# Color Fundamentals

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# Lecture Material

- Digital Image Processing Fourth Edition Rafael C. Gonzalez and Richard E. Woods

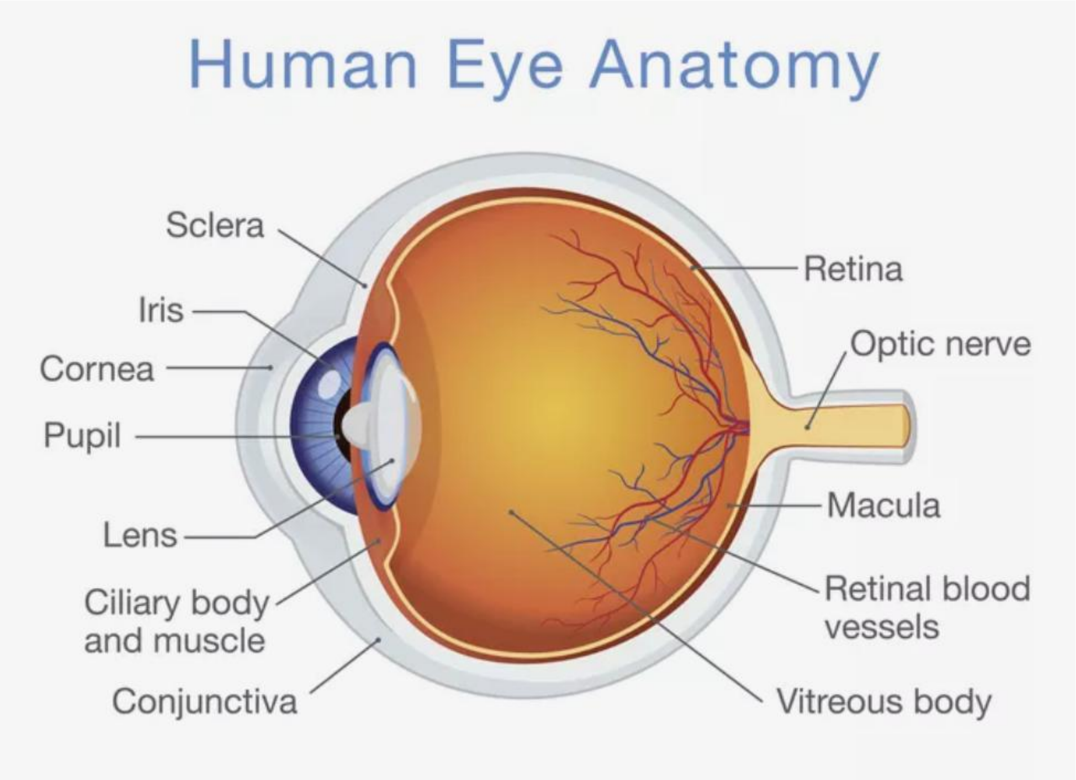
# Digital Image Processing & Human Vision

- Digital Image Processing is built on mathematics but often guided by human intuition and visual judgment.
- Understanding human visual perception is a key first step:
  - How images are formed and perceived by humans.
  - The limitations of human vision (resolution, adaptation to illumination).
  - Comparing human vision vs. electronic imaging devices:
- Helps design techniques aligned with what the human eye can perceive.

# The Human Eye and Vision

- The **eye** provides us with the **sense of sight**.
- It allows us to see and interpret:
  - **Shapes**
  - **Colors**
  - **Dimensions (size & depth)**
- Works by processing the **light reflected or emitted** from objects.
- The eye can detect **bright light** and **dim light**, but it **cannot see in the absence of light**.

# The Human Eye and Vision

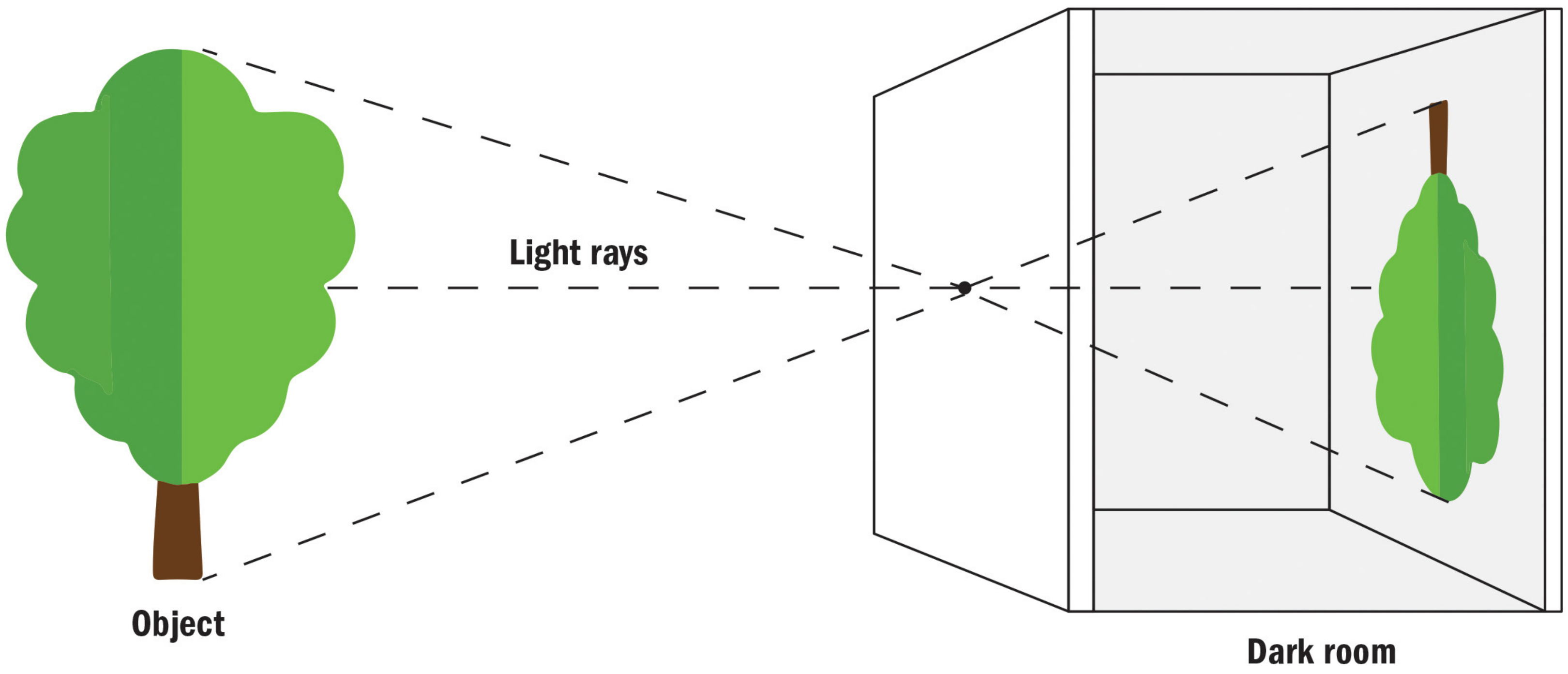



- **Light path**: Cornea → Iris → Lens → Retina
- **Pupil**: Adjustable opening in the iris; regulates light (like a camera aperture).
- **Iris**: Colored part; controls pupil size and amount of incoming light.
- **Lens**: Focuses light rays onto the retina.
- **Retina**: Lining at the back of the eye; contains photoreceptors that send signals to the brain.

