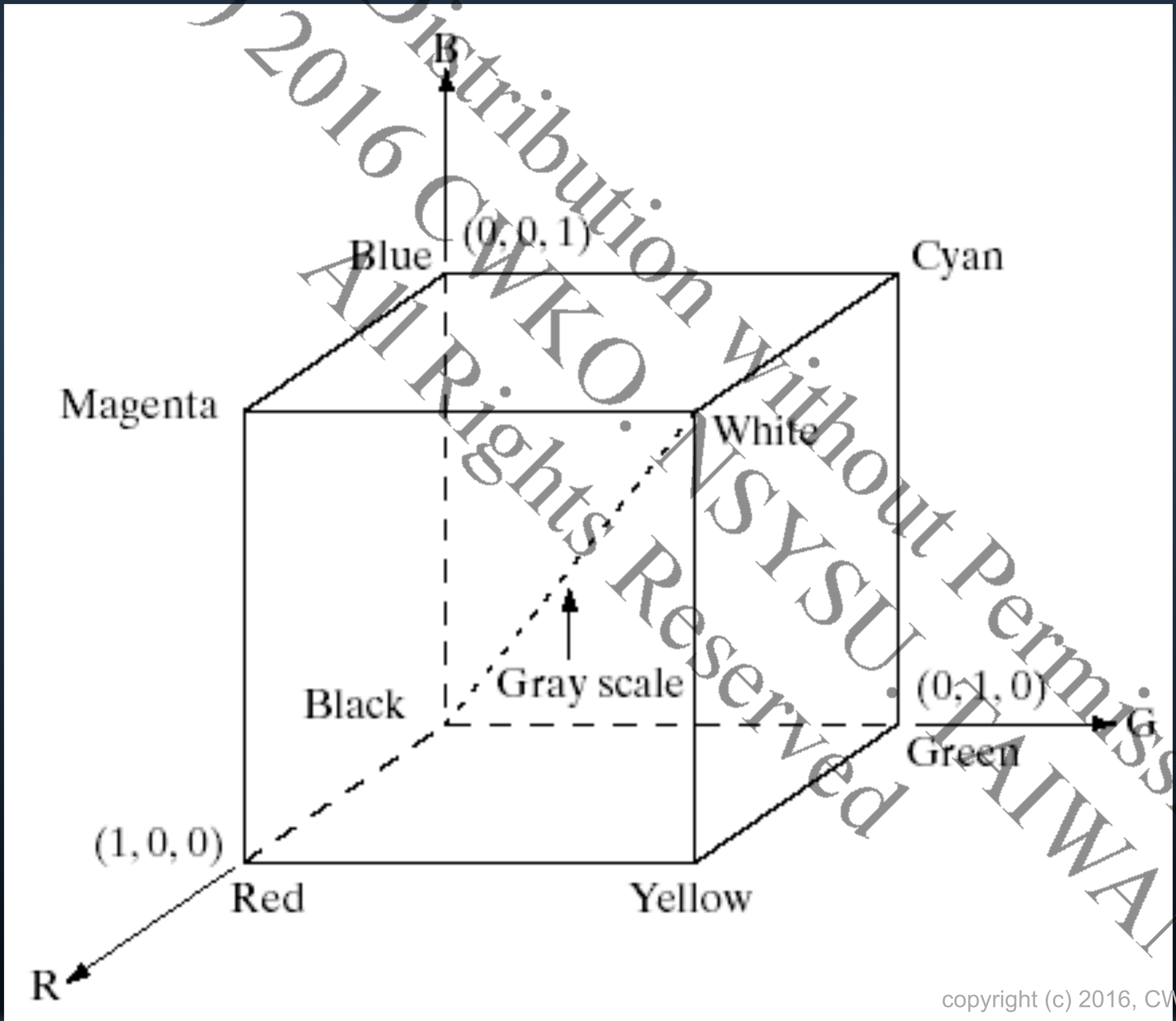
Color Models

- RGB (red, green, blue) color system
  - mainly in color monitors and video cameras.
- CMYK (cyan, magenta, yellow, black)
  - is used in printing devices.
- HSI (hue, saturation, intensity)
  - based on the way humans describe and interpret color.
  - It also helps in separating the color and grayscale information in an image.

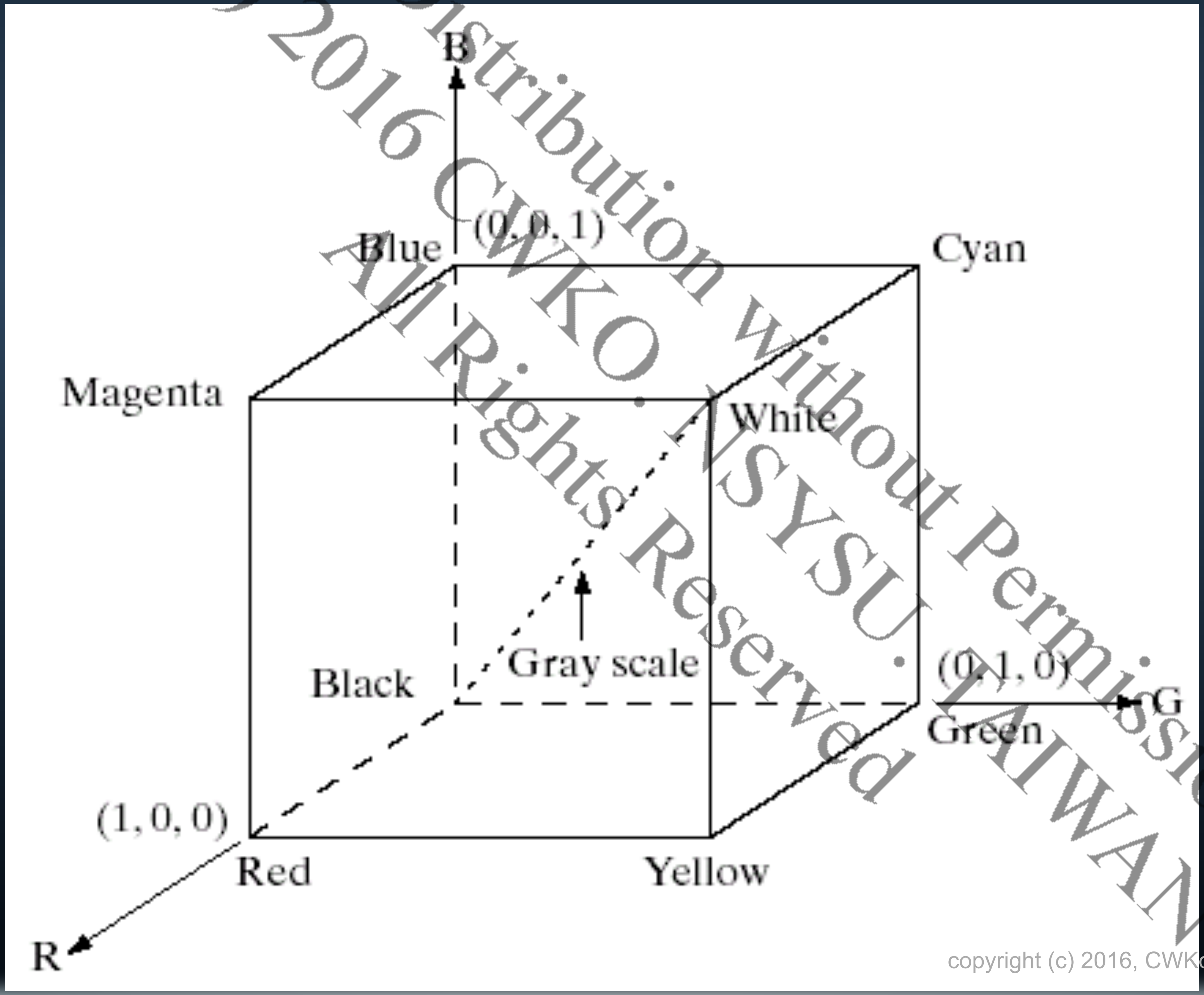
RGB Color Model

- Each color appears in its primary spectral components of red (R), green (G), and blue (B).
- Mainly used for hardware such as color monitors and color video camera.

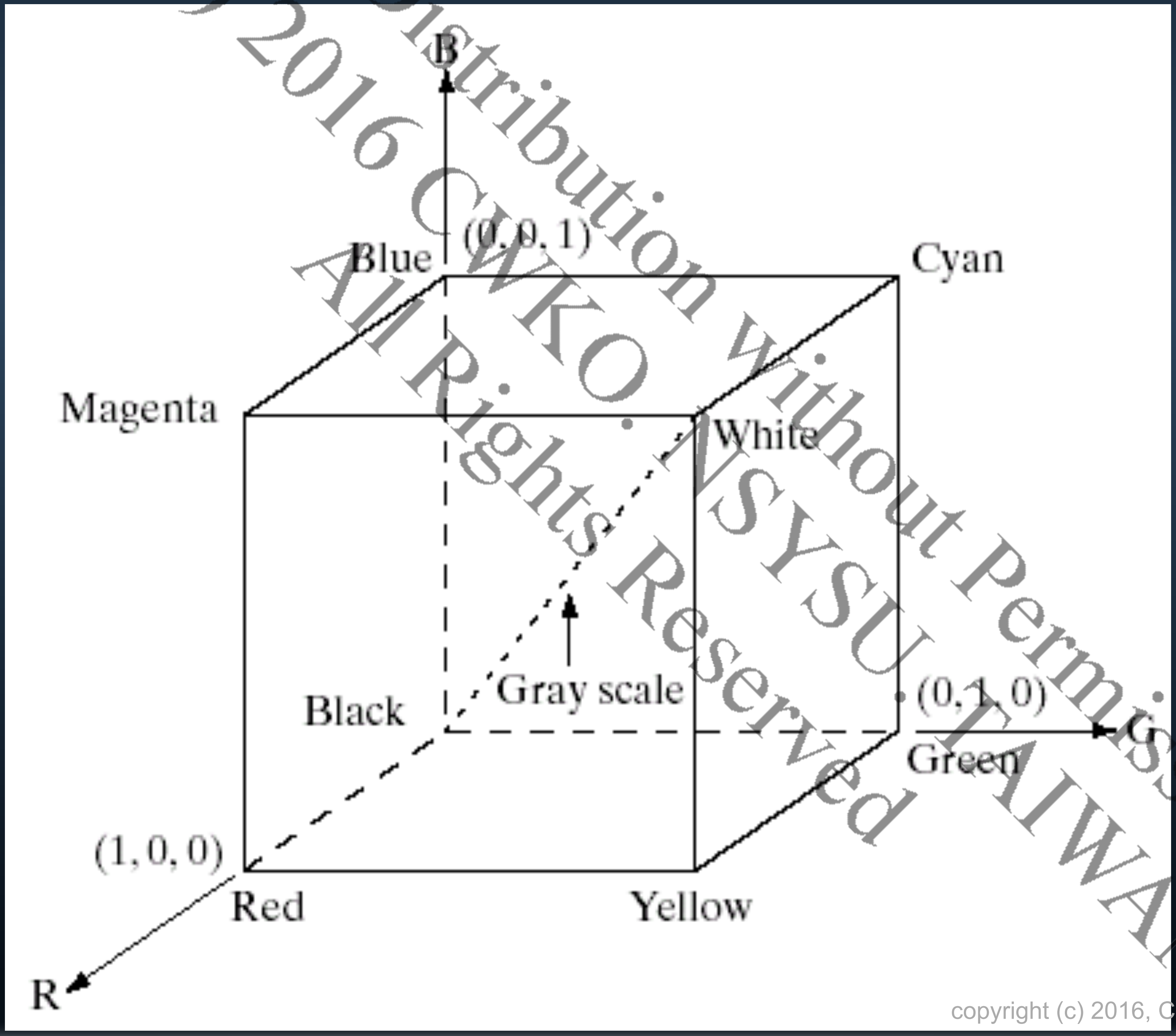
- It is based on a Cartesian coordinate system. All color values are normalized so that the values of R, G, and B are in the range [0,1]. Thus, the color subspace of interest is the unit cube.



- The primary colors red, green, and blue correspond to three corners of the cube
- The secondary colors cyan, magenta, and yellow correspond to three other corners.



- Origin (0,0,0) represents black and (1,1,1) represents white.
- Grayscale (monochrome) is represented by the diagonal joining black to white.



RGB Color Model

- Different points on or inside the cube correspond to different colors and can be represents as a vector or three values or coordinates.
- Each coordinate represents the amount of that primary color present in the given color.

RGB Color Model

- Images in the RGB model consist of three independent component images, one for each primary color.
- When fed to into an RGB monitor, these three images combine on the phosphor screen to produce a composite color image.
- The number of bits used to represent each pixel in RGB space is called pixel depth.

RGB Color model

- if eight bits are used to represent each of the primary components, each RGB color pixel would have a depth of 24 bits.
  → full color image.
- $2^{24} = 16,777,216$

Safe RGB Colors

- Although high-end monitors can display true 24-bit colors, more modest display devices are limited to smaller (typically 256) set of colors.
- Moreover, in many applications, it not useful to use more than a few (say 10-20) colors.

Safe RGB Colors

- Given the variety of display devices, it is useful to have a small subset of colors that are reproduced reliably and faithfully, independently of the display hardware specifics.
- This subset of colors is referred to as safe RGB colors or the set of all-systems-safe colors.
  - They are also referred to as safe web colors or safe browser colors in internet applications.

Safe RGB Colors

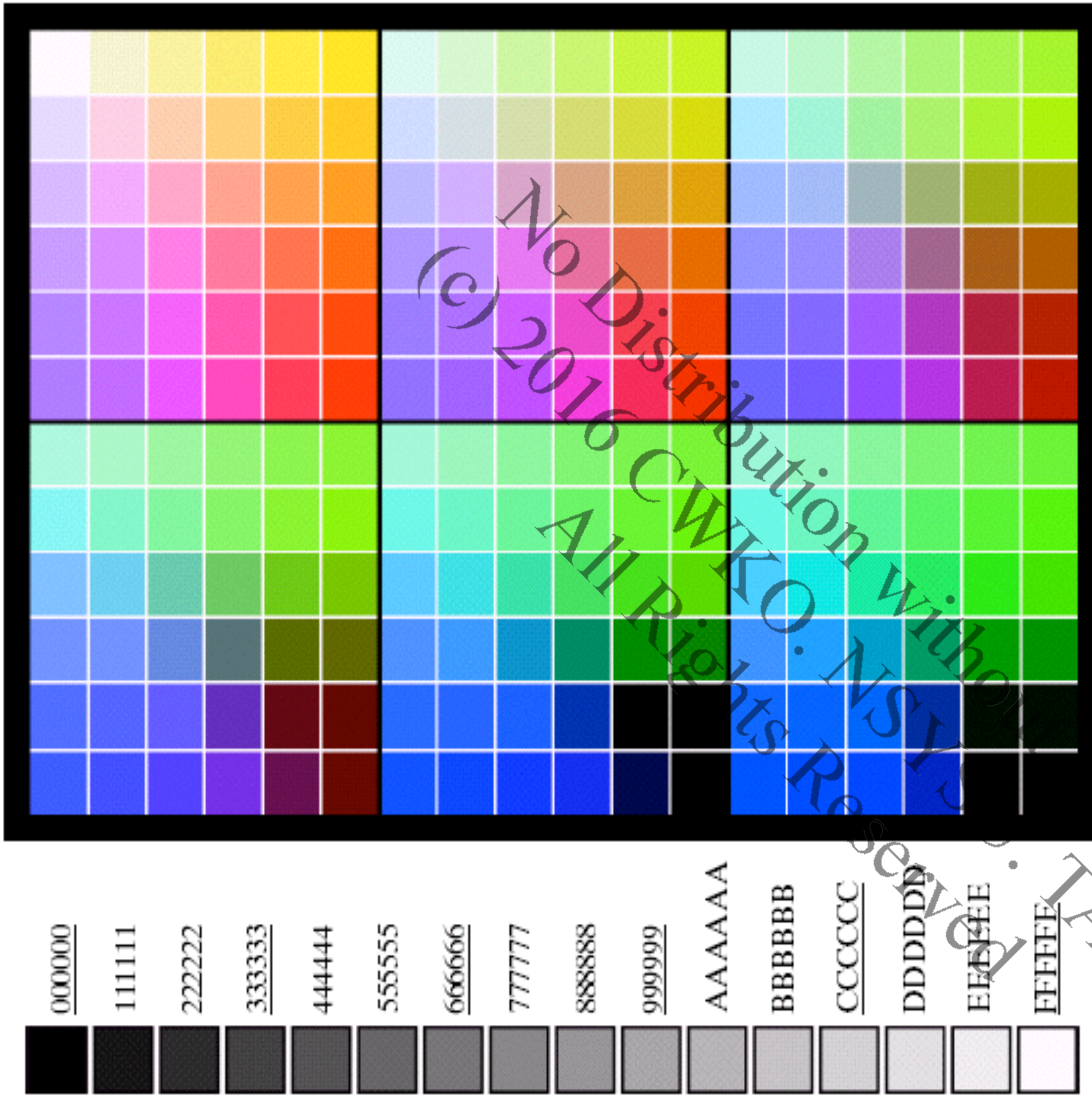
- Assuming 256 distinct colors as the minimum capability of any color display device, a standard notation to refer to these "safe" colors is necessary.
- 40 of these 256 colors are known to be processed differently by various operating systems, leaving 216 colors that are common to most systems.

