# Digital Image Processing

## Lesson 2: Human Perception & Image Representations

**Master Course**

**Fall Semester 2023**

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# Outline

- Human Visual System
  - Visible Light
  - Anatomy of the eye
  - Brightness Perception
  - Color Perception
  - Color Models
- Digital Image representation
  - Digital Image
  - Sampling and quantization
  - Image representation
  - Raster organization
  - Color models

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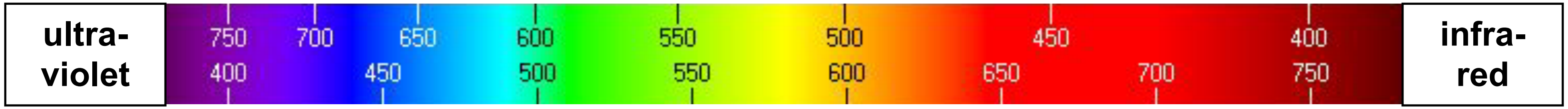
# Visible Light

- Visible light consists of electromagnetic energy having
  - Wavelengths in the range 380 (violet) to 780 nm (red)
  - Frequencies in the range 380 THz (red) to 780 THz (violet)

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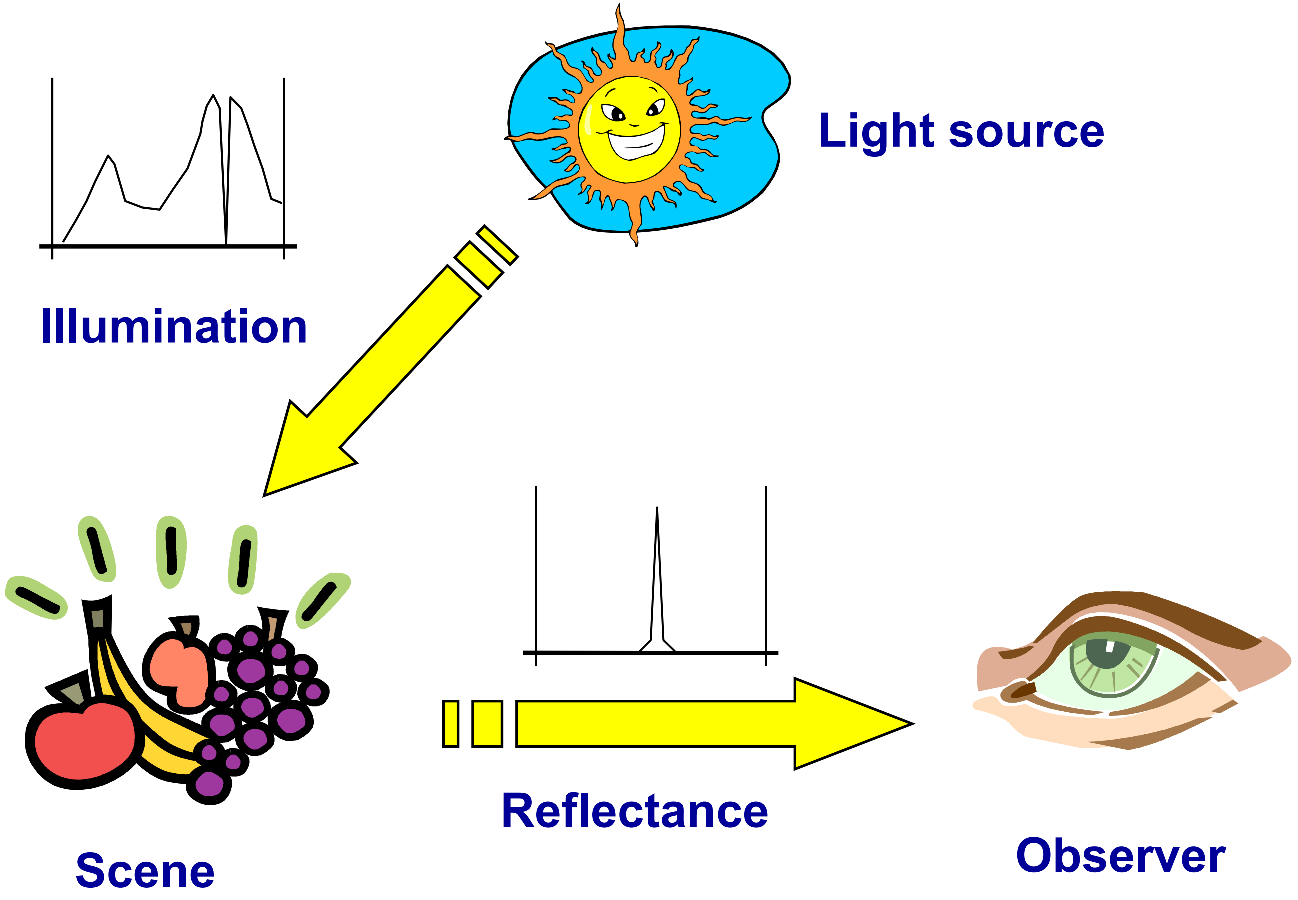
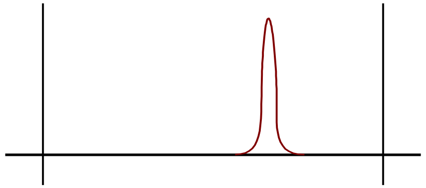
# Origin of Color Perception

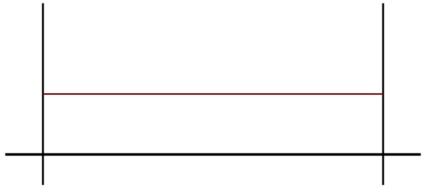


# Light Spectrum

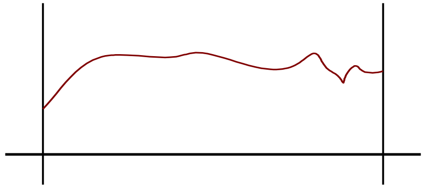
- Light is characterized by its spectral composition
  - Monochromatic light : all the power is concentrated on a single wavelength



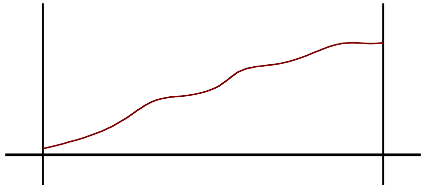
  - Equienergetic light : the energy is uniformly distributed over the spectrum



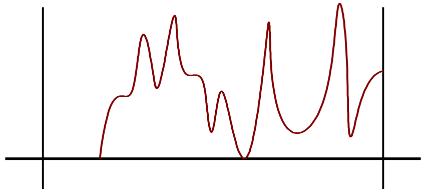
  - Day light



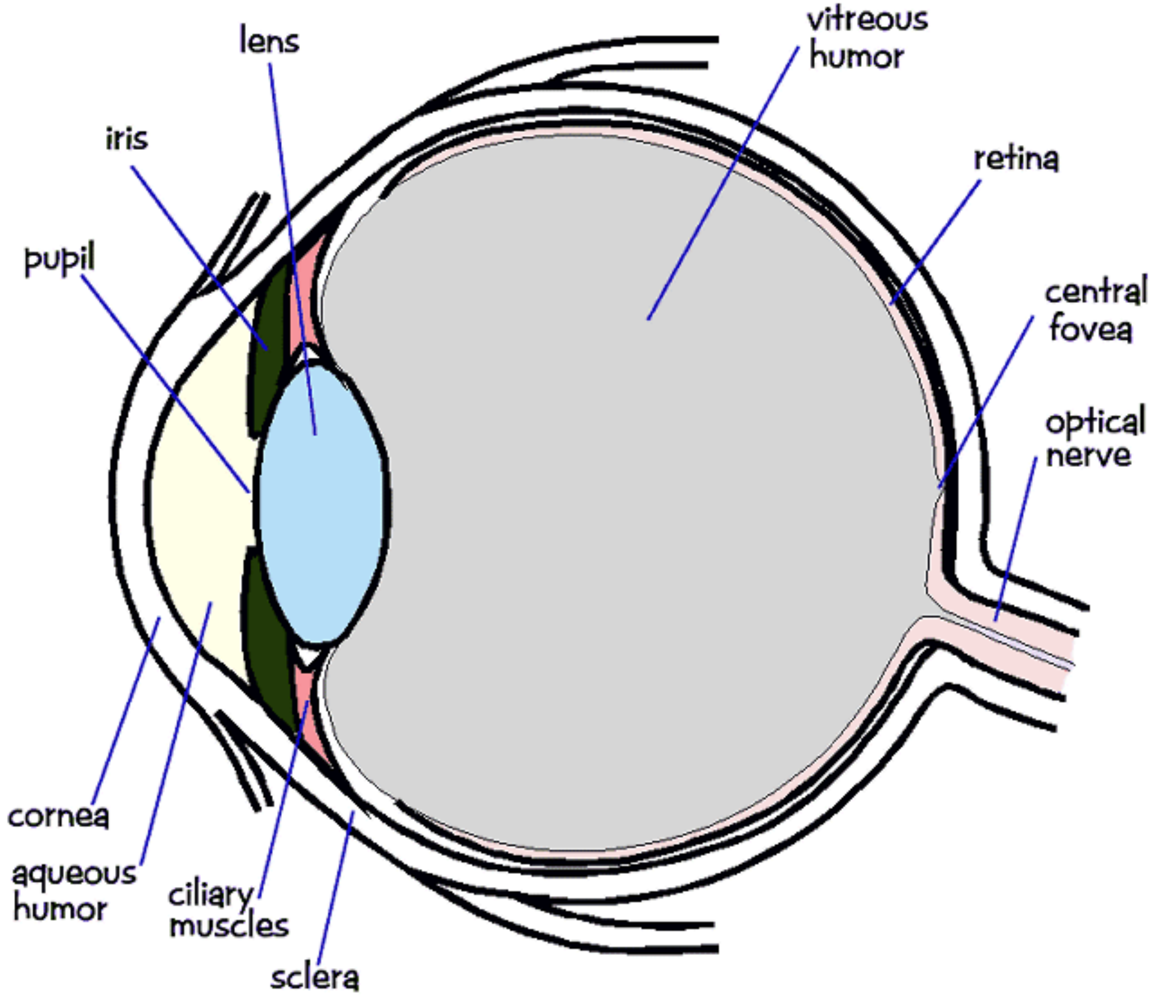
  - Artificial light (for instance tungsten filament)



