

Color

- Physical Color
- Digital Color
- Color Manipulation

What Is Color

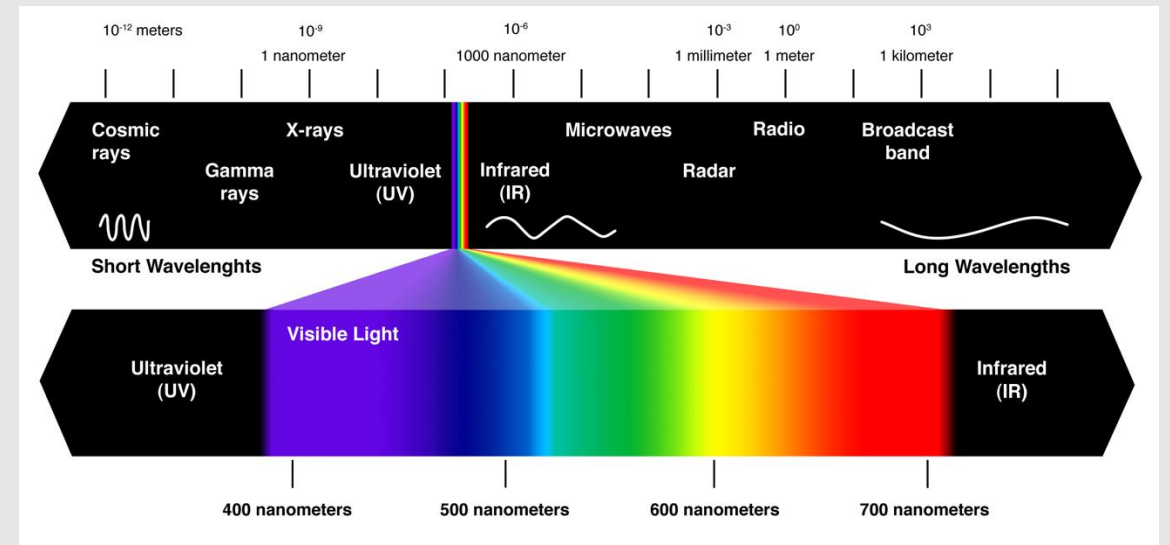
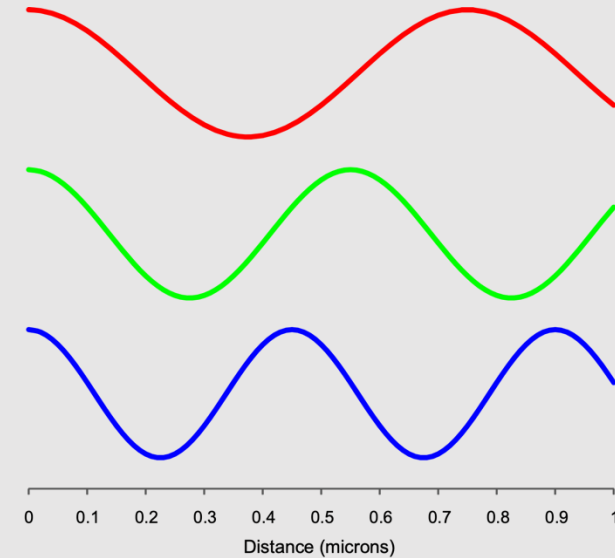
- An object's **visual response** to light
 - A green plant without light will be black
 - A green plant with light will absorb some energy for photosynthesis, and then emit some green light
 - This emission is its visual response
- Color gives us a language for communicating similar visual energies
 - **Example:** picking colors for a house



A Lowe's, Probably.

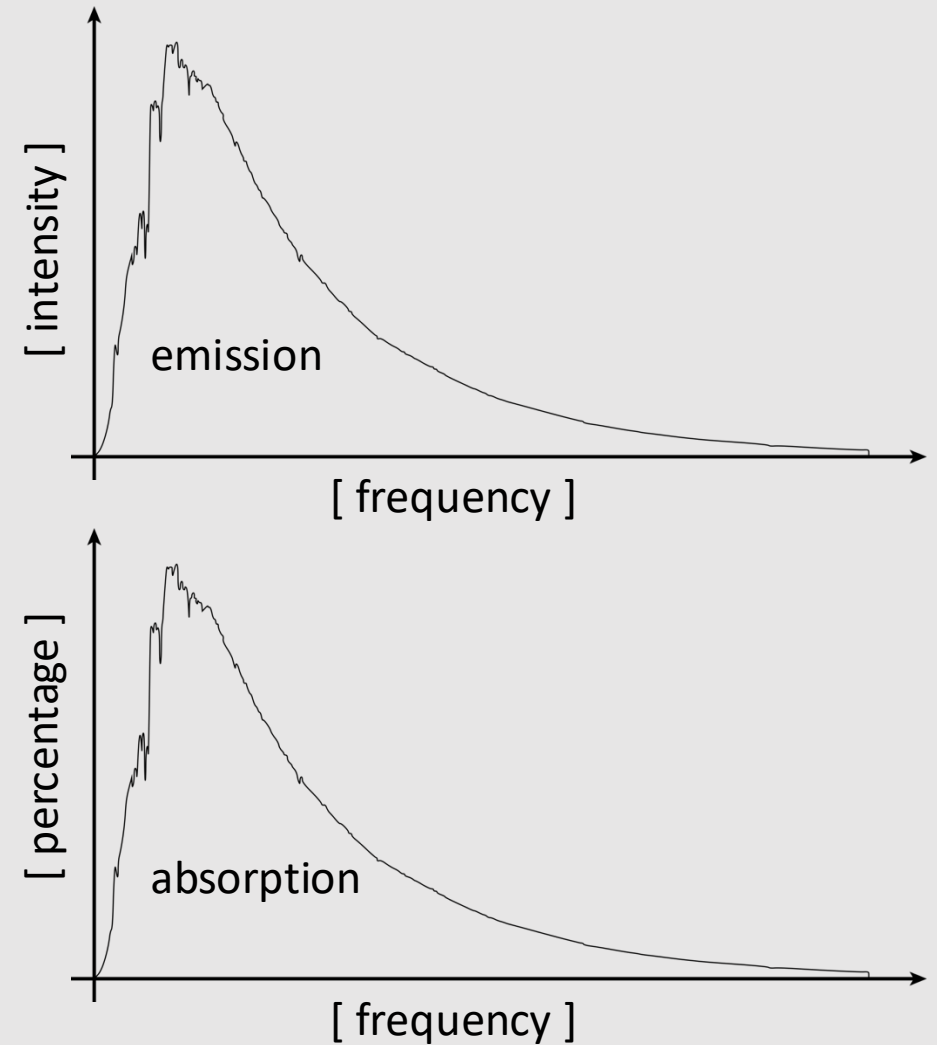
What Is Light

- Light is electromagnetic radiation
 - An oscillation in the electromagnetic field
 - Is light a wave or a particle?
 - Yes.
- Oscillation frequency 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



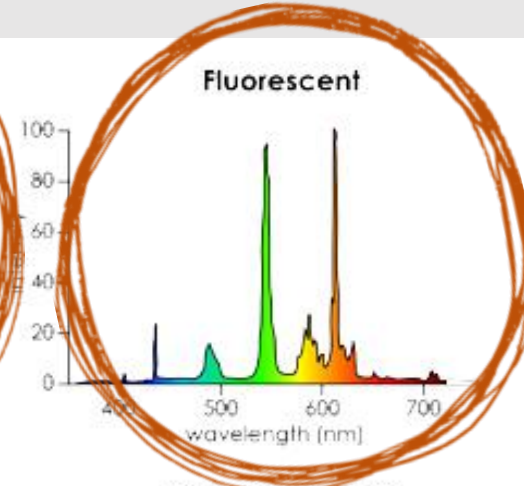
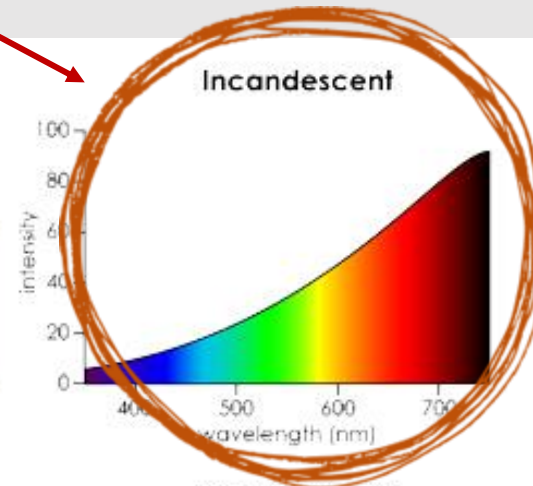
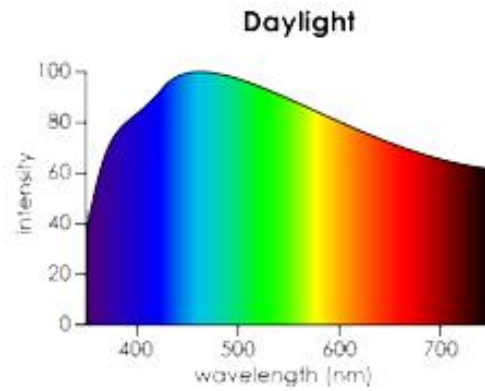
Light Spectrums

- **Emission spectrum** describes range of frequencies emitted from a light source
 - Combination of frequencies gives the 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 frequencies absorbed from a light source
 - Frequencies not absorbed are reflected back
 - Measured as percent absorbed per frequency

