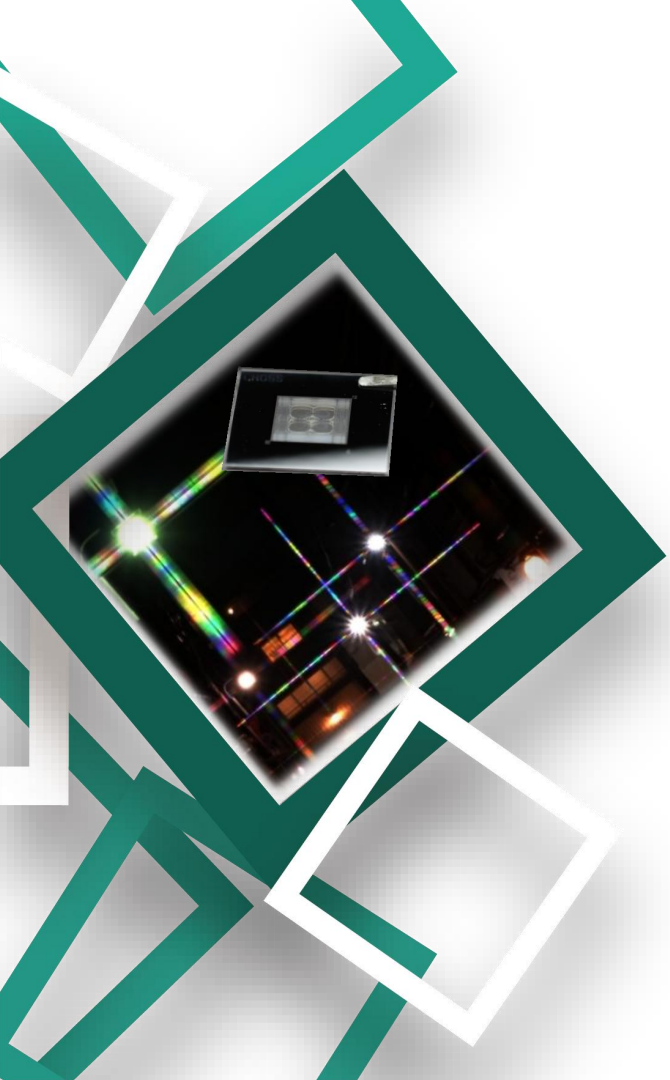

GAMES 204

Computational Imaging

Lecture 02： Color and Human Visual System I

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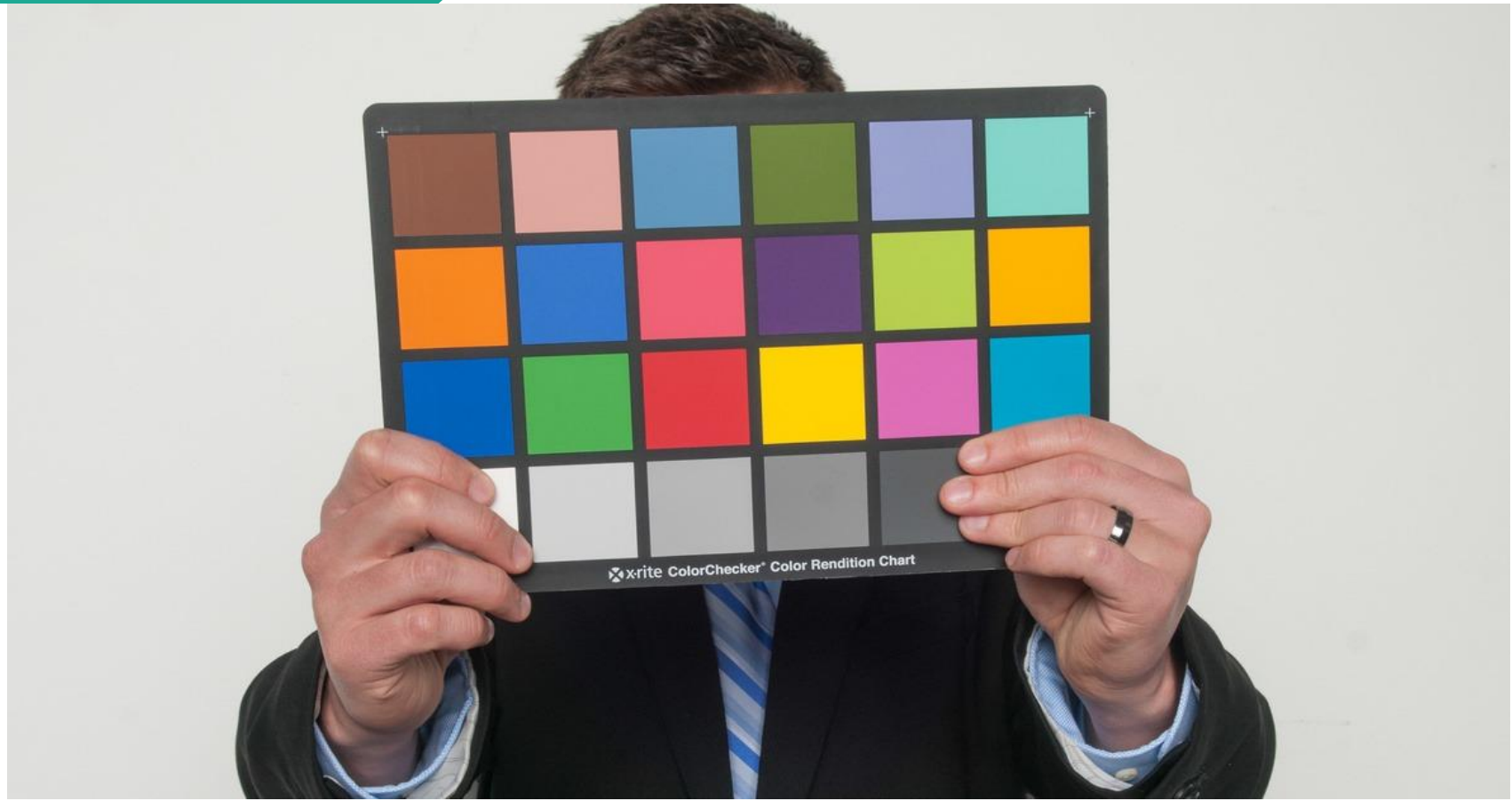
点昀技术（Point Spread Technology）

