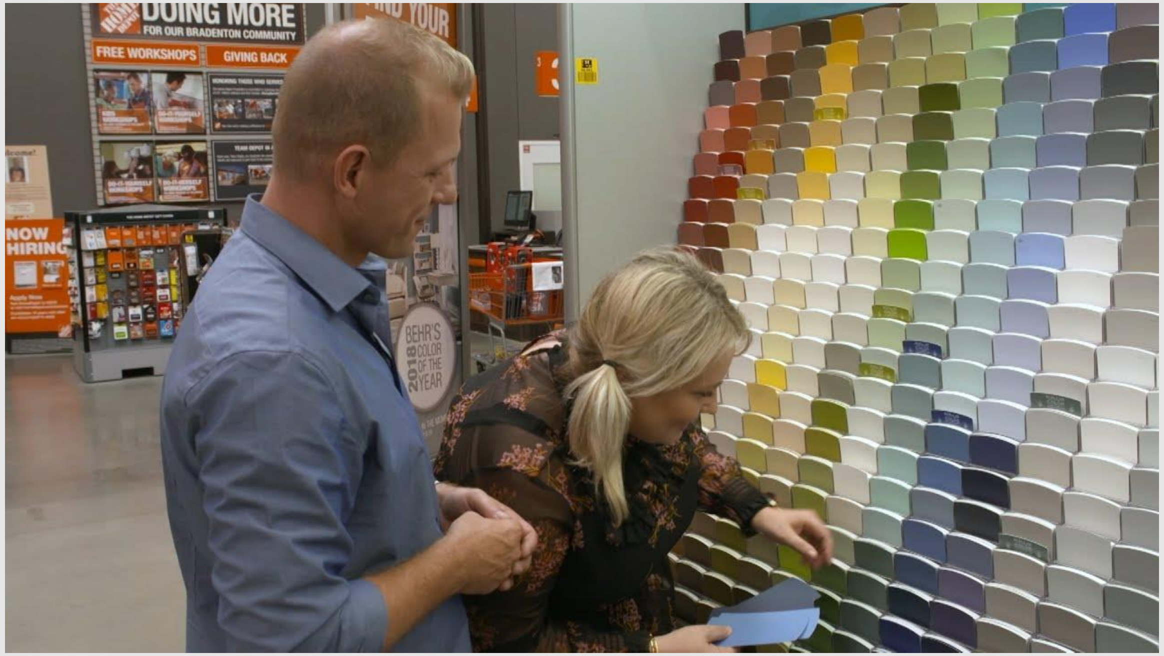
Color

- 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.

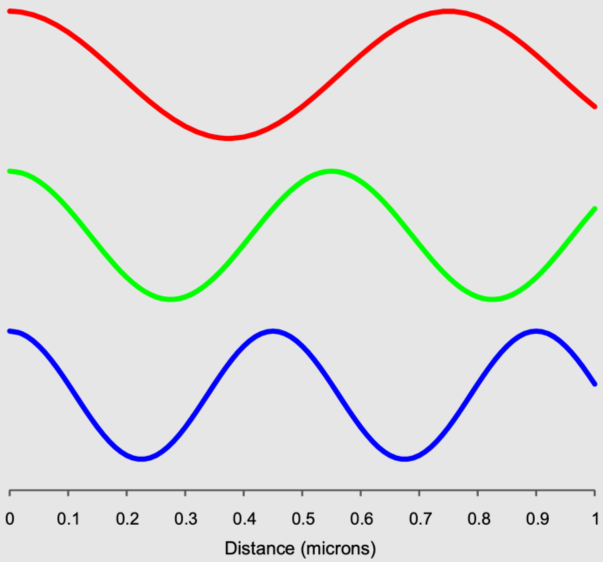
What Is Light

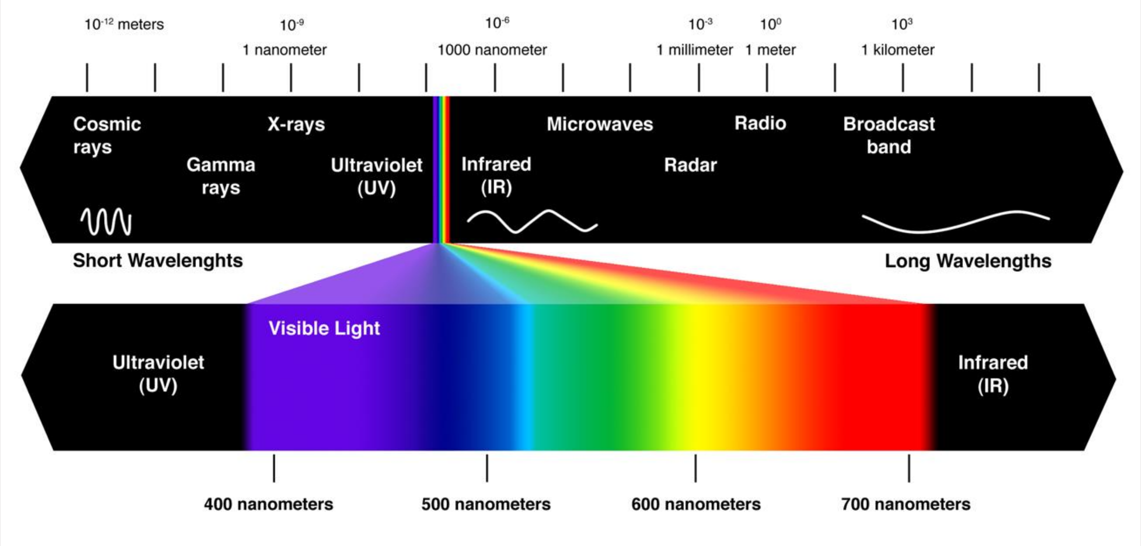
- Light is electromagnetic radiation
  - Generated as an oscillation in the electromagnetic field
  - Is light a wave, or a particle?
    - Yes.

- 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

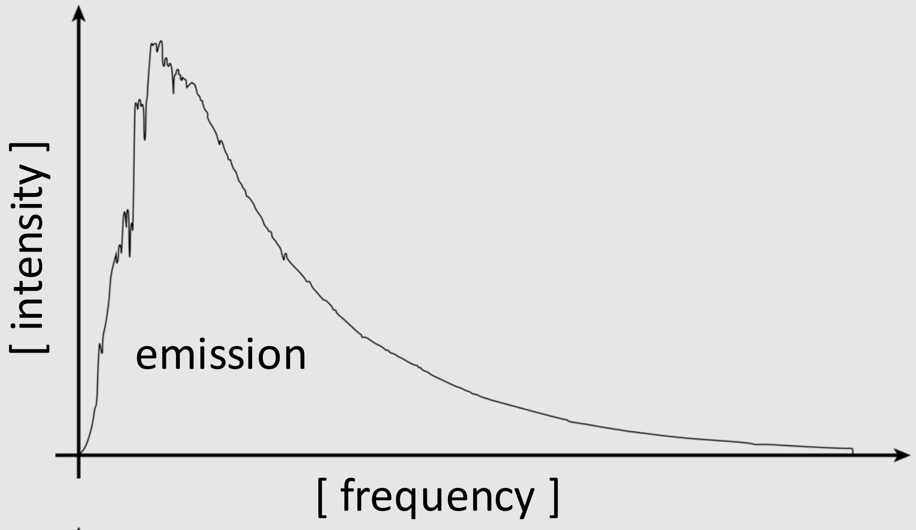
- Color is a range of frequencies
  - Scientifically referred to as a **spectrum**