# Photoreceptors in the Retina

- **Rods**
  - Very sensitive to low light (night vision).
  - Detect motion and intensity, but not color.
  - Example: At night, colors fade and objects look gray.
- **Cones**
  - Active in bright light (day vision).
  - Responsible for sharp details and color vision.
  - 3 types:
    - L-cones → Red
    - M-cones → Green
    - S-cones → Blue

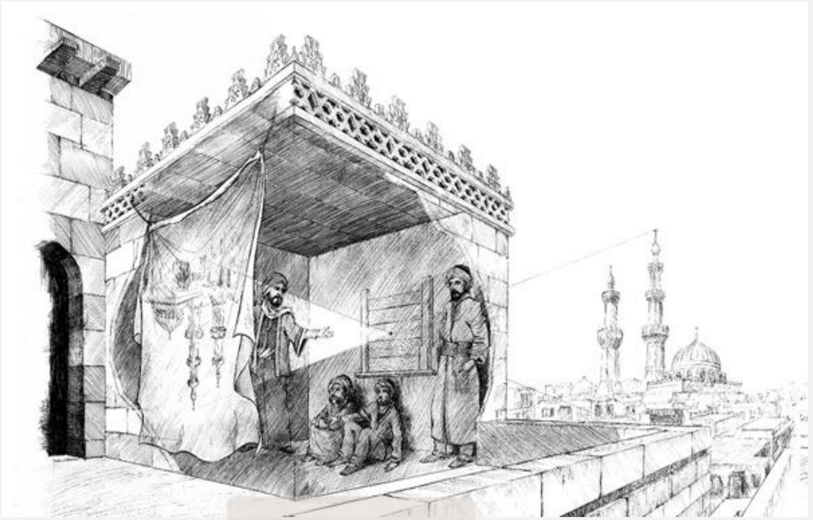
# Camera obscuras



# Camera obscura (pinhole camera)

- Camera Obscuras date back to **400 BC** (and possibly earlier).
- Light passes through a small hole → projects an **inverted image** inside a dark room.
- **Mozi** (China, 400 BC)
  - Light from an illuminated object passing through a pinhole
  - Creates an **upside-down image** inside a dark chamber.
- **Aristotle** (Greece, 4th Century BC)
  - Discovered a way to view **solar eclipses safely**.
  - Saw crescent-shaped sun projections on the ground through **gaps between tree leaves**
  - Realized that light creates images without direct eye contact with the sun.

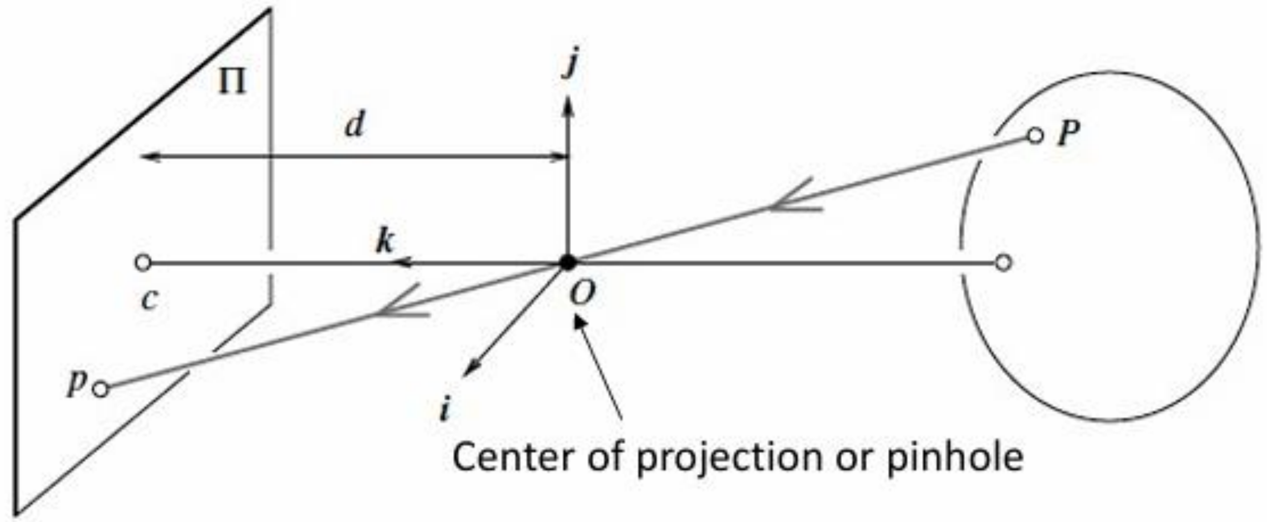
# Camera obscura (pinhole camera)



- **Ibn al-Haytham** (11th Century)
  - First to use a **viewing screen** to clearly see the inverted image.
  - The actual **inventor of the Camera Obscura**
  - Conducted **experiments with candles**
- **Leonardo da Vinci** (1502)
  - Suggested the eye works like a camera obscura
- **Giambattista della Porta** (1535–1615)
  - Improved design by adding a concave lens at the pinhole.
  - Produced clearer, sharper images.
- **Johannes Kepler** (1604)
  - First to use the term “Camera Obscura”.

