ELEG404/604: Digital Imaging & Photography

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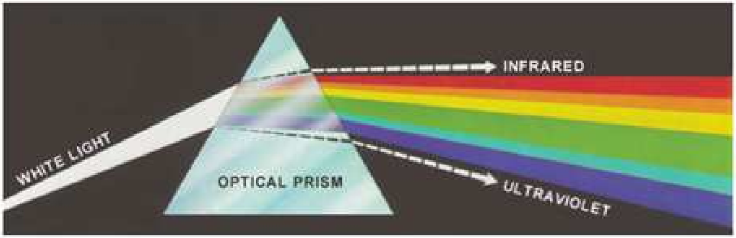
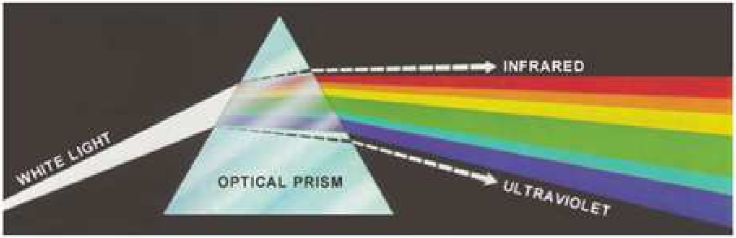
Chapter IX

Color Fundamentals



- The visible light spectrum is continuous

Color Fundamentals



- The visible light spectrum is continuous
- Six broad regions:
  - Violet, blue, green, yellow, orange and red

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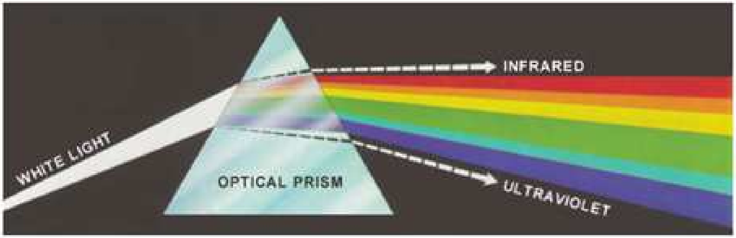
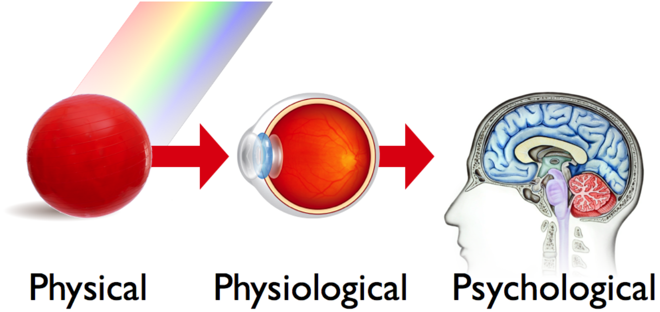


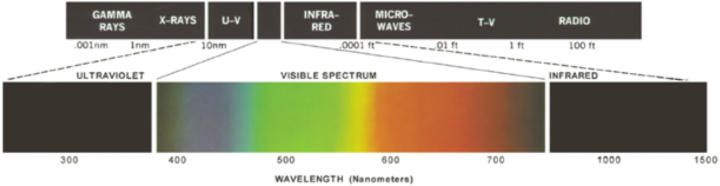
- The visible light spectrum is continuous
- Six broad regions:
  - Violet, blue, green, yellow, orange and red
- Achromatic light is void of color
  - Characterization: intensity (gray level)