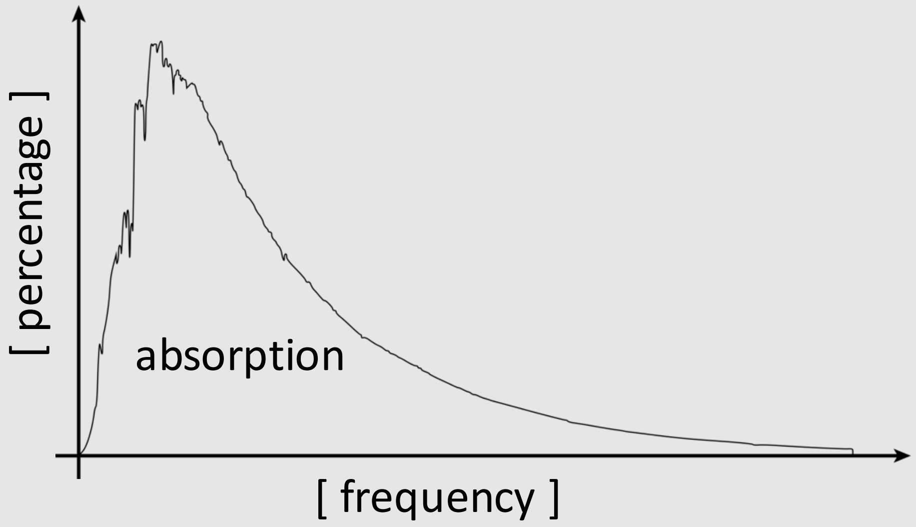


Light Spectrums

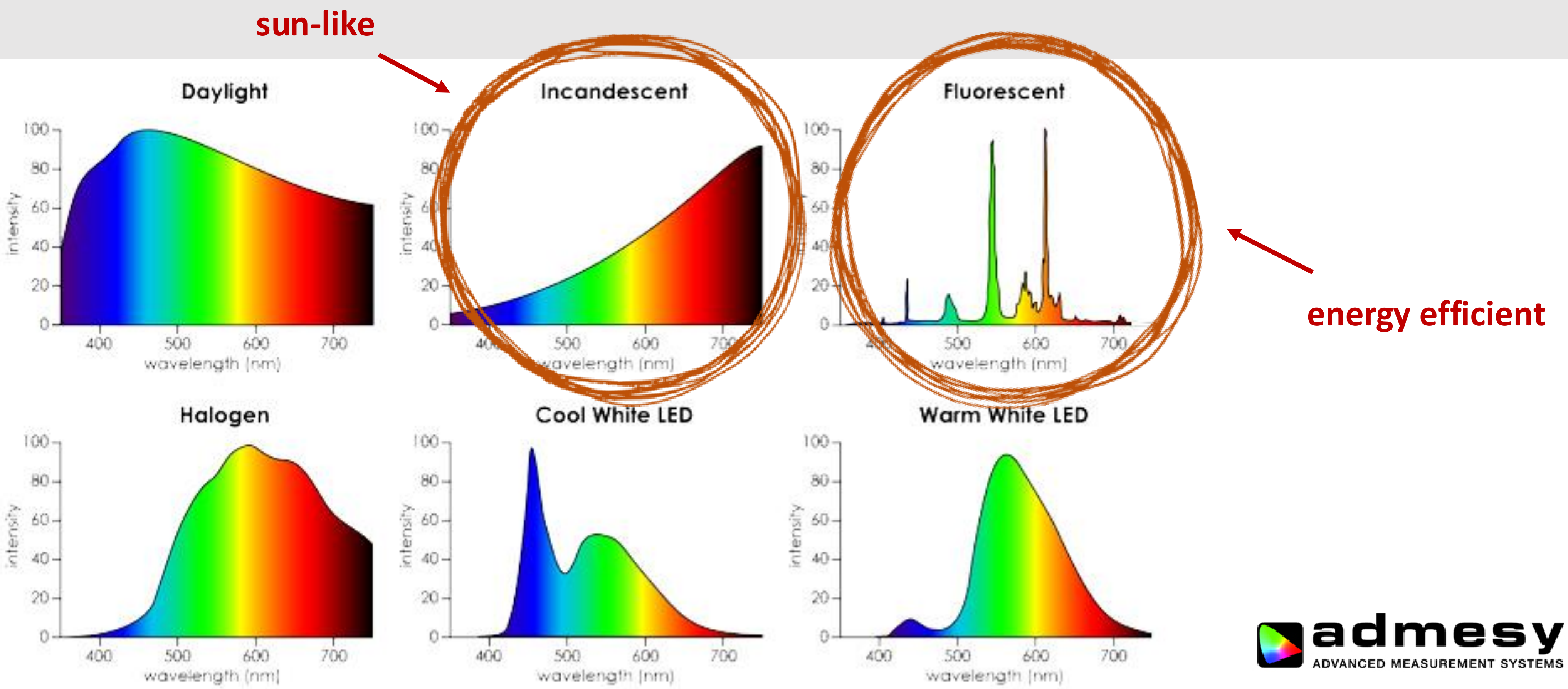
- **Emission spectrum** describes range of light frequencies emitted from a light source
  - Combination of frequencies gives the overall light color
  - Integrating over the spectrum gives the energy output
  - Higher energy output = more energy required to power
    - **Example:** light bulb
  - Measured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



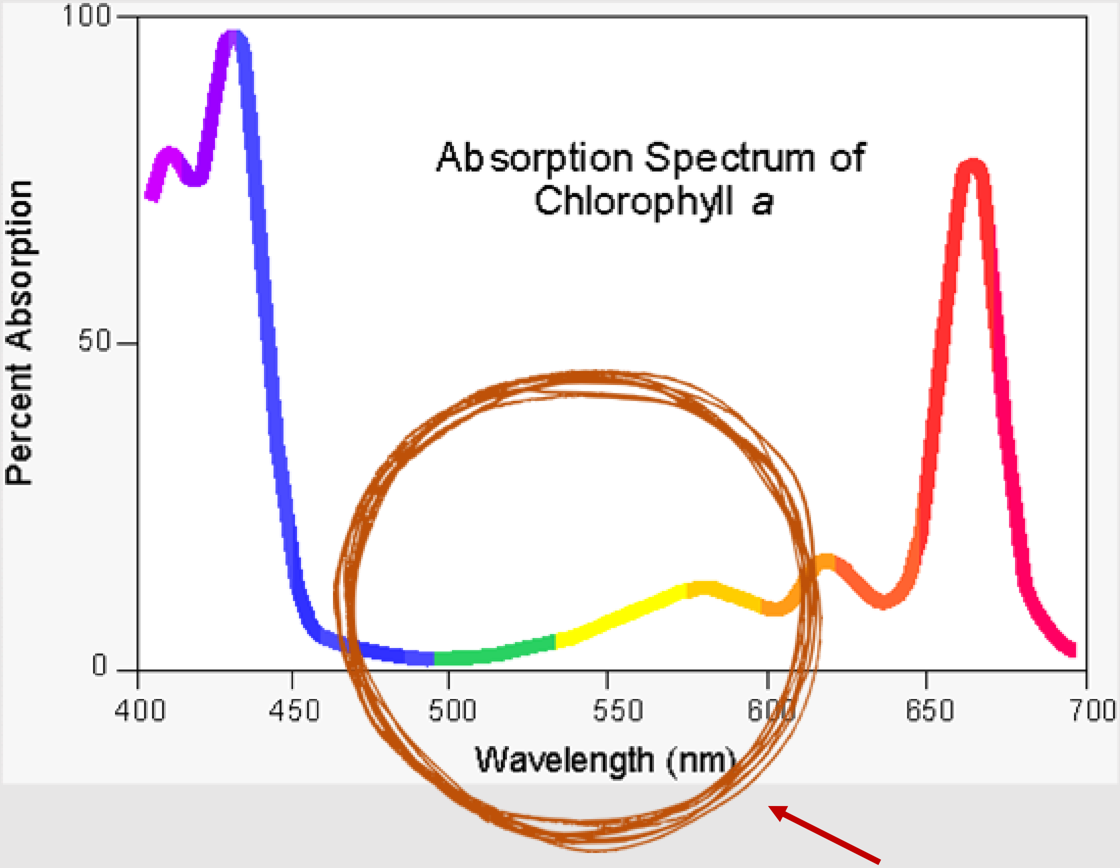
- **Absorption spectrum** describes range of light frequencies absorbed from a light source
  - Frequencies not absorbed are reflected back
  - Measured as percent absorbed per frequency



Emission Spectrum Examples



Absorption Spectrum Examples



plants are green because they do not absorb green light

Absorbed Light

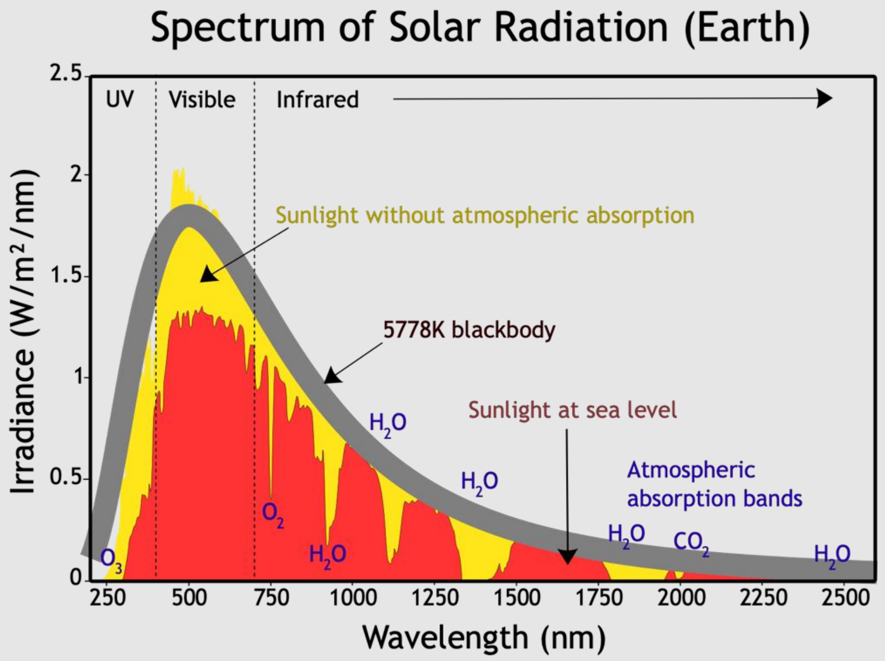
- Converted to heat
  - Wearing dark clothes makes you warmer
- Converted to fuel biological ecosystem
  - Photosynthesis requires energy to move around electrons
- Converted to electrical energy
  - Solar panels are black to absorb as much visible light

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

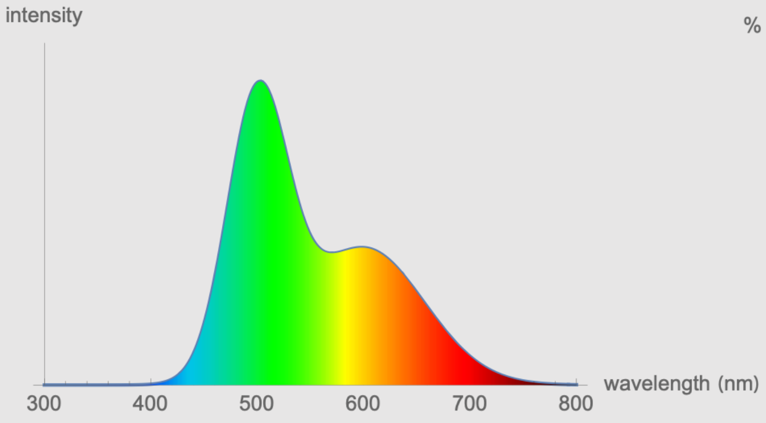
So What Is Color

- Color is emission multiplied by the reflectance
  - Reflectance is whatever percentage is not absorbed

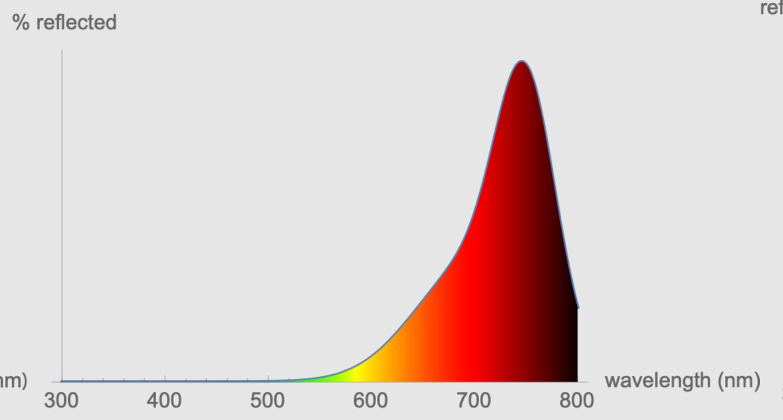
- The sun’s emission is near-equal parts of all visible light
  - Reason why everything is its ‘true’ color under sunlight



