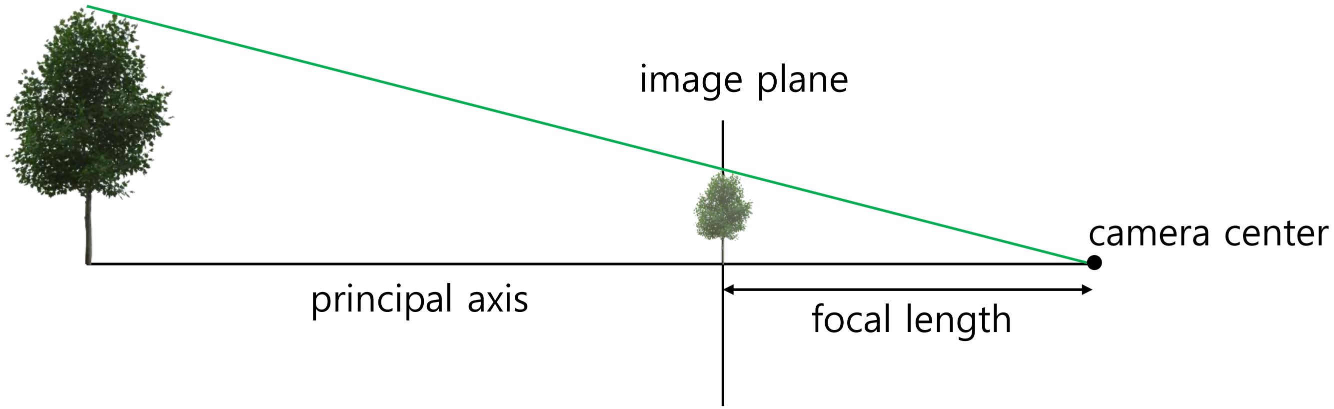
Slides and example codes are available:
https://github.com/mint-lab/cv_tutorial

Color

Sunglok Choi, Assistant Professor, Ph.D.
Computer Science and Engineering Department, SEOULTECH
sunglok@seoultech.ac.kr | https://mint-lab.github.io/

Review) Geometric Image Formation

- **Pinhole camera model**
  - In conclusion, $\mathbf{x} = \mathrm{P}\mathbf{X}$ $(\mathrm{P} = \mathrm{K}\,[\mathrm{R} \mid \mathbf{t}])$



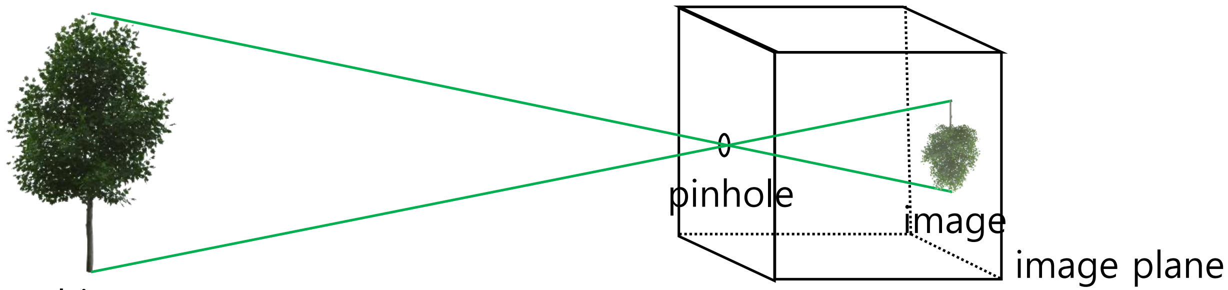


Image: PNG EGG

Photometric Image Formation

- **Real camera model**
  1. A **light source** emits light.
  2. The light is reflected and absorbed or passes through (e.g. transparent) an **object**.
  3. The light goes through the **camera lens** and hits the **image sensor**.

