# Color

- Physical Color
- Digital Color
- Color Manipulation

# What Is Color

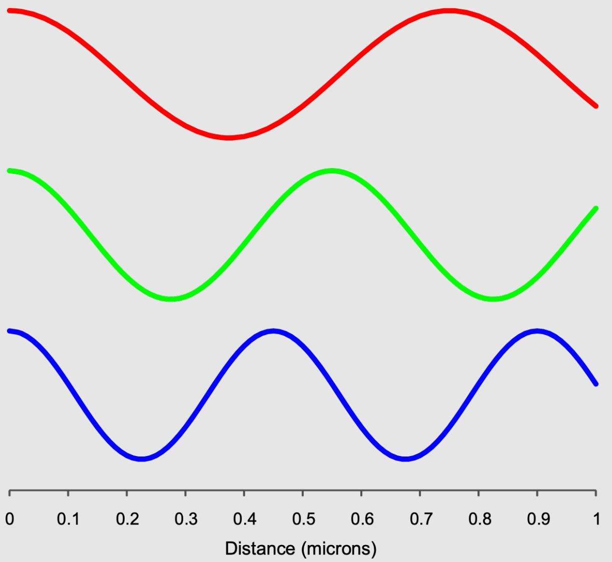
- Color can also be thought of an object's **visual response** to light
  - A green plant without light will be black
  - A green plant with light will absorb some energy for photosynthesis, and then emit some green light
    - This emission is its visual response

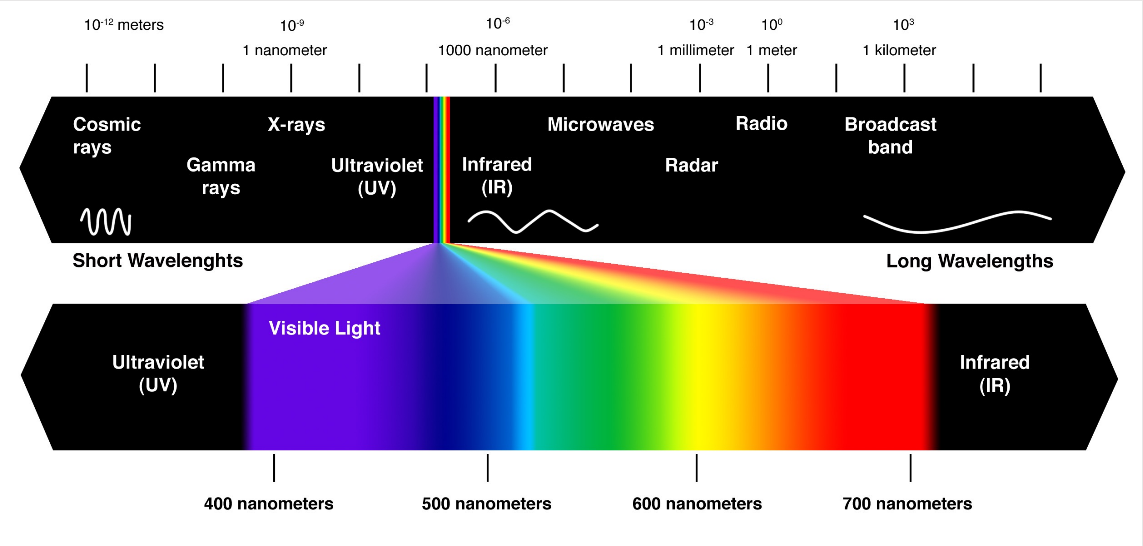
- Color gives us a language for communicating similar energies that our eyes pick up
  - **Example:** picking colors for a house


A Lowe's, Probably.

# What Is Light

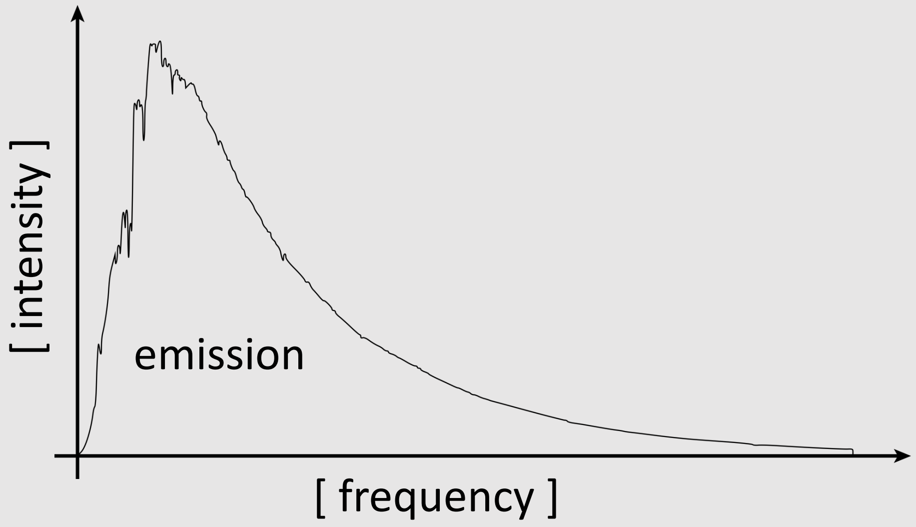
- Light is electromagnetic radiation
  - Generated as an oscillation in the electromagnetic field
  - Is light a wave, or a particle?
    - Yes.
- The frequency of oscillation determines the color of light
  - Most light is not visible!
  - Frequencies visible are a part of the **visible spectrum**
- White is the combination of all visible frequencies
- Black is the absence of all visible frequencies
- Color is a range of frequencies
  - Scientifically referred to as a **spectrum**



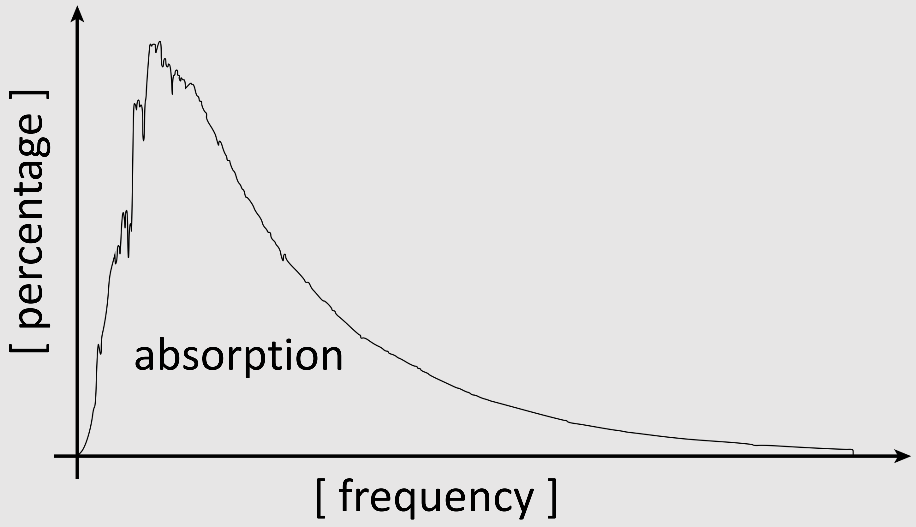



# Light Spectrums

- **Emission spectrum** describes range of light frequencies emitted from a light source
  - Combination of frequencies gives the overall light color
  - Integrating over the spectrum gives the energy output
  - Higher energy output = more energy required to power
    - **Example:** light bulb
  - Measured as intensity per frequency

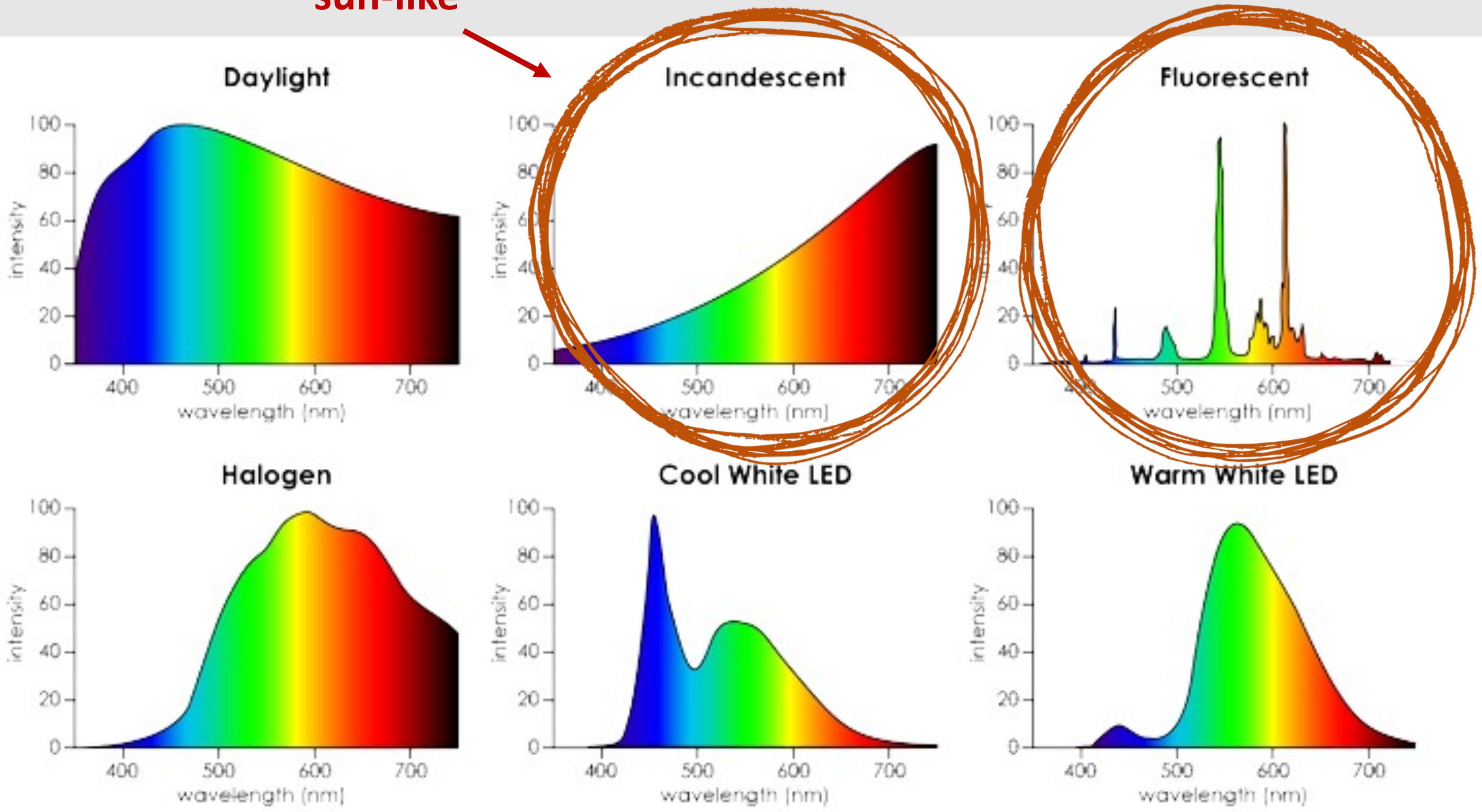



- **Absorption spectrum** describes range of light frequencies absorbed from a light source
  - Frequencies not absorbed are reflected back
  - Measured as percent absorbed per frequency



