Isaac Newton, 1666

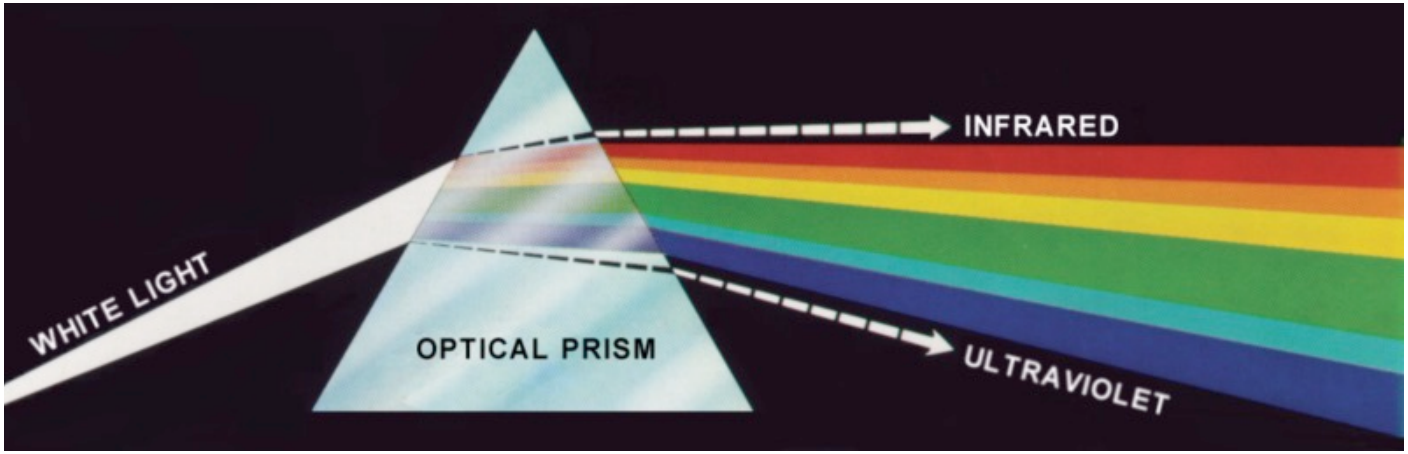
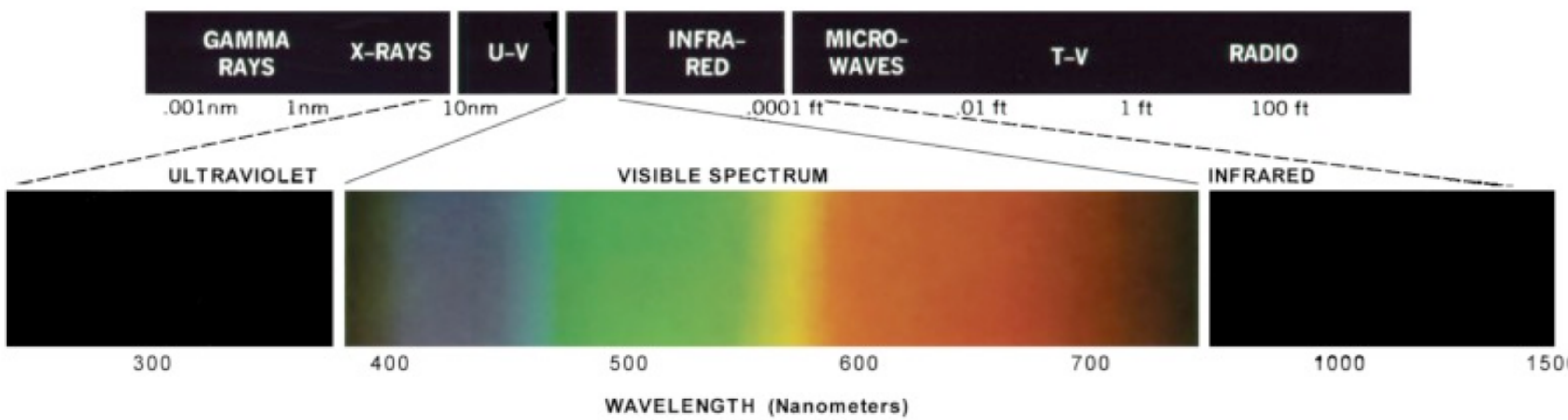


FIGURE 7.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lighting Division.)

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

Electromagnetic Spectrum



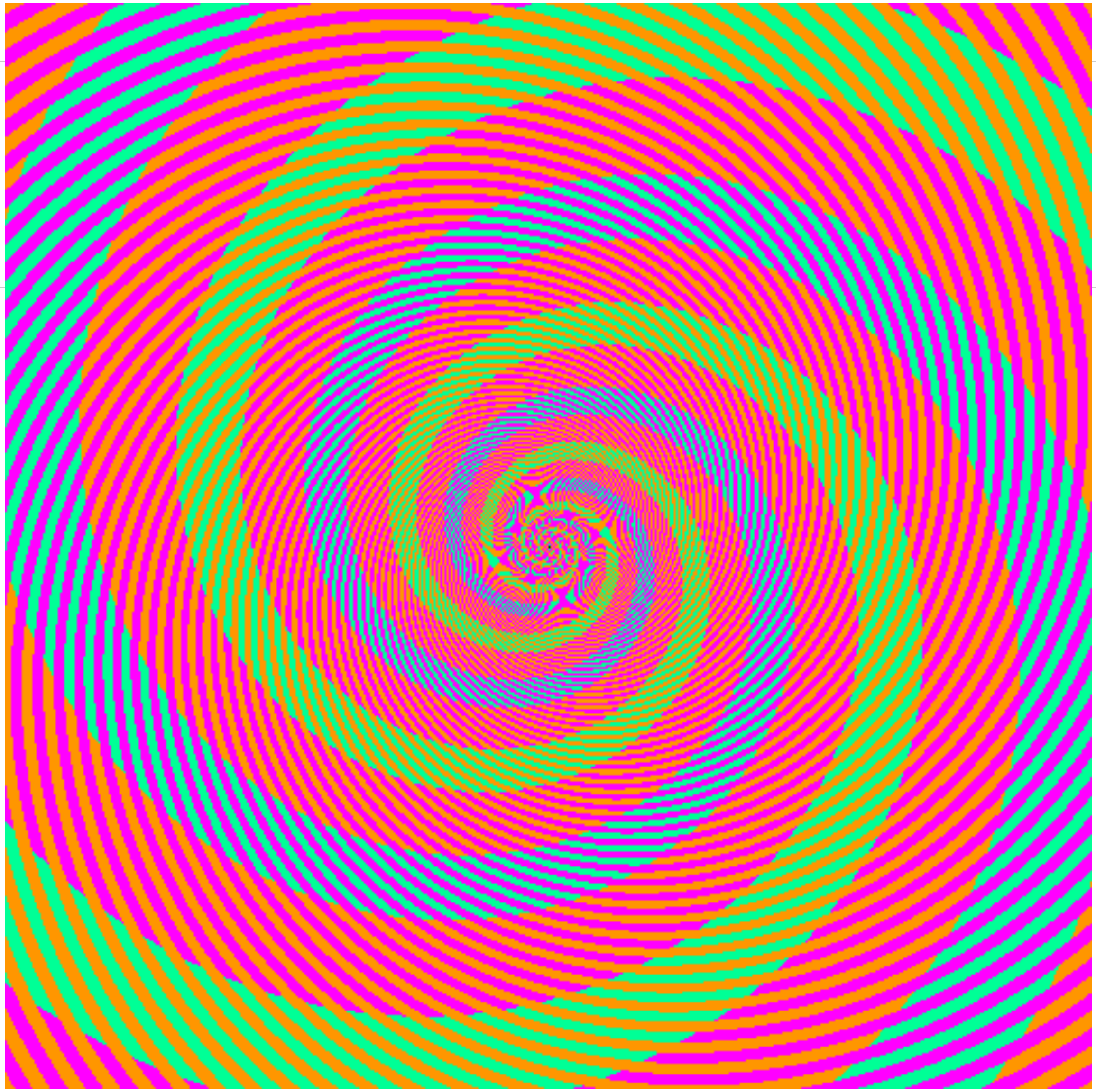
Chapter 7
Color Image Processing: Some Terminology

The only attribute of **achromatic** (void of color) light is its intensity (grey level)

Chromatic light is described using the following basic quantities:
-**Radiance** is the total amount of energy flowing from the light source, measured in Watts
-**Luminance** is the amount of energy perceived by an observer, measured in Lumens
-**Brightness** is subjective luminance

Chapter 7
Appearance of Intensity is Relative

- The appearance  depends on the surrounding ve and not absolute



”Blue” and ”green” are exactly the same color, green! See
https://www.discovermagazine.com/the-sciences/the-blue-and-the-green

Chapter 7
Color Image Processing:
Color Image Representation

Color images can be represented by an intensity function $C(x,y,\lambda)$ which depends on the wavelength λ of the reflected light. (so, for fixed λ, $C(x,y,\lambda)$ represents a monochrome image).

