CTT310: Digital Image Processing

Color Image Processing

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Outline

- Color fundamentals
- Color models
- Pseudocolor image processing
- Full-color image processing

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Motivation of color image processing

- Color is a powerful descriptor that often simplifies object identification and extraction from a scene
- Humans can discern thousands of color shades and intensities, compared to about only two dozen shades of gray

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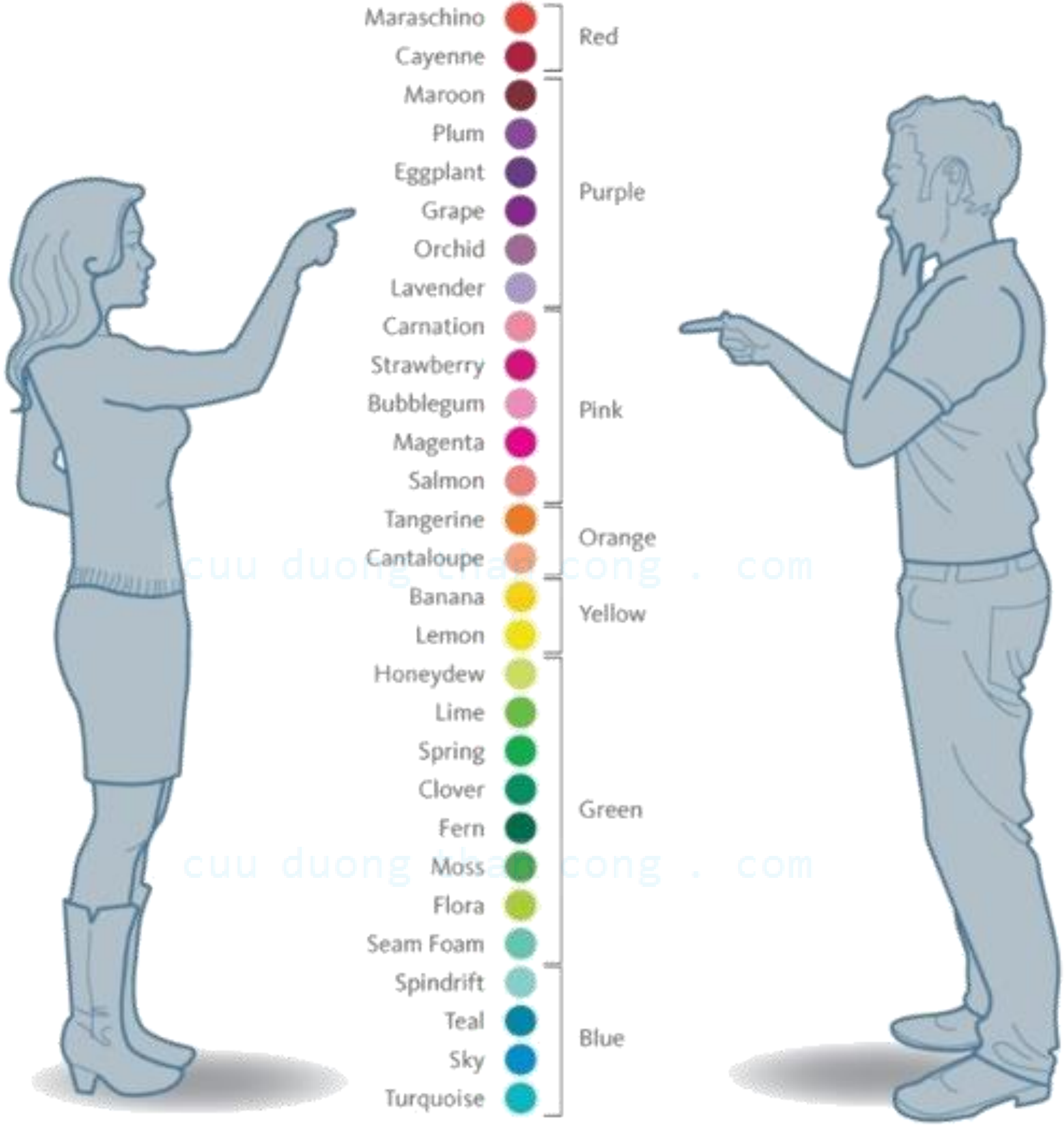

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Can you choose her favorite color?

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Color image processing

- **Color image processing** is divided into two major areas
  - **Full-color processing**
    - The images in question typically are acquired with a full-color sensor, such as a color TV camera or color scanner
  - **Pseudocolor processing**
    - The problem is one of assigning a color to a particular monochrome intensity or range of intensities



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Section 7.1

COLOR FUNDAMENTALS

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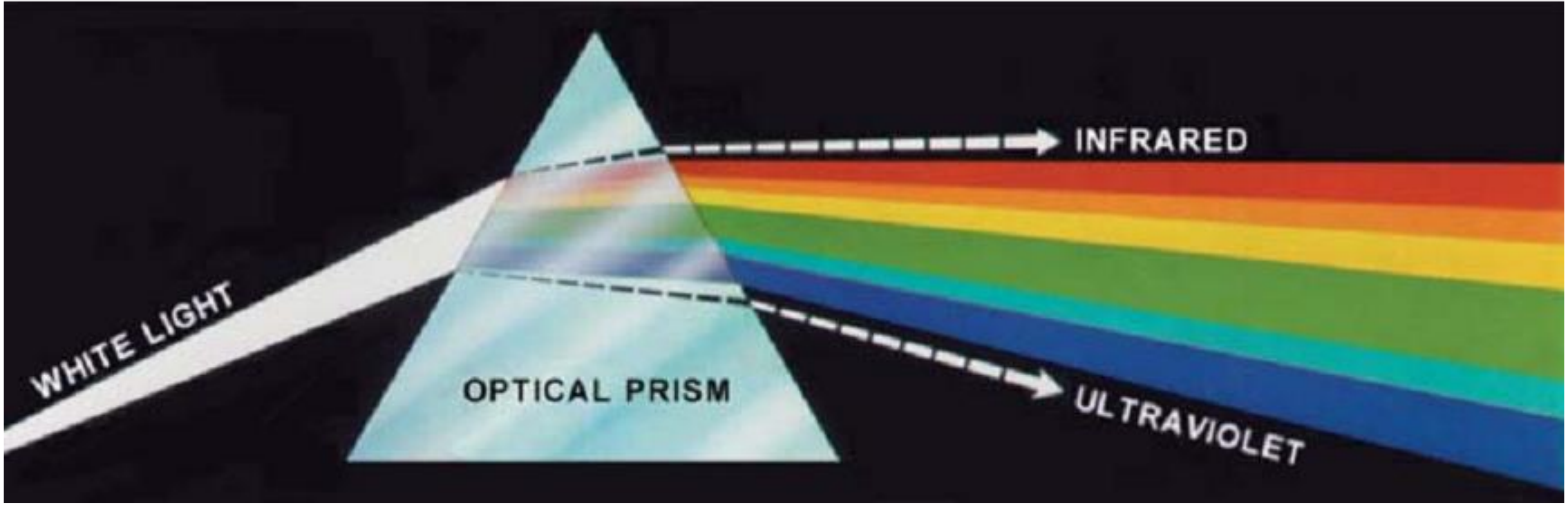

Color spectrum seen by passing white light through a prism.

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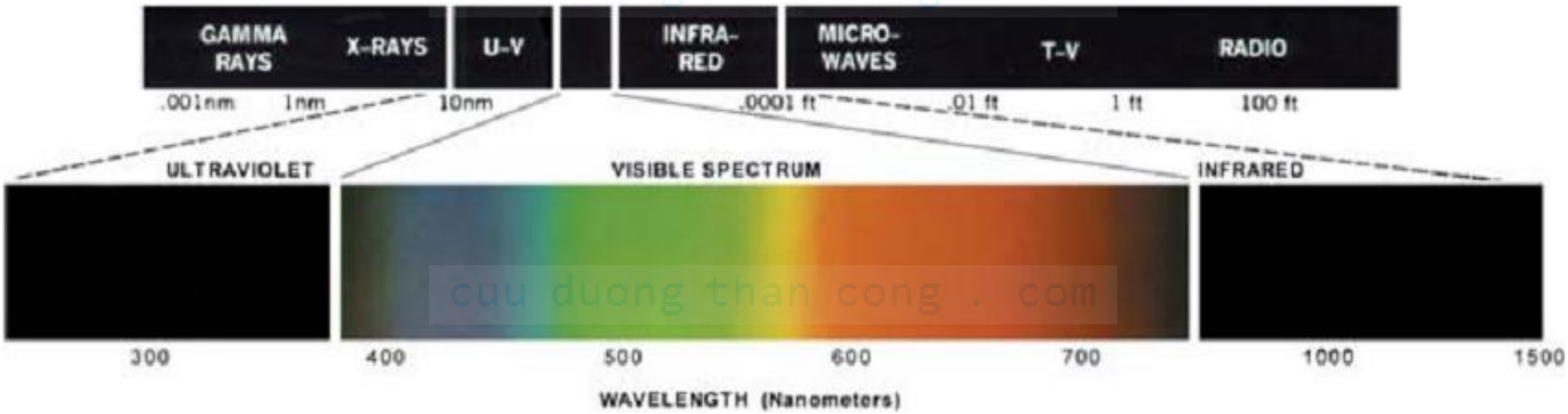

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Visible light is composed of a relatively narrow band of frequencies in the electromagnetic spectrum

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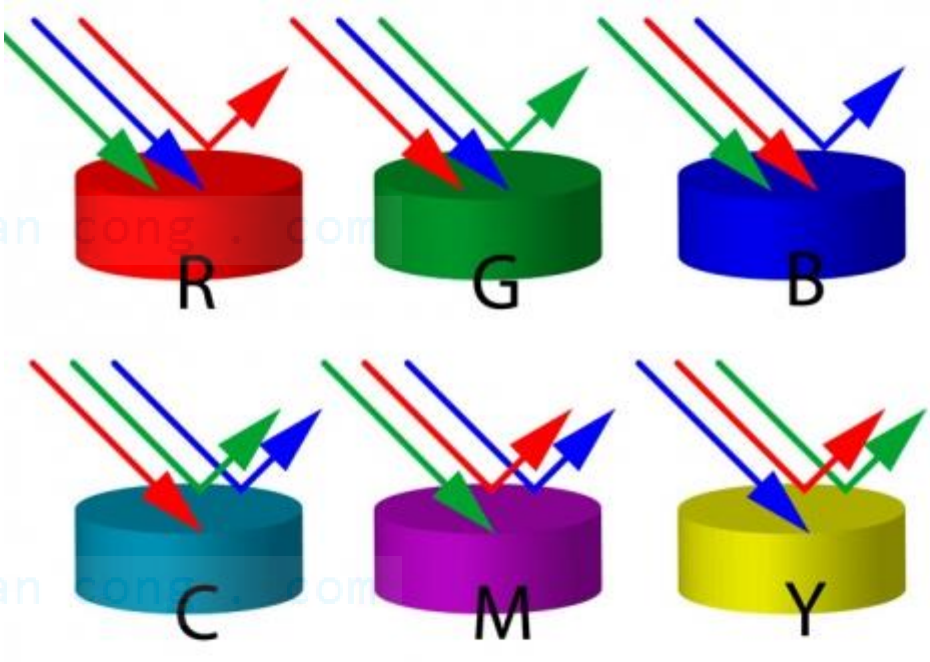
Colors perceived in an object

- The colors that humans and some other animals perceive in an object are determined by the nature of the light reflected from the object
  - For example, green objects reflect light with wavelengths of 500 – 570 nm while absorbing most of the energy at other wavelengths
  - A body that reflects light that is balanced in all visible wavelengths appears white to the observer



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Characterization of light: Achromatic light

- **Achromatic light** (void of color) is what viewers see on a black and white television set
- Its only attribute is **intensity**, or amount
- The term ***gray level*** refers to a scalar measure of intensity that ranges from black, to grays, and finally to white

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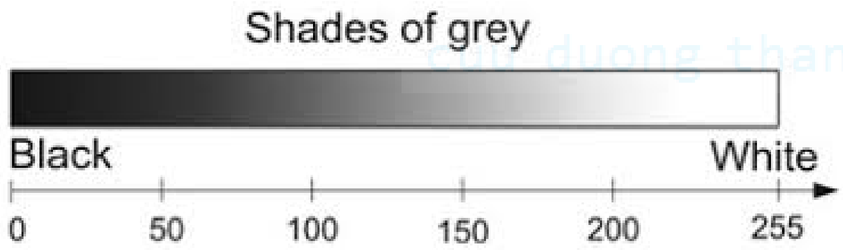

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Characterization of light: Chromatic light

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

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Characterization of light: Chromatic light

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

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Color receptors

- In color normal people, there are three types of color receptors, called **cones**, which vary in their sensitivity to light at different wavelengths
- The human eye combines three primary colors to discern all possible colors
  - 6 – 7 million cones are 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 (but the blue cones are the most sensitive)

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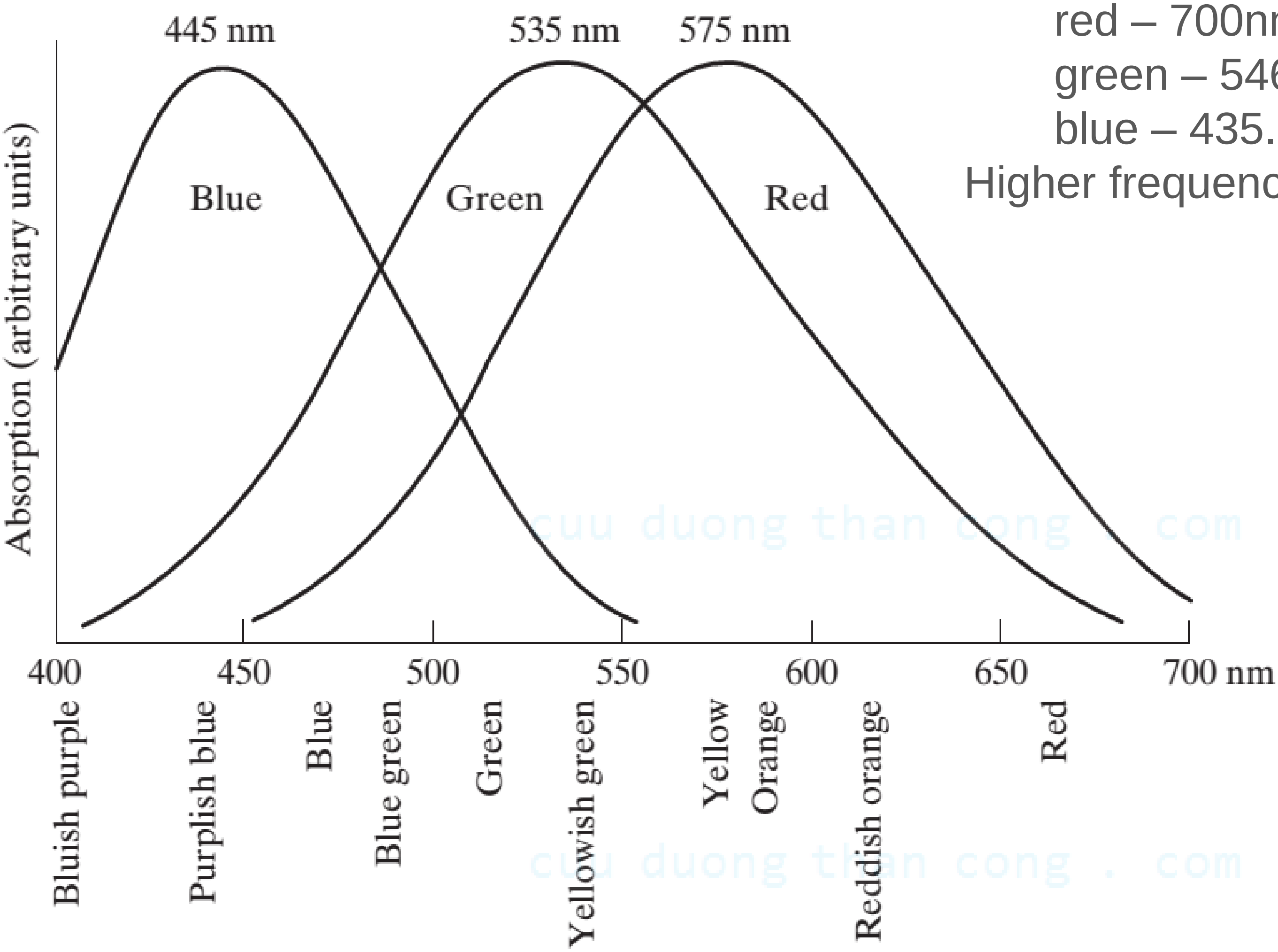
Colors are just different light frequencies

- red – 700nm wavelength
- green – 546.1 nm wavelength
- blue – 435.8 nm wavelength

Higher frequencies are cooler colors



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

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Color deficiency

- Deficiency by optical problems in the eye, or by absent receptor types
  - Usually a result of absent genes
- Some people have fewer than three types of receptor
  - Red-green color blindness is most common in men, while it is less common in women.
    - Red and green receptor genes are carried on the X chromosome, and these are the ones that typically go wrong. Women need two bad X chromosomes to have a deficiency, and this is less likely.

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Primary colors

- Primary colors of **light** are **additive**
  - Primary colors are red, green, and blue
  - Combining red + green + blue yields white

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- Primary colors of **pigment** are **subtractive**
  - Primary colors are cyan, magenta, and yellow
  - Combining cyan + magenta + yellow yields black

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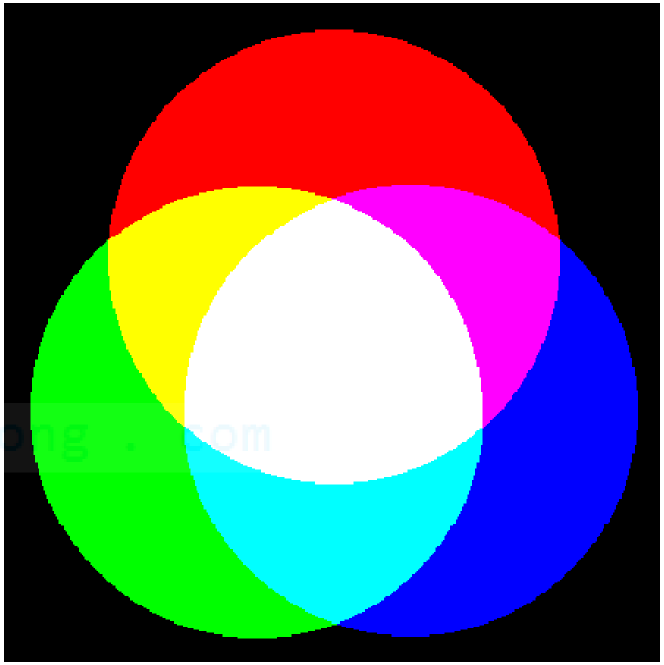
Additive color model



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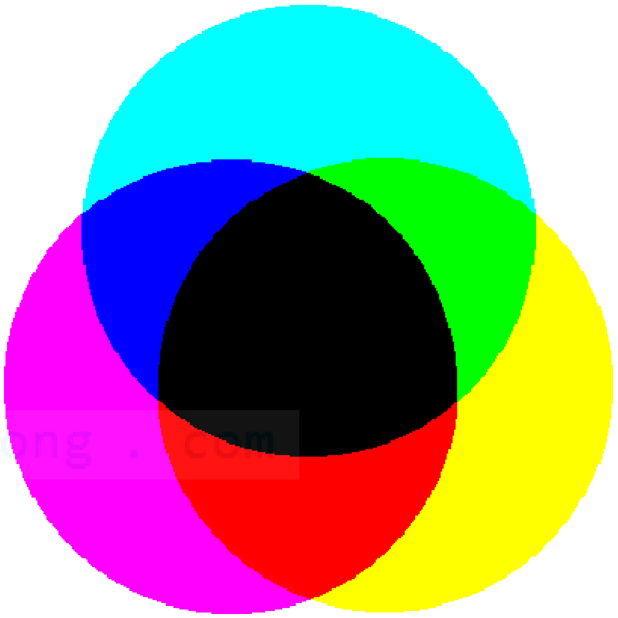
- Active displays, such as computer monitors and television sets, emit combinations of red green and blue light
- This is an **additive color model**

Subtractive color model



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- Passive displays, such as color inkjet printers, absorb light instead of emitting it. Combinations of cyan, magenta and yellow inks are used.
- This is a **subtractive color model**.