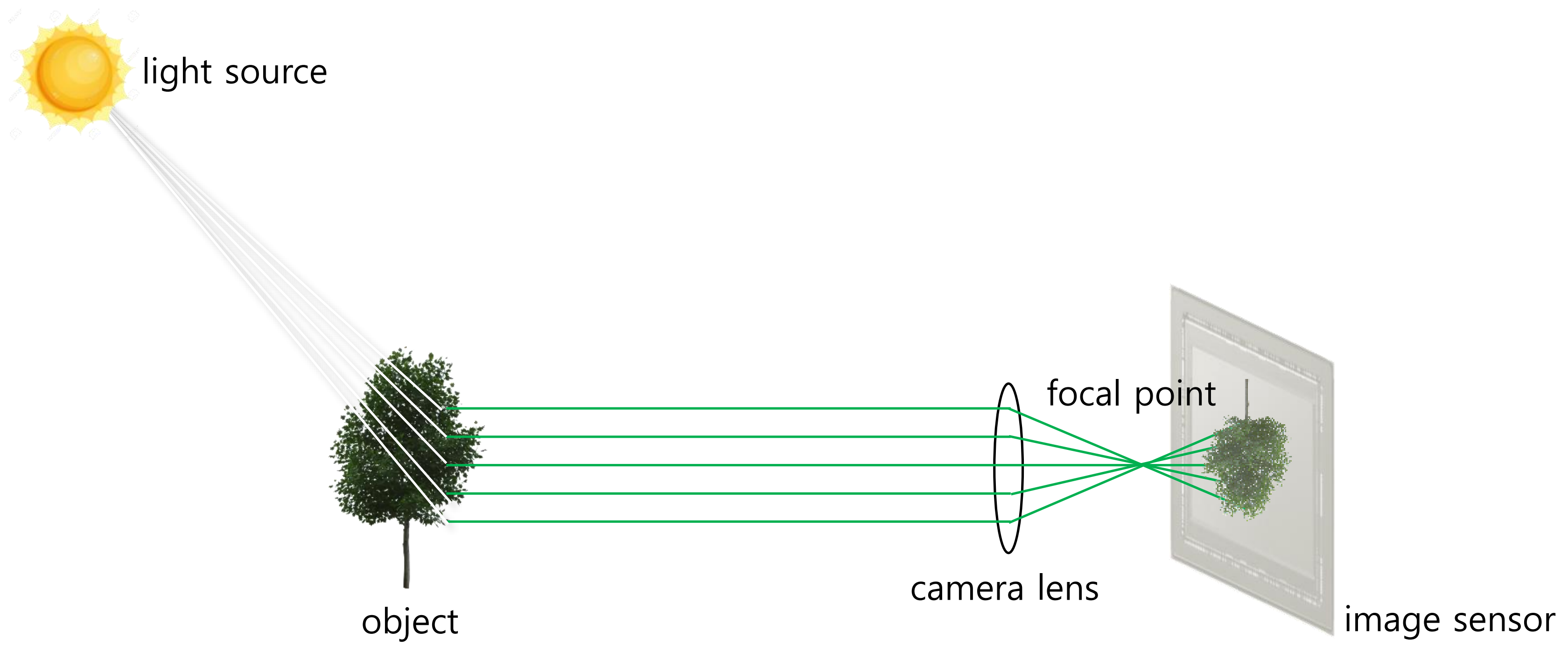


Image: PNG EGG, 123RF, PetaPixel

Light

- The **intensity** of light is the **amount of light energy** per unit area per unit time. (unit: W/m^2 or lux)
- The **color** of light is characterized by the **frequency** (unit: Hz) or **wave length** (unit: m).