- Introduction to Color
- What's Color
- Spectral Power Distribution
- Biological Basis of color
  - Human Eye
  - Photosensor Response
  - Cone Cell Response (L, M, S)
- CFA Array Response
- Metamerism
  - Primary Light
  - Color Matching
- Color Perception: Hue, Saturation, Brightness

Introduction to Color

Introduction to Color



Introduction to Color

http://www.deskcity.org/download/213394-0-0x0.html

Introduction to Color

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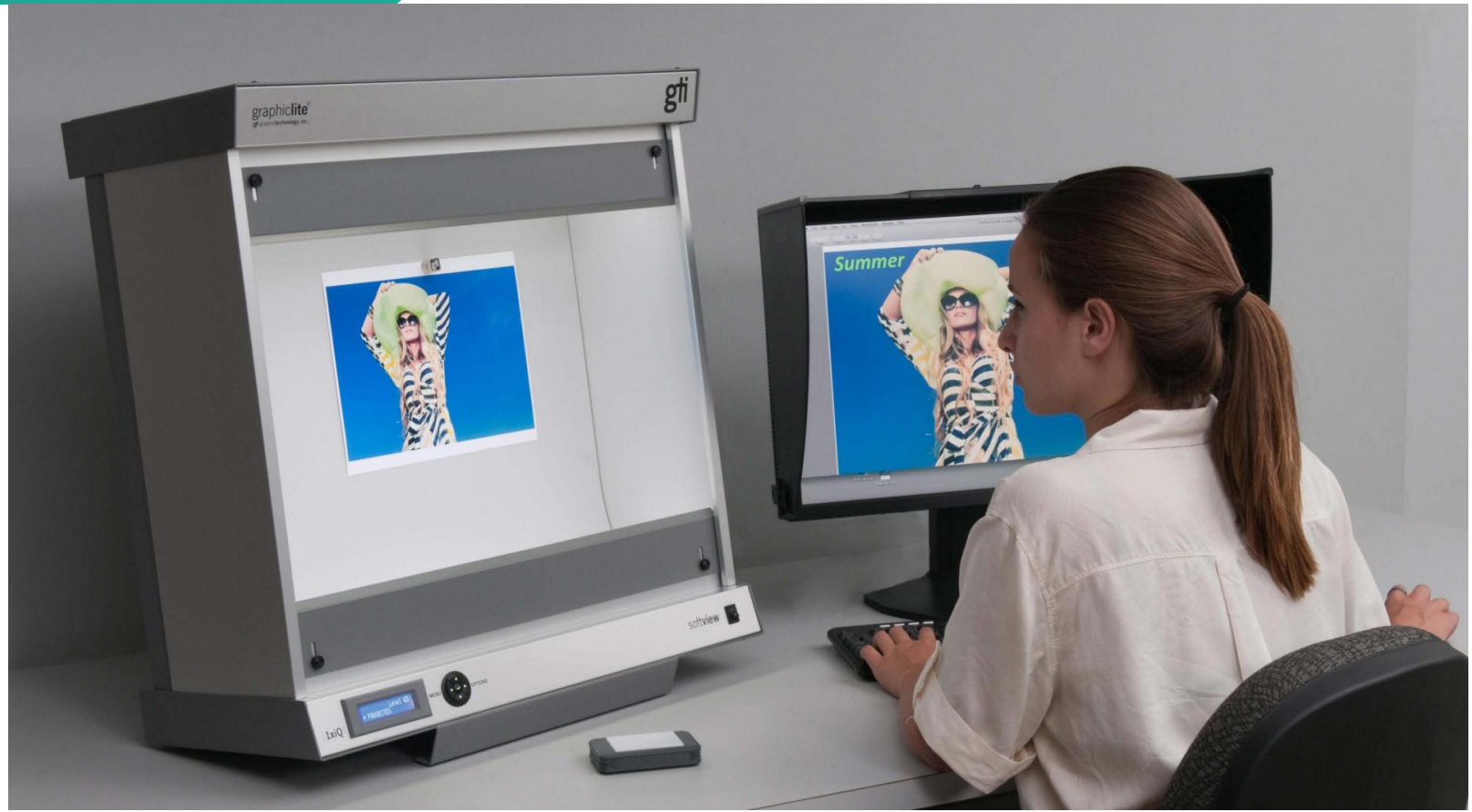
Introduction to Color