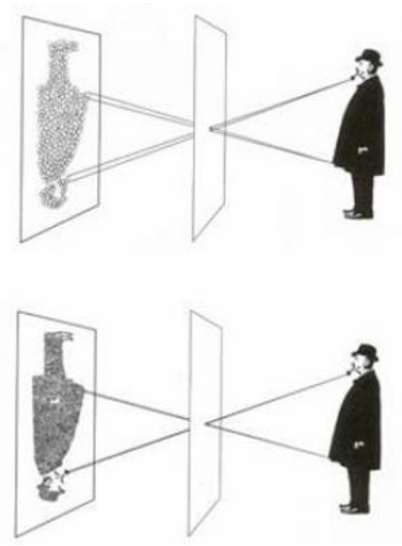
# Pinhole Camera Model

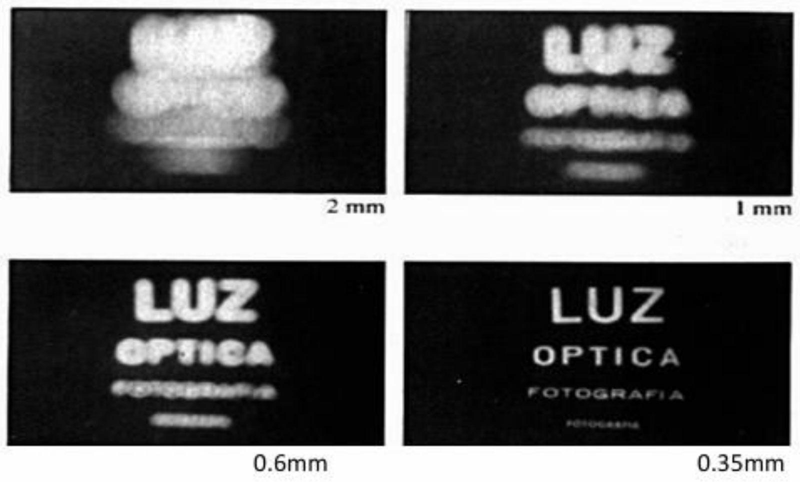
- **Light Rays:** Pass through the pinhole and form an inverted image on the image plane.
- **Focal Length (f):** Distance between the pinhole and the image plane.
- **Optical Axis:** A line perpendicular to the image plane (Π) that passes through the pinhole.
- **Image Center (c):** The point where the optical axis intersects the image plane.



# Effect of Pinhole Size

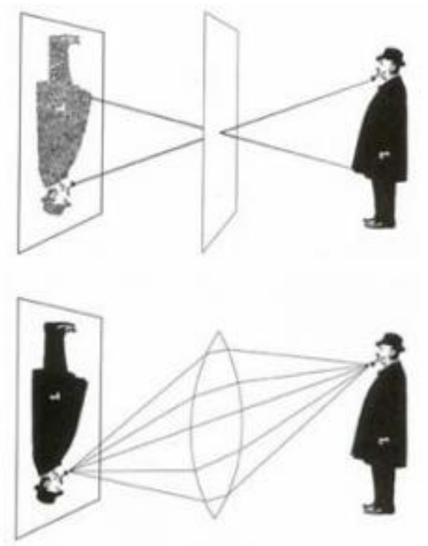
- **Large Aperture:**
  - Allows more light to enter.
  - Light rays spread out → image becomes blurry (not well focused).
- **Small Aperture:**
  - Allows less light to enter.
  - Reduces blurring → image appears sharper, but dimmer.

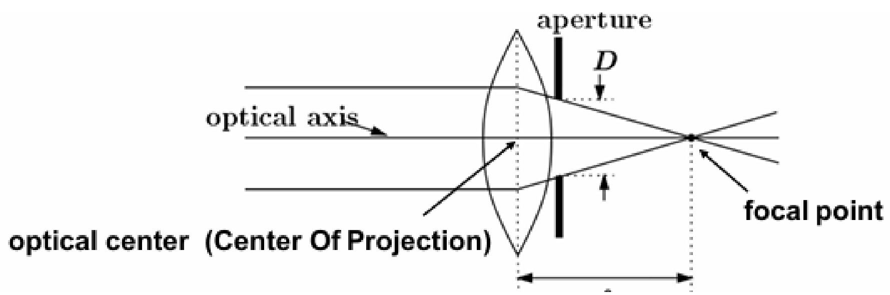




# From Pinhole to Lens

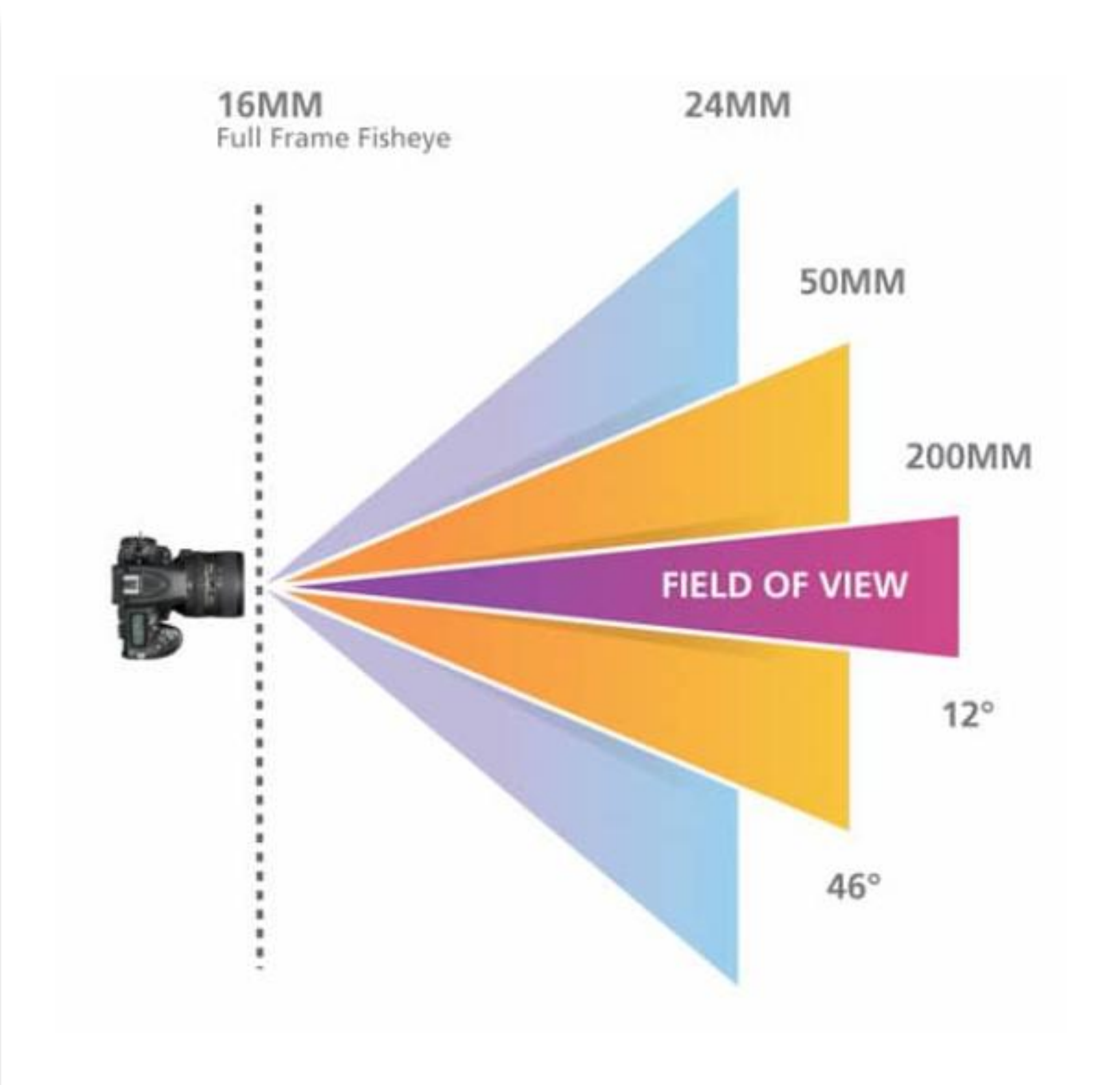
- A **lens** replaces the pinhole.
- Lenses **improve image quality** → sharper and brighter images.
- **Focal Point (F):**
  - Point where parallel rays (to the optical axis) converge.
  - Located at a distance **f** from the lens.