Color Perception

- Object color depends on what wavelength it reflects



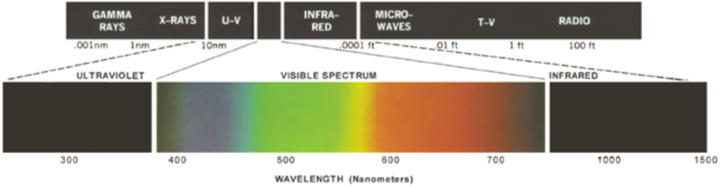
Color Fundamentals



Same luminance but varying brightness

- Chromatic light spectrum: 400-700nm

Color Fundamentals

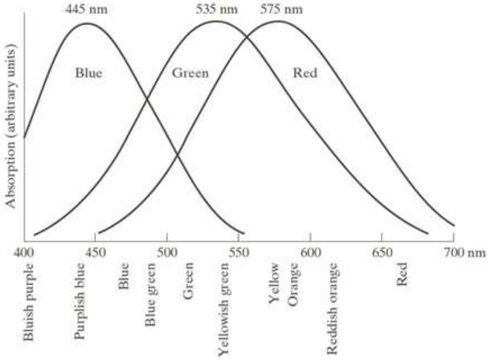


Same luminance but varying brightness

- Chromatic light spectrum: 400-700nm
- Descriptive quantities:
  - Radiance-total energy that flows from a light source
  - Luminance-amount of energy an observer perceives from a light source (lumens)
  - Brightness-subjective descriptor of intensity

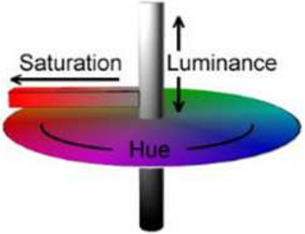
Color Vision Response

- Cone response
  - 6-7 million receptors
  - Tristimulus model
  - Red sensitive: 65%
  - Green sensitive: 33%
  - Blue sensitive: 2%–most sensitive receptors



Color Attributes

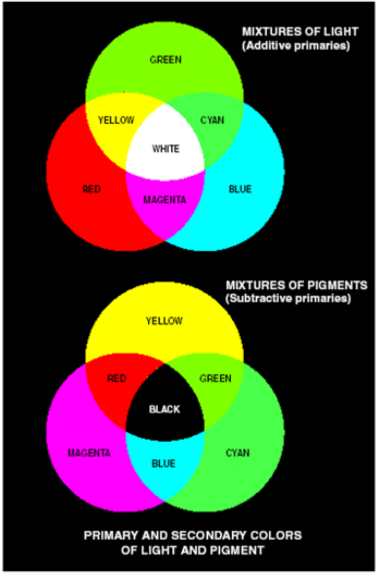
- Brightness: perception of intensity
- Hue: an attribute associated with the dominant wavelength (color)
  - The color of an object determines its hue



- Saturation: relative purity, or the amount of white light mixed with a hue
  - Pure spectrum colors are fully saturated, *e.g.*, red
  - Saturation is inversely proportional to the amount of white light in a color
- Chromaticity: hue and saturation together
  - A color may be characterized by its brightness and chromaticity

Primary and Secondary Colors

- Primary colors of light:
  - Red, green and blue
- Add primary colors to obtain secondary colors of light:
  - Magenta, cyan and yellow
- Primary colors of pigments–absorbs (subtracts) a primary color of light and reflects (transmits) the other two
  - Magenta absorbs green, cyan absorbs red, and yellow absorbs blue
  - Secondary pigments: red, green and blue



Color Vision Response

- Primary colors: red (R), green (G), blue (B)

$$R(\lambda) = \int_0^\infty C(\lambda) R_S(\lambda) d\lambda$$
$$G(\lambda) = \int_0^\infty C(\lambda) G_S(\lambda) d\lambda$$
$$B(\lambda) = \int_0^\infty C(\lambda) B_S(\lambda) d\lambda$$

where $C(\lambda)$ is the spectral distribution of light incident on the retina and R_s,G_s and B_s are the sensitivity of the cones.

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- Two different spectra could produce the same cone response and therefore represent the same to the human eye.