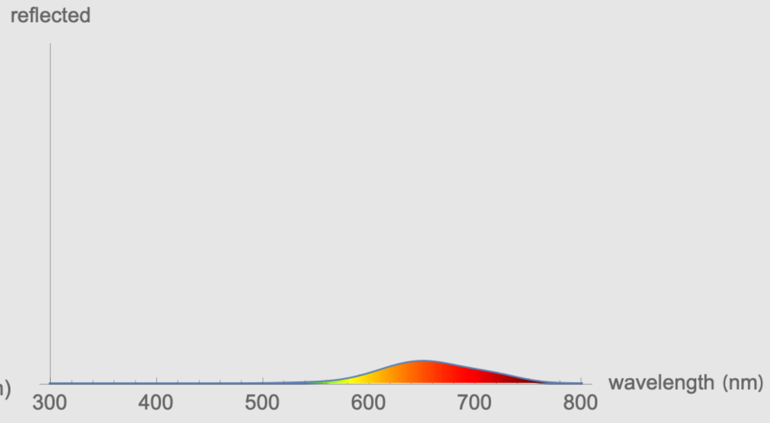
Emission Spectrum E(v)



Reflectance Spectrum R(v)



Result Reflected ER(v)



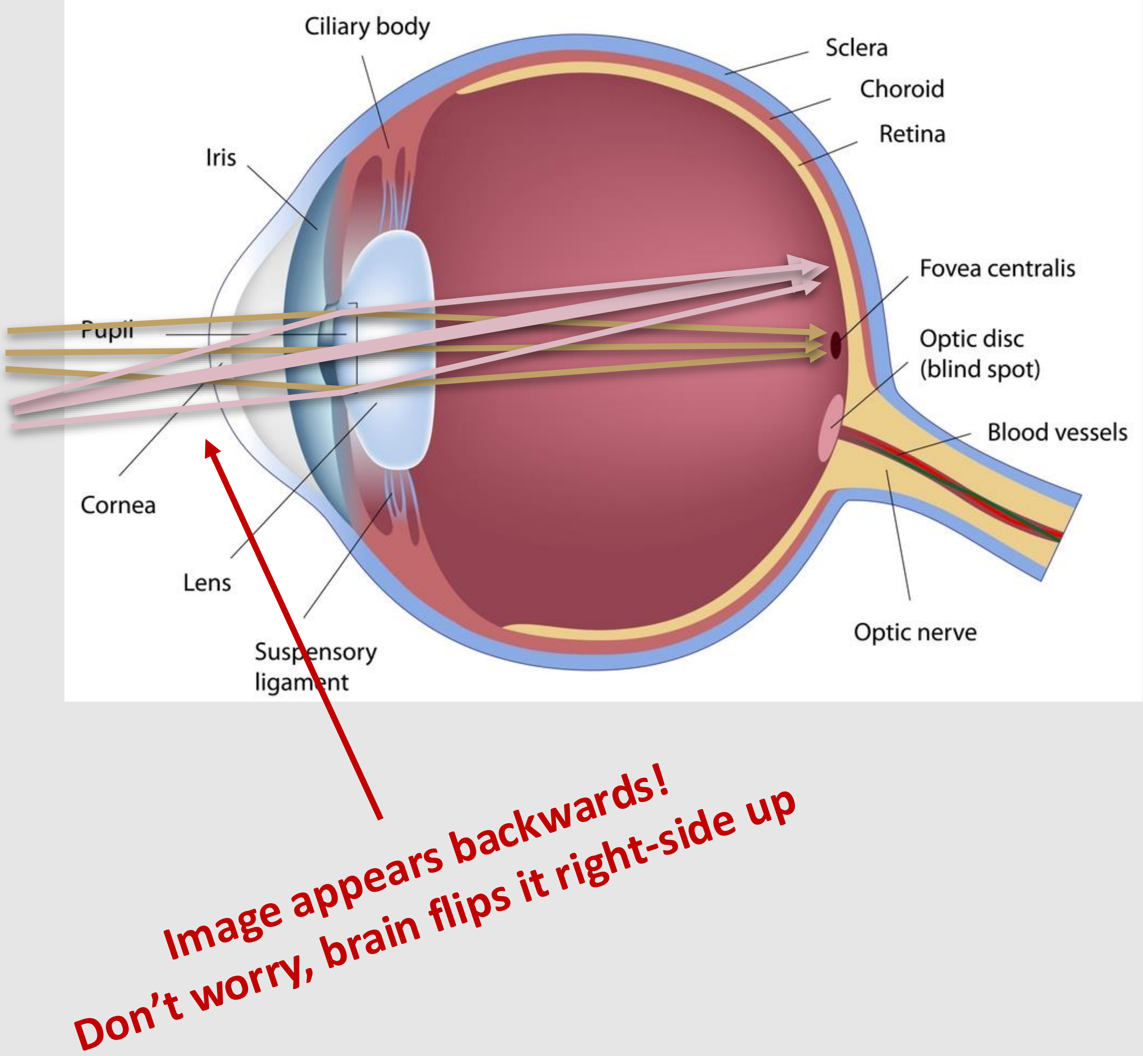
Color By Emission

- 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

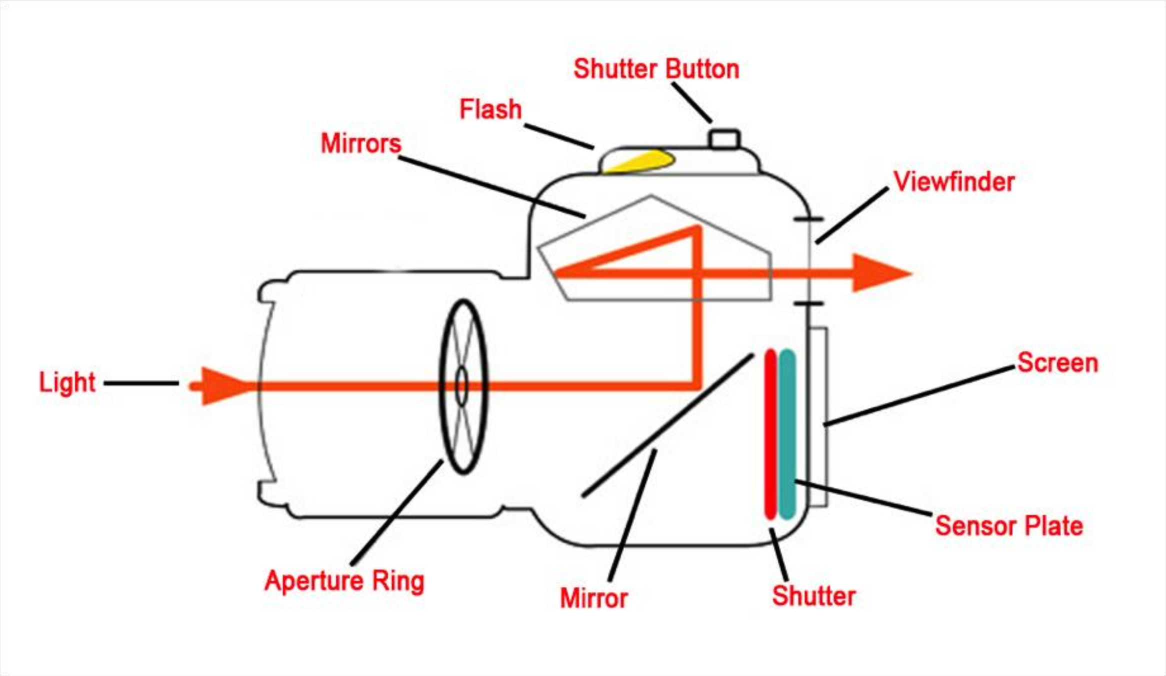
‘Eye’ See What You Mean

- 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

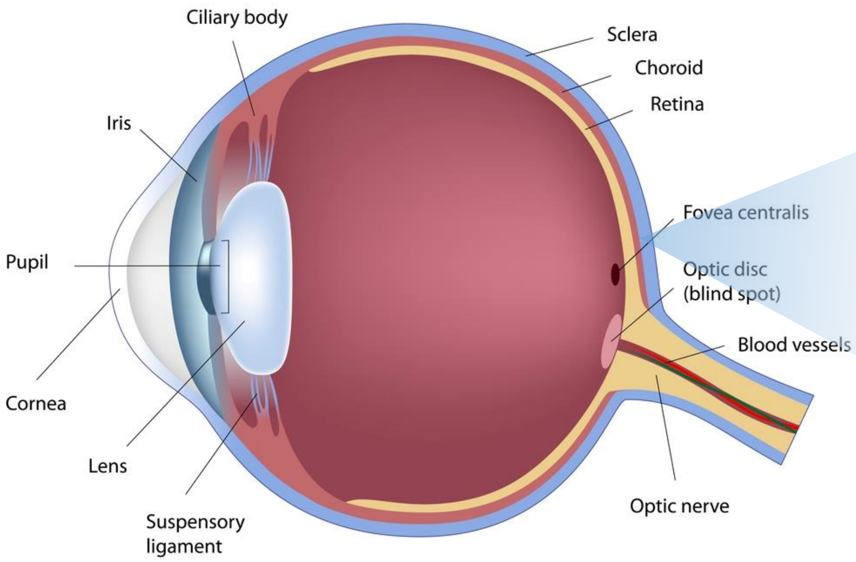


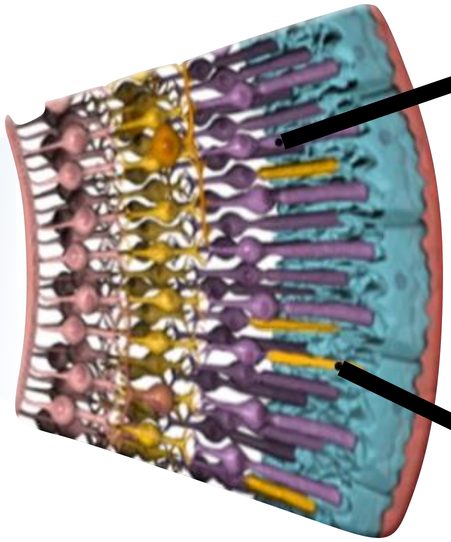
The Biological Camera

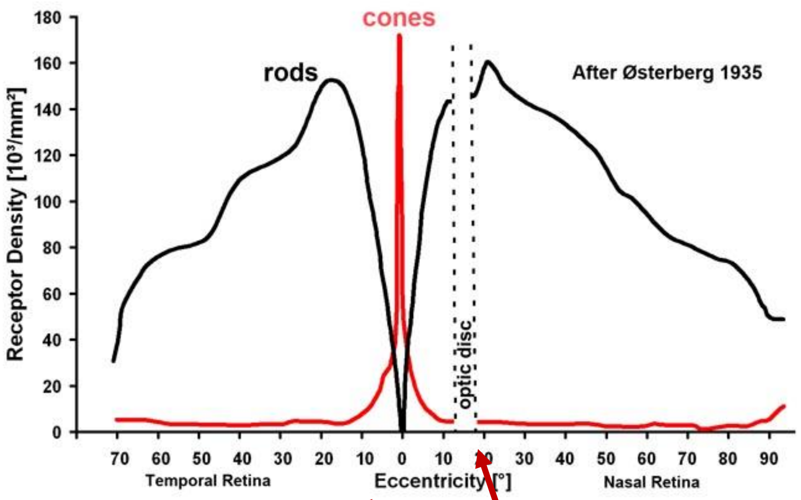


- **Pupil** is the **camera opening**
  - Allows light through
- **Iris** is the **aperture ring**
  - Controls aperture
- **Lens** is the…well, **lens**
  - Can change focus
- **Retina** is the **sensor**
  - Converts light into electrical signal
- **Brain** is the **CPU**
  - Performs additional compute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