Safe RGB Colors

- These 216 colors are formed by a combination of RGB values,
- Each component is restricted to be one of possible six values in the set {0, 51, 102, 153, 204, 255} or using hexadecimal notation {00, 33, 66, 99, CC, FF}.
  - Note that all the values are divisible by 3.

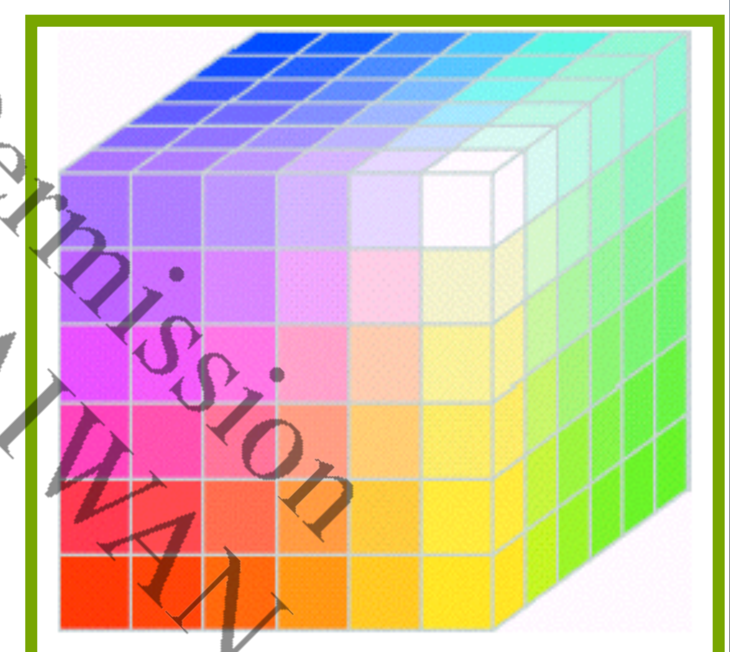
Safe RGB Colors

- These 216 colors have become de facto standard for safe colors, especially in internet applications.
- They are commonly used, whenever it is desired that the colors viewed by most people appear the same.



a
b

FIGURE 6.10
(a) The 216 safe RGB colors.
(b) All the grays in the 256-color RGB system (grays that are part of the safe color group are shown underlined).



Color Models

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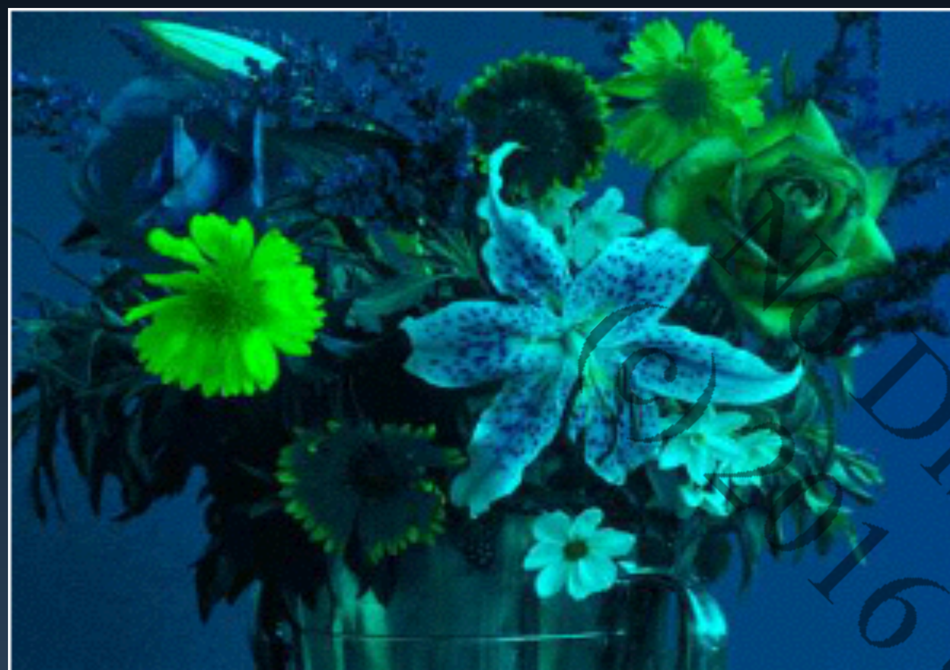
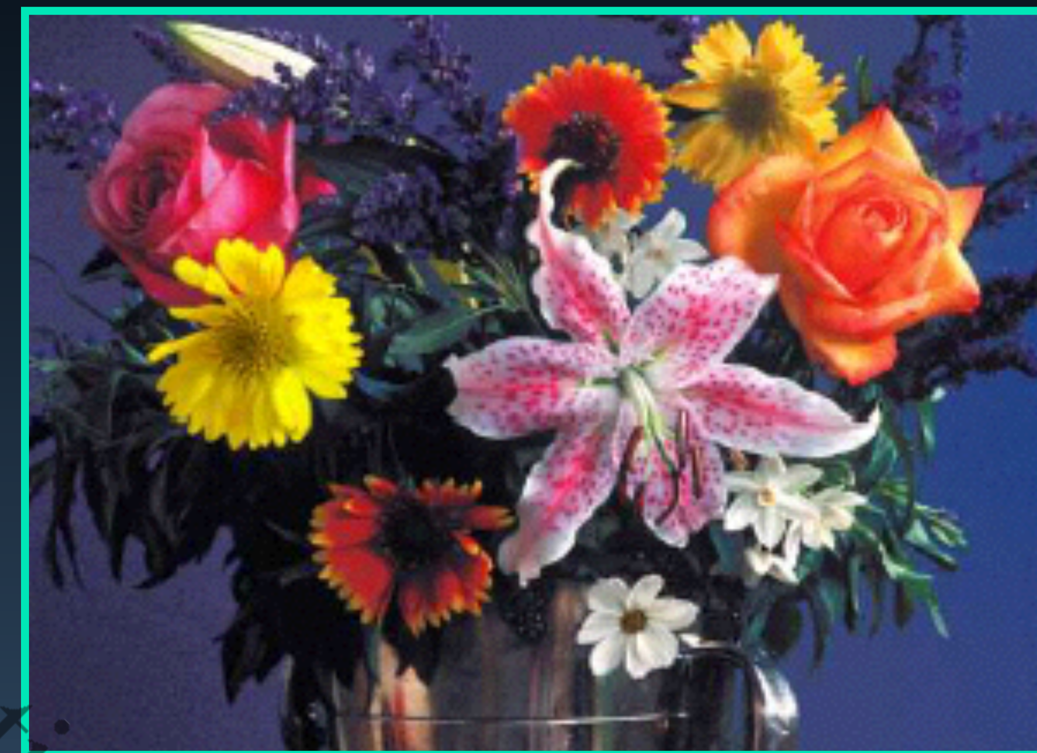
- CMYK (cyan, magenta, yellow, black)
  - is used in printing devices.
- HSI (hue, saturation, intensity)
  - based on the way humans describe and interpret color.
  - It also helps in separating the color and grayscale information in an image.

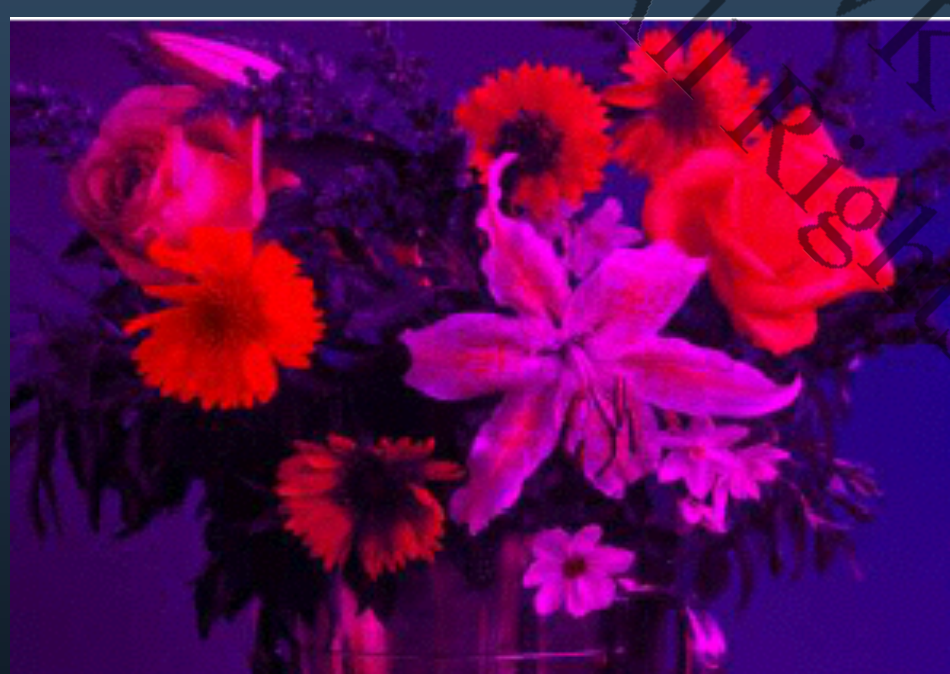
CMY Color Model

- Each color is represented by the three secondary colors — cyan (C), magenta (M), and yellow (Y).
- It is mainly used in devices such as color printers that deposit color pigments.
- It is related to the RGB color model:

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







Characteristics of Color

- Brightness (or value)
  - embodies the chromatic notion of intensity.
- Hue
  - is an attribute associated with the dominant wavelength in a mixture of light waves. It represents the dominant color as perceived by an observer (ex. orange, red, violet).

Characteristics of Color

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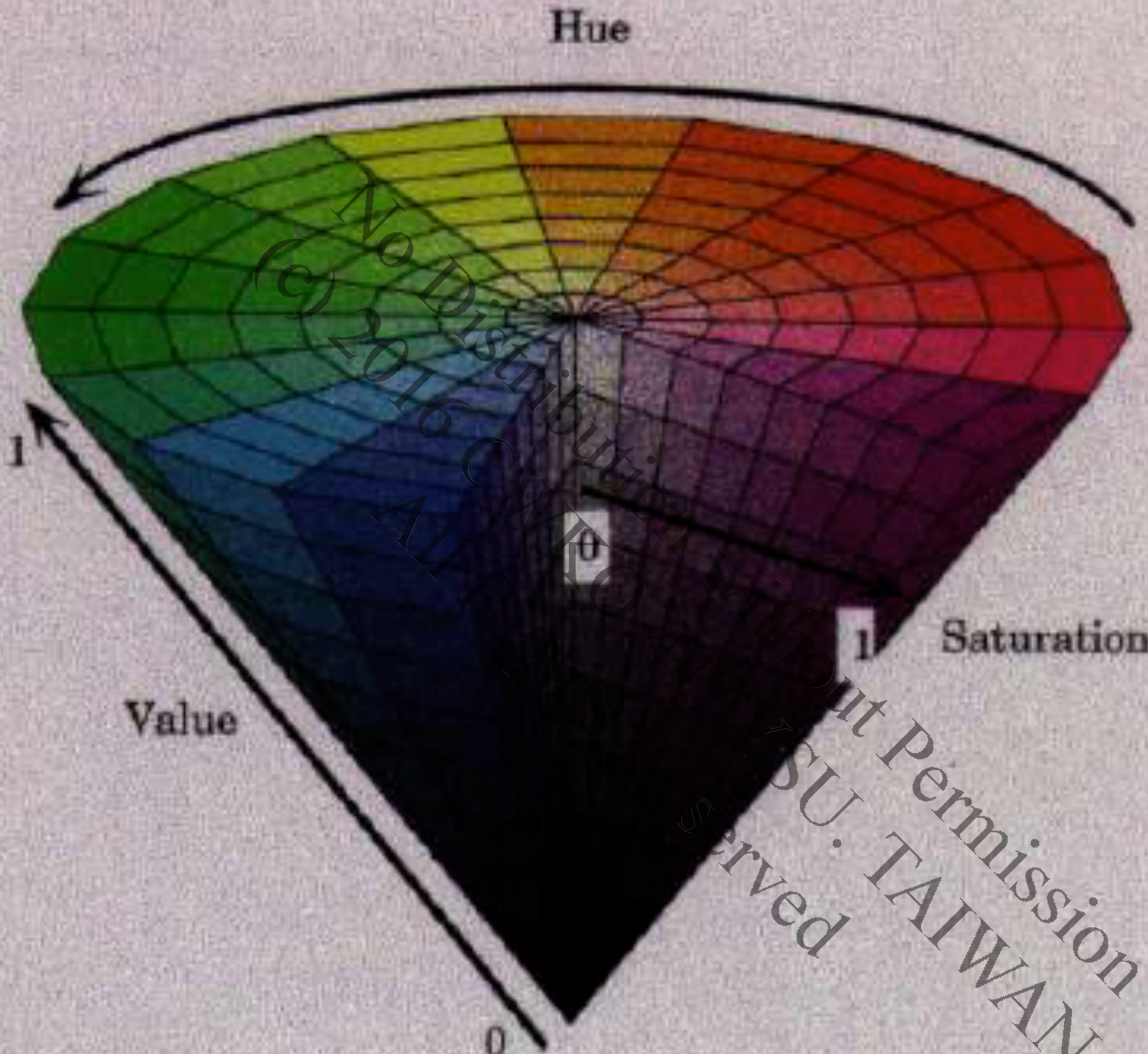

Hue
1
0
Saturation
1
Value
0

HSI or HSV Color Model

- Each color is specified in terms of its Hue (H), Saturation (S) and intensity (I) or value (V).
- The main advantages of this model is that:
  - Chrominance (H, S) and luminance (I) components are decoupled.
  - Hue and saturation is intimately related to the way the human visual system perceives color.