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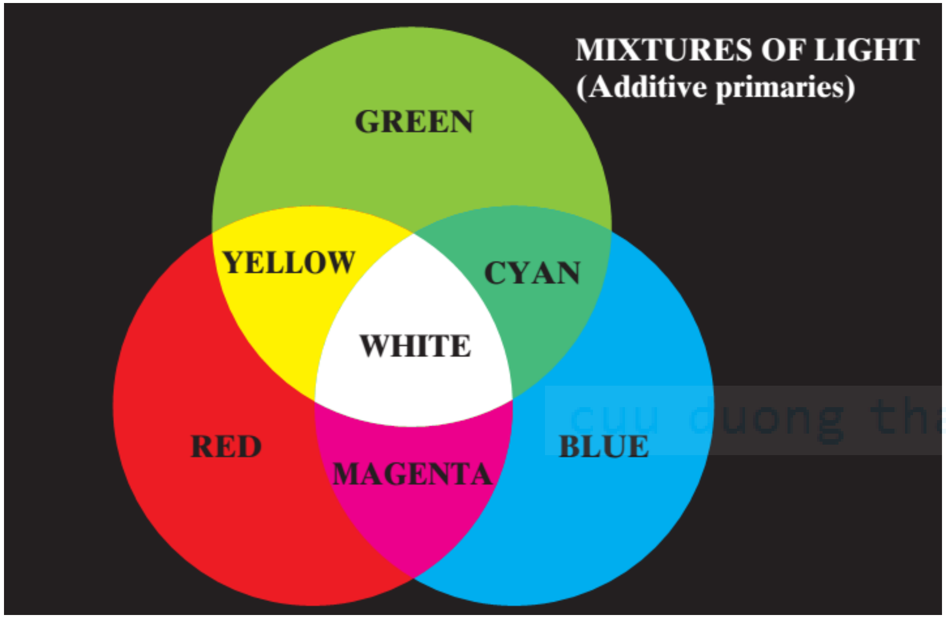
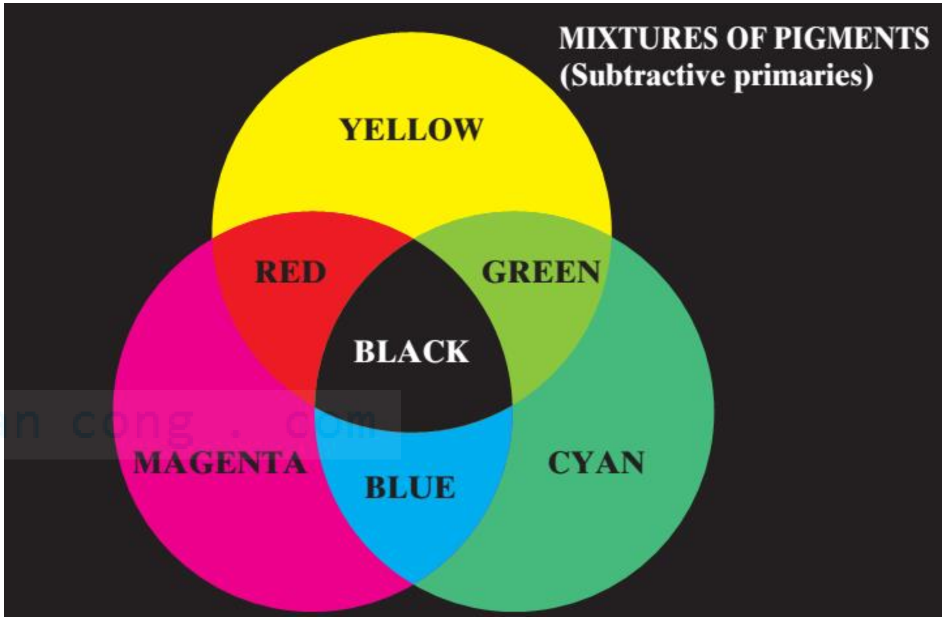
Additive vs. Subtractive color model





Magenta = Red + Blue
Cyan = Blue + Green
Yellow = Green + Red

Magenta = White – Green
Cyan = White - Red
Yellow = White - Blue

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Subtractive mixing of inks

- Inks subtract light from white.
- Inks: Cyan = White – Red, Magenta = White – Green, and Yellow = White – Blue
- For a good choice of inks, and good registration, matching is linear and easy
  - E.g. C+M+Y = White–White = Black, C+M = White–Yellow = Blue
- Usually require CMY and Black, because colored inks are more expensive and registration is hard (CMYK)

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Characterization of color

- The characteristics generally used to distinguish one color from another are *brightness, hue, and saturation*
- **Brightness** embodies the achromatic notion of intensity
- **Hue** represents dominant color perceived by an observer
  - It is associated with the dominant wavelength in a mixture of light waves. 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

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Characterization of color

- Hue and saturation taken together are called **chromaticity**
- Therefore, a color may be characterized by its brightness and chromaticity
- Let the amounts of red, green, and blue needed to form any particular color be the *tristimuslus values*, denoted by X, Y, and Z, respectively
- A color is then specified by its *trichromatic coefficients*

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

  - where $x + y + z = 1$, and they can be obtained directly from curves or tables that have been compiled from extensive experimental results (Poynton [1996]) or the CIE chromaticity diagram

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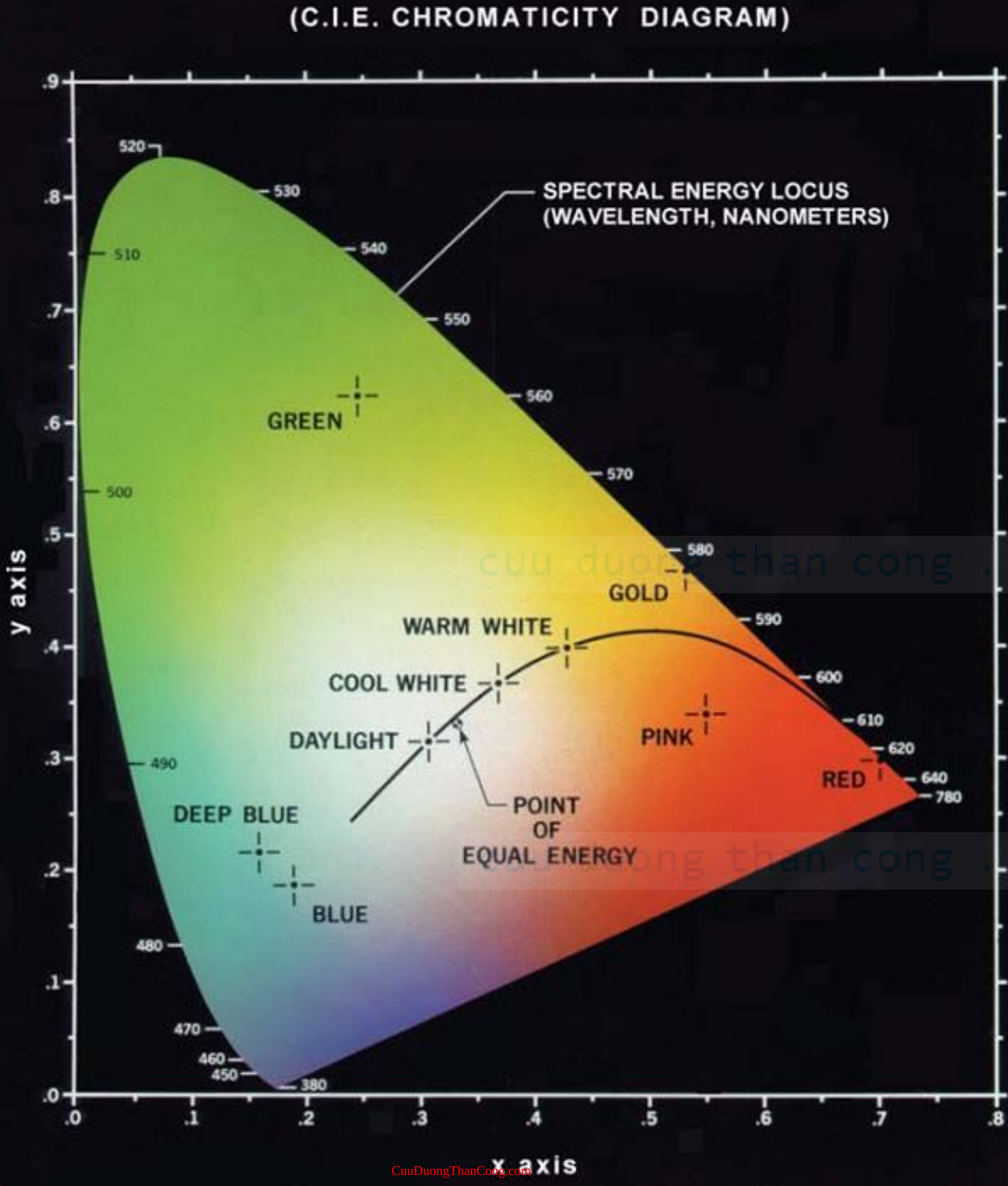

The blobby region represents visible colors. There are sets of (x, y) coordinates that do not represent real colors because the primaries are not real lights

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Interpreting the CIE chromaticity diagram

- The CIE chromaticity diagram shows color composition as a function of x (red) and y (green)
  - E.g., the point marked green has approximately 62% green, 25% red and the blue content is approximately $z = 1 - x - y = 13\%$
- The pure colors of the spectrum are positioned around the boundary of the tongue-shaped chromaticity diagram
  - Any point not actually on the boundary but within the diagram represents some mixture of spectrum colors
- Any three given colors in the diagram form a triangle and any color on the boundary or inside the triangle can be produced by various combinations of the three initial colors

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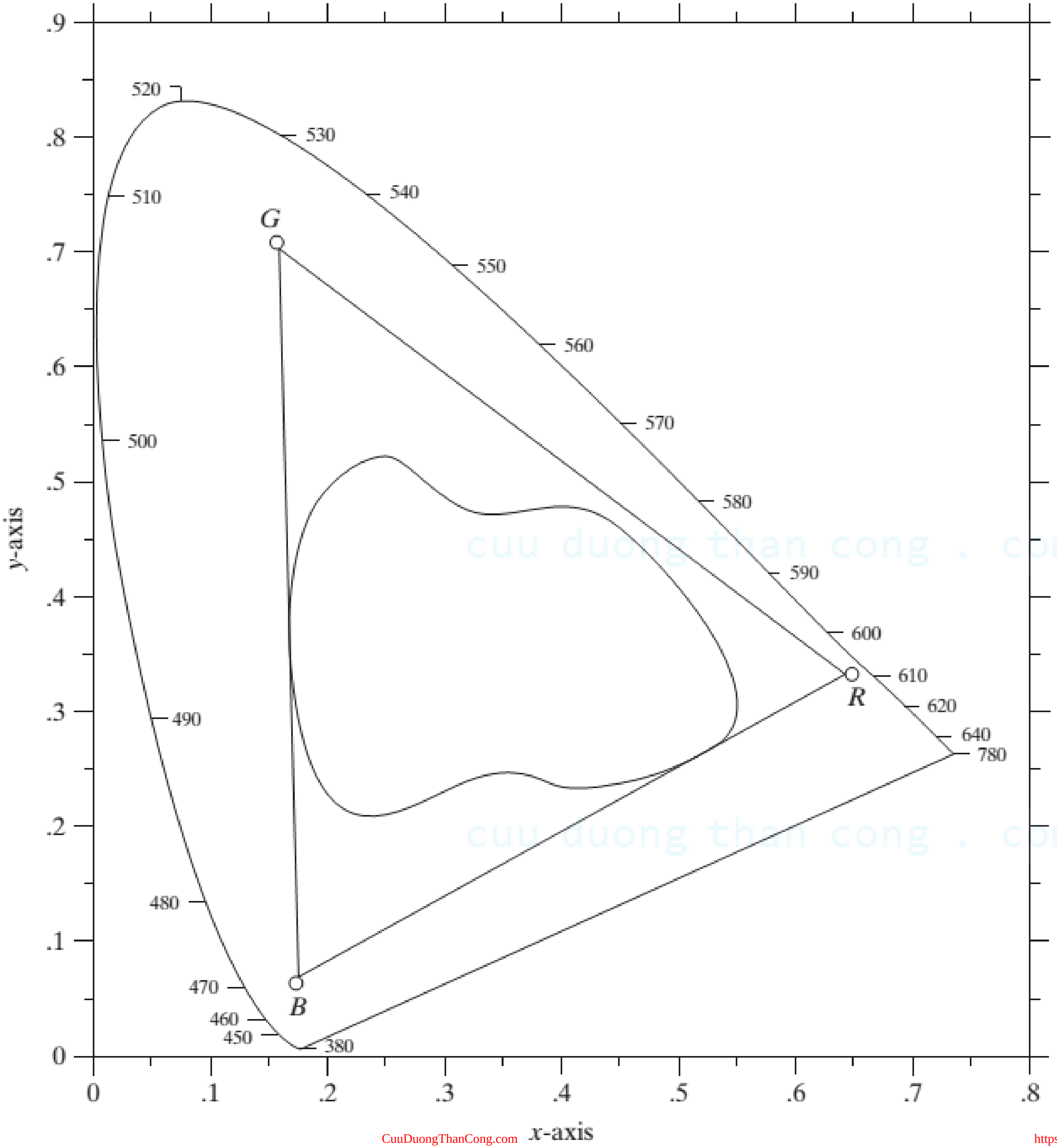

Typical color gamut of color monitors (triangle) and color printing devices (irregular region)

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Interpreting the color gamut

- The triangle shows a typical range of colors (called the *color gamut*) produced by RGB monitors
- The irregular region inside the triangle is representative of the color gamut of today's high-quality color printing devices
  - Its boundary is irregular because color printing is a combination of additive and subtractive color mixing, which is much more difficult to control than that of displaying colors on a monitor
- For a good choice of inks, there is a linear transform between XYZ and CMY

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Section 7.2

COLOR MODELS

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Color models

- A **color model** (color space, color system) is a specification of a coordinate system and a subspace within that system where each color is represented by a single point
- 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 (such as in the creation of color graphics for animation)

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Color models

- For digital image processing, the hardware-oriented models most commonly used in practice are
  - the **RGB** (red, green, blue) 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

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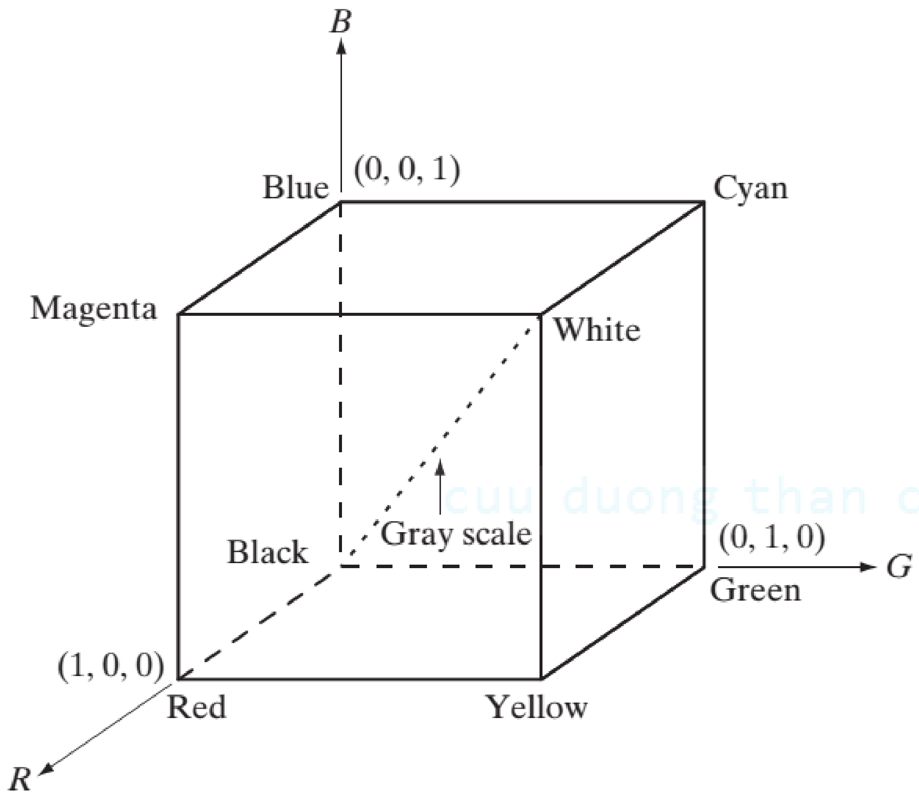
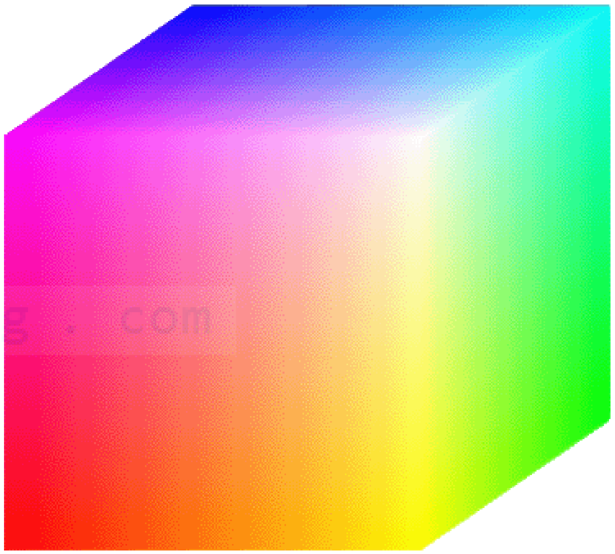
RGB color model: Color cube





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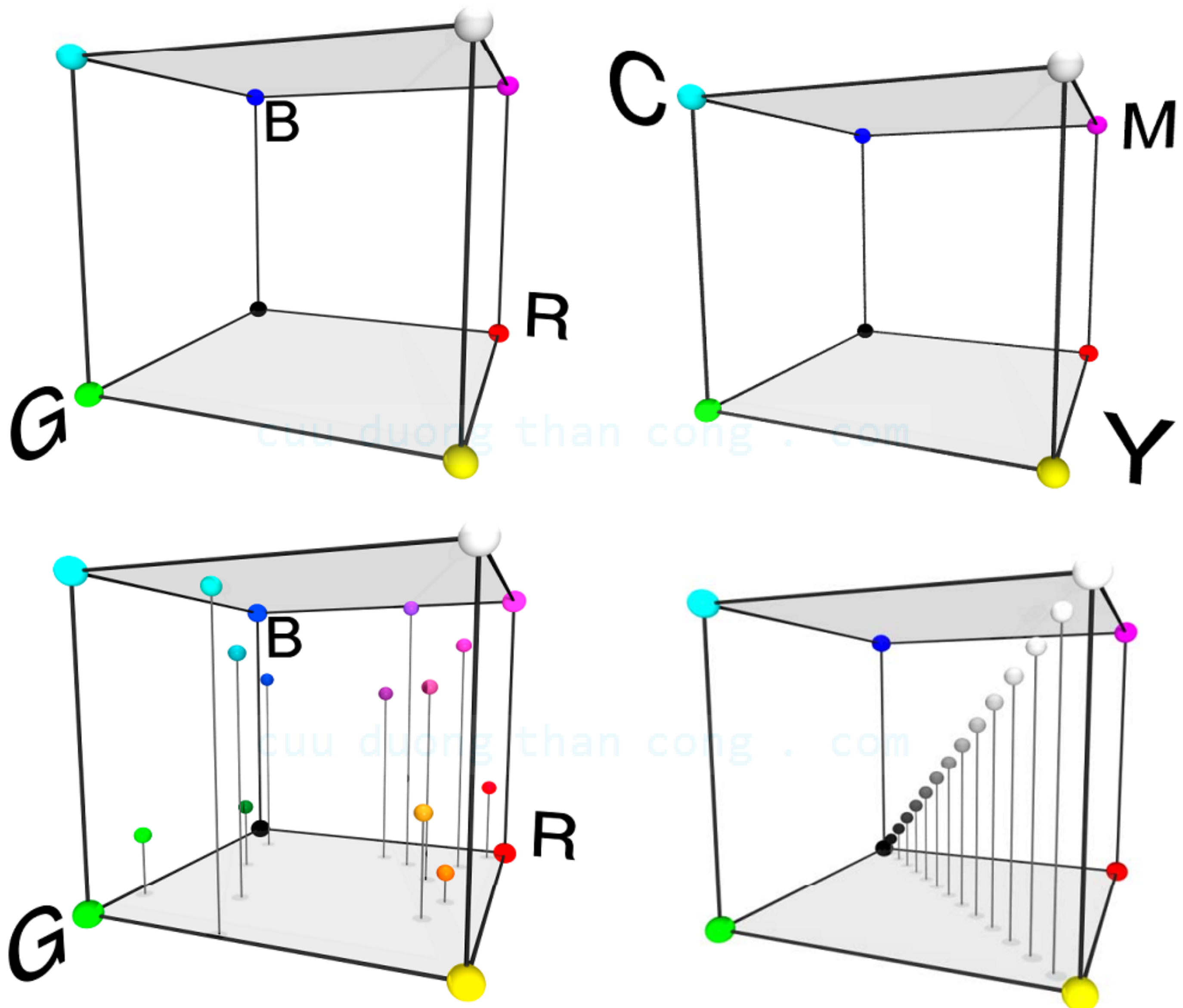
- The **RGB color model** is based on a Cartesian coordinate system. Each color appears in its primary spectral components of red, green, and blue

RGB color model: Color cube



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RGB color model: Pixel depth

- The number of bits used to represent each pixel in RGB space is called the **pixel depth** (or called bits per pixel)
  - Describes the ability of an image to accurately reproduce colors
  - E.g. consider an 8-bit RGB image where each of the red, green, and blue images is an 8-bit image, each RGB color pixel is said to have a depth of 24 bits
- The term *full-color image* is used often to denote a 24-bit RGB color image.
- The total number of colors in a 24-bit RGB image is

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

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a	b
c	d

Images that have (a) 1 bit per pixel, (b) 2 bits per pixel, (c) 5 bits per pixel and (d) 24 bits per pixel

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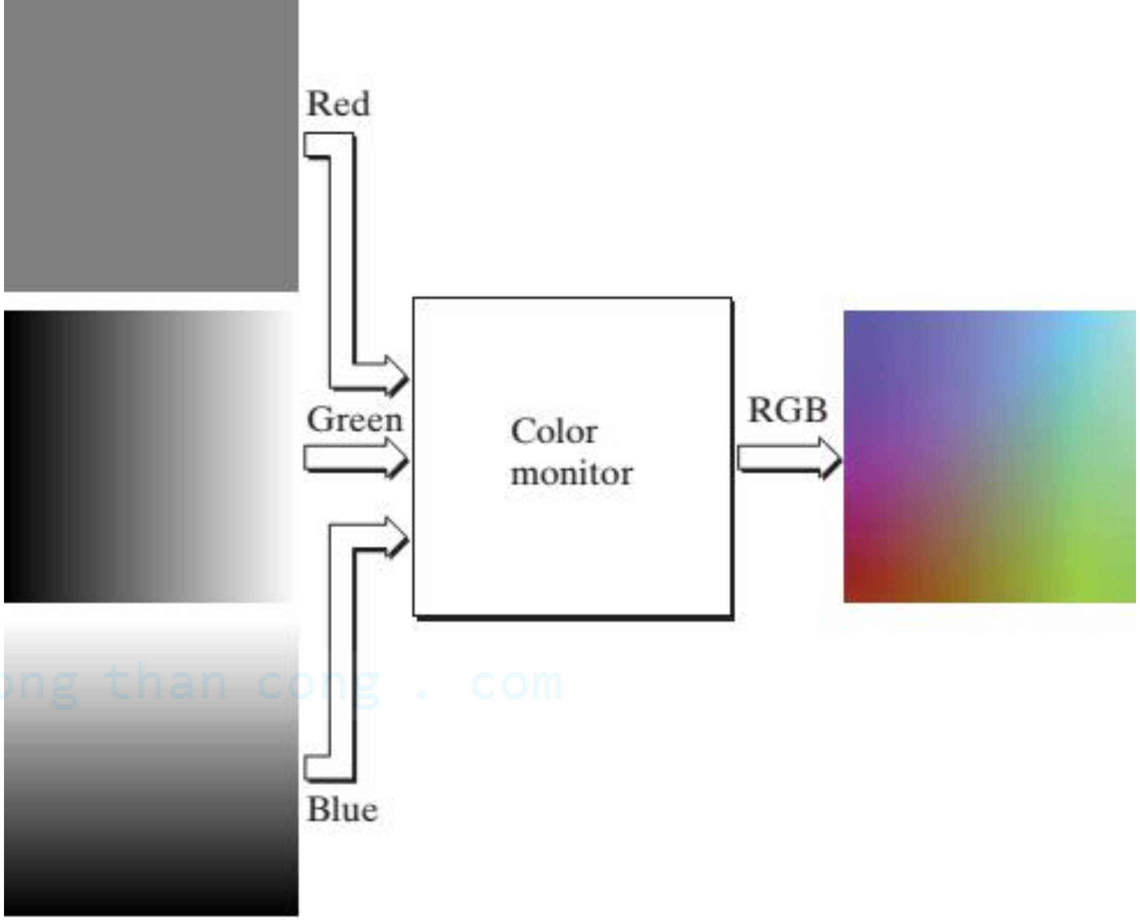
a

b

(a) Generating the RGB image of the cross-sectional color plane (127, G, B).
(b) The three hidden surface planes in the color cube