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Metamerism

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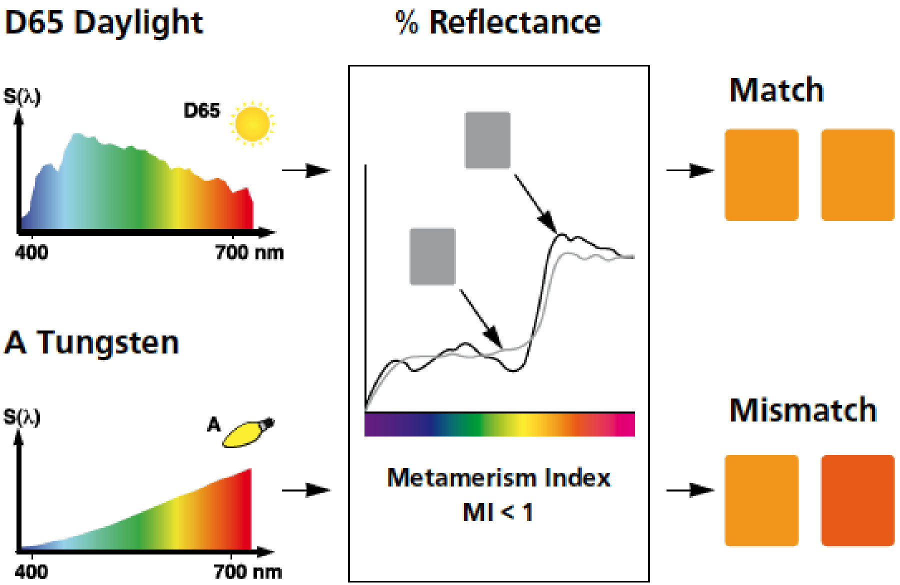
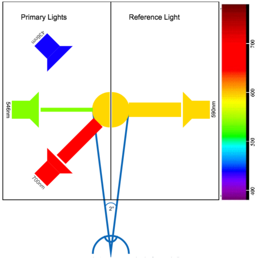
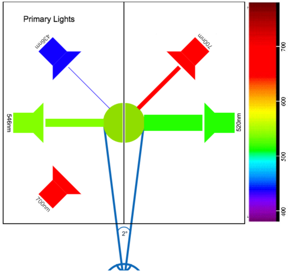
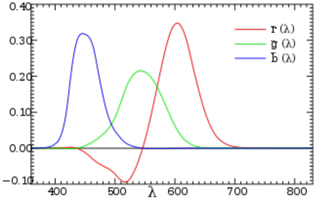

D65 Daylight
% Reflectance
S(λ)
D65
400
700 nm
Match
A Tungsten
Mismatch
S(λ)
A
400
700 nm
Metamerism Index
MI < 1

Color Matching

- International Commission on Illumination (CIE) standard definitions:
  - Blue (435.8 nm), Green (546.1 nm), Red (700 nm)
- Defined in 1931, it doesn't really match human perception. It is based on experimental data.

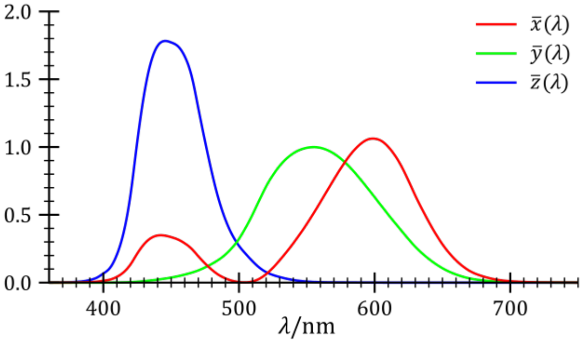






CIE XYZ System

- Hypothetical primary sources such that all the tristimulus values are positive
- $Y \equiv$luminance
- Convenient for colormetric calculations



Tristimulus Representation

- Tristimulus values: X, Y, Z
- Trichromatic coefficients:

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

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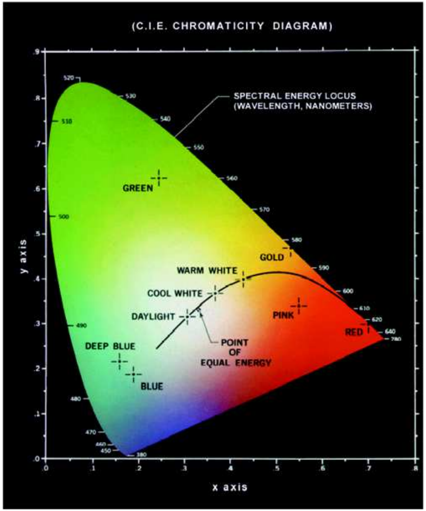
- Alternate approach: chromaticity diagram
  - Gives color composition as a function of x and y
  - Solve for z according to the above expression
  - Projects 3–D color space on to two dimensions