HSI or HSV Color Model

- RGB model is suited for image color generation.
- HSI model is suited for image color description.
- It is related to the RGB model:
  - Eq. 6.2-2 ~ 4

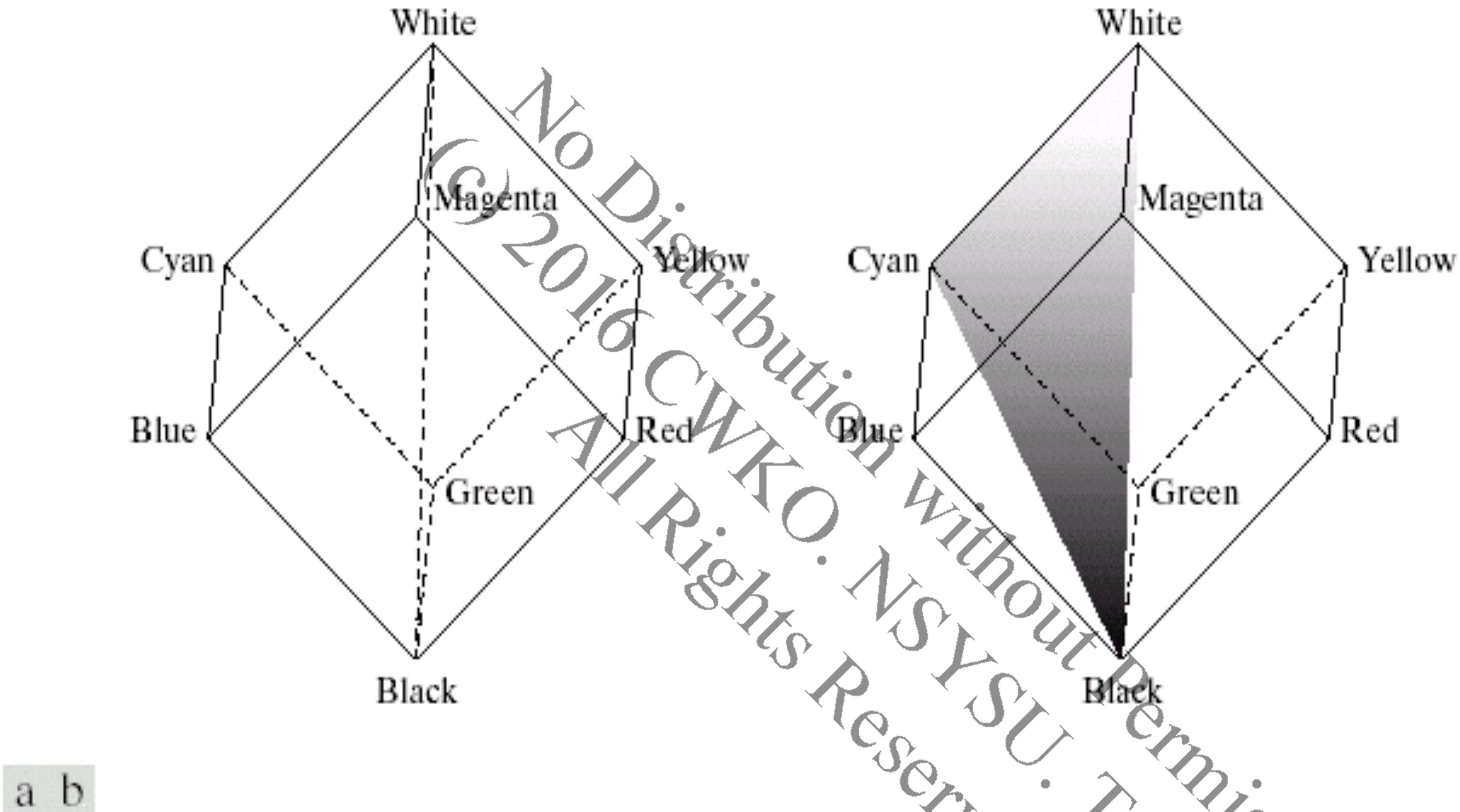
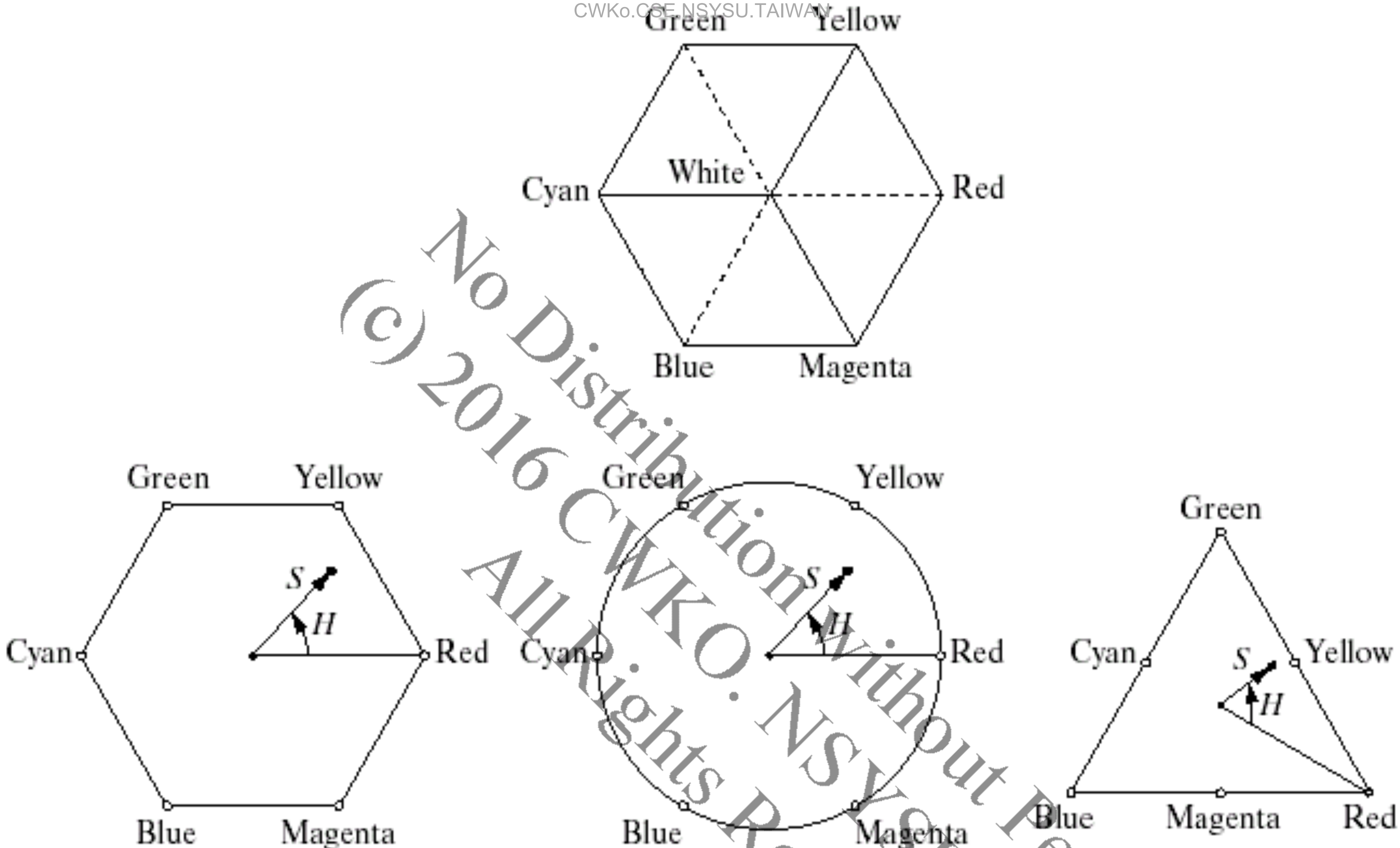
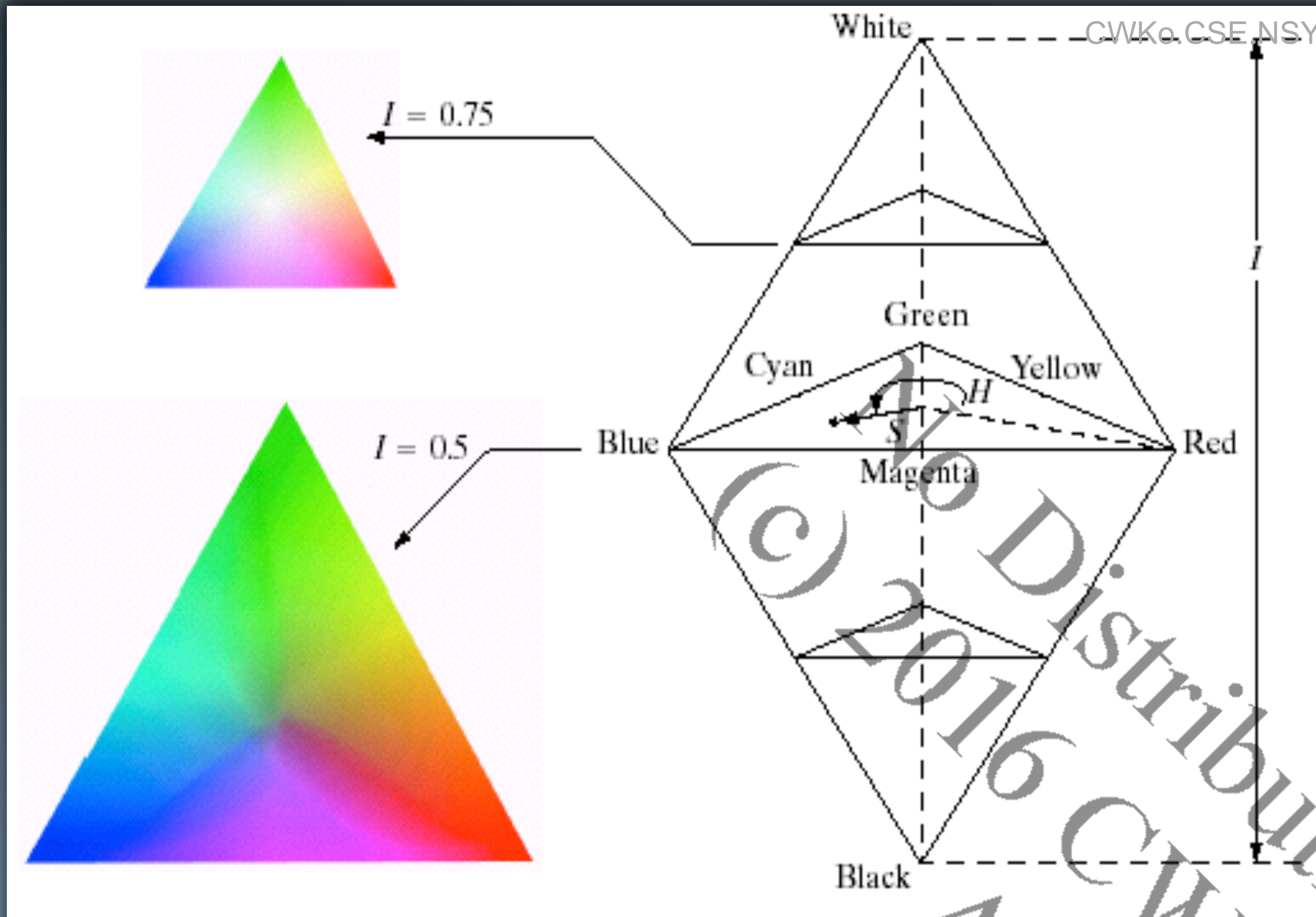


FIGURE 6.12 Conceptual relationships between the RGB and HSI color models.



a
b c d

FIGURE 6.13 Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and 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.