As in the monochrome case, $0 < C(x,y,\lambda) < C_{max}$

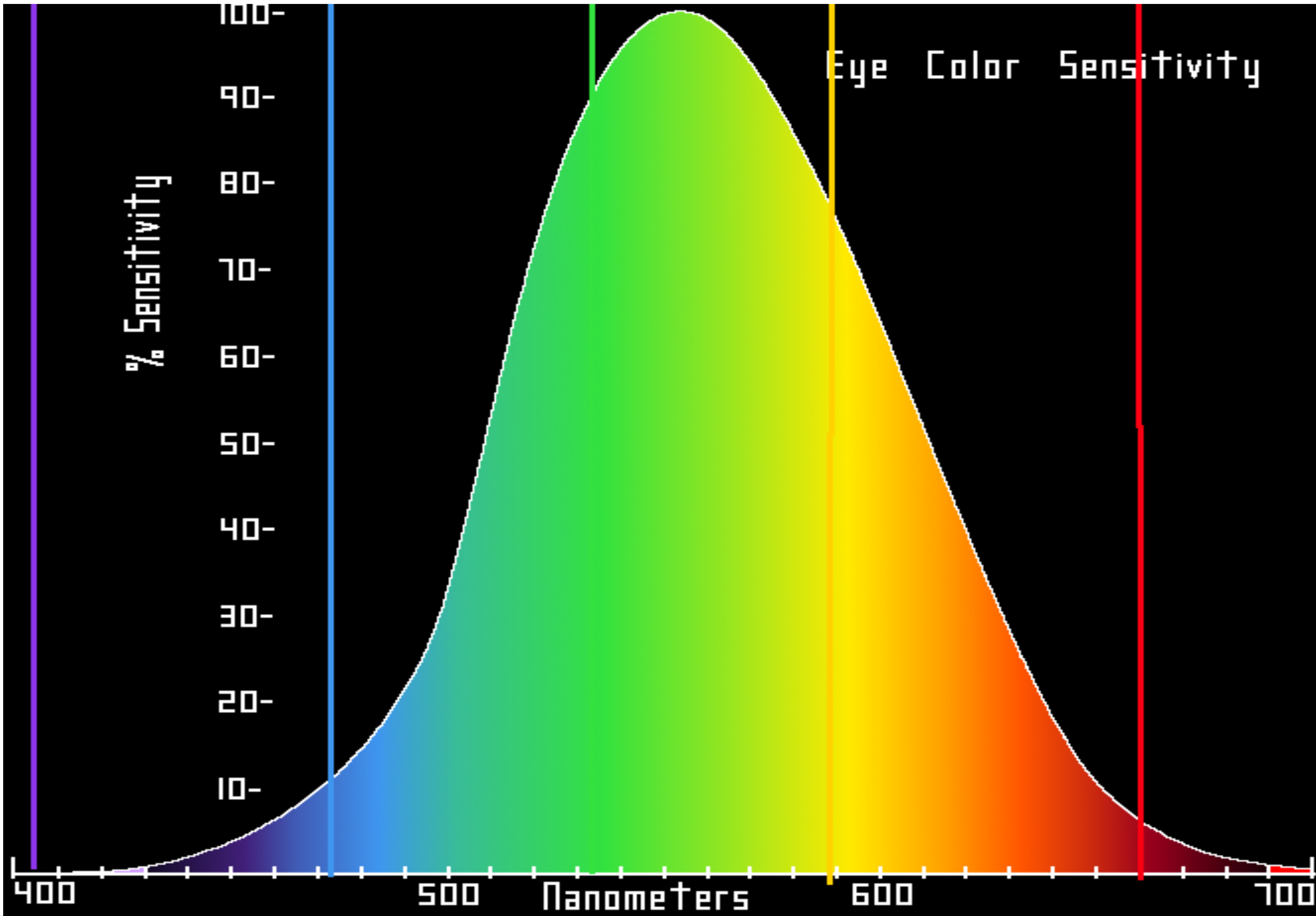
The brightness response of a human observer to an image will therefore be

$$f(x,y) = \int_0^\infty C(x,y,\lambda)\, V(\lambda)\, d\lambda$$

where $V(\lambda)$ is the response factor of the human eye at frequency λ, and it is called the relative luminous efficiency function of the visual system.

For the human eye, $V(\lambda)$ is a bell-shaped function, see the plot on the next slide.

Relative luminous efficiency function of the human visual system as a function of wavelength



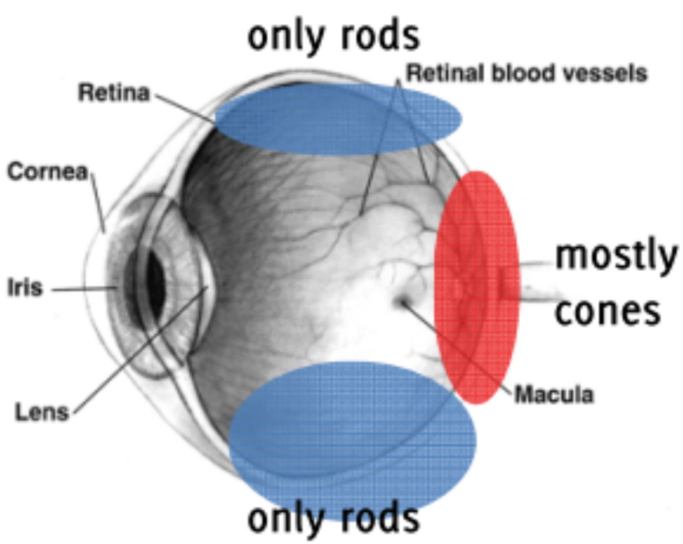
Human Eye

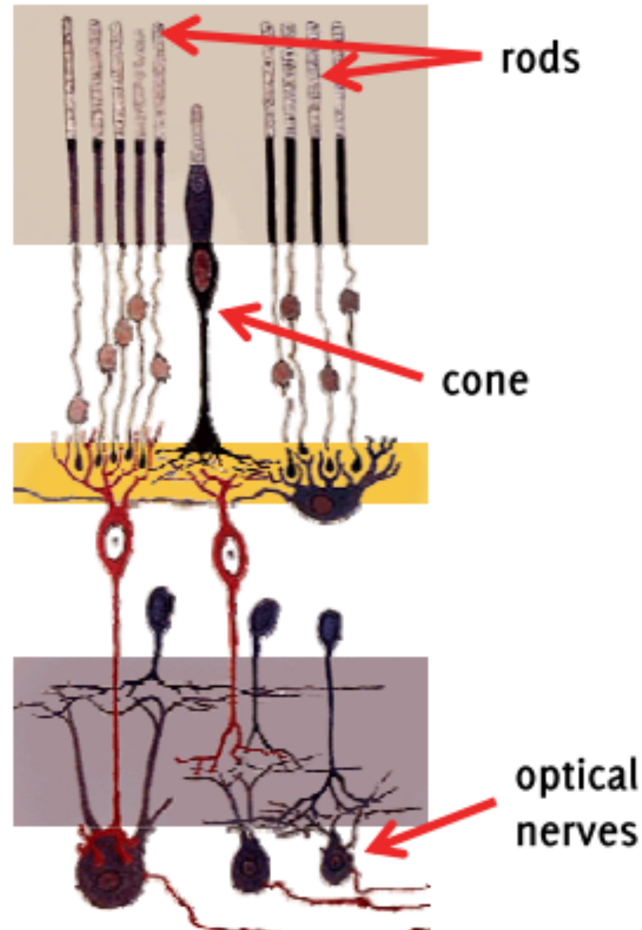
- The human eye senses this spectrum using a combination of photoreceptor cells, called Rods and Cones to make vision possible.
- **Rod cells are effective for low-intensity light vision**, but can only sense the **intensity of light**, whereas **cone cells can discern color**, but they function best in **bright light**.
- There are 6-7 million Cones (some say 5M) and a. 100 million Rods in the human eye
- **Three types of cone cells exist in your eye**, with each being more sensitive to either short (S), medium (M), or long (L) wavelength light.
- These principal sensing categories correspond roughly to **red**, **green** and **blue**: (65% of cones are sensitive to red, 33% to green and 2% to blue)

The Human Eye

The first light sensing organs appeared 540 million years ago

- Rods and Cones
  - (stavar och tappar)





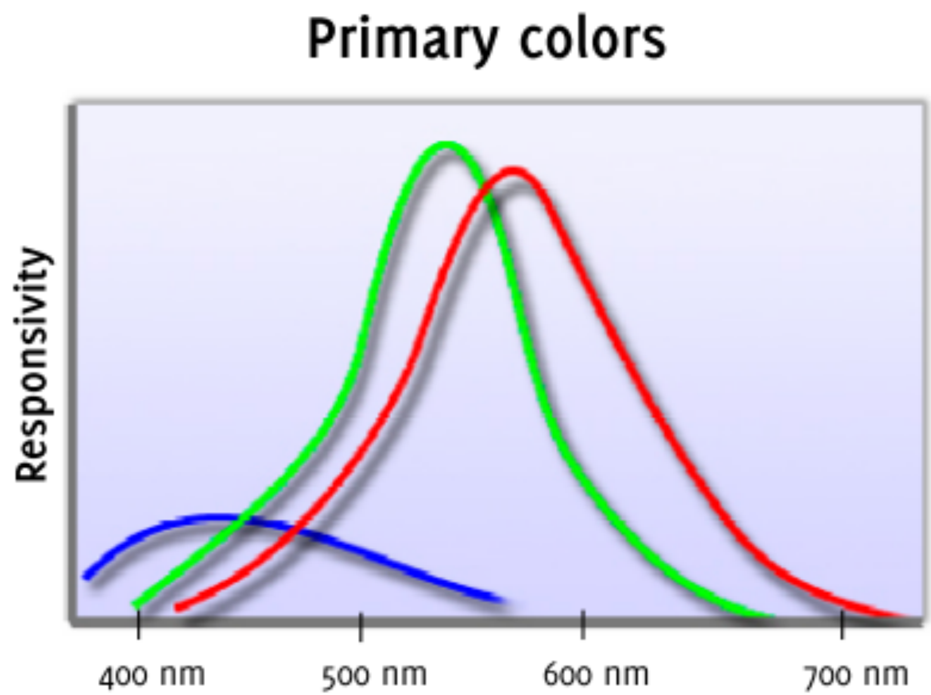
The Rods

- Approx. 100 million rod cells per eye
- Light-sensitive receptors
- Used for night-vision
- **Not used for color-vision!**
- Rods have a slower response time compared to cones, i.e. the frequency of its temporal sampling is lower

Some calculations suggest the resolution of the eye to be 9000 x 9000 pixels

The Cones

- Approx 5 million cone cells per eye
- Three types:
  - S, peak at 445 nm (2%)
  - M, peak at 535 nm (33%)
  - L, peak at 575 nm (65%)
- Most sensitive to green light!