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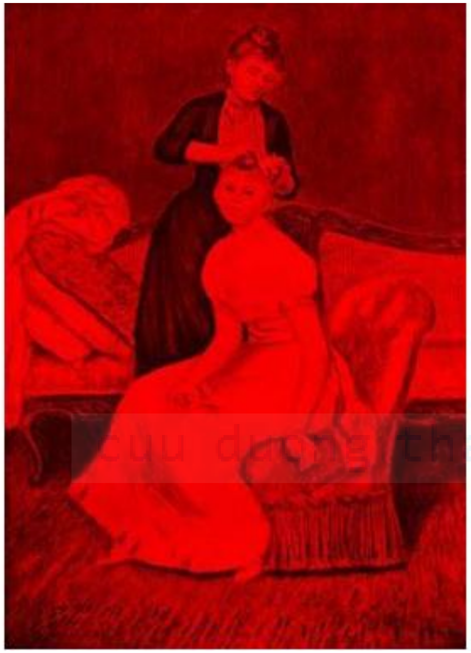
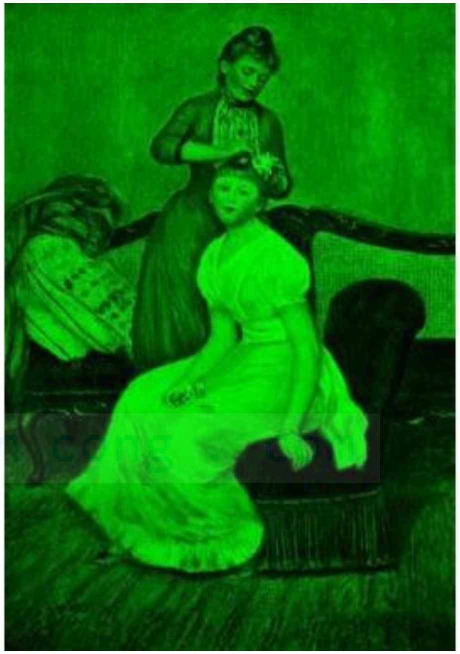
Original



Red band



Green band

Blue band

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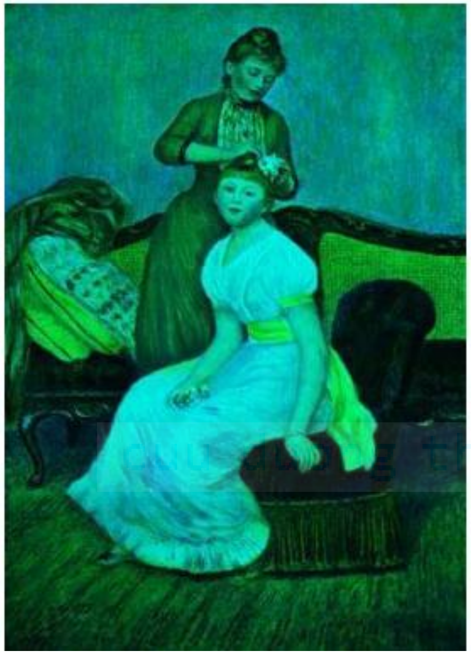
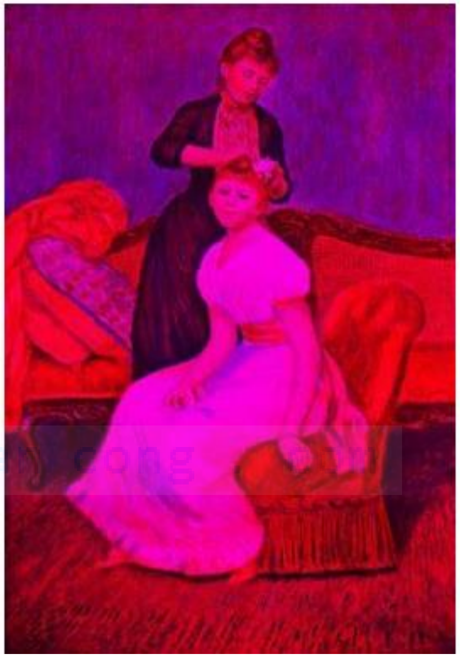
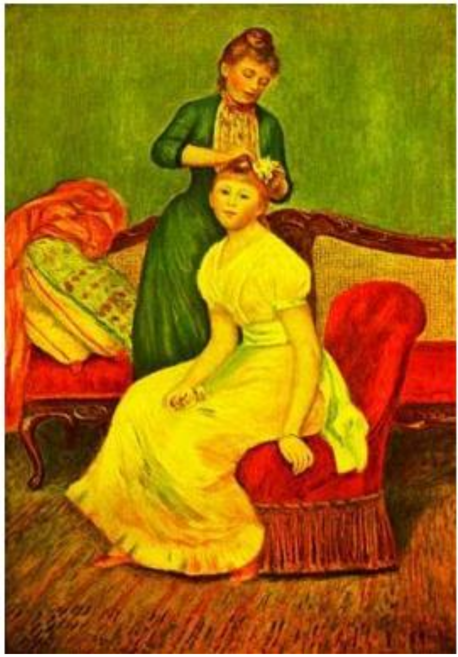
Original



No red



No green



No blue

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Original

Red

Green

Blue

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Safe RGB colors

- Many systems in use today are limited to 256 colors due to the rendering hardware or it simply makes no sense to use more than a few hundred, and sometimes fewer, colors
  - E.g. the pseudocolor image processing techniques

- The set of **safe RGB colors**, or the set of all-systems-safe colors (also called safe Web or safe browser colors for Internet applications) include 216 colors
  - These colors are likely to be reproduced faithfully, reasonably independently of viewer hardware
  - Each safe color can be form from three RGB values and its value can only be 0, 51, 102, 153, 204 or 255

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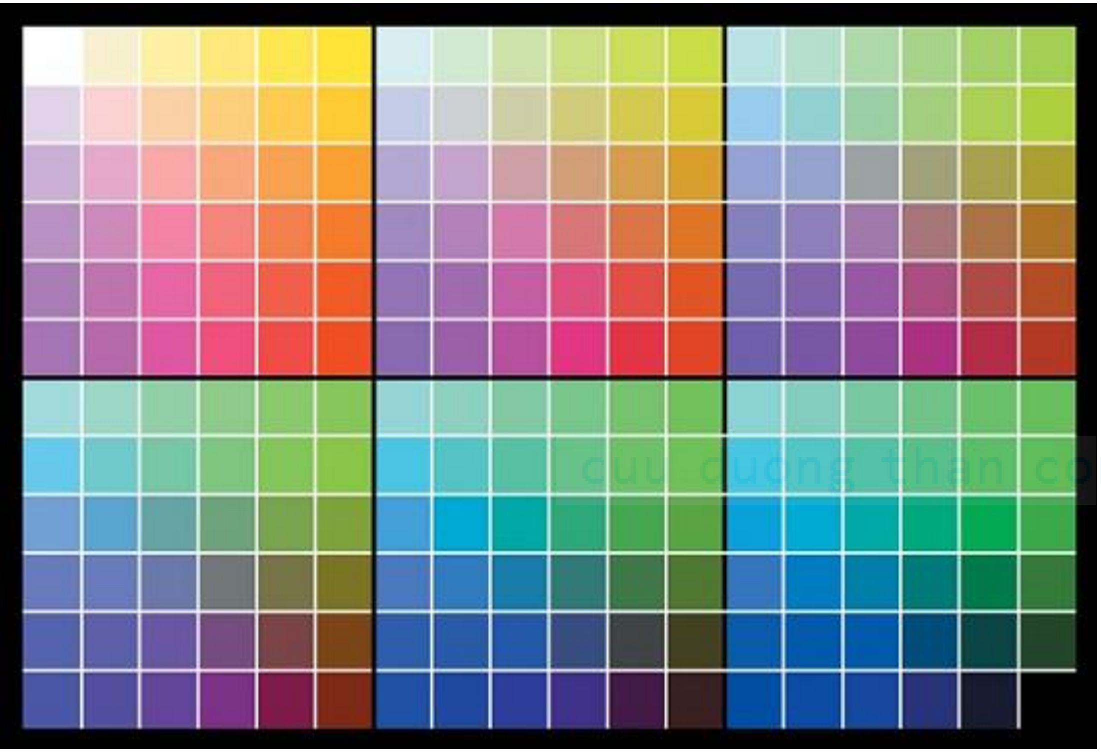
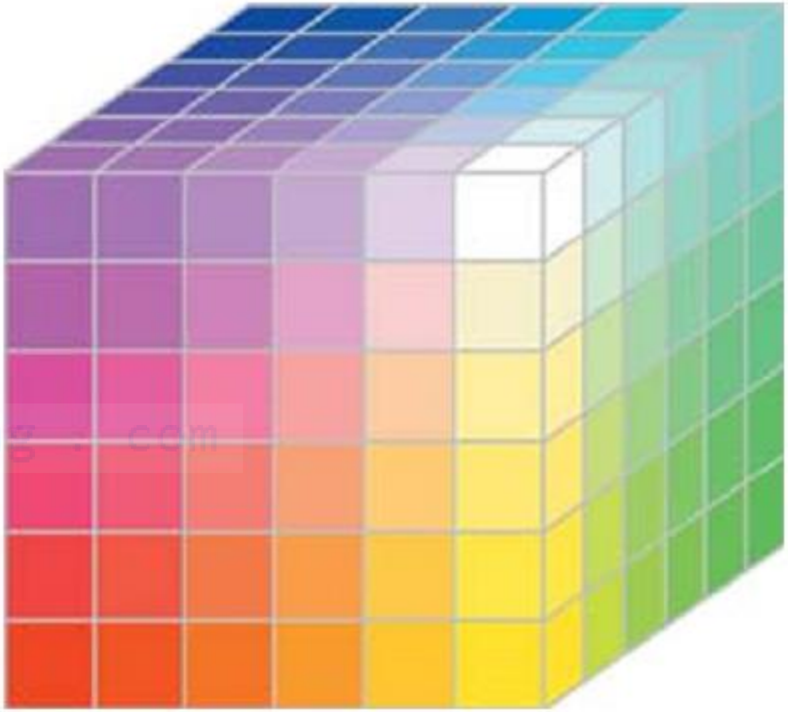
Safe RGB colors



The 216 safe RGB colors



RGB safe-color cube

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- Unlike the full-color cube, which is solid, the safe-color cube has valid colors only on the surface planes

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The CMY and CMYK color models

- Most devices that deposit colored pigments on paper, such as color printers and copiers, require CMY data input or perform an RGB to CMY conversion internally

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

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- The inverse operation from CMY to RGB generally is of little practical interest

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The CMY and CMYK color models

- Equal amounts of the pigment primaries, cyan, magenta, and yellow should produce black.
- However, in practice, combining these colors for printing produces a muddy-looking black
- So, in order to produce true black (which is the predominant color in printing), a fourth color, black, is added, giving rise to the CMYK color model

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Drawbacks of RGB

- RGB is ideal **for image color generation**
  - E.g. image capture by a color camera or image display in a monitor
  - It matches nicely with the fact that the human eye is strongly perceptive to red, green, and blue primaries
- But its use for **color description** is much more limited
  - E.g. one does not refer to the color of an automobile by giving the percentage of each of the primaries composing its color
  - Humans view a color object and describe it by its hue, saturation, and brightness

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Light intensity

- Intensity is a weighted function of the $r, g, and\ b$ values
- The human eye does not weight each component identically!

$$intensity = 0.299 * Red + 0.587 * Green + 0.144 * Blue$$

- Assume three light sources have the same actual intensity but are colored red, green, and blue.

The **green** light will appear brightest followed by **red** and **blue**

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The HSI color model

- The **HSI color model** is an ideal tool for developing image processing algorithms based on color descriptions that are natural and intuitive to human
- **Hue**
  - A subjective measure of color
  - Average human eye can perceive ~200 different colors
- **Saturation**
  - Relative purity of the color. Mixing more “white” with a color reduces its saturation
  - Pink has the same hue as red but less saturation
- **Intensity**
  - The brightness or darkness of an object

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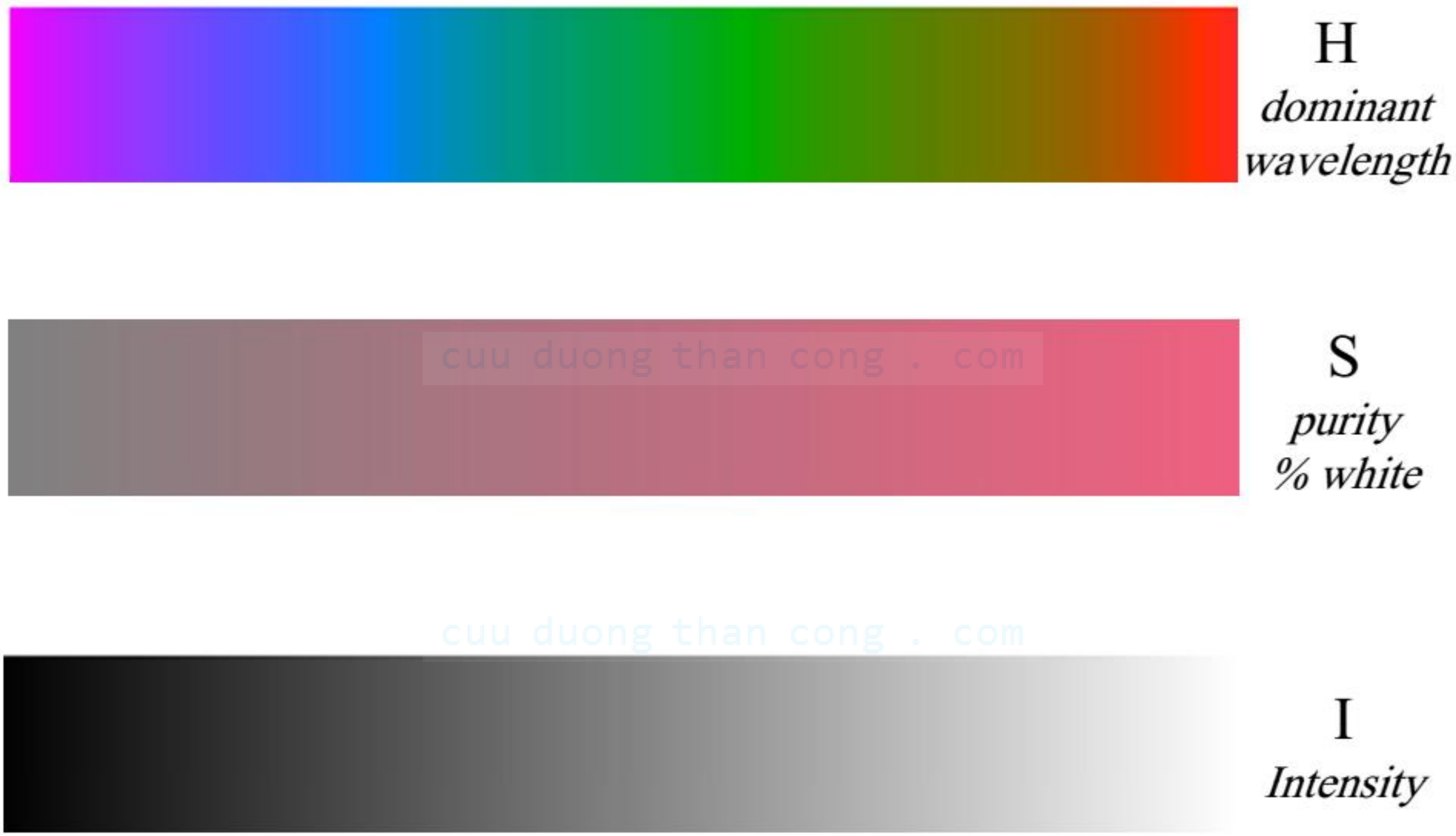
The HSI color model



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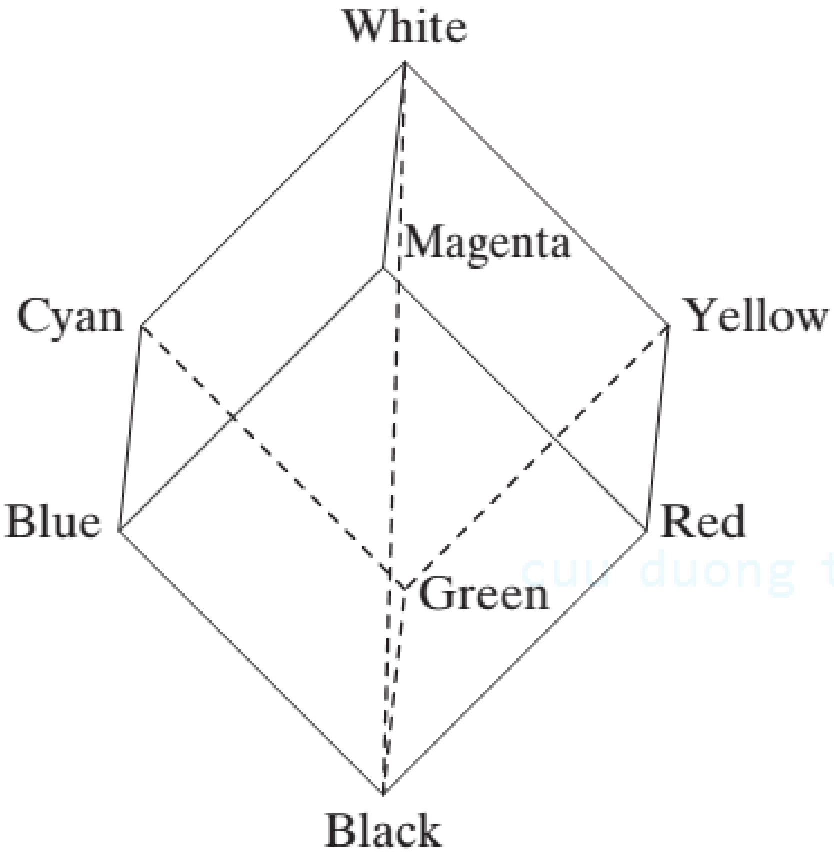

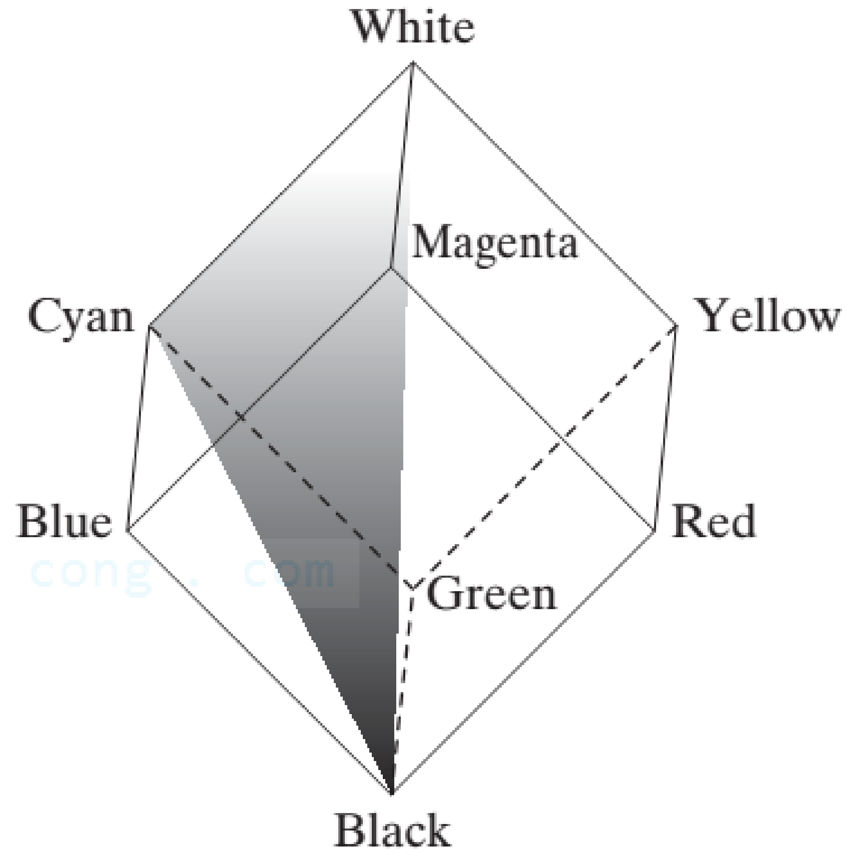

Conceptual relationships between the RGB and HSI color models

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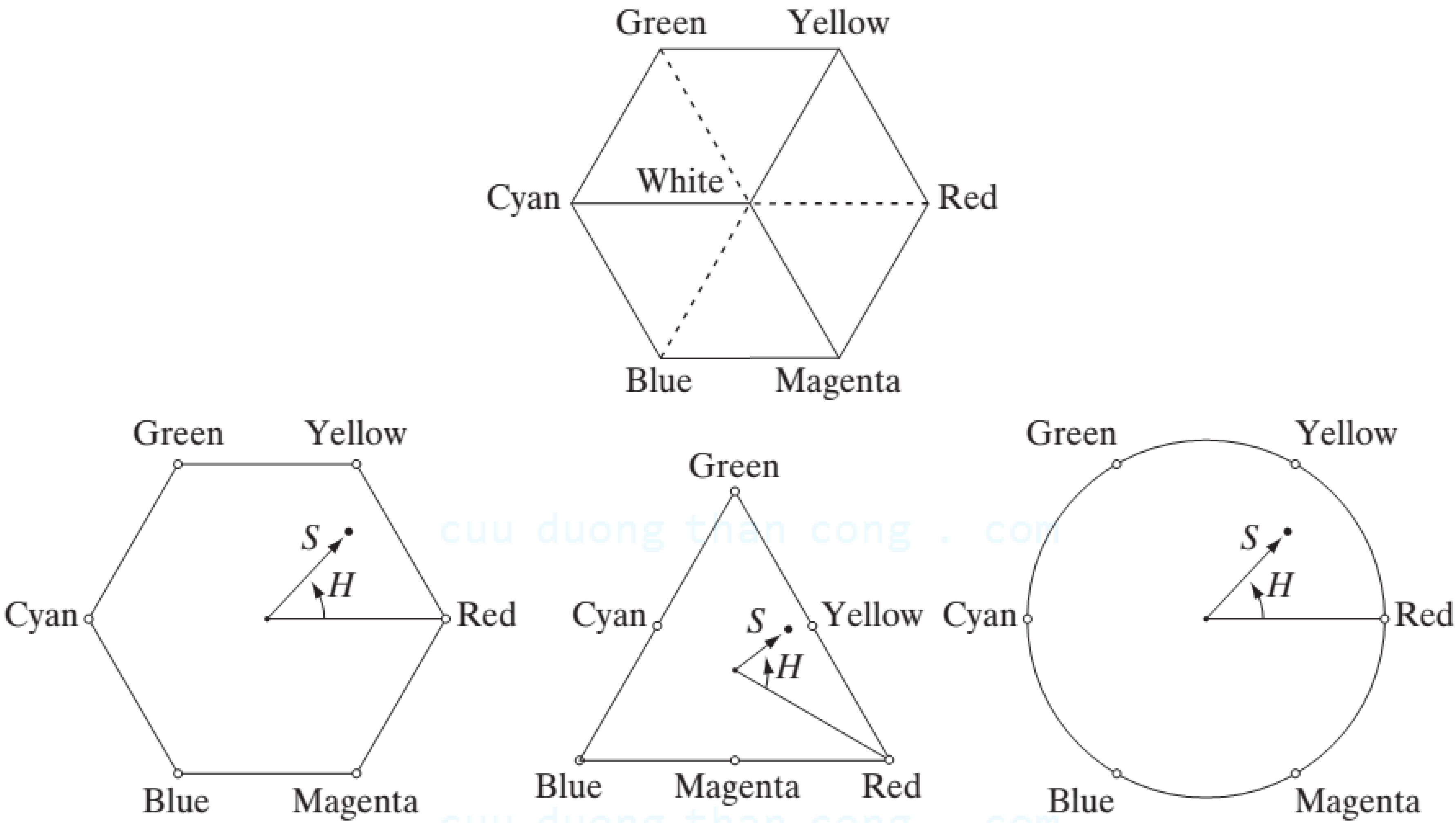

Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and the length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis

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The HSI color model

- **Hue** 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
- **Saturation** (distance from the vertical axis) is the length of the vector from the origin to the point
  - Note that the origin is defined by the intersection of the color plane with the vertical intensity axis.
  - Values range from 0 to 1
- **Intensity** is denoted as the distance "up" the axis from black
  - Values range from 0 to 1

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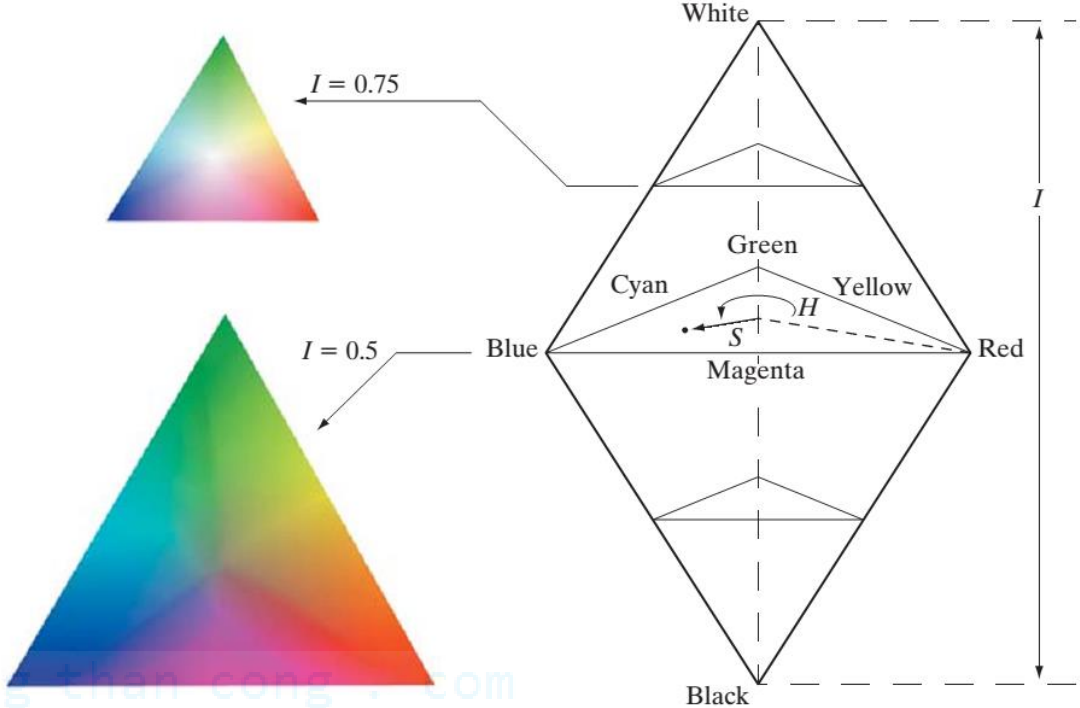
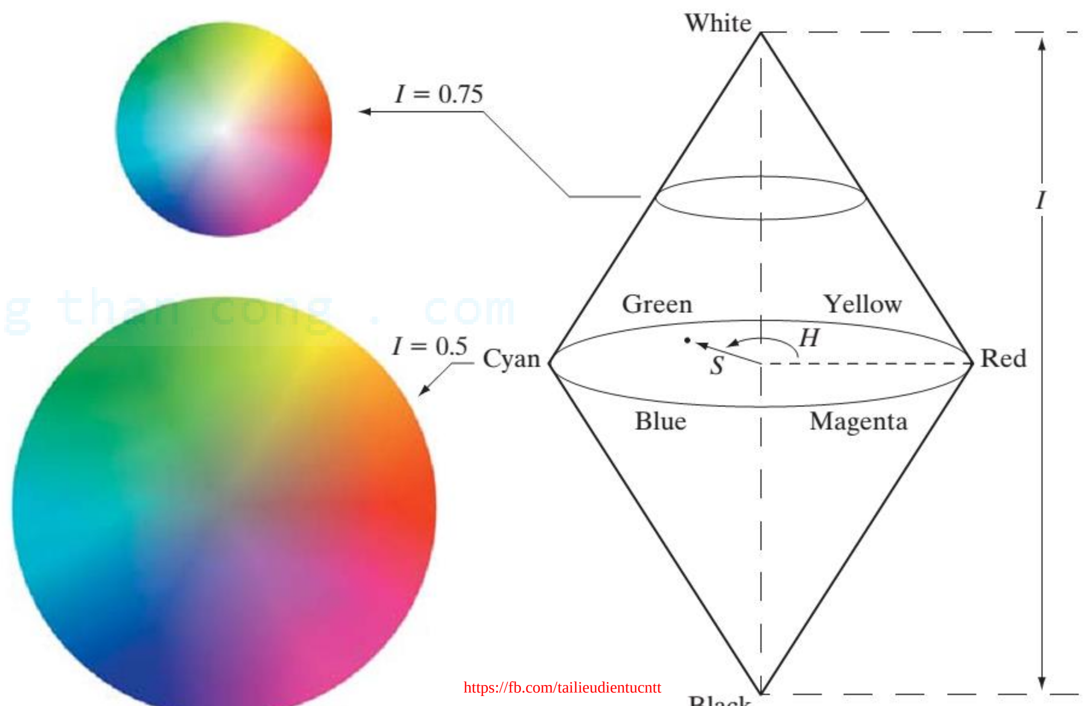
a

b

The HSI color model based on (a) triangular and (b) circular color planes. The triangles and circles are perpendicular to the vertical intensity axis



The shape chosen does not matter because any one of these shapes can be warped into one of the other two by a geometric transformation



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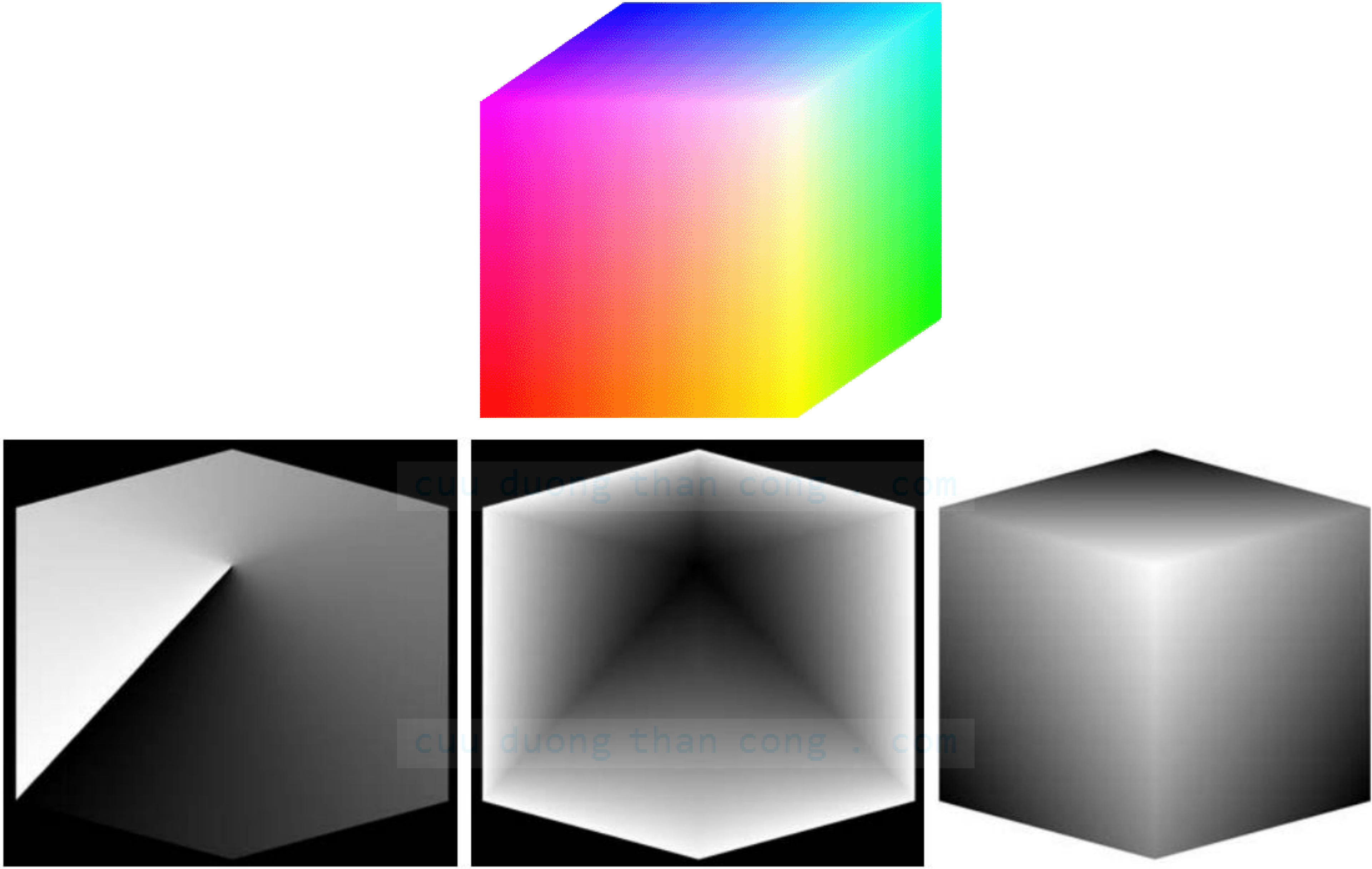

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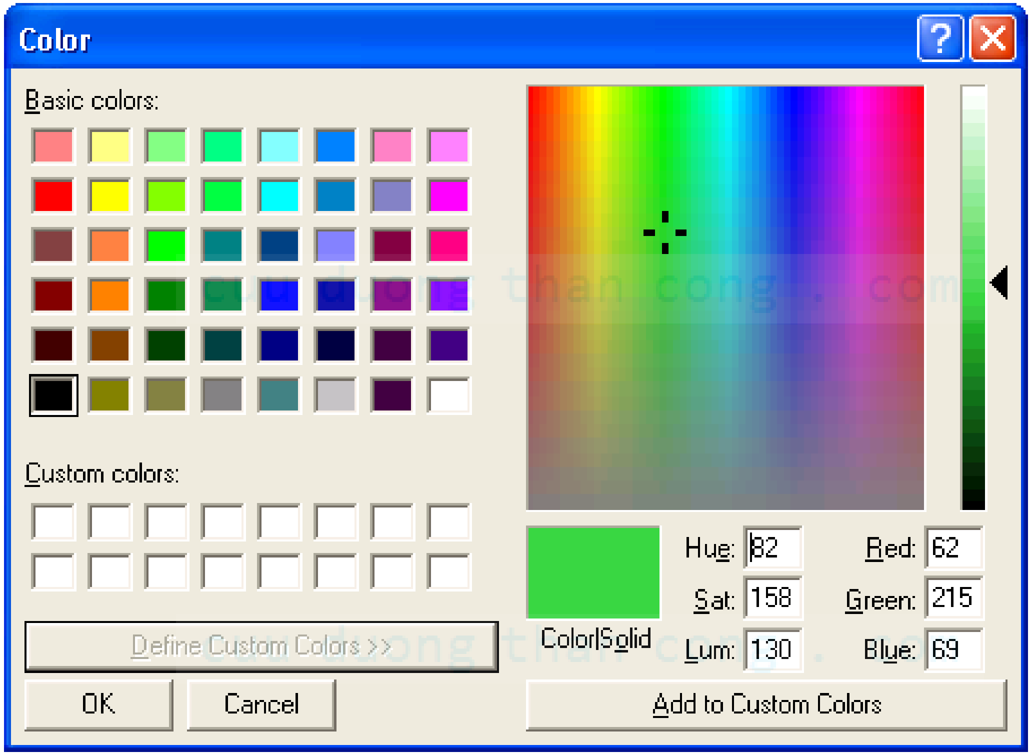
a b c

HSI components of the image in the RGB cube. (a) Hue, (b) saturation, and (c) intensity images

HSI vs. RGB

- RGB and HSI are commonly used to specify colors in software applications



Color dialog box of Windows

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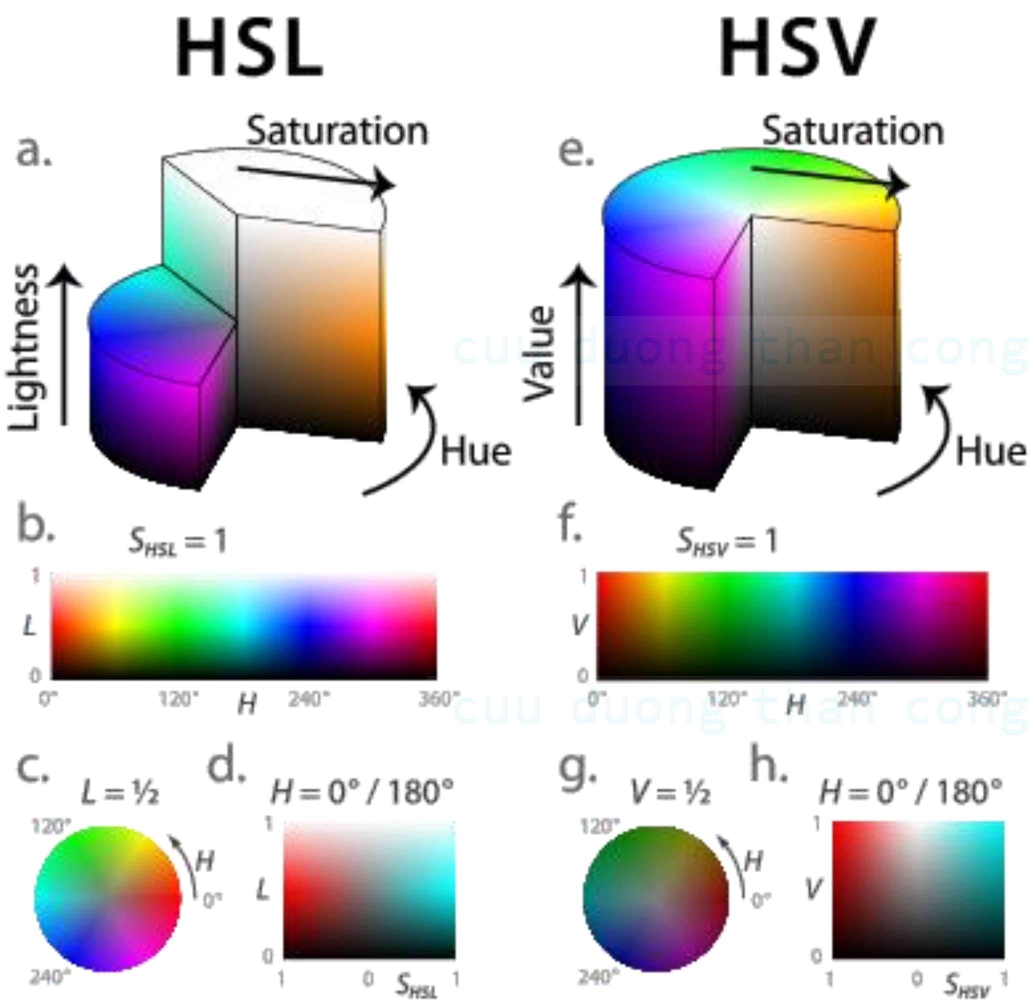
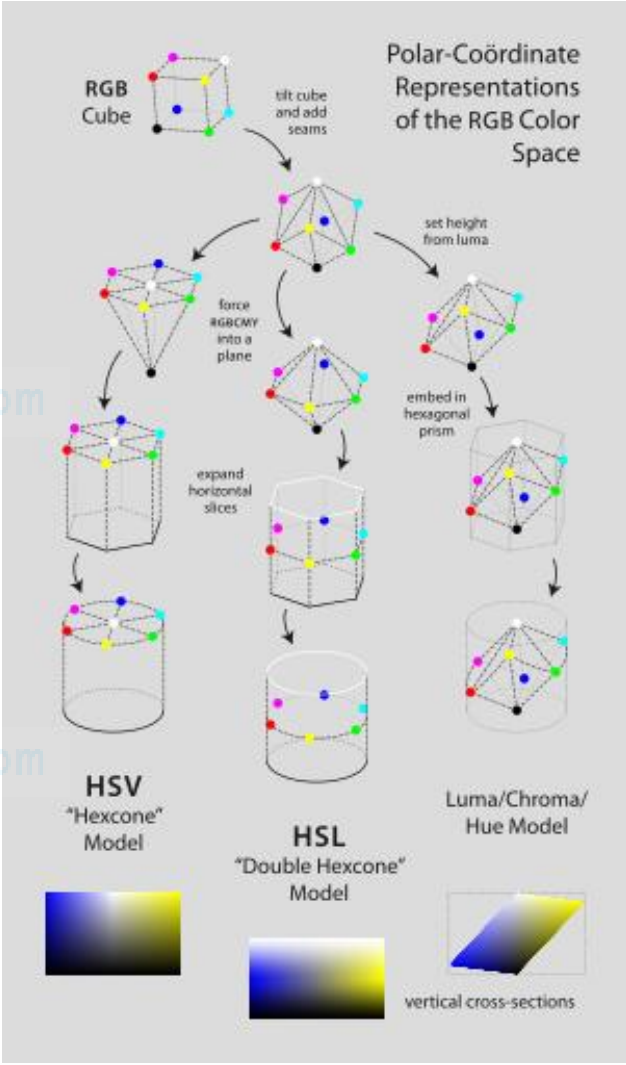
- HSI has variants such as HSL, HSB and HSV





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Conversion between HSI and RGB

- Converting color from RGB to HSI

$$H = \begin{cases} \theta & if\ B \leq G \\ 360 - \theta & if\ B > G \end{cases} \quad with \quad \theta = \cos^{-1}\left\{ \frac{\frac{1}{2}[(R-G)+(R-B)]}{[(R-G)^2+(R-B)(G-B)]^{1/2}} \right\}$$

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

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

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Conversion between HSI and RGB

- Converting color from HSI to RGB

$\boldsymbol{RG\ sector}\ (\mathbf{0 \le H \le 120})$

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

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

$$G = 1 - (R + B)$$

$\boldsymbol{GB\ sector}\ (\mathbf{120 \le H \le 240})$

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

$$G = I\left[1 + \frac{S\cos(H - 120)}{\cos(60 - (H - 120))}\right]$$

$$B = 1 - (R + G)$$

$\boldsymbol{BR\ sector}\ (\mathbf{240 \le H \le 360})$

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

$$B = I\left[1 + \frac{S\cos(H - 240)}{\cos(60 - (H - 240))}\right]$$

$$R = 1 - (G + B)$$

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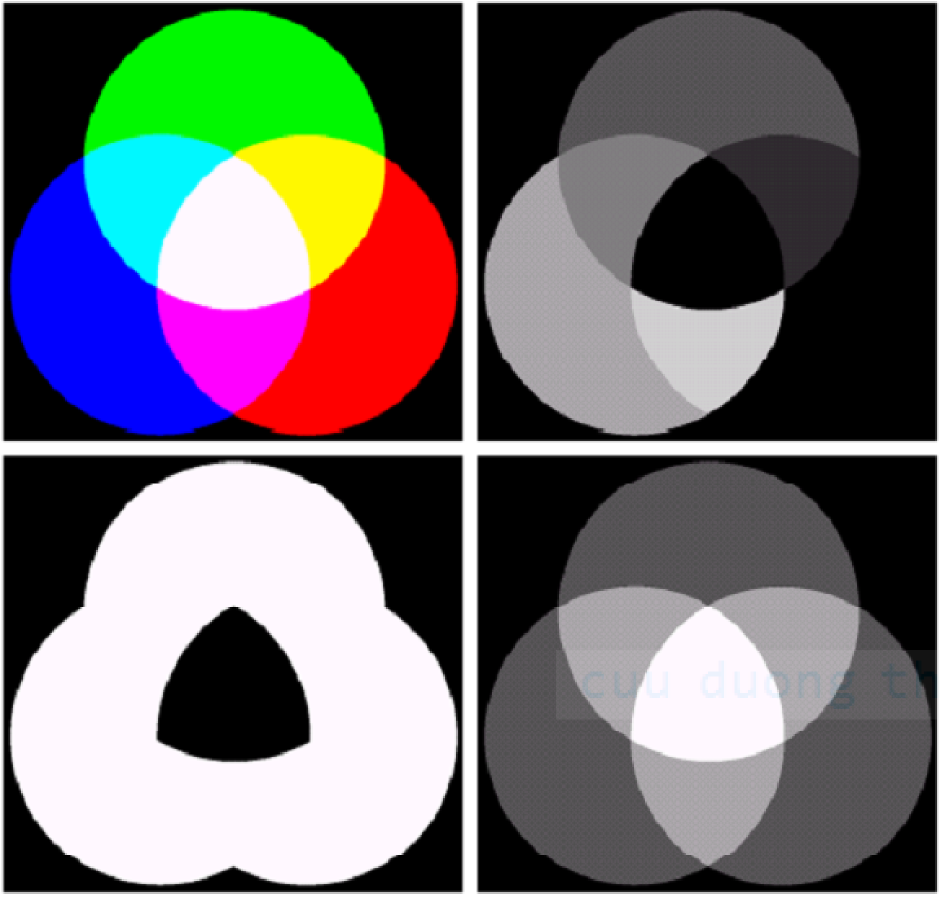
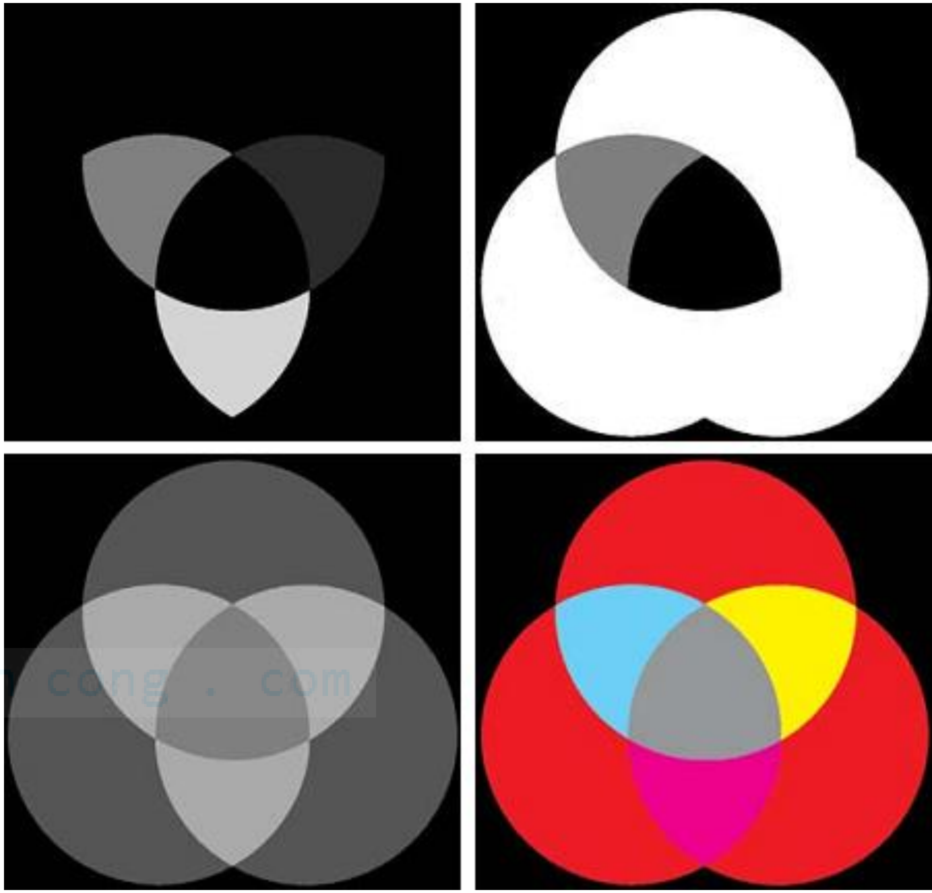


a b
c d

(a) RGB image and the components of its corresponding HSI image: (b) hue, (c) saturation, and (d) intensity



a b
c d

(a)–(c) Modified HSI component images.
(d) Resulting RGB image

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

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Section 7.3

PSEUDOCOLOR IMAGE PROCESSING

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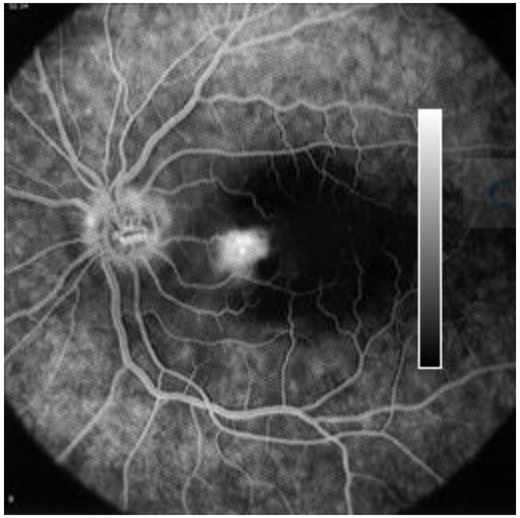
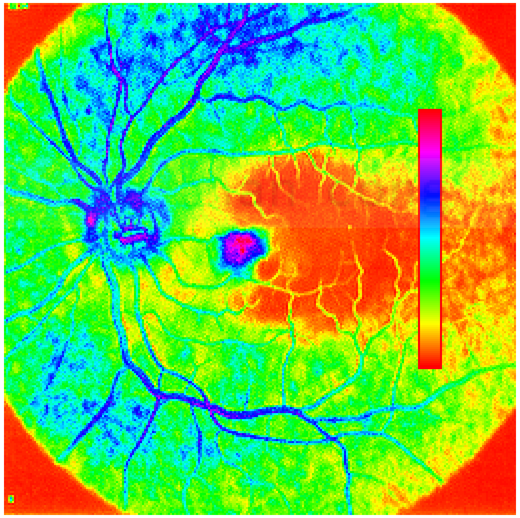
Pseudocolor image processing