# Emission Spectrum Examples

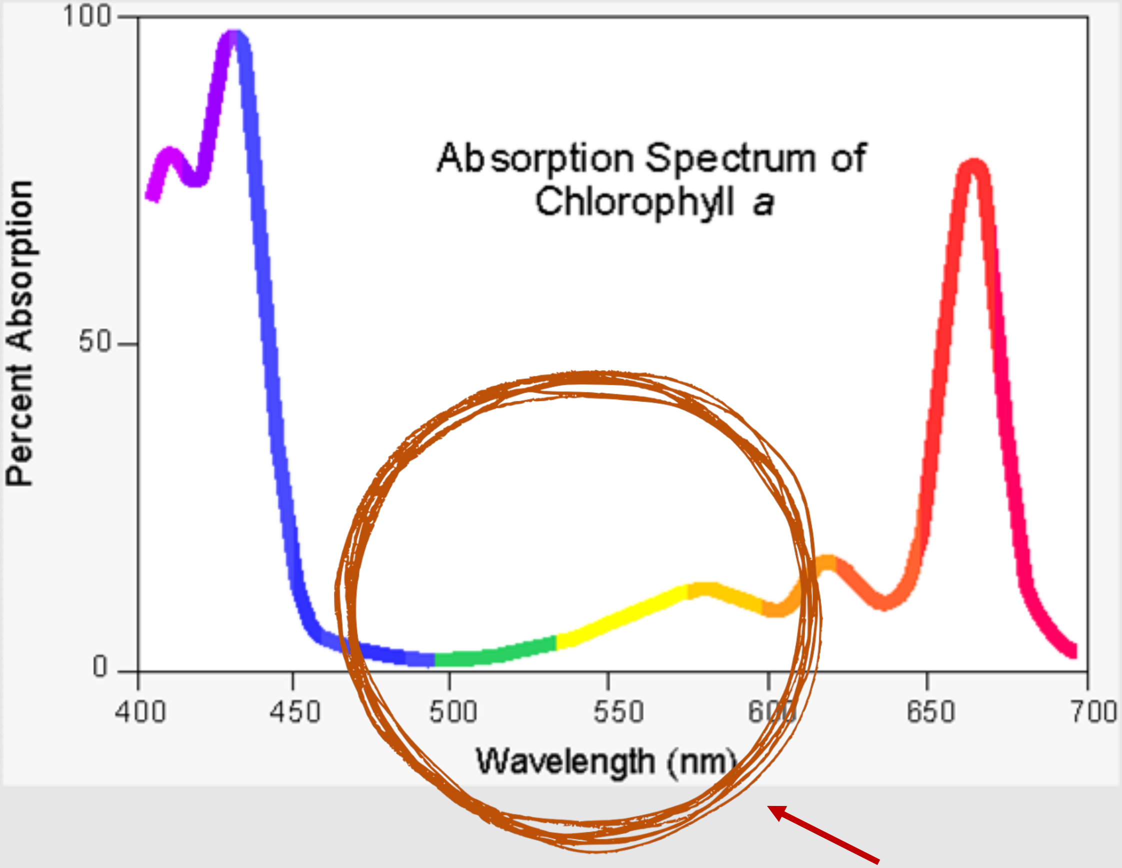
sun-like




energy efficient

admesy
ADVANCED MEASUREMENT SYSTEMS

# Absorption Spectrum Examples




**plants are green because they do not absorb green light**

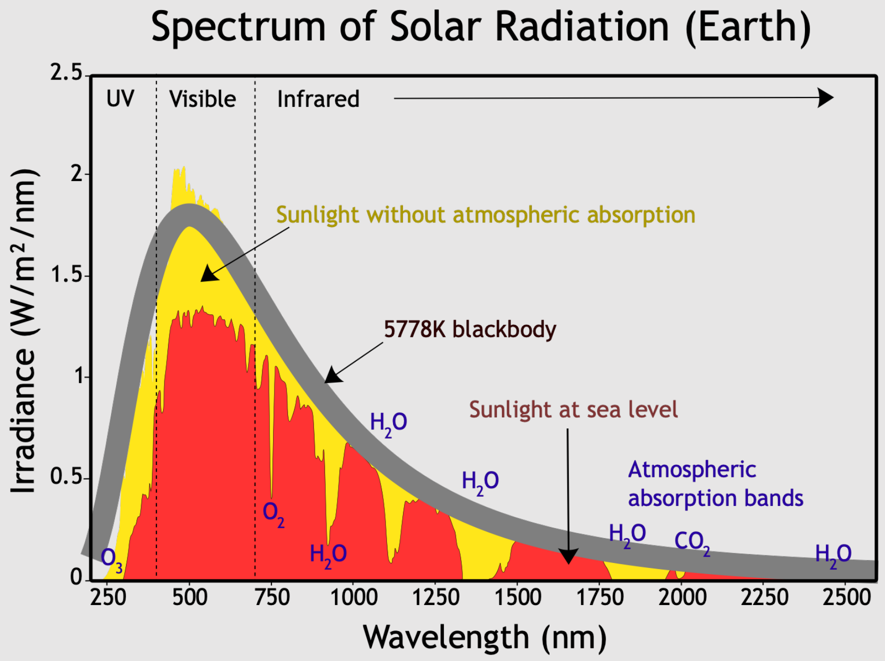
# Absorbed Light

- Converted to heat
  - Wearing dark clothes makes you warmer
- Converted to fuel biological ecosystem
  - Photosynthesis requires energy to move around electrons
- Converted to electrical energy
  - Solar panels are black to absorb as much visible light

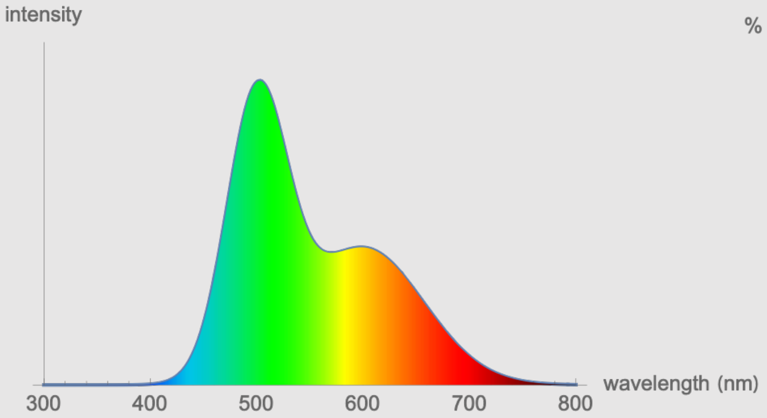
**This thing absorbs everything**
**( he absorbed my pizza rolls once )**

# So What Is Color

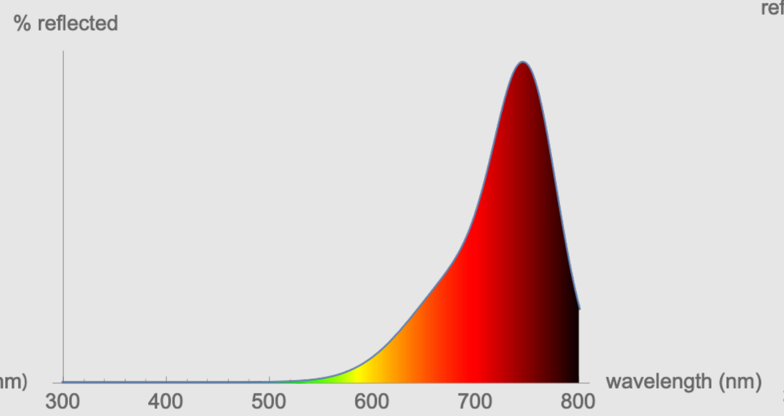
- Color is emission multiplied by the reflectance
  - Reflectance is whatever percentage is not absorbed
- The sun’s emission is near-equal parts of all visible light
  - Reason why everything is its ‘true’ color under sunlight



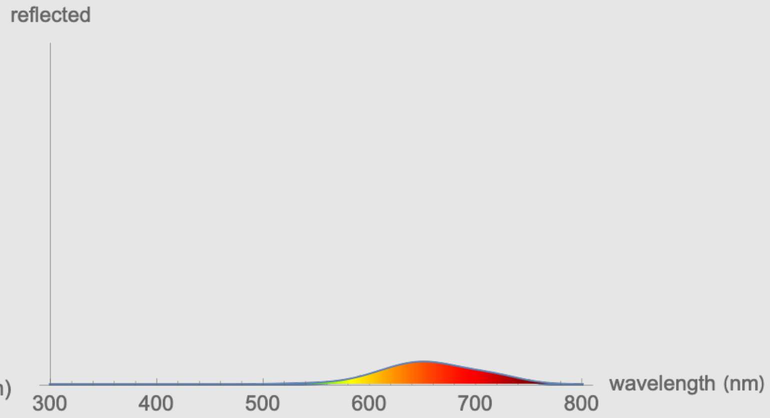

Emission Spectrum E(v)




Reflectance Spectrum R(v)




Result Reflected ER(v)