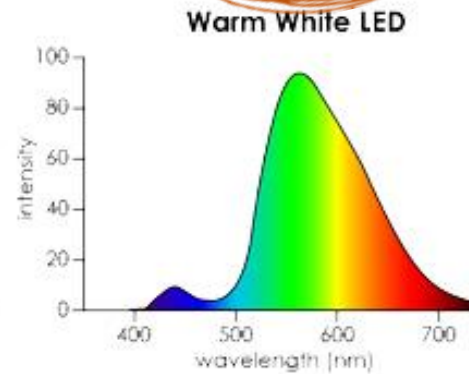
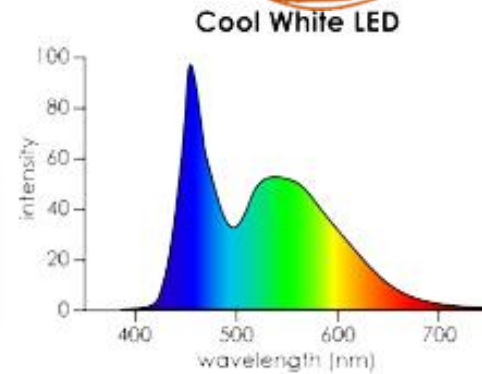
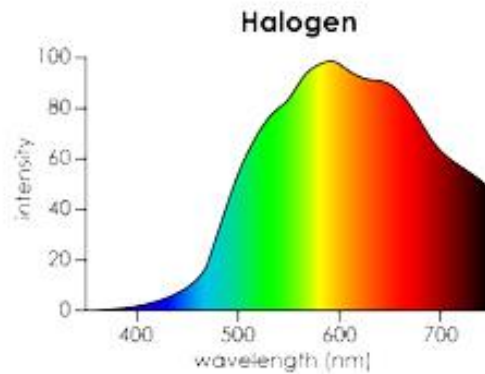


Emission Spectrum Examples

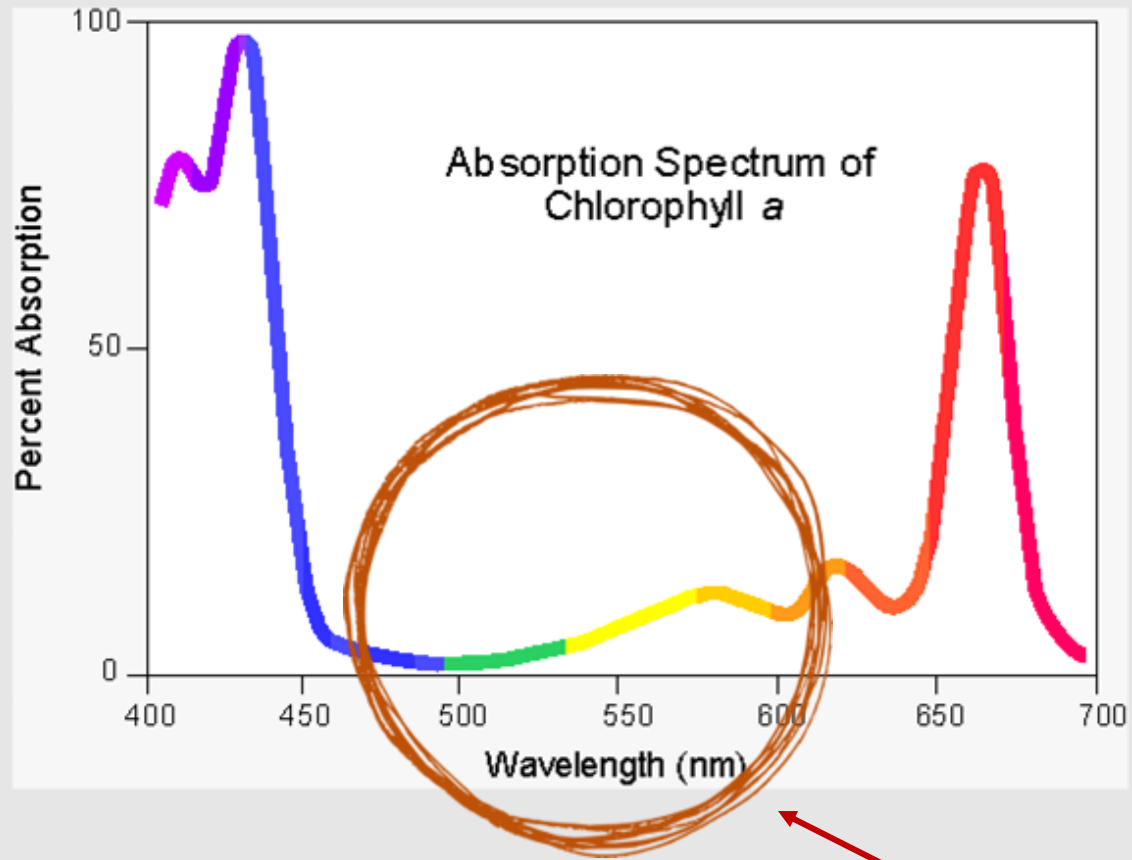
sun-like



energy efficient



Absorption Spectrum Examples



plants are green because they do not absorb green light

Absorbed Light



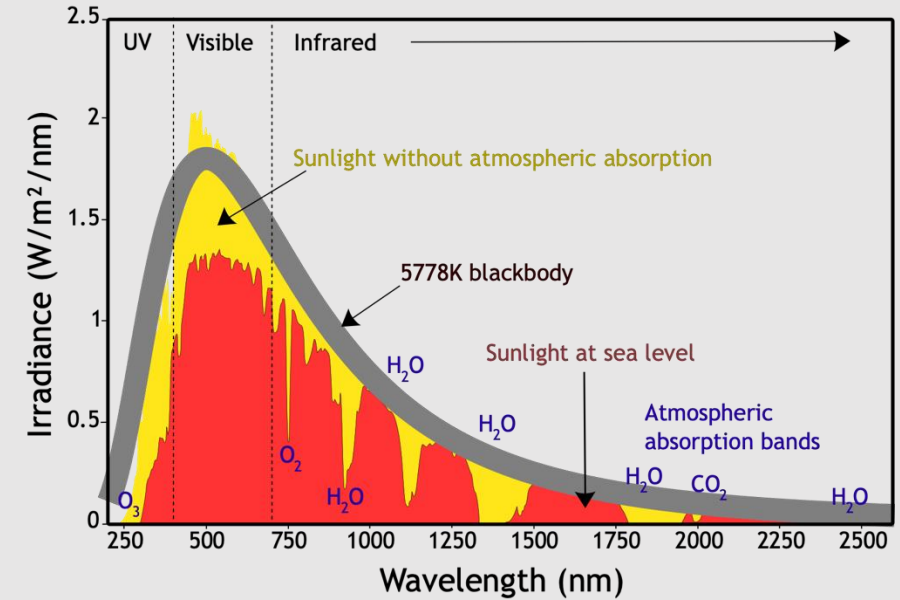
- Converted to heat
 - Wearing dark clothes makes you warmer
- Converted to fuel biological ecosystem
 - Photosynthesis requires energy to move around electrons
- Converted to electrical energy
 - Solar panels are black to absorb as much visible light

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

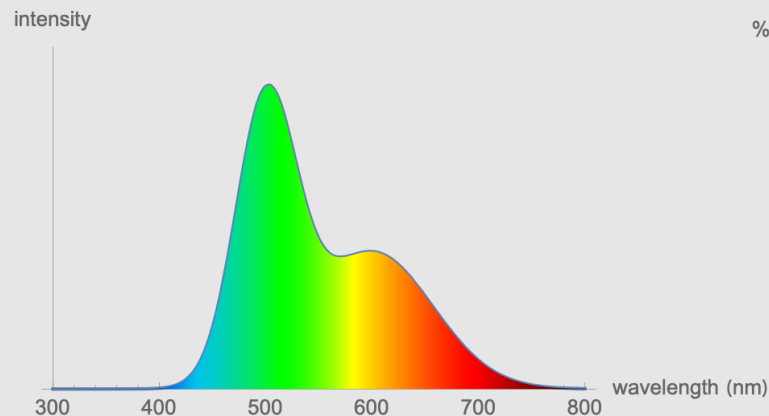
So What Is Color

- Color is emission multiplied by 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

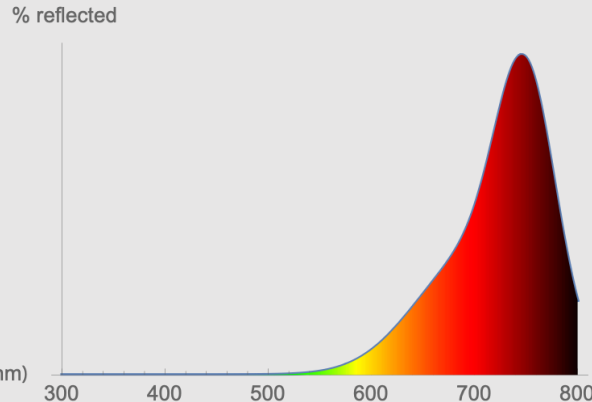
Spectrum of Solar Radiation (Earth)