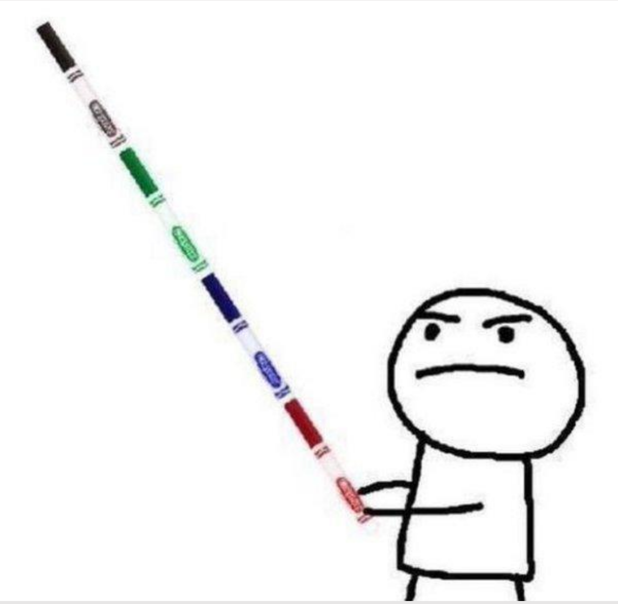
- Close right eye
- Stare at the plus
- Move closer to the screen
- Move farther from the screen
- Continue until the plus sign disappears

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

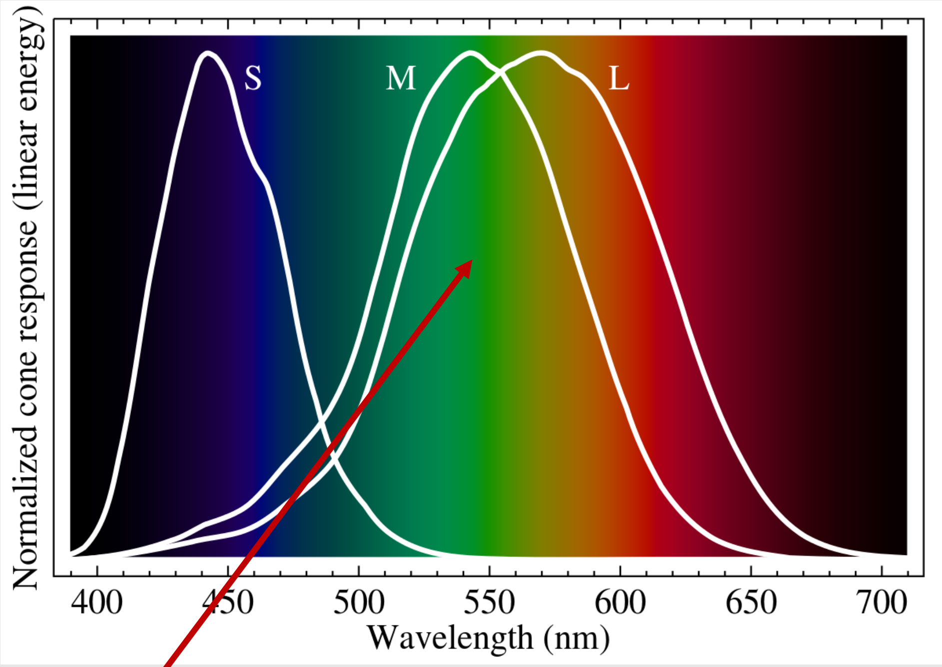
- Each cone integrates the emission & response to produce a single signal to transmit to the brain

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

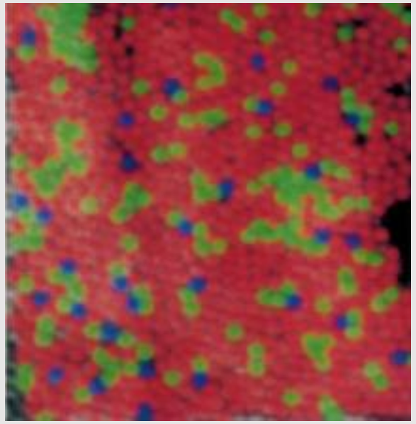
$$M = \int_\lambda \Phi(\lambda) M(\lambda) d\lambda$$

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

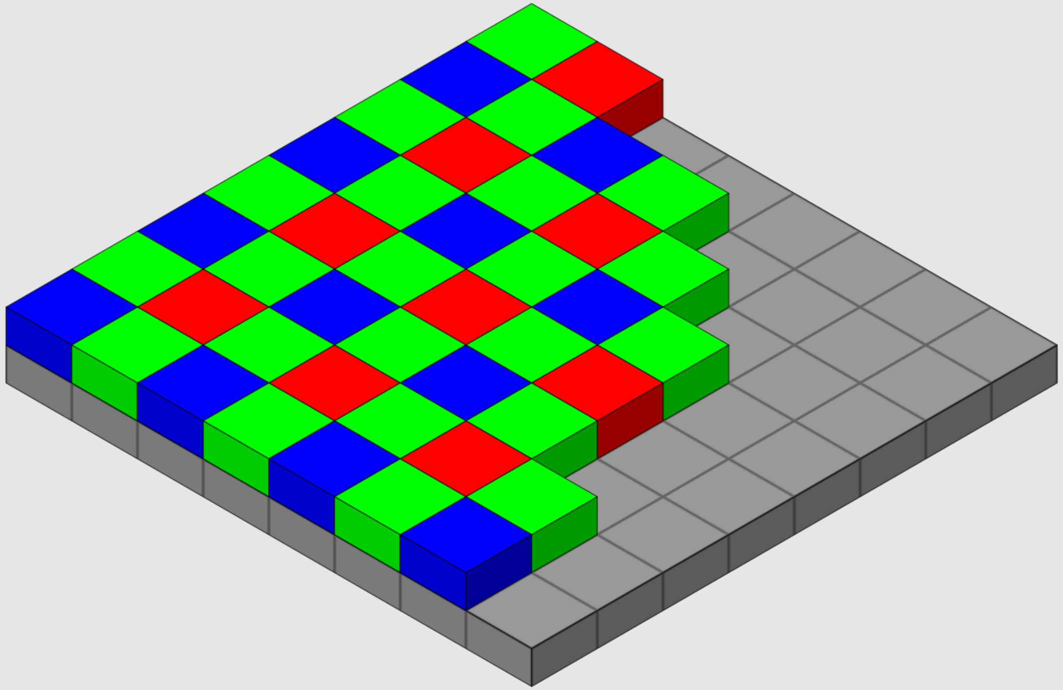
- Uneven distribution of cone types in eye
  - ~64% L cones, ~ 32% M cones ~4% S cones

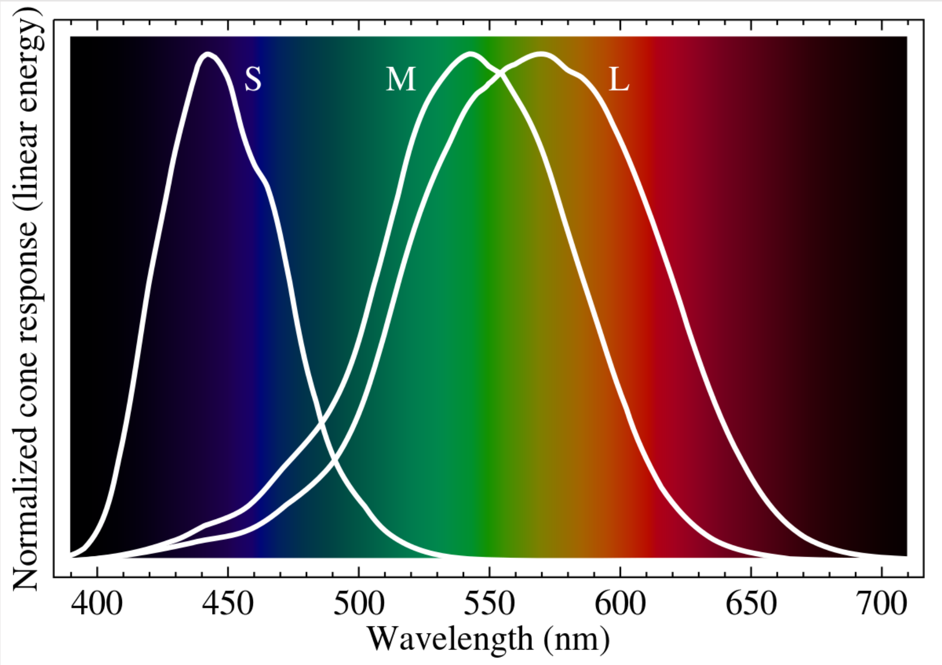


A lot of green picked up!