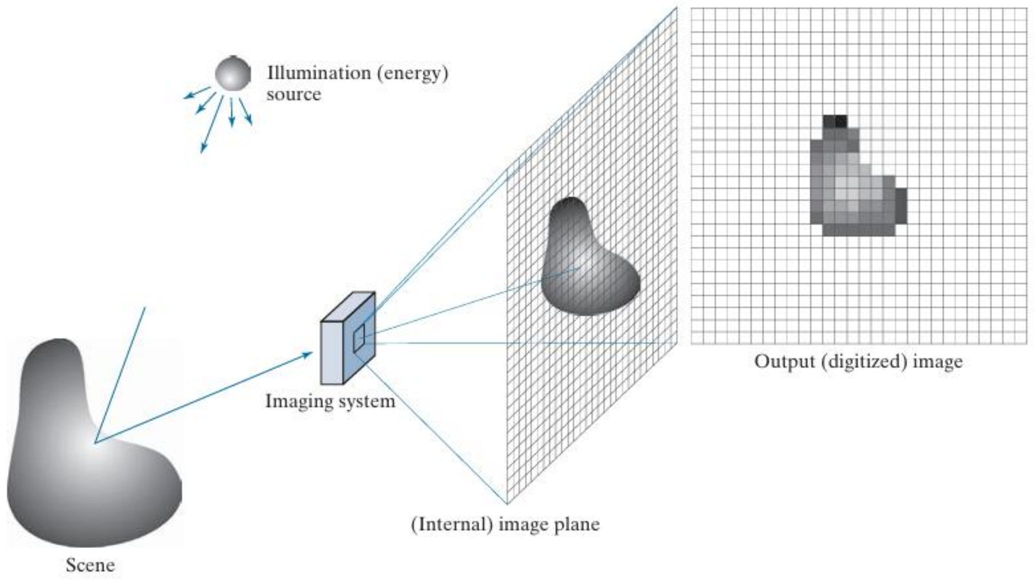


# Field of View

- The portion of scene space that actually projects onto the retina of the camera.
- Focal Length (f):
  - Distance from the lens to the image plane/sensor.
    - Small f → wide field of view.
    - Large f → narrow field of view.



# Image Acquisition using Sensor Arrays




- The **sensor** is a **2D grid of pixels**.
- Each **pixel** is a **light-sensitive element**.
- A pixel measures the **intensity of light** falling on it.
- Pixels **convert light into electrical signals**.
- Camera circuitry **translates signals into digital numbers**.
- All pixel values together form the **digital image**.

# Simple Image Formation Model

- An image is represented as a function:

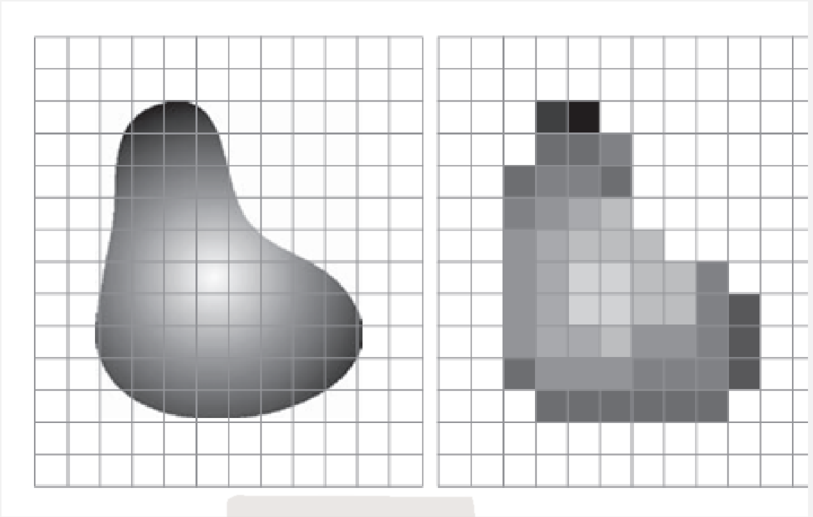
$$f(x, y) = i(x, y)r(x, y)$$

- **Illumination i(x,y):**
  - Amount of light falling on the scene.
  - Depends on the light source (sun, lamp, etc.).
- **Reflectance r(x,y) :**
  - Proportion of light reflected by the surface.
  - Depends on material properties (white paper vs. black cloth).
- Example:
  - Bright light + white surface → high intensity (bright pixel).
  - Low light + white surface → medium intensity (gray pixel).
  - Bright light + black surface → low intensity (dark pixel).

# Image Sampling And Quantization

- Generate digital images from sensed data.
- **Sensor Output:**
  - Continuous voltage waveform.
  - Amplitude & spatial behavior depend on physical phenomenon being sensed.
- **To create a digital image,** Continuous data must be converted to digital format.
- **Two key processes:**
  - **Sampling** → Discretize spatial coordinates (x, y).
  - **Quantization** → Discretize amplitude (intensity values).

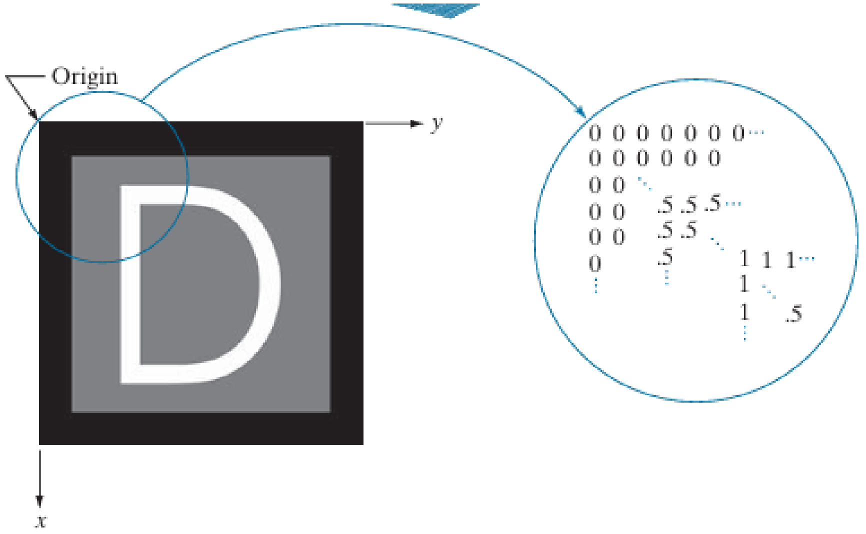
# Image Sampling And Quantization



- **Sampling**
  - Number of sensors determines **sampling in both horizontal and vertical directions**.
  - Sampling provides **discrete spatial locations**, but **intensity remains continuous**.
- **Quantization**
  - Converts each sensor's continuous intensity value into a **digital value**.
  - **Intensity scale** is divided into **discrete levels**.
  - Example:
    - **8 levels** from black → white.
    - Each level has a **specific digital value**.
    - Each sample is assigned to the **nearest level**.
- Quality depends on **number of sensors and number of intensity levels**.