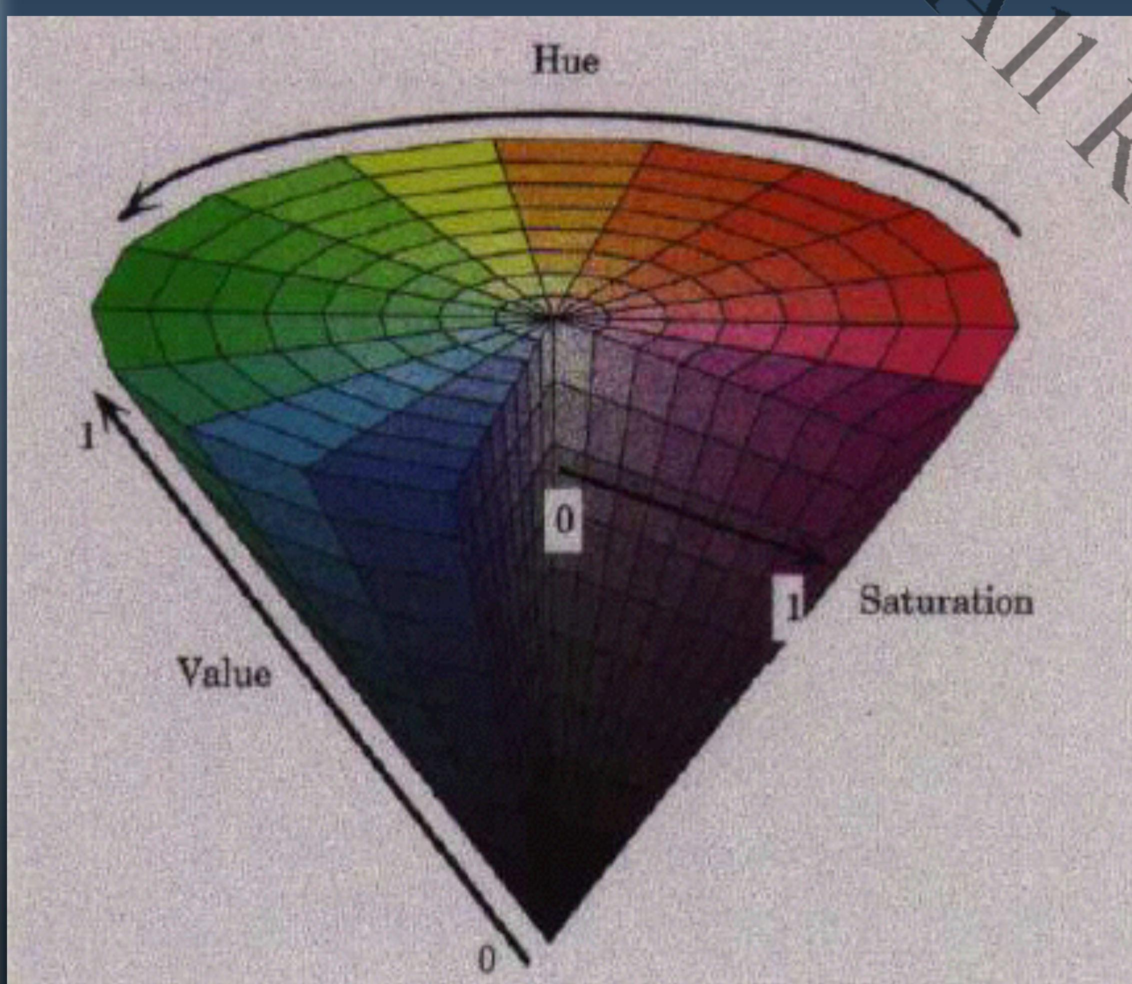


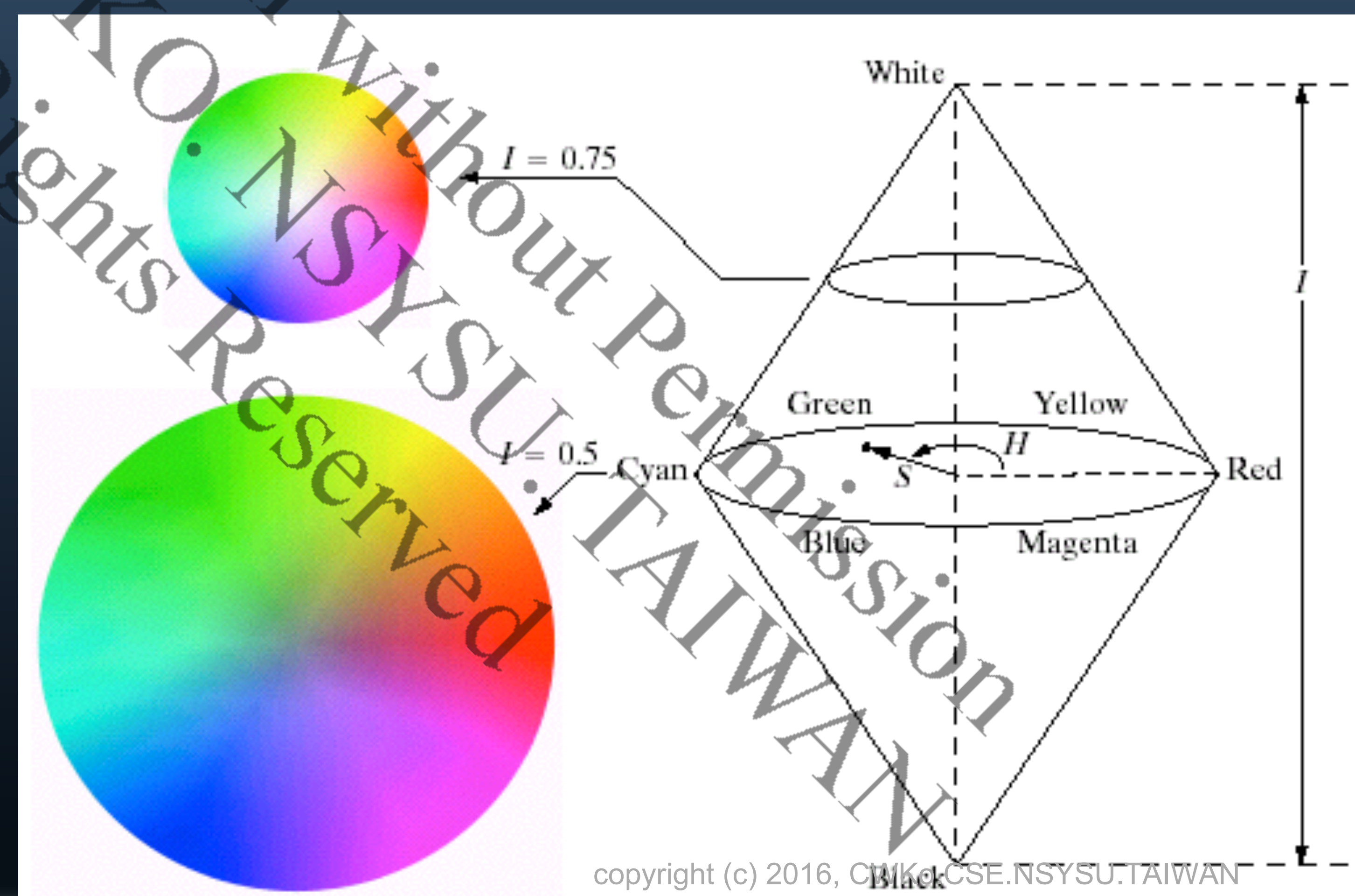
$$H = \begin{cases} \theta & \text{if } B \le G \\ 360 - \theta & \text{if } B > G \end{cases}$$

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

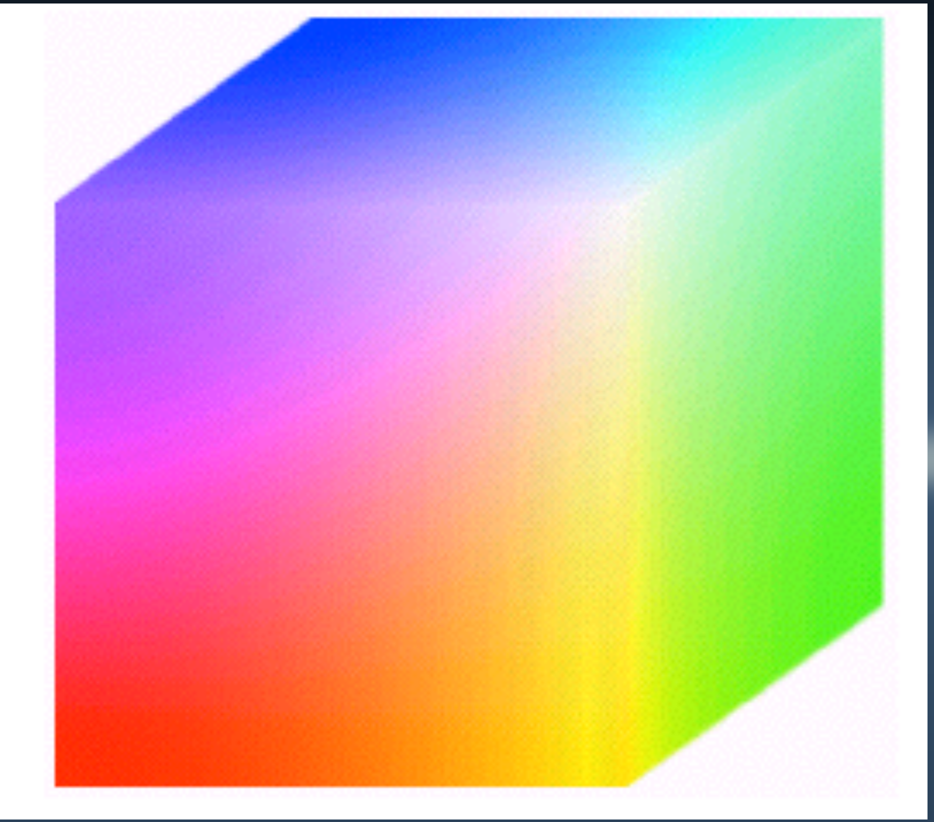
$$S = 1 - \frac{3}{(R+G+B)}\left[\min(R,G,B)\right]$$

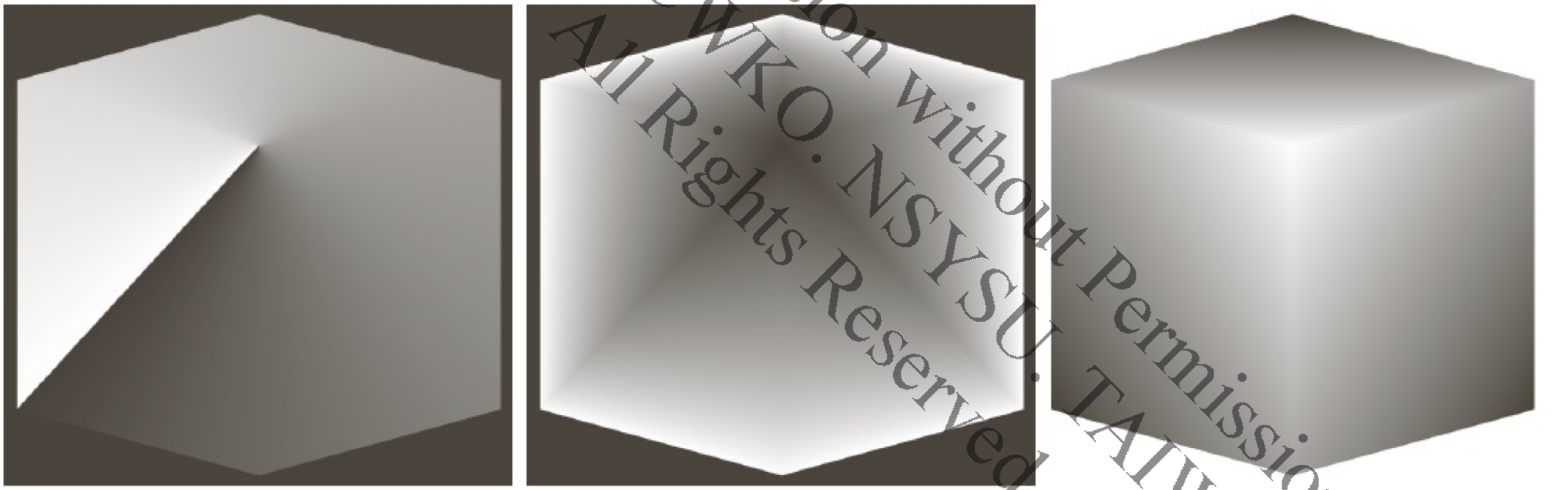
$$I = \frac{1}{3}(R+G+B)$$





RGB to HSI



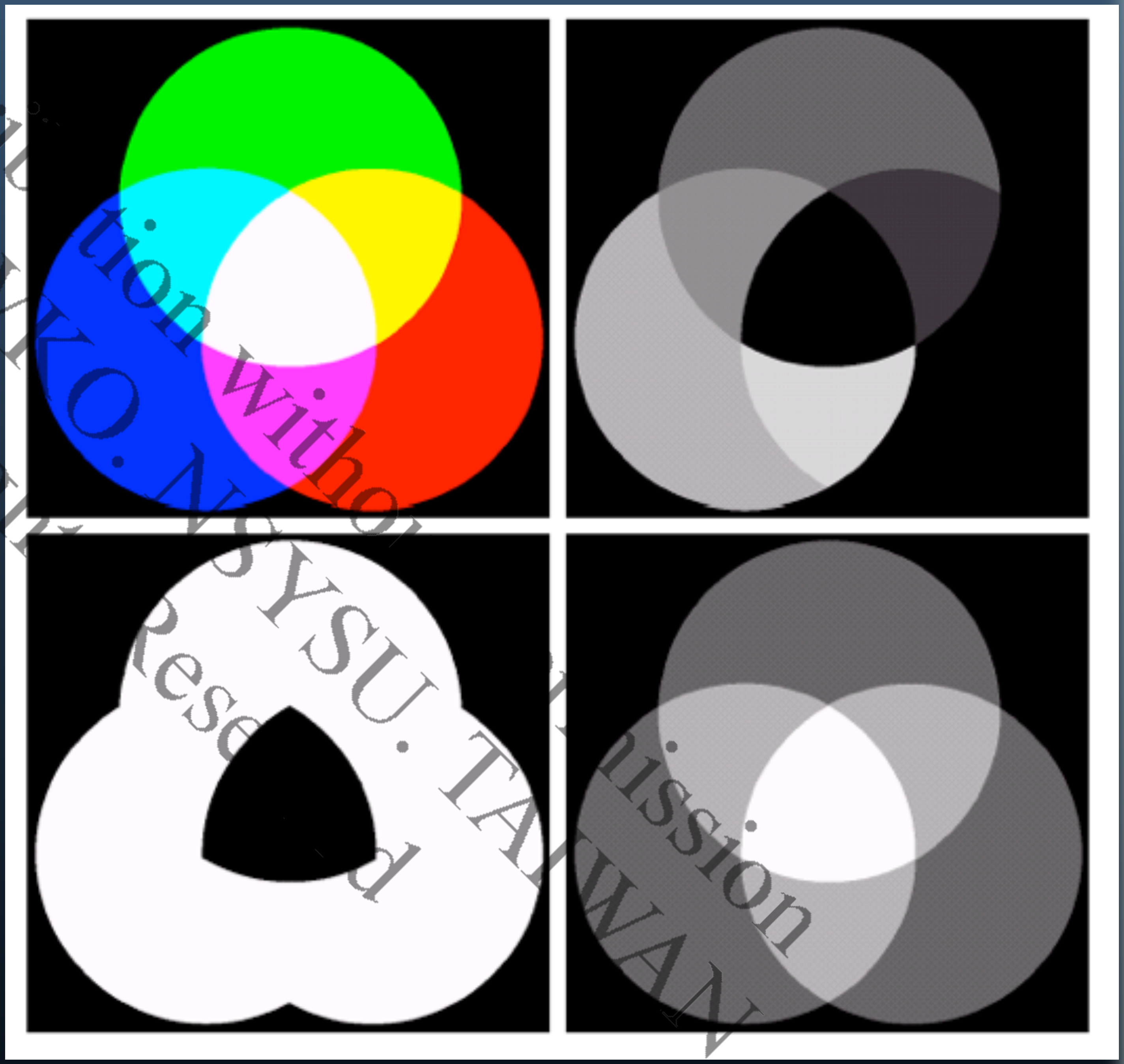


a b c

FIGURE 6.15 HSI components of the image in Fig. 6.8. (a) Hue, (b) saturation, and (c) intensity images.

Manipulation of HSI Components

- Consider the primary colors chart above and the corresponding HSI component images.



Manipulation of HSI components

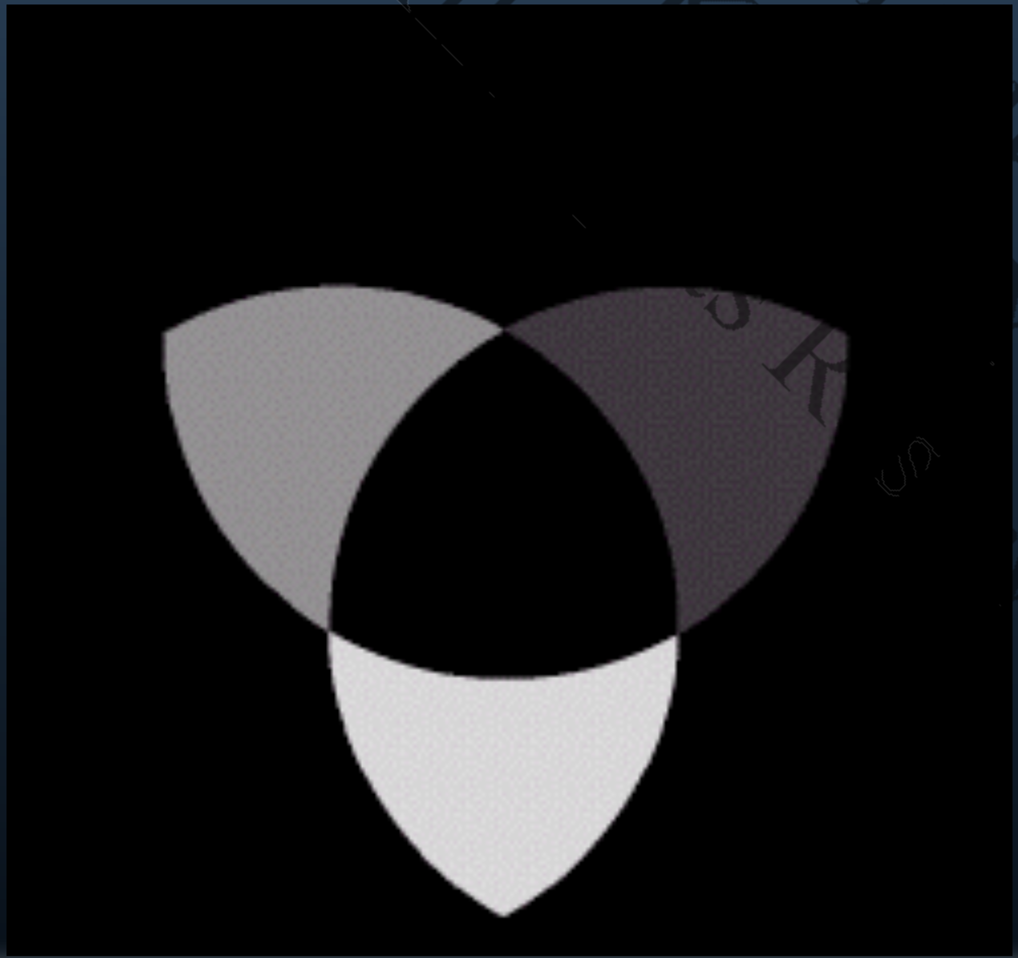
- To change the individual color of any region in the RGB image, we change the value of the corresponding region in the Hue image.
- Then we convert the new H image with the original S and I images to get the transformed RGB image.