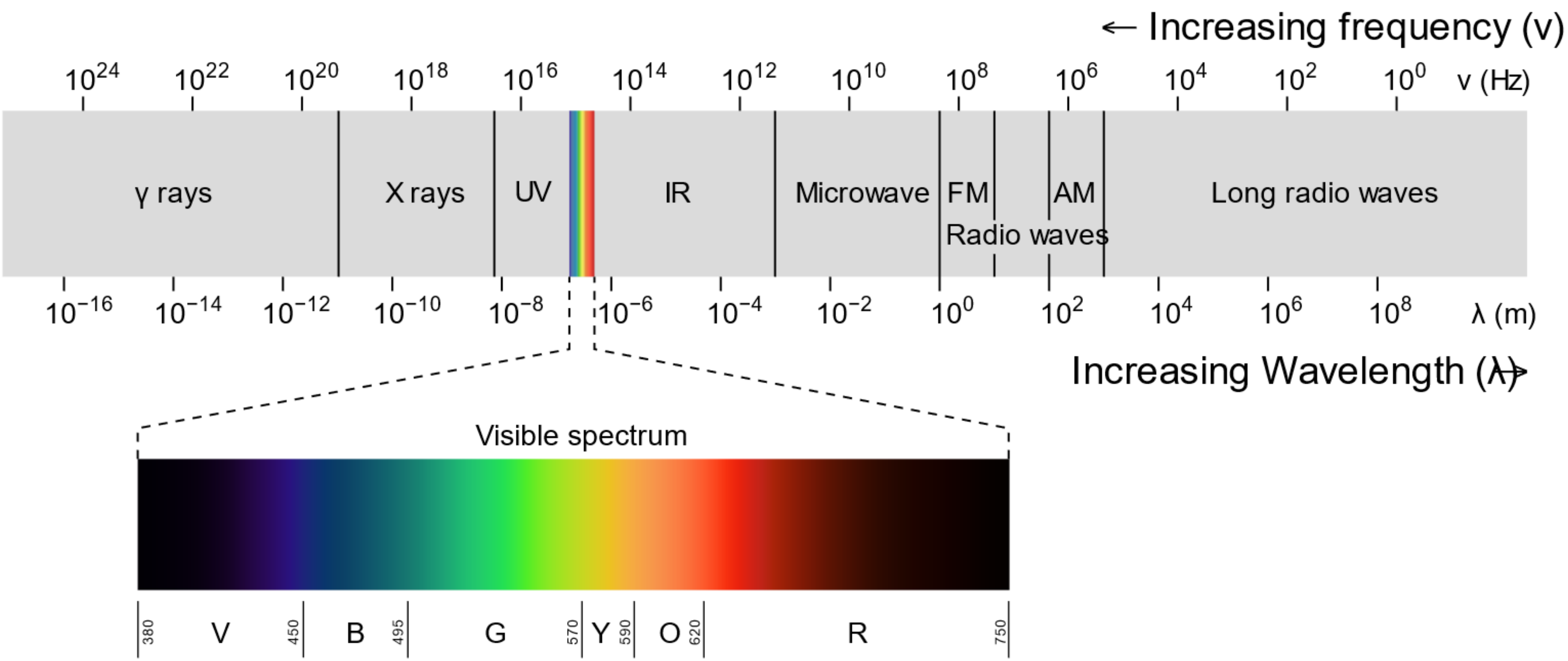


Image: Wikipedia

Photometric Image Formation

- CCD and CMOS sensors are an array of photodetectors that can detect the intensity of light.
- Q) How does a camera control the intensity of light?
  - Aperture (조리개 in Korean)
    - A hole of a camera (unit: f-number)
  - Shutter speed (a.k.a. exposure time)
    - The length of time that an image sensor is exposed to light
  - ISO sensitivity (a.k.a. exposure index)
  - Additional light sources (e.g. flash)

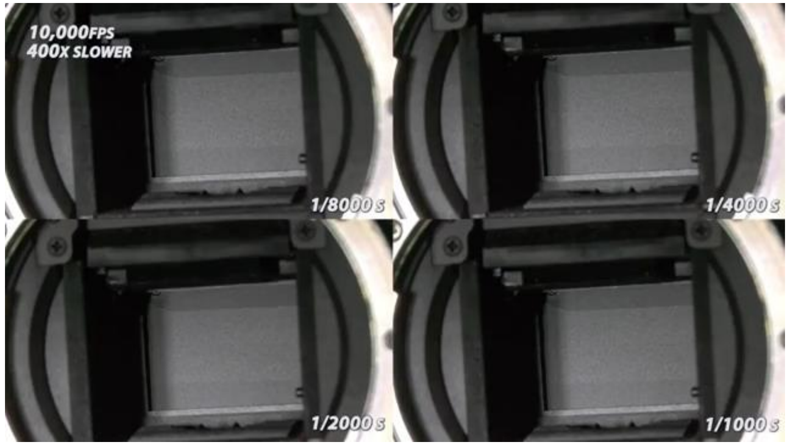
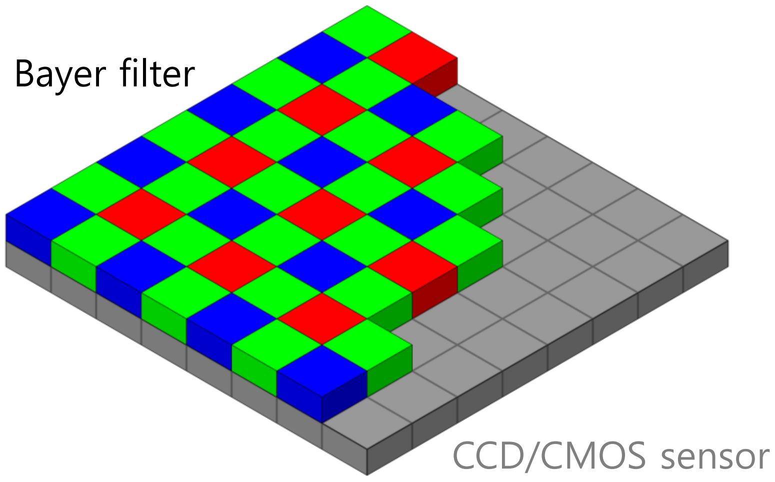
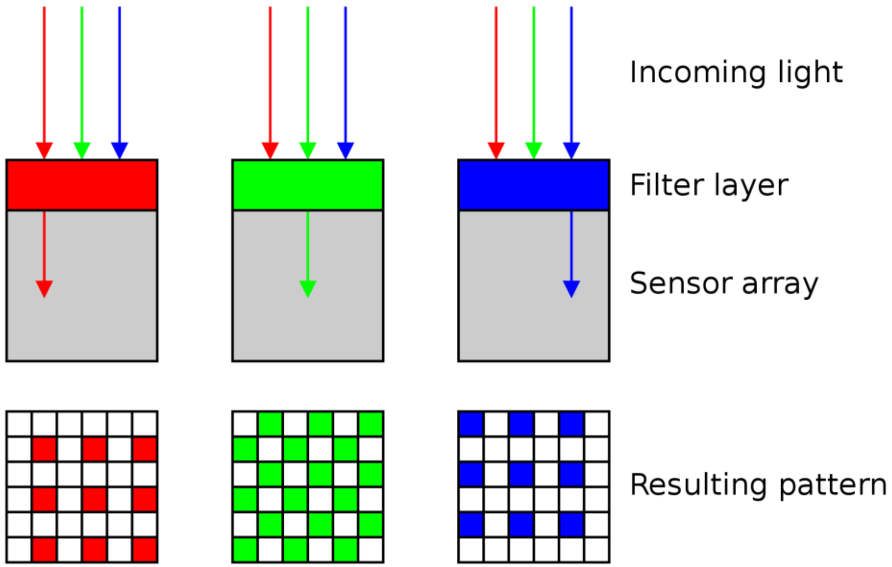