  - Reflected light



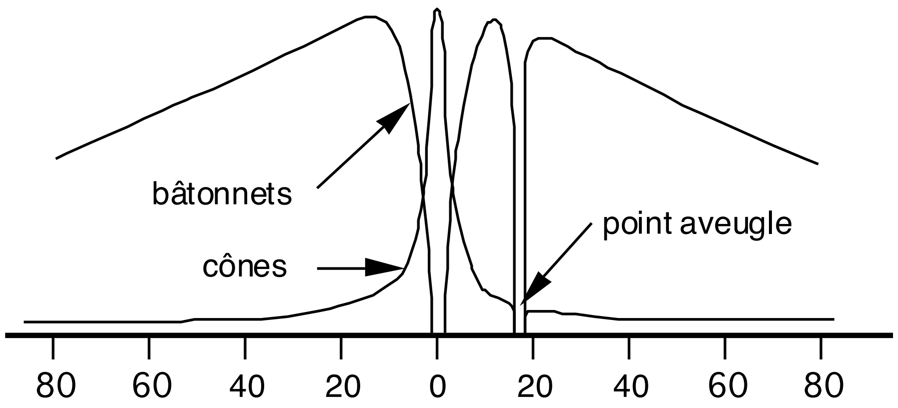
# Eye Anatomy

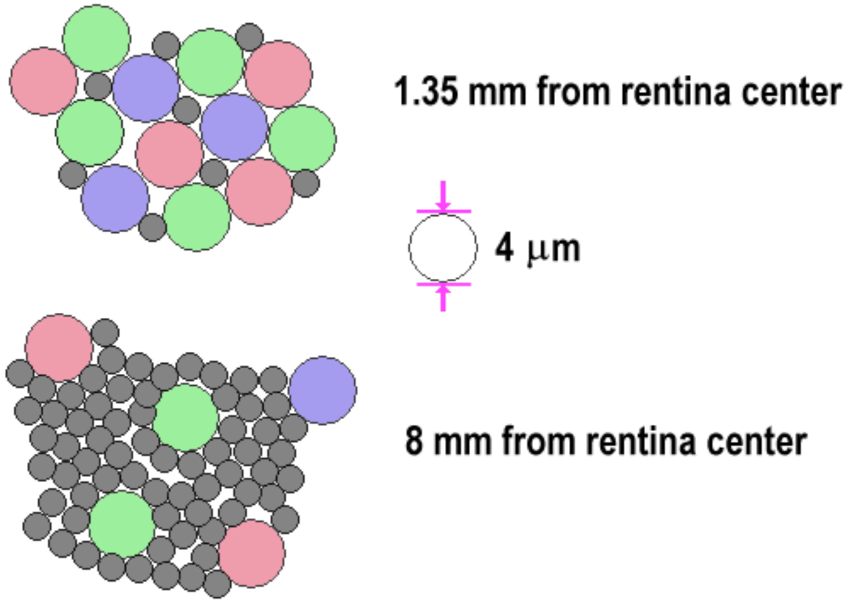



source: http://graphics.lcs.mit.edu/classes/6.837/F98/Lecture4/

# Composition of the Retina

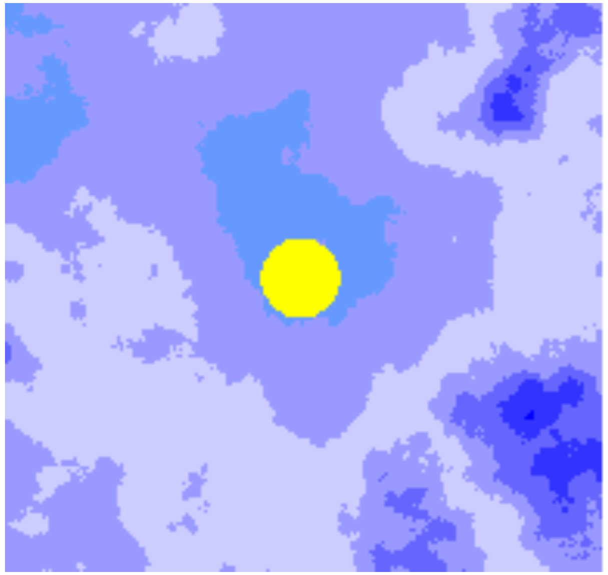
- The **retina** is composed of two types of cells:
  - 150 millions of **rods**, which are sensitive to brightness
  - 7 millions of **cones**, which are responsible for color perception
- The **fovea** is a region densely packed with cones




- The **blind spot** has no rods nor cones

# Blind Spot Experiment



1 2 3 4 5 6

source: http://www.yorku.ca/eye/blndspo1.htm

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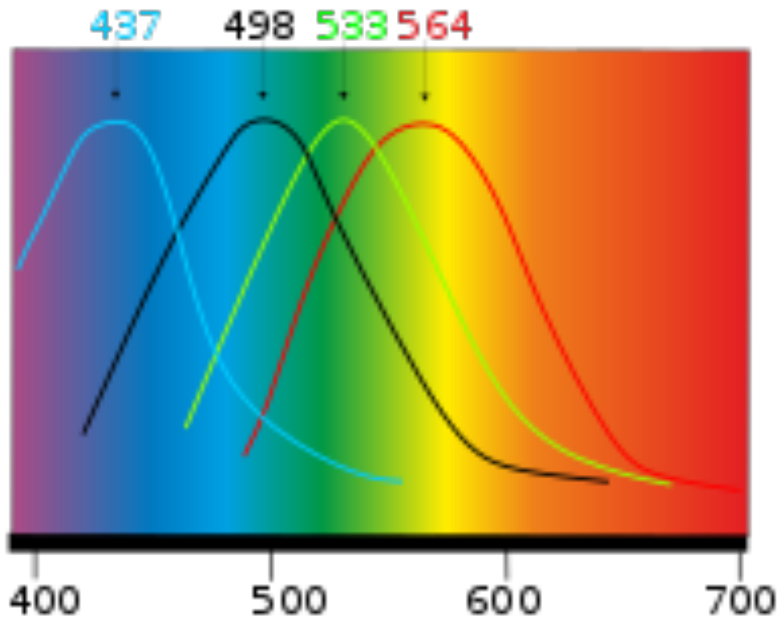
# Human Visual System

- Human vision has two complementary vision mechanisms
  - **Scotopic vision**:
    - Provided by the rods
    - Low levels of illumination
    - Monochromatic
    - Low acuity
  - **Photopic vision**:
    - Provided by the cones
    - High level of illumination
    - Color sensitive
    - High acuity
      (but chromatic aberration!)

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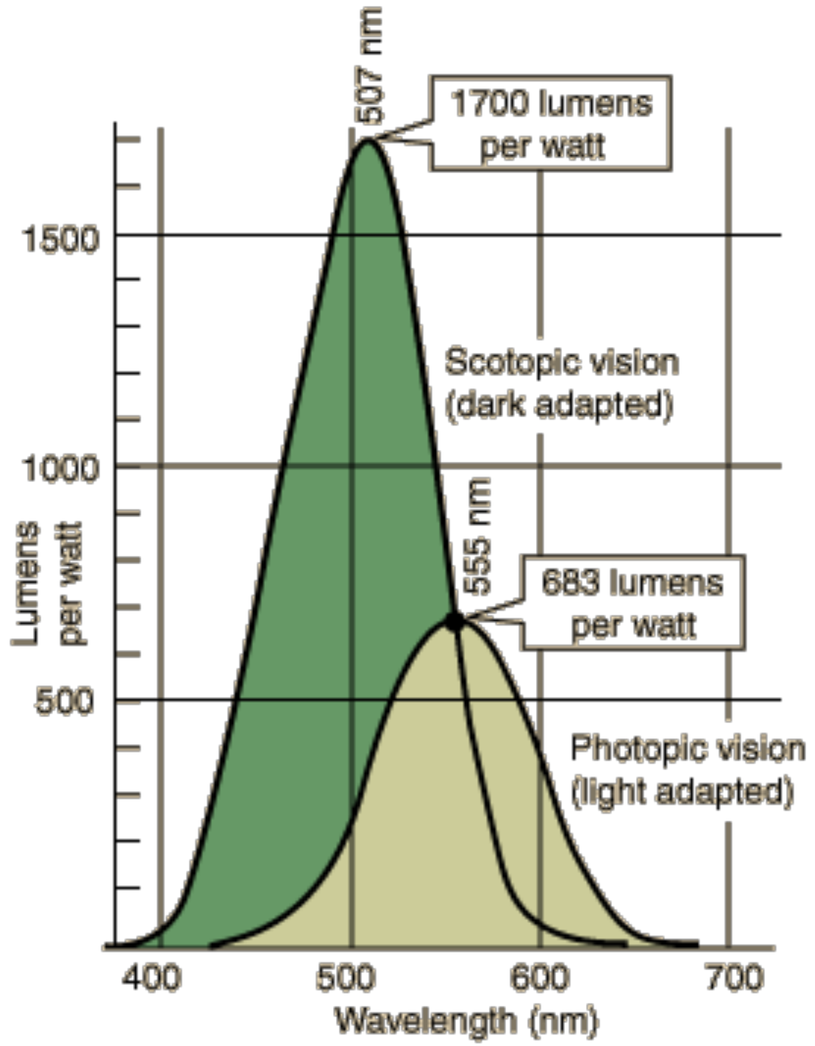
# Mesopic Vision

- The combination of
  - Photopic vision
  - Scotopic vision

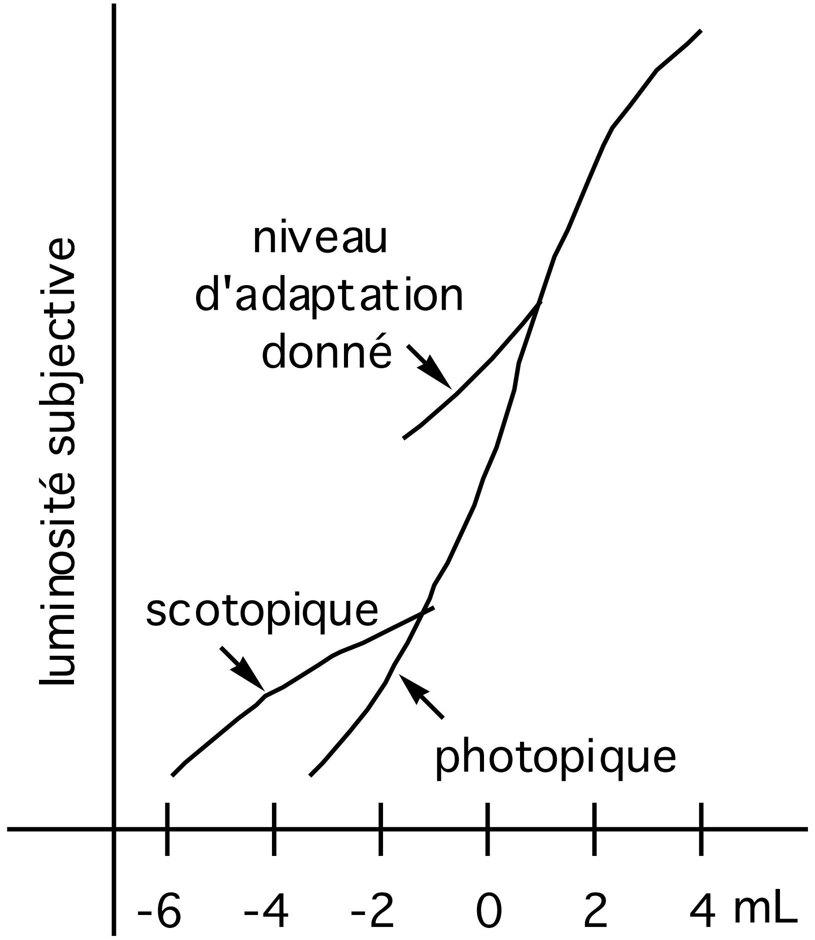
  is called **mesopic vision**



# Brightness Perception

- The **sensitivity** of the human visual system covers a wide range of light intensity
  - The global range is about $10^{10}$ !
  - The range for photopic vision it is about $10^{6}$

- For a given **brightness adaptation**, the range of intensity levels that can be discriminate simultaneously is between $10^{2}$ and $10^{3}$