Graphiclite

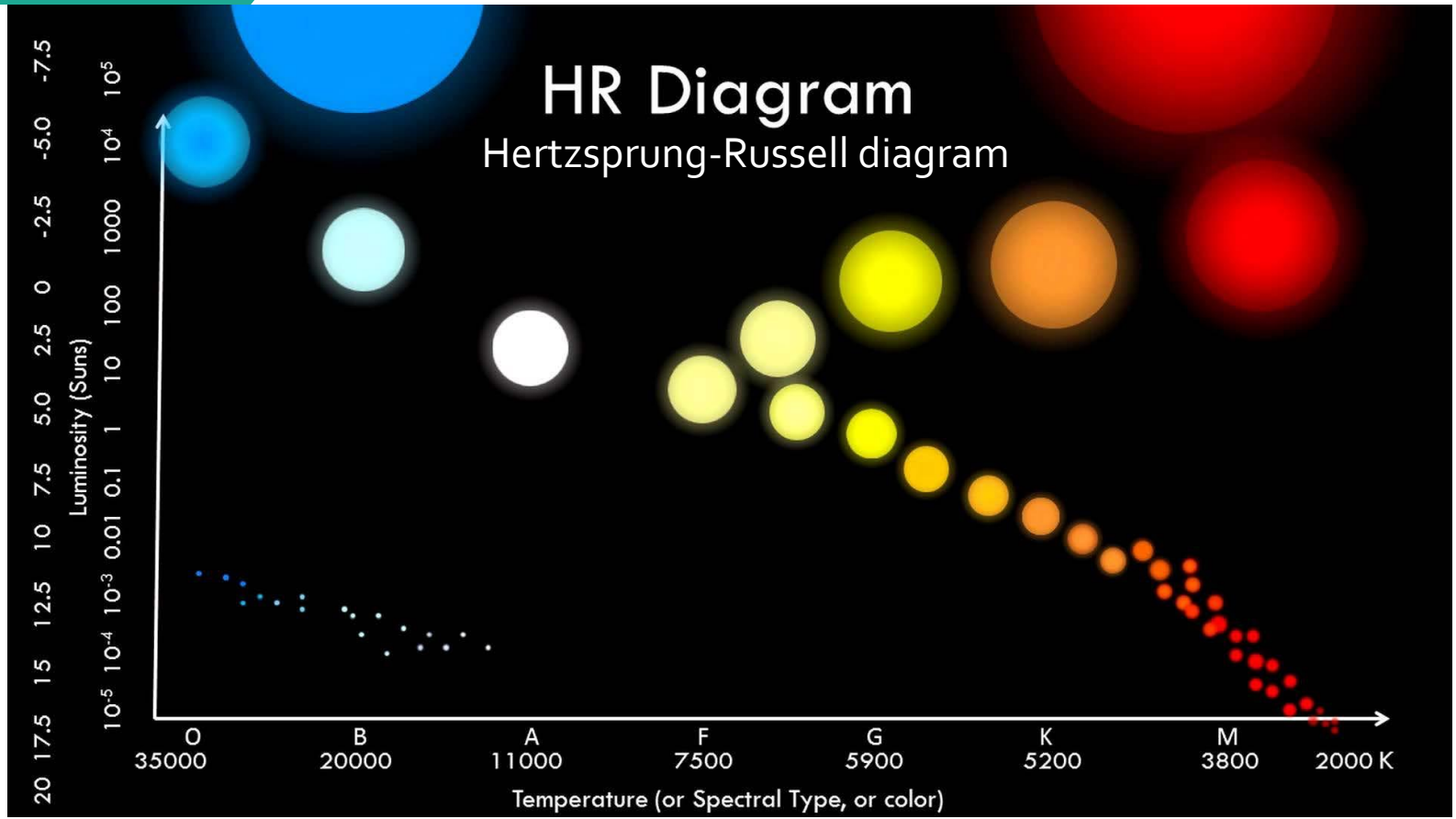
Introduction to Color

On Screen

Printed

What is Color

What is Color



Credit: Adric Riedel https://www.youtube.com/watch?v=5880z17Xj80

What is Color

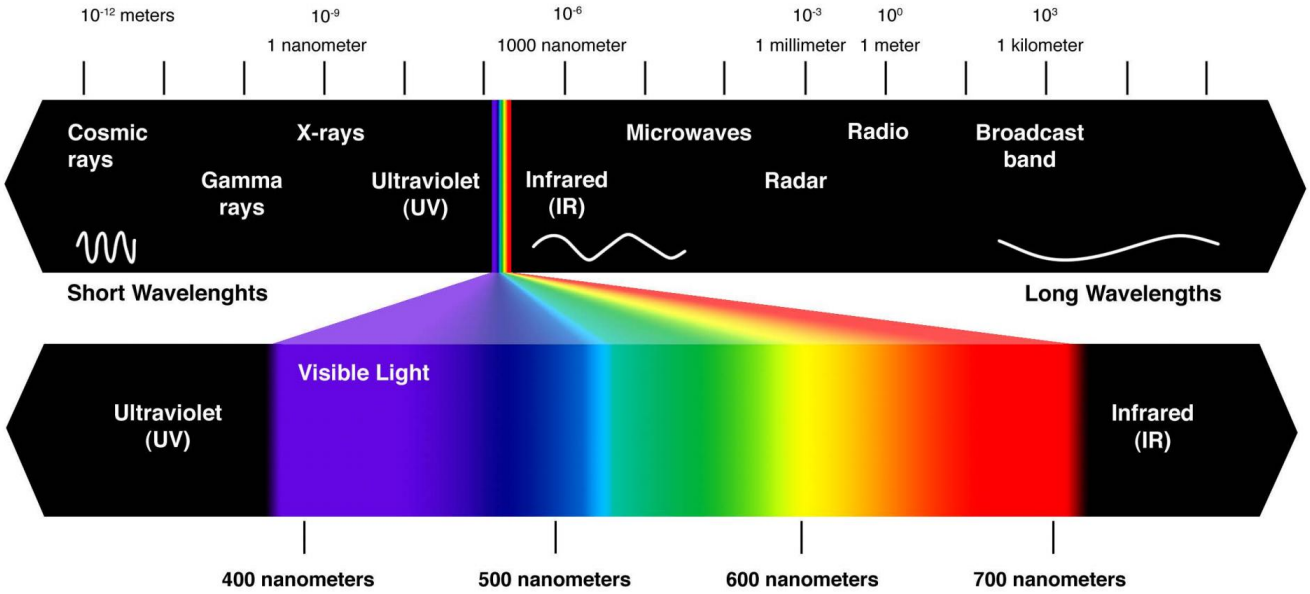
Slide Credit: Ren Ng

What is Color

- To see Color, you have to have **light**. When light shines on an **object** some light bounces of the object then received by **our eyes**.
- Color is a phenomenon of human perception; it is not a universal property of light
- Colors are the perceptual sensations that arise from seeing light of different spectral power distributions
- Different wavelengths of light are not “colors”!