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

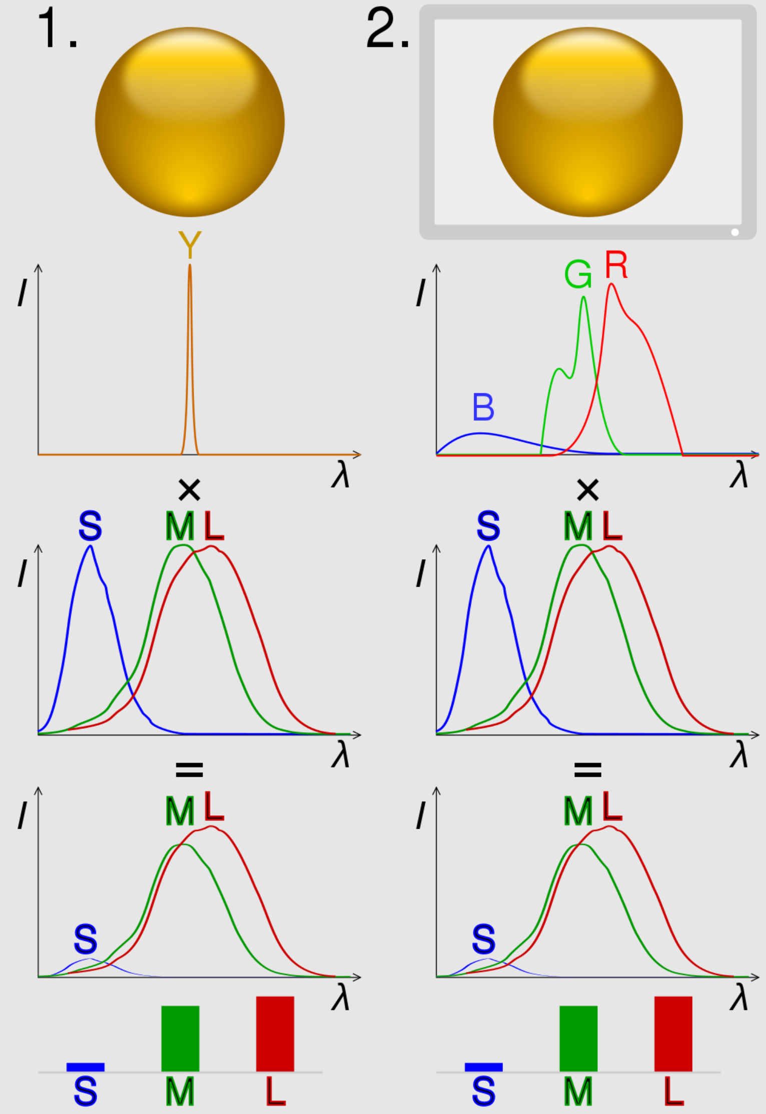
- Camera sensor has 2x as many green sensors as blue or red

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



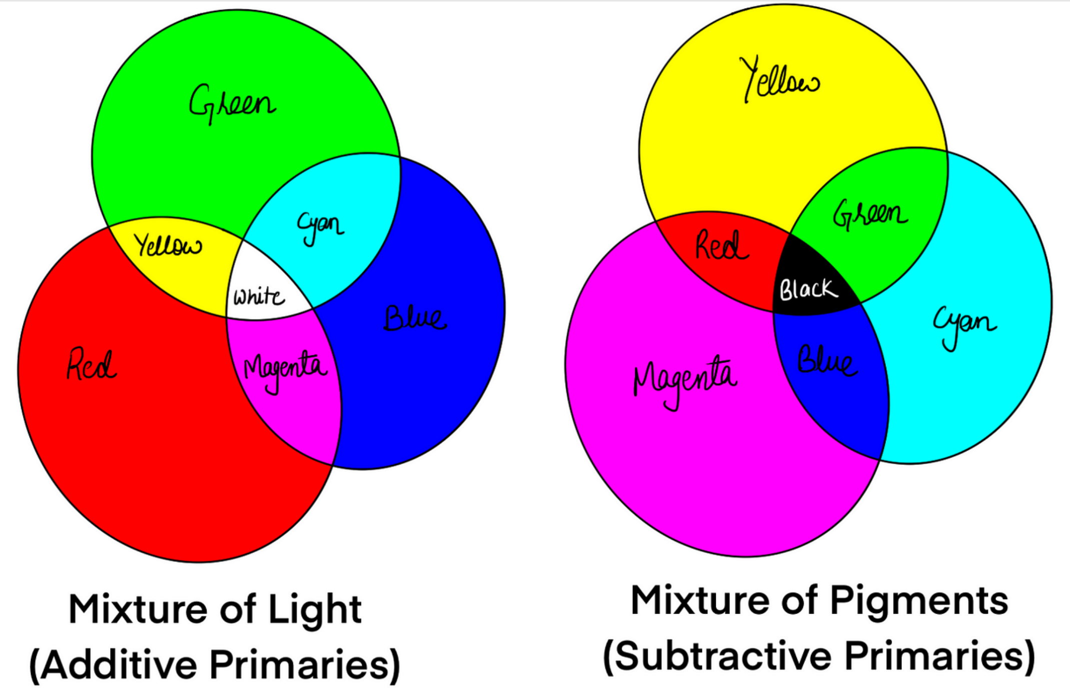
- ~~Physical Color~~
- Digital Color
- Color Manipulation

Color Models

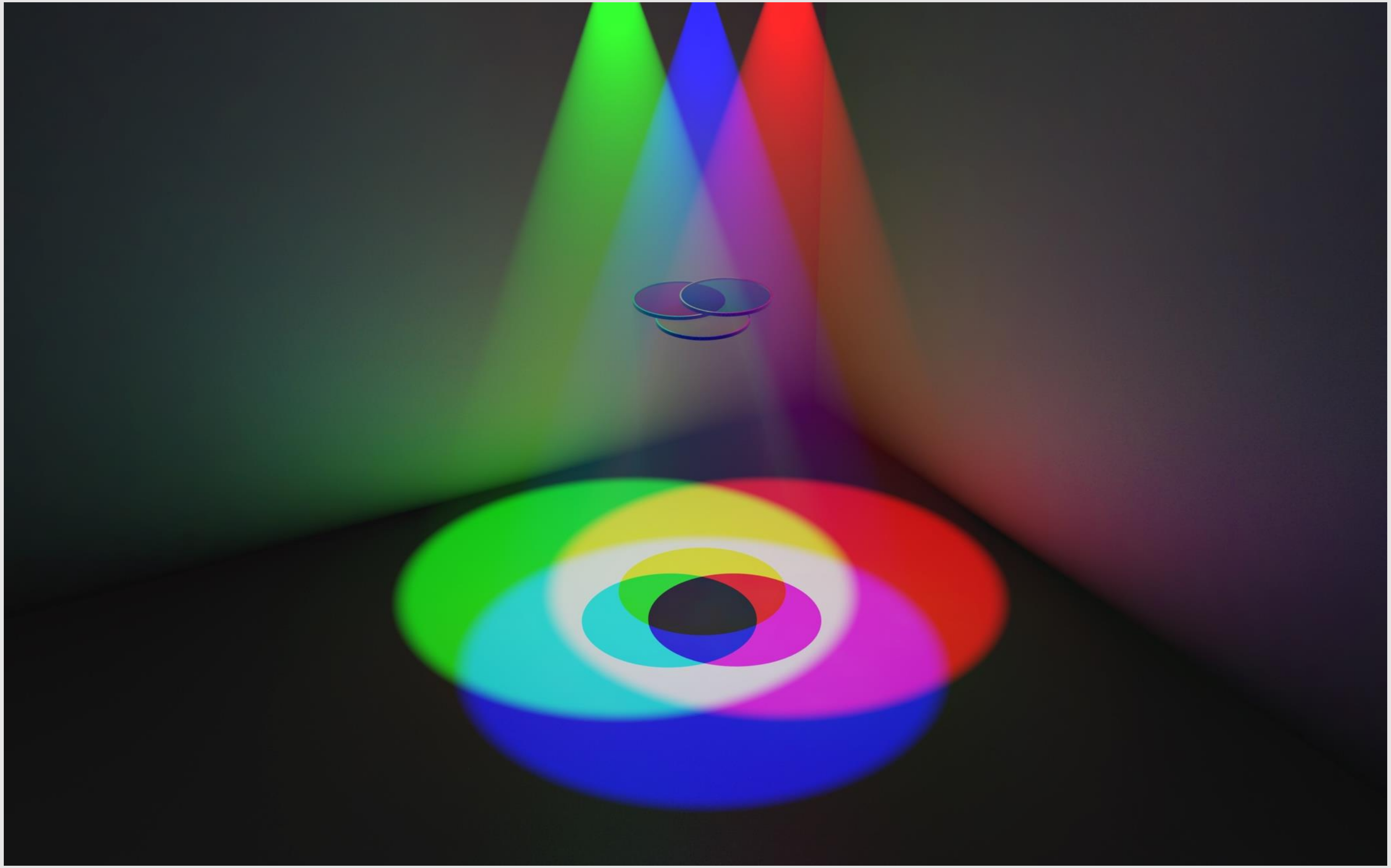
- Things to consider when picking a color:
  - Gamut
    - The area of color that is covered
  - Conversion
    - Converting from digital to print
  - Convenience
    - Easy for users to pick the color they want
  - Storage
    - Low data overhead