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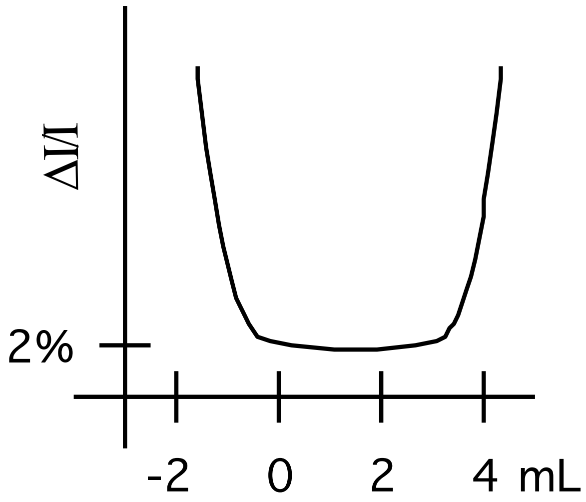
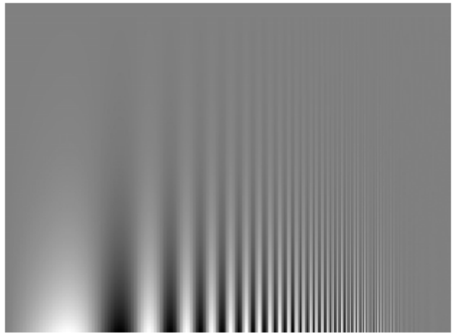
# Brightness Discrimination

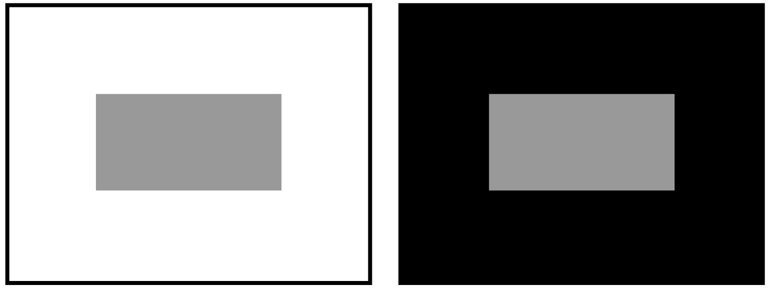
- The just-noticeable difference between intensity levels is nearly constant at about 2 percent over a very wide range of brightness levels

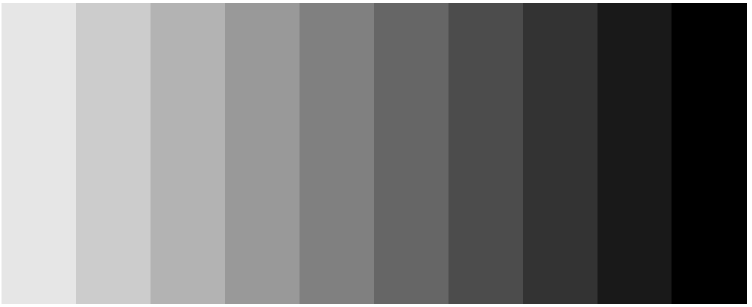


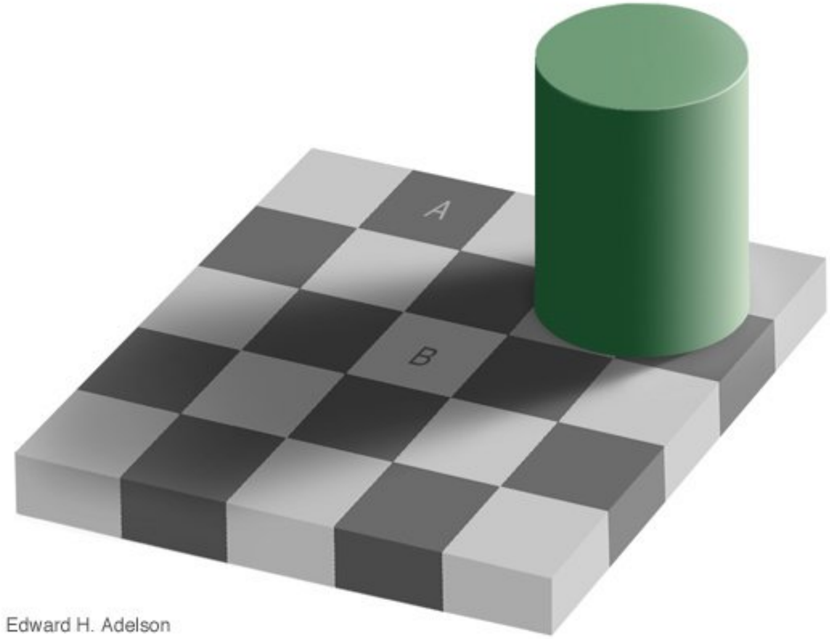

- Intensity discrimination depend on context
  - Brightness discrimination vs. frequencies



# Brightness Illusions

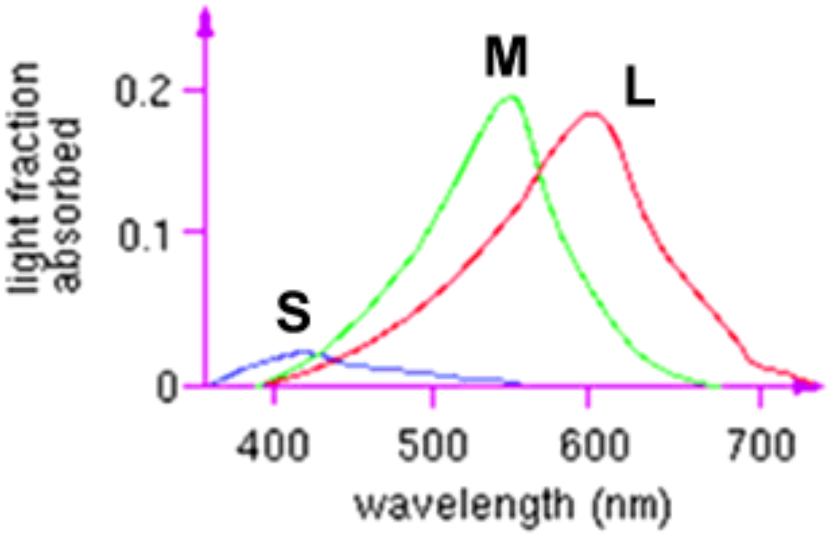







# Color Perception

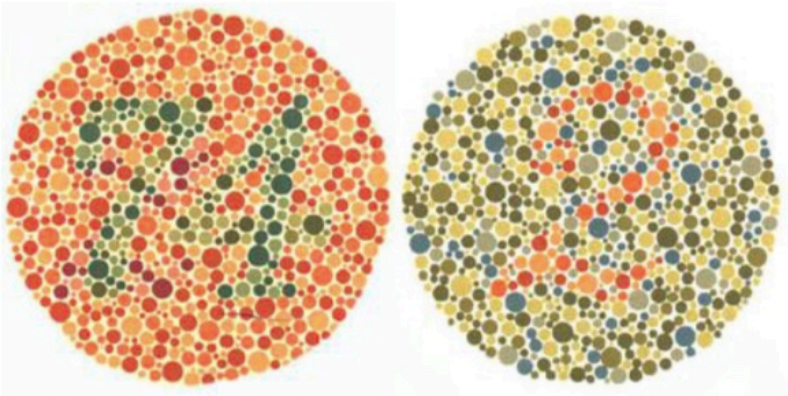
- Color perception of human beings results from the simultaneous stimulation of the three types of cones (trichromy)
- Different spectra can result in a perceptually identical sensations
- Perception of color is also affected by surround effects and adaptation




- Lights at 430, 560, and 610 nm are respectively violet, blue-green, and yellow-green (not blue, green, and red)

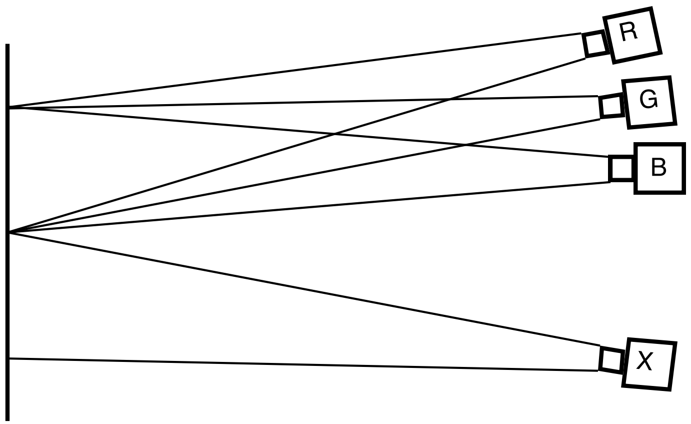
# Color Blindness

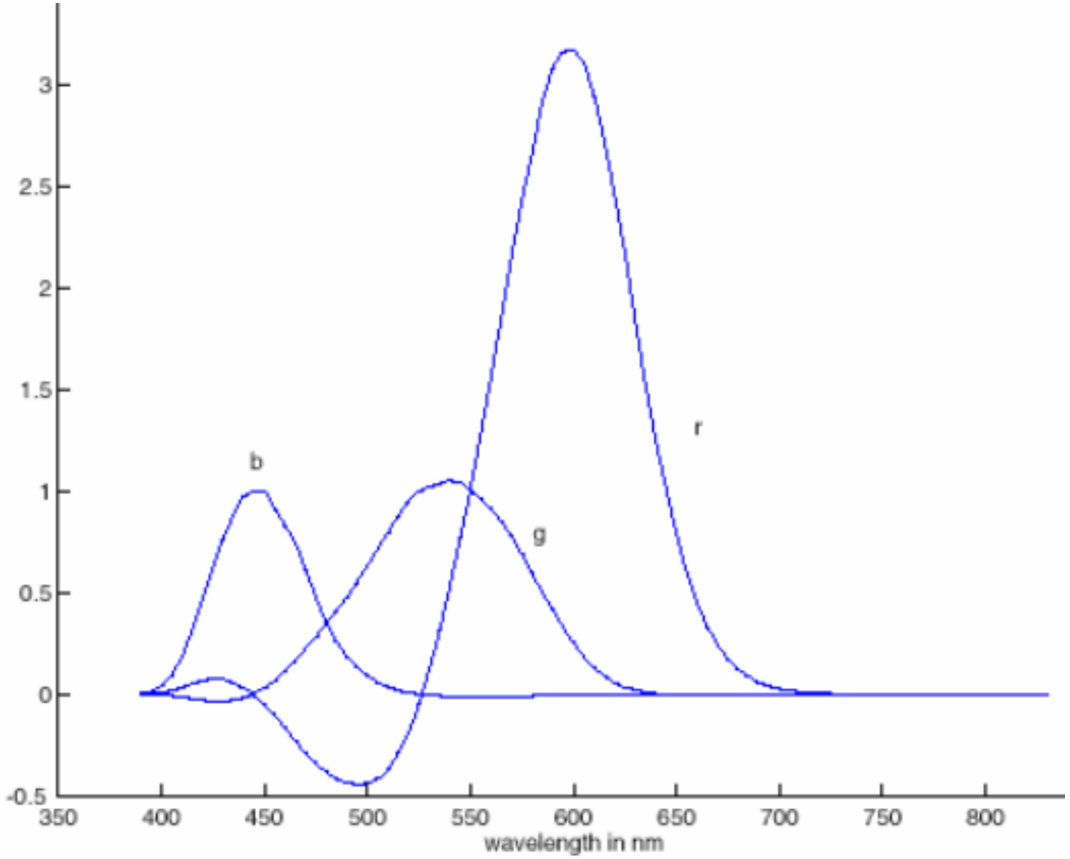
- **Color blindness** is the decreased ability to distinguish colors
  - It can impair tasks such as selecting ripe fruits
- Males are more frequently affected than females



# Color Matching Experiment

- Observers match color of a given wavelength X, by mixing three pure light (at fixed wave lengths)
  - R=700nm
  - G=546.1nm
  - B=435.8nm