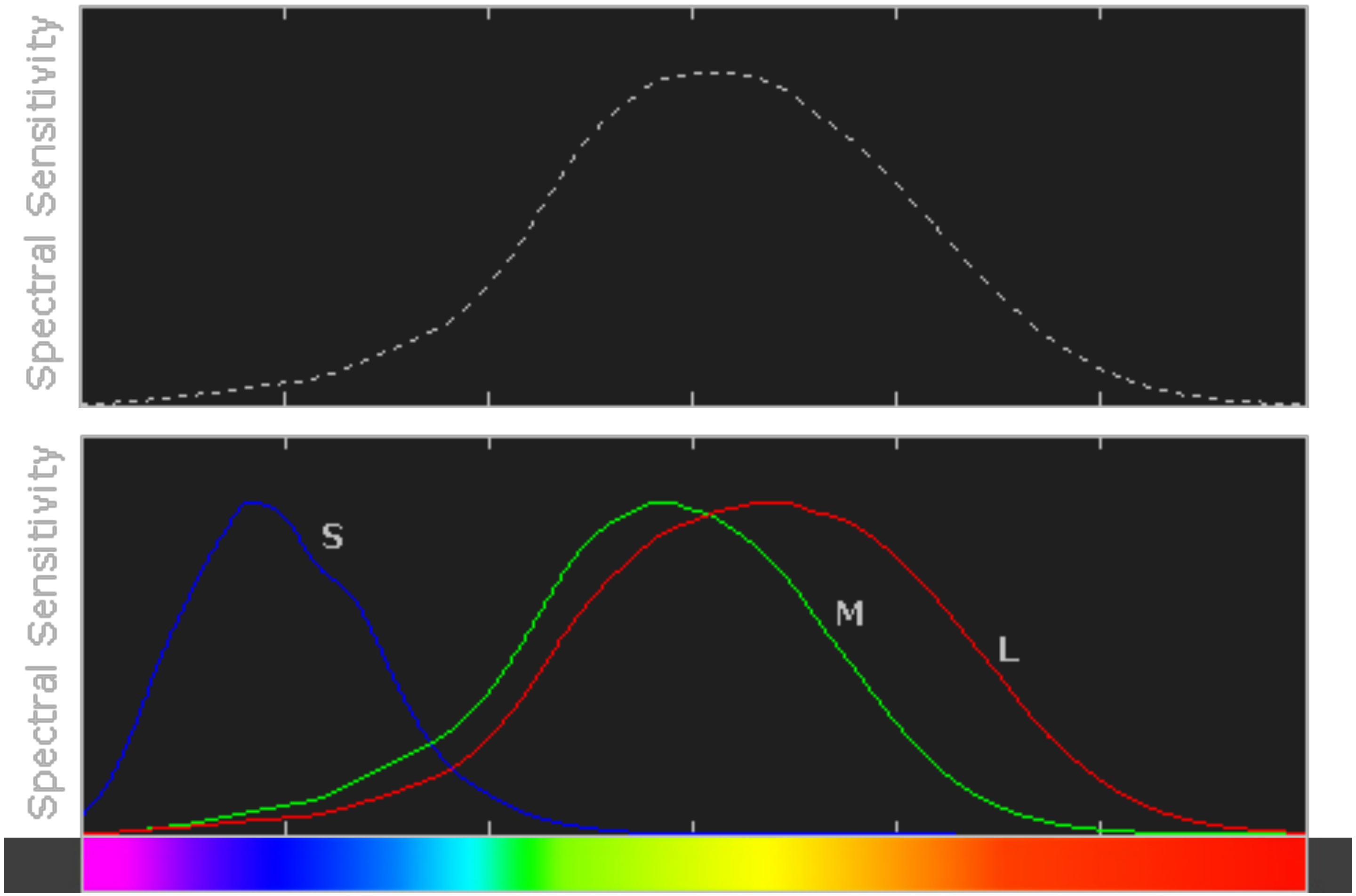
Chapter 7
Color Image Processing: Human Eye

- The set of signals possible to sense at all three cone cells describes the **range of colors** we can see with our eyes.

- The diagram in the next slide illustrates the **relative sensitivity** of each type of cell for the entire visible spectrum.

- These curves are often also referred to as the "**tristimulus functions**."

Tristimulus functions



Raw data courtesy of the Colour and Vision Research Laboratories (CVRL), UCL.

- We have three brightness response functions describing the absorption of light in red, green and blue cones:

$$f_R(x,y) = \int_0^\infty C(x,y,\lambda)\, V_R(\lambda)\, d\lambda$$

$$f_G(x,y) = \int_0^\infty C(x,y,\lambda)\, V_G(\lambda)\, d\lambda$$

$$f_B(x,y) = \int_0^\infty C(x,y,\lambda)\, V_B(\lambda)\, d\lambda$$

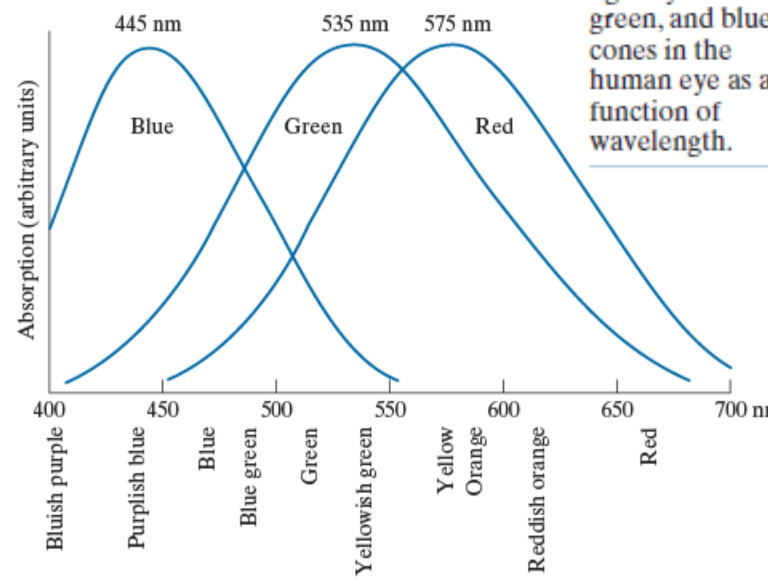


FIGURE 7.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

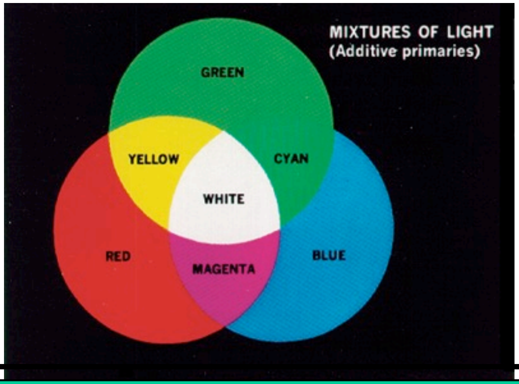
The above experimental curves became available in 1965.

Due to these absorption characteristics, colors are seen as variable combinations of so called "**primary colors**" **red**, **green** and **blue**.

In **1931**, CIE (International Commission on Illumination) designated the following:
Blue = 435.8nm
Green = 546.1nm
Red = 700nm

- Remember that there is no single color called red, green or blue in the color spectrum!
- Also, these fixed RGB components cannot generate ALL spectrum colors!

Primary colors of light can be added in pairs to produce secondary colors of light: e.g. magenta, cyan and yellow.



Mix all three primary colors in light produces white color

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

Light Properties

- Illumination
  - **Achromatic light** - *"White" or uncolored light that contains all visual wavelengths in a "complete mix".*
  - **Chromatic light** - *Colored light.*
  - **Monochromatic light** - *A single wavelength, e.g., a laser.*
- Reflection
  - No color that we "see" consists of only one wavelength
  - The dominating wavelength reflected by an object decides the "color tone" or hue.
  - If many wavelengths are reflected in equal amounts, an object appears gray.

Chapter 7
Color Image Representation

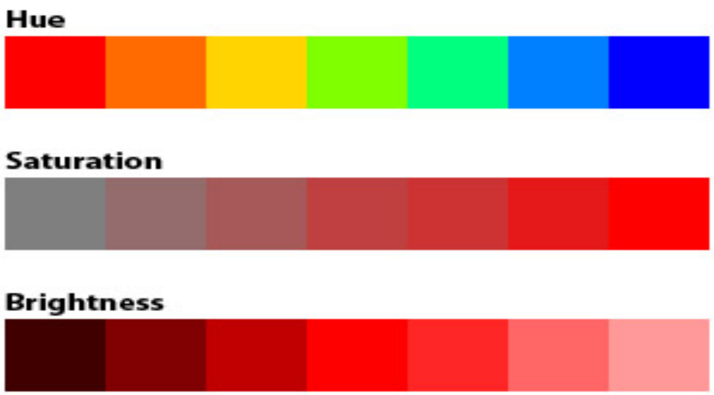
Colors are distinguished from each other through **hue**, **saturation** and **brightness** (intensity).

Hue is associated with the dominant wavelength in the mixture and represents the perceived dominant color.

Saturation refers to the relative purity or the amount of white light mixed with a hue.

Together hue and saturation are called **chromaticity**.

Brightness (intensity) embodies the achromatic notion of intensity.