Image: Wikipedia and YouTube

Photometric Image Formation

- CCD and CMOS sensors are an array of photodetectors that can detect the intensity of light.
- Q) How does a camera capture (or distinguish) the color of light?
  - Color filter array for RGB separation
    - e.g. Bayer filter is a the most common for RGB.
  - A demosaicing algorithm (inside of a camera) reconstructs RGB images (4) from raw Bayer images (3).





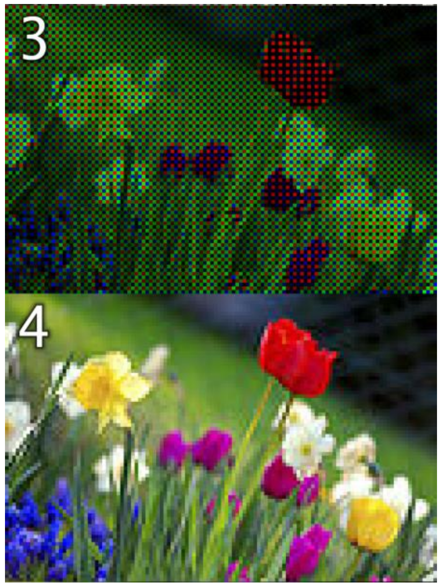


Image: Wikipedia

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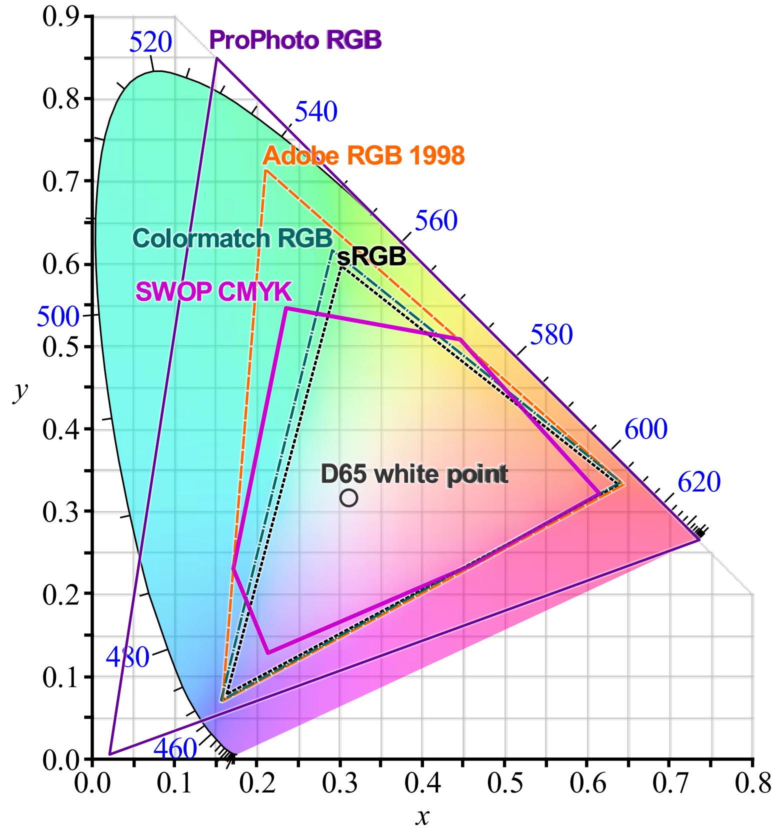
  - Color spaces for **human-friendly color selection**
  - Color spaces for **human visual perception**
  - Example) Color space conversion
  - Example) Color histogram equalization

Color Spaces

- **Color space** is a specific system for representing color numerically and graphically. [show its list]
- Color spaces for **media (e.g. display and printing)**
  - **RGB**: An additive color space for displays (emitting light; e.g. television)
    - **sRGB**: A standard RGB color (IEC 61966-2-1:1999)
      used in monitors, printers, and WWW