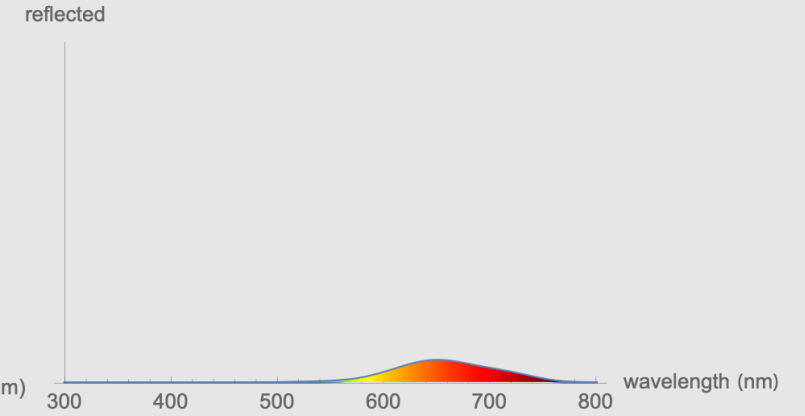
Emission Spectrum $E(\nu)$



Reflectance Spectrum $R(\nu)$



Result Reflected $ER(\nu)$



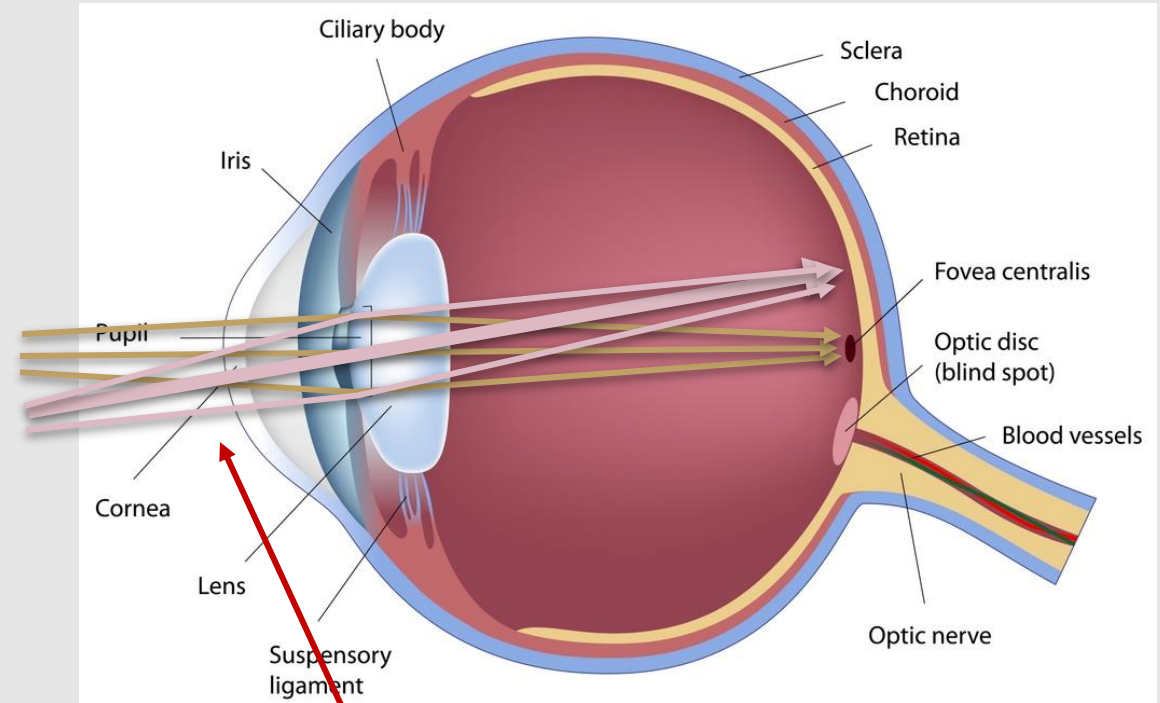
Color By Emission

- Color of objects change by changing 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



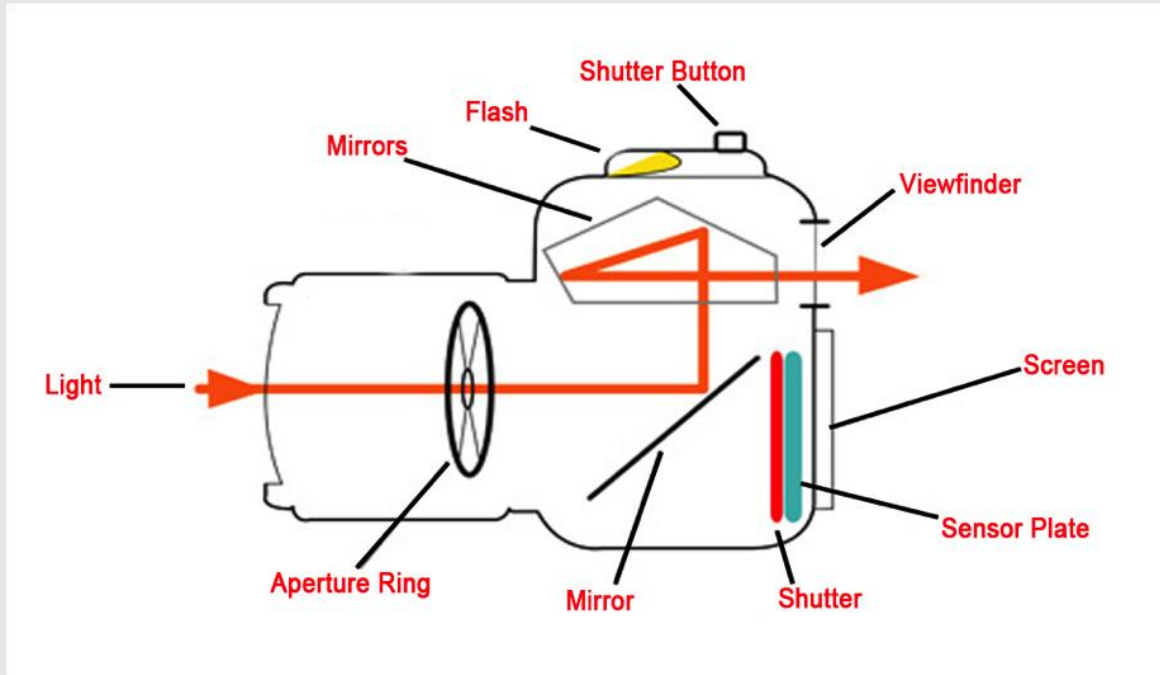
'Eye' See What You Mean

- Eyes are biological cameras
 - Light passes through the pupil
 - Iris controls how much light enters eye
 - Retina 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 bend the lense 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



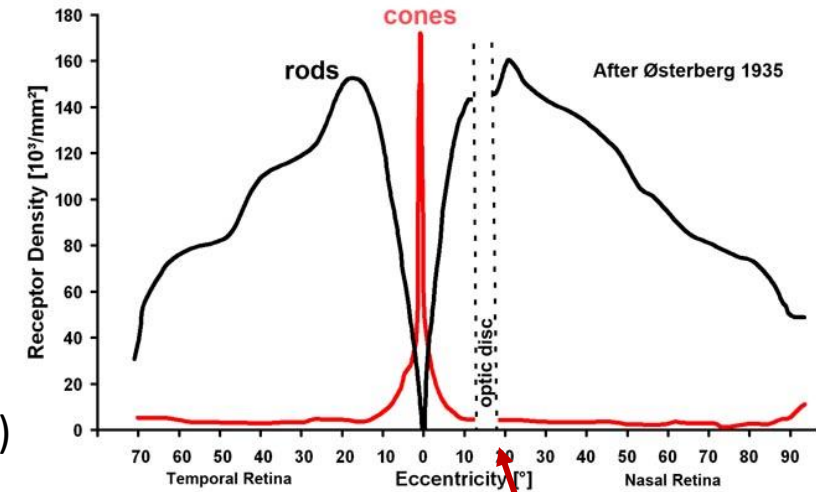
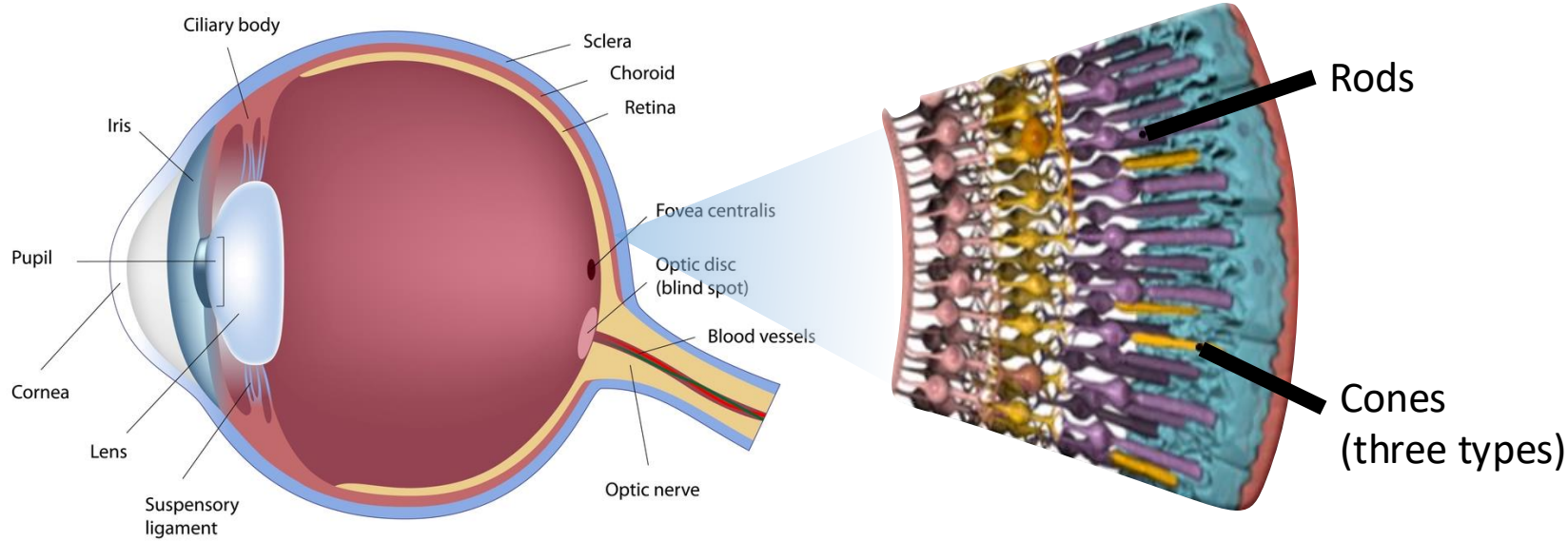
**Image appears backwards!
Don't worry, brain flips it right-side up**

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

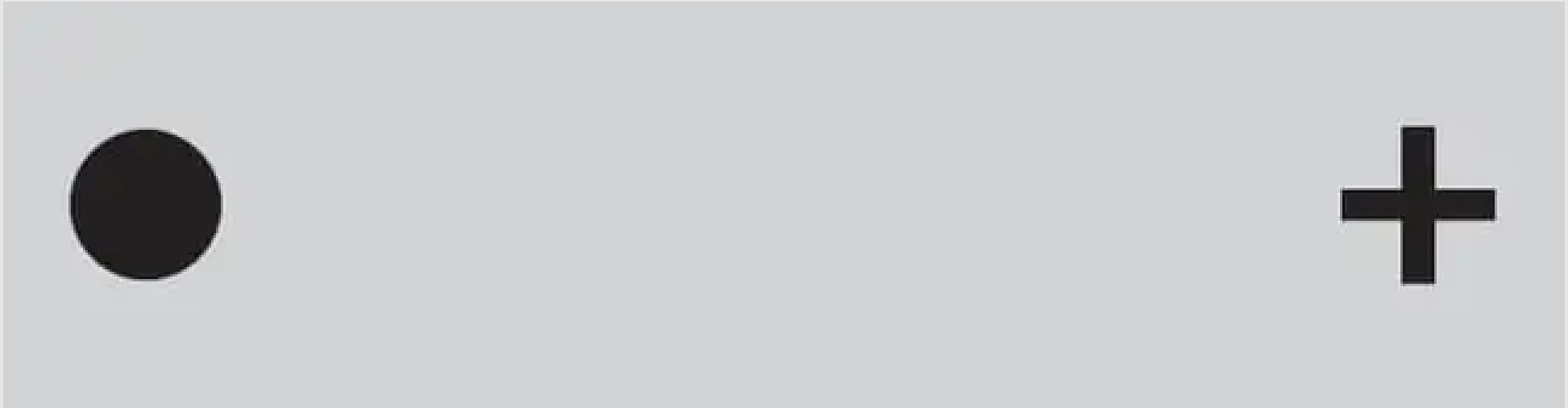


- Cones are primary receptors near fovea used under high-light viewing conditions
 - Approx. 6-7 million cones in the human eye
 - Capture color
- Rods are primary receptors far from fovea used under low-light viewing conditions
 - Approx. 120 million rods in human eye
 - Capture intensity

Best vision at center of cones!