# Representing Digital Images

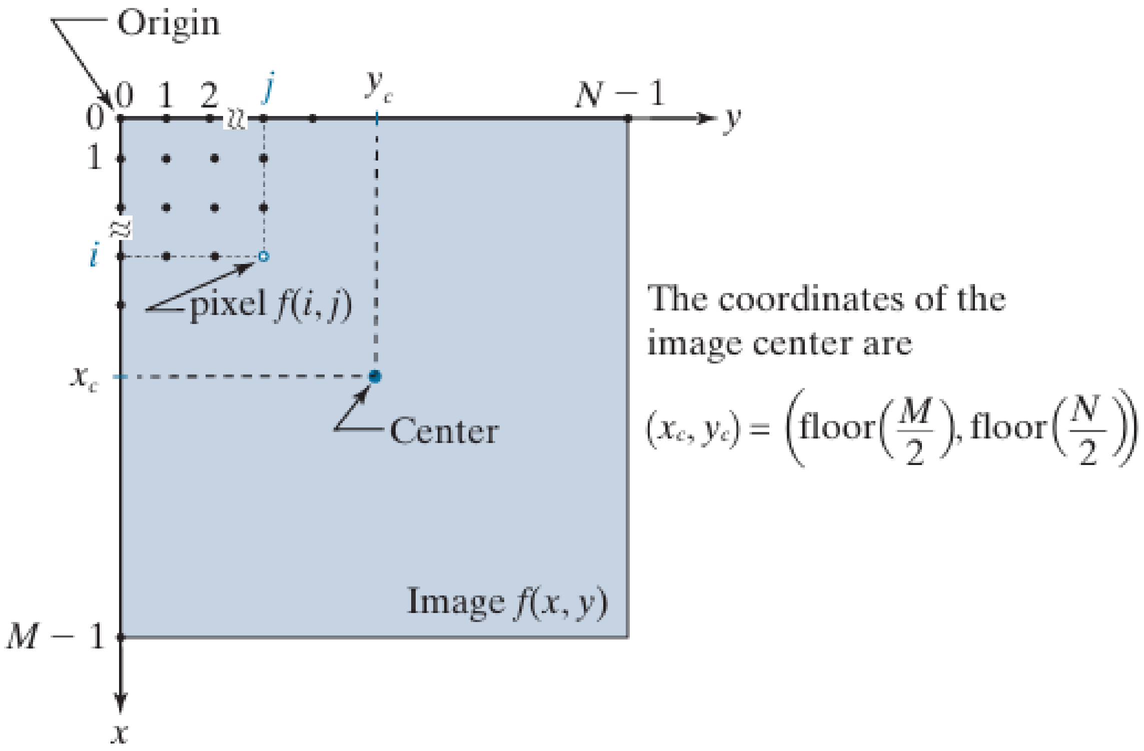
- Converting a continuous image into a digital form
- Digital image obtained via:
  - **Sampling** → discrete spatial locations
  - **Quantization** → convert intensity to discrete values
  - Digital image $f(x,y)$ with: $M$ rows and $N$ columns
  - **Top-left corner:** f(0,0)




$$f(x,y) = \begin{bmatrix} f(0,0) & f(0,1) & \cdots & f(0,N-1) \\ f(1,0) & f(1,1) & \cdots & f(1,N-1) \\ \vdots & \vdots & & \vdots \\ f(M-1,0) & f(M-1,1) & \cdots & f(M-1,N-1) \end{bmatrix}$$

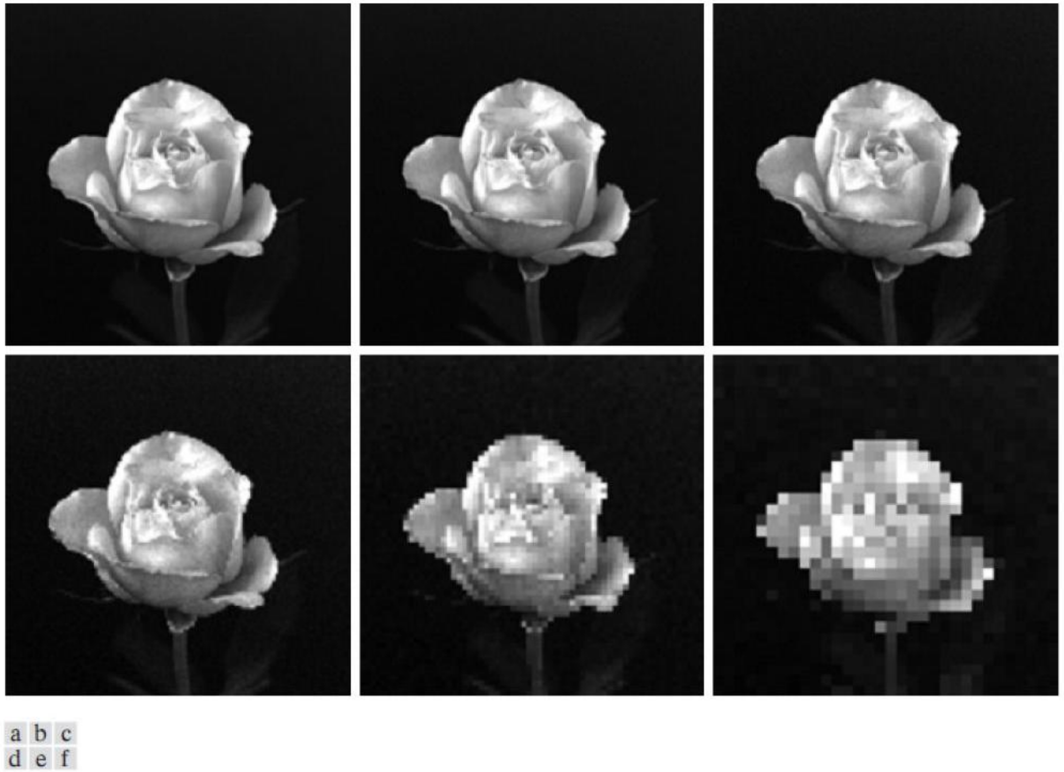
# Representing Digital Images

- The origin (0,0) is defined at the top-left corner.
- Digital images are stored as **2D matrices.**
- Center coordinates found by:
  - center=([M/2],[N/2])



# Spatial Resolution

- Each pixel records a **small portion of the scene.**
- More pixels → can distinguish **smaller details** → higher spatial resolution.
- Same lens and same distance:
    - 20 Megapixel Camera → more pixels covering the same scene → finer details visible
    - 8 Megapixel Camera → fewer pixels → less detailed image



# Intensity Resolution (Depth)

- **Intensity resolution** = smallest discernible change in **intensity/brightness**.
- Determines **how finely we can distinguish shades or brightness levels** in an image.
- Typically, an integer power of 2:
  - 8 bits → 256 levels ($2^8$) → most common

# Why Use Color?

There is a rabbit in this image.