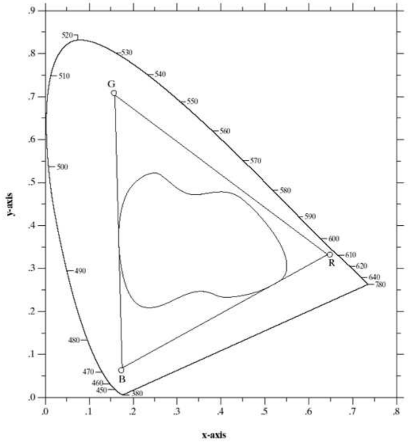
Chromaticity Diagram

- Pure colors are on the boundary
  - Fully saturated
- Interior points are mixtures
  - A line between two colors indicates all possible mixtures of two colors
- *Color gamut:* triangle defined by three colors
  - Three color mixtures are restricted to the gamut
  - No three-color gamut completely encloses the chromaticity diagram



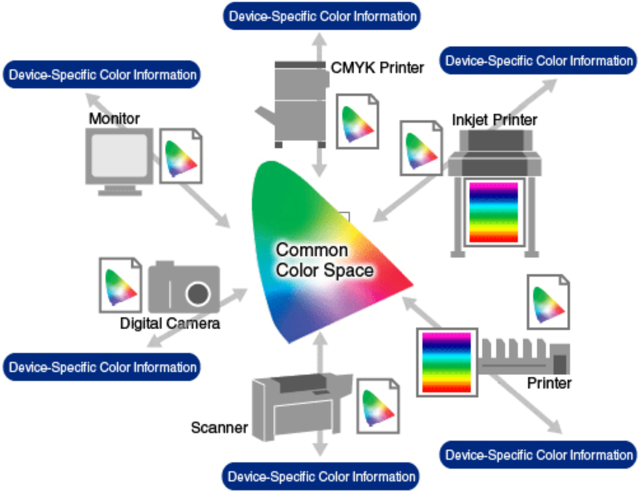
Color Gamut Examples

- RGB monitor color gamut
  - Regular (triangular) shape
  - Based on three highly controllable light primaries
- Printing device color gamut
  - Combination of additive and subtracted color mixing
  - Difficult control process
- Neither gamut includes all colors–monitor is better



Color Spaces

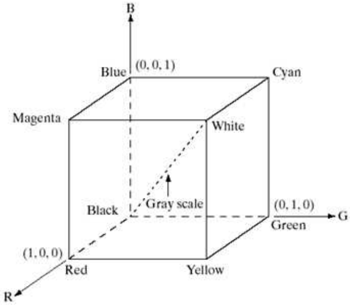
- Hardware-oriented
  - RGB (monitors and cameras)
  - CMY - CMYK (printers)
- Application-oriented
  - Perception-Based (HSI, HSL, HSV)
  - Adequate color spaces in which distances model color mismatches (Lab, Luv)

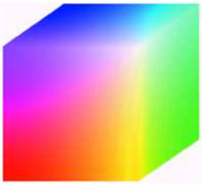


The RGB Color Model (Space)

RGB is the most widely used hardware-oriented color space

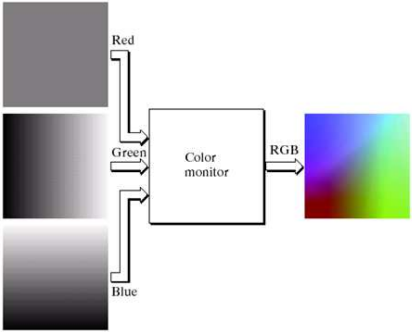
- Graphics boards, monitors, cameras, etc
- Normalized RGB values
- Grayscale is a diagonal line through the cube
- Quantization determines color depth
  - Full-color: 24 bit representations (16,77,216 colors)