Human blind spot

A Little Trick



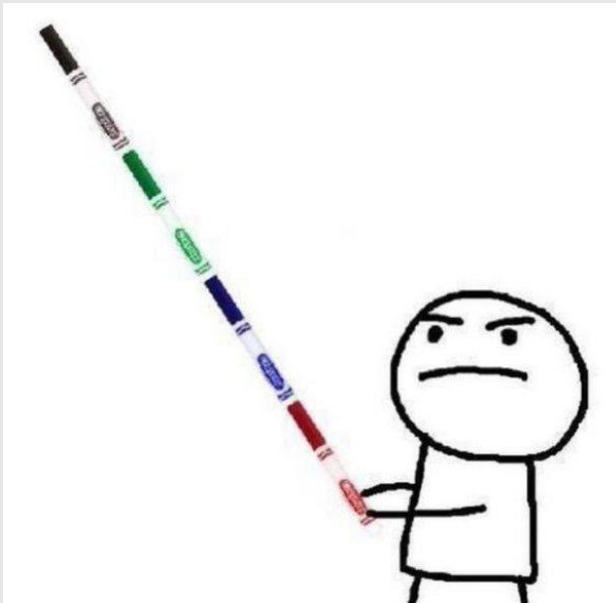
- Close left eye
 - Stare at the circle
 - Move closer to the screen
 - Move farther from the screen
 - Continue until the plus sign disappears
- Close right eye
 - Stare at the plus
 - Move closer to the screen
 - Move farther from the screen
 - Continue until the plus sign disappears

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

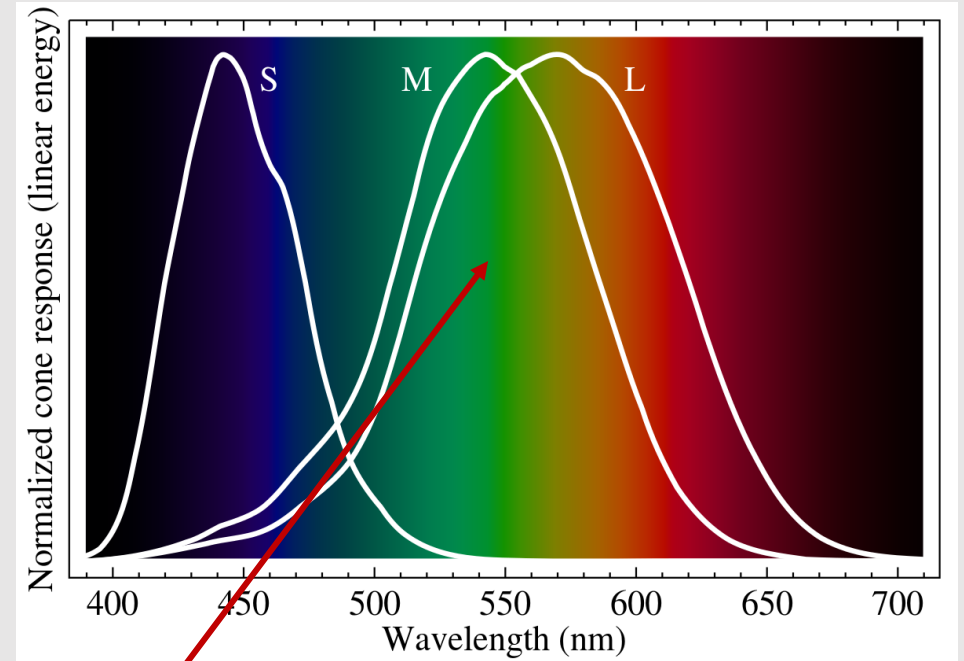
- Long, Medium, and Small cones pick up Long, Medium, and Small wavelengths respectively
- Each cone picks up a range of colors given by their response functions
 - Not much different than absorption spectrum
- Each cone integrates the emission & response to produce a single signal to transmit to the brain

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

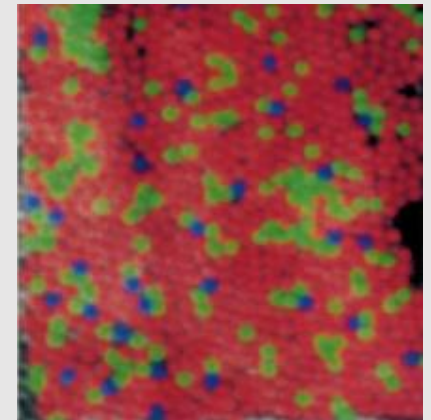
$$M = \int_{\lambda} \Phi(\lambda) M(\lambda) d\lambda$$

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

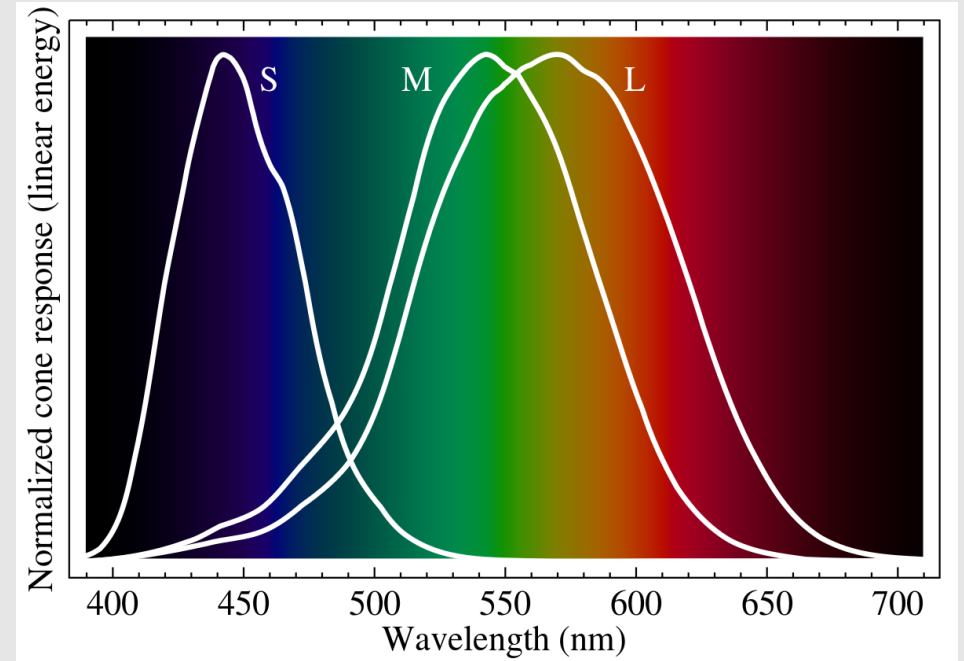
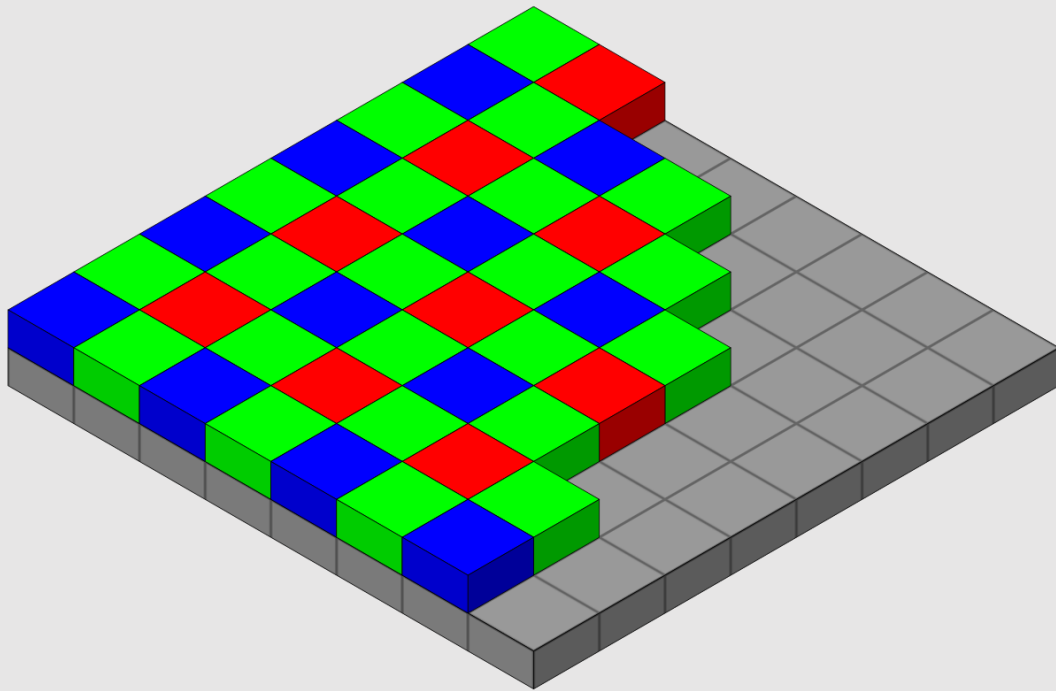
- Uneven distribution of cone types in eye
 - ~64% L cones, ~ 32% M cones ~4% S cones



A lot of green picked up!