- **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

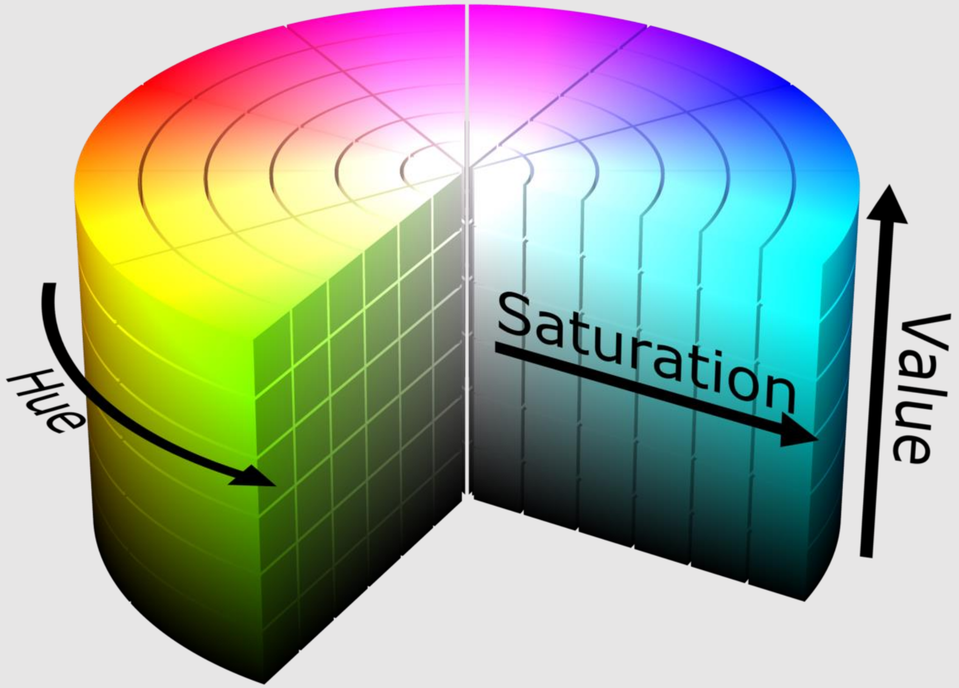


Let's Shed Some Light Here

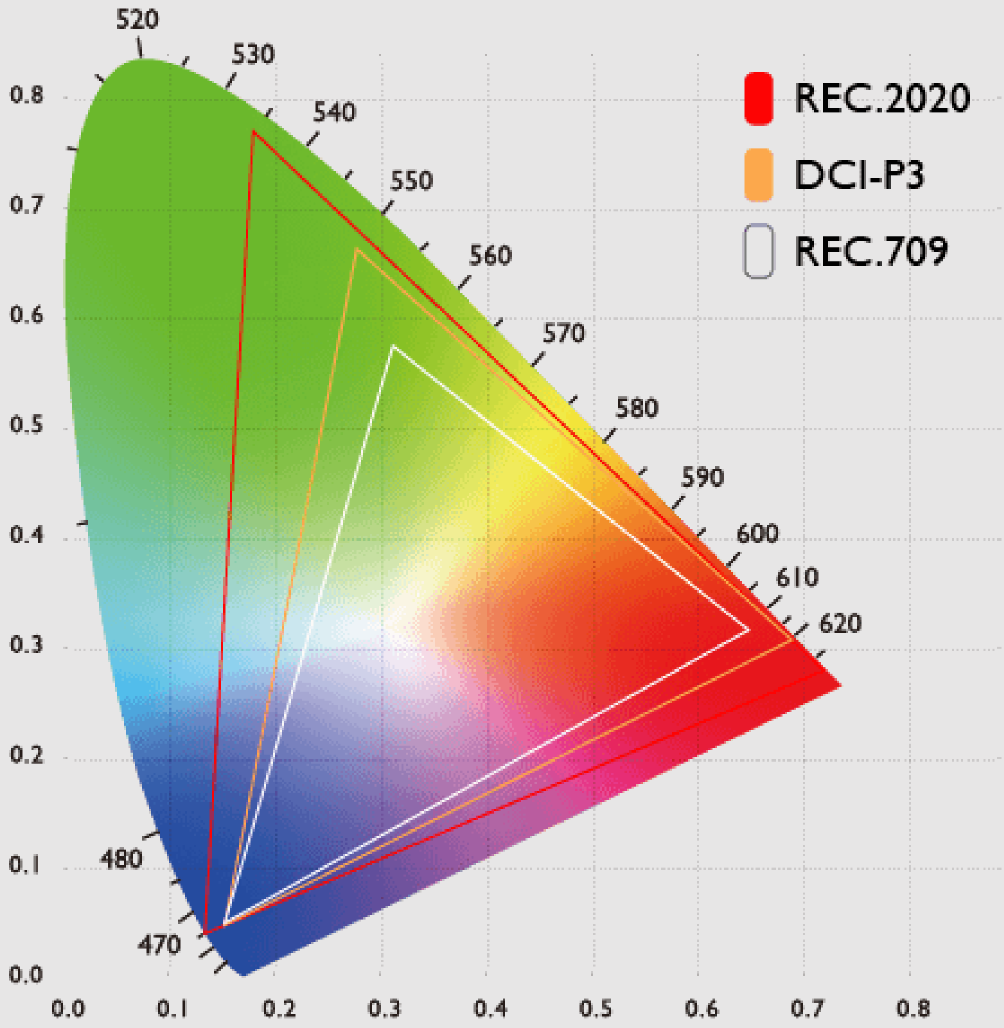


Types of Color Models

- **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)

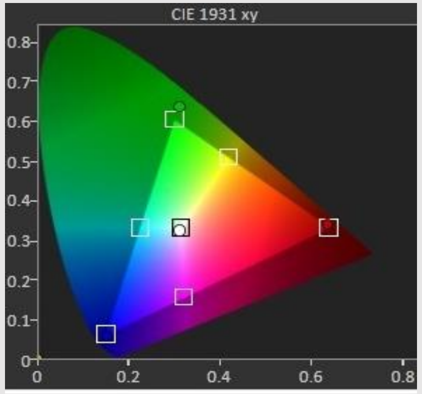
- **Idea:** define RGB color space as 3 vertices on the CIEE XY color space

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

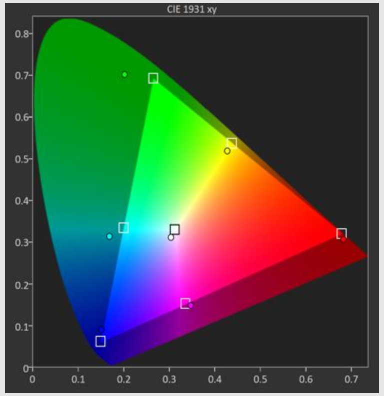
  - Any color within the triangle can be produced with an RGB display
  - Can share common RGB spaces for consistency:
    - REC.709
    - DCI-P3
    - REC.200

Absolute Color Spaces

$799

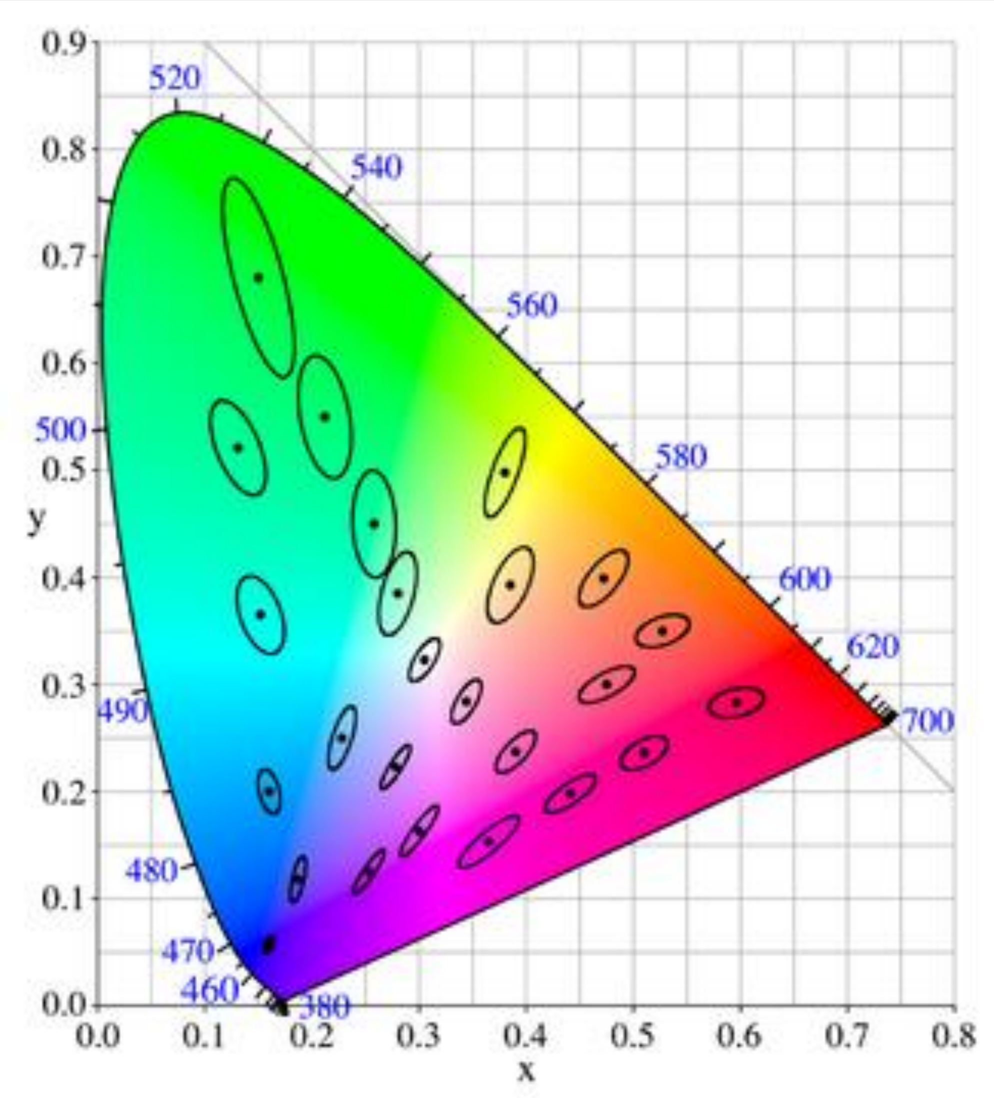


$1999



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

MacAdam Ellipses

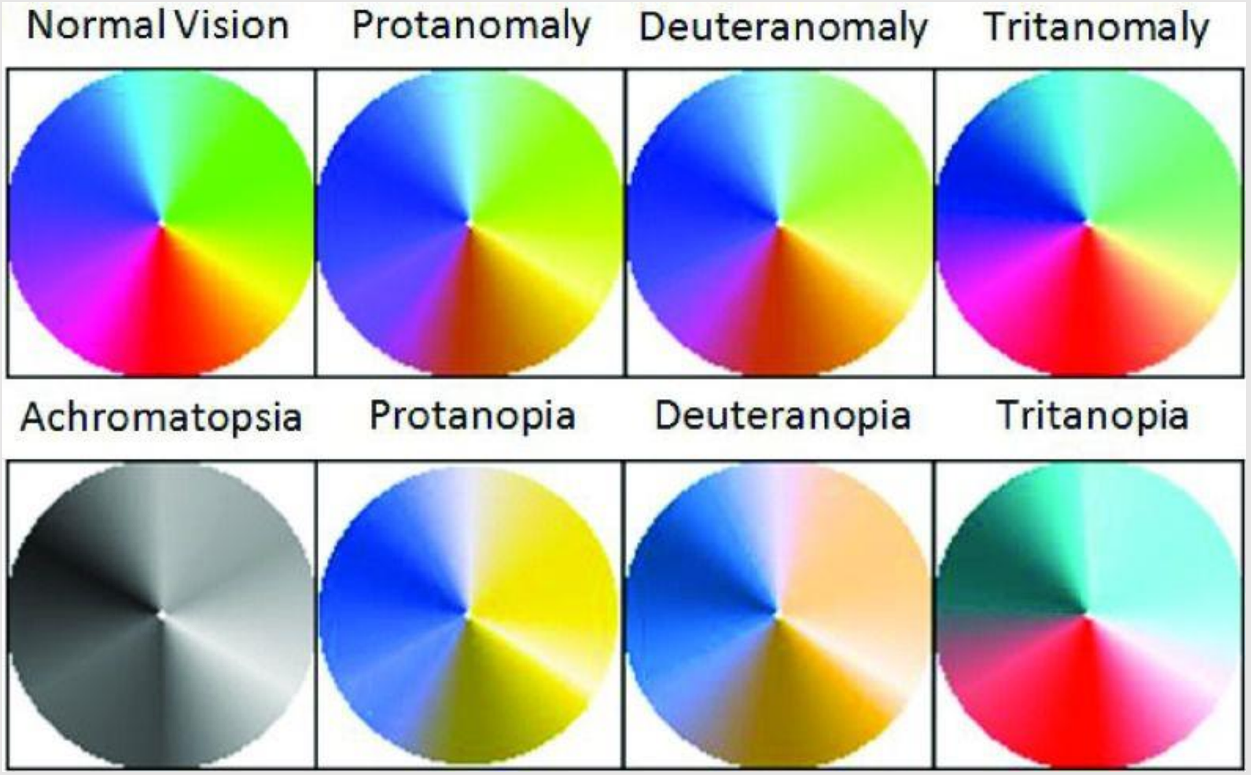


- Any color sampled from an ellipse is the same as the color in the center to the human eye
  - Not a transitive property: two colors on the extreme will look different