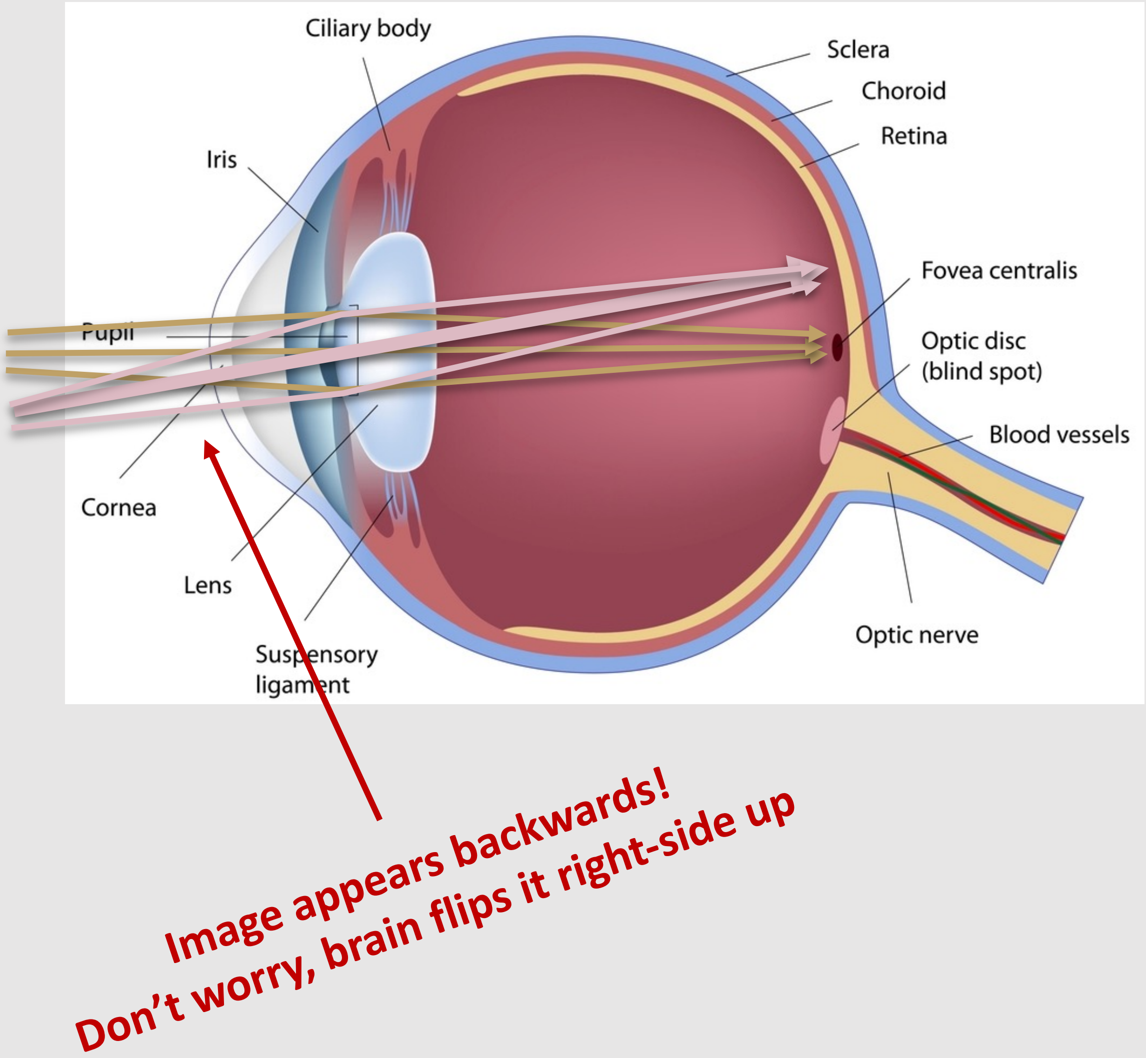
# Color By Emission

- We can change the color of objects by changing the emitted light
  - Plants under red light will appear red, etc.
- Red and blue plants appear much darker
  - Most light absorbed for photosynthesis
- Can also use non-visible light (UV) to show colors not originally there

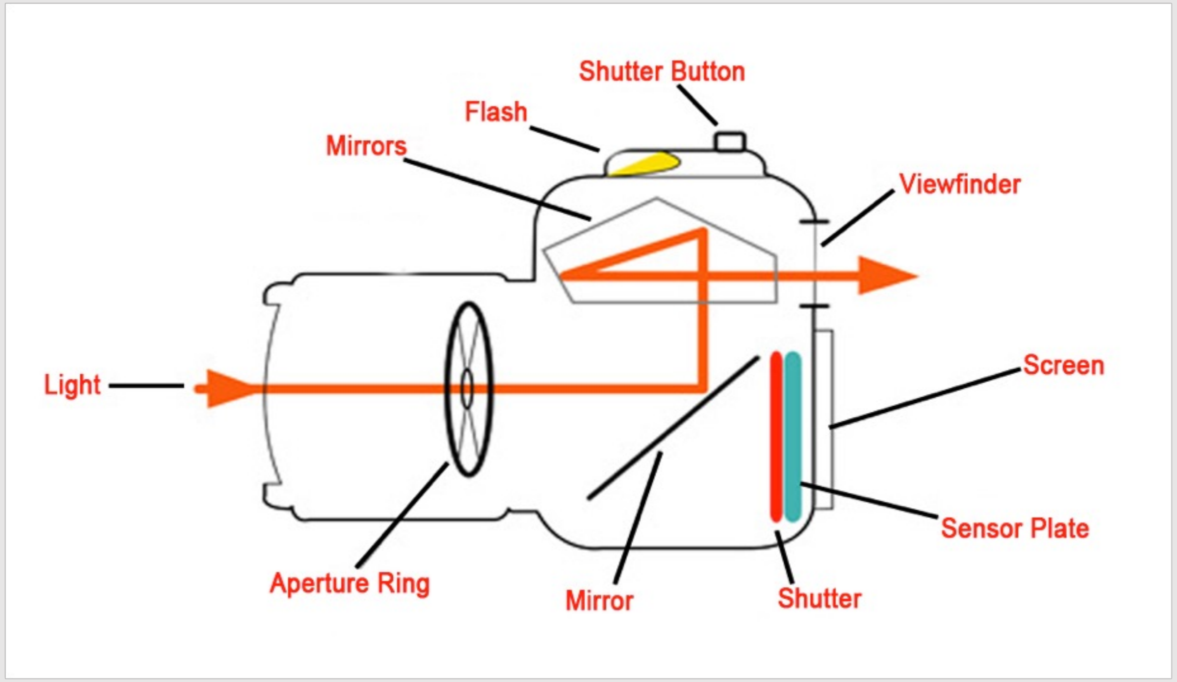
# 'Eye' See What You Mean

- Eyes are biological cameras
  - Light passes through the pupil [black dot in the eye]
  - Iris controls how much light enters eye [colored ring around pupil]
    - Eyes are sensitive to too much light
    - Iris protects the eyes
  - Lens behind the eye converges light rays to back of the eye
    - Ciliary muscles around the lens allow the lens to be bent to change focus on nearby/far objects

- 130+ million retina cells at the back of the eye
  - Cells pick up light and convert it to electrical signal
  - Electric signal passes through optic nerve to reach the brain

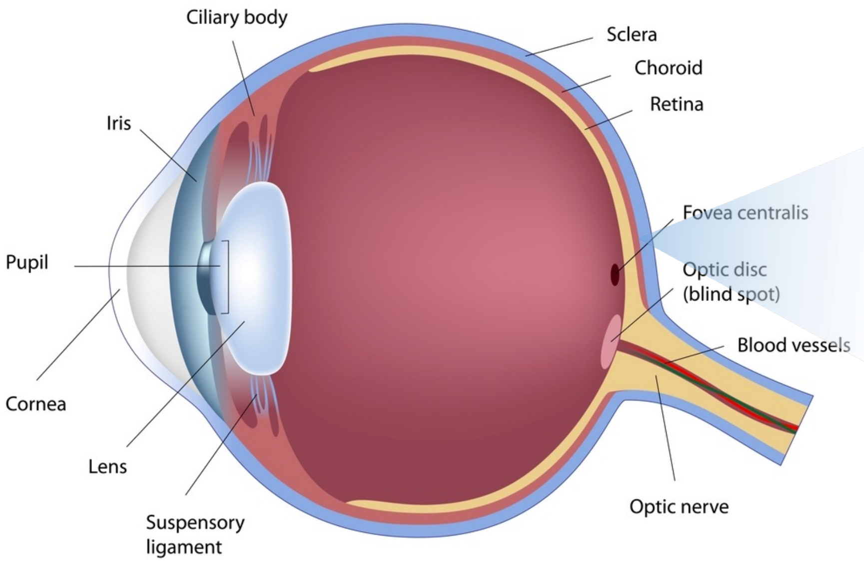


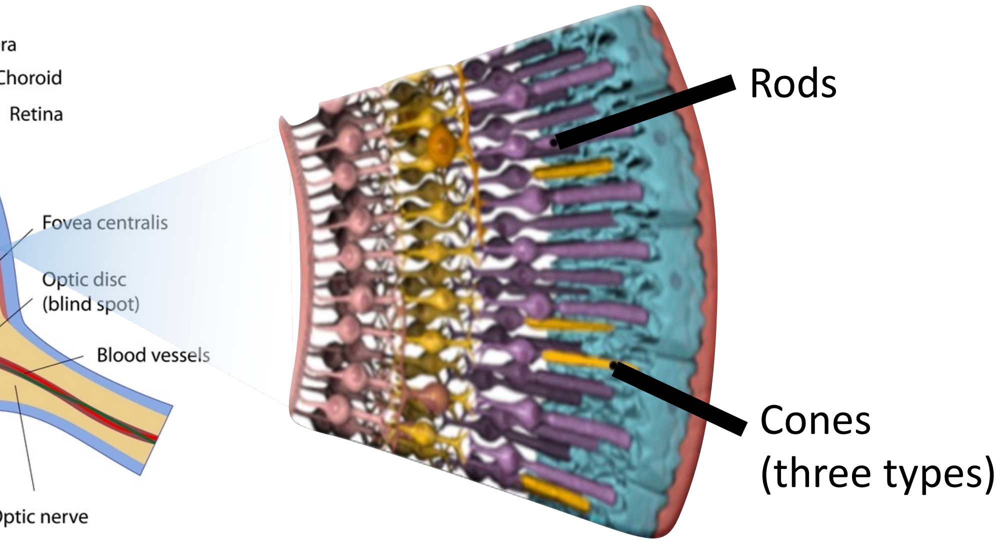
# The Biological Camera

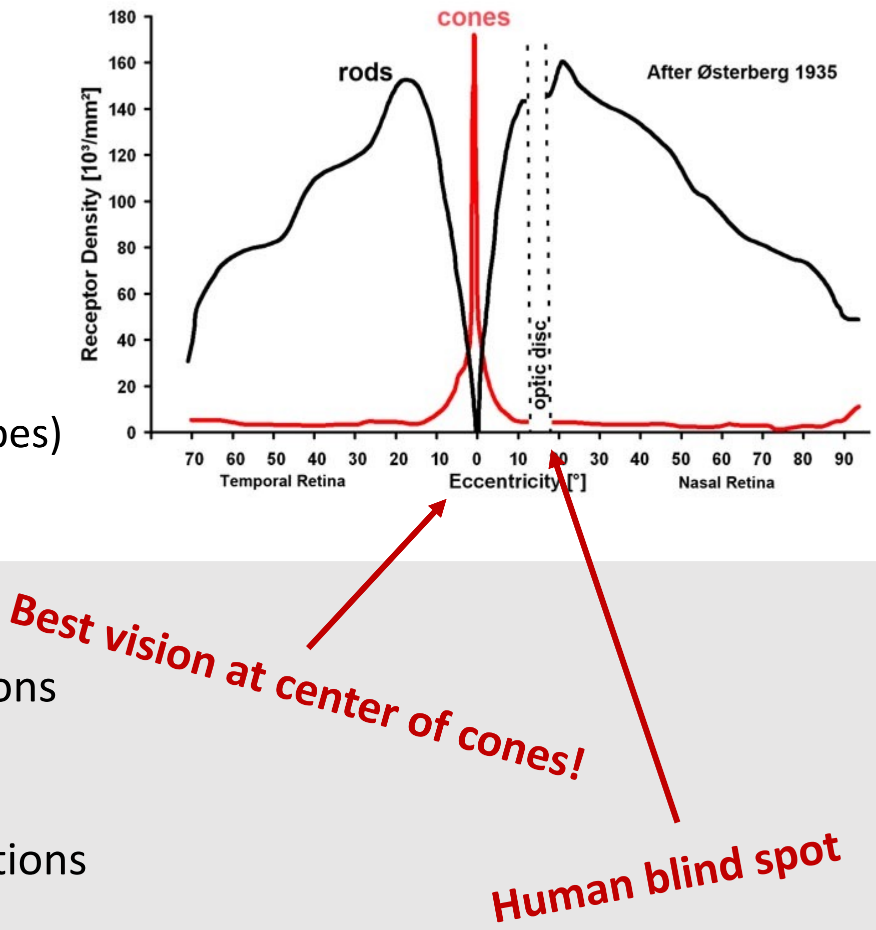



- **Pupil** is the **camera opening**
  - Allows light through
- **Iris** is the **aperture ring**
  - Controls aperture
- **Lens** is the…well, **lens**
  - Can change focus
- **Retina** is the **sensor**
  - Converts light into electrical signal
- **Brain** is the **CPU**
  - Performs additional compute to correct raw image signal