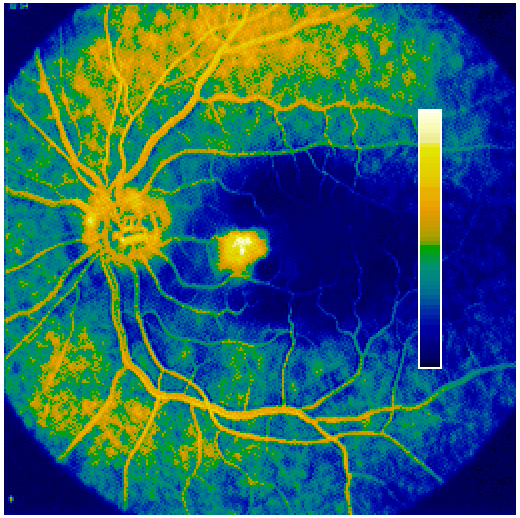
- **Pseudocolor** (or false color) **image processing** assigns colors to gray values based on a specified criterion



Monochrome image



Result of using "Rainbow" color table



Result of using "SApseudo" color table

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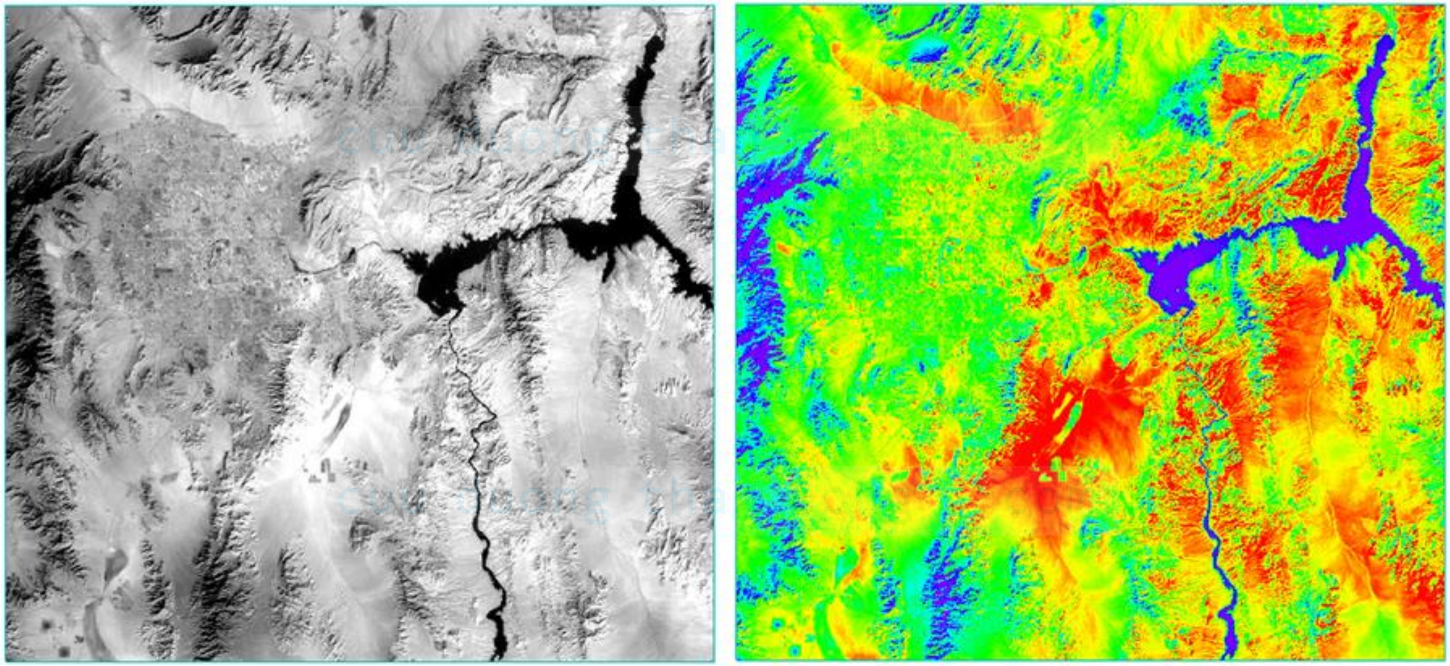
Pseudocolor image processing

- For human visualization and interpretation of gray-scale events in an image or sequence of images
  - Humans can discern thousands of color shades and intensities, compared to only two dozen or so shades of gray



Left image: cool areas are dark while light areas are warmer. Right image: temperature is shown as a color gradient, cool areas are blue and warm areas are red.

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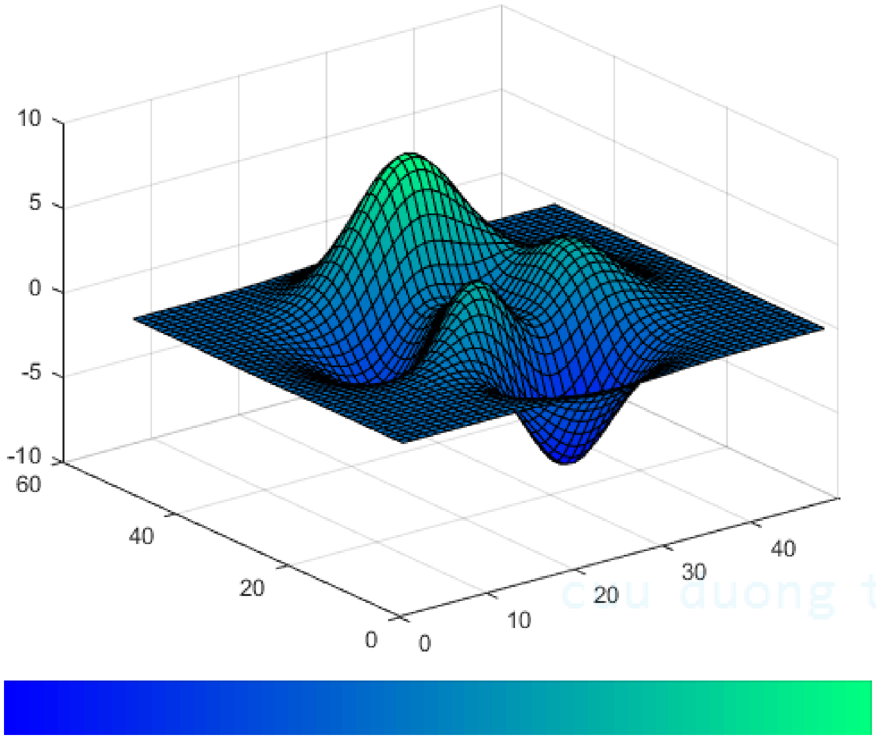

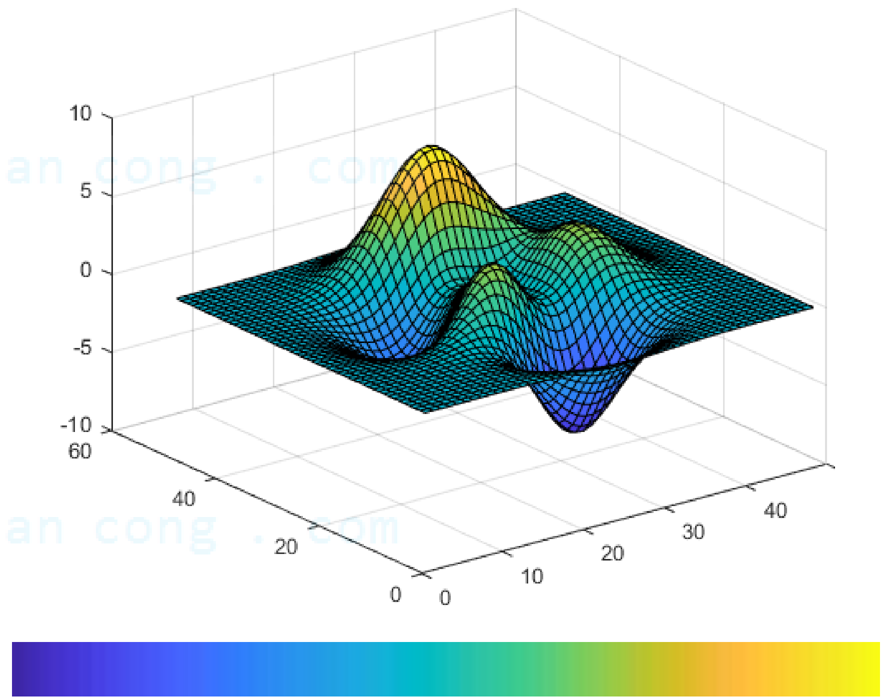

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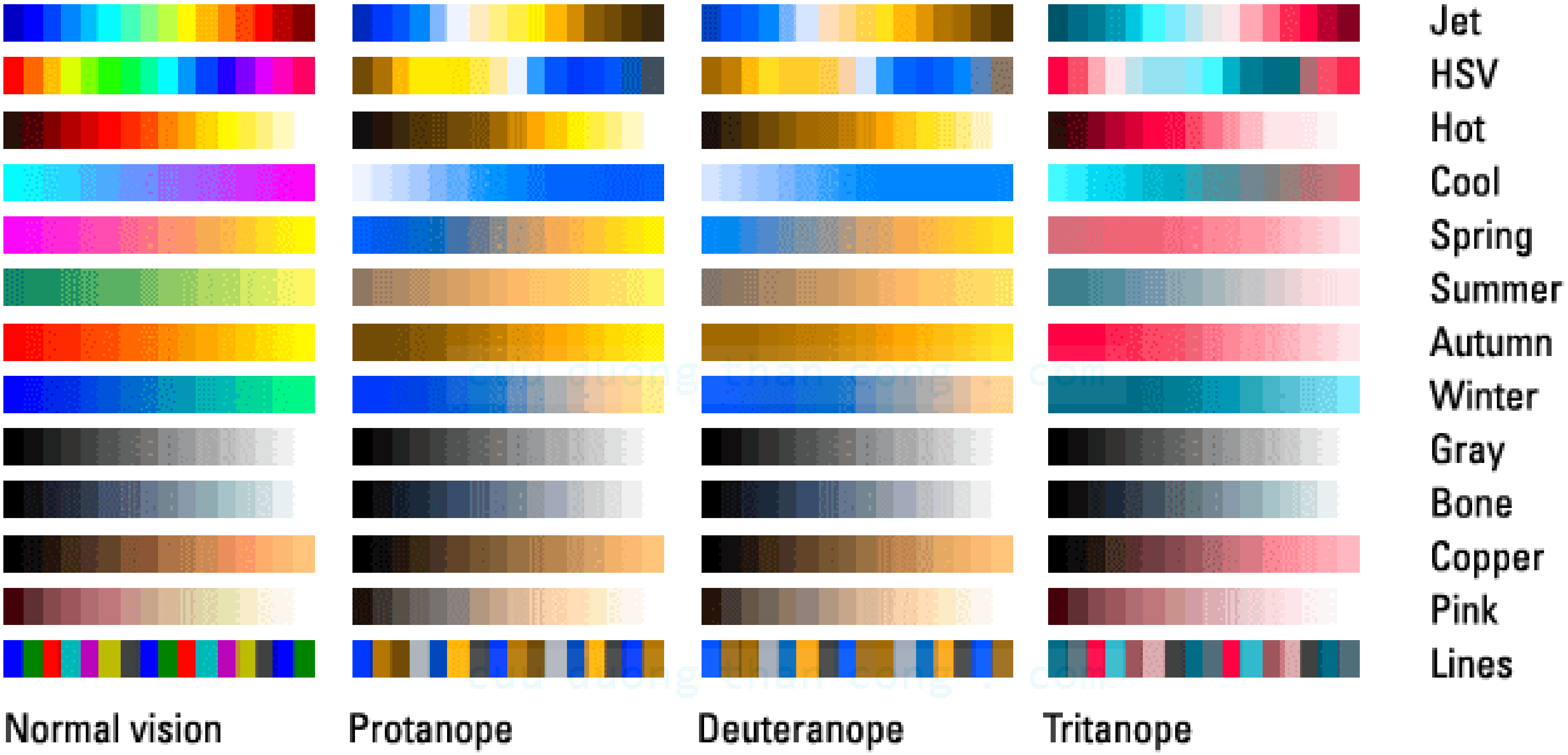
Matlab colormaps as seen by color-blind users



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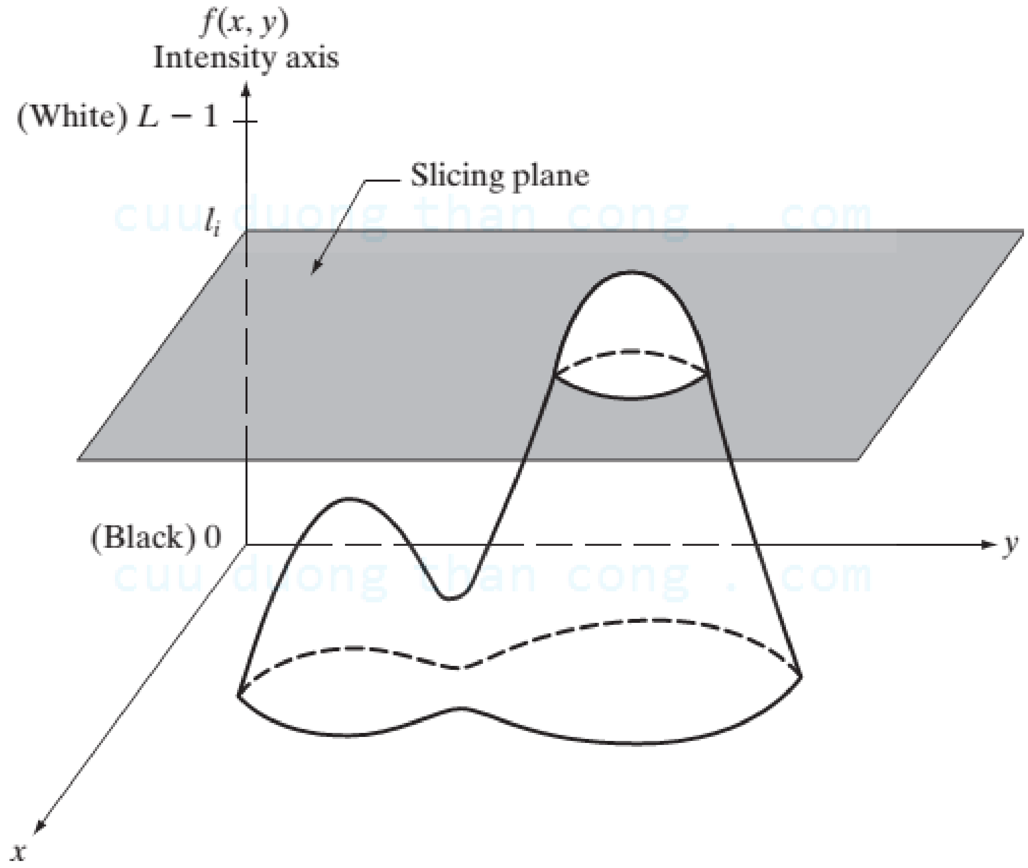
Intensity slicing

- **Intensity slicing** places planes parallel to the coordinate plane of the image; each plane then "slices" the function in the area of intersection



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Intensity slicing

- Let $[0, L-1]$ represent the gray scale, level l_0 represent black $[f(x,y)=0]$ and l_{L-1} for white $[f(x,y)=L-1]$
- Suppose that P planes perpendicular to the intensity axis are define at levels $l_1, l_2, \dots, l_P$, $0 < P < L-1$. The P planes partition the gray scale into $P+1$ intervals $V_1, V_2, \dots, V_{P+1}$
- Intensity to color assignments are made by

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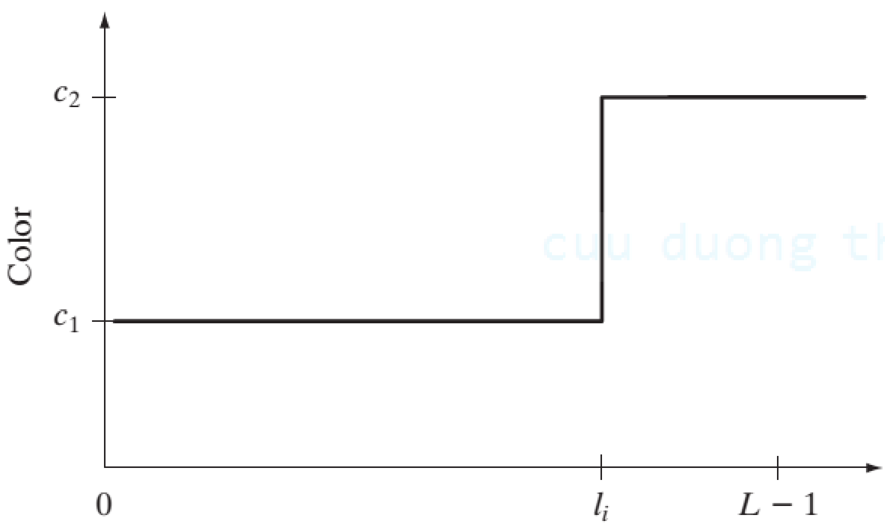
$$\boldsymbol{f(x,y) = c_k} \quad \textbf{if } \boldsymbol{f(x,y) \in V_k}$$



- where c_k is the color associated with the kth intensity interval V_k defined by the partitioning planes at $l = k-1$ and $l = k$

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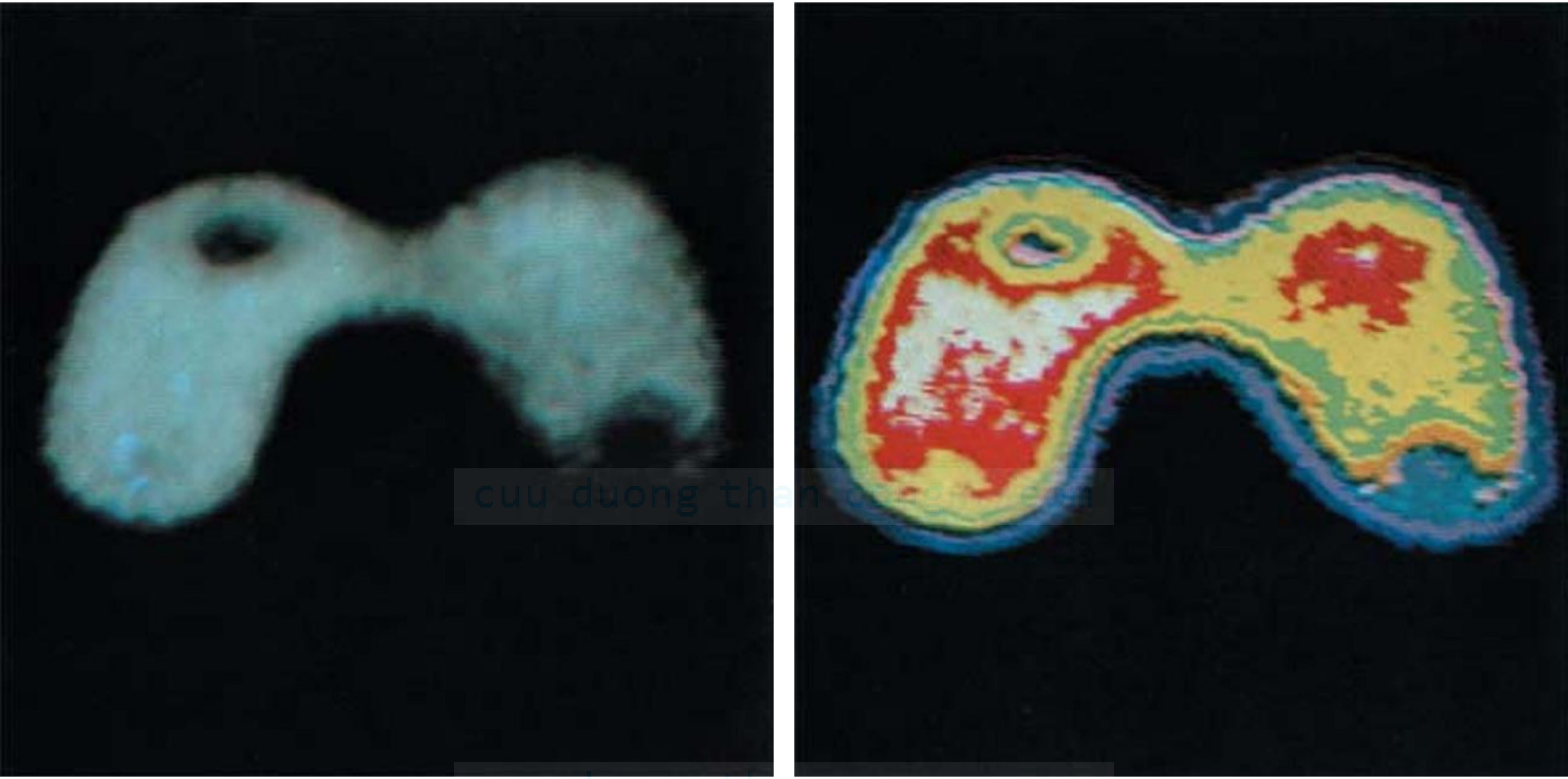

a b

(a) Monochrome image of the Picker Thyroid Phantom. (b) Result of density slicing into eight colors. (Courtesy of Dr. J. L. Blankenship, Instrumentation and Controls Division, Oak Ridge National Laboratory.)