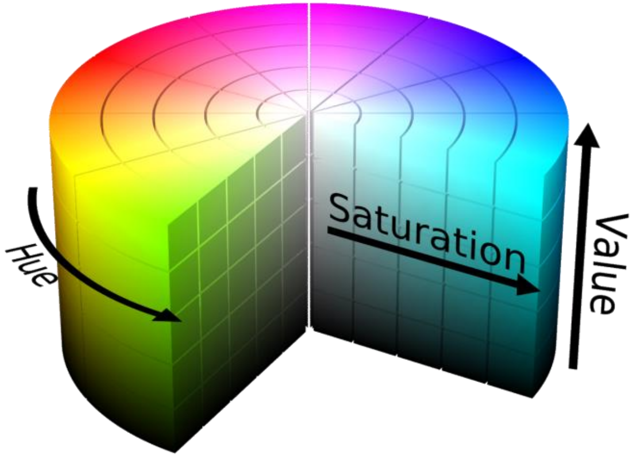


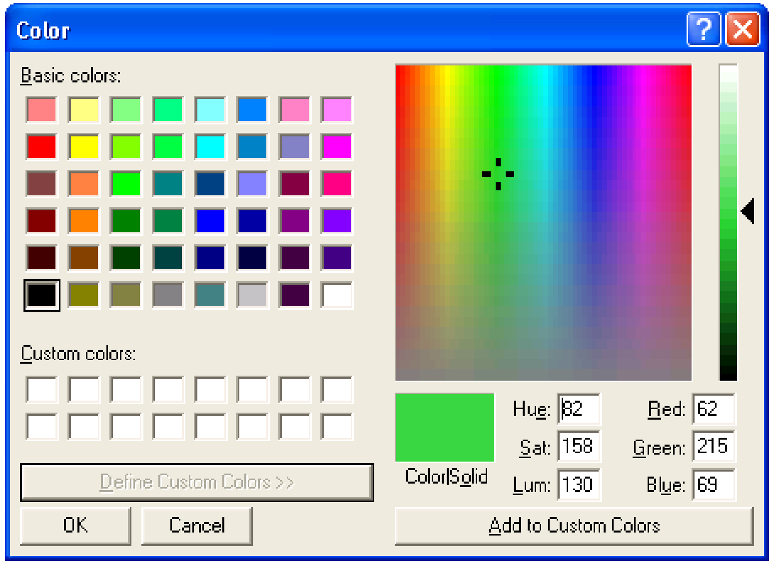
  - **CMY**(K): An subtractive color space for printing on white papers
  - **YCbCr** (digital) and **YUV** (analog): Color spaces for video transmission and compression with *economic* bandwidth
    - How? Human eyes has less resolution in color perception than intensity perception. → e.g. Y: 8-bit, Cb/Cr: 4-bit

Image: Wikipedia

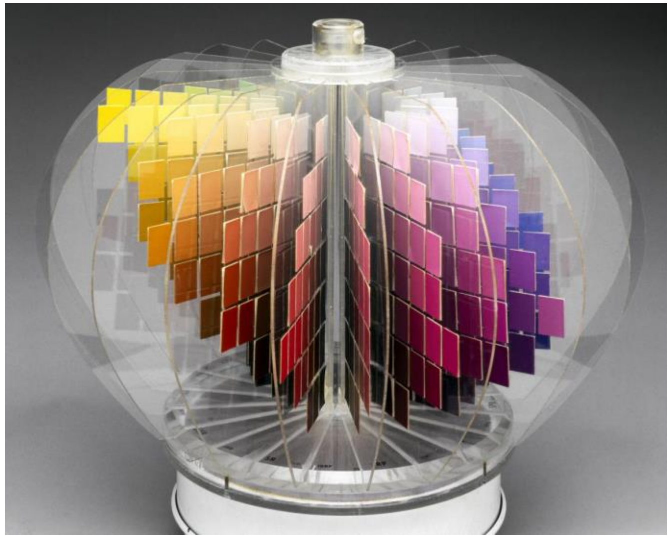
Color Spaces

- Cylindrical-coordinate color spaces for **human-friendly color selection**
  - [HSV (HSL)](): Hue-Saturation-Value (색상-채도-명도 in Korean) designed by computer graphics researchers (1970s)
  - [Munsell](): Hue-Chroma-Value (색상-채도-명도 in Korean) used for paints, crayons, papers, soils, wires, … (since 1905)