The Biological Camera [Again]



- Eyes perceive green color better than any other color
 - 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

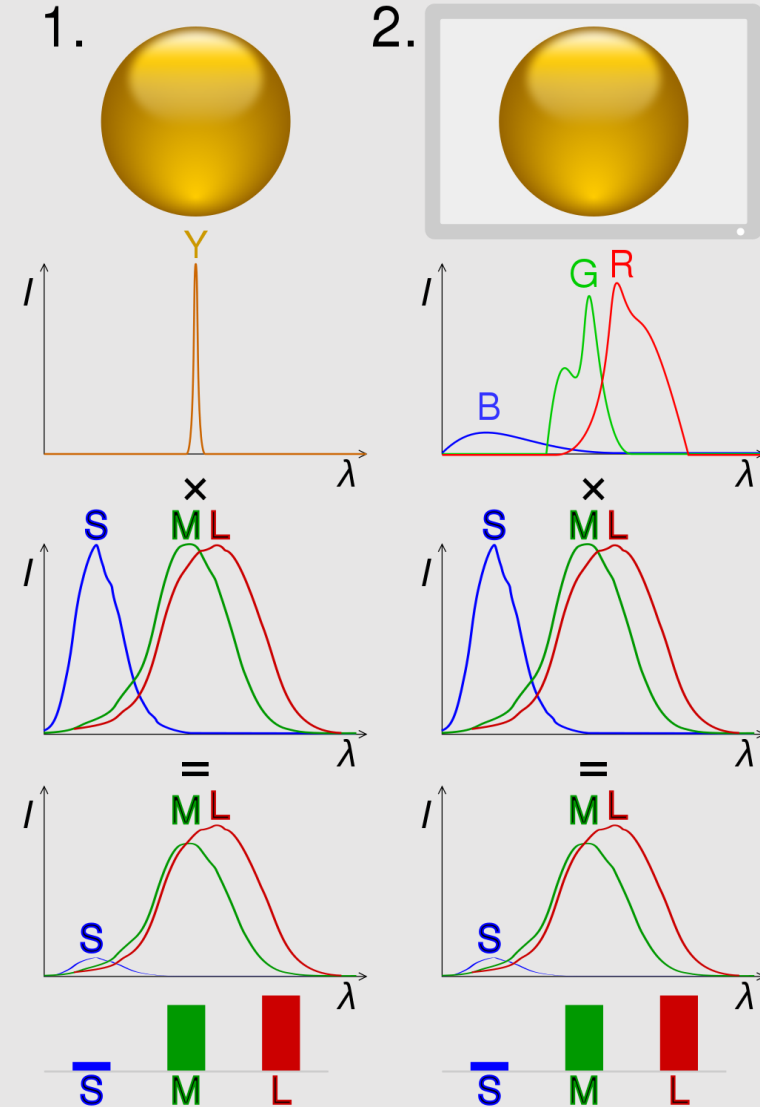
King of the See

- **Mantis Shrimp** are a larger breed of shrimp that live in tropical waters
 - 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