# Rods & Cones

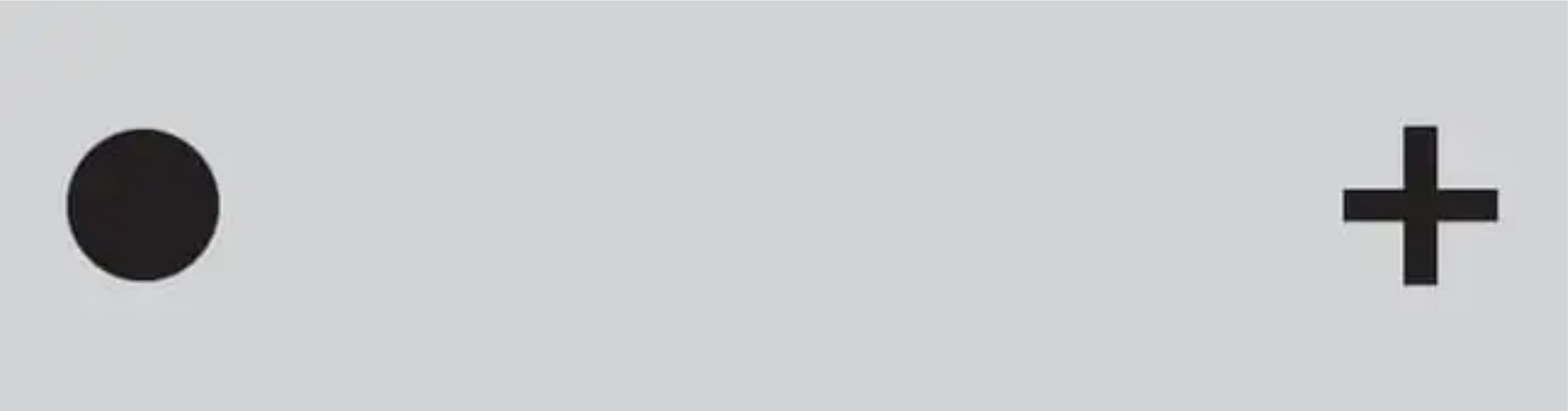



- Cones are primary receptors near fovea used under high-light viewing conditions
  - Approx. 6-7 million cones in the human eye
  - Capture color
- Rods are primary receptors far from fovea used under low-light viewing conditions
  - Approx. 120 million rods in human eye
  - Capture intensity

# A Little Trick



- Close left eye
- Stare at the circle
- Move closer to the screen
- Move farther from the screen
- Continue until the plus sign disappears

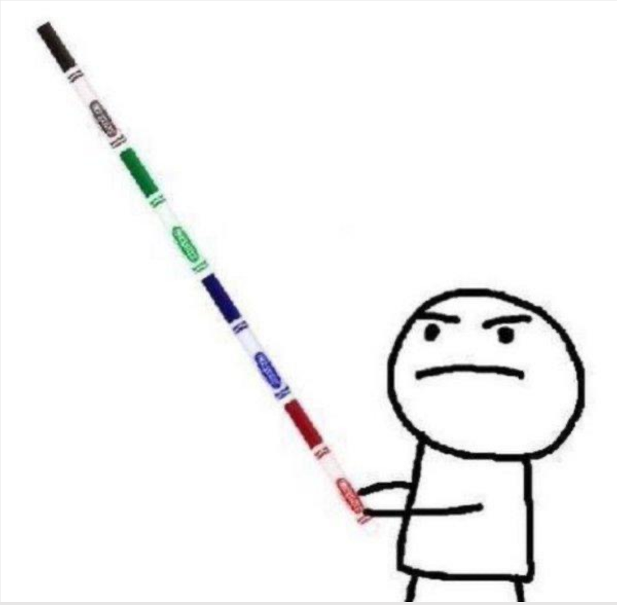
- Close right eye
- Stare at the plus
- Move closer to the screen
- Move farther from the screen
- Continue until the plus sign disappears

Works best on a laptop/device close to you!**

**https://www.webmd.com/eye-health/what-to-know-blind-spots-scotoma

# Another Little Trick

- Grab someone and try it at home!
  - Have them hold up colored markers in peripheral [side] vision, bringing closer to center
  - Once you see a marker, guess the color
    - As the marker comes closer to center, did you get the color right?



# Spectral Response of Cones

- Long, Medium, and Small cones pick up Long, Medium, and Small wavelengths respectively
- Each cone picks up a range of colors given by their response functions
  - Not much different than absorption spectrum

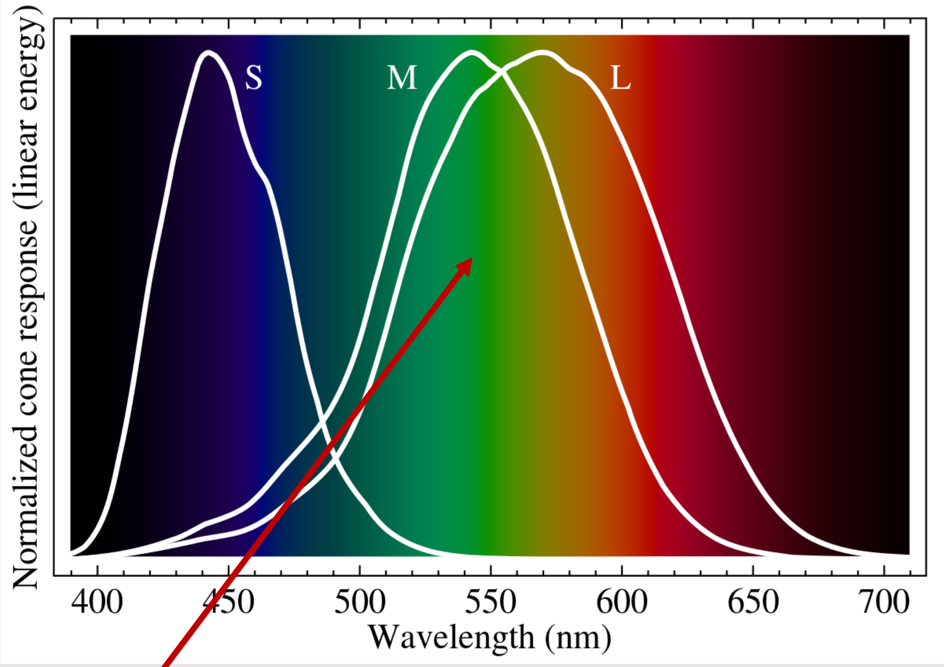
- Each cone integrates the emission & response to produce a single signal to transmit to the brain

$$S = \int_\lambda \Phi(\lambda) S(\lambda) d\lambda$$

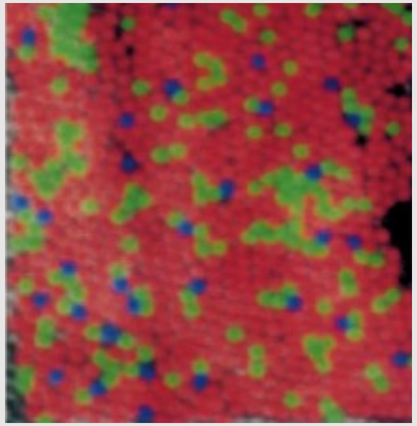
$$M = \int_\lambda \Phi(\lambda) M(\lambda) d\lambda$$

$$L = \int_\lambda \Phi(\lambda) L(\lambda) d\lambda$$

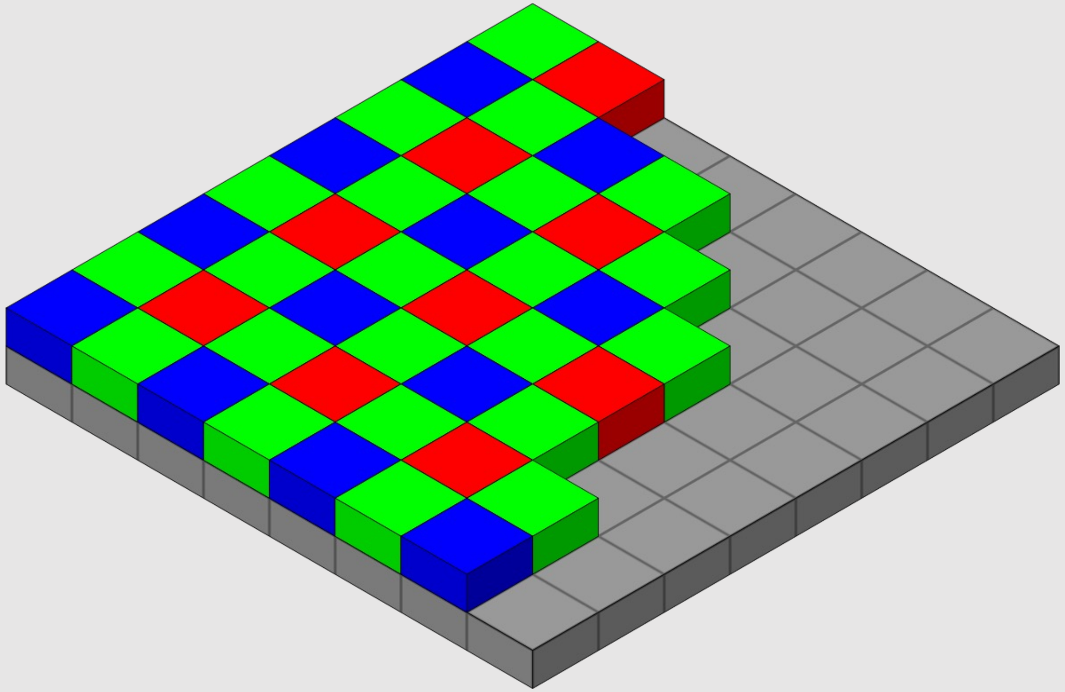
- Uneven distribution of cone types in eye
  - ~64% L cones, ~ 32% M cones ~4% S cones