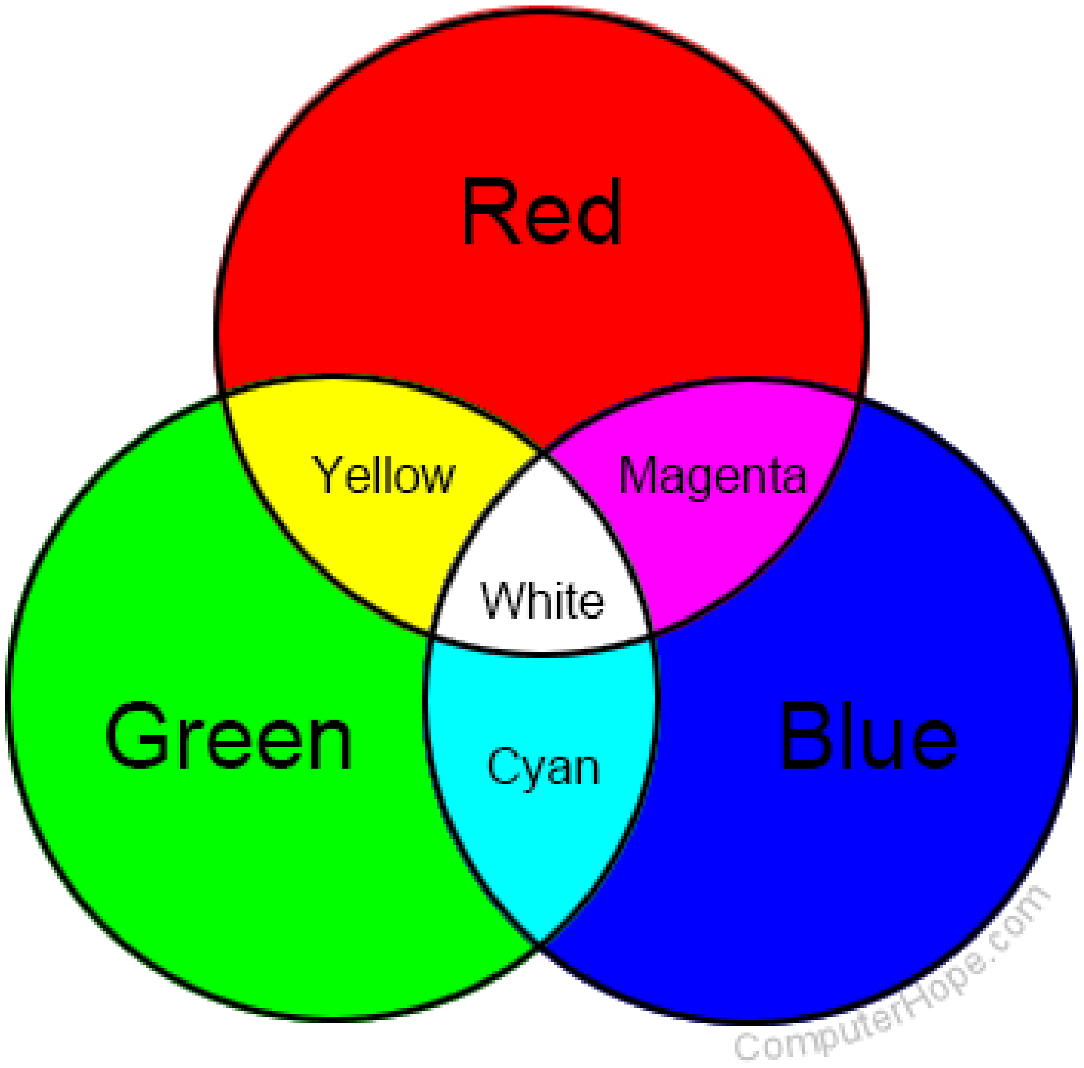
- Powerful descriptor → simplifies object identification and extraction.
- Human visual perception → can distinguish thousands of colors, vs ~24 shades of gray

# Cones and Color Vision in the Human Eye

- Cones are sensors in the eye responsible for color vision.
- Cones are divided into three main types:
  - Red-sensitive cones → ~65%
  - Green-sensitive cones → ~33%
  - Blue-sensitive cones → ~2%
- Human eye perceives **colors as combinations of the primary colors**: Red (R), Green (G), Blue (B)

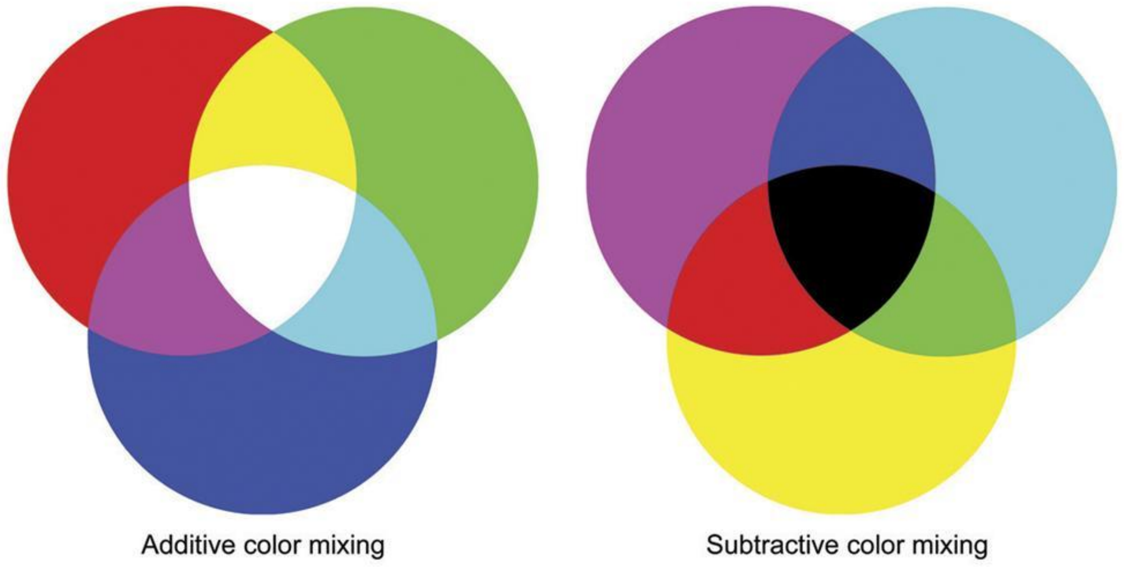
# Primary and Secondary Colors of Light

- **Primary Colors:** Red (R), Green (G), Blue (B)
- Mixing all three primary colors in the correct intensities → **White**
- **Secondary Colors:** Produced by **adding two primary colors:**
    - Magenta (Red + Blue)
    - Cyan (Green + Blue)
    - Yellow (Red + Green)
- Mixing a secondary color with its opposite primary color → **White**
- Pure Green → R=0, G=255, B=0