Color Dialog Box

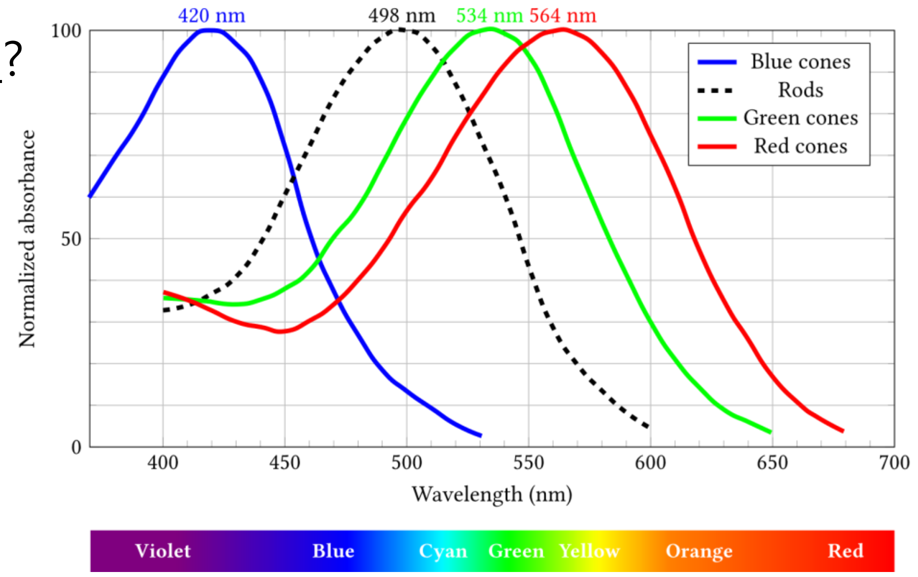


Munsell color tree

Image: Wikipedia, Microsoft, Works That Works

Color Spaces

- Q) Why are color spaces represented in the three-dimensional space?
  - Human eyes have three different cone cells (원추세포 in Korean).
    - They response long(L), middle(M), and short(S) wavelength of light.
  - Human eyes are tristimulus and trichromacy.
  - Its color space is also defined as LMS color space.



- Color spaces for **human visual perception**
  - **XYZ** (a.k.a. CIE 1931 XYZ): A standard color space based on physiologically perceived colors by human observers
    - Note) Y ~ luminance (명암 in Korean), Z ~ blue of CIE RGB, X ~ mixture
    - The Hunt-Pointer-Estevez matrix (1980)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 1.91020 & -1.11212 & 0.20191 \\ 0.37095 & 0.62905 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

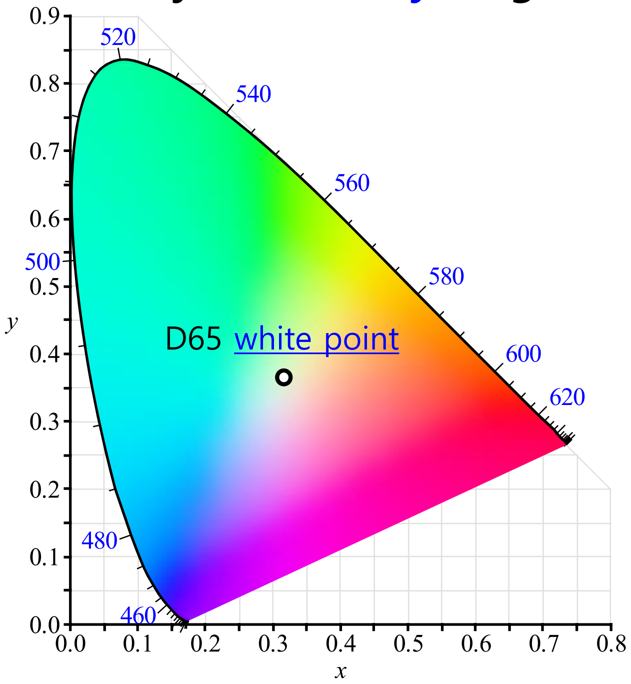
Image: Wikipedia

Color Spaces

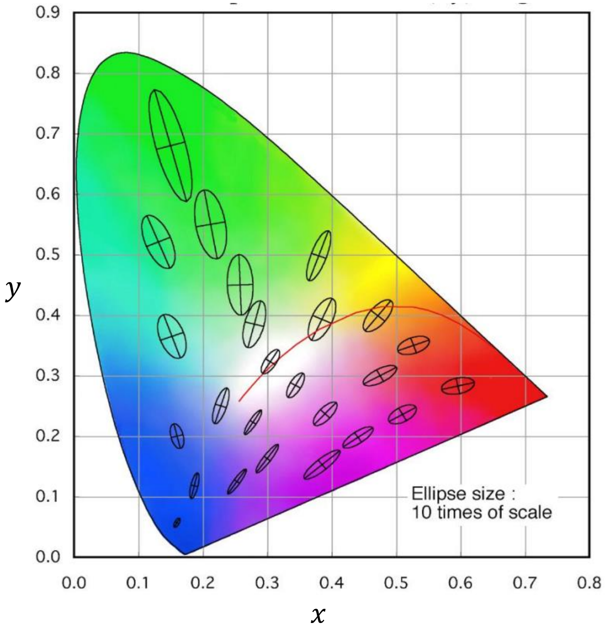
- Color spaces for **human visual perception**
  - **XYZ** (a.k.a. CIE 1931 XYZ): A standard color space based on physiologically perceived colors by human observers
  - **xyY** (a.k.a. CIE xyY): A standard color space to represent the quality of color (regardless of its luminance)

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

  - **LAB** (a.k.a CIE L*a*b*) and **LUV** (a.k.a. CIE 1976 L*u*v*): Standard color spaces for better representation
    - **CIE xy chromacity diagram**