- Three matching curves are obtained

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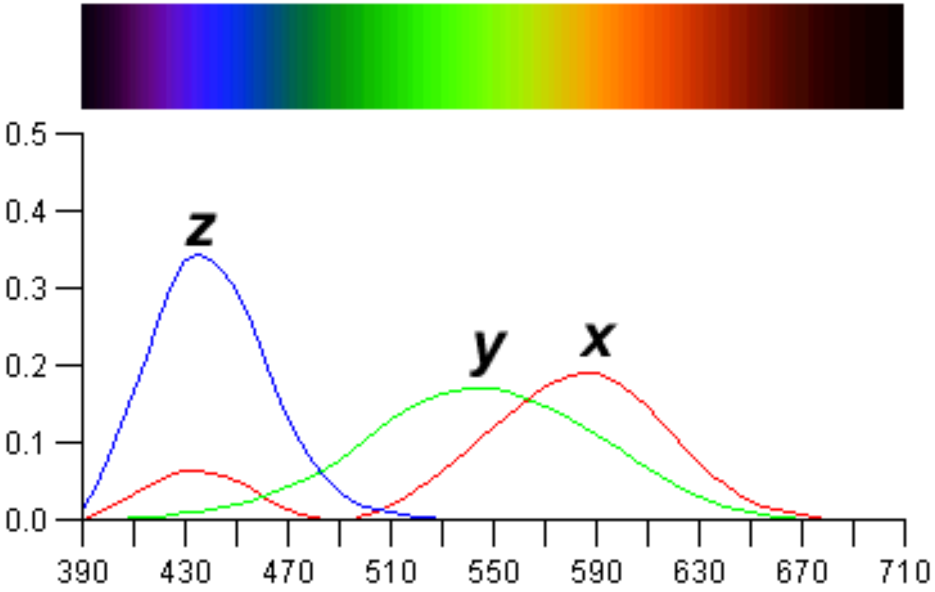
# XYZ Colour Space

- CIE ("Commission Internationale d'Eclairage") has defined three new hypothetical light sources, x, y, and z which yield positive matching curves:




**X = 0.49 R + 0.31 G + 0.20 B**

**Y = 0.17697 R + 0.8124 G + 0.01063 B**

**Z = 0.01 G + 0.99 B**

- The values of X, Y, Z the three-dimensional CIE XYZ space



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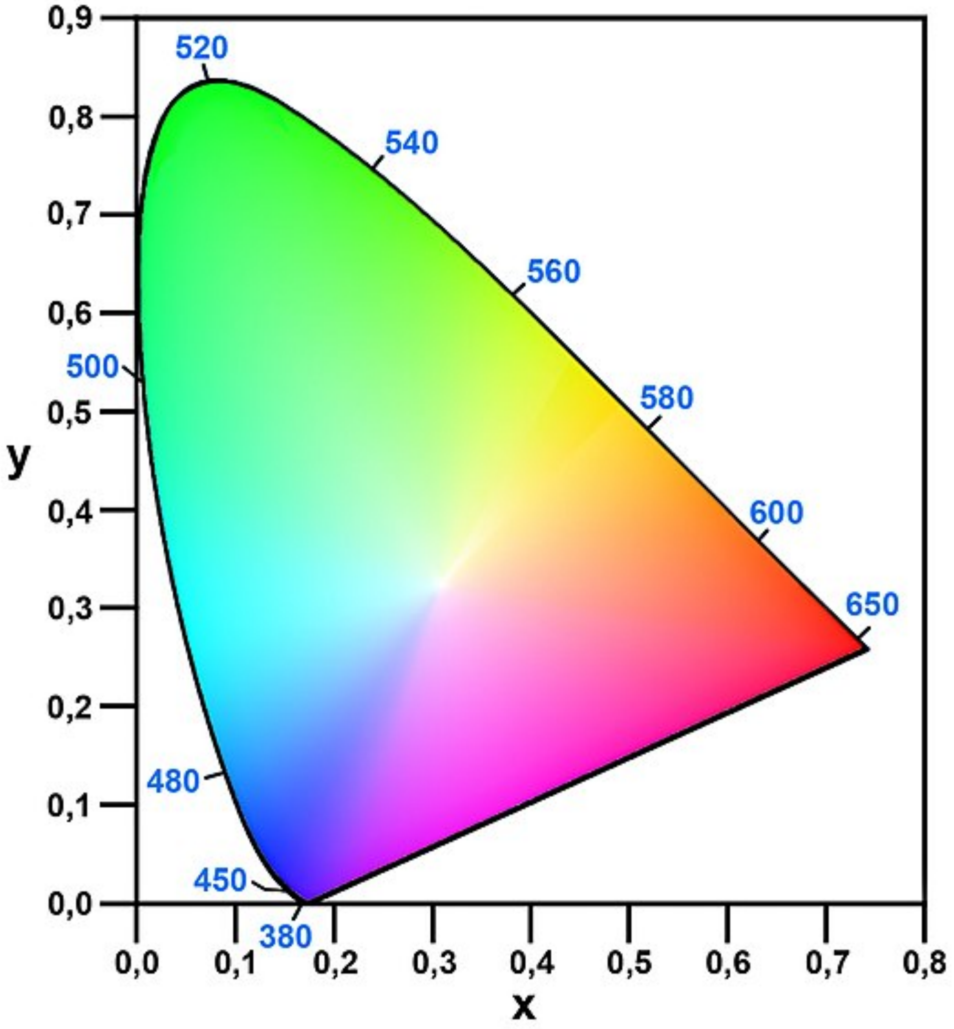
# Chromaticity Diagram

- Pure colors are normalized and projected on 2D space

  $$x = X / (X+Y+Z)$$
  $$y = Y / (X+Y+Z)$$

  - Outer edge consists of single wavelength primaries
  - Inner points correspond to color mixtures

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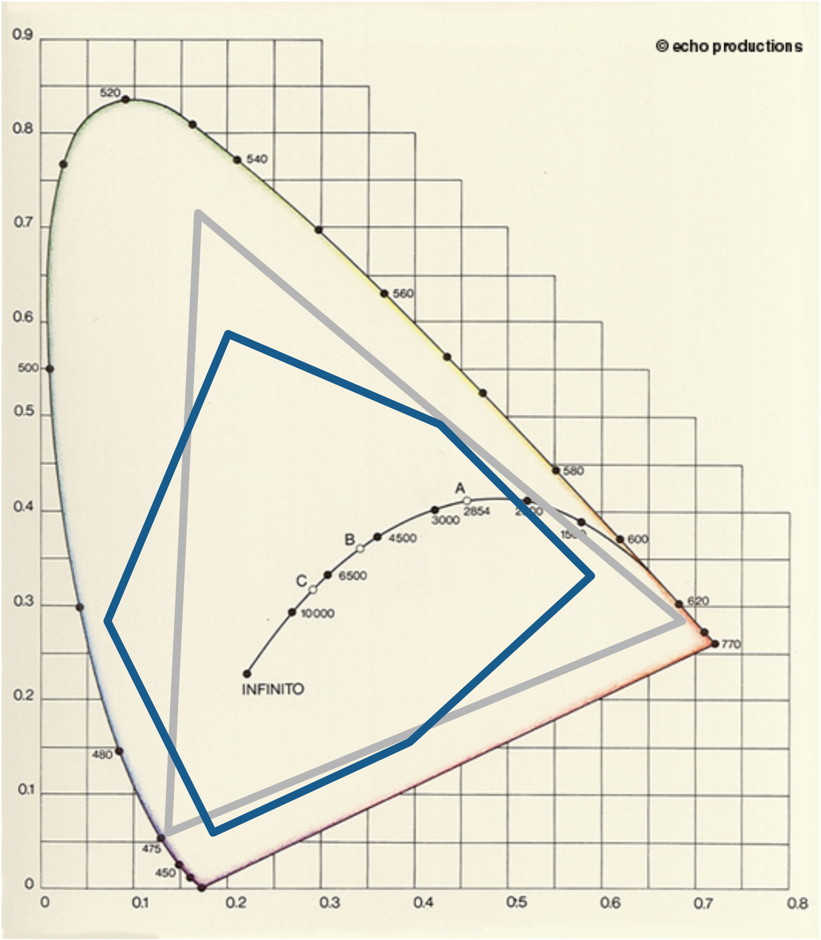
# Monitor Color Gamut

- The displayable colors belong to a triangle defined by the three primary colors of the monitor
  - Vertices represent the primary colors
  - Combination of colors are linear
  - White is located at the center of mass

- What about the gamut of a printer using CMY color space?



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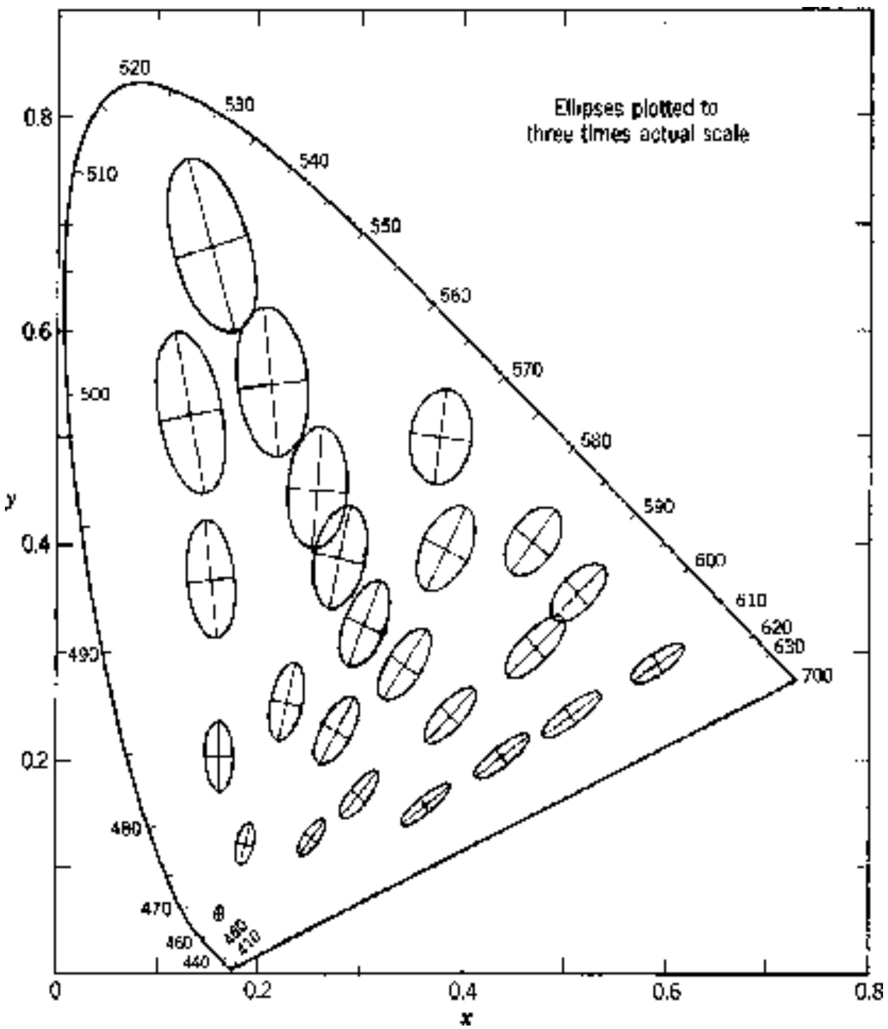
# Perceptible Color Differences

- In the CIE chromaticity diagram, perceptible color differences are not uniformly distributed