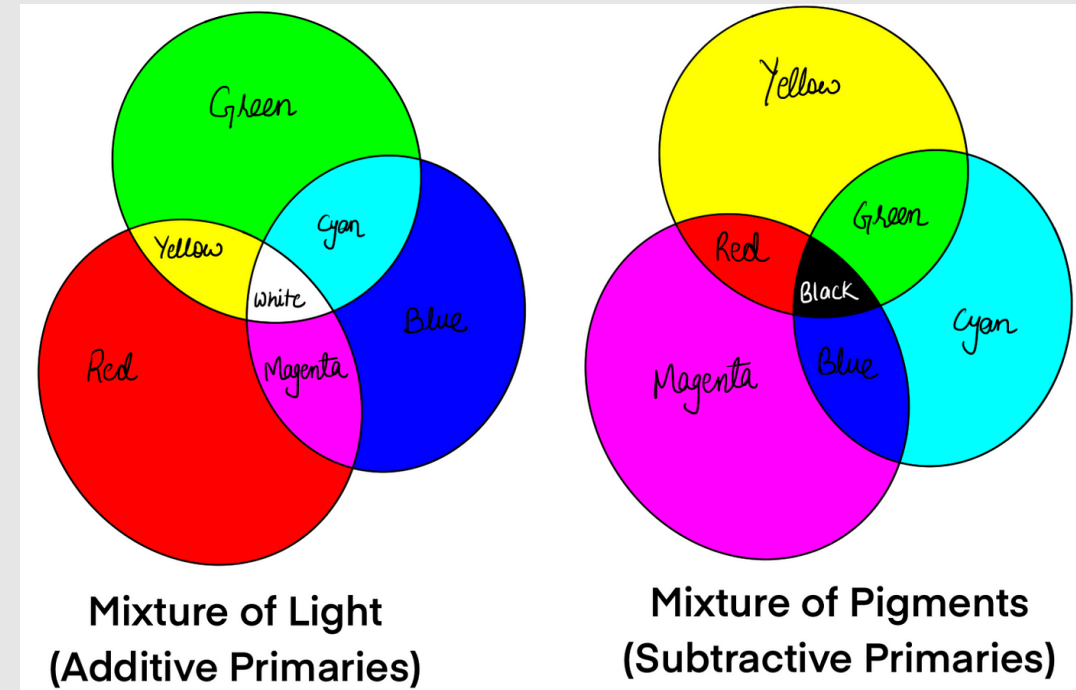
- ~~Physical Color~~

- Digital Color

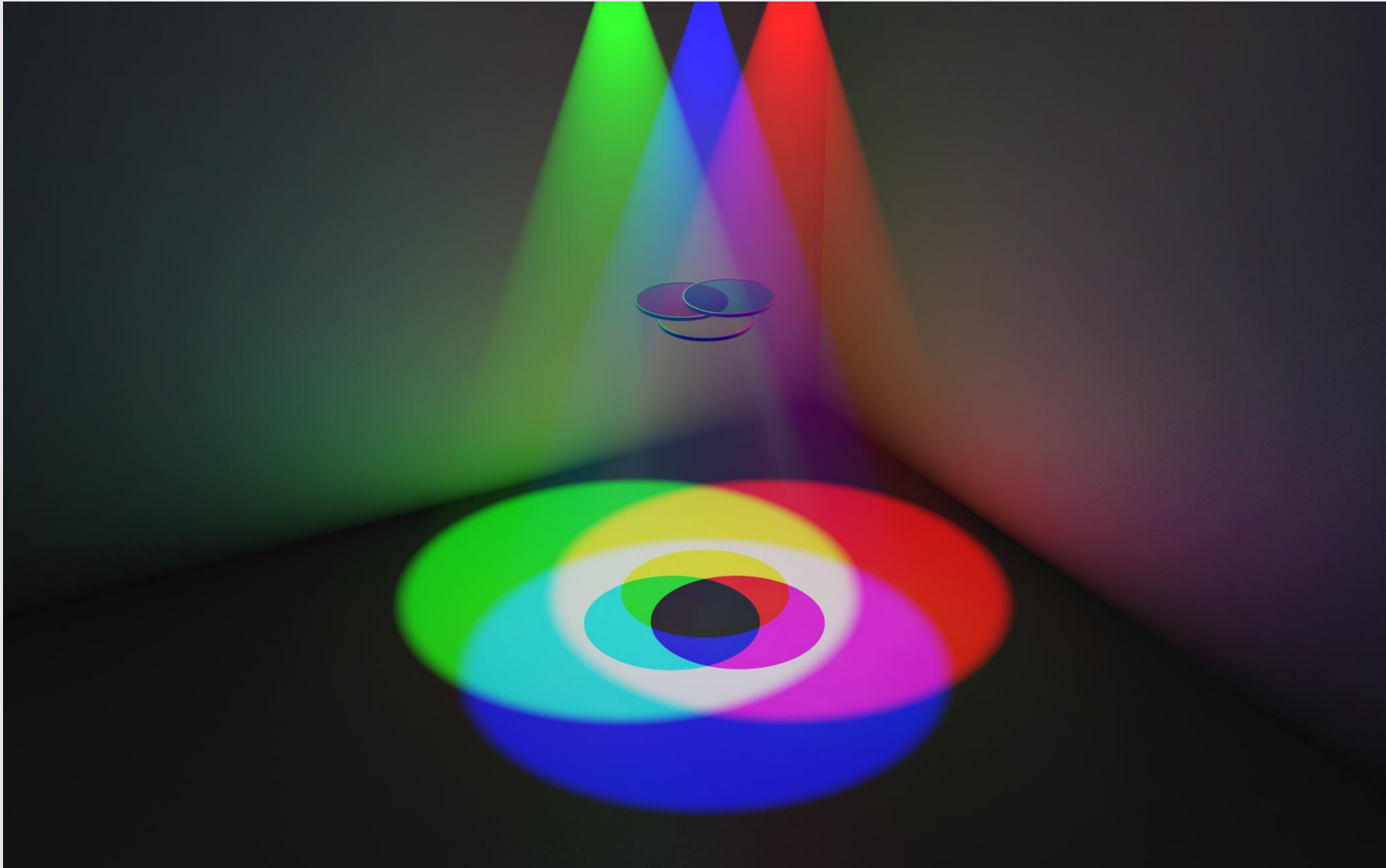
- Color Manipulation

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

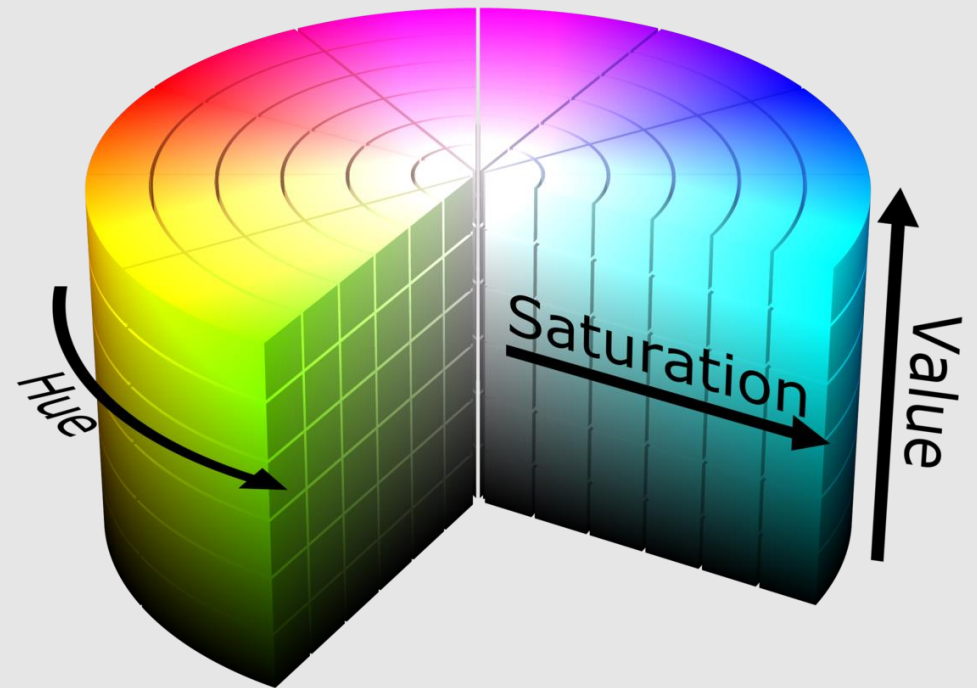


Let's Shed Some Light Here

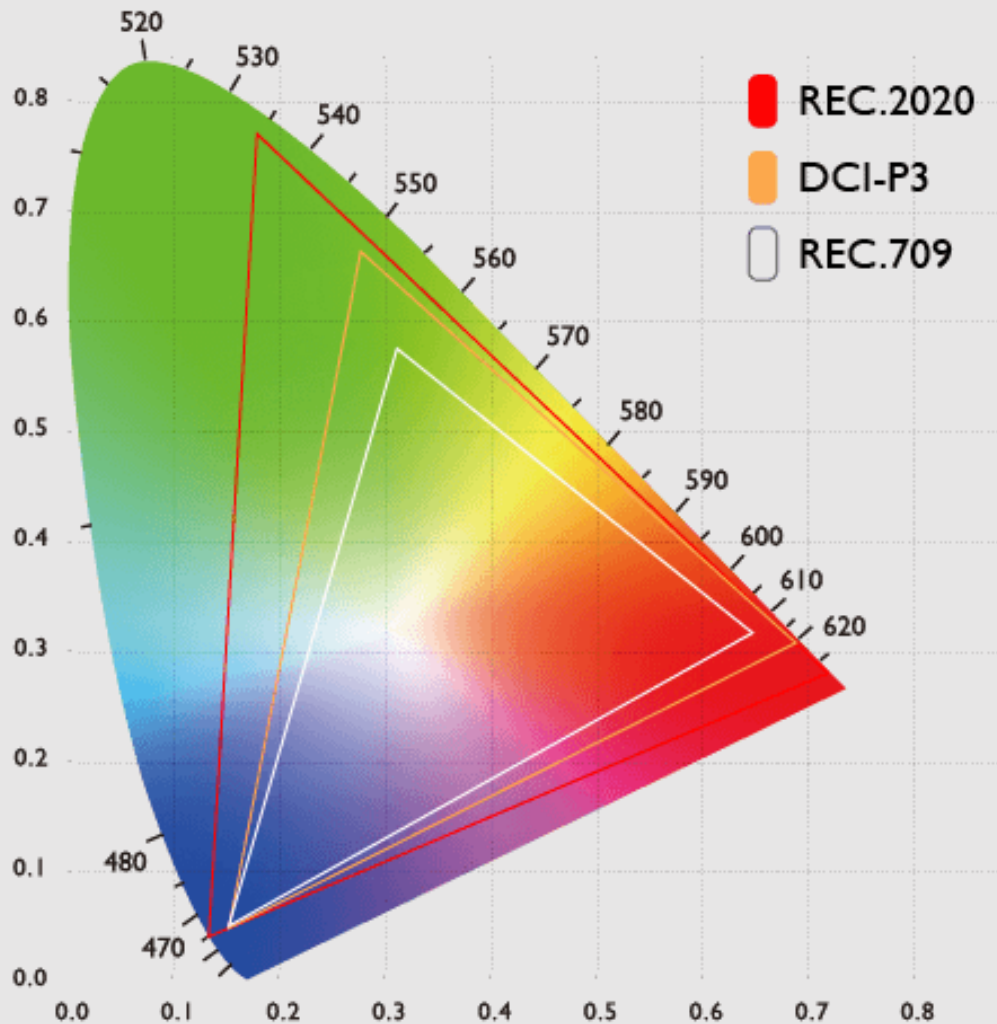


Types of Color Models

- **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

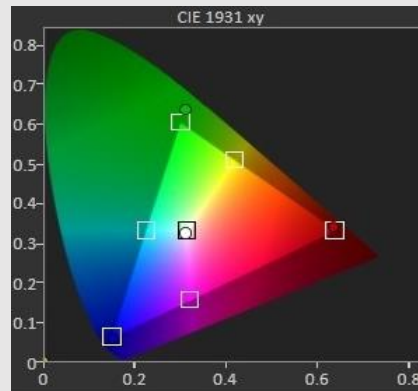
$$\begin{aligned}R &= 0.65x + 0.31y \\B &= 0.15x + 0.05y \\G &= 0.31x + 0.57y\end{aligned}$$