- **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



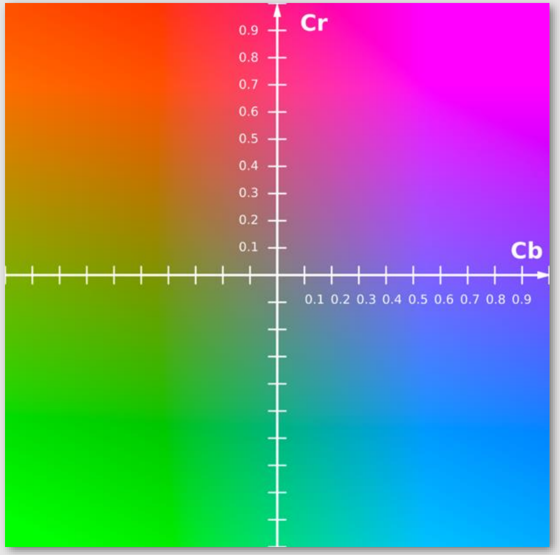
Encoding Color Values

- 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
    - **Cr** = 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

$$y = x + b$$

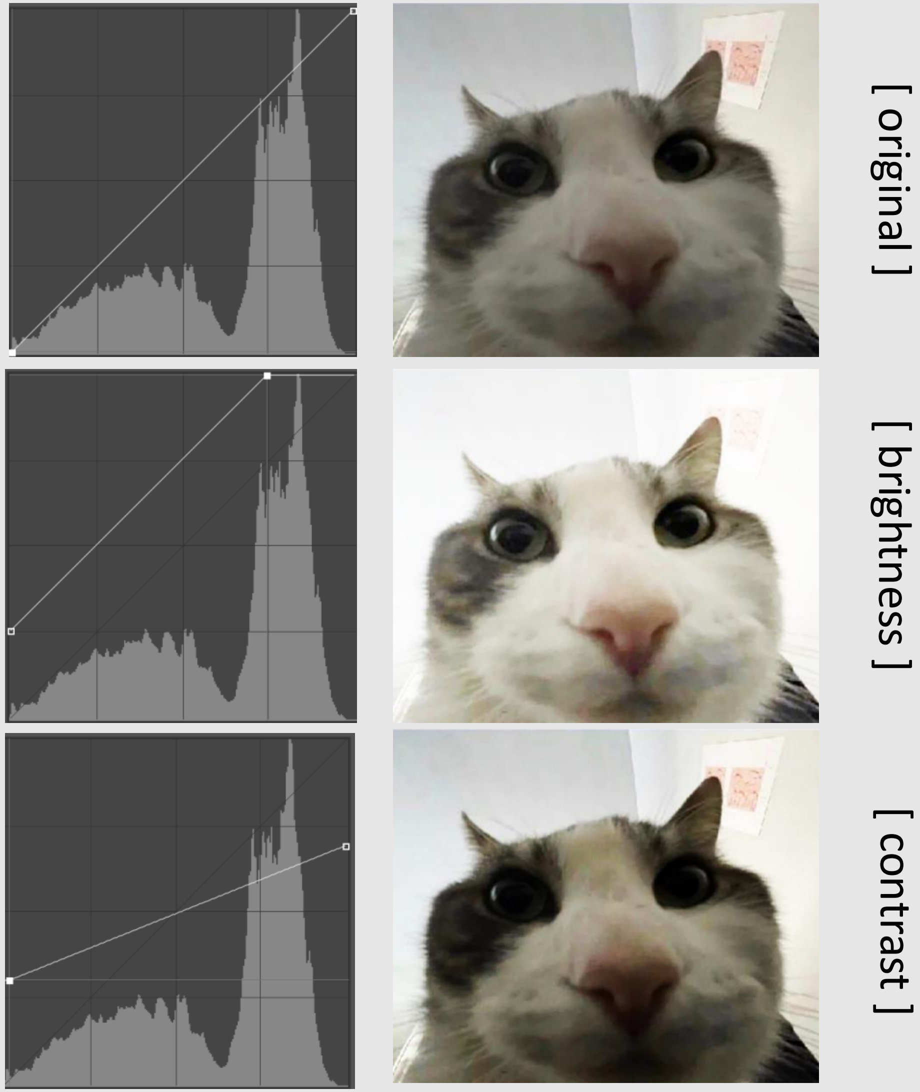
- Contrast brings colors closer to the average grey color

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

- 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]!**



Saturation

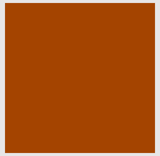
- Saturation moves colors closer or farther from their ‘max’ value
  - Compute the greyscale value of a color using the weighted greyscale average:

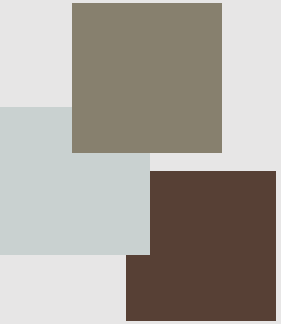
    $$x.grey = 0.299 * x.r + 0.587 * x.g + 0.114 * x.b$$

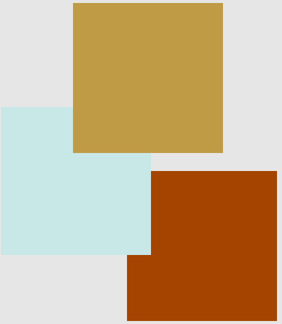
  - Linearly interpolate the original color with the grey color:

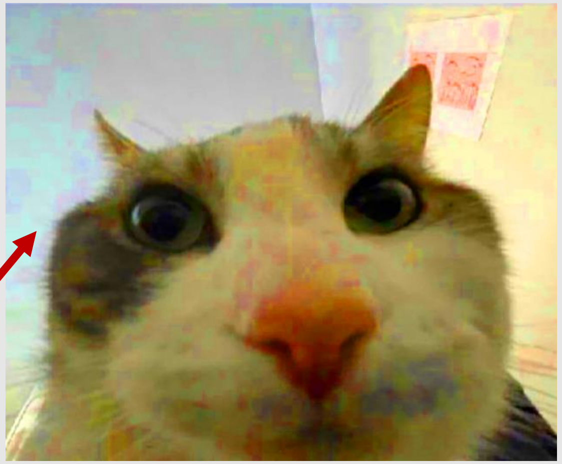
    $$y = a * x + (1 - a) * x.grey$$

  - 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

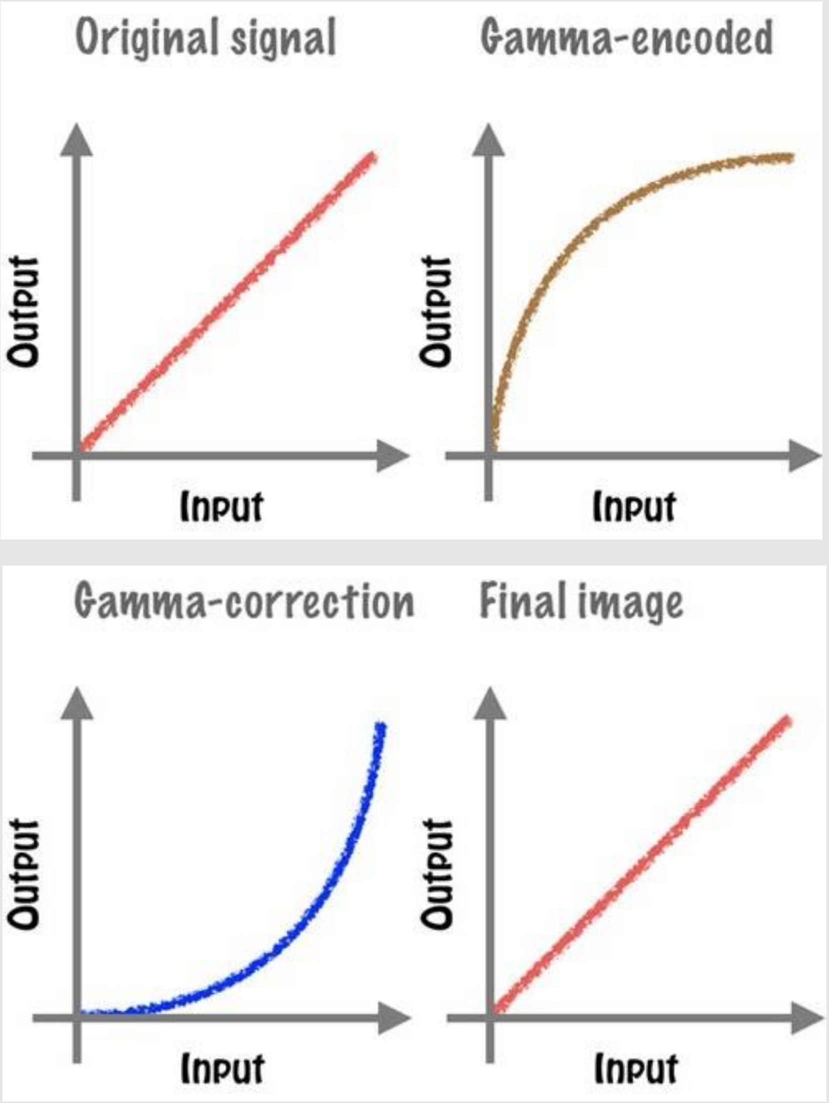
- When we look at an object, using two lights does not make it twice as bright **[non-linear]**
  - When a camera captures an object, using two lights emits two times the amount of photos, and the sensor picks up twice as many photons, making the observation twice as bright **[linear]**