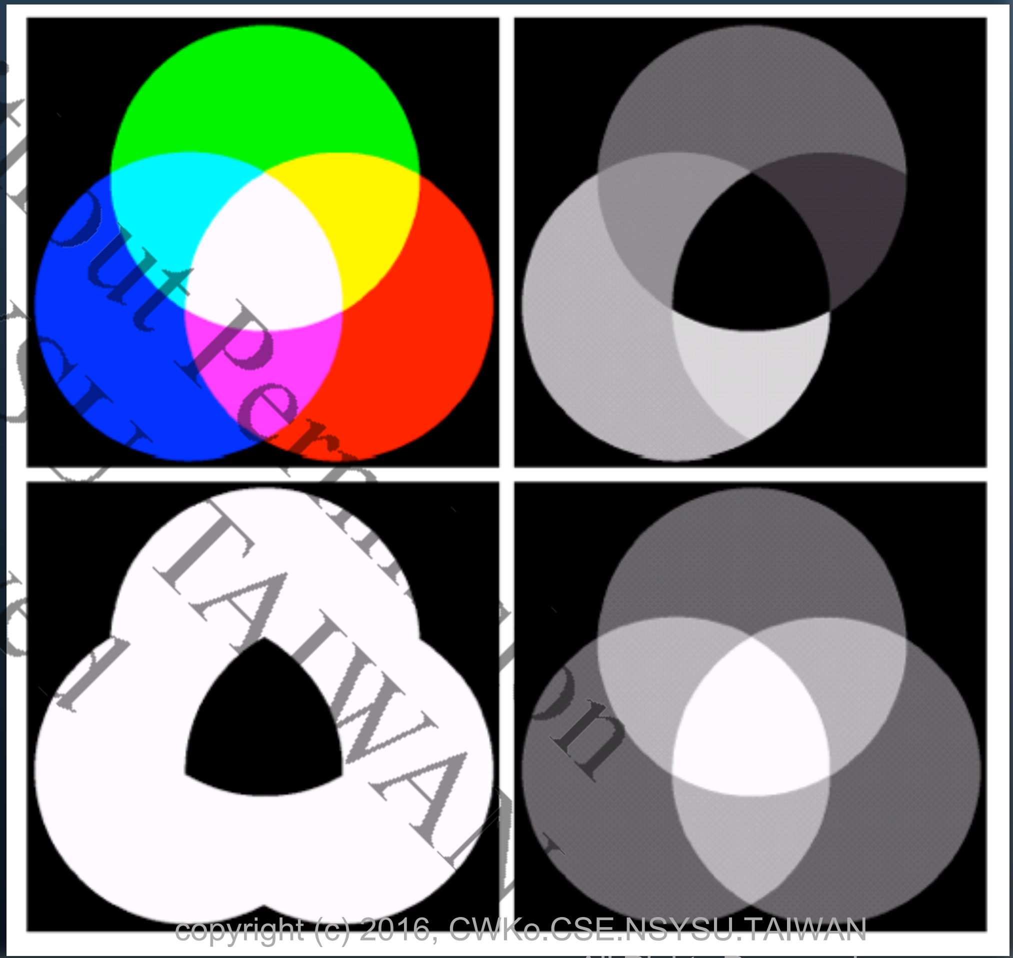
Manipulation of HSI components

- We can modify saturation and intensity like-wise, by manipulating the corresponding component image in the HSI model.

For Example

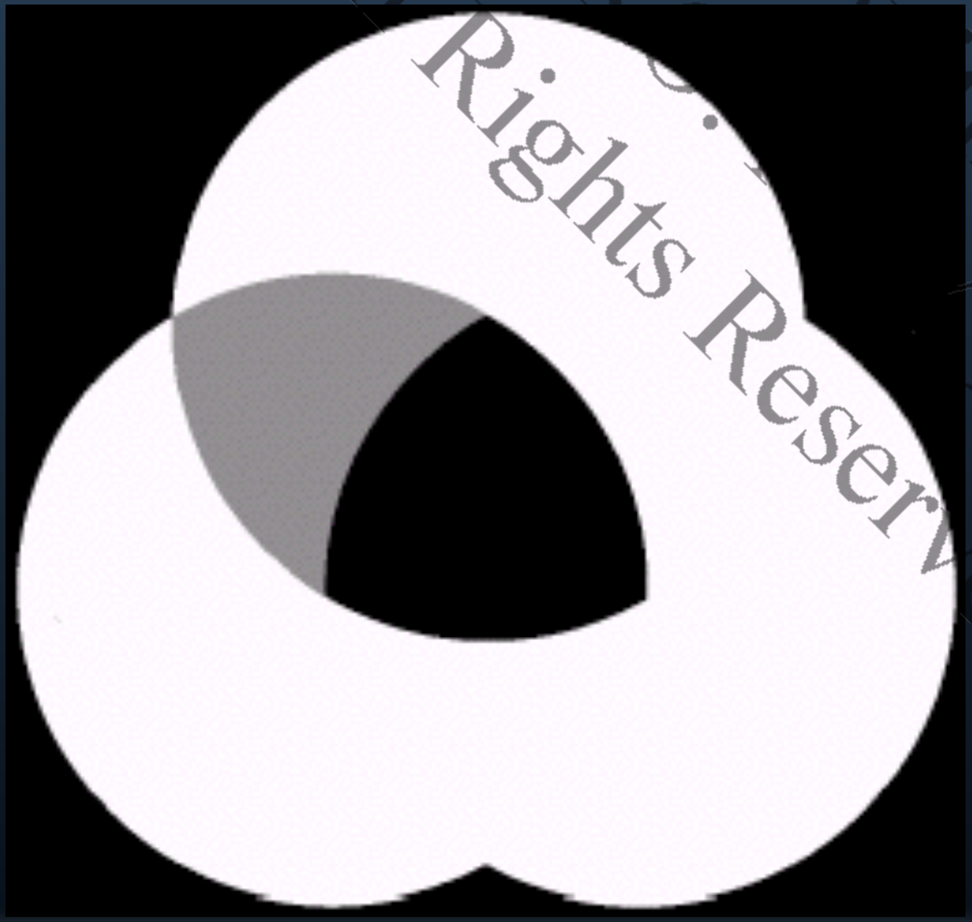
- Change all the green and blue regions into red by setting to 0 the corresponding regions in the H component image.

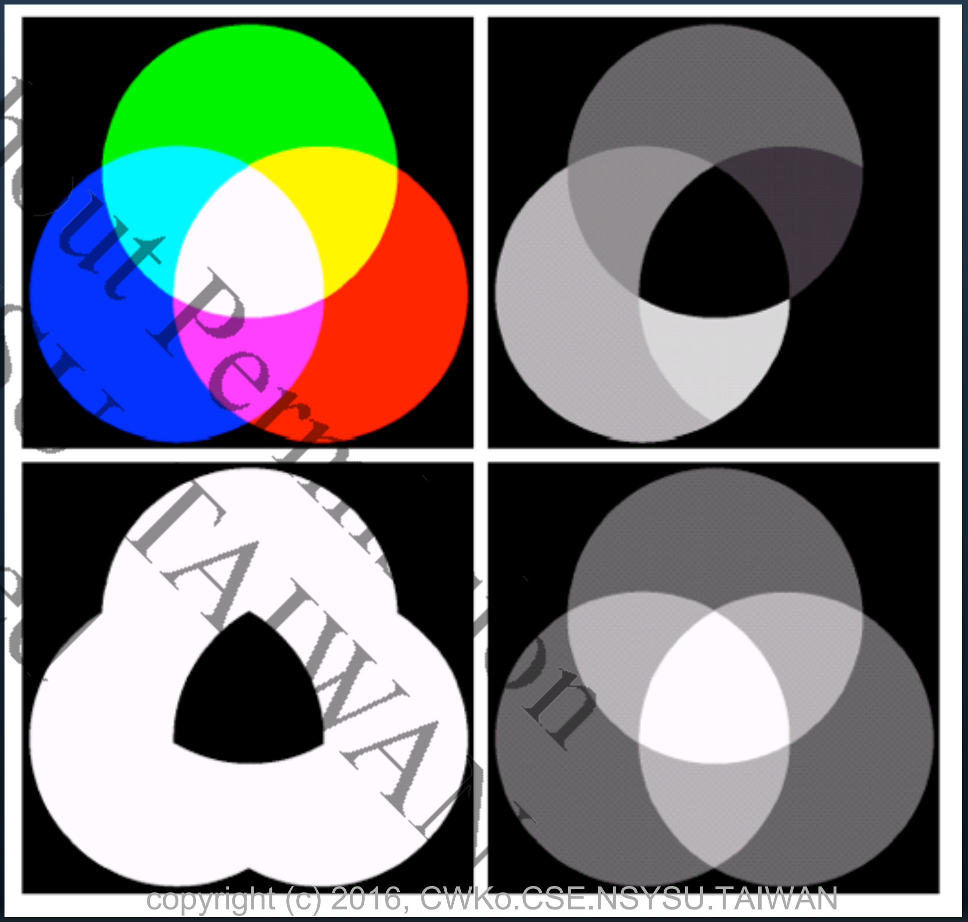




For Example

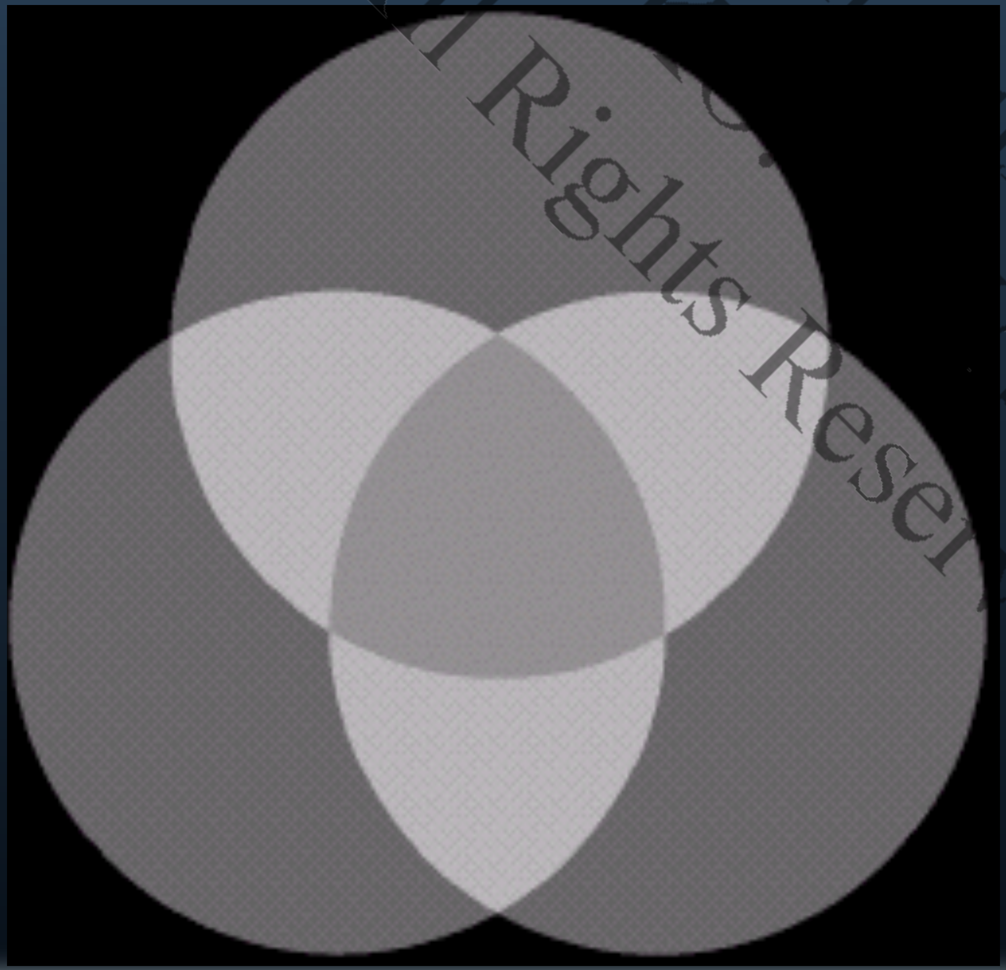
- Reduce the saturation of the Cyan region by ½ by manipulating the corresponding region in the S component image.