Electromagnetic Radiation

- Light is electromagnetic radiation (oscillating electromagnetic field)
- Perceived color is related to frequency of oscillation



Spectral Power Distribution

Spectral Power Distribution (SPD)

- The power per unit area per unit wavelength of an illumination (radiant exitance).

$$M(\lambda) = \frac{\partial^2 \Phi}{\partial A \, \partial \lambda} \approx \frac{\Phi}{A \, \Delta \lambda}$$

Units: Radiometric units / nanometer (e.g., watts / nm) [Note: Can also be unit-less]

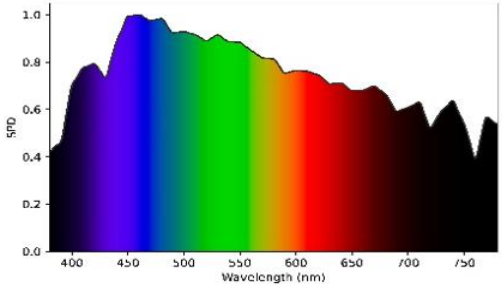
- Not: often visualize **SPD** in "relative units" scaled to maximum power wavelength when absolute units are not important (the diagrams in this lecture do this)

$$M_{\text{rel}}(\lambda) = \frac{M(\lambda)}{M(\lambda_0)}$$

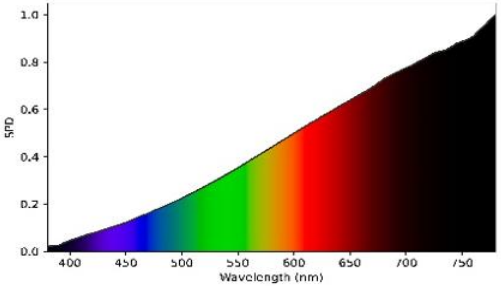
https://en.wikipedia.org/wiki/Spectral_power_distribution

Spectral Power Distribution of Common Light Sources

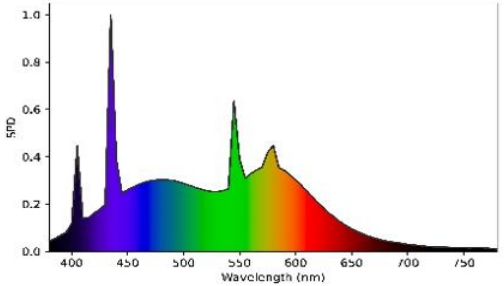
Describes light intensity as a function of frequency



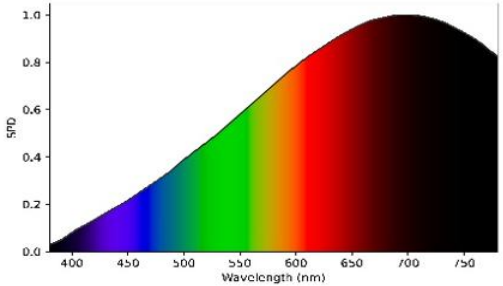
Daylight



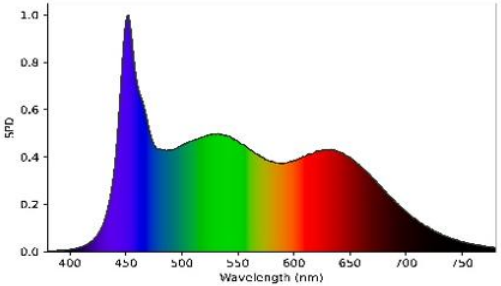
Incandescent



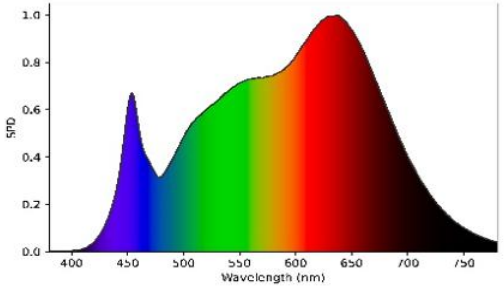
Fluorescent



Halogen



Cool White LED



Warm White LED

Image Credit: Luminus

Emission Spectrum—Example

"Quality" of light:

Incandescent:

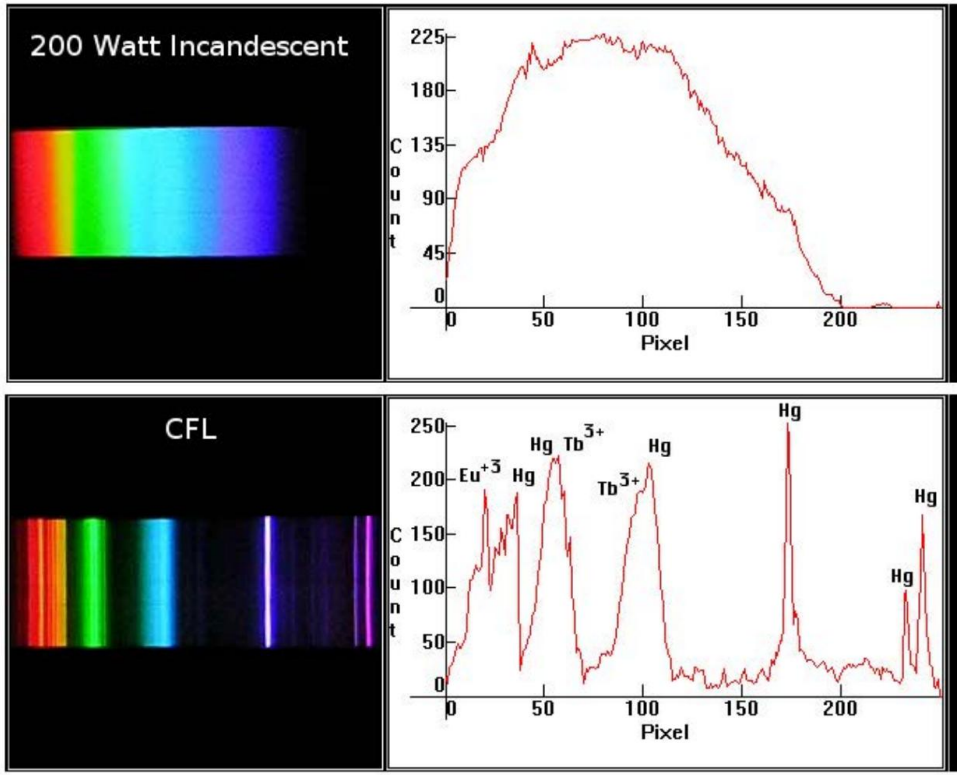
+more sun-like

-power-hungry

CFL:

-"choppy" spectrum

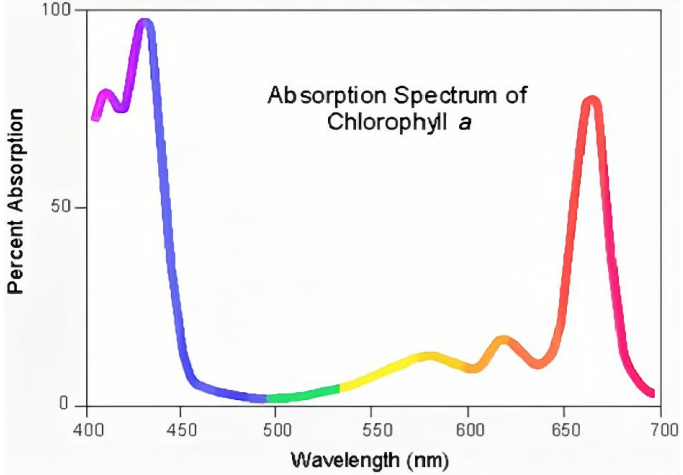
+power efficient



Slide credit: Ren Ng; Image credit: Misuba

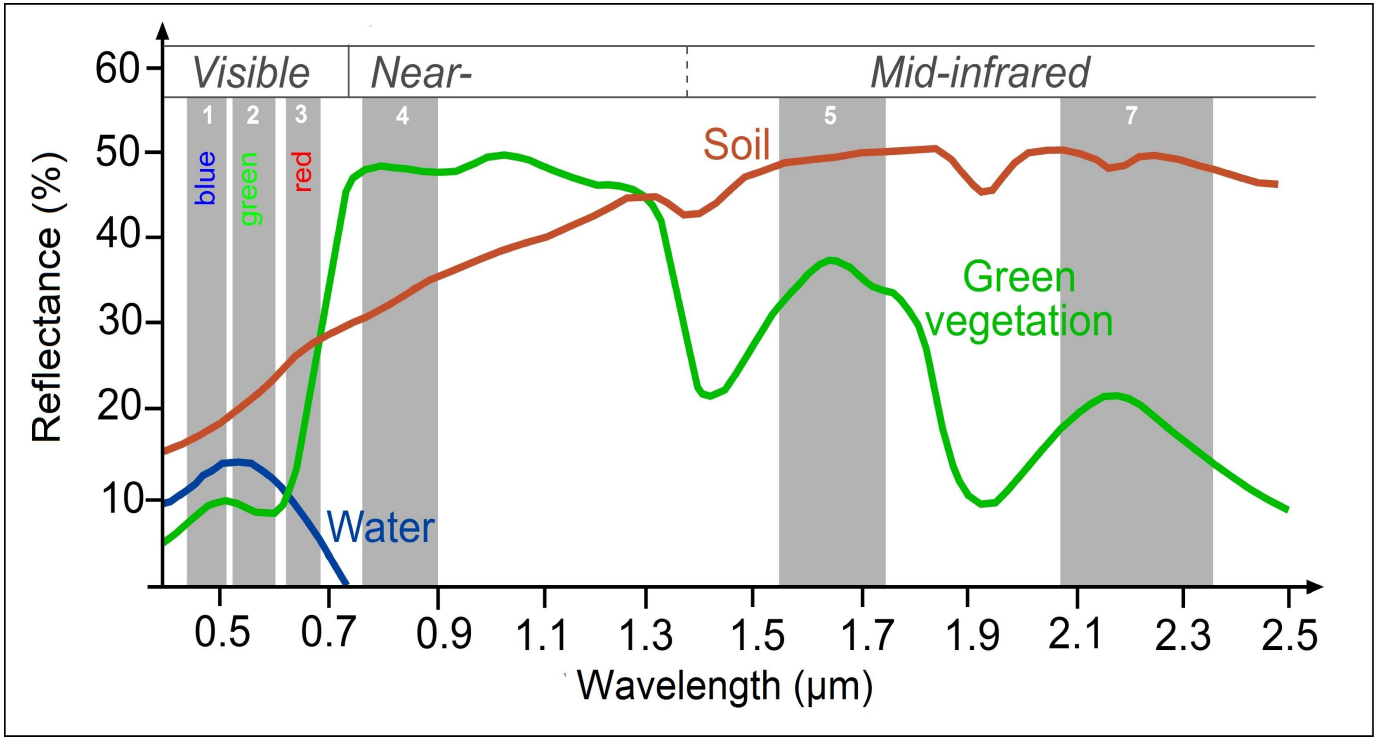
Absorption Spectrum

- Emission spectrum is intensity as a function of frequency
- Absorption spectrum is fraction absorbed as function of frequency