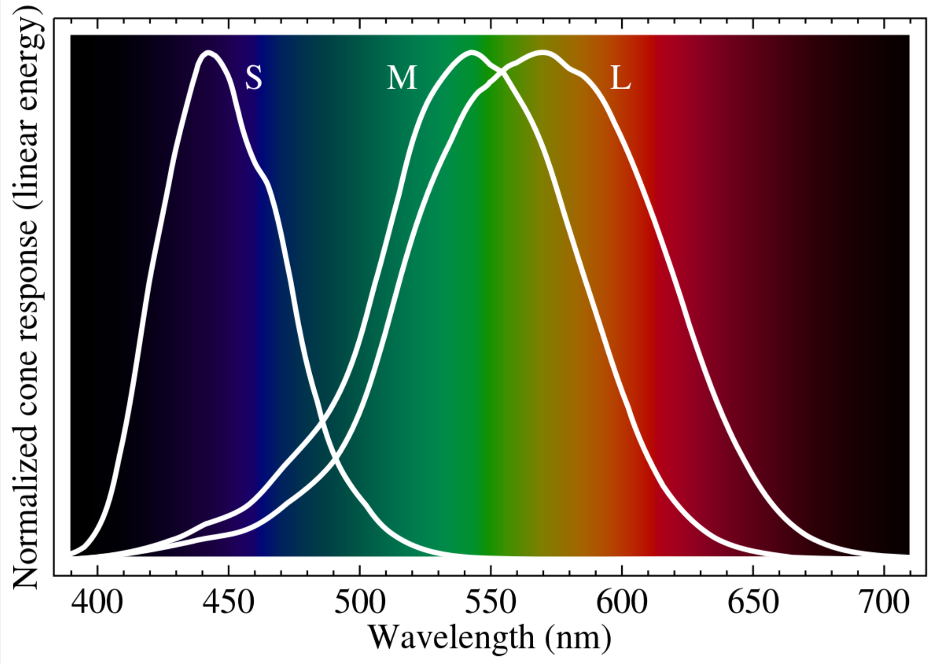



A lot of green picked up!



# The Biological Camera [Again]






- Eyes perceive green color better than any other color
  - Thought to be an evolutionary property of humans
  - Sun emits more green light, our eyes adapt to capture more green light

- Camera sensor has 2x as many green sensors as blue or red

# King of the See

- **Mantis Shrimp** are a larger breed of shrimp that live in tropical waters
  - Known to have the most complex eyes of any creature studied on Earth

- Humans have 3 different cone receptors (SML)
  - These guys have 12
  - Can also detect UV and polarized light

- Does this mean shrimp see better than us?
  - Cognitive ability of a shrimp is much less than humans, leading shrimp to have a hard time distinguishing between colors

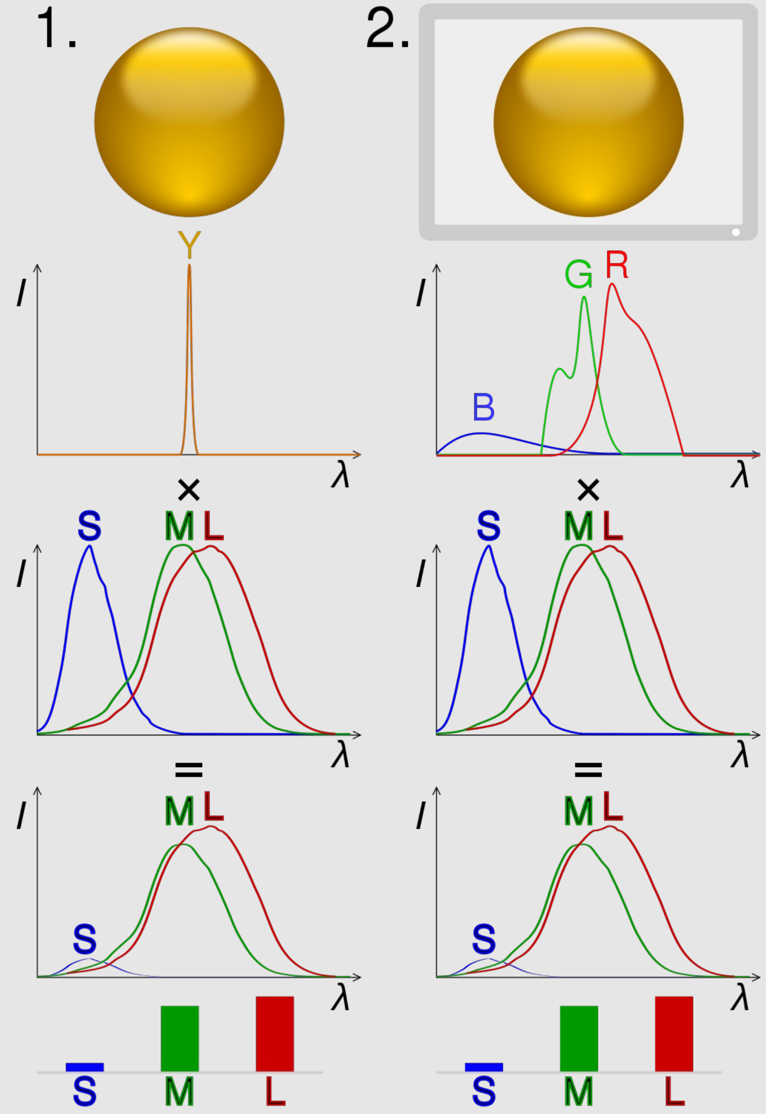
- **Lesson:** to have good eyes, you need a good brain

# Metamers

- Different spectrums can be integrated over the SML activations to produce the same SML colors
  - Yellow can be made from yellow wavelengths
  - Yellow can also be made from equal parts red and green wavelengths

- Important for color reproduction!
  - No need to capture the entire spectral distribution, just the end SML values are enough
    - **Led the way for digital color spaces**

- **Problem:** trying to represent colors in print
  - Digital colors (pixels) have full control of emission
  - Physical colors (prints) only have control of absorption
    - Changing the emission (lighting) will change the resulting image colors



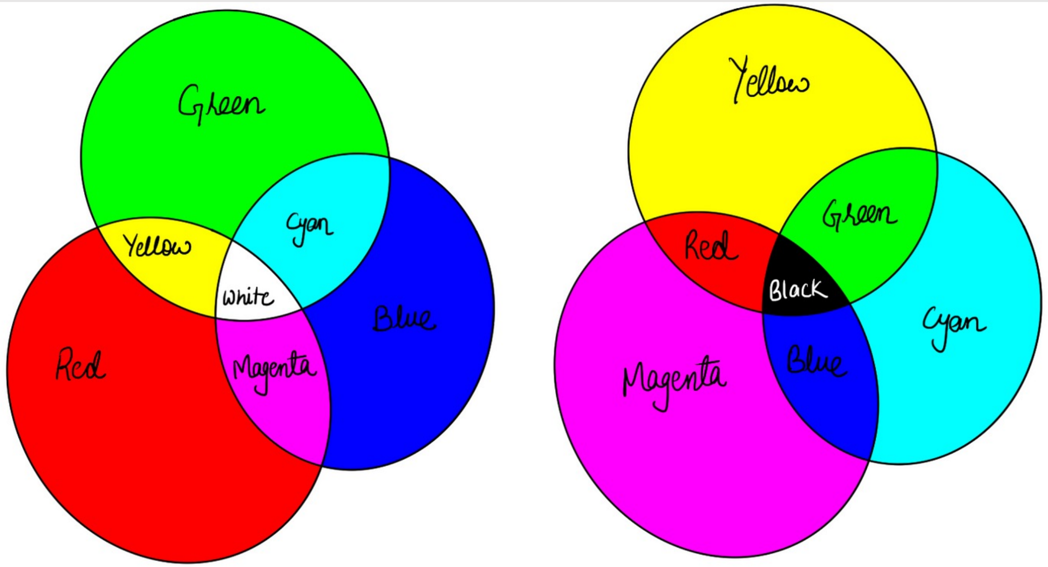
- ~~Physical Color~~
- Digital Color
- Color Manipulation

# Color Models

- Things to consider when picking a color:
  - Gamut
    - The area of color that is covered
  - Conversion
    - Converting from digital to print
  - Convenience
    - Easy for users to pick the color they want
  - Storage
    - Low data overhead

- **Additive color** starts with black and add colors
  - **Ex:** a black display emits no light, turning on RGB pixels adds a blending of emissions to create colors in regions
  - **Common:** RGB

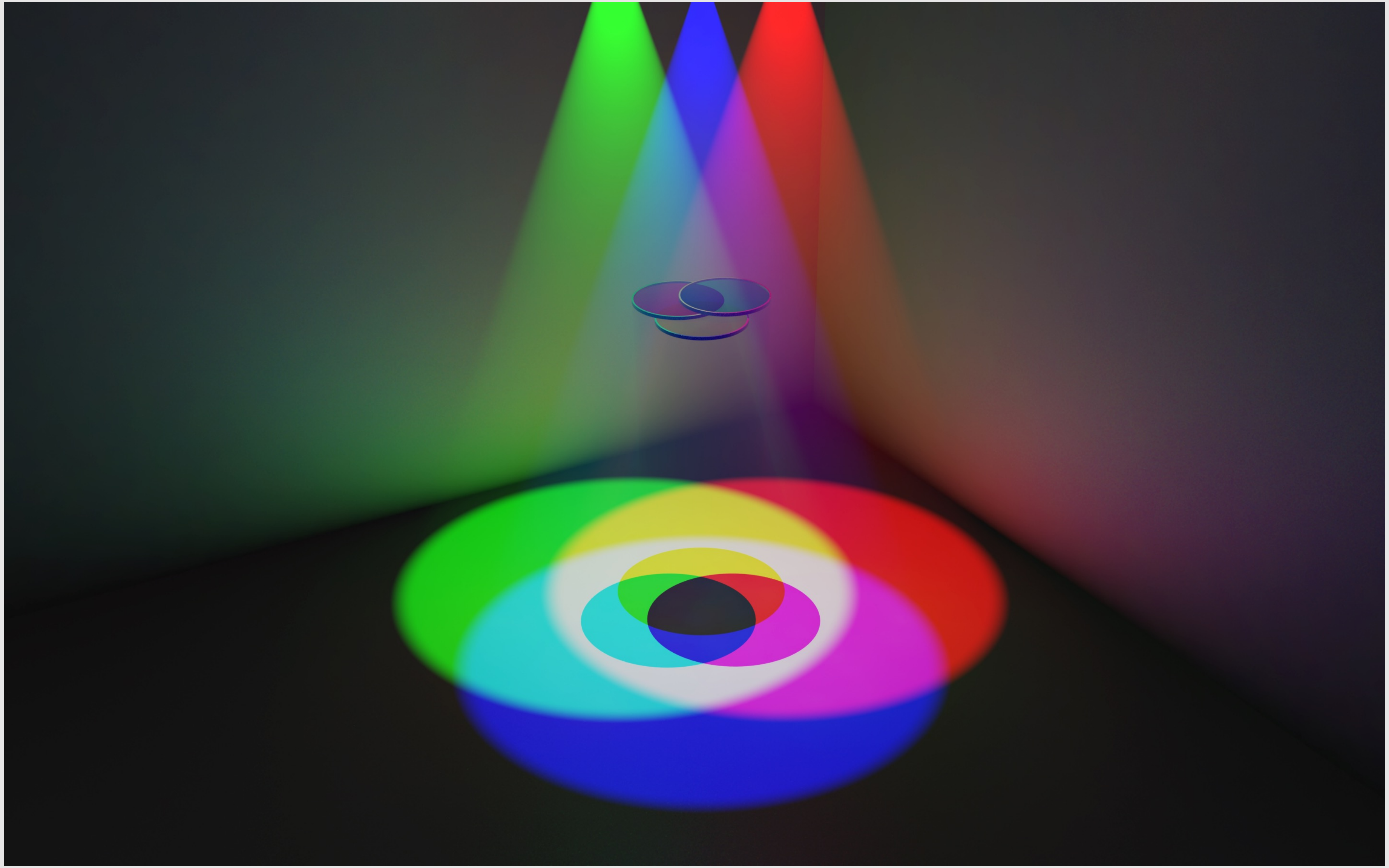
- **Subtractive color** starts with white and remove colors
  - **Ex:** a white paper reflects all light, printing on a paper removes reflectance of certain colors in printed areas
  - **Common:** CMYK