- *Tristimulus Values* (X,Y,Z) are the amounts of red, green and blue needed to form any particular color.
- A color is specified by its trichromatic coefficients defined as:

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

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

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

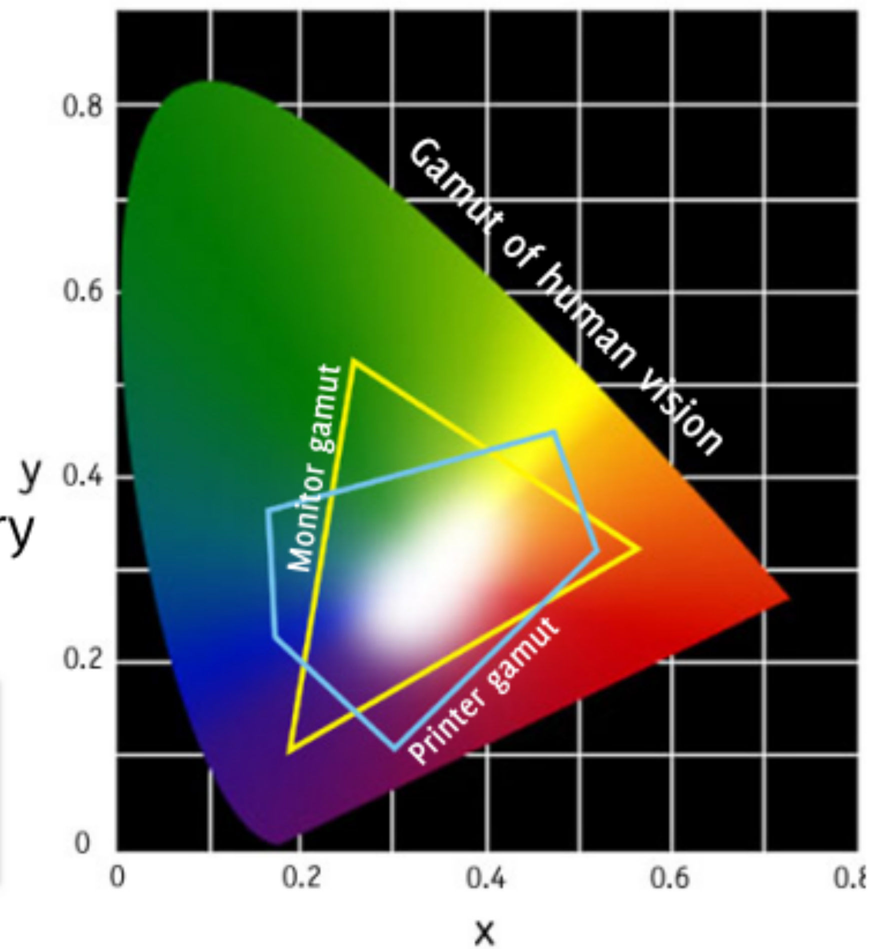
- Note that x+y+z = 1! i,e. only two of the trichromatic coefficients are independent

- Experimental curves and tables are used to find the tristimulus values needed to generate a given color.

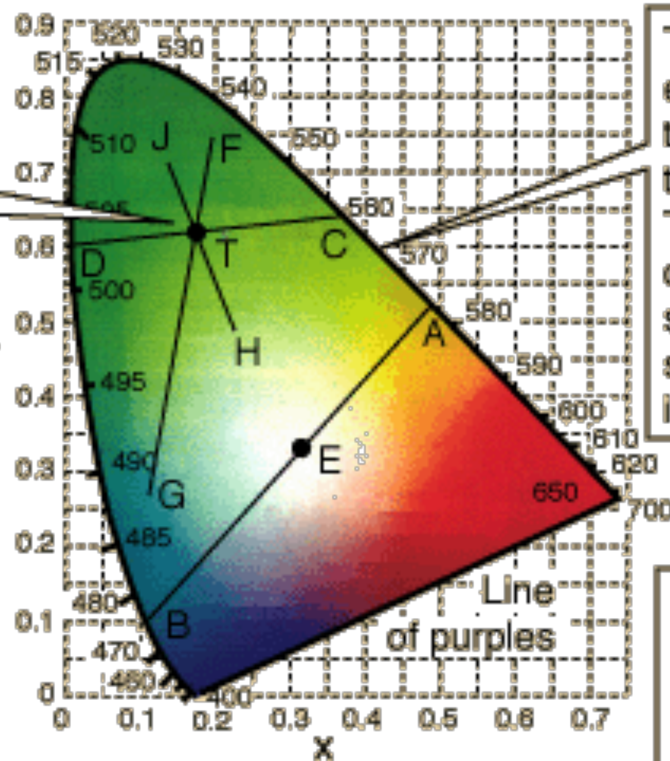
CIE 1931 Color Space

- The projection of $X + Y + Z = 1$ creates **CIE *xy* chromaticity diagram**
- CIE standard white when
  $x = y = z$
- Not possible to produce all colors by mixing three primary colors.

Gamut: subset of colors which can be accurately represented in a given circumstance



The combination of light wavelengths to produce a given perceived color is not unique. The pairs CD, FG and JH can each produce the color T if combined in the right proportions.



The solid line outline encompasses all the hues that are perceivable to the normal human eye. The horseshoe shaped curve contains the spectral colors. The straight line at the bottom is the line of purples.

Any point within the curve represents a unique perceivable hue. But there are many combinations that will produce that hue.

E is the achromatic point. AB or any pair for which the connecting line passes through E can form a complementary color pair.

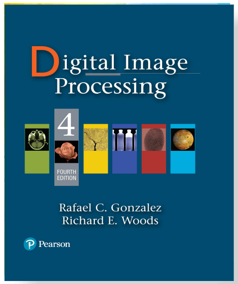
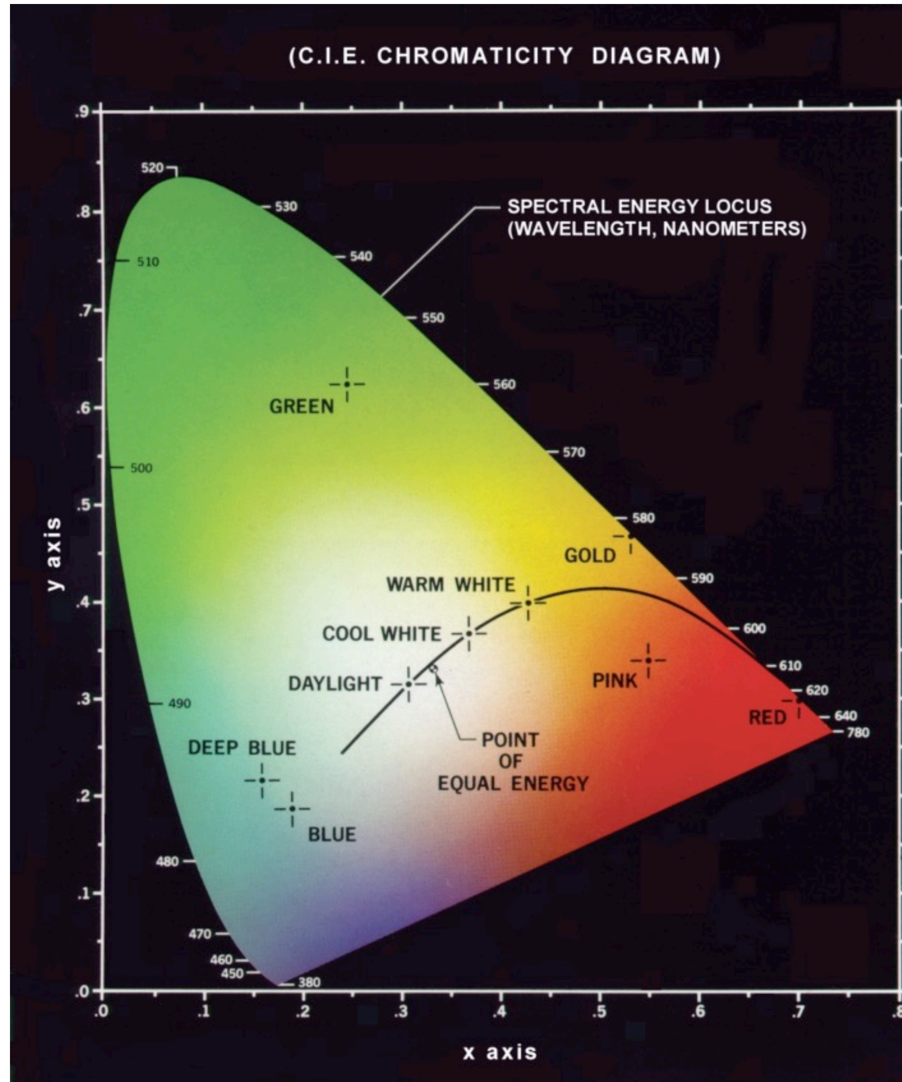


FIGURE 7.5 The CIE chromaticity diagram. (Courtesy of the General Electric Co., Lighting Division.)

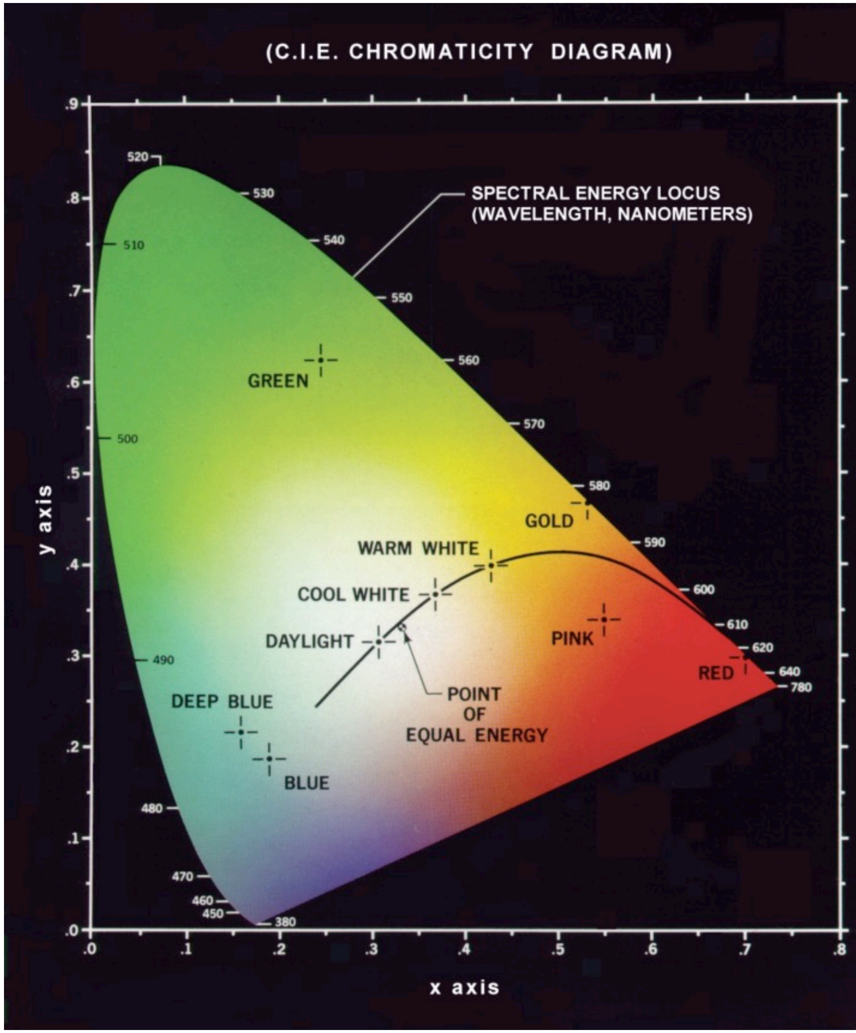


Example: the point shown as GREEN is made of 62% green, 25% red and 13% blue.