RGB Color Image Generation

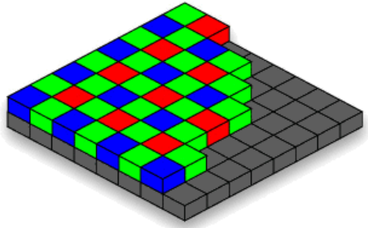
- Monochrome images represent each color component
- Hyperplane examples:
  - Fix one dimension
  - Example shows three hidden sides of the color cube

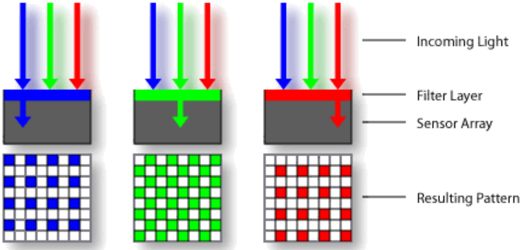


(R = 0) (G = 0) (B = 0)

RGB Color Image Generation

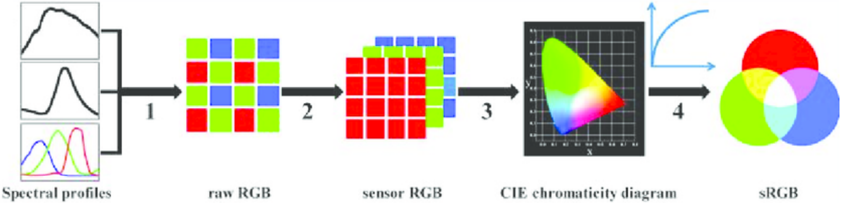
- Acquisition process: reverse operation
  - Filter light to obtain RGB components
- The data acquired by the sensor is in the color space of the camera.





Acquisition of Color Images

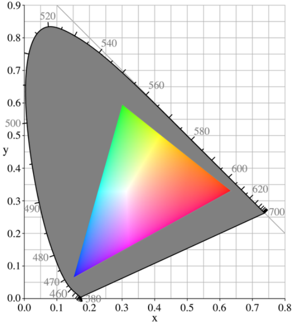
- Sensor color filter array data
- White Balance
- Demosaicking
- Color transformation to unrendered color space
- Color transformation to rendered color space



CIE XYZ Color Space to sRGB

Linear transformation given by

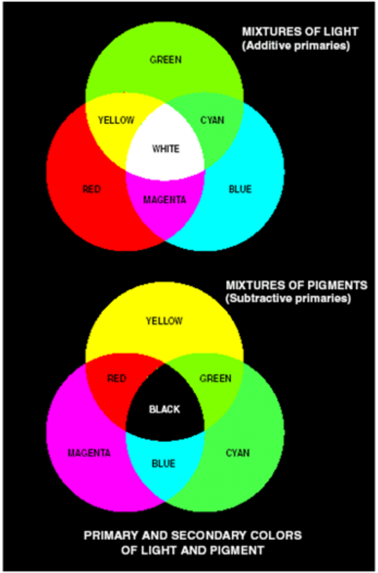
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$



The CMY and CMYK Color Spaces

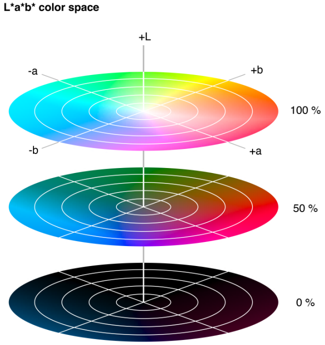
- CMY: cyan, magenta and yellow
- CMYK: adds black
  - Black is difficult (and costly) to reproduce with CMY
  - Four color printing
- Subtracted primaries are widely used in printing