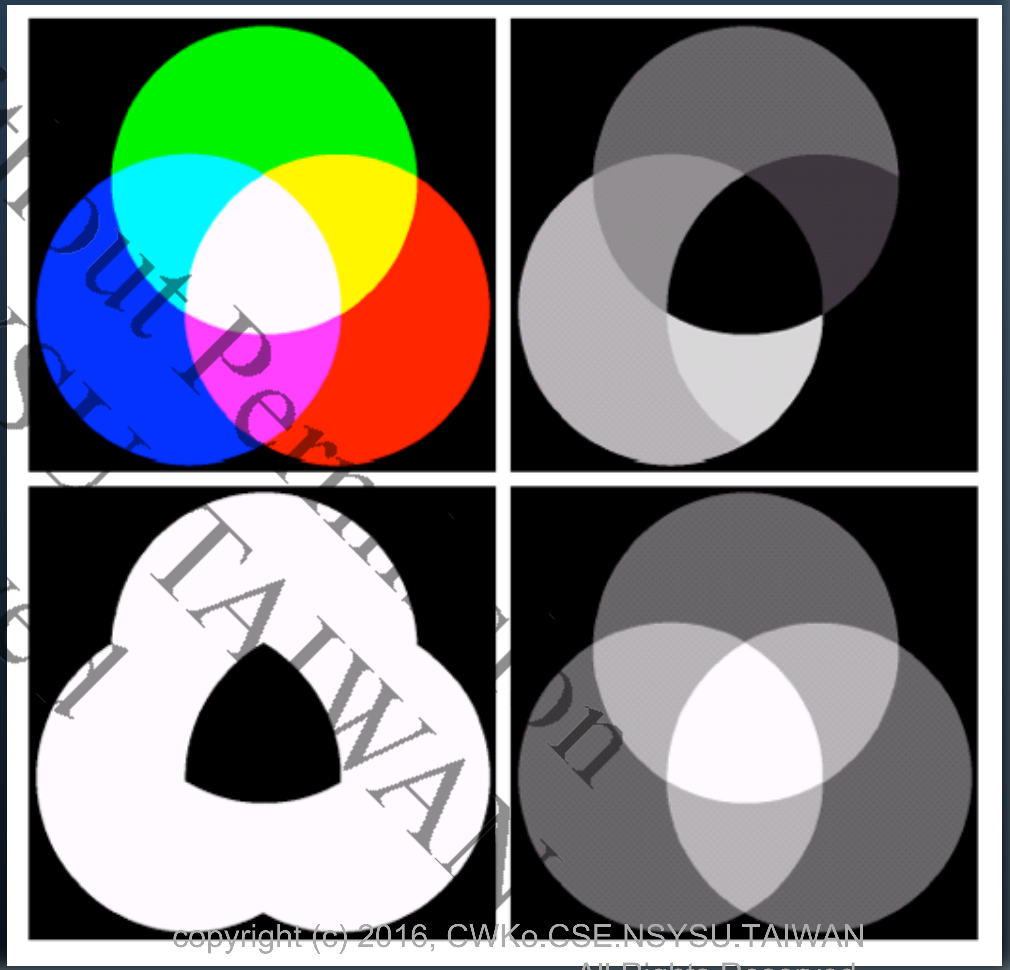




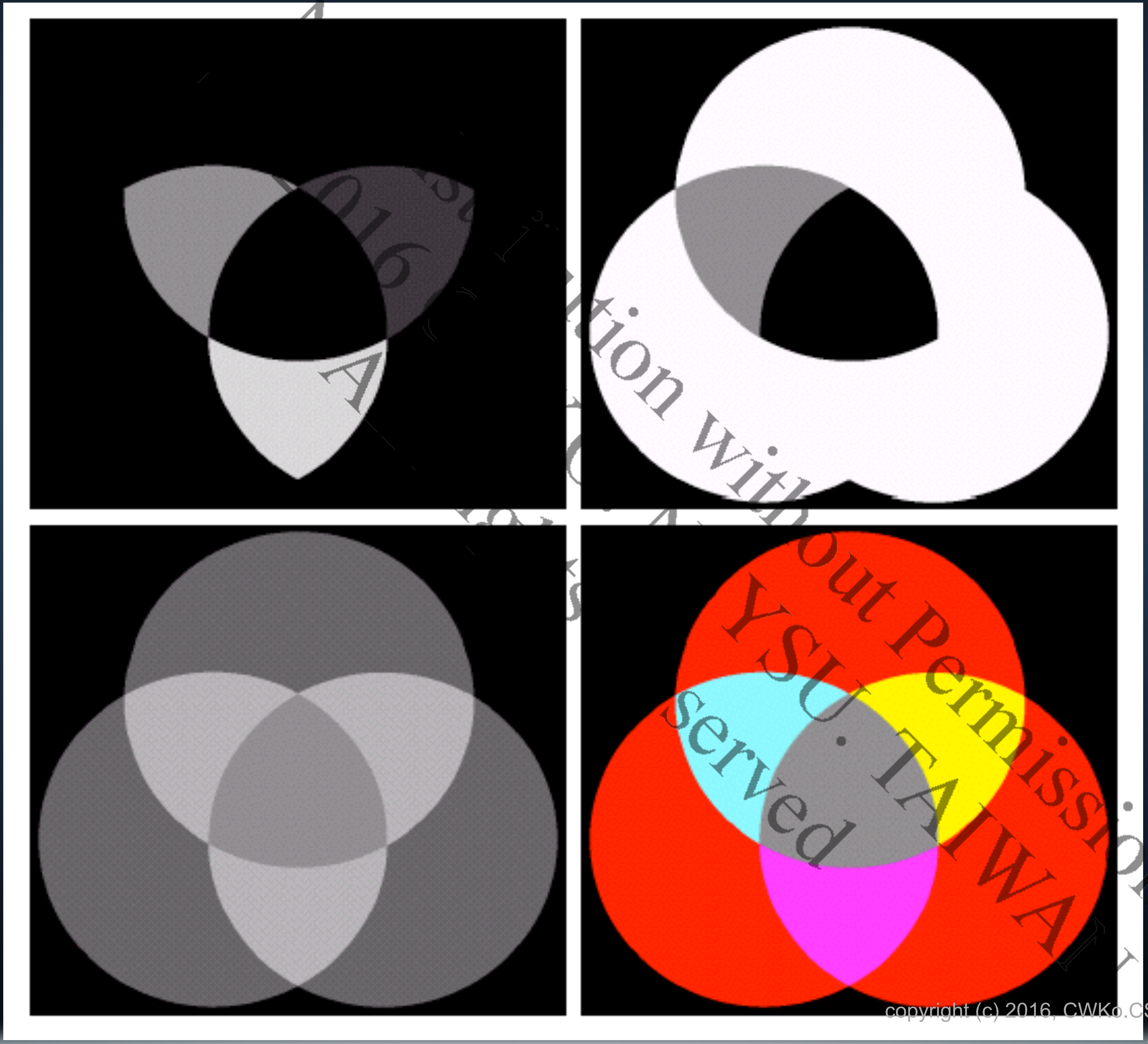
For Example

- Reduce by ½ the intensity of the white region by manipulating the corresponding region in the I component image.





- The resulting H, S, and I images are converted back to RGB



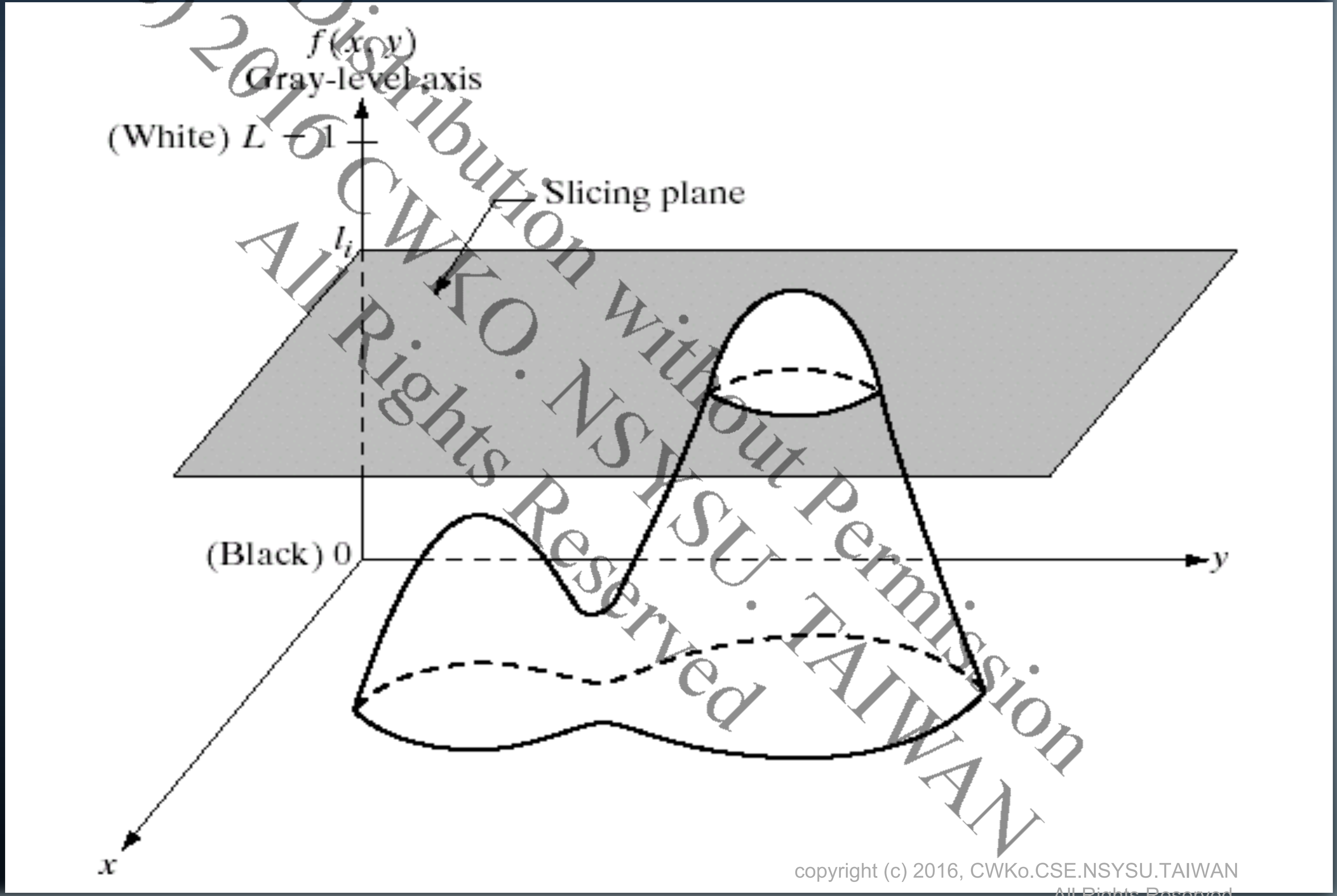
Pseudo Coloring

- Assign colors to monochrome images, based on various properties of their gray-level content.
- It is mainly used for human visualization and interpretation.
- Several transformations can be used for this purpose.

Intensity Slicing

- View an image as a 2-D intensity function. Slice the intensity (or density) function by a plane parallel to the coordinate axes.
- Pixel with gray-values above the plane are color coded with one color and those below are coded with a different color.

- This gives a two-color image. Similar to thresholding but with colors.
- Technique can be easily extended to more than one plane.



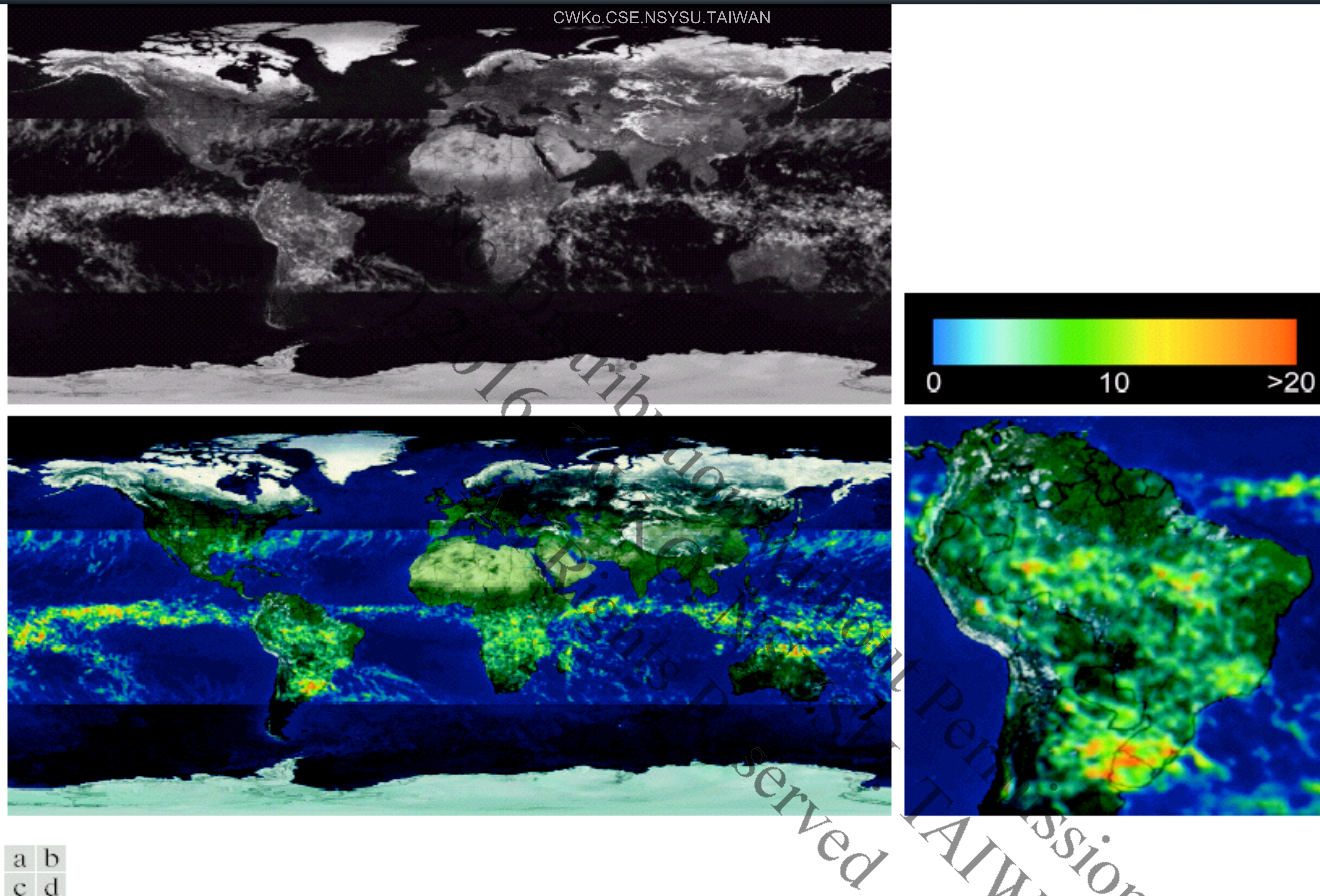


FIGURE 6.22 (a) Gray-scale image in which intensity (in the lighter horizontal band shown) corresponds to average monthly rainfall. (b) Colors assigned to intensity values. (c) Color-coded image. (d) Zoom of the South America region. (Courtesy of NASA.)

Gray Level to Color Transformations

- Perform three independent transformations on the gray-level of an input monochrome image.
- The outputs of the three transformations are fed to the Red, Green, and Blue channels of a color monitor.

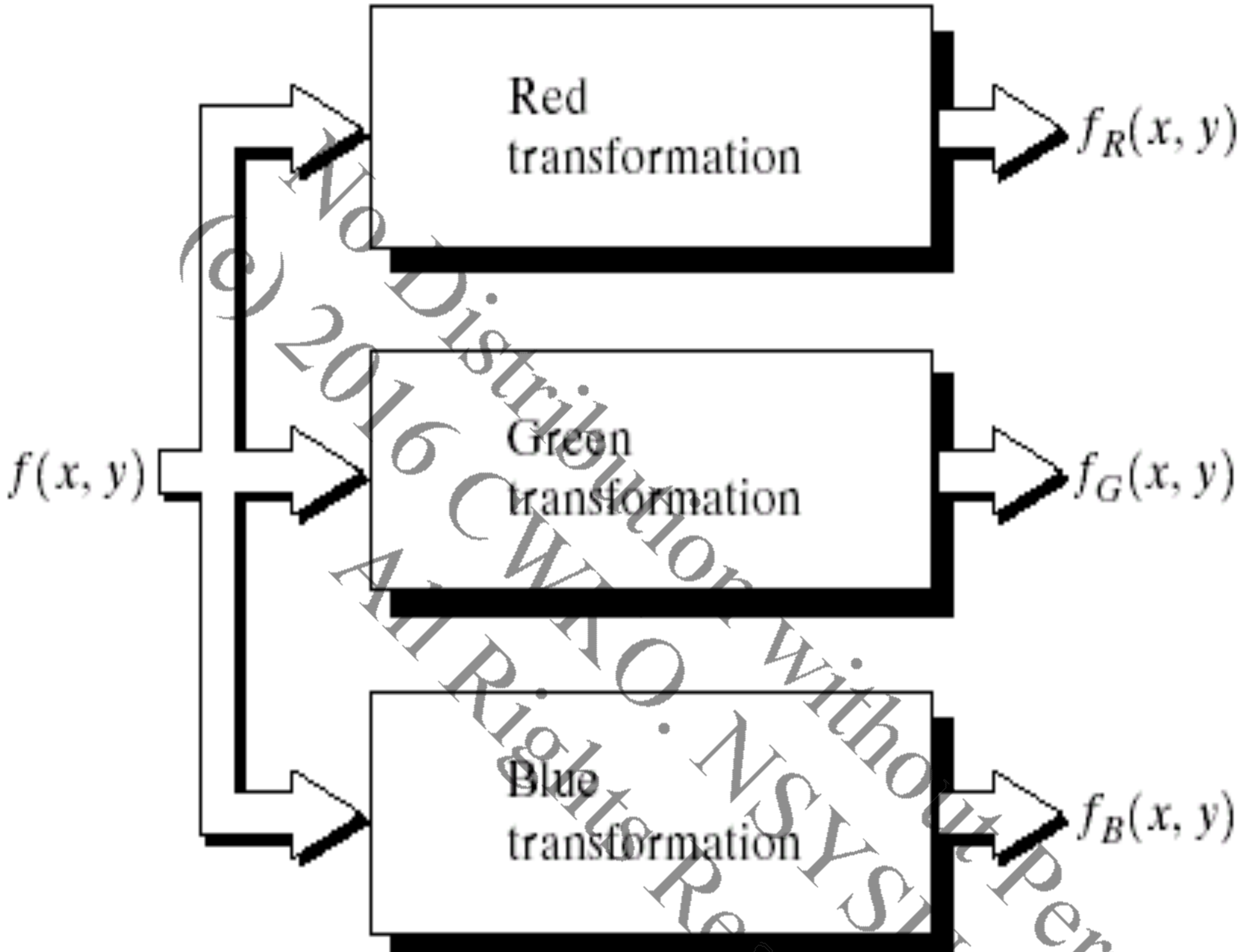


FIGURE 6.23 Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

- This is frequently used in multispectral imaging, where different sensors produce individual monochrome images, each in a different spectral band.