Mixture of Light (Additive Primaries)

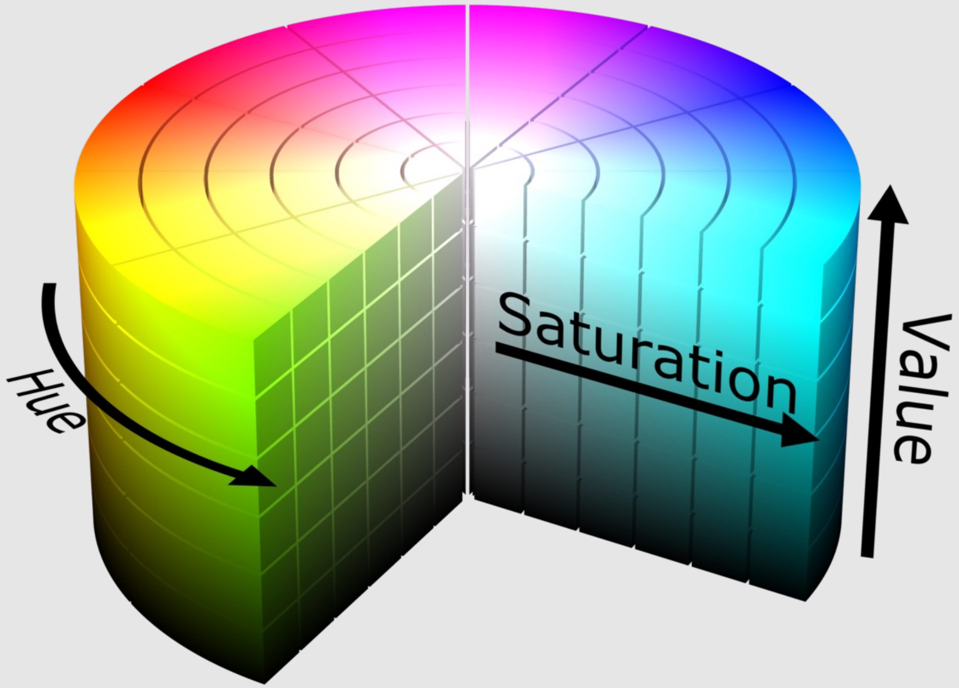
Mixture of Pigments (Subtractive Primaries)

# Let’s Shed Some Light Here

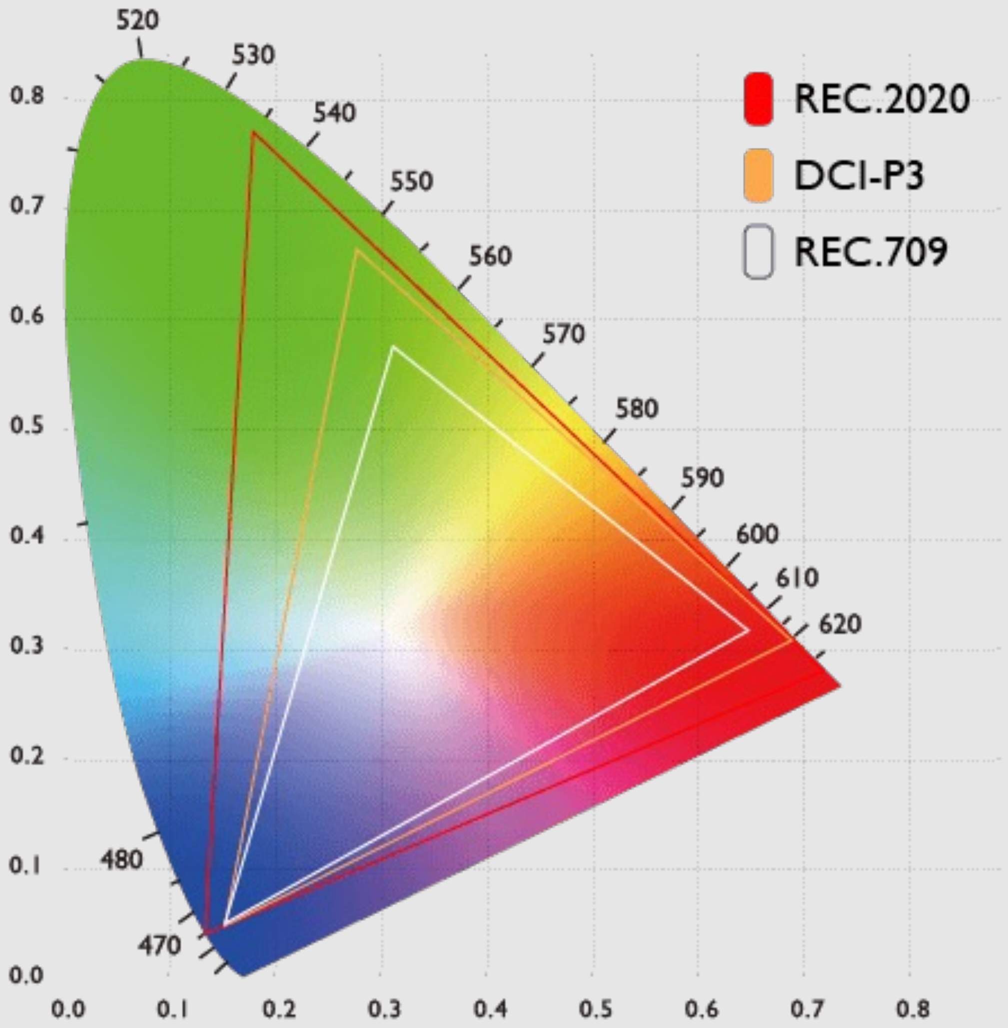


# Types of Color Models

- **RGB [ Red Green Blue ]**
  - Ubiquitous RGB displays
- **CMYK [ Cyan Magenta Yellow Key ]**
  - Common for printing
- **HSV [ Hue Saturation Value ]**
  - Most intuitive
- **SML [ Small Medium Large ]**
  - Weighted average of cone response spectrums
- **XYZ [ 3D color space ]**
  - Absolute color space



# Absolute Color Spaces



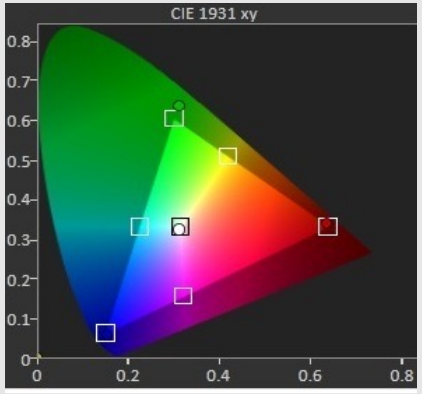

- An **absolute color space** will always present the same color given the same coordinates
  - RGB is not an absolute color space
  - XYZ is an absolute color space
    - CIEE XY space drops Z (luminance)
- **Idea:** define RGB color space as 3 vertices on the CIEE XY color space

$$
\begin{aligned}
R &= 0.65x + 0.31y \\
B &= 0.15x + 0.05y \\
G &= 0.31x + 0.57y
\end{aligned}
$$

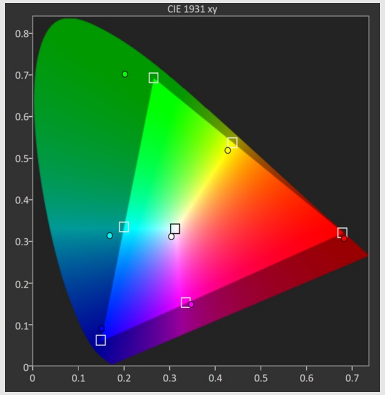
  - Any color within the triangle can be produced with an RGB display
  - Can share common RGB spaces for consistency:
    - REC.709
    - DCI-P3
    - REC.200

# Absolute Color Spaces


$799

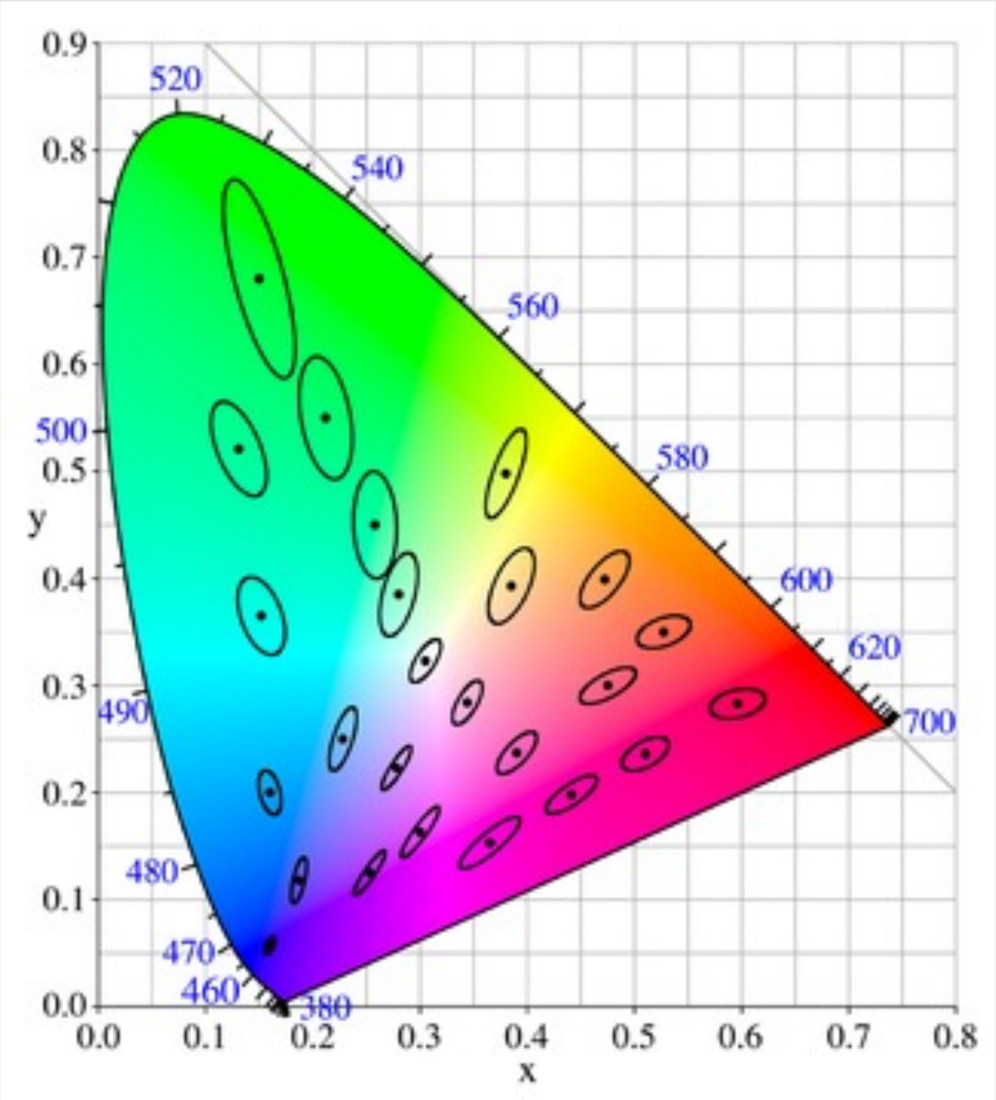



$1999




Producing high-range RGB color displays aren't cheap.