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



Lab Color Space

- CIELAB is used extensively in imaging
- Transforms to and from CIELAB to other color spaces are commonly employed.
- L^* ≡brightness, a^* ≡red-green, b^* ≡yellow-blue



$L^*a^*b^*$ Color Space

$$L^* = 25\left(\frac{100Y}{Y_0}\right)^{1/3} - 16,\ 1 \leq 100Y \leq 100$$

$$a^* = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{X}{X_0}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

- X_0, Y_0, Z_0 tristimulus values of reference white

$L^*a^*b^*$ Color Space

- Radial distance serve as measure of perceived chroma.

$$C_{ab} = \sqrt{a^{*2} + b^{*2}}$$

- The angular position as perceived hue

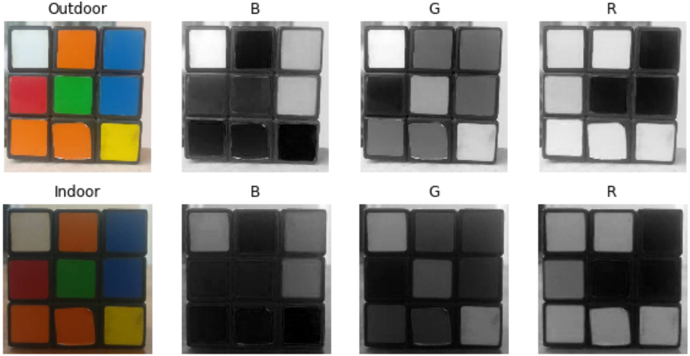
$$h_{ab} = \tan^{-1}\left(\frac{a^*}{b^*}\right)$$

- The perceived color difference is measured by the Euclidean distance

$$\Delta E_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

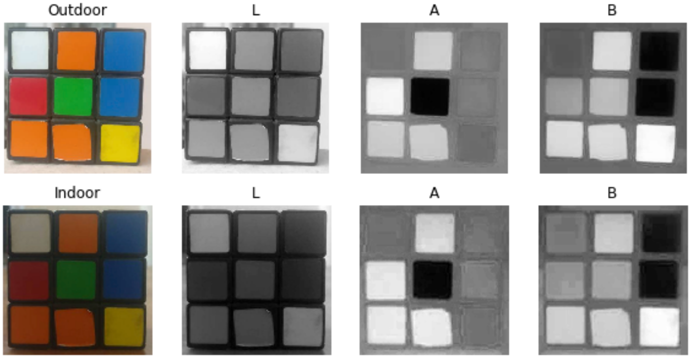
- A ΔE_{ab} value of around 2.3 correspond to a Just Noticeable Difference.

RGB vs $L^*a^*b^*$



- Significant perceptual non-uniformity
- Mixing of chrominance and luminance.

RGB vs $L^*a^*b^*$



- Perceptually uniform color space which approximates how we perceive color.
- Separates the luminance and chrominance components into different channels.
- Changes in illumination mostly affects the L component.

The HSI Color Space

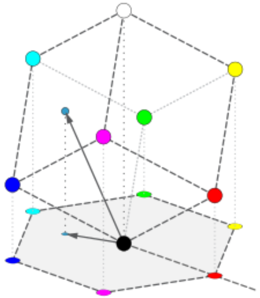
- Hue, saturation, intensity: human perceptual descriptions of color
- Decouples intensity (gray level) from hue and saturation

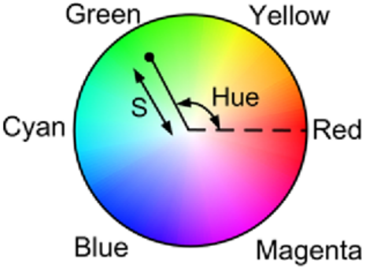
a b c

FIGURE 7.37 HSI components of the RGB color image in Fig. 7.36(a). (a) Hue. (b) Saturation. (c) Intensity.