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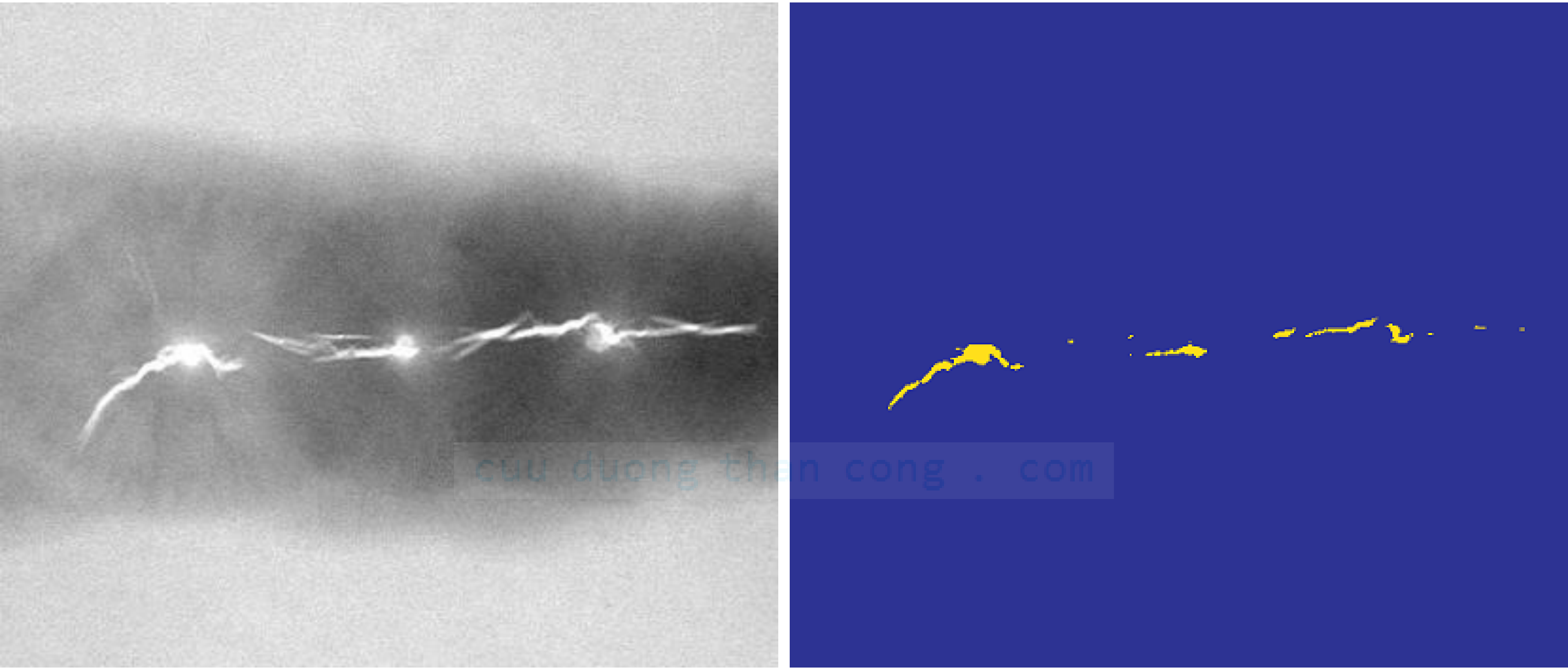

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a b

(a) Monochrome X-ray image of a weld. (b) Result of color coding. (Original image courtesy of X-TEK Systems, Ltd.)

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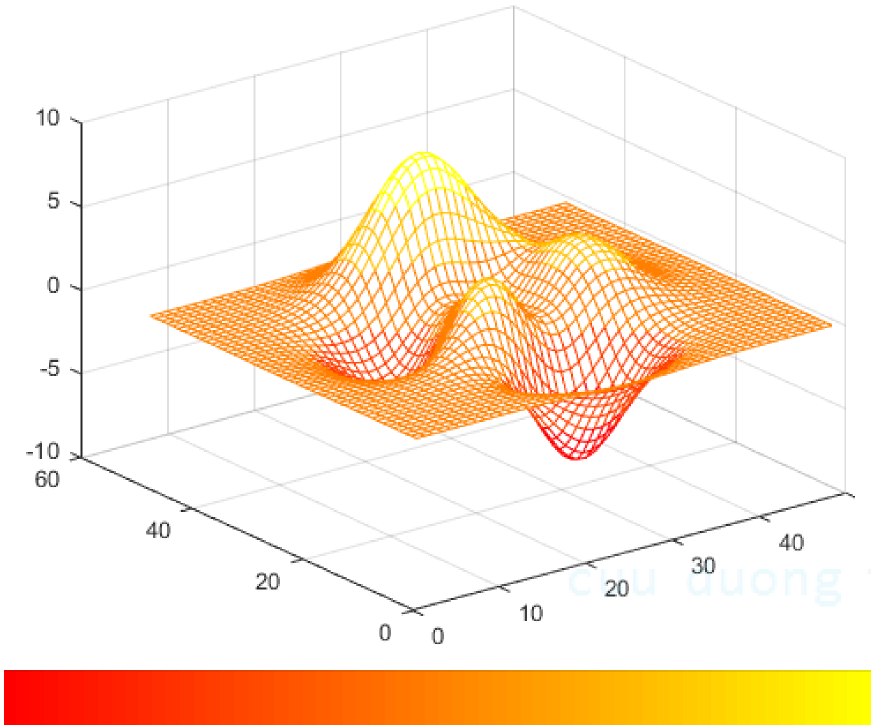

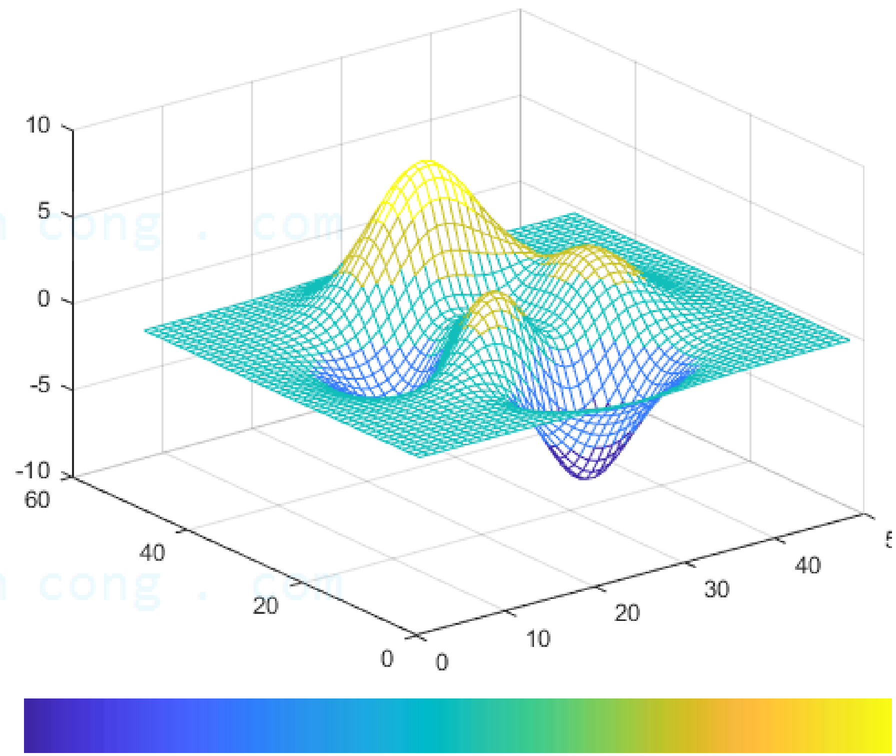

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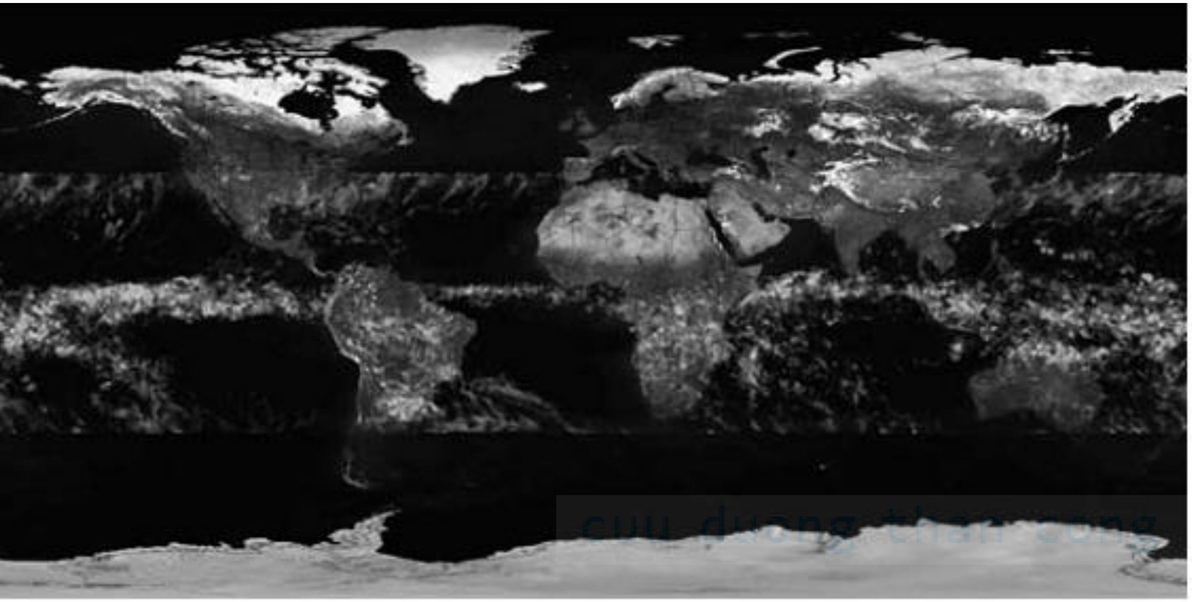
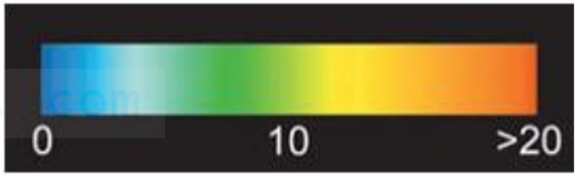
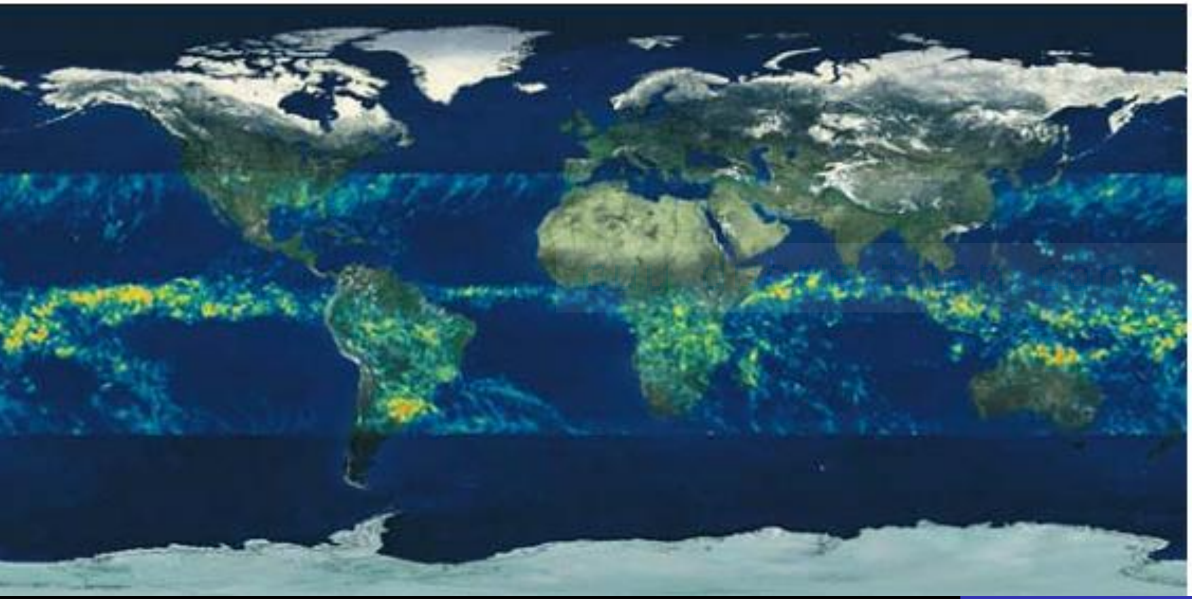
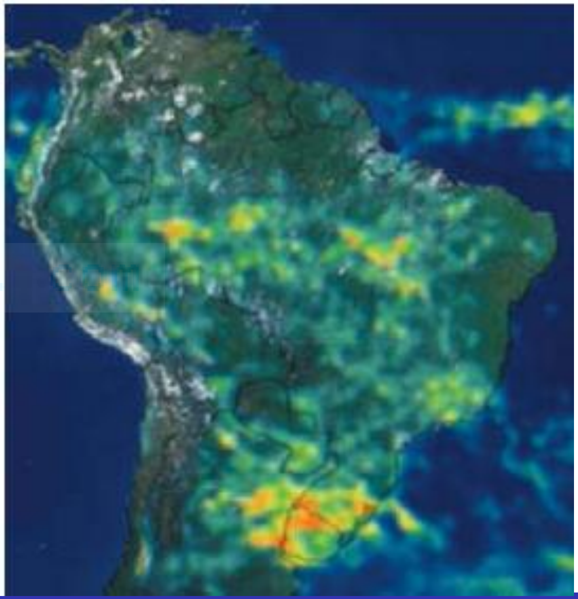
a b
c d

(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 American region. (Courtesy of NASA.)









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Section 7.4

FULL-COLOR IMAGE PROCESSING

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Full-color image processing

- Full-color image processing approaches fall into two major categories
  - Process each component individually and then form a composite processed color image from the individually processed components
  - Work with color pixels directly

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Full-color image processing

- Take the RGB system as an example
- Each color point can be interpreted as a vector extending from the origin to that point in the RGB coordinate system

$$\mathbf{c}(x,y) = \begin{bmatrix} c_R(x,y) \\ c_G(x,y) \\ c_R(x,y) \end{bmatrix} = \begin{bmatrix} R(x,y) \\ G(x,y) \\ B(x,y) \end{bmatrix}$$

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- For an image of size $M \times N$, there are MN such vectors, $\mathbf{c}(x,y)$, for $x = 0,1,2,\ldots M-1$ and $y = 0,1,2,\ldots N-1$

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Per-color-component and vector-based processing

- Individual color component processing are **not always equivalent** to direct processing in color vector space
- Condition for equivalence
  - The process has to be applicable to both vectors and scalars.
  - The operation on each component of a vector must be independent of the other components.

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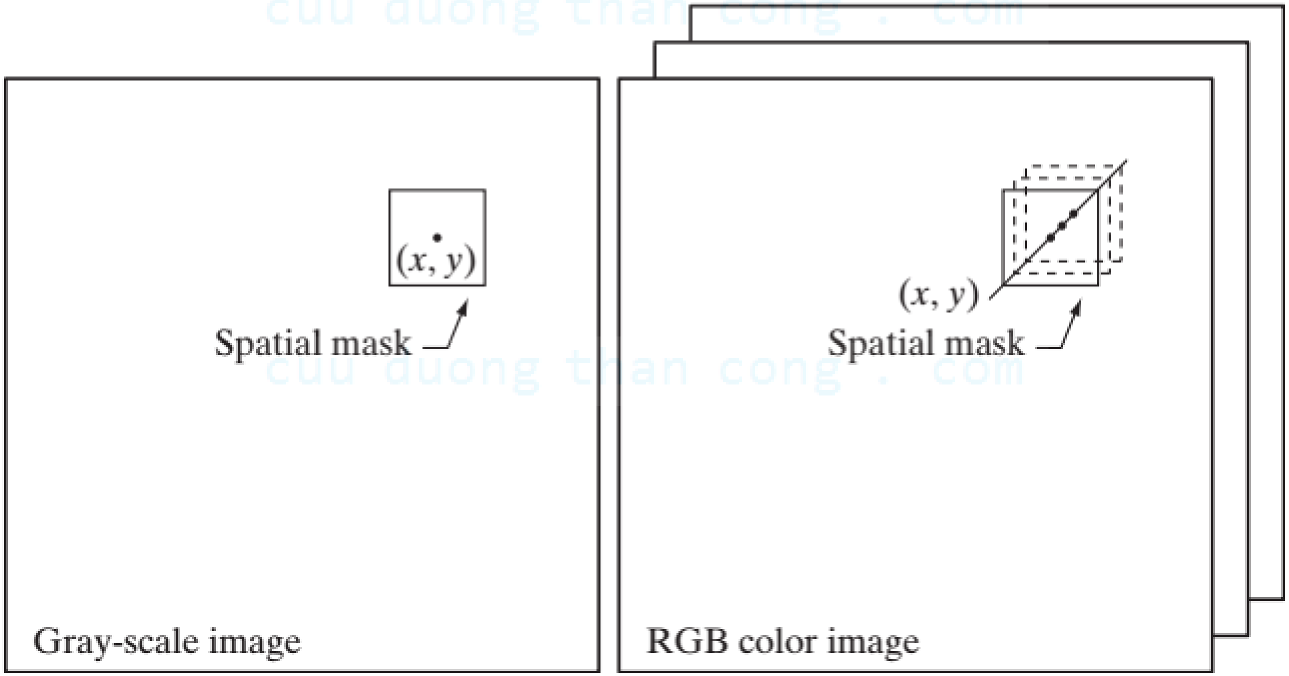

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Formulation of color transformations

- Color transformations is modeled using the expression

$$\boldsymbol{g}(\boldsymbol{x},\boldsymbol{y}) = \boldsymbol{T}[\boldsymbol{f}(\boldsymbol{x},\boldsymbol{y})]$$

  - where $f(x, y)$ is a color input image, $g(x, y)$ is the transformed or processed color output image, and T is an operator on f over a spatial neighborhood of (x, y).

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- The pixel values here are triplets or quartets from the color space chosen to represent the images.

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Formulation of color transformations

- Particularly, color transformations are of the form

$$\boldsymbol{s_i = T_i(r_1, r_2, \ldots, r_n)} \quad i = 1, 2, \ldots, n$$

  - where r_i and s_i are the color components of f and g at any point (x, y), n is the number of color components, and $\{T_1, T_2, \ldots, T_n\}$ is a set of transformation or color mapping functions that operate on r_i to produce s_i.
- The color space chosen to describe the pixels of f and g determines the value of n.
  - E.g., $n = 3$ for RGB color space is selected, for example, and r_1, r_2, and r_3 denote the red, green, and blue components

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Formulation of color transformations

- Any transformation can theoretically be performed in any color model but some are better suited to specific models.
  - For a given transformation, the cost of converting between representations must be factored into the decision regarding the color space in which to implement it.
- **Same output** regardless of the chosen color space

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- For example, modify the intensity of the full-color image using $g(x,y) = kf(x,y)\ \ (0 < k < 1)$
  - HSI: $s_1 = r_1,\ \ s_2 = r_2, s_3 = kr_3$
  - RGB: $s_i = kr_i,\ \ i = 1,2,3$
  - CMY: $s_i = kr_i + (1-k),\ \ i = 1,2,3$
  - HIS involves the fewest number of operations but the conversion calculations are more computationally intense.