- Empirical studies show that the human eye is most sensitive to blue variations



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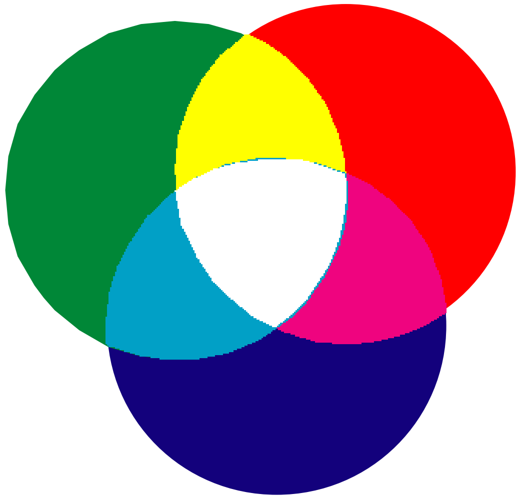
# Additive vs Subtractive Color Spaces

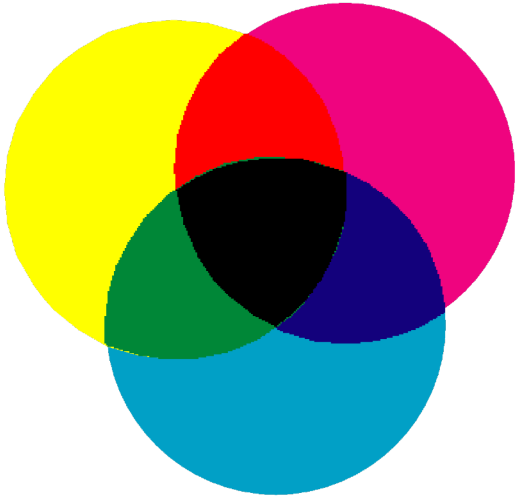
- RGB is an additive color model in which red, green, and blue light are combined to create other colors.
  - It is the most used color model
  - It is used for monitor displays



- CMY (and CYMK) are subtractive color models in which cyan, magenta, yellow (and black) pigments are mixed to produce various colors

  $K = \min(1 - R, 1 - G, 1 - B)$
  $C = 1 - R - K, M = 1 - G - K, Y = 1 - B - K$

  - It is used for printing



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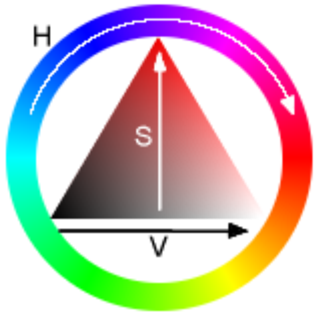
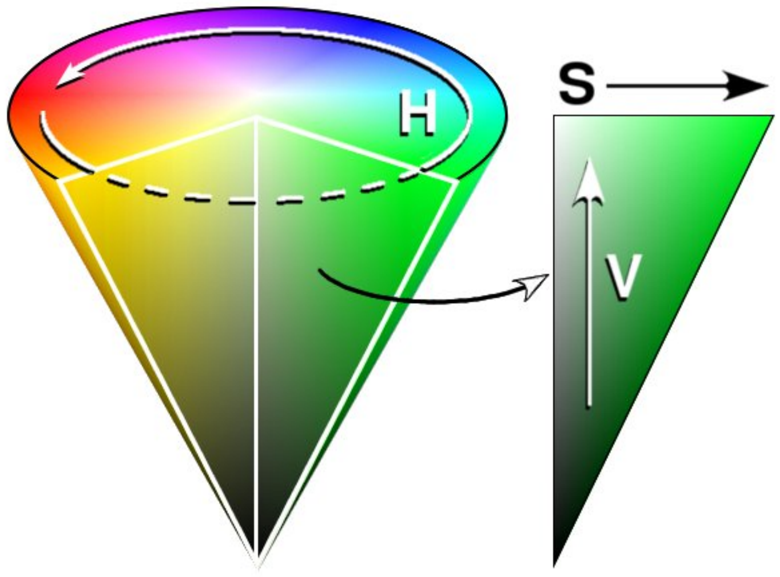
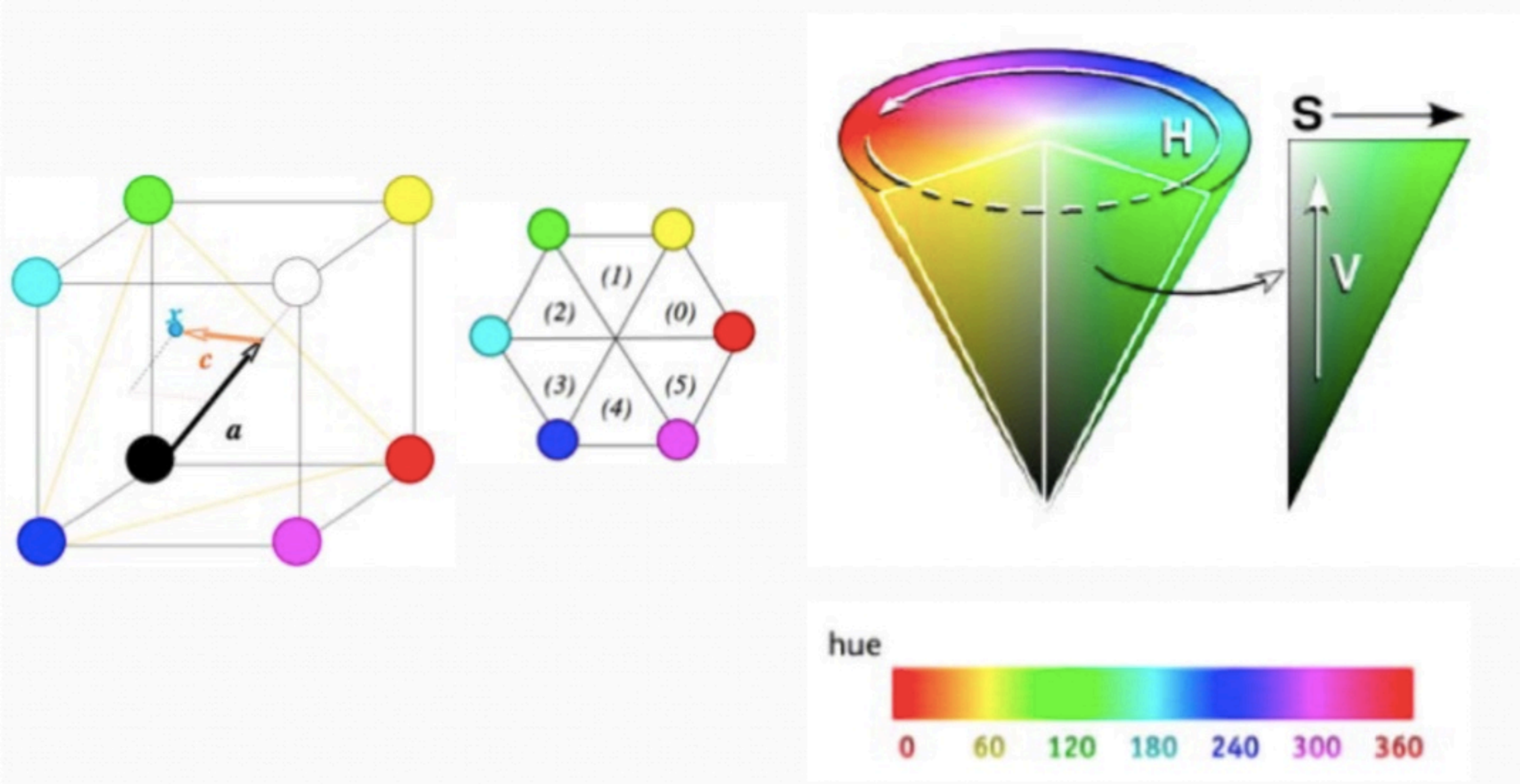
# HSV Color Model: Hue Saturation Value




- The HSV (**Hue, Saturation, Value**) color model is often preferred because it is often more natural to think about a color in terms of hue and saturation than in terms of additive or subtractive color
  - H (from 0 to 360) represents the color type (such as red, blue, or yellow):
  - S (from 0 to 100) represents the "purity" of the color:
  - V (from 0 to 100) represents the brightness



# Better Understanding of the HSV Color Model

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# YUV Color Space

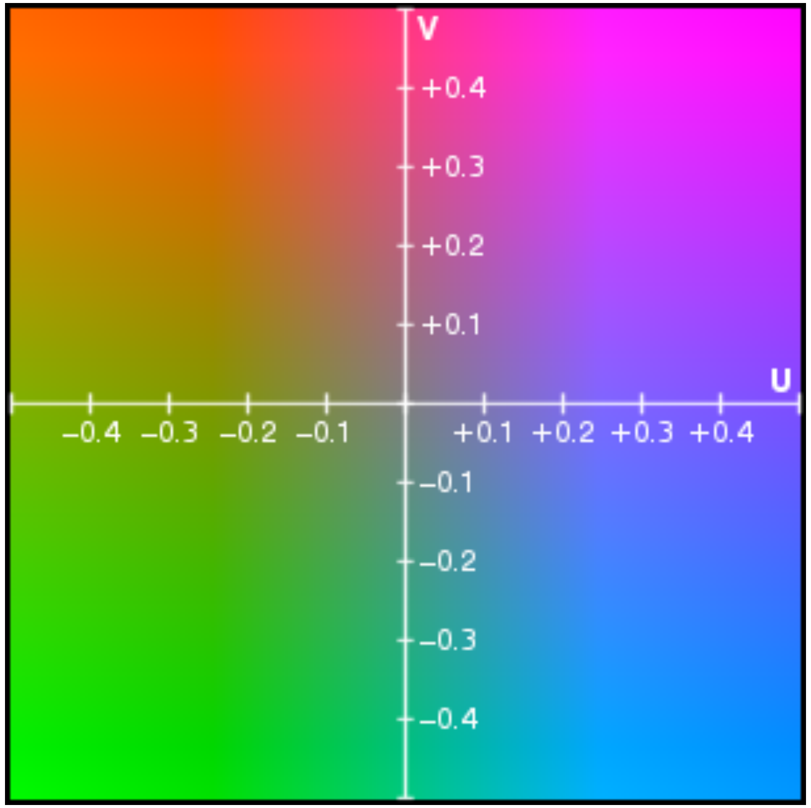
- YUV color space used in PAL television
  - a linear combination of RGB

$$Y = +\ 0.299R + 0.587G + 0.114B$$

$$U = +\ 0.492(B - Y) = -\ 0.147R - 0.289G + 0.436B$$

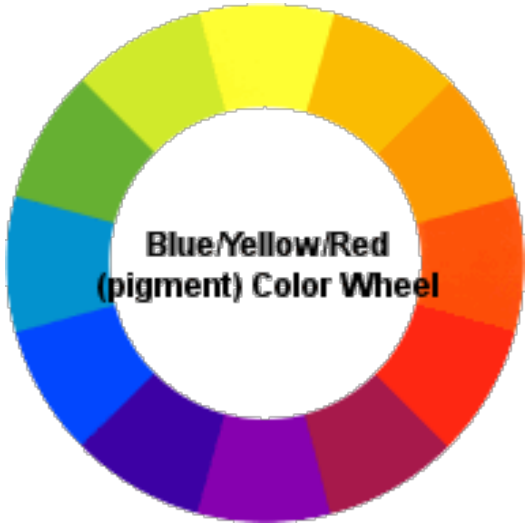
$$V = +\ 0.877(R - Y) = +\ 0.615R - 0.515G - 0.100B$$