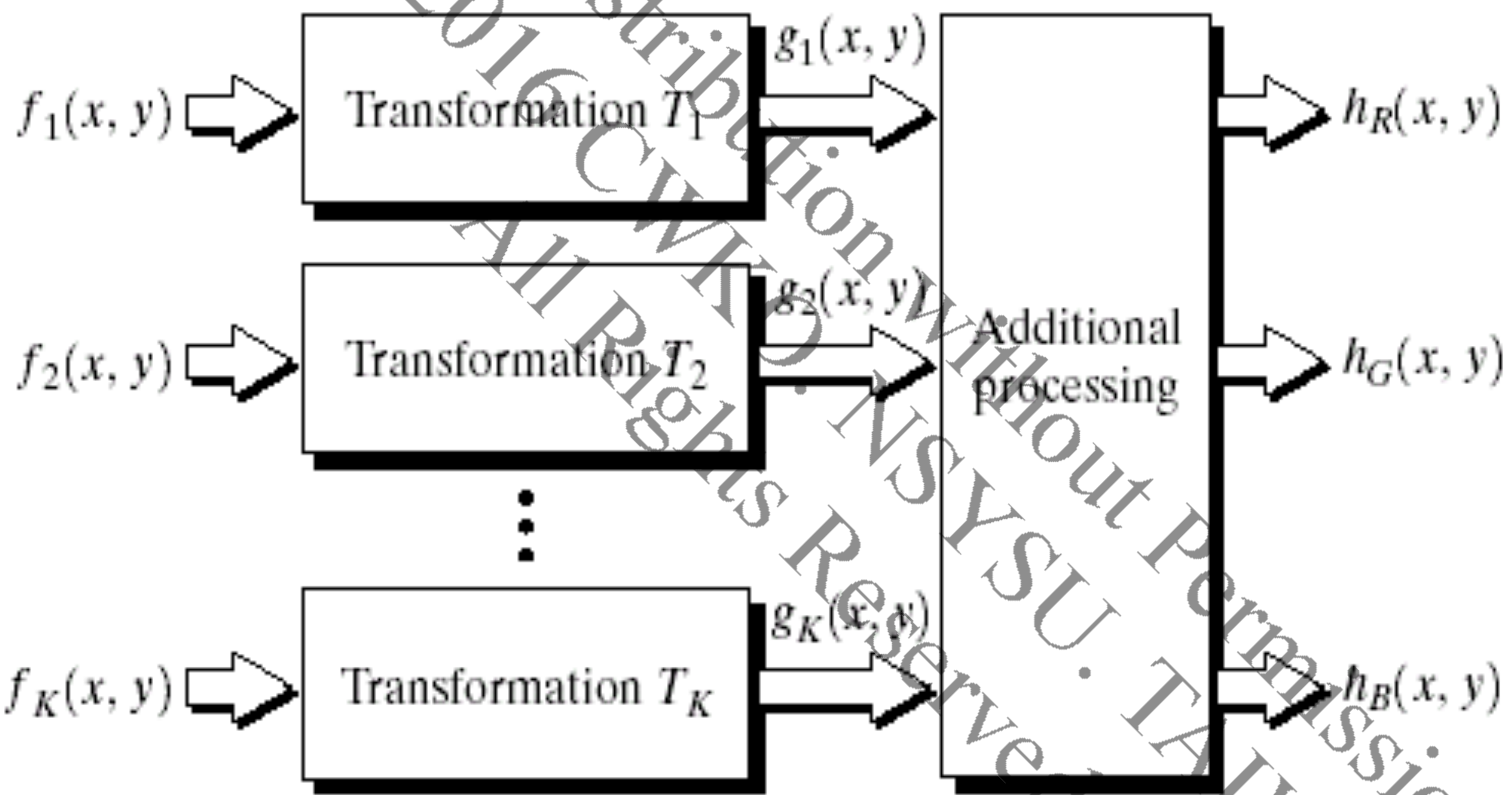


FIGURE 6.26 A pseudocolor coding approach used when several monochrome images are available.

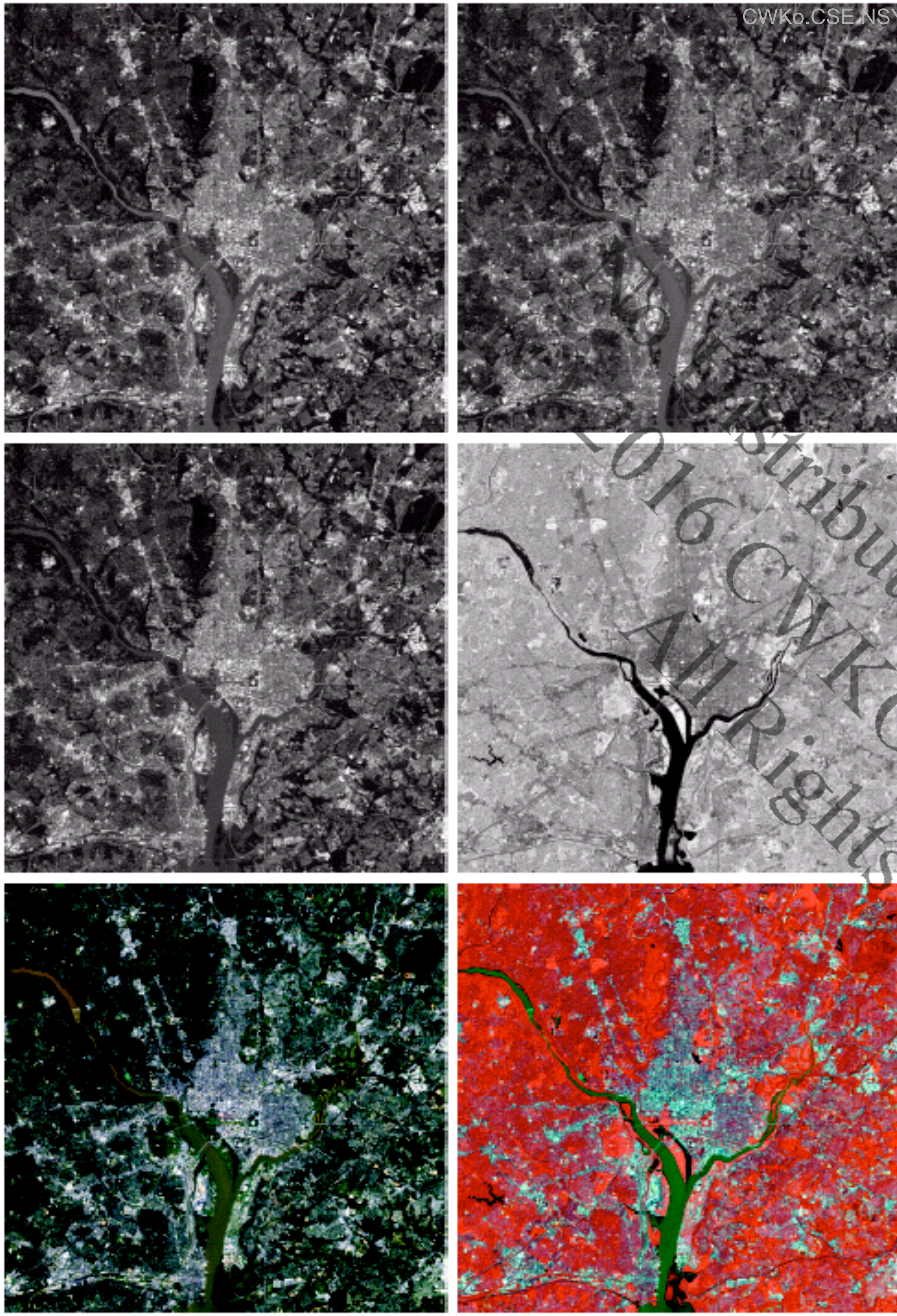


FIGURE 6.27 (a)–(d) Images in bands 1-4 in Fig. 1.10 (see Table 1.1). (e) Color composite image obtained by treating (a), (b), and (c) as the red, green, blue components of an RGB image. (f) Image obtained in the same manner, but using in the red channel the near-infrared image in (d). (Original multispectral images courtesy of NASA.)

Color Transformations

- It is useful to think of a color image as a vector valued image, where each pixel has associated with it, as vector of three values.
- Each components of this vector corresponds to a different aspect of color, depending on the color model being used.
  - [R, G, B], [H, S, I]

Color Transformations

- We can think of color transformations as a transformation of vectors.

$$s_i = T_i(r_1, r_2, \ldots, r_n) \qquad i = 1,2,\ldots,n$$

$$g(m,n) \qquad\qquad f(m,n)$$

Color Transformations

- In theory, any color transformation can be performed in any color space model. However, in practice, some transformations are better suited to specific models.
- The cost of conversion between the models must be a factor in implementation of a particular transformation.

Example: Modifying Intensity

$$g(m,n) = kf(m,n) \qquad 0 < k < 1$$

In HSI space

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ kr_3 \end{bmatrix}$$

In RGB space,

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} kr_1 \\ kr_2 \\ kr_3 \end{bmatrix}$$

In CMY space,

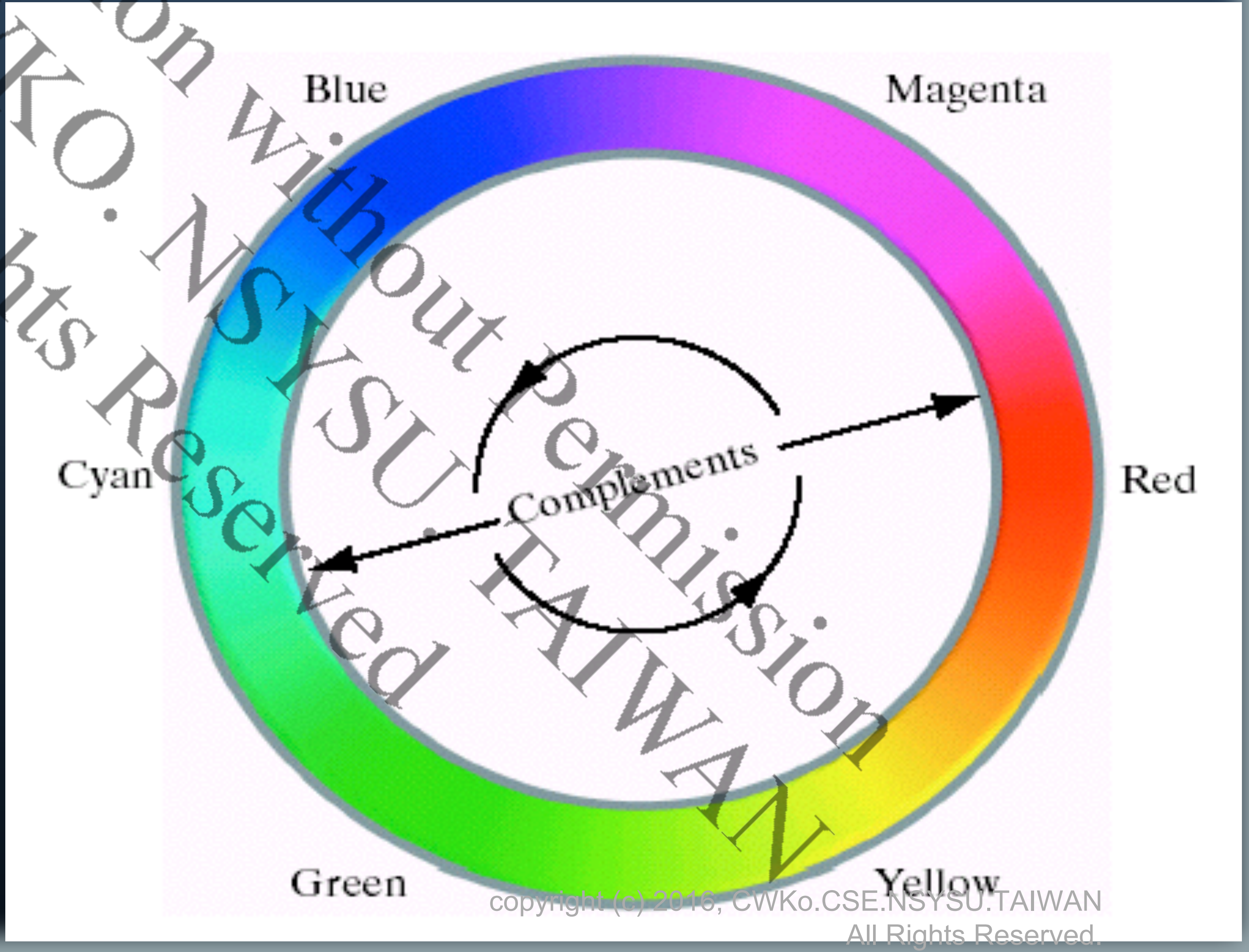
$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} kr_1 \\ kr_2 \\ kr_3 \end{bmatrix} + (1-k)$$

a b
c d e

FIGURE 6.31 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)–(e) The required RGB, CMY, and HSI transformation functions. (Original image courtesy of MedData Interactive.)

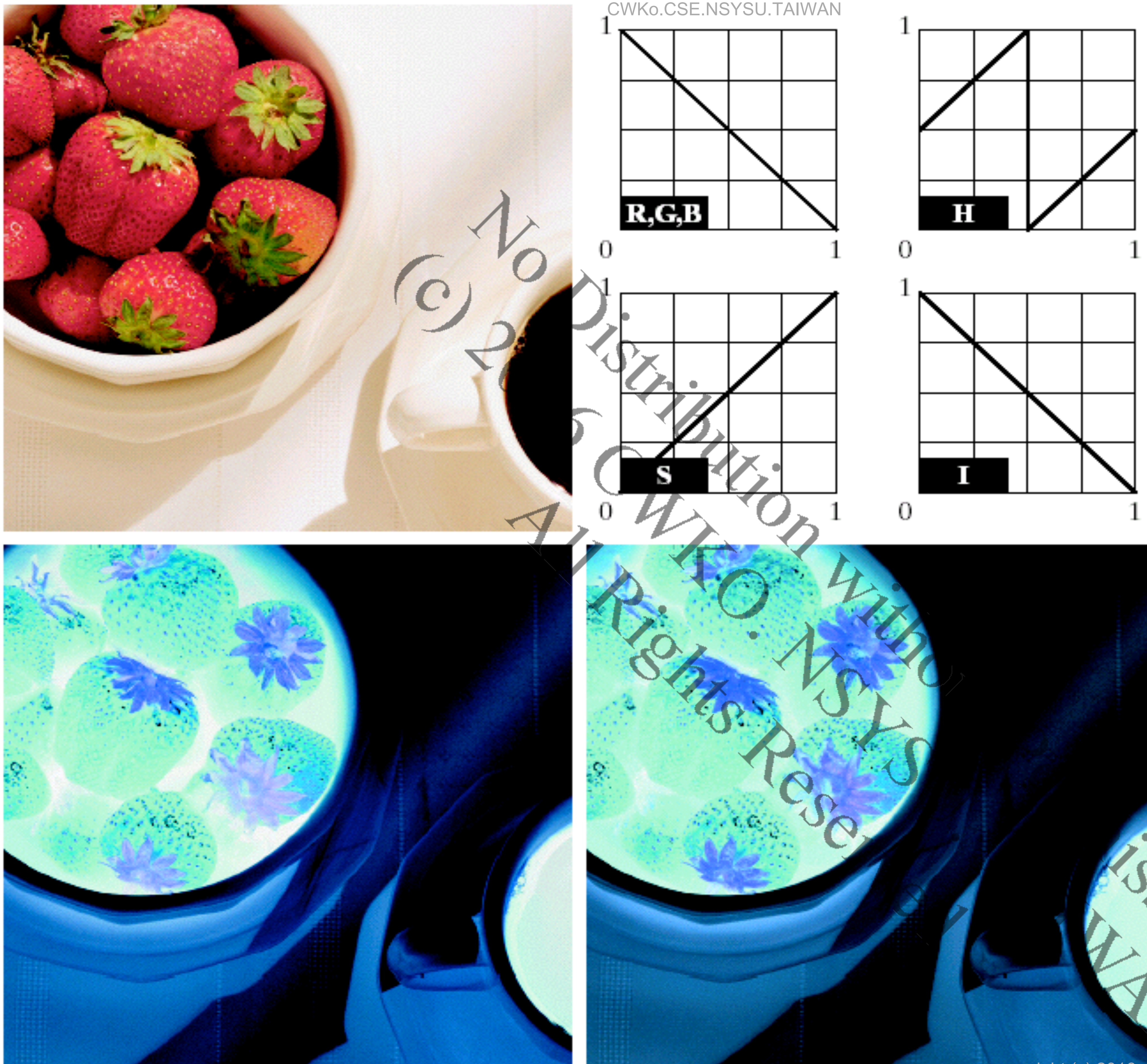
Color Complement

- Hues opposite one another in a color circle are called complements.
- This is analogous to gray-scale negatives.