# Primary Colors of Light vs Primary Colors of Pigments

- Light colors (RGB) are **additive** → mixing produces **white**
- Pigment colors (CMY) are **subtractive** → mixing absorbs light and can produce **black**



# Primary pigment colors

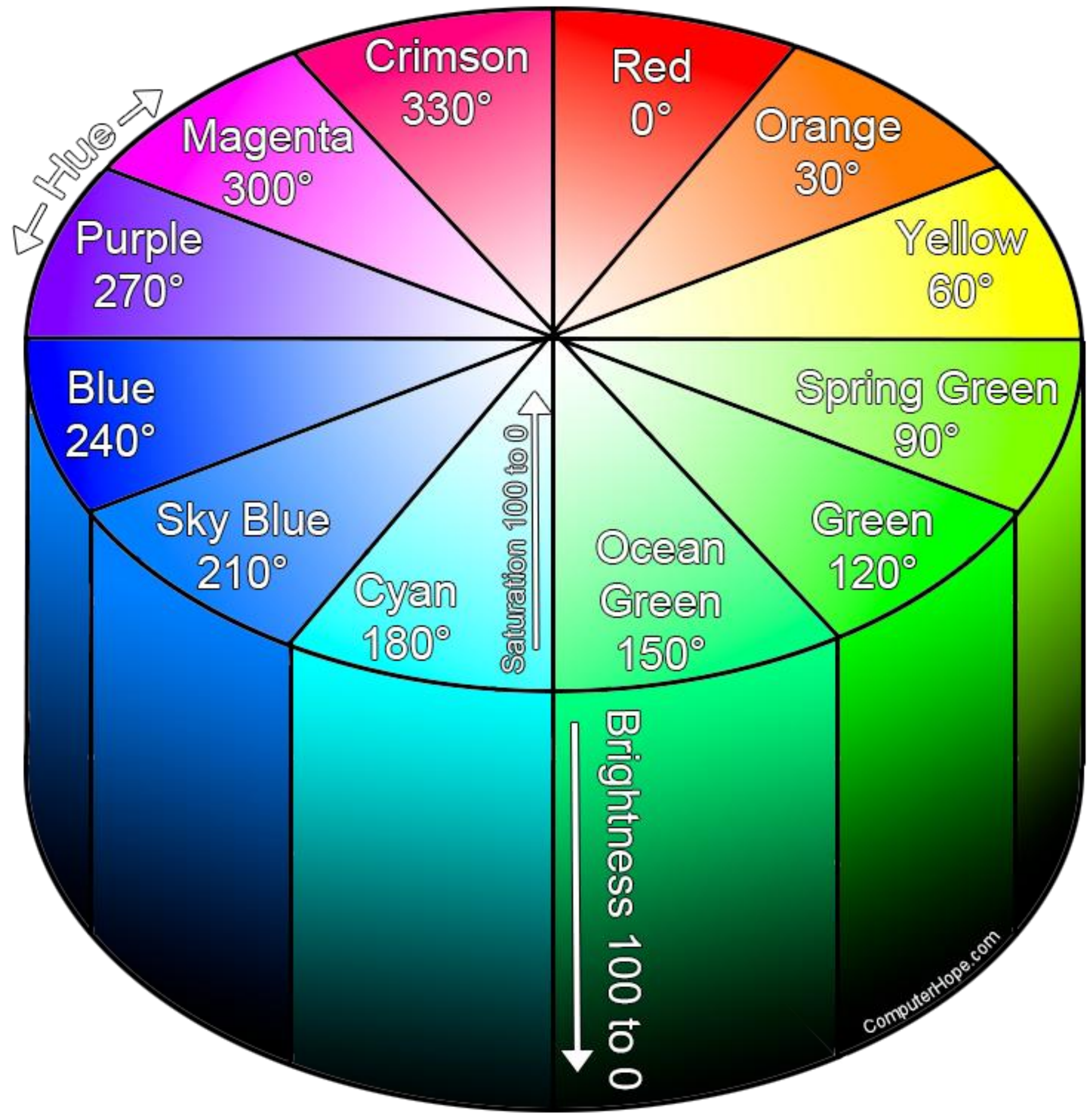
- A primary pigment **absorbs (subtracts) one primary color of light** and reflects or transmits the other two colors
- **Primary pigment colors**:
  - Cyan (absorbs Red, reflects Green + Blue)
  - Magenta (absorbs Green, reflects Red + Blue)
  - Yellow (absorbs Blue, reflects Red + Green)

# Secondary Colors of Pigments

- Produced by mixing **two primary pigments**:
  - **Red** ← Magenta + Yellow
  - **Green** ← Cyan + Yellow
  - **Blue** ← Cyan + Magenta
- Mixing all three primary pigments (Cyan, Magenta, Yellow) → Black
- Or mixing **a secondary pigment with its opposite primary → Black**

# Main Characteristics of Colors

- All colors can be defined using Hue, Saturation, and Brightness (HSB), an alternative to RGB, describing a color's type, intensity, and brightness
  - Brightness
  - Hue
  - Saturation



# Brightness

- **Brightness (Lightness / Luminance)**
  - Represents intensity (lightness or darkness)
  - Measures how light or dark a color appears.
  - Adjusting brightness does not change the hue, only how light or dark it looks.

# Hue

- Defined by the **dominant wavelength** of light
- Determines the **perceived color** (e.g., red, orange, yellow)
- When we say, “the object is red,” we are describing its hue
- Represented on a 360° color wheel:
  - 0° = Red
  - 120° = Green
  - 240° = Blue
  - 360° = Red (loop)


# Saturation

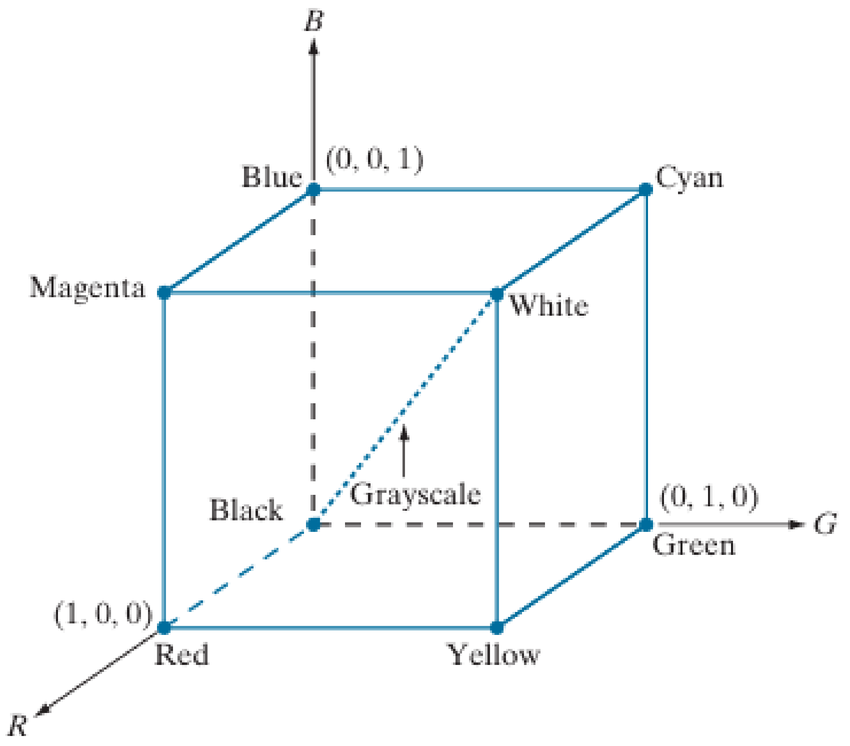
- Refers to the **purity of a color**
- Pure spectrum colors → **fully saturated**
- Adding white light → **reduces saturation**
- Example:
  - Pure Purple → Saturated
  - lavender (Purple + White) → Less Saturated