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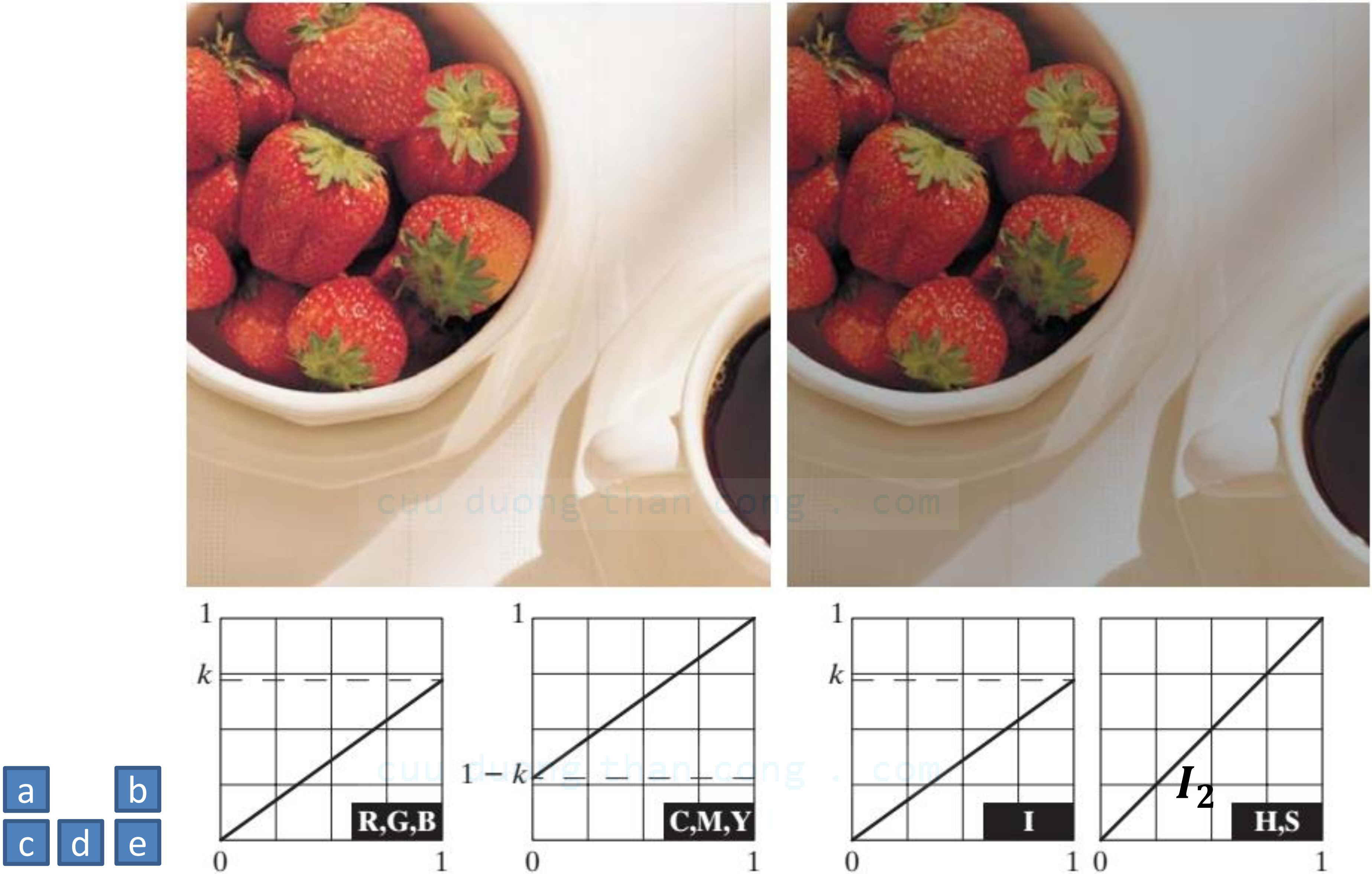

Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c)–(e) The required RGB, CMY, and HSI transformation functions

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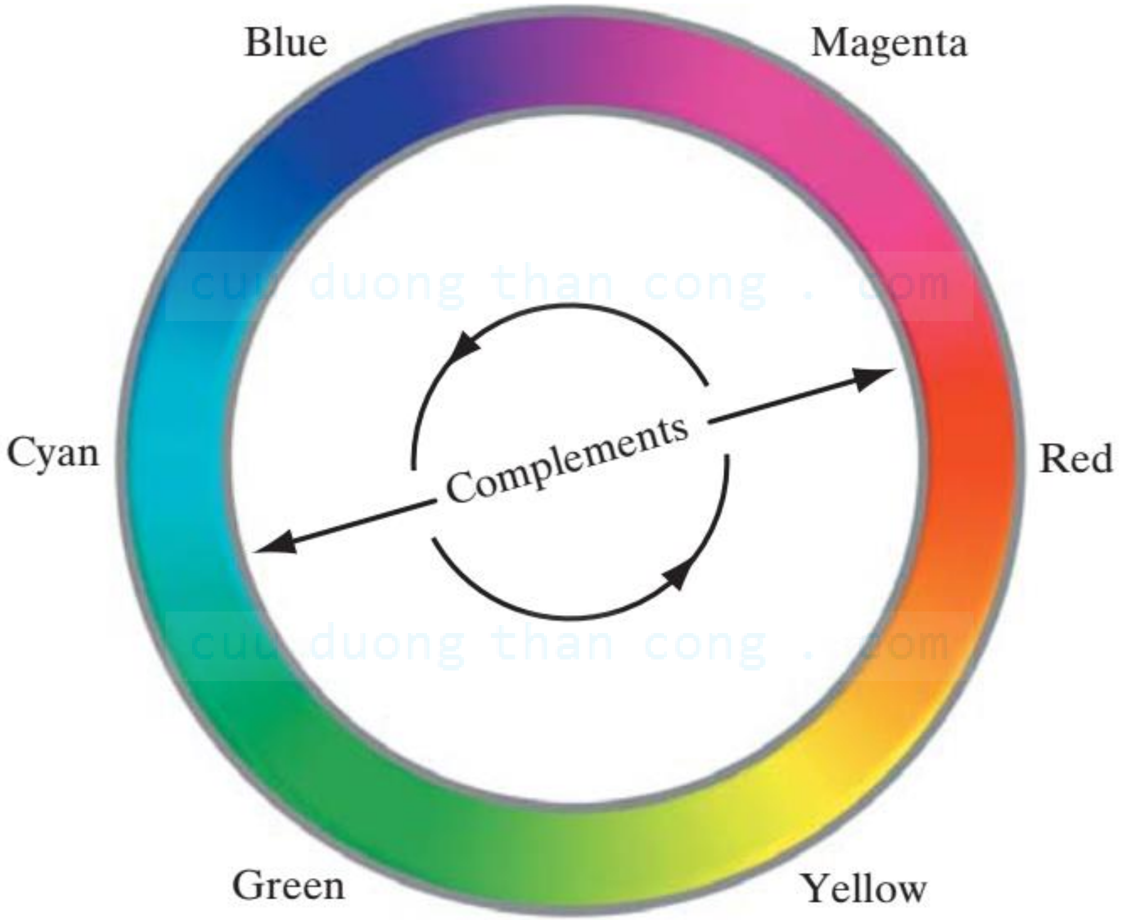
Color complements

- The hues directly opposite one another on the color circle are called **complements**.



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Color complements

- It is analogous to the gray-scale image negative.
- Enhance detail that is embedded in dark regions of a color image, particularly when the regions are dominant in size.

- The RGB complement transformation functions do not have a straightforward HSI space equivalent.
  - The saturation component of the complement cannot be computed from the saturation component of the input image alone.

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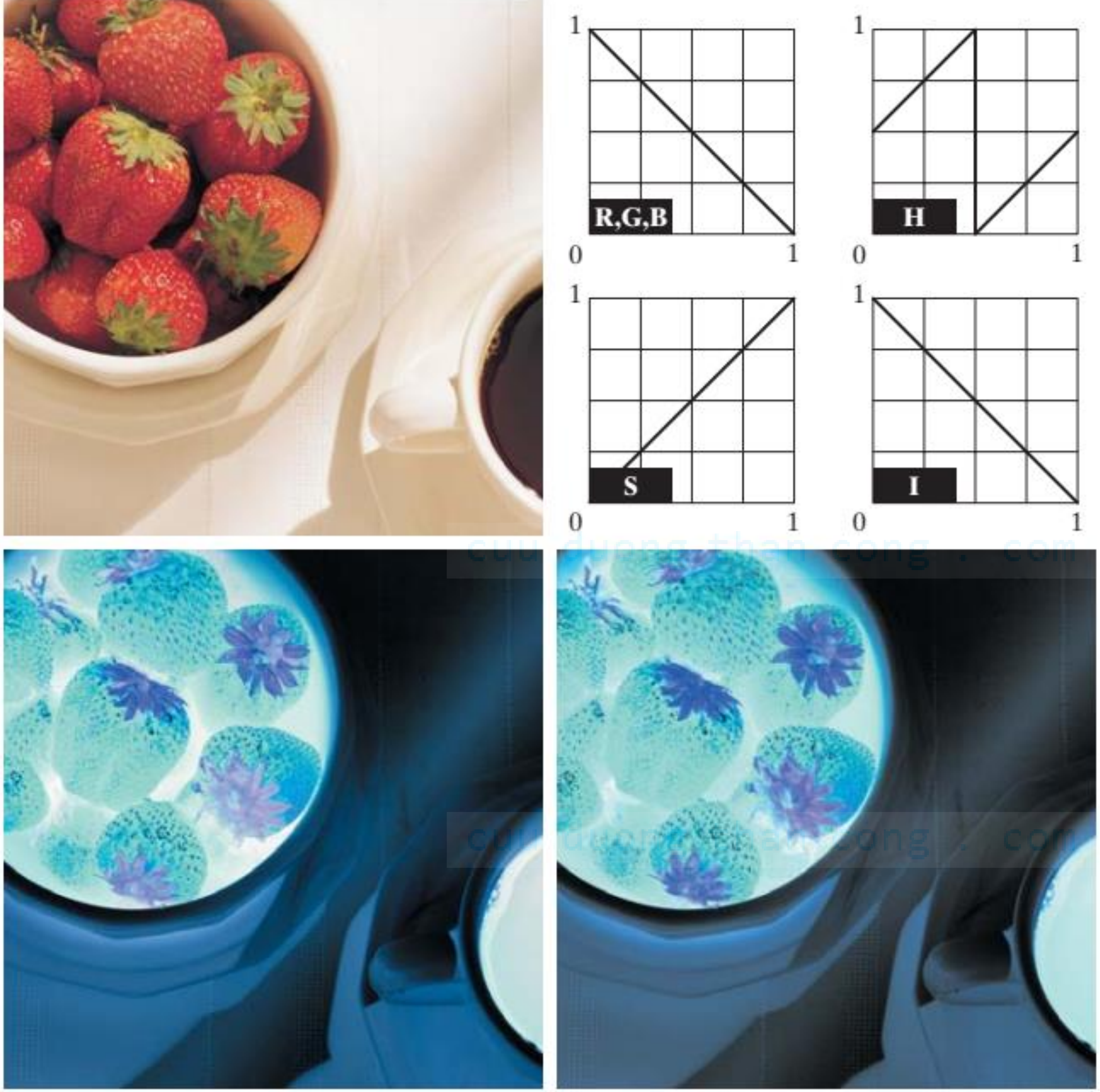

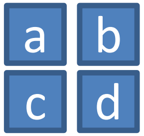

Color complement transformations.
(a) Original image.
(b) Complement transformation functions.
(c) Complement of (a) based on the RGB mapping functions.
(d) An approximation of the RGB complement using HSI transformations.

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Color slicing

- Highlighting a specific range of colors in an image is useful for separating objects from their surroundings.
- The basic idea is either to
  - (1) display the colors of interest so that they stand out from the background or
  - (2) use the region defined by the colors as a mask for further processing.

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Color slicing

- Map the colors outside some range of interest to a non-prominent neutral color.
- **Approach 1:** the colors of interest are enclosed by a cube (or hypercube for $n > 3$) of width W and centered at prototypical color with components $(a_1, a_2, \ldots a_n)$

$$s_i = \begin{cases} 0.5 & if \left[\left|r_i - a_j\right| > \dfrac{W}{2}\right]_{any\ 1 \le j \le n} \\ r_i & otherwise \end{cases} \quad i = 1,2,\ldots,n$$

  - The colors around the prototype are highlighted by forcing all other colors to the midpoint of the reference color space (an arbitrarily chosen neutral point).
  - E.g., a suitable neutral point for RGB color space is the middle gray or color (0.5, 0.5, 0.5).

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Color slicing

- Map the colors outside some range of interest to a non-prominent neutral color.
- **Approach 2:** the colors of interest are enclosed by a sphere (or hypersphere for $n > 3$) of radius R_0 and centered at prototypical color with components $(a_1, a_2, \ldots a_n)$

$$s_i = \begin{cases} 0.5 & \text{if } \sum_{j=1}^{n} (r_i - a_j)^2 > R_0^2 \\ r_i & \text{otherwise} \end{cases} \quad i = 1,2,..,n$$

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- Other variations include implementing multiple color prototypes and reducing the intensity of the colors outside the region of interest.

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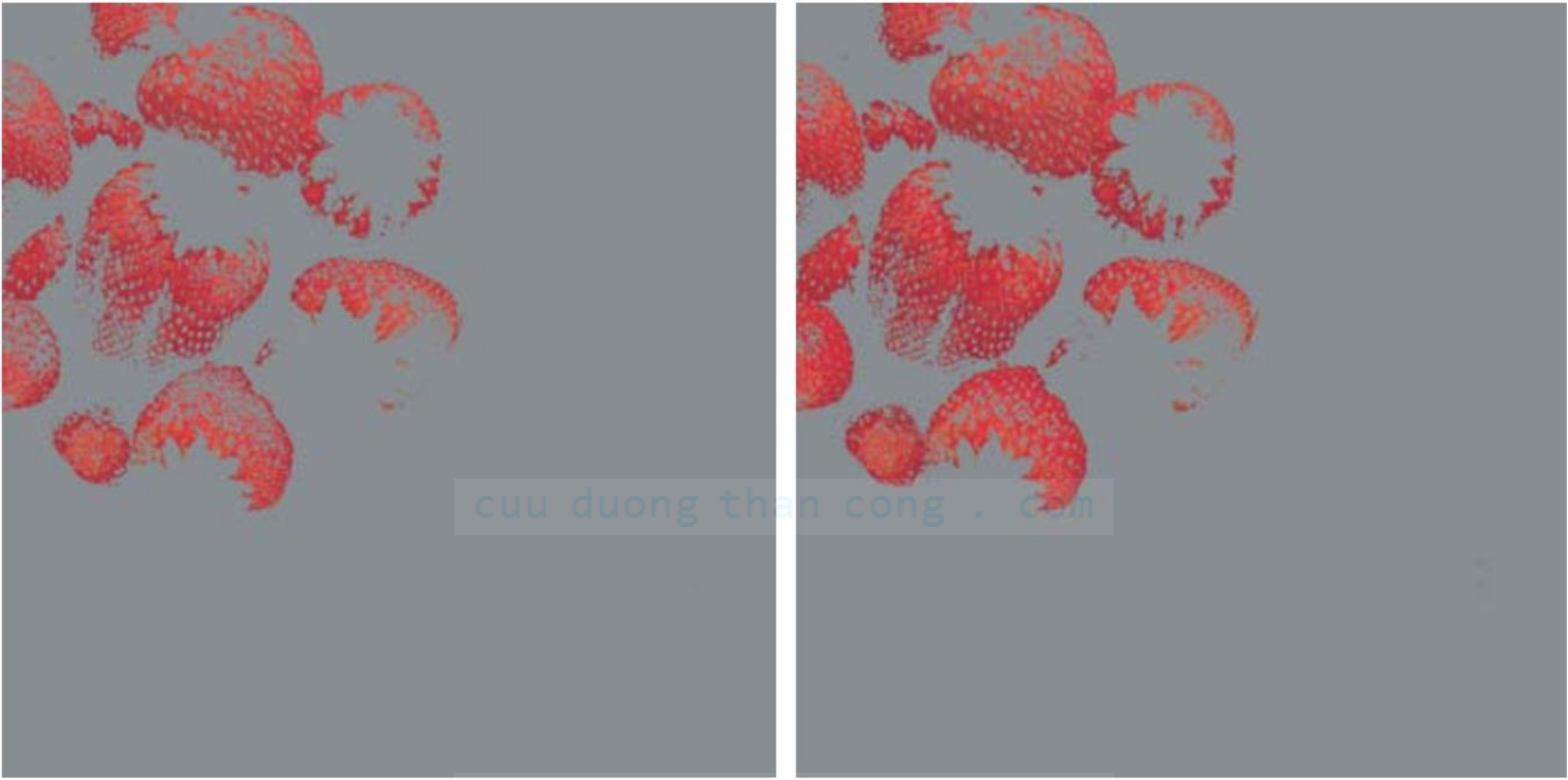

a b

Color-slicing transformations that detect (a) reds within an RGB cube of width centered at (0.6863, 0.1608, 0.1922), and (b) reds within an RGB sphere of radius 0.1765 centered at the same point. Pixels outside the cube and sphere were replaced by color (0.5, 0.5, 0.5).

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Tone and color corrections

- It is necessary to maintain a high degree of color consistency between the monitors used and the eventual output devices.
  - The colors of the monitor should represent accurately any digitally scanned source images, as well as the final printed output
- **CIE L*a*b* model**, also called CIELAB (CIE [1978], Robertson [1977])
  - A device-independent color model that best relates the color gamuts of the monitors and output devices, as well as any other devices being used, to one another.
  - Its gamut encompasses the entire visible spectrum and can represent accurately the colors of any display, print, or input device.
  - Not a directly displayable format (conversion to another color space is required)

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Device-independent color model

- **CIE L*a*b* model**, also called CIELAB (CIE [1978], Robertson [1977])
- Best relates the color gamuts of the monitors and output devices, as well as any other devices to one another.
  - Its gamut encompasses the entire visible spectrum and can represent accurately the colors of any display, print, or input device.
- Not a directly displayable format (conversion to another color space is required)

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Tonal corrections

- The **tonal range** (or **key type**) of an image refers to its general distribution of color intensities.
  - Most of the information in high-key images is concentrated at high (or light) intensities,
  - The colors of low-key images are located predominantly at low intensities, and
  - Middle-key images lie in between.

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- It is often desirable to distribute the intensities of a color image equally between the highlights and the shadows
  - RGB and CMY(K) spaces: mapping all three (or four) color components with the same transformation function
  - HSI space: only the intensity component is modified.

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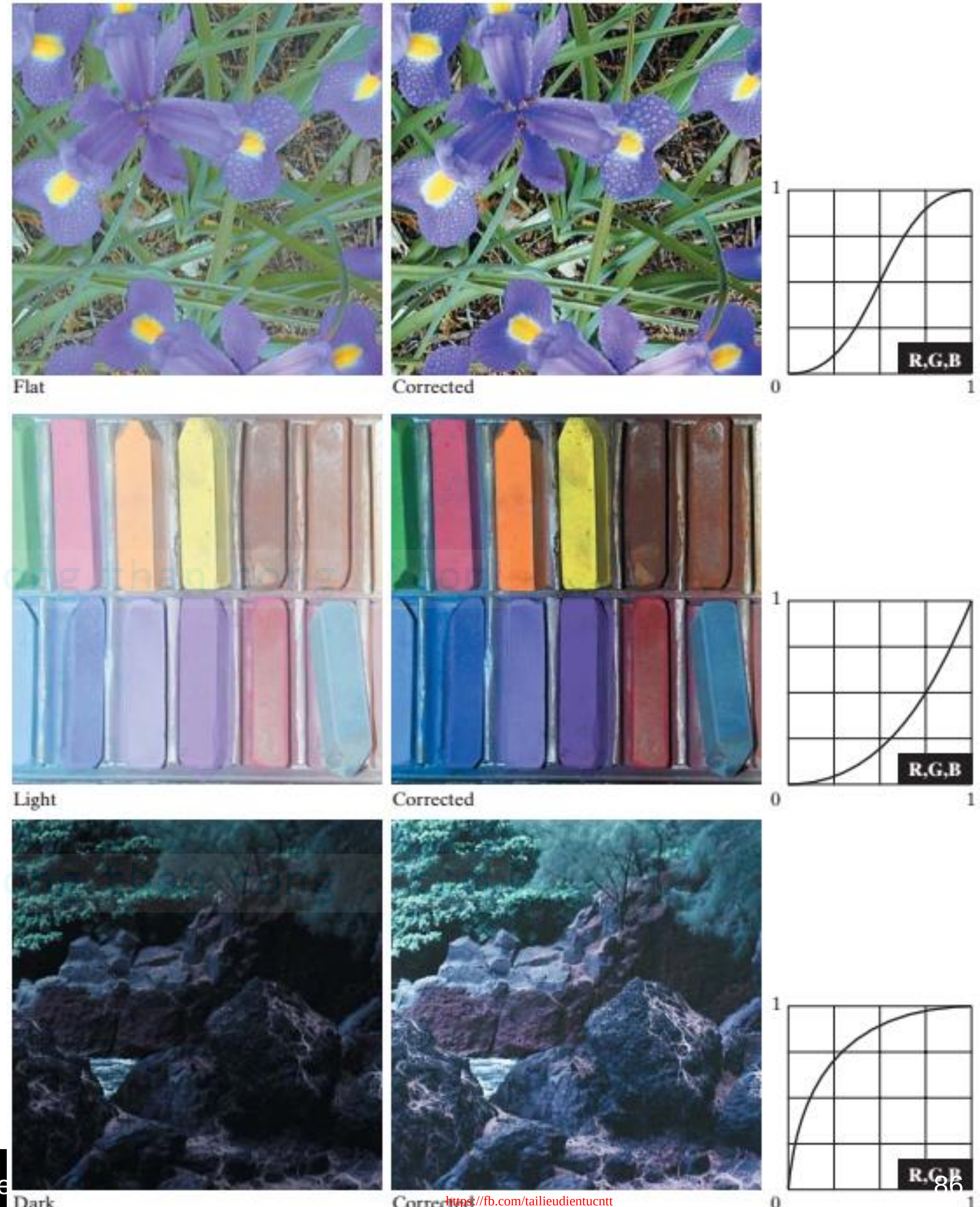
Tonal corrections for flat, light (high key), and dark (low key) color images. Adjusting the red, green, and blue components equally does not always alter the image hues significantly



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Color corrections

- When adjusting the color components of an image, it is important to realize that every action affects the overall color balance of the image.
  - The perception of one color is affected by its surrounding colors.
- The color wheel can be used to predict how one color component will affect others.
  - The proportion of any color can be increased by decreasing the amount of the opposite (or complementary) color in the image.
  - A color can be increased by raising the proportion of the two immediately adjacent colors or decreasing the percentage of the two colors adjacent to the complement.
  - E.g., an abundance of magenta in an RGB image can be decreased by (1) removing both red and blue or (2) adding green.