  - Y represent luminance (brightness)
  - U,V represent chrominance (color)
- Other similar color spaces
  - YIQ is used in NTSC
  - YDbDr is used in SECAM
  - YCbCr is used in Video and JPEG compression



# Other Color Models

- The most complete color model used to describe all the colors visible to the human eye is CIE L*a*b* (CIELAB)
  - It is based directly on XYZ as an attempt to linearize the perceptibility of color differences
- There are some commercial color spaces:
  - Panton, Munsell
- Artists use a traditional wheel of 12 colors:
  - Three primary colors,
  - Three secondary colors (created by mixing primary colors)
  - Six tertiary colors (created by mixing the primary and secondary colors)



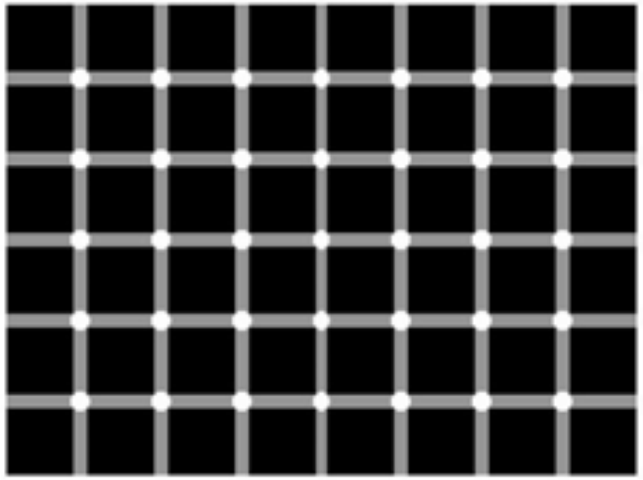

- The Natural Color System (NCS) is based on the six elementary color percepts of human vision: white, black, red, yellow, green, and blue.

# Conclusion on Human Perception and Colors

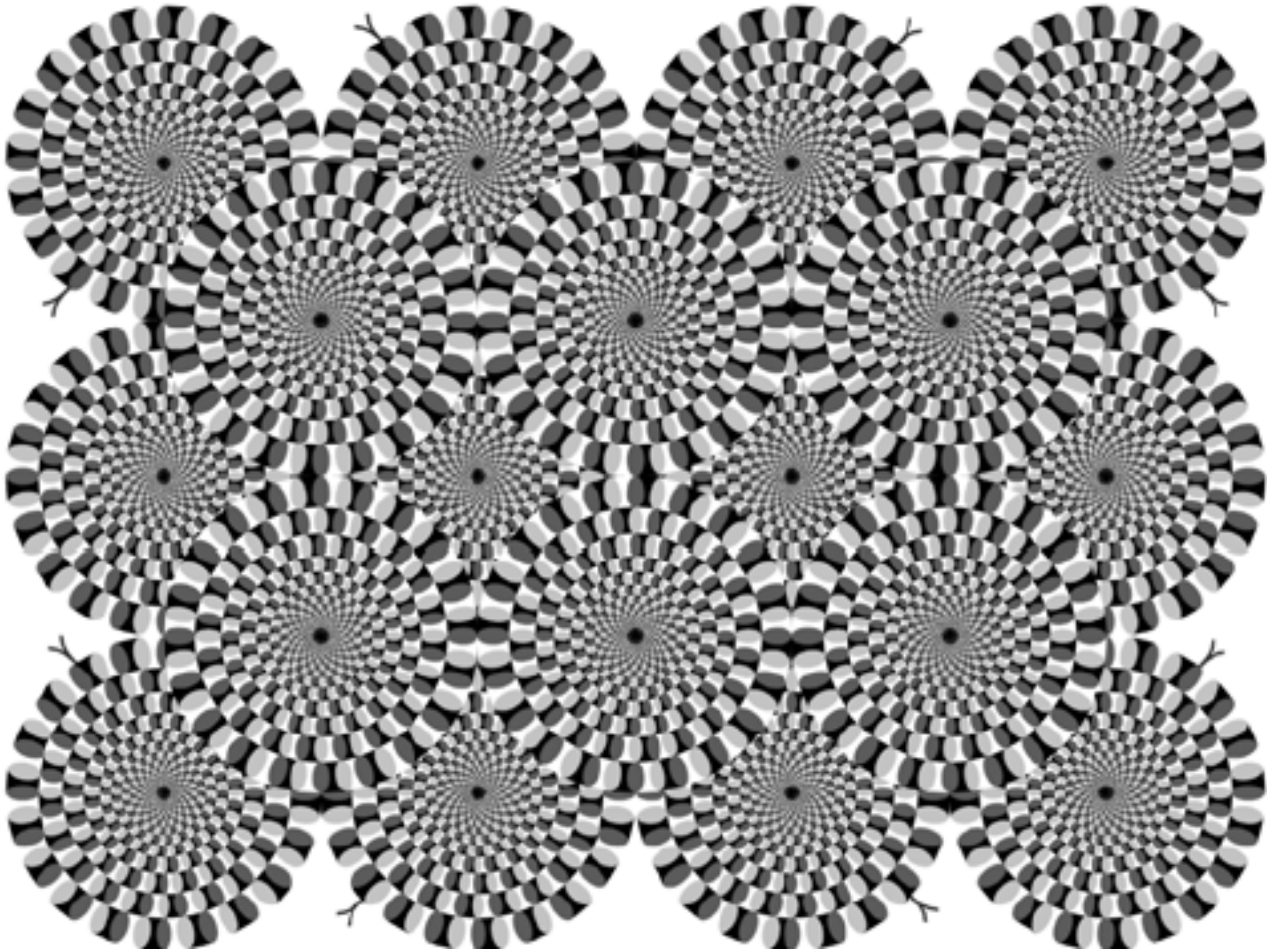
- The visual system of humans is very complex
  - It consists of a combination of scotopic and photopic vision
- Color matching depends on lighting conditions (metamerism phenomena)
- Color perception is highly subjective (changes from one observer to the other)
- Acurate color processing needs calibrated environments
- Color sensitivity has not yet been understood in all details

**Some additional funny visual artifacts are shown next**

# Visual Artifacts (1)



# Visual Artifacts (2)



# Outline

- Human Visual System
  - Visible Light
  - Anatomy of the eye
  - Brightness Perception
  - Color Perception
  - Color Models
- Digital Image representation
  - Reminder: Digital Image
  - Sampling and quantization
  - Image representation
  - Raster organization
  - Color models



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# Image as a function

- In the analogic world, an **image** is considered to be a continuous function of two real variables

  $$I = f(x, y)$$

- In most cases the function $f$ is supposed to be defined in a rectangular domain

  $$x \in [xmin, xmax],\ y \in [ymin, ymax]$$

- The result of the function can be
  - a scalar

    $$f(x, y) \in [0, imax]$$

  - or a vector

    $$f(x, y) \in [0, imax]^n$$

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# Digital Image

- A **digital image** is an image handled by a computer
- A natural image is transformed to a digital image by a **digitization** process which contains two aspects
  - **Sampling** for the image domain
  - **Quantization** for the image values
- A sample of a digital image is called a **pixel**
- The pixels values are often referred to as **intensities**

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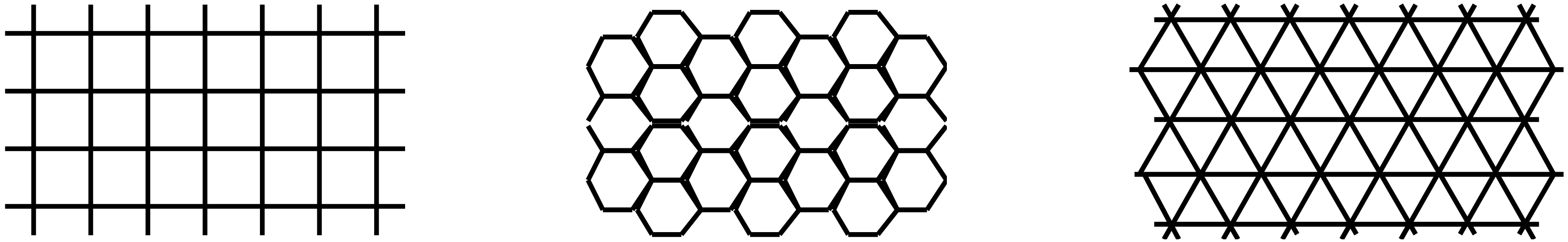
# Digital Image Types

- Binary images (often black and white)
- Monochrome images
  - Fixed number of gray levels (often 256 levels)
  - Intensity from a continuous space (float numbers)
- Color images
  - Indexed color : index used to select the color from a color table
  - True color images using 3 channels (for various color spaces : RGB, HSV, ...)
  - Optionally, with an additional transparency channel
- Multispectral images (with several wavelength bands)
- Range images (measuring distance to the observer)
- Animated images (varying in time)
  - Frame rate (at 25 or 30 fps)

# Sampling Grid

- Several **planar paving schemes** may be used



  - Squared : orthogonal raster, isometric, easiest to implement
  - Hexagonal : with interesting geometrical properties (neighborhood)
  - Triangular

- There is a fundamental theory on sampling that will be studied later

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# Sampling and Resolution

- Sampling defines a **resolution** which is measured in **dpi** (dots per inch)
  - Screen resolutions: 72 - 144 dpi, Retina displays: more than 200 dpi
  - Laser printers: 300 - 1200 dpi, High quality printing: up to 9’600 dpi
  - Office scanner resolution : 300 - 1200 dpi

images with 256 x 256, 128 x 128, 64 x 64 pixels



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# Quantization

- **Quantization** determines the number of (gray) levels
- The number of levels is chosen accordingly to quality

Example: images with 256, 16 and 4 gray levels

- Printers are restricted to 2 levels (black ink, paper)
  - Gray levels are simulated by dithering at a higher resolution