- 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

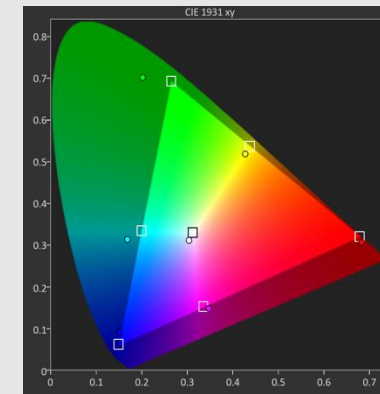
Absolute Color Spaces



\$799

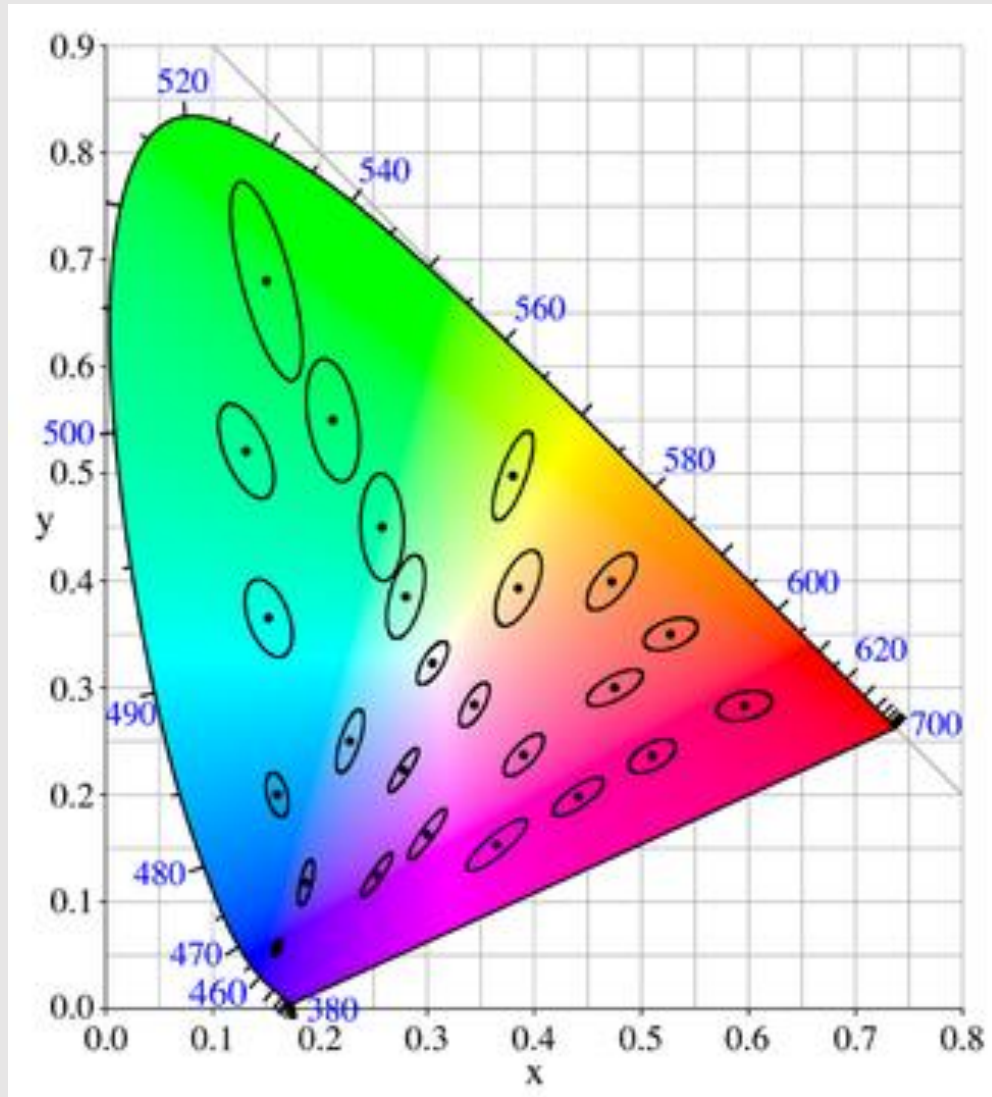


\$1999



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

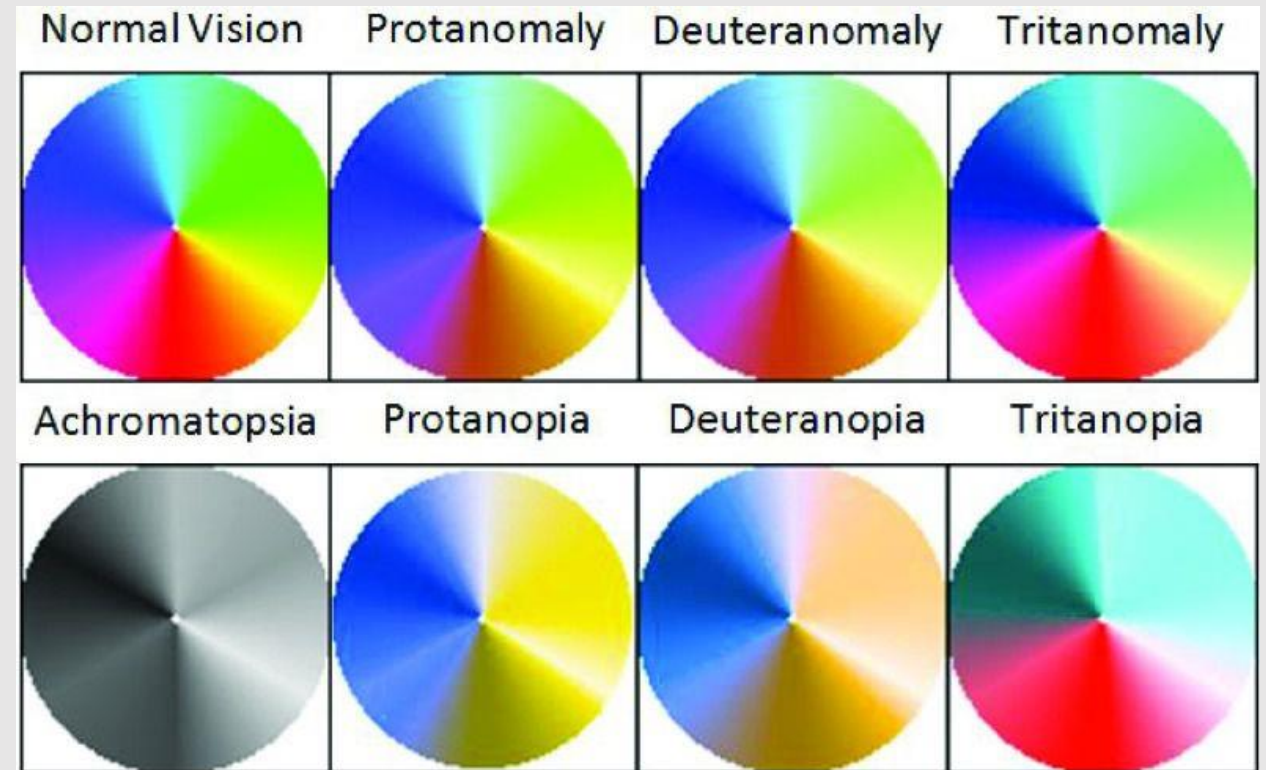
MacAdam Ellipses



- 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
 - “pure” color
 - Radius of ellipse in a given direction measures the lack of chromaticity difference

Nonstandard Color Vision

- Morphological differences in eye 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 universally recognizable as possible

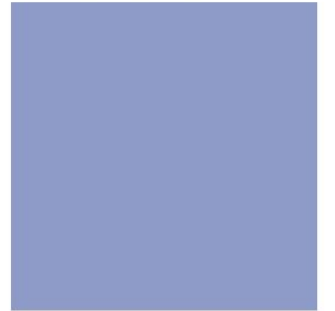


Encoding Color Values

- RGB colors commonly encoded as 8-bits per channel
 - 256 possible values
 - With alpha, another 8 bits
 - Displays 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



swatch colour taken
directly from dress
hex code 8f9cc6



Gold/Brown colour
from lace parts
hex code 745e39



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!

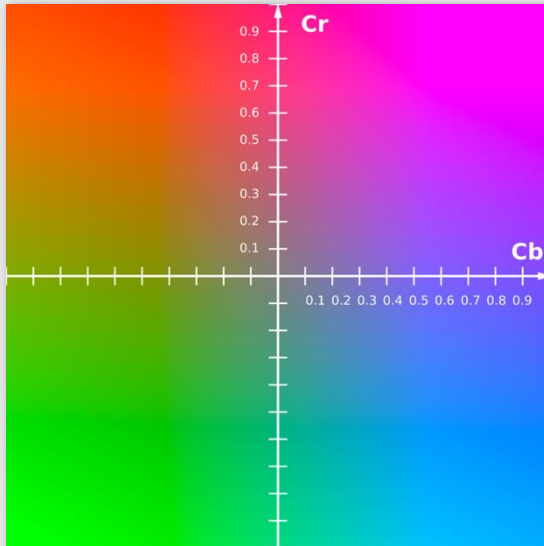
- **Y'** channel holds high frequency data
- **Cb, Cr** channels hold low frequency data



[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 lost
 - Depends on the gamut of the output device
- Lots of standards & software
 - ICC Profiles
 - Adobe Color Management



[RGB]



[CMYK]

Color Conversion

What we see:



What animals with a larger color range than ours see:



- 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

$$y = x + b$$

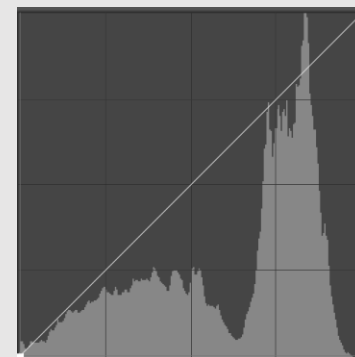
- Contrast brings colors closer to the average grey color

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

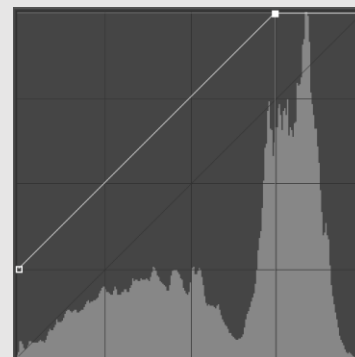
- Can be combined as a 2-for-1 deal
 - Commonly found as a single effect in most color-grading software:

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

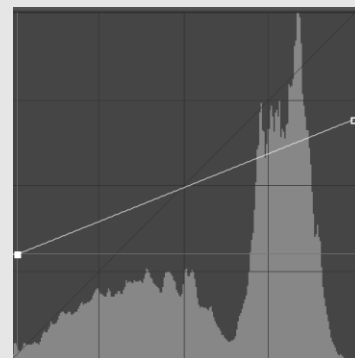
- Values must be clamped back to range [0.0, 1.0]!**



[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:

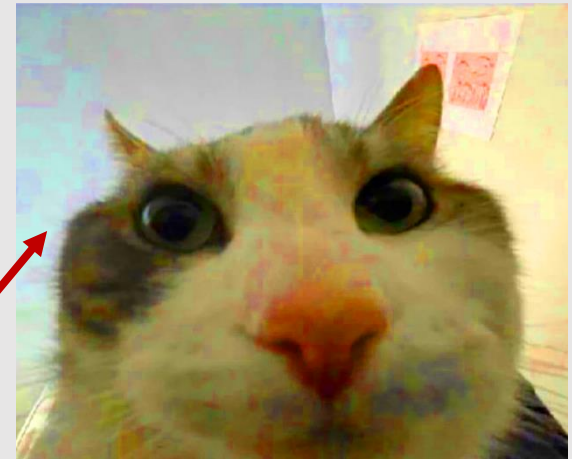
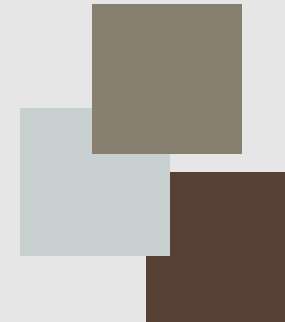
$$x.\text{grey} = 0.299 * x.r + 0.587 * x.g + 0.114 * x.b$$

- Linearly interpolate the original color with the grey color:

$$y = a * x + (1 - a) * x.\text{grey}$$

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

$$2 * \text{brown} - 1 * \text{grey} = \text{orange}$$



artifacts of jpeg compression!

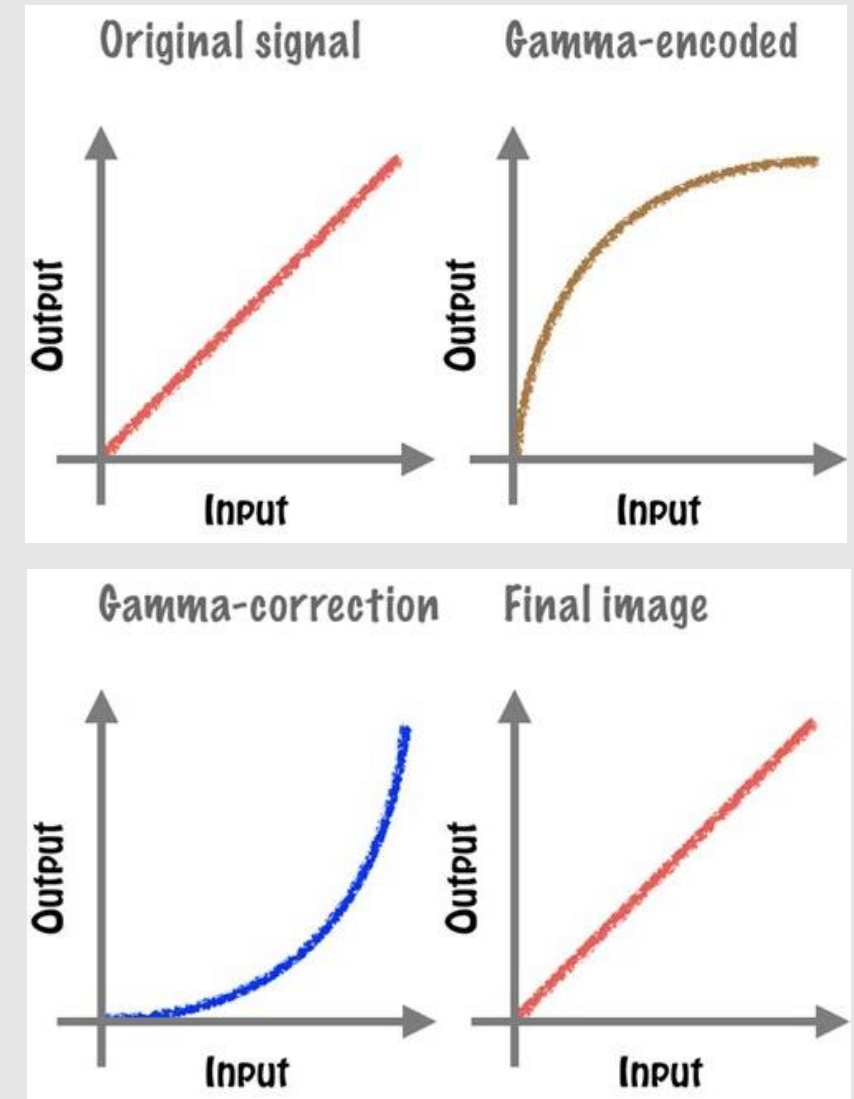
Gamma Correction

- 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 photons, and the sensor picks up twice as many photons, making the observation twice as bright [**linear**]
- Cameras tend to map colors too brightly, while having a hard time capturing darkness
 - Gamma correction modifies the signal by some γ :