# MacAdam Ellipses

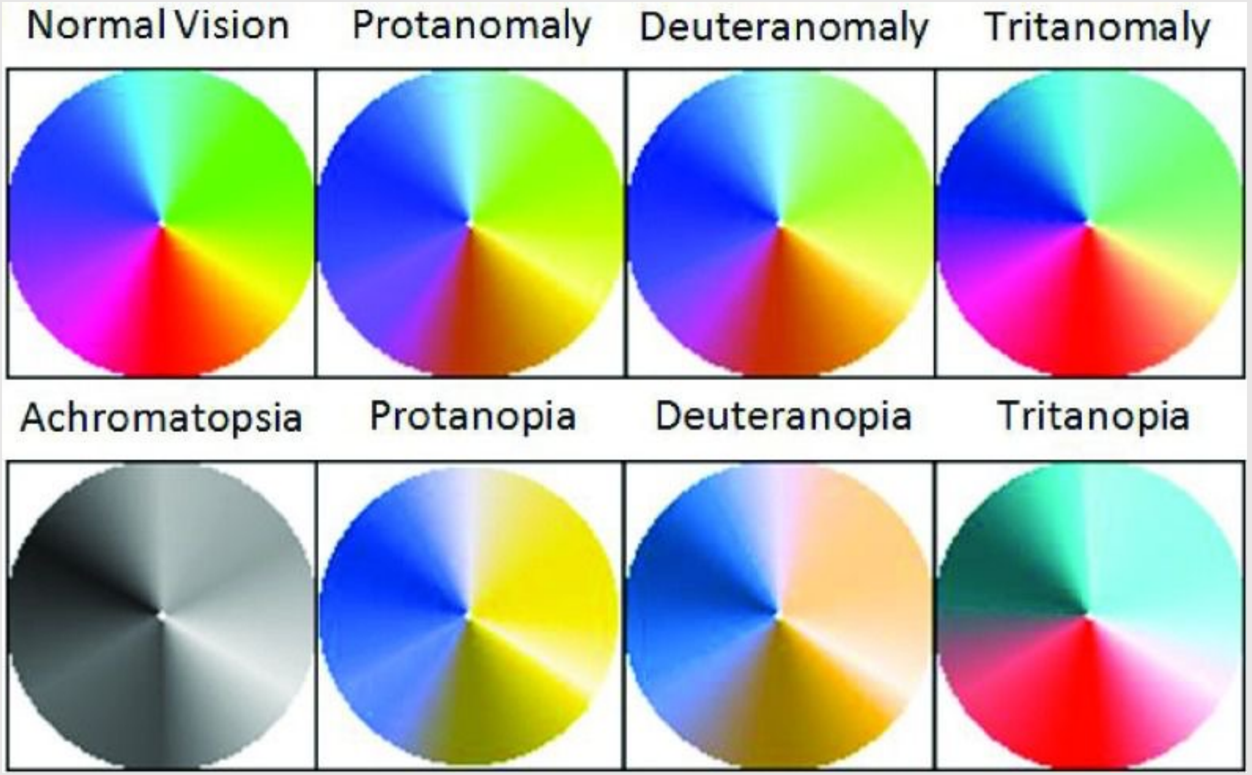



- Any color sampled from an ellipse is the same as the color in the center to the human eye
    - Not a transitive property: two colors on the extreme will look different

- **Chromaticity** is a color absent of any luminance
    - Radius of ellipse in a given direction measures the lack of chromaticity difference in changing a given color by a given amount to the human eye

# Nonstandard Color Vision

- Morphological differences in eye can cause people & animals to see different ranges of color
  - 2 cones instead of 3
  - Different response functions per cone
  - Different cone sensitivity
  - More or less cones
- Alternative chromaticity diagrams help visualize color gamut, useful for designing, e.g., widely-accessible interfaces
- **Important for color theory:** pick colors that are universally (or as universally) recognizable as possible



# Encoding Color Values

- RGB colors commonly encoded as 8-bits per channel
  - 256 possible values
  - If including alpha, add another 8 bits
    - Displays can now handle 16/24/32 bit channels
    - Continue to use 8-bits for backwards compatibility

- Hex format: #1B1F8A
  - 2 hex digits = 8 bits
  - Common in web development

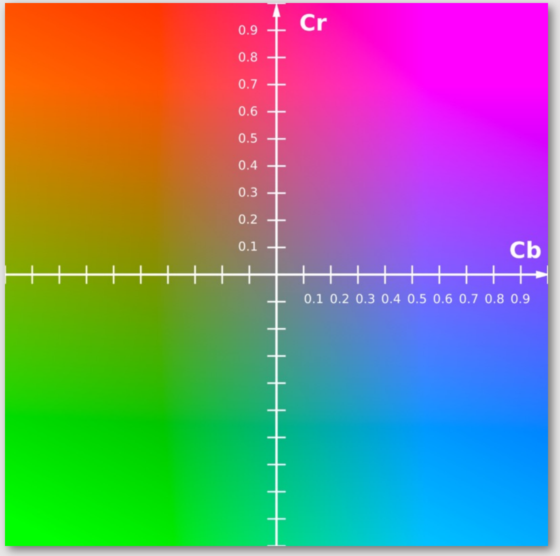
- Uint8 format: (27, 31, 138)
  - Range of 0 - 255
  - Maps to displays easily

- Float format: (0.106, 0.082, 0.541)
  - Range of 0.0 – 1.0
  - Better precision with operation
  - Requires conversion to Uint8 at the end

# Compressing Colors

- **Y'CbCr** color scheme common for modern digital video
  - **Y'** = luma: perceived luminance
  - **Cb** = blue-yellow deviation from gray
  - **Cb** = red-cyan deviation from gray

- Great compression properties!
  - **Y'** channel holds high frequency data
  - **Cb, Cr** channels hold low frequency data




**[ original ]**

**[ Y' channel ]**

**[ Cb channel ]**

**[ Cr channel ]**

# Compressing Colors

Human vision much more sensitive to luminance than color!

[ original ]

[ full res Y' ]

[ low res CbCr ]

[ composite ]

Downsampled by a factor of 20 in each dim.
400x less samples

- ~~Physical Color~~
- ~~Digital Color~~
- Color Manipulation

# Color Conversion

- Convert color from one model (RGB) to another (CMYK)
  - In a perfect world, want to match output spectrum
  - Even matching perception of color would be terrific (metamers)
- In reality, information will be lost
  - Depends on the gamut of the output device
- Lots of standards & software
  - ICC Profiles
  - Adobe Color Management

**[ RGB ]**

**[ CMYK ]**

# Color Conversion


- Difficulty converting between colors
  - **RGB -> RGBA**
    - Fill alpha value with 1.0
  - **RGBA -> RGB**
    - Pre-multiply alpha value
    - Drop alpha value altogether
  - **Grey -> RGB**
    - Copy grey value to each channel
  - **Grey -> RGBA**
    - Convert Grey -> RGB then RGB -> RGBA
  - **RGB -> Grey**
    - Take the average of each channel
    - Take a weighted average based on human perception
  - **RGBA -> Grey**
    - Convert RGBA -> RGB then RGB -> Grey

# Brightness & Contrast

- Consider a color mapping from the range [0.0, 1.0]:

$$y = x$$

- Brightness brings colors closer to white or black

$$y = x + b$$

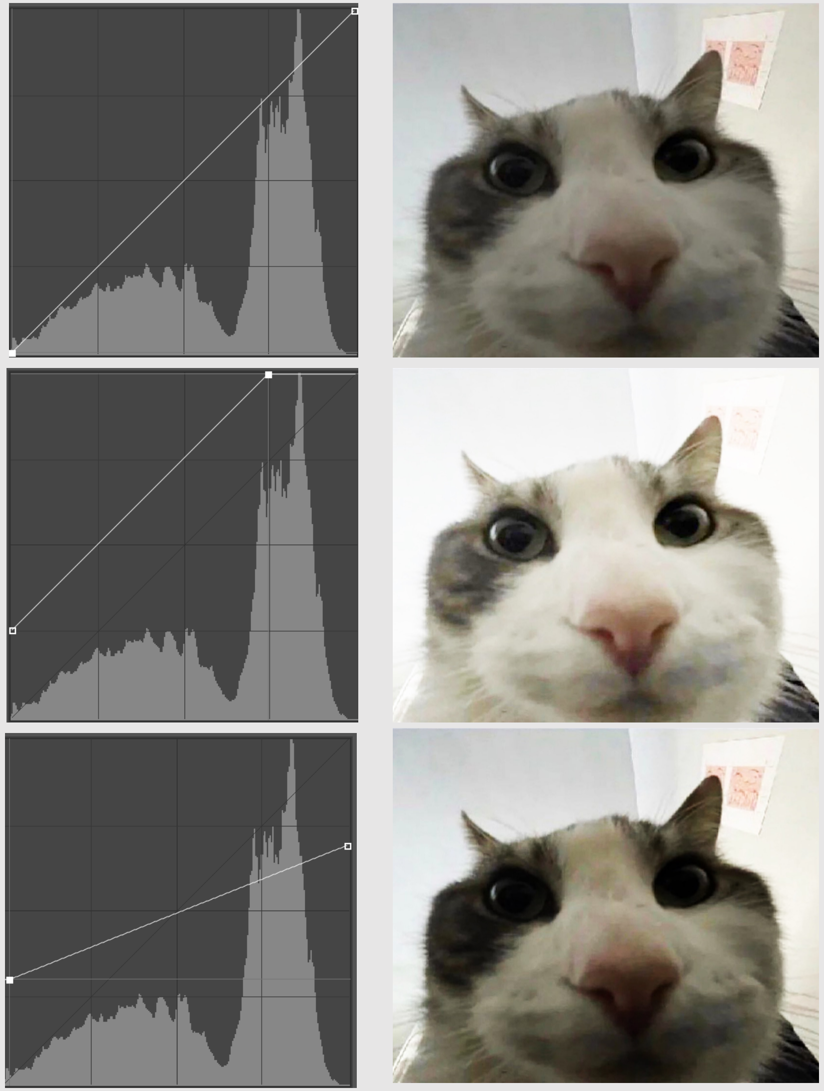
- Contrast brings colors closer to the average grey color

$$y = c * (x - 0.5) + 0.5$$

- They can be combined as a 2-for-1 deal
  - Commonly found as a single effect in most color-grading software:

$$y = c * (x - 0.5) + 0.5 + b$$

- **Values must be clamped back to range [0.0, 1.0]!**



[ original ]