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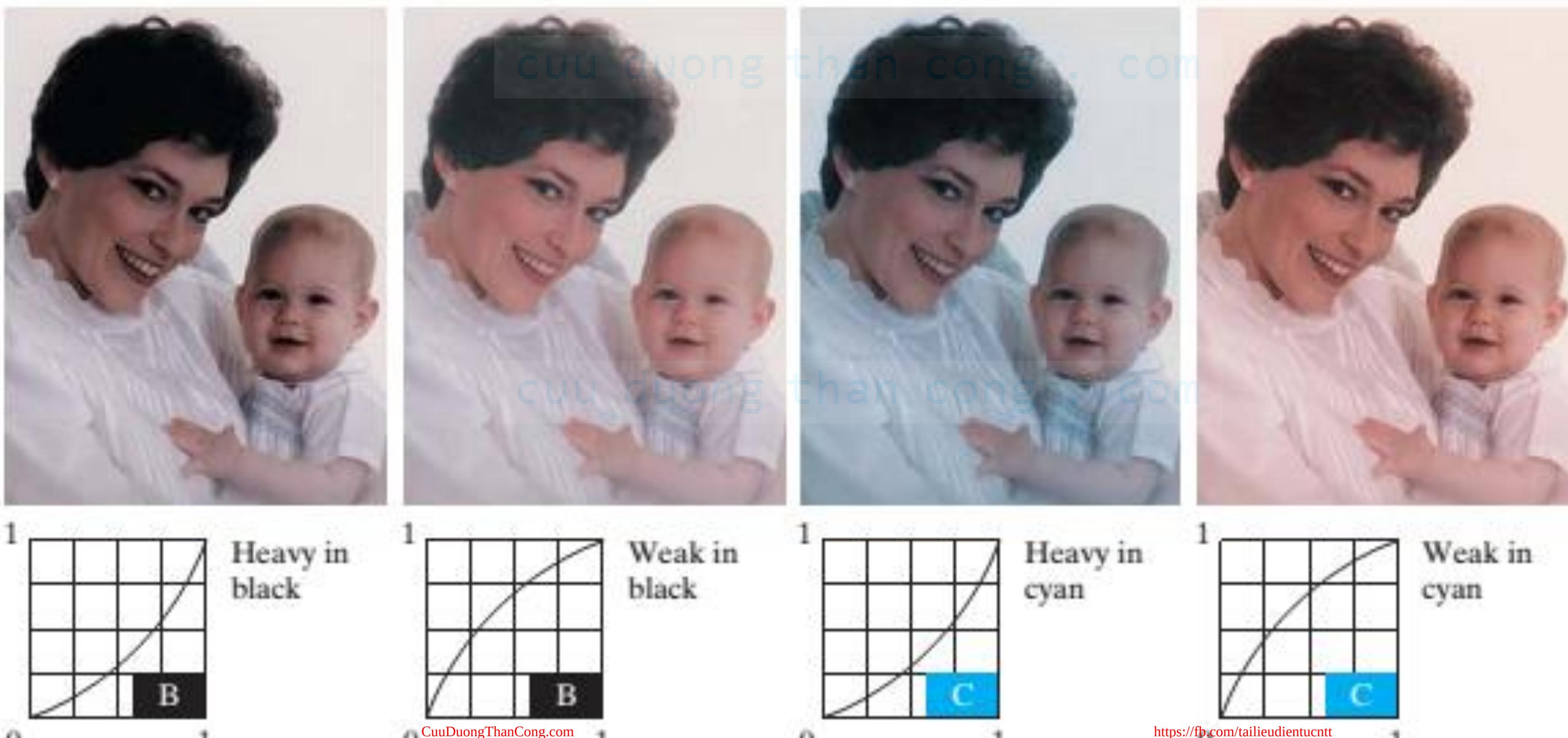
Color balancing corrections for CMYK color images

Original/Corrected



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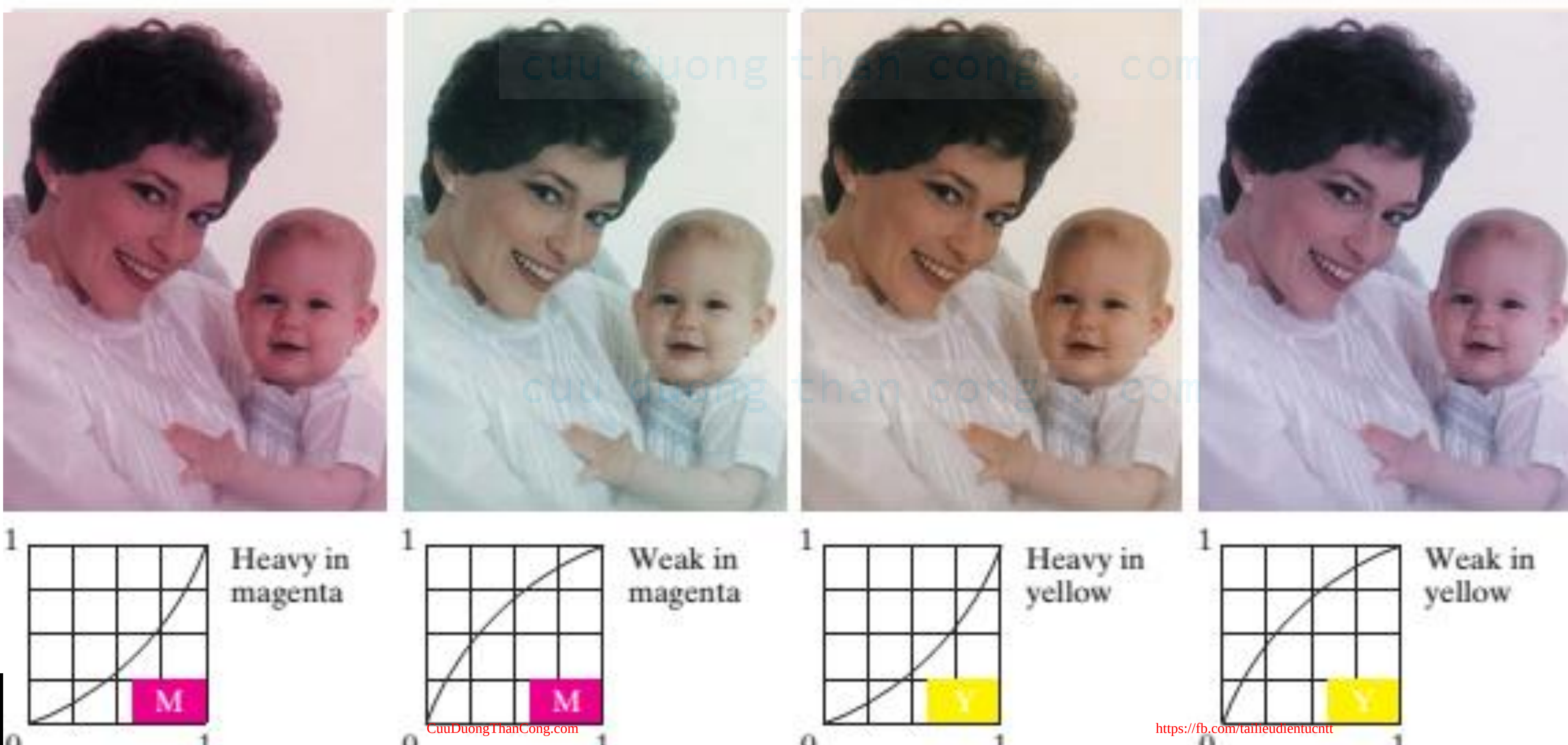
Color balancing corrections for CMYK color images

Original/Corrected



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Histogram processing

- It is generally unwise to histogram equalize the color components independently, resulting in erroneous color.
- Better logical solution: spread the color intensities uniformly, leaving the colors themselves (e.g., hues) unchanged.

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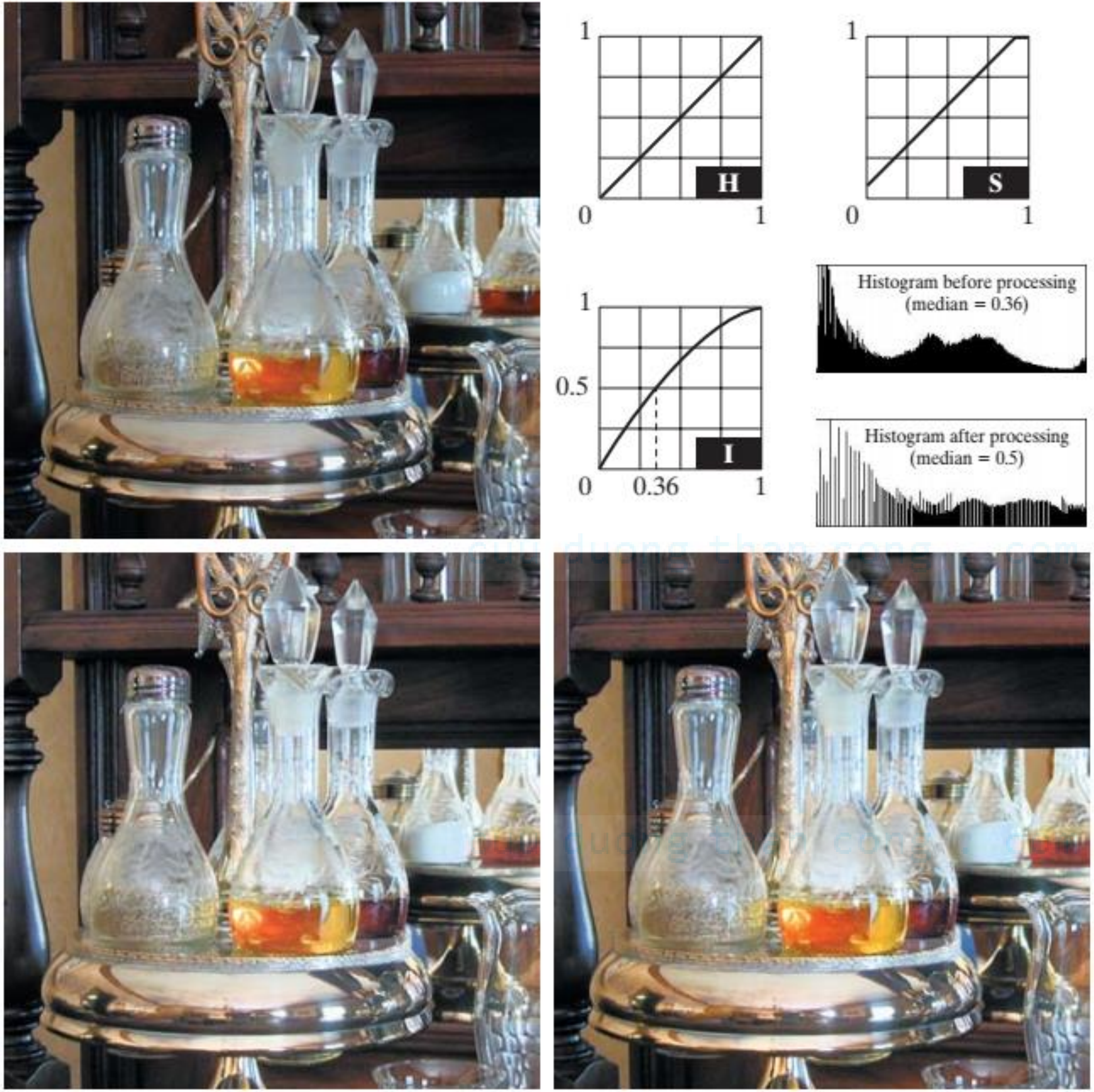

a b
c d

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

Color image smoothing

- Let S_{xy} denote the set of coordinates defining a neighborhood centered at (x, y) in an RGB color image.
- The average of the RGB component vectors in this neighborhood is
- $$\bar{\mathbf{c}}(x,y) = \frac{1}{K}\sum_{(s,t)\in S_{xy}} \mathbf{c}(s,t) = \begin{bmatrix} \frac{1}{K}\sum_{(s,t)\in S_{xy}} R(s,t) \\ \frac{1}{K}\sum_{(s,t)\in S_{xy}} G(s,t) \\ \frac{1}{K}\sum_{(s,t)\in S_{xy}} B(s,t) \end{bmatrix}$$
- Smoothing by neighborhood averaging can be carried out on a per-color-plane basis, resulting the same effect as when the averaging is performed using RGB color vectors

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

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a b c

HSI components of the RGB color image in the previous slide
(a) Hue. (b) Saturation. (c) Intensity.

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a b c

Image smoothing with a 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.

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Color image sharpening

- Let S_{xy} denote the set of coordinates defining a neighborhood centered at (x, y) in an RGB color image.
- In the RGB color system, the Laplacian of vector $\mathbf{c}$ is

$$\nabla^2[\bar{\mathbf{c}}(x,y)] = \begin{bmatrix} \nabla^2[R(x,y)] \\ \nabla^2[G(x,y)] \\ \nabla^2[B(x,y)] \end{bmatrix}$$

- The Laplacian of a full-color image can be estimated by computing the Laplacian of each component image separately

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a b c

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

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Color edge detection

- The aforementioned gradient is NOT for vector quantities.
- Computing the gradient on individual images and then using the results to form a color image will lead to erroneous results.
- The per-component approach usually yields acceptable results for detecting edges only.
- If accuracy is an issue, a new definition of the gradient applicable to vector quantities is needed

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Color edge detection

- Consider the two $M \times M$ color images (M odd), I_1 and I_2.
- Compute the gradient image of each of the component images and add the results to form the two corresponding RGB gradient images
- The value of the gradient at point $\left[\frac{M+1}{2}, \frac{M+1}{2}\right]$ would be the same in both cases.
- Intuitively, we would expect the gradient at that point to be stronger for the image in I_1
  - The edges of the R, G, and B images of I_1 are in the same direction, as opposed to I_2, in which only two edges are in the same direction.

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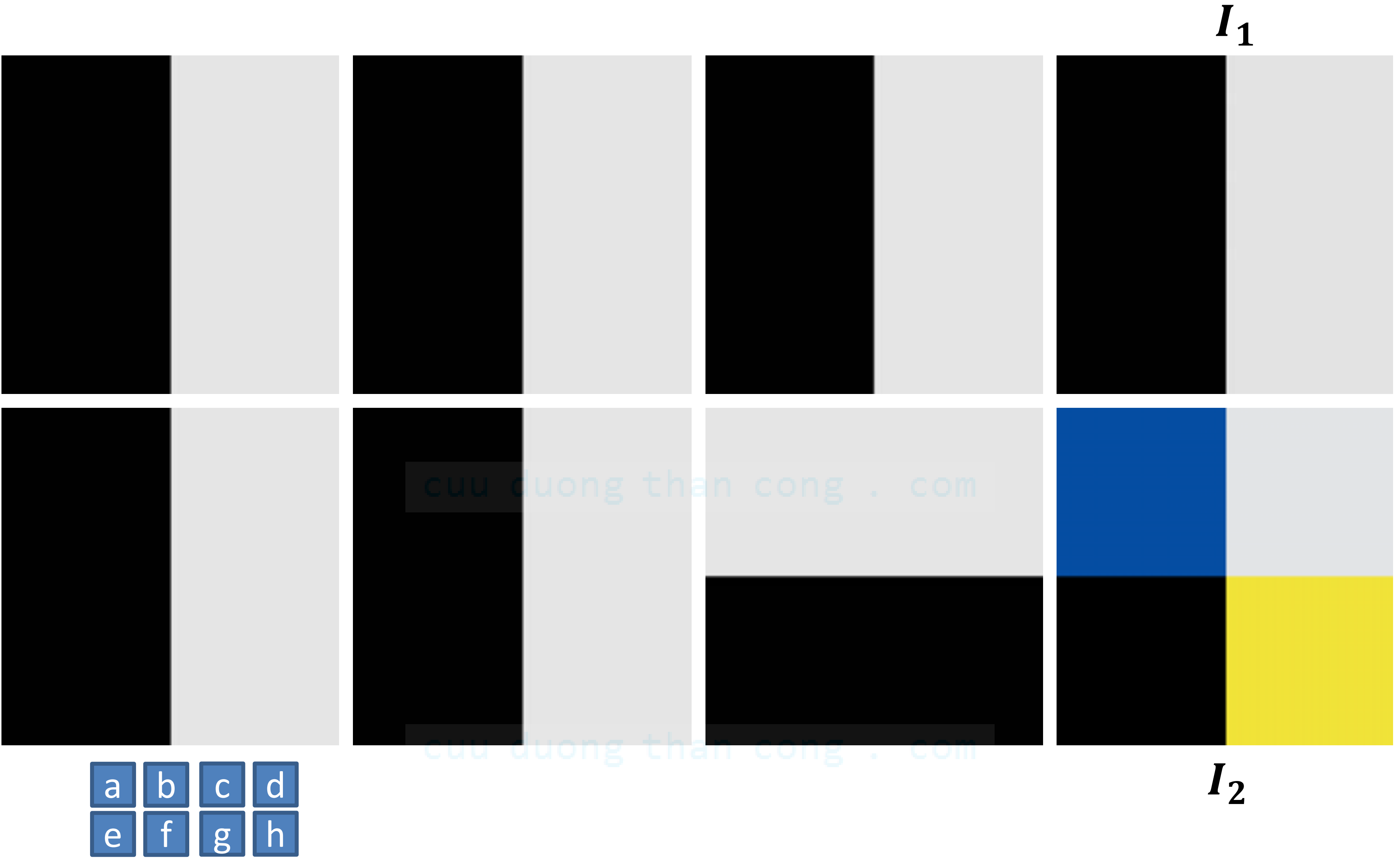

(a)–(c) R, G, and B component images and (d) resulting RGB color image.
(e)–(g) R, G, and B component images and (h) resulting RGB color image.

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Color edge detection

- Di Zenzo [1986]: Define the gradient (magnitude and direction) of the vector $\mathbf{c}$ at any point (x, y)
- Let $\mathbf{r}, \mathbf{g}$, and $\mathbf{b}$ be unit vectors along the R, G, and B axis of RGB color space

$$\mathbf{u} = \frac{\partial R}{\partial x}\mathbf{r} + \frac{\partial G}{\partial x}\mathbf{g} + \frac{\partial B}{\partial x}\mathbf{b} \qquad \mathbf{v} = \frac{\partial R}{\partial y}\mathbf{r} + \frac{\partial G}{\partial y}\mathbf{g} + \frac{\partial B}{\partial y}\mathbf{b}$$

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Color edge detection

- Let the quantities and be defined in terms of the dot product of those vectors

$$g_{xx} = \mathbf{u} \cdot \mathbf{u} = \mathbf{u}^{\mathbf{T}}\mathbf{u} = \left|\frac{\partial R}{\partial x}\right|^{\mathbf{2}} + \left|\frac{\partial G}{\partial x}\right|^{\mathbf{2}} + \left|\frac{\partial B}{\partial x}\right|^{\mathbf{2}}$$

$$g_{xx} = \mathbf{v} \cdot \mathbf{v} = \mathbf{v}^{\mathbf{T}}\mathbf{v} = \left|\frac{\partial R}{\partial y}\right|^{\mathbf{2}} + \left|\frac{\partial G}{\partial y}\right|^{\mathbf{2}} + \left|\frac{\partial B}{\partial y}\right|^{\mathbf{2}}$$

$$g_{xy} = \mathbf{u} \cdot \mathbf{v} = \mathbf{u}^{\mathbf{T}}\mathbf{v} = \frac{\partial R}{\partial x}\frac{\partial R}{\partial y} + \frac{\partial G}{\partial x}\frac{\partial G}{\partial y} + \frac{\partial B}{\partial x}\frac{\partial B}{\partial y}$$

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Color edge detection

- The direction of maximum rate of change of $\mathbf{c}(x, y)$ is
$$\theta(x, y) = \frac{1}{2}\tan^{-1}\left[\frac{2g_{xy}}{g_{xx} - g_{yy}}\right]$$
- The value of the rate of change at (x, y) in the direction of $\theta(x, y)$ is given by

$$F_\theta(x, y) = \left\{\frac{1}{2}\left[\left(g_{xx} + g_{yy}\right) + \left(g_{xx} - g_{yy}\right)\cos 2\theta(x, y) + 2g_{xy}\sin 2\theta(x, y)\right]\right\}^{\frac{1}{2}}$$

- Each point (x, y) is associated with a pair of orthogonal directions, along one of those directions F is maximum, and it is minimum along the other.

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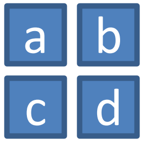

(a) RGB image.
(b) Gradient computed in RGB color vector space.
(c) Gradients computed on a per-image basis and then added.
(d) Difference between (b) and (c).

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a b c

Component gradient images of the RGB color image. (a) Red component, (b) green component, and (c) blue component. These three images were added and scaled to produce the image (c) in the previous slide.

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Noise in color images

- The noise models discussed are applicable to color images.
- Usually, the noise content of a color image has the same characteristics in each color channel,
- However, it is possible for color channels to be affected differently by noise.
  - Electronics of a particular channel to malfunction.
  - Different noise levels are more likely to be caused by differences in the relative strength of illumination available to each color channels.
    - E.g., use of a red (reject) filter in a CCD camera will reduce the strength of illumination available to the red sensor, so the resulting red component would tend to be noisier than the other two components.

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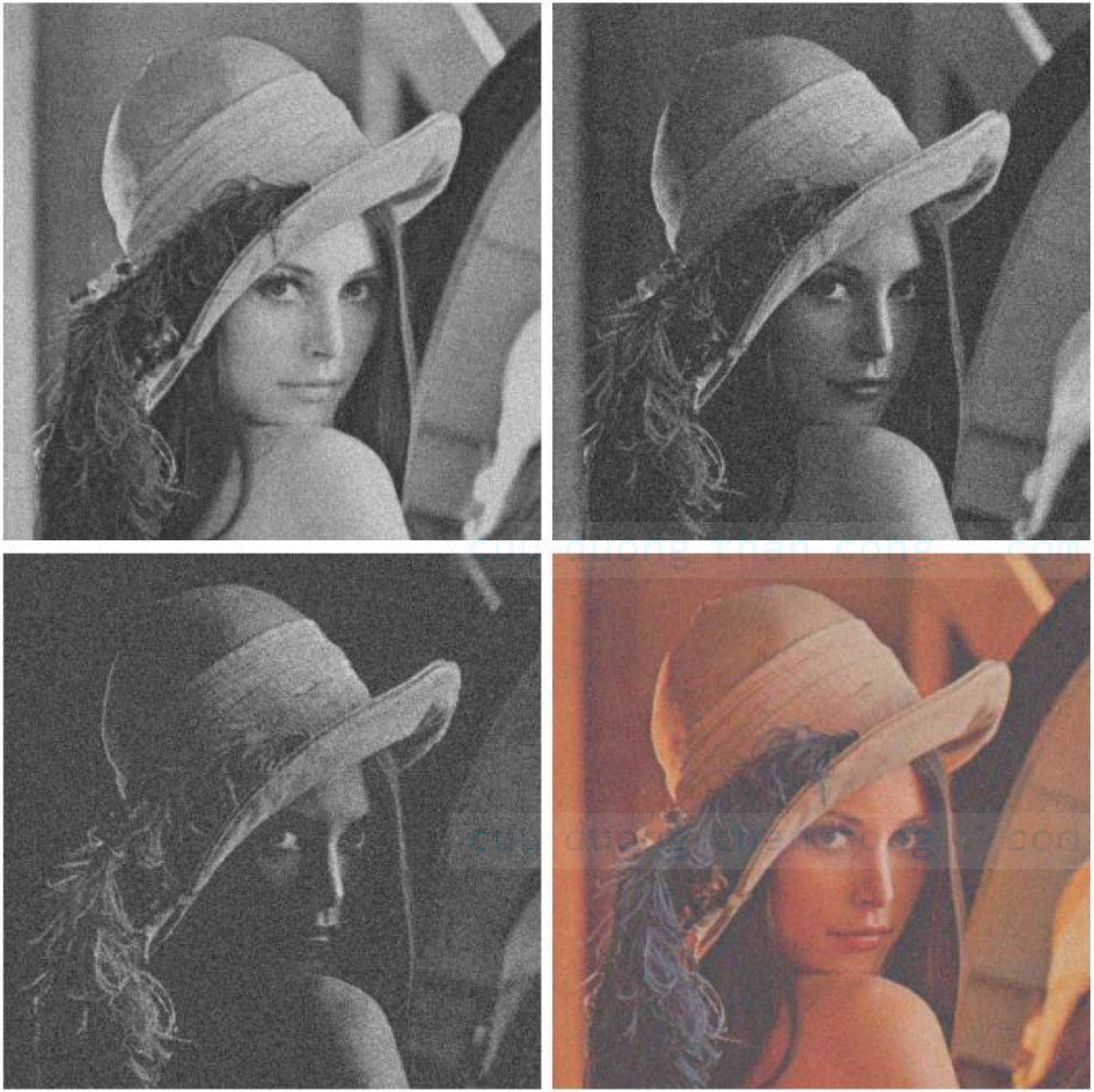

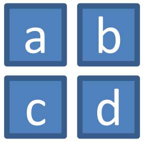

(a)–(c) Red, green, and blue component images corrupted by additive Gaussian noise of mean 0 and variance 800.
(d) Resulting RGB image

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a b c

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HSI components of the noisy color image in Fig. 6.48(d). (a) Hue. (b) Saturation. (c) Intensity.

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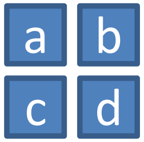

(a) RGB image with green plane corrupted by salt-and-pepper noise. (b) Hue component of HSI image. (c) Saturation component. (d) Intensity component.

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Noise in color images

- Noise reduction by using an averaging filter gives the same result in vector space as it does if the component images are processed independently.
- Other filters, however, cannot be formulated in this manner.
  - E.g., the class of order statistics filters, to implement a median filter in color vector space it is necessary to find a scheme for ordering vectors in a way that the median makes sense.

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References

- Rafael C. Gonzalez, Richard E. Woods, “Digital Image Processing”, 3rd edition, 2008. Chapter 6

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