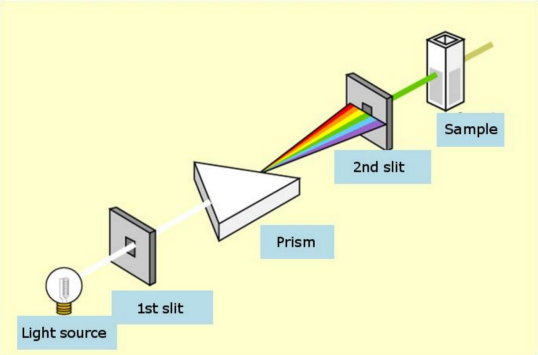


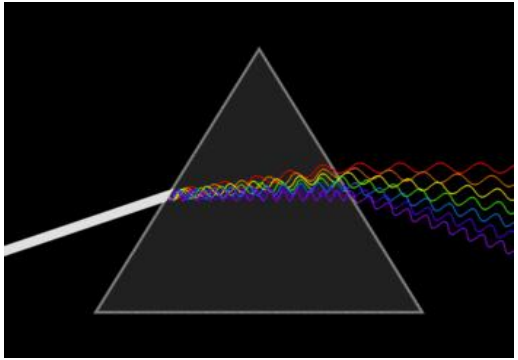
What color is an object with this absorption spectrum?

Spectral Reflectance

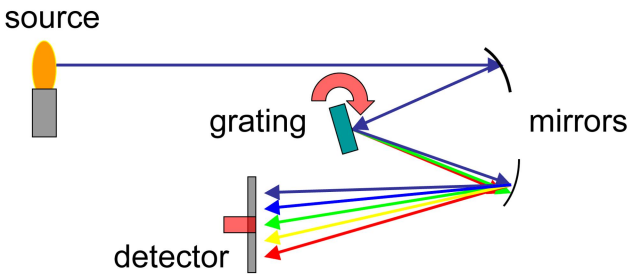


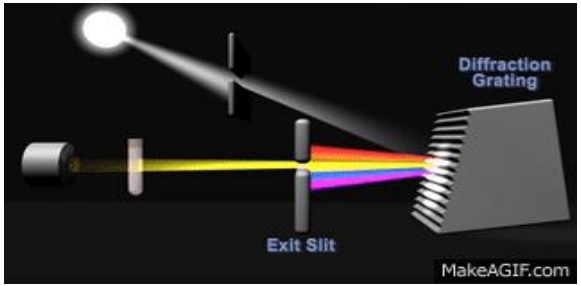
Measuring the Spectral Power Distribution