CIE 1931 with MacAdam ellipse



CIE 1976 with MacAdam ellipse

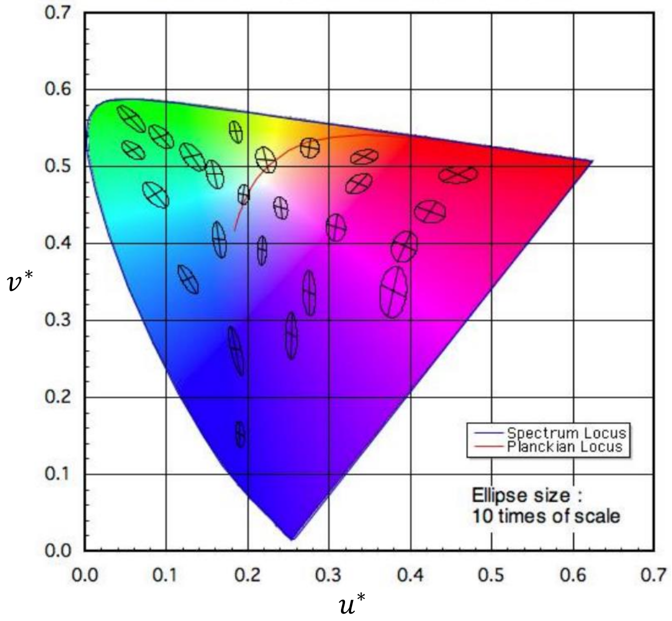
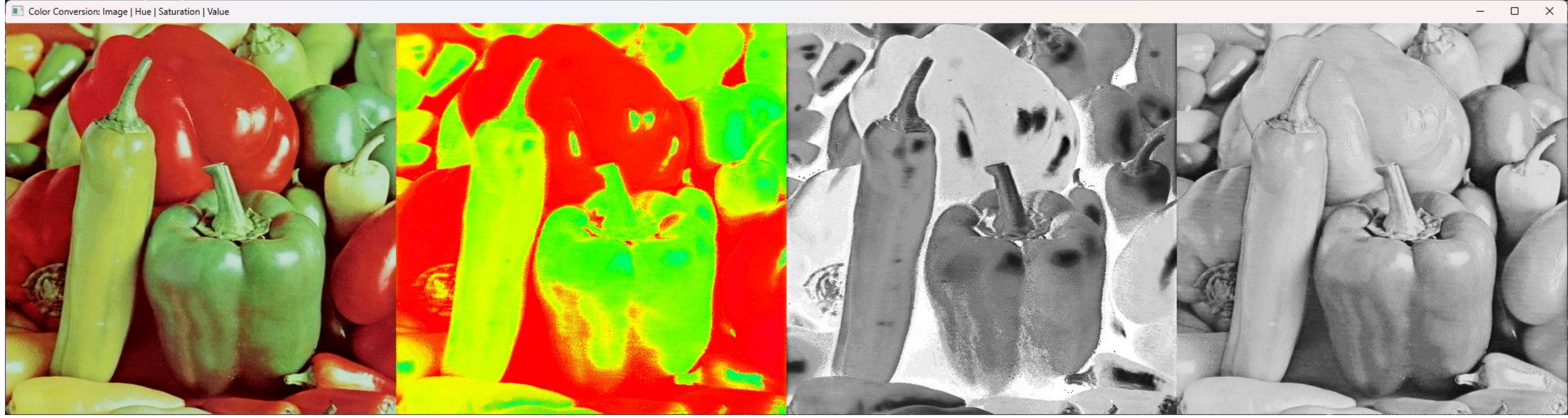


Image: Wikipedia, Yoshi Ohno

Color Spaces

- Example) Color space conversion (HSV)




```
import numpy as np
import cv2 as cv

img = cv.imread('../data/peppers.tif')
assert img is not None, 'Cannot read the given image'

# Convert the BGR image to its HSV image
img_hsv = cv.cvtColor(img, cv.COLOR_BGR2HSV)

# Show hue, saturation, and value channels as color images
img_hue = np.dstack((img_hsv[:,:,0],
                     np.full_like(img_hsv[:,:,0], 255),
                     np.full_like(img_hsv[:,:,0], 255)))
img_hue = cv.cvtColor(img_hue, cv.COLOR_HSV2BGR)
img_sat = np.dstack((img_hsv[:,:,1], ) * 3)
img_val = np.dstack((img_hsv[:,:,2], ) * 3)
merge = np.hstack((img, img_hue, img_sat, img_val))
cv.imshow('Color Conversion: Image | Hue | Saturation | Value', merge)
cv.waitKey()
cv.destroyAllWindows()
```

Solutions to Algorithms only for Gray-scale Images

- **Some algorithms only support a gray-scale image**, not a color image.
  - e.g. Histogram equalization, edge detection, …

```python
# Read the given image as gray scale
img = cv.imread('../data/lena.tif', cv.IMREAD_GRAYSCALE)
```

- Why? (Difficulty)
  - Three-dimensional comparison? (e.g. [0, 75, 0] vs. [25, 25, 25])
  - Three-dimensional transformation → Natural color?

- Ad-hoc solutions
  - ~~Idea #1) Apply the algorithm to each RGB channel~~
  - Idea #2) Apply the algorithm to **the luminance channel**
    - e.g. RGB → **Y**CbCr → RGB
    - Note) The definition of luminance is important.