# Color Models (Color Spaces / Color Systems)

- Provide a **standard way** to specify colors
- Allow communication of colors using **numbers**, not just names
- Hardware-Oriented Models or Application-Oriented Models
- Examples of Color Models:
  - **RGB Model**
  - **CMY/CMYK model**
  - **HSV Model**

# RGB Color Model

- Colors are represented by **3 primary components**:
  - R = Red, G = Green, B = Blue
  - Each color = a combination of R, G, and B
- RGB is represented in a 3D cube
- Each color = a **point** inside or on the cube



# RGB Image Representation

- In digital images, we specify the levels of R, G and B with 8-bit integers
- RGB color pixel is a triplet of values (R, G, B)
- Each RGB color pixel has a depth of 24 bits.

# CMY and CMYK Color Models

- **CMY = Cyan, Magenta, Yellow**
  - Secondary colors of **light (RGB)**
  - Primary colors of **pigments/printing**
- Each pigment **removes** one primary color of light
  - **Cyan pigment** absorbs **Red**, reflects (Green + Blue = Cyan)
  - **Magenta pigment** absorbs **Green**, reflects (Red + Blue = Magenta)
  - **Yellow pigment** absorbs **Blue**, reflects (Red + Green = Yellow)

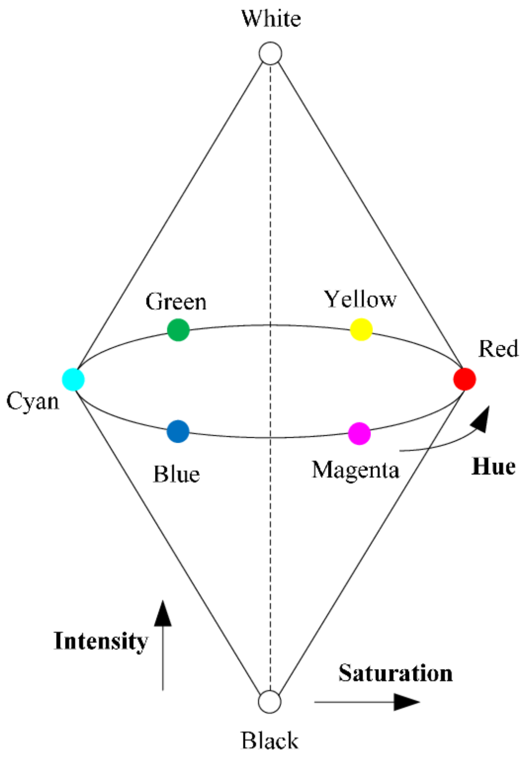
**RGB to CMY conversion**

$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1.00 \\ 1.00 \\ 1.00 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

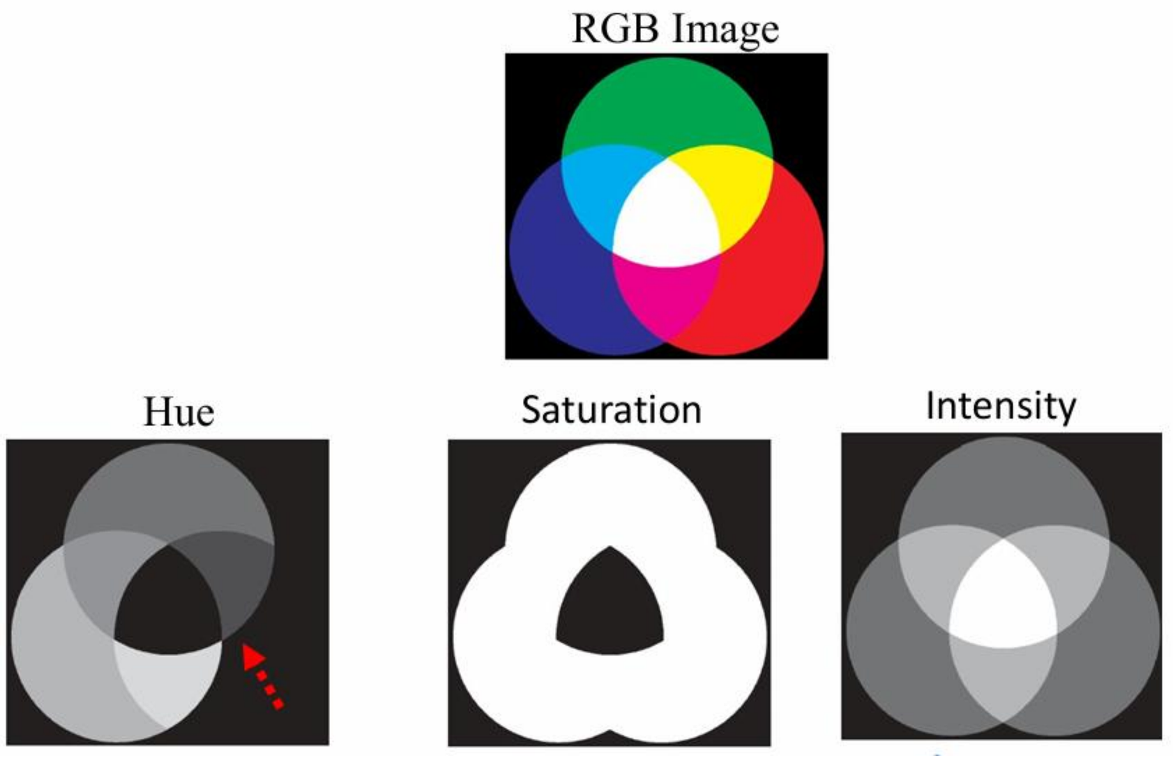
R, G, B values are normalized to [0 1]

# HSI Color Model

- RGB and CMYK is not practical for human interpretation.
- **HSI = Hue + Saturation + Intensity**
  - **Hue**: the actual color (red, blue, green...)
  - **Saturation**: purity of the color (dull ↔ vivid)
  - **Intensity**: brightness/lightness (dark ↔ bright)



# HSI Component Images




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

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

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

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

# Thank You