The HSI Color Space

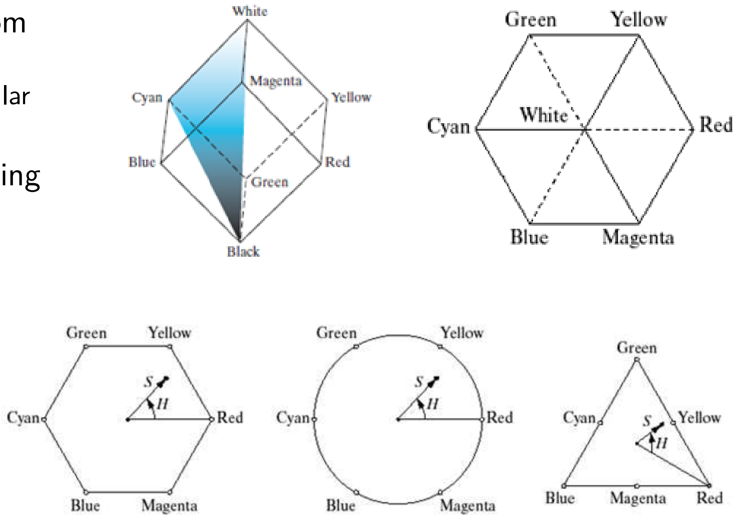
- Rotate RGB cube so intensity is the vertical axis
  - The intensity component of any color is its vertical component
  - Saturation: distance from vertical axis
    - Zero saturation: colors (gray values) on the vertical axis
    - Fully saturated: pure colors on the cube boundaries
  - Hue: primary color indicated as an angle of rotation



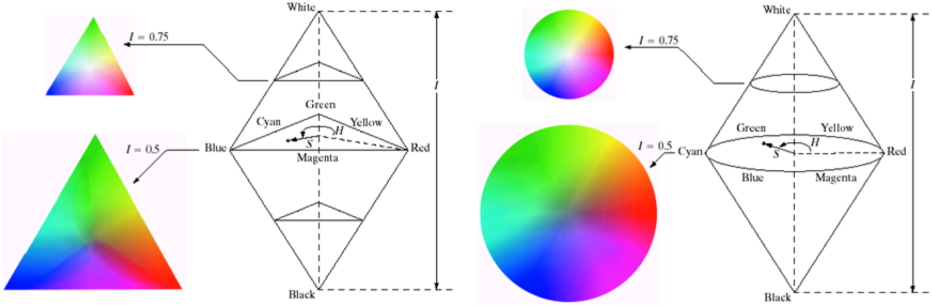


The HSI Color Space

- View the HSI space from top down
  - Slicing plane perpendicular to intensity
- Intensity: height of slicing plane
- Saturation: distance from center
- Hue: rotation angle from red
- Natural shape: hexagon



Common HSI representations



RGB to HSI Conversion

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

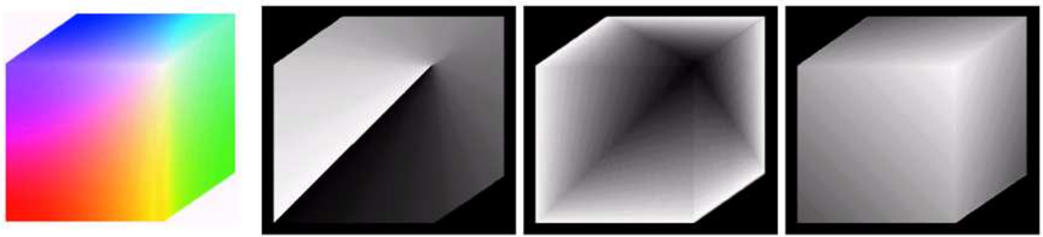
$$\theta = \cos^{-1}\left\{ \frac{[(R-G)+(R-B)]/2}{[(R-G)^2+(R-B)(G-B)]^{1/2}} \right\}$$

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

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

- Result for normalized (circular) representation
- Take care to note which HSI representation is being used
- HSI to RGB conversion depends on hue region

HSI Component Example



- HSI representation of the color cube
  - Normalized values represented as gray values
  - Only values on surface cube shown
- Explain:
  - Sharp transition in hue
  - Dark and light corners in saturation
  - Uniform intensity