- Pure colors are mapped on the boundary of the chromaticity diagram, fully saturated colors
- Colors inside the diagram are combinations of these colors
- Reference white is the point of equal energy, with zero saturation value

The diagram is useful for color mixing, e.g.

- a straight line joining any two points defines all colors generated by adding those colors,
- in particular, if one of these points is reference white and the other is some color on the boundary, then the colors on the line in-between represent all the shades of that particular spectrum color



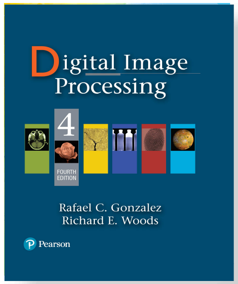
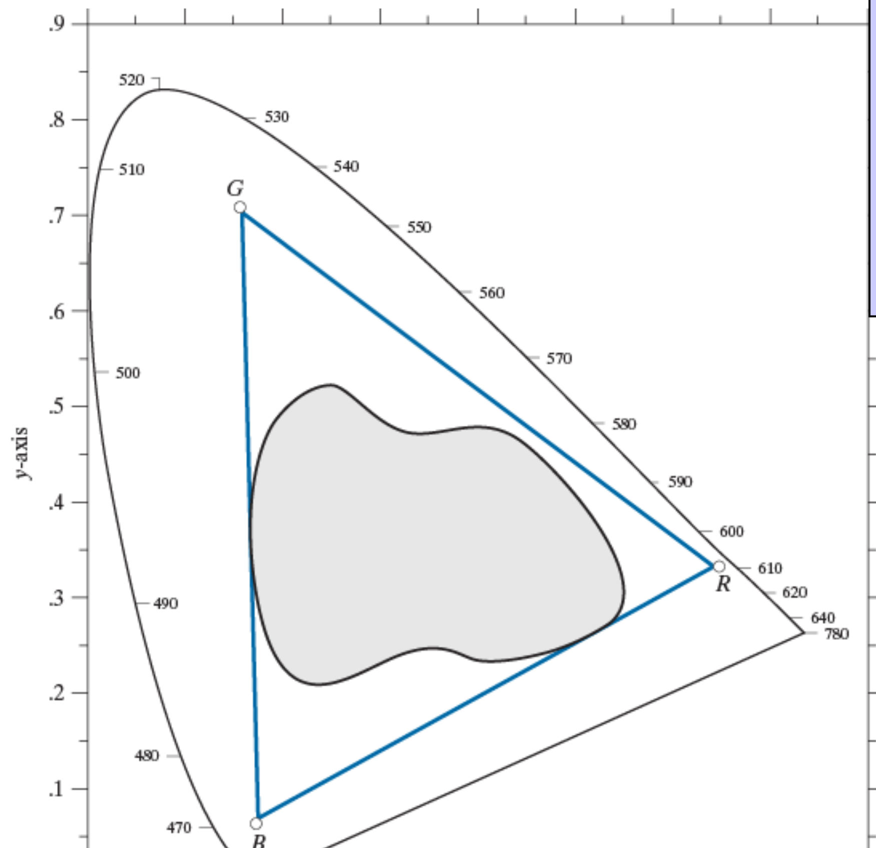


FIGURE 7.6 Illustrative color gamut of color monitors (triangle) and color printing devices (shaded region).

Typical color gamut of an RGB display



color gamut of a high quality color printer, irregular shape is due to additive and subtractive color combinations

Remember that due to the shape of the chromaticity diagram, no fixed three colors can reproduce all colors inside the diagram!

Chapter 7
Color Image Processing: Color Models

Color models or color spaces refer to a **<u>color coordinate system</u>** in which each point represents one color.

Different models are defined (standardized) for different purposes, e.g.

<u>Hardware oriented models</u>:

- RGB for color monitors (CRT and LCD) and video cameras,
- CMYK (cyan, magenta, yellow and black) for color printers

<u>Color manipulation models</u>:

- HSI, HSV (hue, saturation and brightness) is closest to the human visual system
- Lab is most **<u>uniform color space</u>**
- YCbCr (or YUV) is often used in video where chroma is down-sampled (recall that the human visual system is much more sensitive to luminance than to color)
- XYZ is known as the raw format
- others

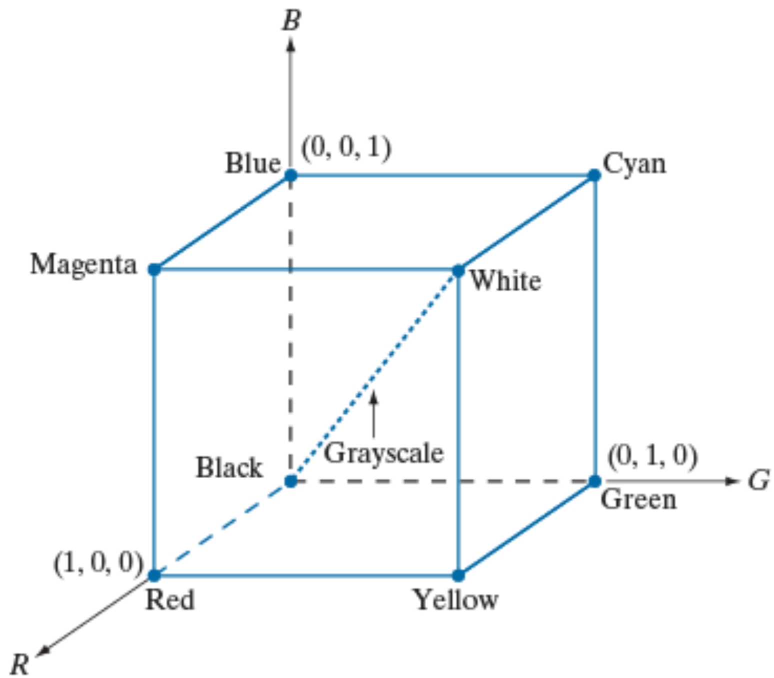
Two important aspects to retain about color models:

❖ Conversion between color models can be either linear or nonlinear,

❖ Some models can be more useful as they can decouple color and gray-scale components of a color image, e.g. HSI, YUV.

RGB Color Model

FIGURE 7.7 Schematic of the RGB color cube. Points along the main diagonal have gray values, from black at the origin to white at point (1, 1, 1).



- The eight vertices of the cube are occupied by red, green and blue (primary colors) magenta, cyan and yellow (secondary colors) and finally black and white.
- RGB values have been normalized in the range [0,1]

FIGURE 7.8
A 24-bit RGB color cube.

- **Pixel depth** refers to the number of bits used to represent each pixel in the RGB space

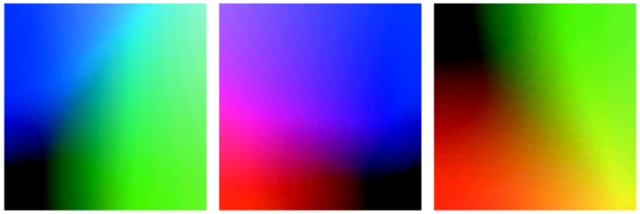
- If each pixel component (red, green and blue) is represented by 8 bits, the pixel is said
- to have a depth of 24 bits.

- A **full-color** image refers to a 24-bit RGB color image. The number of possible colors
- in a full-color image is:

$$(2^8)^3 = 16{,}777{,}216 \text{ colors (or 16 million colors)}$$

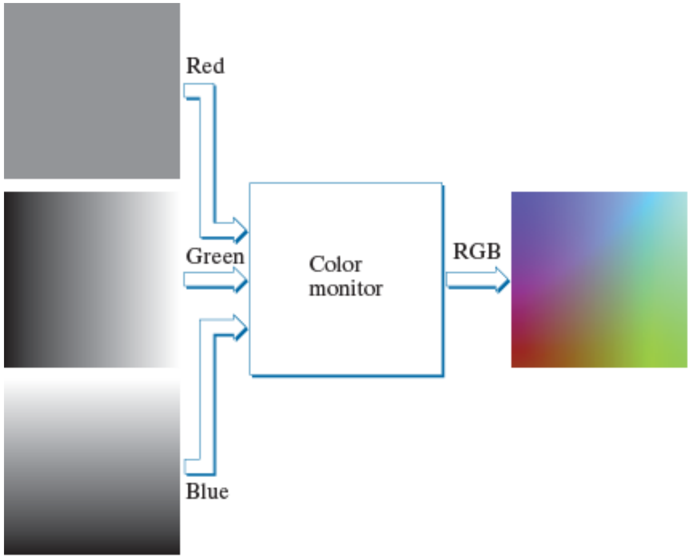
RGB color cube

FIGURE 7.8
A 24-bit RGB color cube.



(R = 0) (G = 0) (B = 0)

The hidden surfaces of the cube



a
b

FIGURE 7.9 (a) Generating the RGB image of the cross-sectional color plane (127, G, B). (b) The three hidden surface planes in the color cube of Fig. 7.8.

An example showing how to generate the RGB image for the cross-sectional color plane (127,G,B)
Note that each plane is represented as a gray-scale image.

Note: color image acquisition is the reverse process, i.e. three filters are used, each is sensitive to each of the three primary colors

Chapter 7
Color Image Processing: Color Models

CMY and CMYK Color Models

Most devices that deposit color pigments on paper, e.g. printers and copiers, use CMY inputs or perform RGB to CMY conversion internally:

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

Remarks:

- Recall that all color values have been normalized in the range [0,1]
- A surface coated with cyan does not contain red, that is C = 1 – R
- Equal amounts of pigment primaries should produce black
- In printing, this appears as muddy-looking black; therefore, a fourth color, black is added, leading to CMYK color model (four-color printing).