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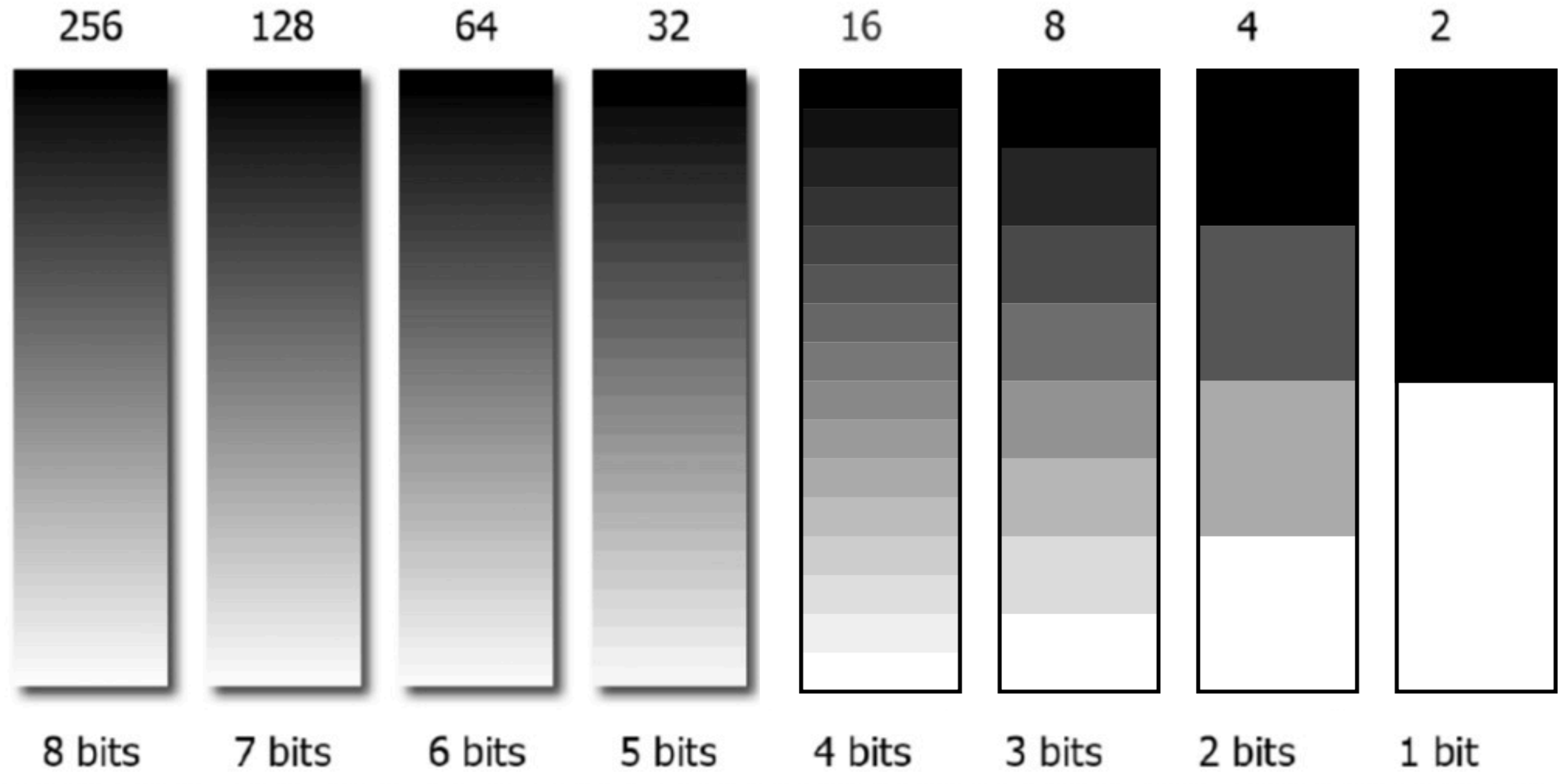
# Gray Level Visualization

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# Color representation

- A pixel value of a color image is defined by a 3-component vector
  - most frequently used components are RGB (Red-Green-Blue)
- Thus, a color image consists in a combination of three monochrome images, called **channels**, **planes** or **banks**



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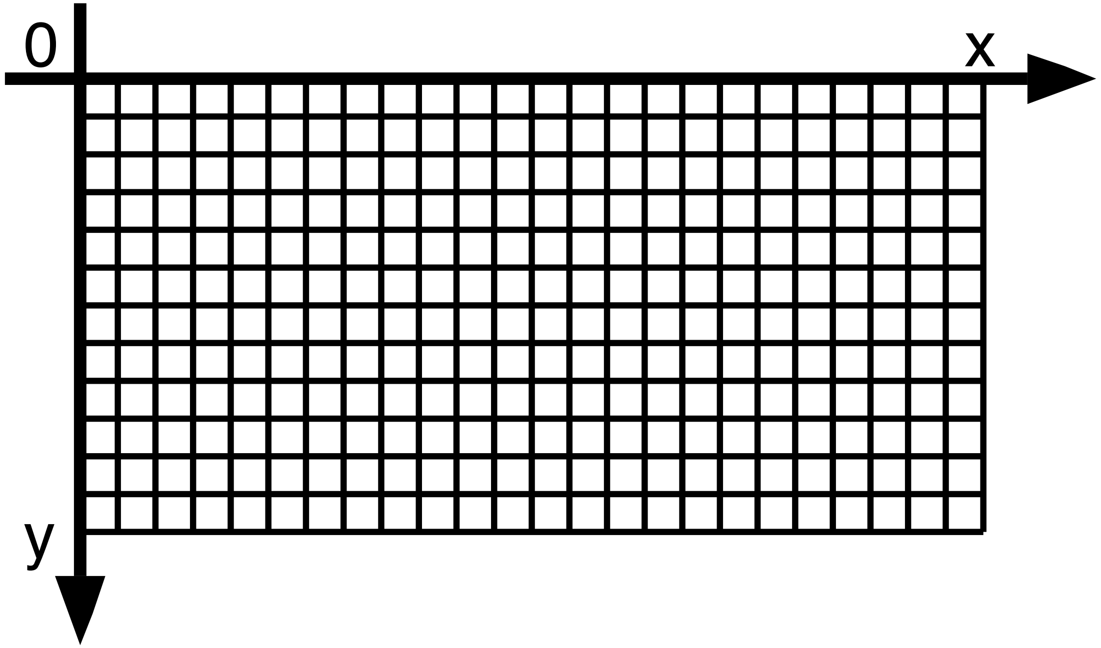
# Image Representation

- The image's representation has an important impact on performance
  - In main memory : random access, locality principle
  - On files : compactness, streamability

- Variable parameters
  - Sampling grid
  - Resolution and size
  - Coordinate system
  - Raster organization
  - Quantization
  - Color representation
  - Coding

# Coordinate System

- Most commonly used coordinate system:
  - The origin in the upper right
  - The x axis extending to the right
  - The y axis extending downwards



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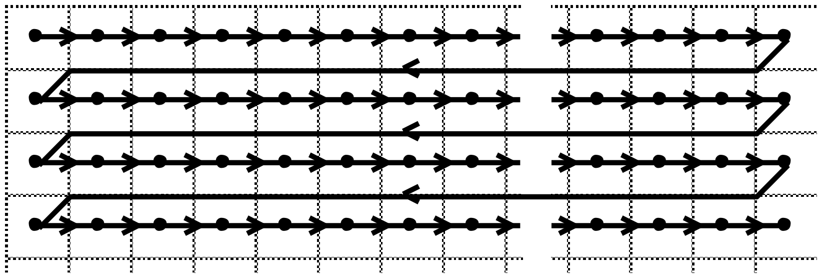
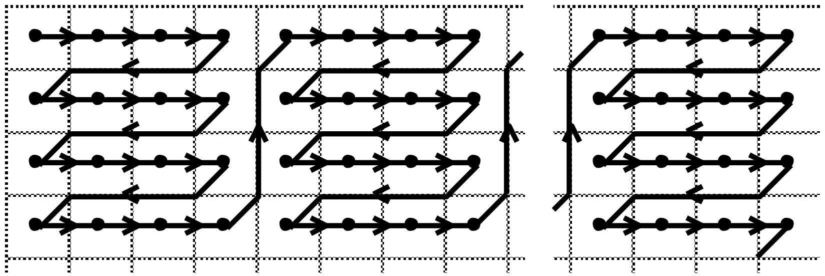
# Raster Organization

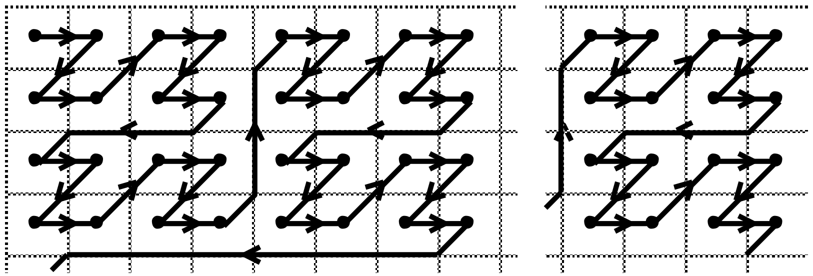
- The raster organization defines the pixel order by mapping coordinates to pixel addresses



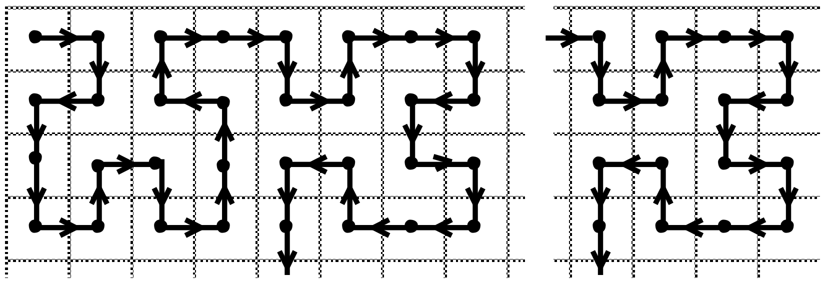
by scanlines



by tiles



by quadtrees



by Peano path



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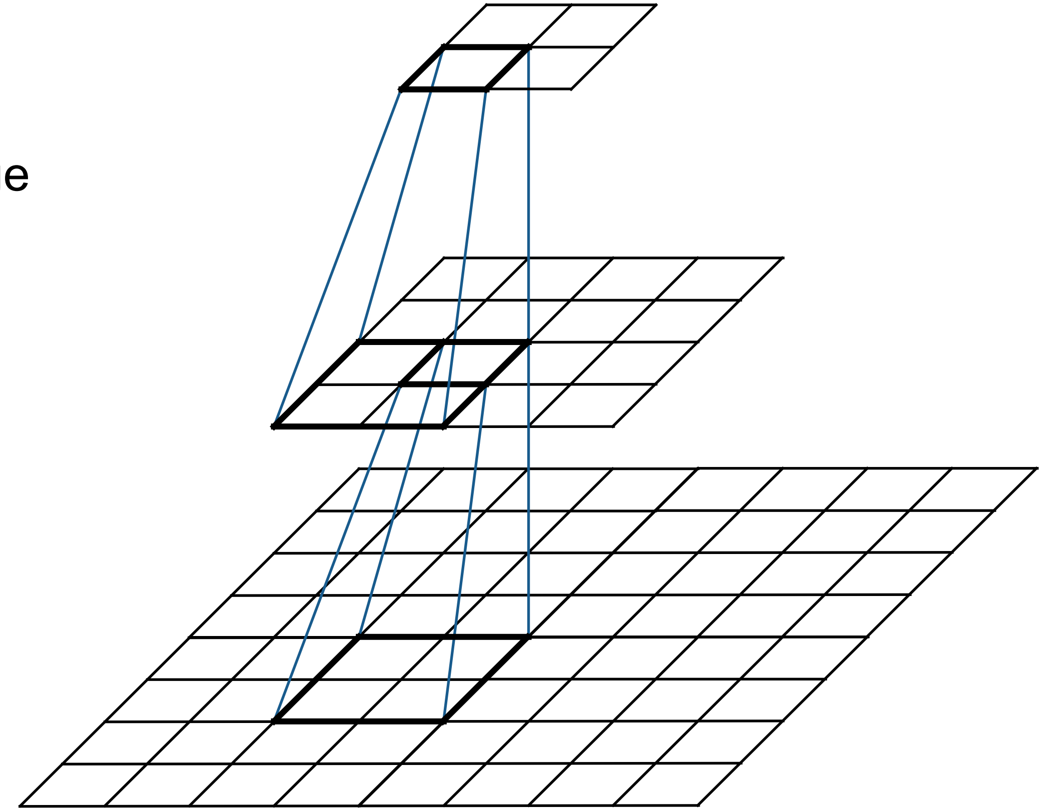
# Pyramidal Representation

- The image is represented as a sequence of layers
  - With increasing resolution
  - First layer contains a low resolution image
  - Subsequent layers contain color differences to the upper level