[ brightness ]

[ contrast ]

# Saturation

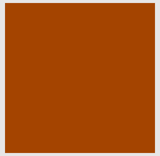
- Saturation moves colors closer or farther from their 'max' value
  - Compute the greyscale value of a color using the weighted greyscale average:

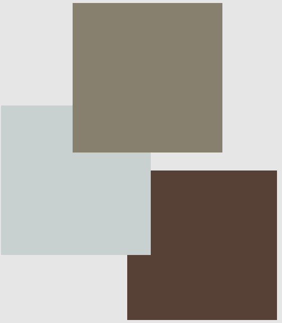
    $x.grey = 0.299 * x.r + 0.587 * x.g + 0.114 * x.b$

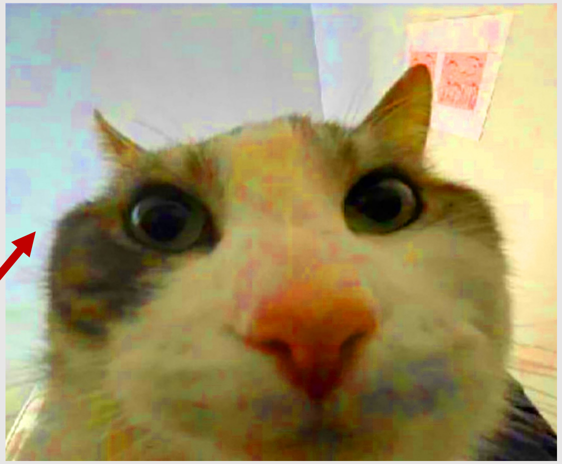
  - Linearly interpolate the original color with the grey color:

    $y = a * x + (1 - a) * x.grey$

  - If $a > 1$ then the output image becomes oversaturated
  - If $a < 0$ then the output image becomes undersaturated

$2 *$  $- 1 *$  = 





artifacts of jpeg compression!

# Gamma Correction

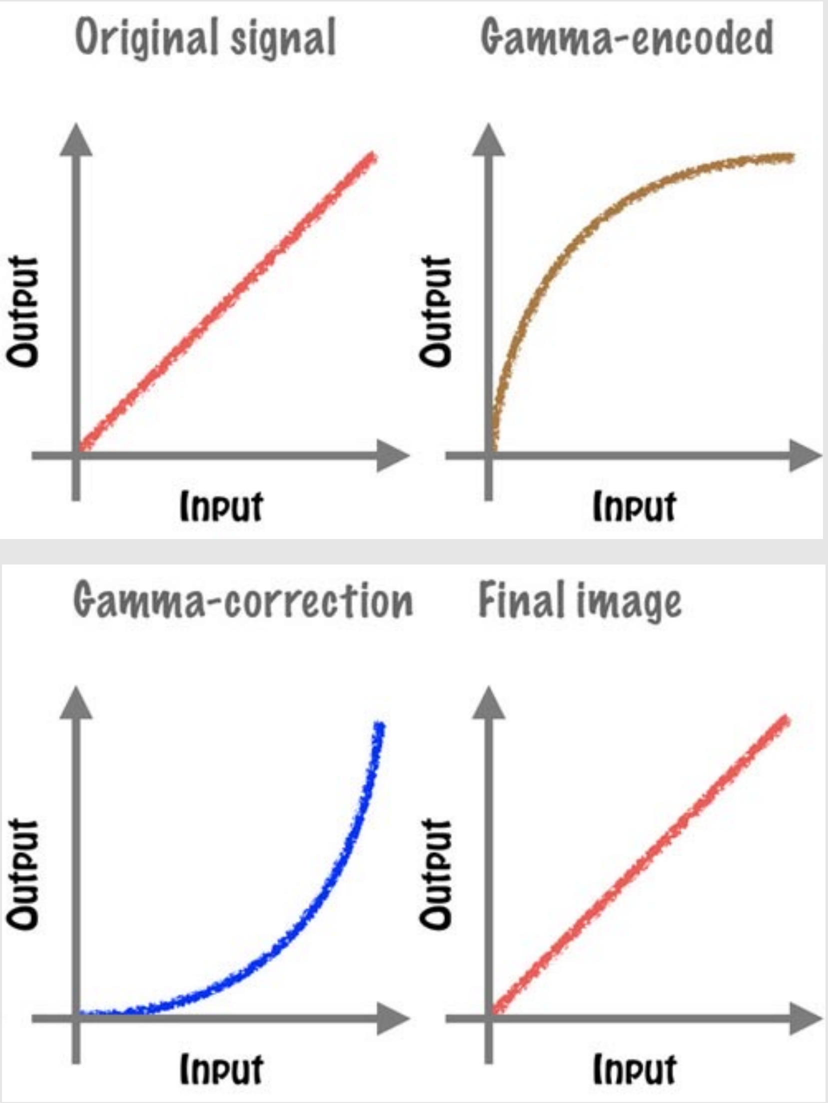
- When we look at an object, using two lights does not make it twice as bright **[non-linear]**
  - When a camera captures an object, using two lights emits two times the amount of photos, and the sensor picks up twice as many photons, making the observation twice as bright **[linear]**

- Cameras have a tendency to map colors too brightly, while having a hard time capturing darkness
  - Gamma correction modifies the signal by some $\gamma$:

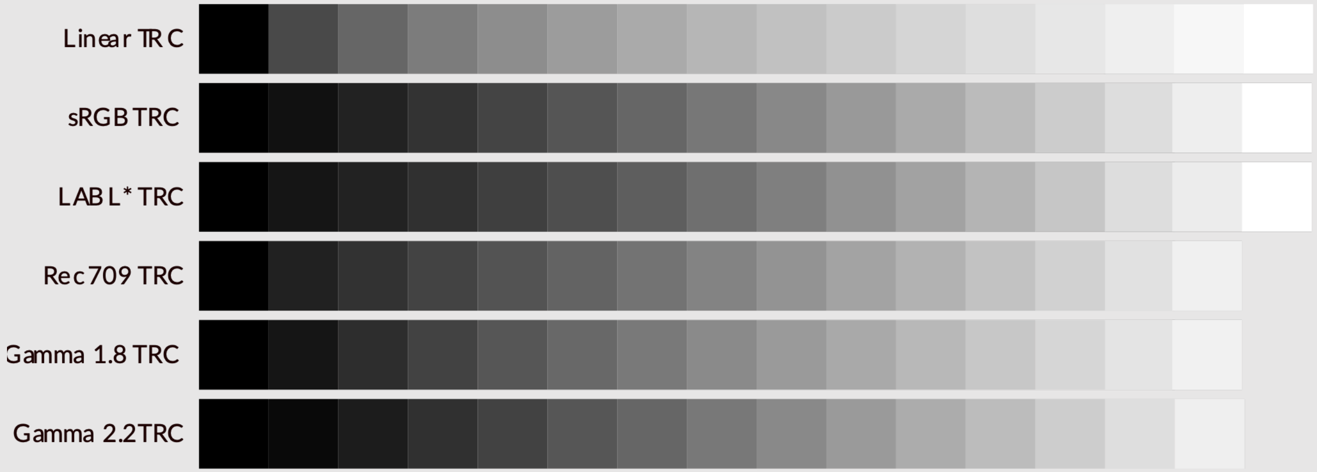
$$y = x^{-\gamma}$$

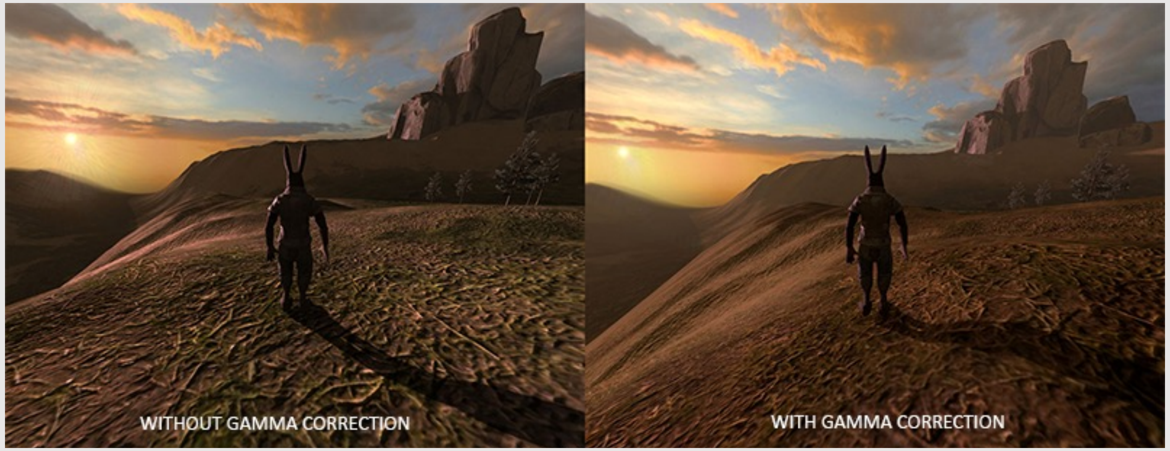
  - Then, when displaying the image, un-modifies the gamma:

$$y = x^{\gamma}$$



# Why Bother With Gamma Correction?




- Luminance is discretized into 8-bits from [0, 255]
  - Cameras pick up a lot of bright light
    - Small changes in darkness will not be captured by the sensor
    - Leads to ‘dark bands’
- **Idea:** if a majority of the data is on the brighter end, let’s encode luminance as a logarithmic curve rather than a linear curve
  - Small changes in darkness can now be captured
- Apply inverse of gamma correction for displays
  - Display emits light, eyes will autocorrect for it in a non-linear fashion the same as with real life
- **Main idea:** cameras should save data non-linearly the same way eyes see the data

How do we use color in computer graphics?

# Graphic Design

- Colors convey different emotions
  - Pick the right set of colors to convey the right emotions
  - Find relationships between colors
    - Known as **color theory**

# Color Theory

- Color theory combines several physical and cognitive abilities of humans to produce ‘appealing’ colors
  - Human optical ability
  - Psychological responses
  - Culture

- Goal is to make designs with physically recognizable colors that also invoke some targeted emotional response
  - Ex: Food colors invoke hunger

Me Picking Colors For Graphics Design (2023) Colorized.