“Additive” vs. “Subtractive” Colors

- When light from different sources reaches our eye directly, the colors are *additive* (think of it as an OR operation on what is transmitted)
- When white light is *reflected* by an object, it is because all of the other colors are *absorbed*
- So, if you mix two colors of paint the new color will absorb what both would.
- That is, the colors are subtractive (think of it as an AND operation on what is reflected).

“Additive” vs. “Subtractive” Colors

- CMY (Cyan, Magenta, Yellow) used in printing, etc.

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

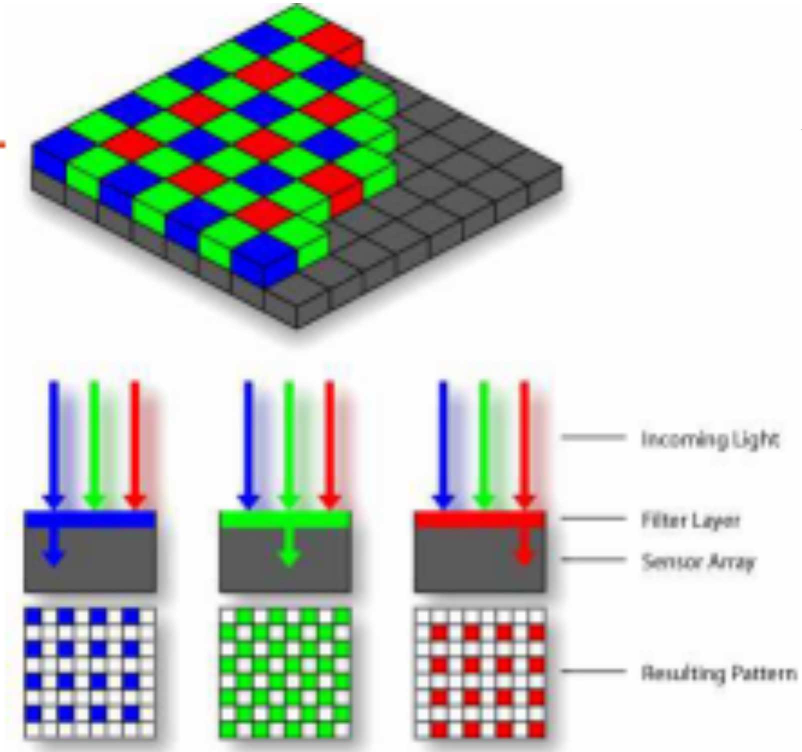
- *E.g.*, when a cyan painted surface is illuminated by white light, no red is reflected

RGB Image Formation in Cameras

- Most video cameras use RGB space
- Expensive variants use 3 CCDs (charge-coupled devices), each with a filter for the respective wavelength of light
- More common variants have a single CCD with different filters

The Bayer Filter

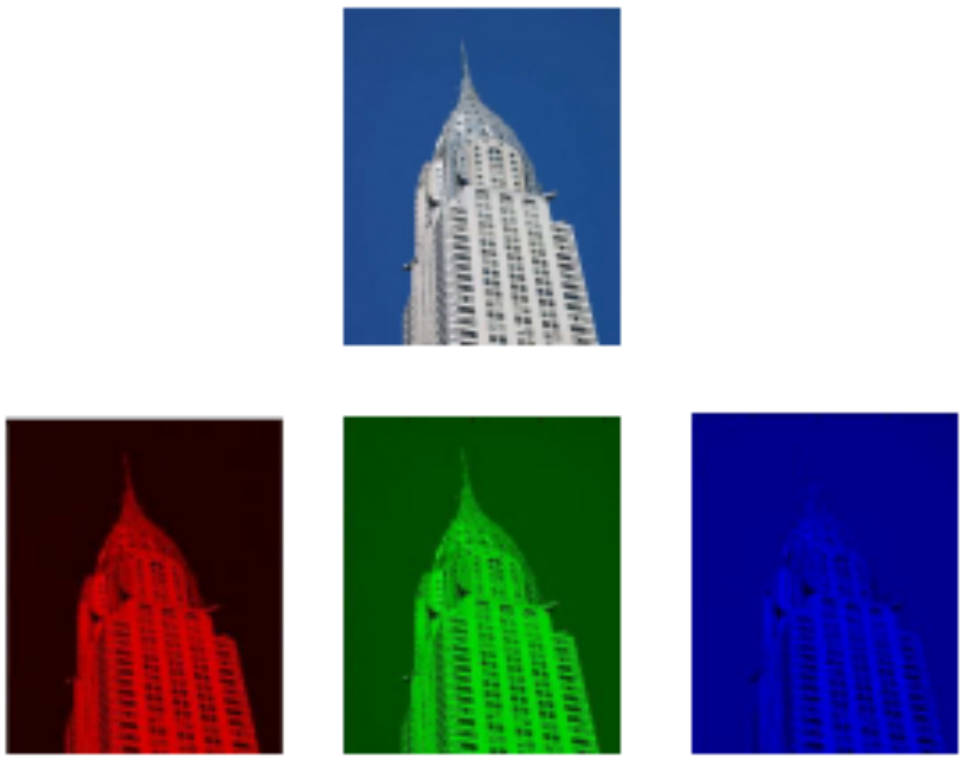
- Based upon the observation that human vision is much more responsive to green light than red or blue
- Half the pixels in the CCD are allocated to green, ¼ to red and ¼ to blue



- Color is generated for the whole CCD by interpolating neighbor values
- The image we get has already undergone a "lossy compression"

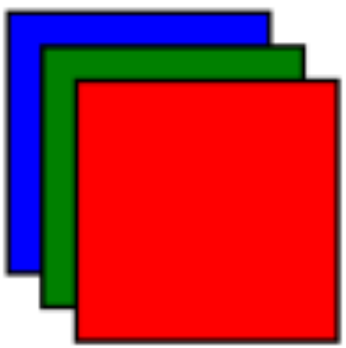
RGB Image Composition

- In a computer, an RGB image is represented by 3 image planes

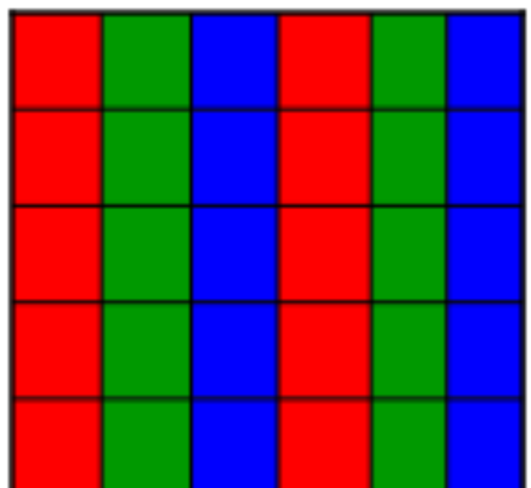


RGB Image Format

- Images pixels can be either *planar* or *packed* format
- Planar format separates the colors into three contiguous arrays in memory
- Packed alternate R->G->B->R->… in memory



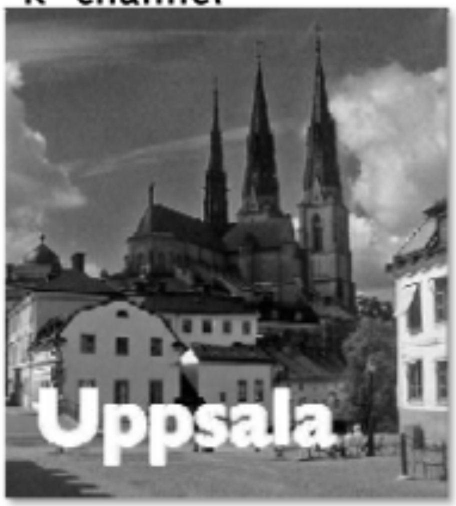
Planar



Packed

Additative Mix

R channel



G channel

B channel

RGB:

RGB - Pros & Cons

- Mimicing the human color perception*
- Easy and straightforward
- Suited for hardware implemenation

* RGB (from the point of view of the three types of cones we have in the retina whose responses peak at Red, Green and Blue wavelengths), but HSI is the color system that really mimics how humans perceive and identify colors.

- Not practical for human description of colors
- No decoupler of intensity

HSI Color Model

Although RGB and CMY color models are very well suited for hardware and RGB reflects well the sensitivity of the human eye to these primary colors, both are not suited for describing color in a way that is easily interpreted by humans.

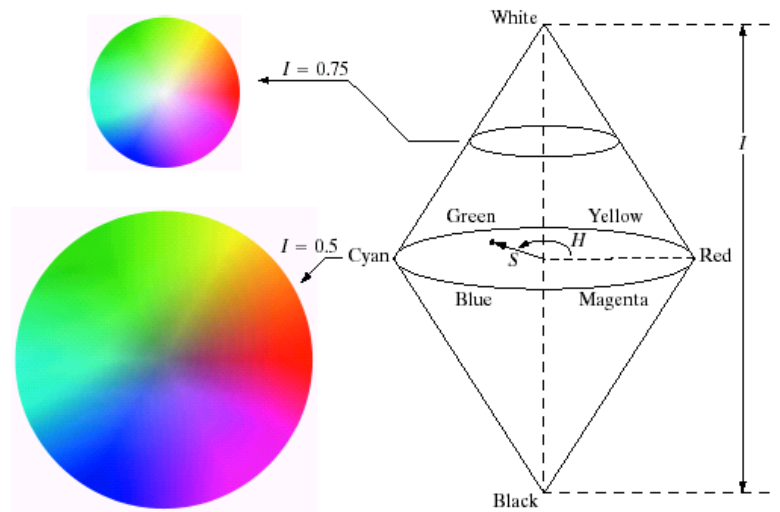
When humans see a color object, they tend to describe it by its **hue**, **saturation** and **brightness**, i.e. HSI model is used

In addition, HSI decouples brightness from the chroma components.