- Suitable for streaming image formats



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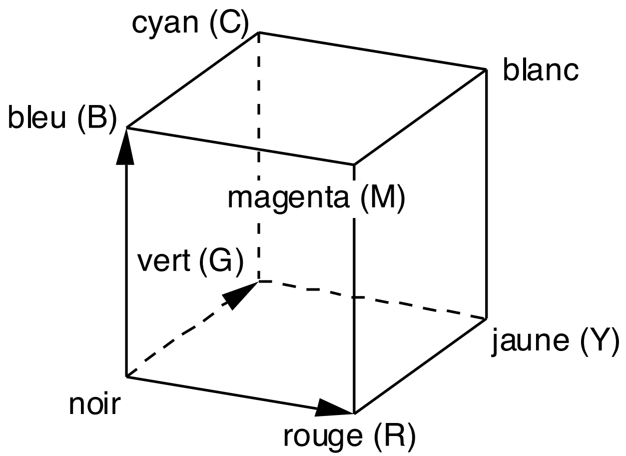
# Quantization

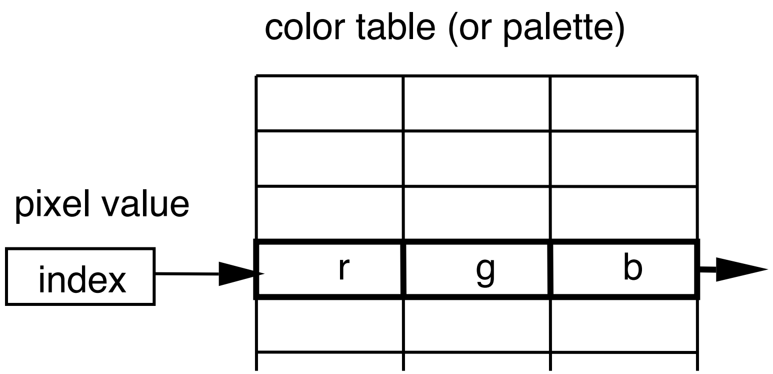
- **Quantization** determines the range of pixel values
- Monochrome case
  - **256 levels** (8 bits) are considered sufficient for most applications
  - more bits are required for high accuracy applications
- Color case
  - color tables have generally between 256 and 65536 colors
  - standard 24 bits (3x8bits) true color can represent more than **16 million colors**
  - very high color accuracy needs 32 or 48 bits !

# Color Representation

- Direct color :
  - each pixel has 3 components :
    r, g, b (red, green, blue intensities)




- Indexed color :
  - each pixel is represented by an index, corresponding to an entry in a color map



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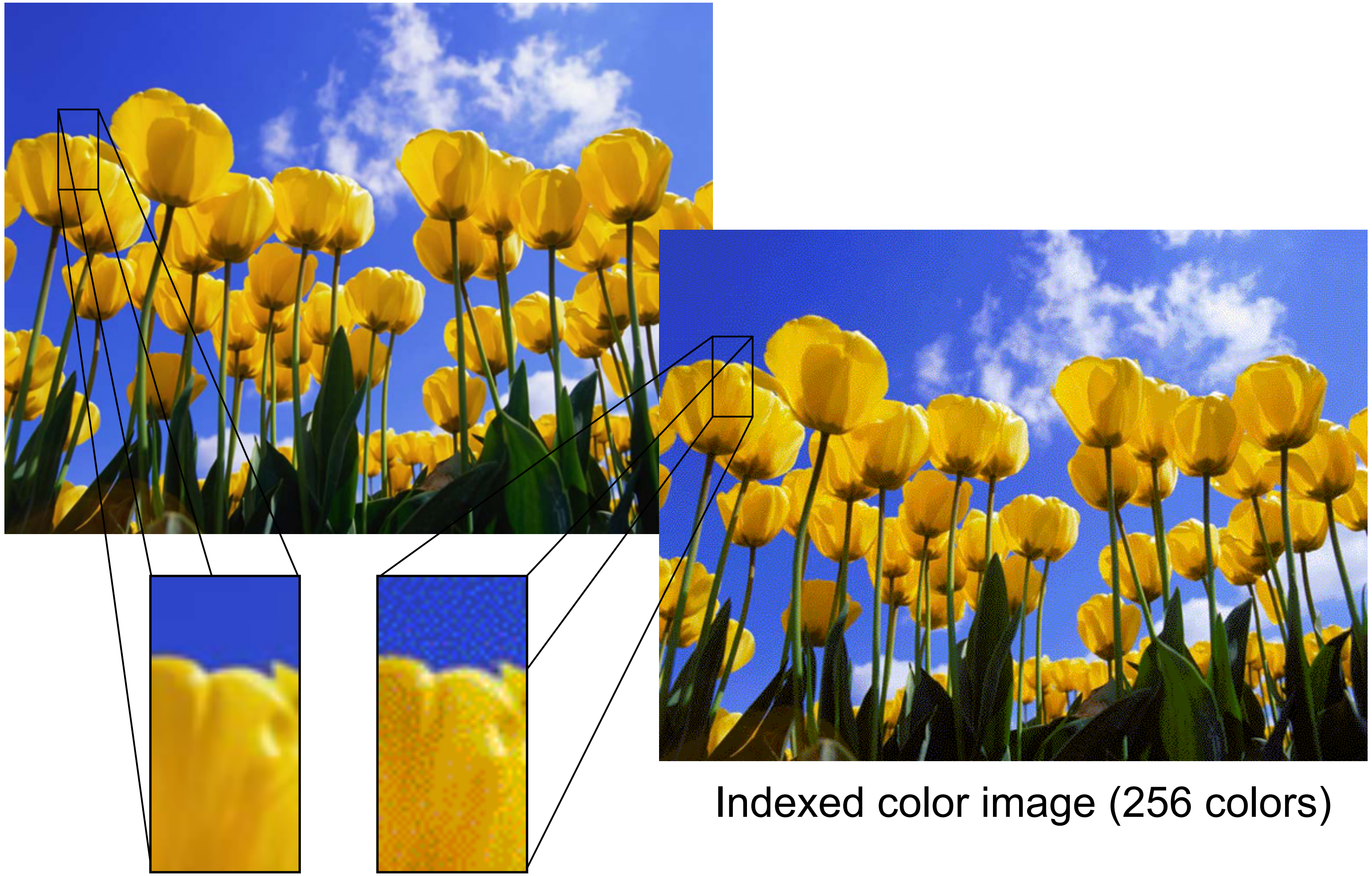
# Real vs. Indexed Color

Real color image (16 million colors)



Indexed color image (256 colors)



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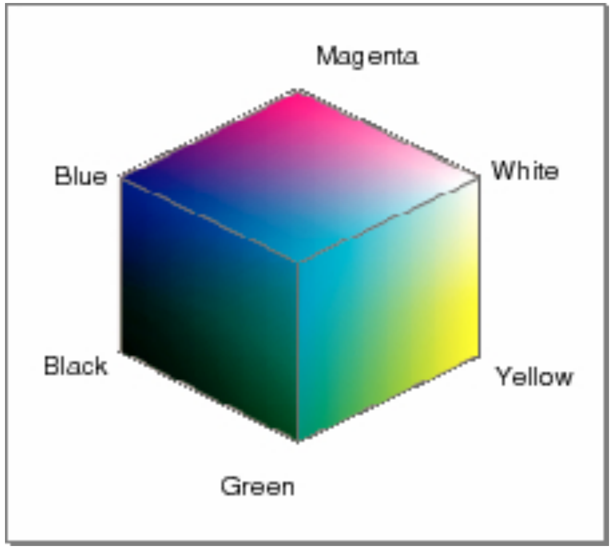
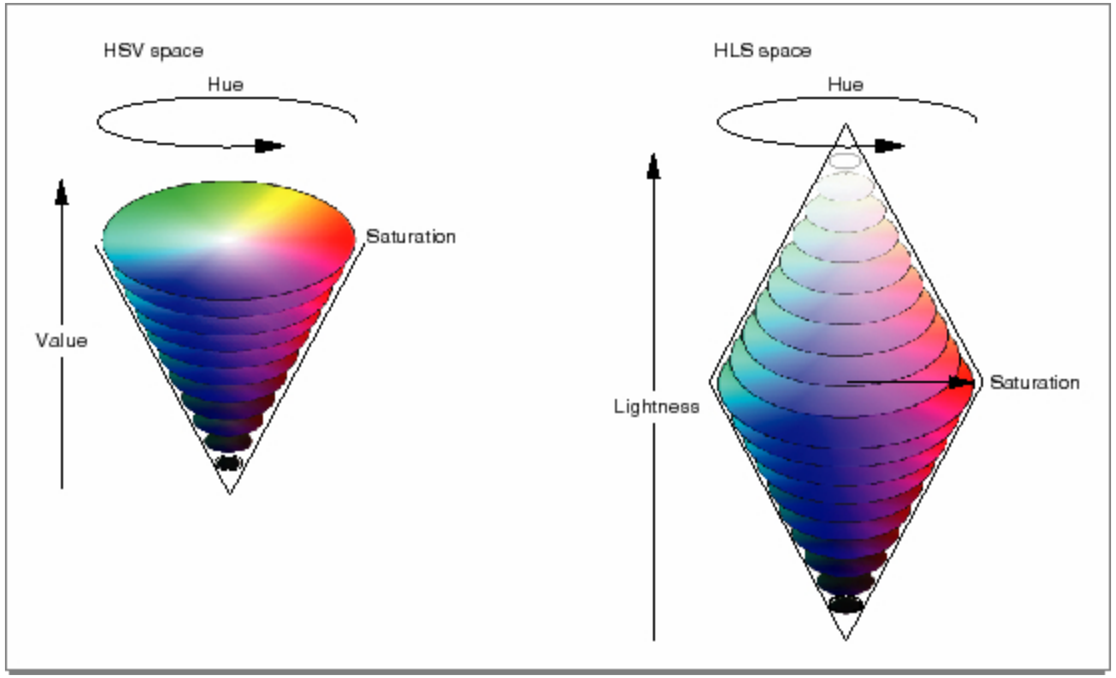
# Alternative Color Spaces

- There exist many different color spaces !
  - CMY : Cyan, Magenta, Yellow (complements to RGB)
  - HSV : Hue, Saturation, Value
  - HLS : Hue, Luminosity, Saturation
  - ... many others



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# File Size and Bandwidth

- Raw image data uses prohibitive storage resources
  - Binary image of a A4 page at 300dpi : 1MB
  - Screen shot of a 1024 x 768 color image : 2MB
  - Digital picture at 2560 x 1920 (5M pixel) : 15MB
  - Digital video (640x480x25) : 22MB per second, 1.3 GB per minute !

- For storage and network transfer, data compression is required
  - Compression methods can be lossy or lossless

# File Format Descriptors

- A format descriptor is needed to represent additional information
  - Type of image (binary, gray levels, color, ...)
  - Size (width, height) in number of pixels
  - Physical dimension (in cm, inch, ...) or resolution (in dpi, ...)
  - Sample model (pixel order, pixel coding, byte order, bit order)
  - Color model (color coding)
  - Color table (optionally)
  - Link(s) to pixel data
  - Optionally other information (capture conditions, location, date, history, keywords for indexing, general comments, ...)

# Non Proprietary File Formats

| | Binary | Grayscale | Indexed color | True color | Progressive | Compressed | Lossless | Lossy |
|---|---|---|---|---|---|---|---|---|
| GIF - Graphics Interchange Format | X | X | X | | X | X | X | |
| TIFF - Tag Image File Format | X | X | X | | | X | X | |
| JBIG - Joint Bi-level Image exp. Group | X | X | | | | X | X | |
| JPEG - Joint Photographic Expert Group | | X | | X | X | X | | X |
| PNG - Portable Network Graphics | X | X | X | X | X | X | X | X |

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