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

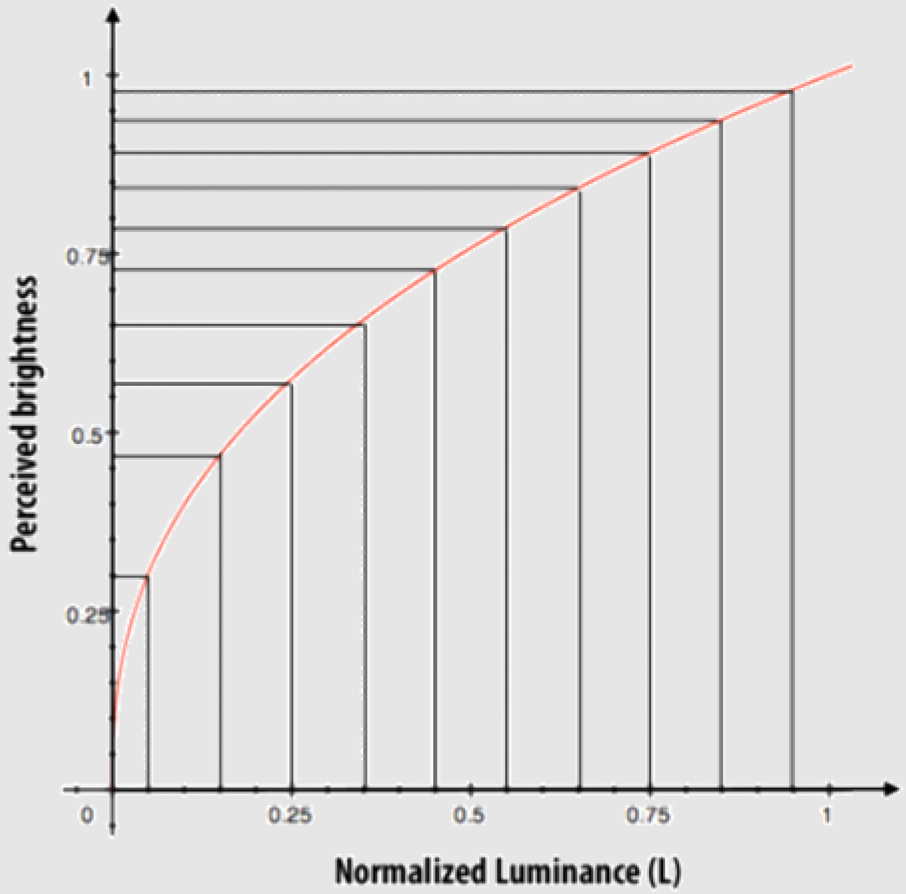
$$y = x^{-\gamma}$$

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

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

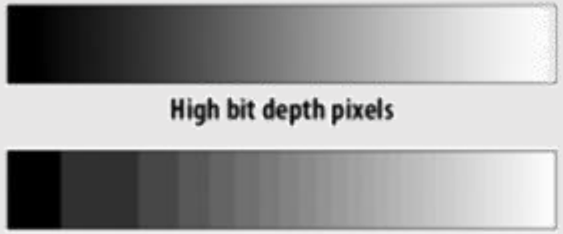


Quantization Error

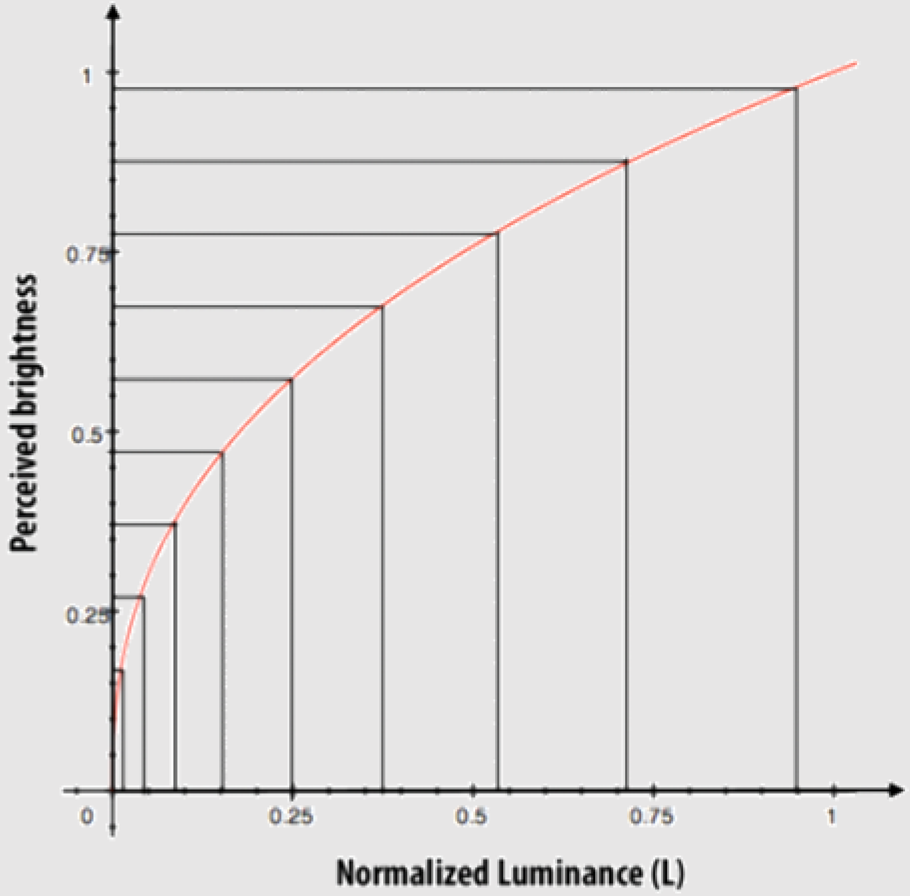


- Most images are not RAW files

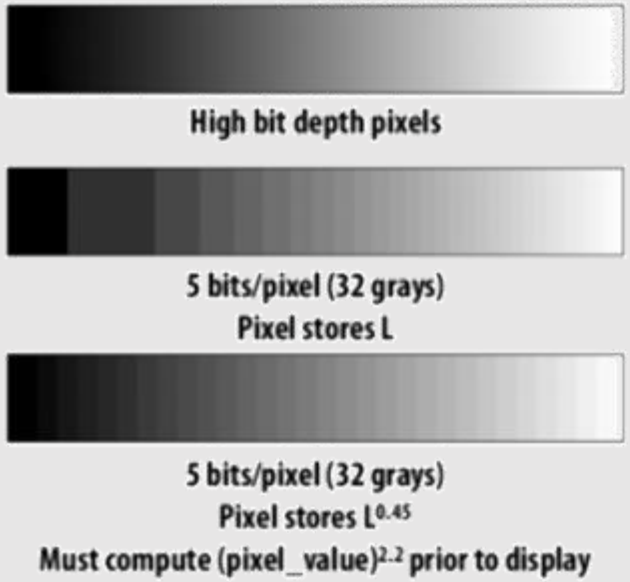
- 8-bit sensor pixels
- Can represent 256 luminance values
- Risks quantization of dark areas of image



Quantization Fix

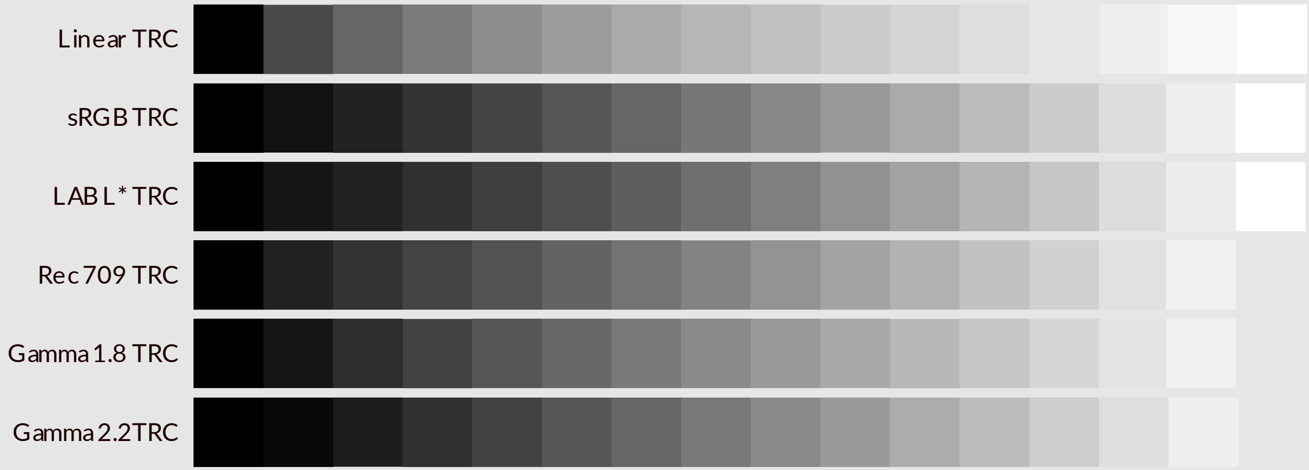


- Evenly distribute values over perceptible range
  - Make better use of available bits
- **Rule of thumb:** human eye cannot differentiate differences in luminance less than 1%



- Caution: should blending images average brightness or luminance?

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**

Red	Orange	Yellow	Green	Blue
Excitement Strength Love Energy	Confidence Success Bravery Sociability	Creativity Happiness Warmth Cheer	Nature Healing Freshness Quality	Trust Peace Loyalty Competence
Pink	**Purple**	**Brown**	**Black**	**White**
Compassion Sincerity Sophstication Sweet	Royalty Luxury Spirituality Ambition	Dependable Rugged Trustworthy Simple	Formality Dramatic Sophistication Security	Clean Simplicity Innocence Honest

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.