Chapter 7
Color Image Processing:
HSI Color Image Representation

Three Perceptual Measures

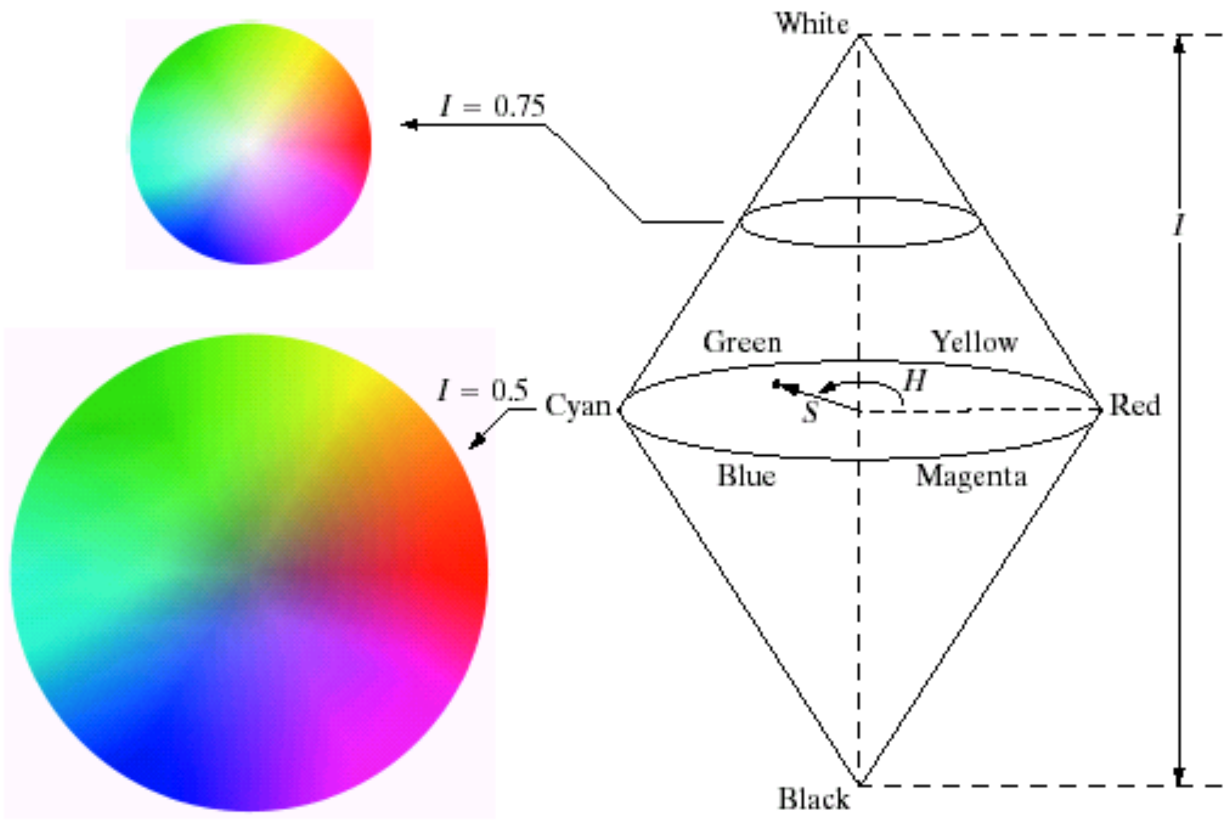
1. ***Intensity*** *or* **Brightness**: varies along the vertical axis and measures the extent to which an area appears to exhibit light. It is proportional to the electromagnetic energy radiated by the source.



2. ***Hue****:* denoted by H and varies along the circumference. It measures the extent to which an area matches colors red, orange, yellow, blue or purple (or a mixture of any two). In other words, hue is a parameter which distinguishes the color of the source, i.e., is the color red, yellow, blue, etc.

3. **Saturation**: the quantity which distinguishes a pure spectral light from a pastel shade of the same hue. It is simply a measure of white light added to the pure spectral color. In other words, saturation is the colorfulness of an area judged in proportion to the brightness of the object itself. Saturation varies along the radial axis.

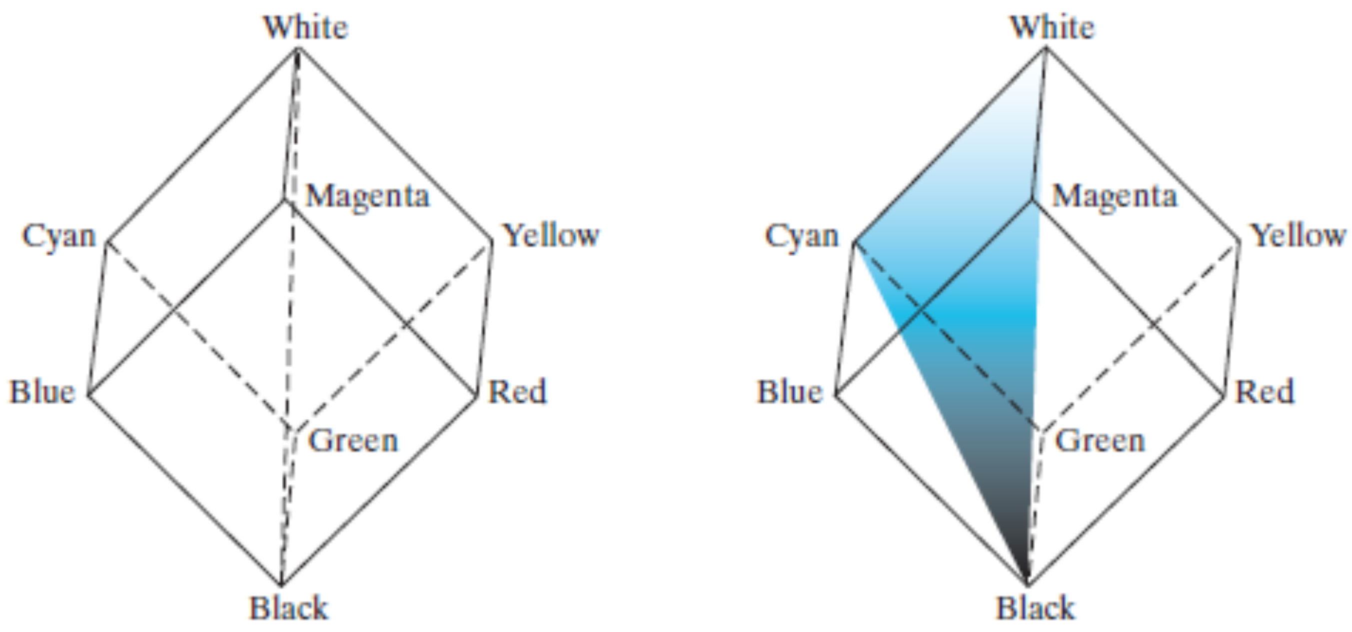
Chapter 7
Color Image Processing:
HSI Color Image Representation



Conceptual relationships between RGB and HIS models

a b

FIGURE 7.10 Conceptual relationships between the RGB and HSI color models.



Chapter 7
Color Image Processing: Color Models
HSI-RGB Color Model Conversions

From RGB to HSI:

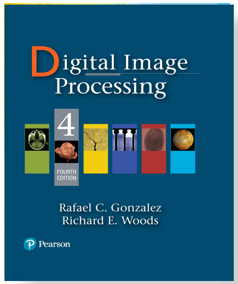
the hue is: $$H = \begin{cases} \theta & if \quad B \leq G \\ 360 - \theta & if \quad B > G \end{cases}$$

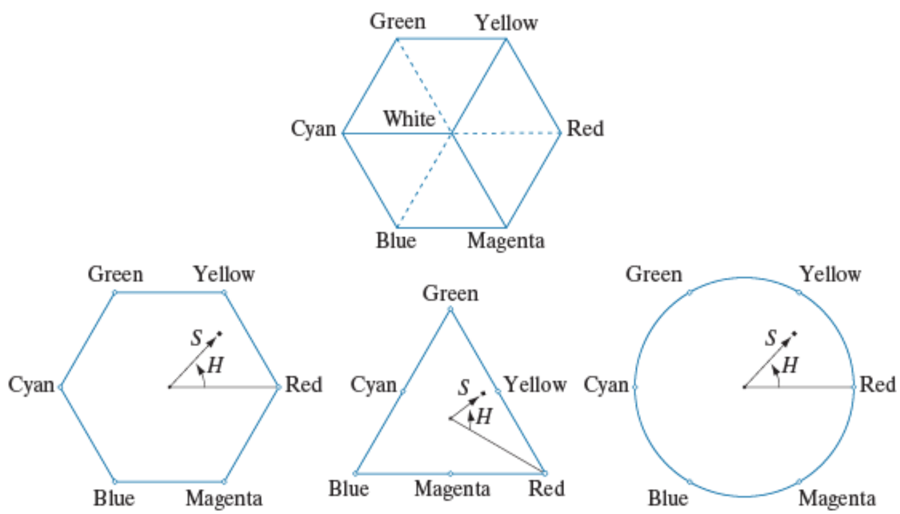
with $$\theta = \cos^{-1}\left\{ \frac{\frac{1}{2}[(R-G)+(R-B)]}{[(R-G)^2 + (R-B)(G-B)]^{\frac{1}{2}}} \right\}$$

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

and the intensity is: $$I = \tfrac{1}{3}(R+G+B)$$

- It's assumed that RGB values are normalized and θ is measured with respect to the Red axis.
- To convert back from HSI to RGB, we need to split the Hue component into 3 sectors (next slide)





a
b c d

FIGURE 7.11 Hue and saturation in the HSI color model. The dot is any color point. The angle from the red axis gives the hue. The length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.

We have 3 sectors of interest, corresponding to the 120° intervals separating the primary colors (Red – Green (RG) sector, GB sector, BR sector).

Chapter 7
Color Image Processing: Color Models
HSI-RGB Color Model Conversions

From HSI to RGB: Given values of HSI in [0,1], let's find the corresponding values of RGB in the same range.

Note: Conversion from HSI to RGB depends on which sector H is located.