Color Complement

- This transformation is useful in enhancing details embedded in dark portions of a color image.
- Complementation can be easily implemented in the RGB space.
- However, there is no simple equivalent of this in the HSI space. An approximation is possible.



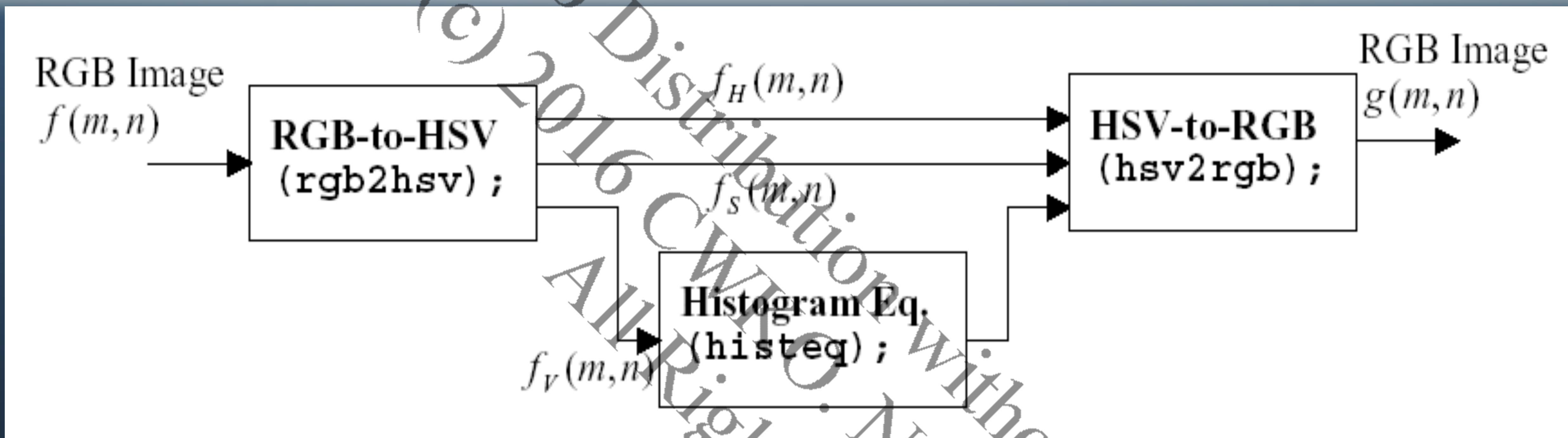
a b
c d

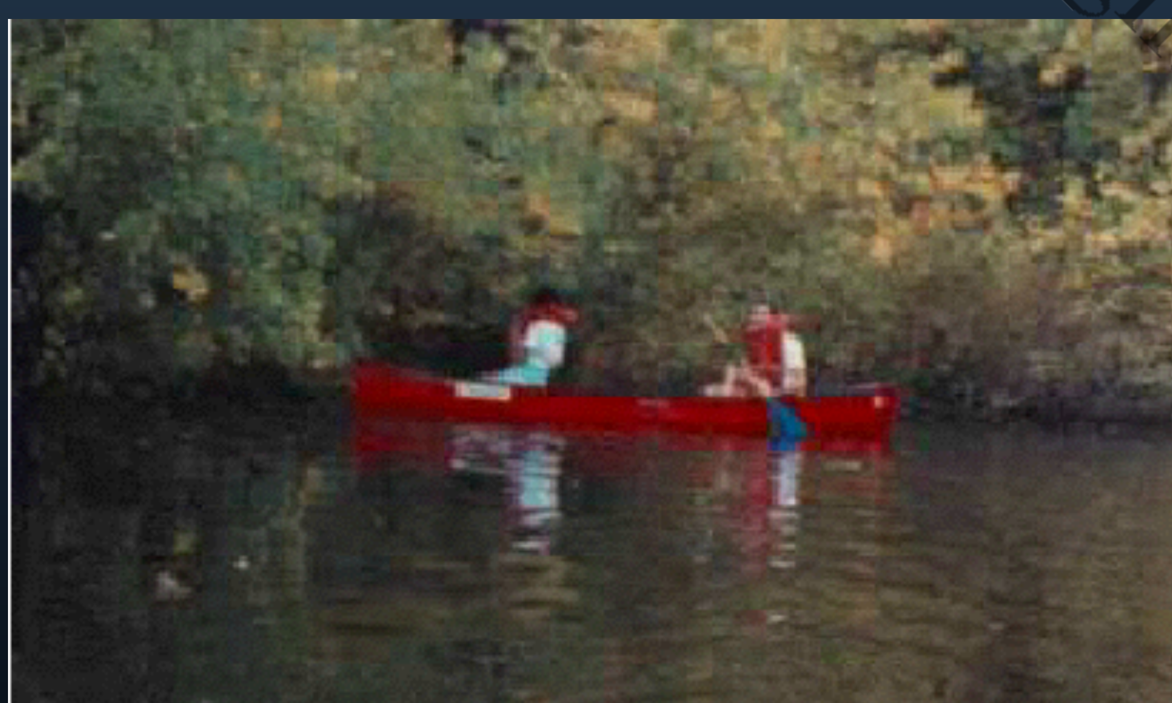
FIGURE 6.33 Color complement transformations. (a) Original image. (b) Complement transformation functions. (c) Complement of (a) based on the RGB mapping functions. (d) An approximation of the RGB complement using HSI transformations.

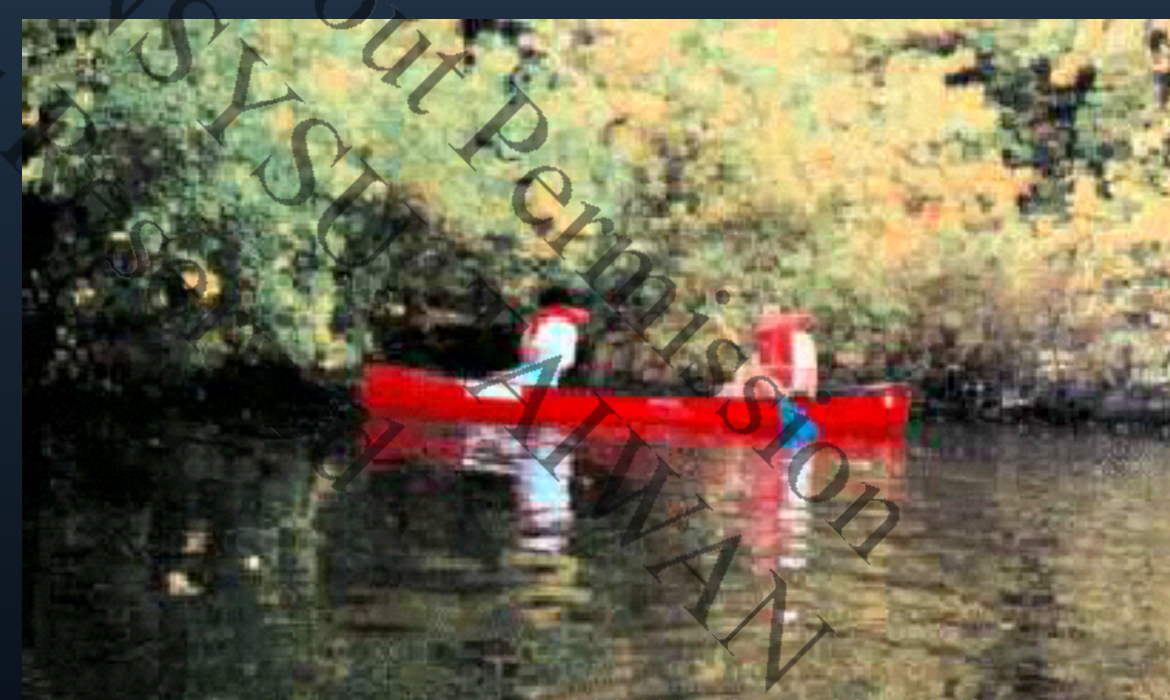
Color Slicing

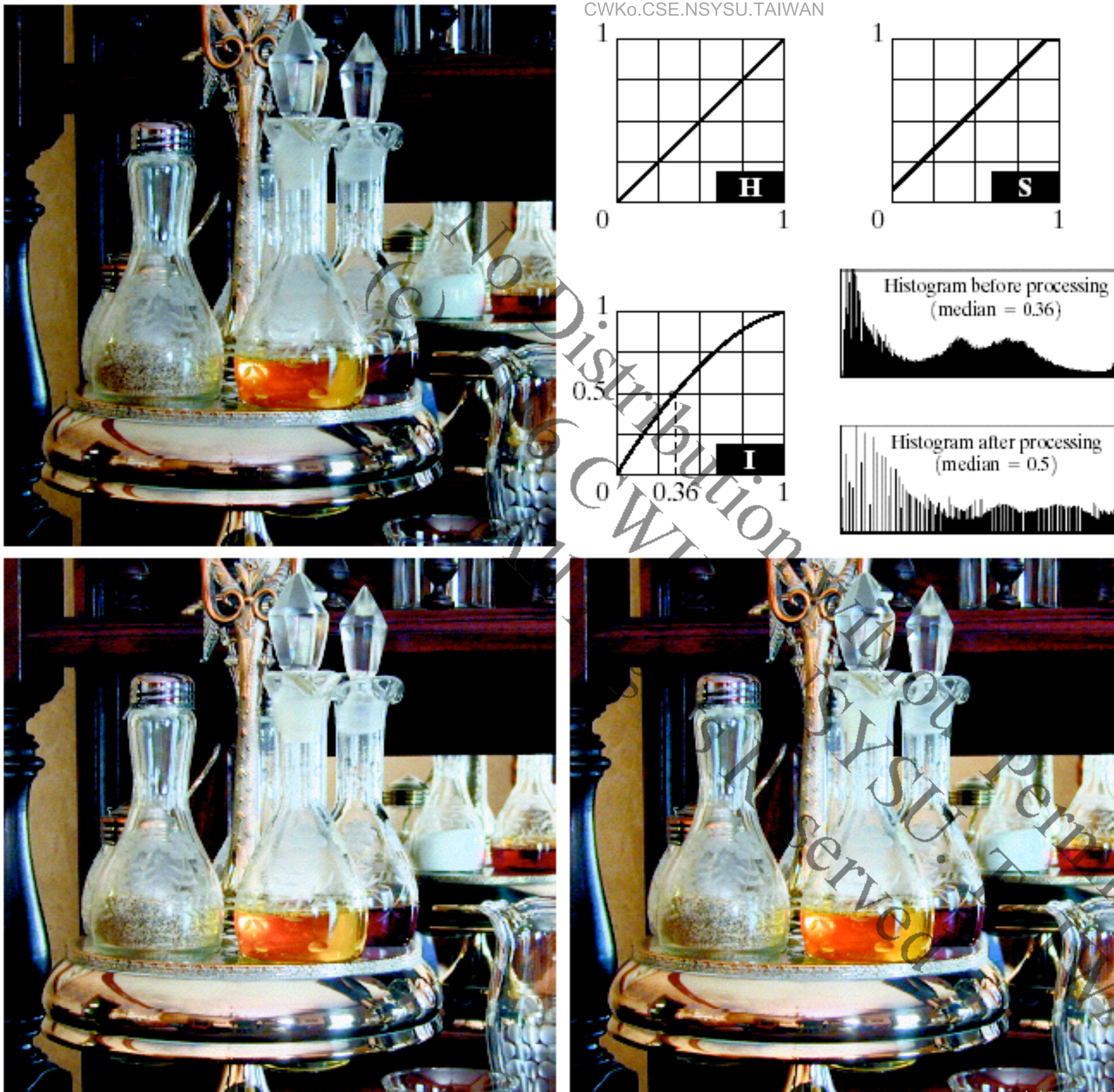
- Color slicing is similar to intensity slicing

Color Histogram Equalization









a b
c d

FIGURE 6.37 Histogram equalization (followed by saturation adjustment) in the HSI color space.

Smoothing of Color Images

- We must deal with component vectors instead of scalar gray-level values.
- This can be done either in the RGB domain or the HSI domain.

Smoothing of Color Images

- In the RGB domain, all the three color components are individually transformed by an appropriate smoothing mask, say a 3x3 mask:

$$\frac{1}{9}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

Smoothing of Color Images

- In the HSI domain, only the I component is transformed by means of a spatial smoothing mask, leaving the H and S components unchanged.

Smoothing of Color Images

- In general, the final result in the two cases would be different.
- Because the average of two colors is a color intermediate between the two, the former approach has the potential of introducing colors not present in the original image.
- The latter approach does not have this problem, since the Hue and Saturation components are preserved.

a	b
c	d

FIGURE 6.38
(a) RGB image.
(b) Red component image.
(c) Green component.
(d) Blue component.

FIGURE 6.39 HSI components of the RGB color image in Fig. 6.38(a). (a) Hue. (b) Saturation. (c) Intensity.

a b c

FIGURE 6.40 Image smoothing with a 5 × 5 averaging mask. (a) Result of processing each RGB component image. (b) Result of processing the intensity component of the HSI image and converting to RGB. (c) Difference between the two results.

Color Image Sharpening

- Sharpening of color images can be performed in a manner analogous to smoothing, using appropriate masks, say the Laplacian mask

$$\begin{bmatrix} 0 & -1 & 0 \\ -1 & 4 & -1 \\ 0 & -1 & 0 \end{bmatrix} \quad \begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

a b c

FIGURE 6.41 Image sharpening with the Laplacian. (a) Result of processing each RGB channel. (b) Result of processing the intensity component and converting to RGB. (c) Difference between the two results.

Noise in Color Images

- The previously discussed noise models are applicable to color images as well.
- Typically, noise affects all the three color components.

Noise in Color Images

- Across the three color channels, the noise is independent and its statistical characteristic are identical.
- However, due to different illumination conditions or selective malfunction of camera hardware in a particular channel, this may not be the case.

Noise in Color Images

- Noise filtering by means of a simple averaging can be accomplished by performing the operation independently on the R, G, and B channels and combining the results.
- However, more complicated filters like the median filter are not as straight-forward to formulate in the color domain and will not be pursued here.