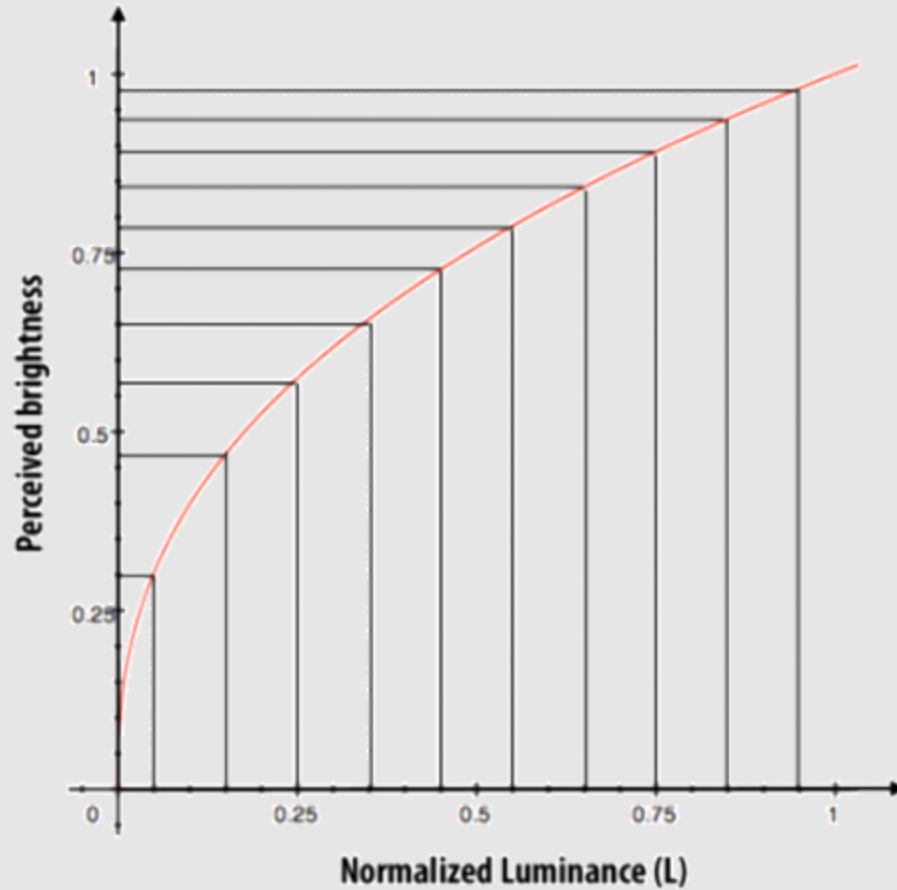
$$y = x^{-\gamma}$$

- When displaying the image, un-modifies the gamma:

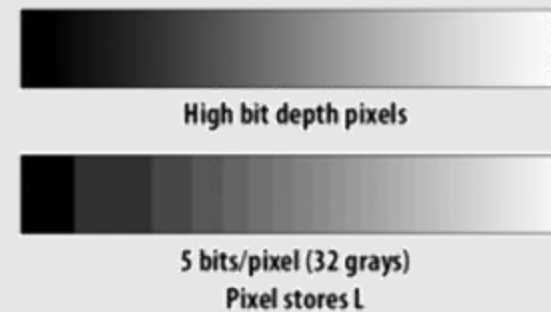
$$y = x^{\gamma}$$



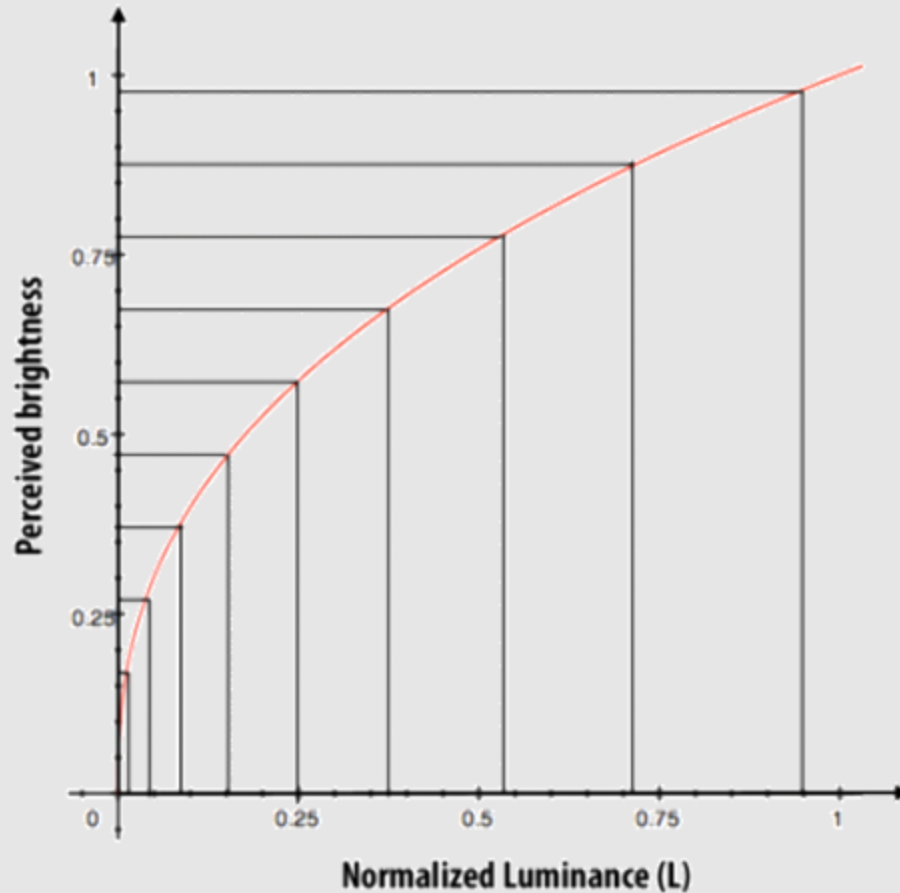
Quantization Error



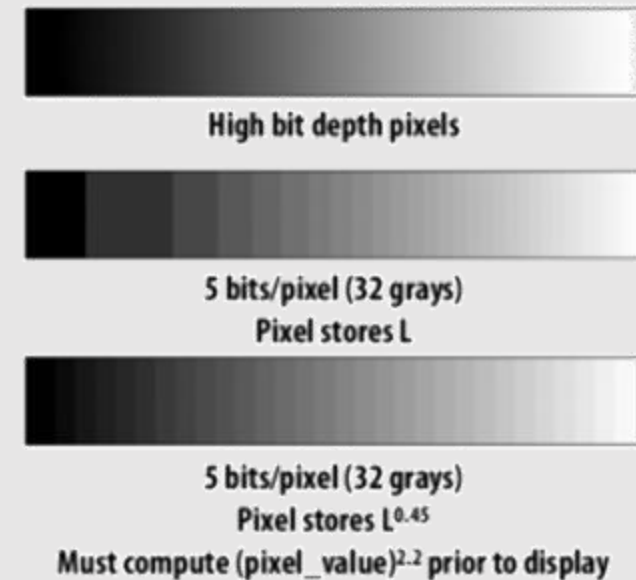
- Most images are not RAW files
- 8-bit sensor pixels
- Can represent 256 luminance values
- Risks quantization of dark areas of image



Quantization Fix

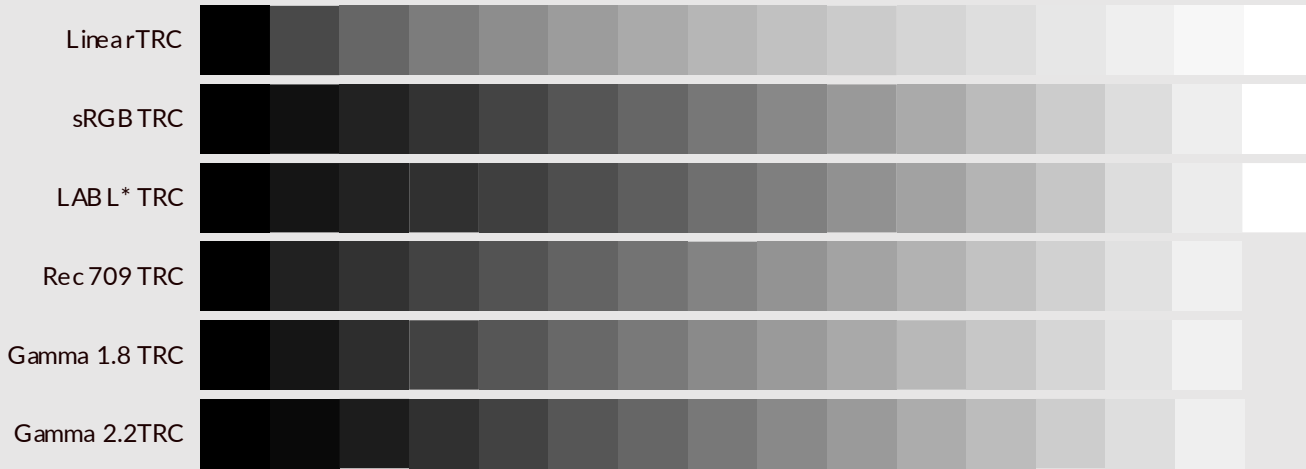


- Evenly distribute values over perceptible range
 - Make better use of available bits
- **Rule of thumb:** human eye cannot differentiate differences in luminance less than 1%



- **Q:** 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 majority of data is on the brighter end, 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 Excitement Strength Love Energy	Orange Confidence Success Bravery Sociability	Yellow Creativity Happiness Warmth Cheer	Green Nature Healing Freshness Quality	Blue Trust Peace Loyalty Competence
Pink Compassion Sincerity Sophistication Sweet	Purple Royalty Luxury Spirituality Ambition	Brown Dependable Rugged Trustworthy Simple	Black Formality Dramatic Sophistication Security	White 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.