RG sector ($0° \leq H < 120°$)

$$B = I(1 - S) \qquad R = I\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \qquad G = 3I - (R + B)$$

RG sector ($120° \leq H < 240°$), first $H = H - 120°$

$$R = I(1 - S) \qquad G = I\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \qquad B = 3I - (R + G)$$

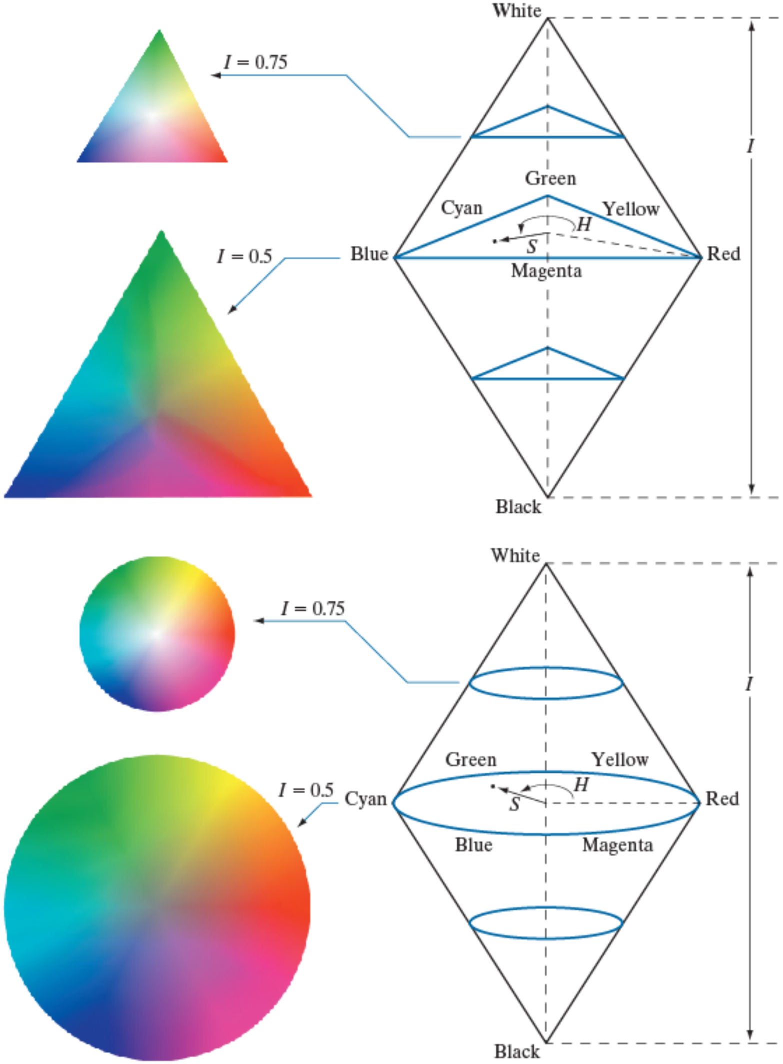
RG sector ($240° \leq H \leq 360°$), first $H = H - 240°$

$$G = I(1 - S) \qquad B = I\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \qquad R = 3I - (G + B)$$

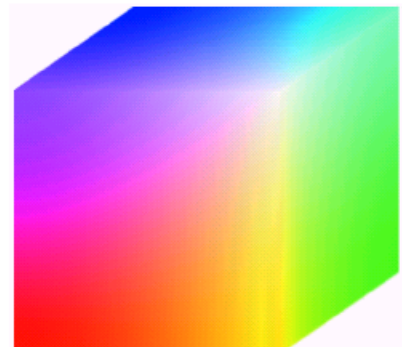
Chapter 7
Color Image Processing

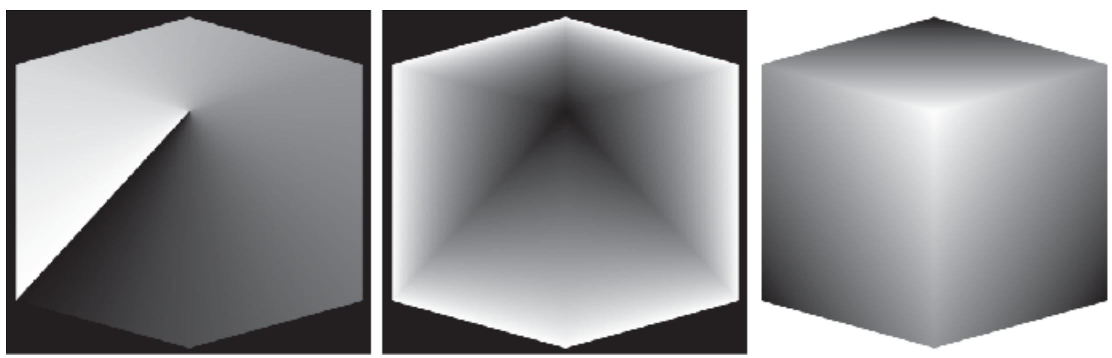
a
b

FIGURE 7.12 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 HSI components of the RGB 24-bit color cube image





a b c

FIGURE 7.13 HSI components of the image in Fig. 7.8: (a) hue, (b) saturation, and (c) intensity images.

Chapter 7

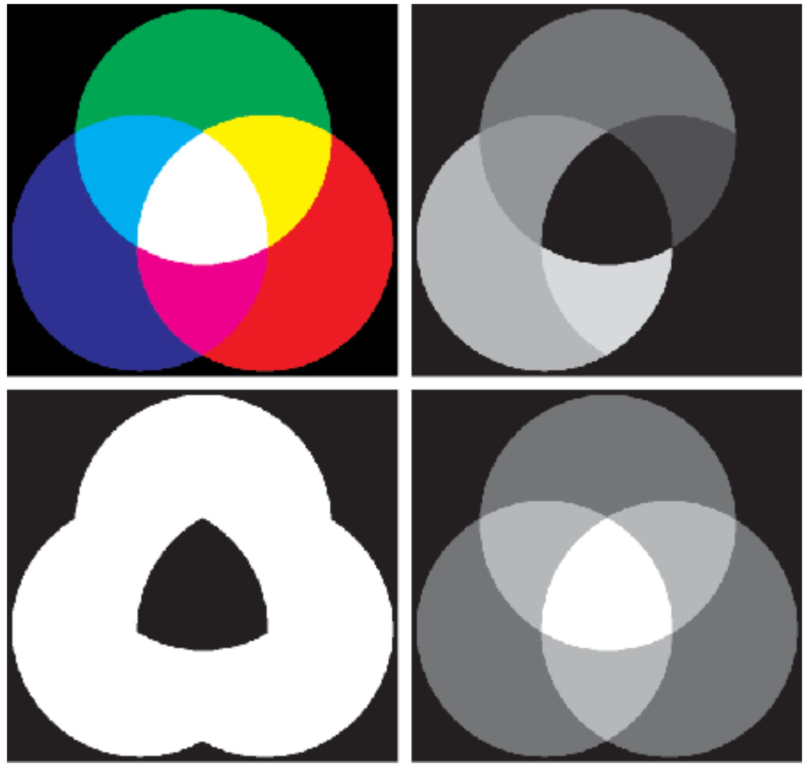
Color Image Processing

Manipulating HSI Component Images

a b
c d

FIGURE 7.14 (a) RGB image and the components of its corresponding HSI image: (b) hue, (c) saturation, and (d) intensity.

RGB image composed of primary and secondary colors



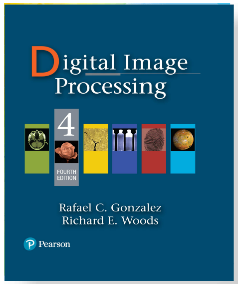
Hue component

Notice how red is mapped to black since its hue is 0 (by convention)

Saturation component

Intensity component

Idea: can change any of these color components independently by changing the gray levels of that component.



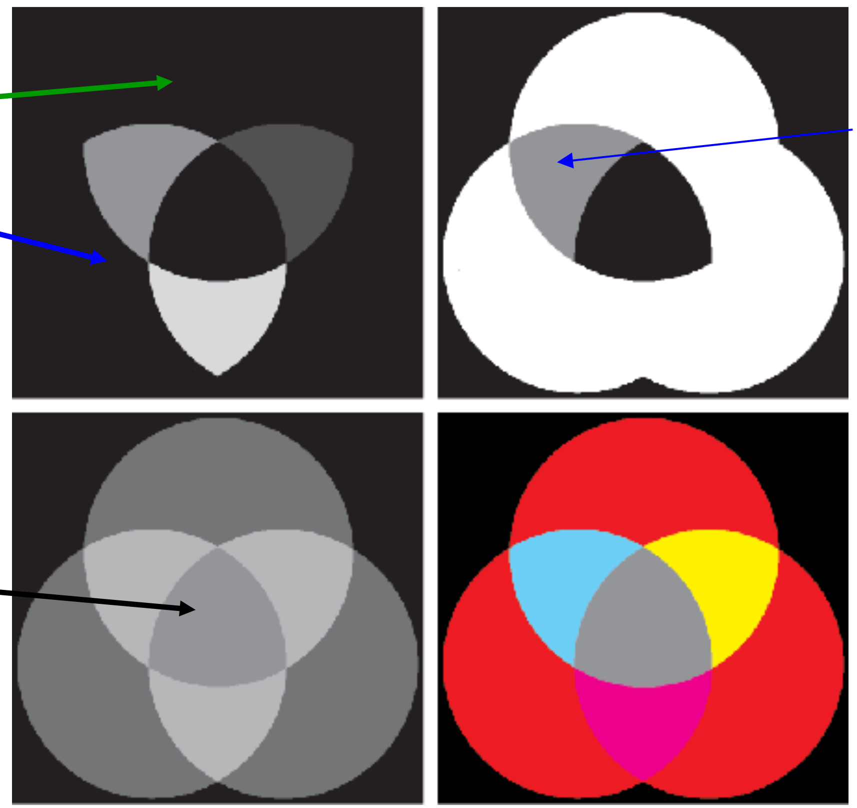
Example of modifying HSI components

a b
c d

FIGURE 7.15
(a)-(c) Modified HSI component images.
(d) Resulting RGB image. (See Fig. 7.14 for the original HSI images.)

Modified hue where blue and green are set to 0 (red)

Modified saturation where saturation of the cyan region is halved



Modified intensity where intensity of the central white region is halved

Finally, this is the modified HSI image converted back to RGB.

Note how the outer circles became red, cyan saturation is reduced and white central region became gray.

HSI color model allows independent control over the hue, saturation and intensity values.

Usage of HSI

- Intensity is decoupled
  - That's often where we want to "operate"

Original image

RGB image
histogram equalized for each channel individually

HSI image
histogram equalized for the I-channel only