Color

L*a*b*

I (Intensity)

HS**V**

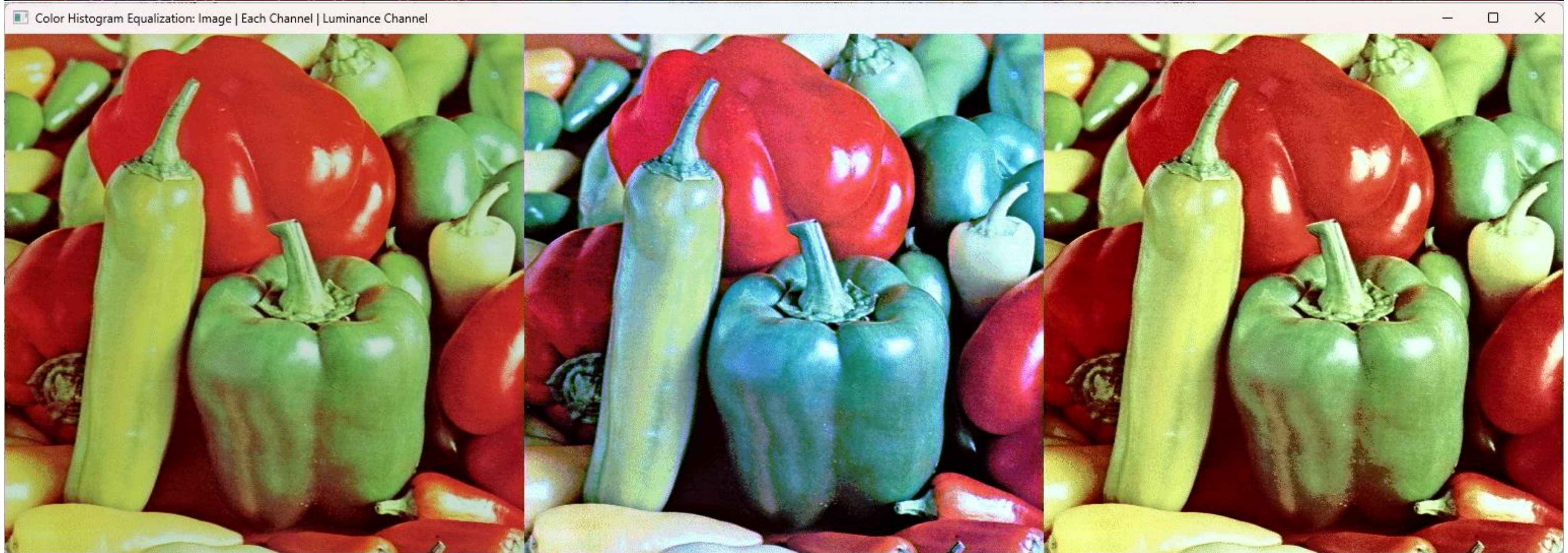
HS**L**

Solutions to Algorithms only for Gray-scale Images

- Example) Color histogram equalization

```
img_list = [...]

# Initialize a control parameter
img_select = 0

while True:
    # Read the given image
    img = cv.imread(img_list[img_select])

    # Apply histogram equalization to each channel
    img_hist1 = np.dstack((cv.equalizeHist(img[:,:,0]),
                           cv.equalizeHist(img[:,:,1]),
                           cv.equalizeHist(img[:,:,2])))

    # Apply histogram equalization only to the luminance channel in YCbCr
    img_cvt = cv.cvtColor(img, cv.COLOR_BGR2YCrCb)
    img_hist2 = np.dstack((cv.equalizeHist(img_cvt[:,:,0]),
                           img_cvt[:,:,1],
                           img_cvt[:,:,2]))
    img_hist2 = cv.cvtColor(img_hist2, cv.COLOR_YCrCb2BGR)

    # Show all images
    merge = np.hstack((img, img_hist1, img_hist2))
    cv.imshow('Color Histogram Equalization: Image | Each Channel | Luminance Channel', merge)
    key = cv.waitKey()
    if key == 27: # ESC
```


Color Histogram Equalization: Image | Each Channel | Luminance Channel


Color Histogram Equalization: Image | Each Channel | Luminance Channel

Summary

- Review) Geometric Image Formation
- **Photometric Image Formation**
  - CCD/CMOS sensor: Light intensity sensor
  - Color camera = **Bayer filter** + CCD/CMOS sensor
- **Color Spaces**
  - Color spaces for **media**: RGB, CMY(K), YCbCr, and YUV
  - Color spaces for **human-friendly color selection**: HSV, HSL, and Munsell
  - Color spaces for **human visual perception**: XYZ, xzY, LAB (L*a*b*), and LUV (L*u*v*)
  - Example) Color space conversion
- How to use algorithms only support gray-scale images
  - Example) Color histogram equalization
  - Note) There are many definitions for luminance.