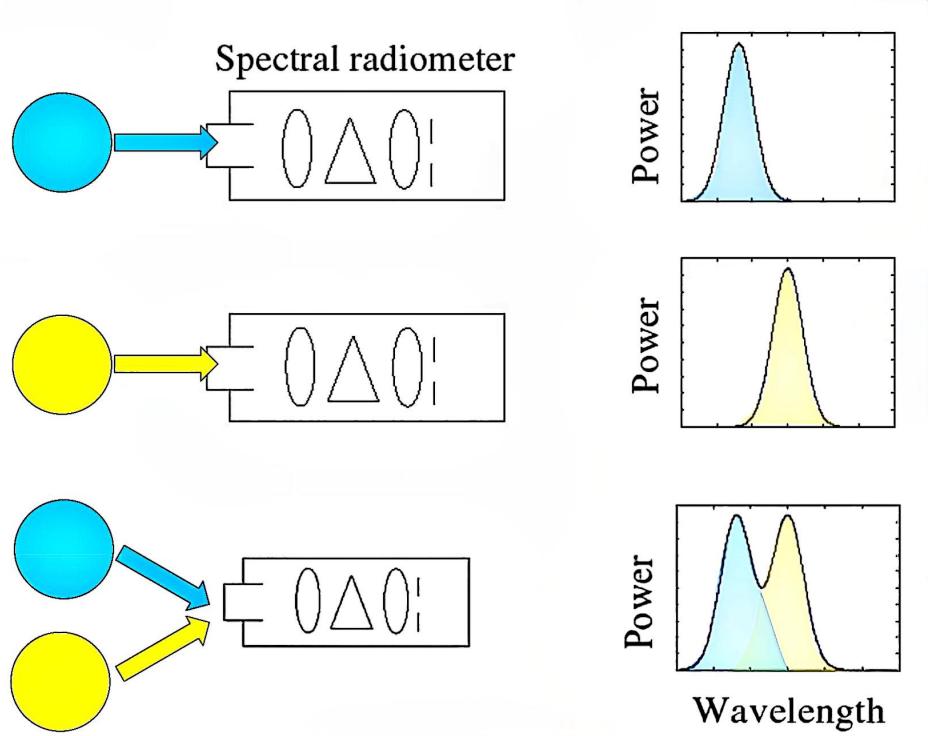
Monochromator with Prism





Spectrometer with Grating

Linearity of SPD

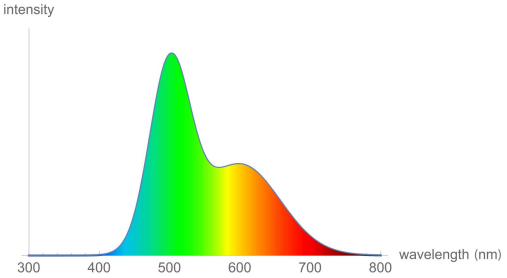


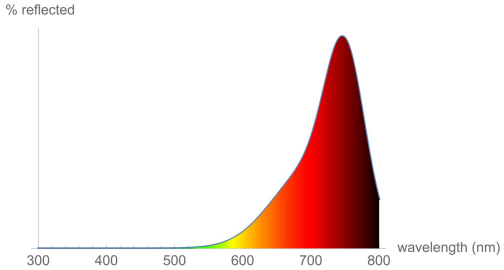
Slide credit: Ren Ng

Interaction of Emission and Refection

- Consider what happens when light gets reflected from a surface
  - ν — frequency of light (Greek "nu")
  - Light source has emission spectrum f(ν)
  - Surface has refection spectrum g(ν)
  - Resulting intensity is the product f(ν)g(ν)

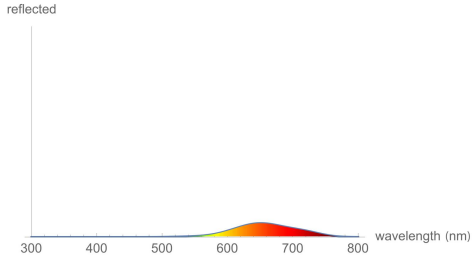
f(ν)





g(ν)

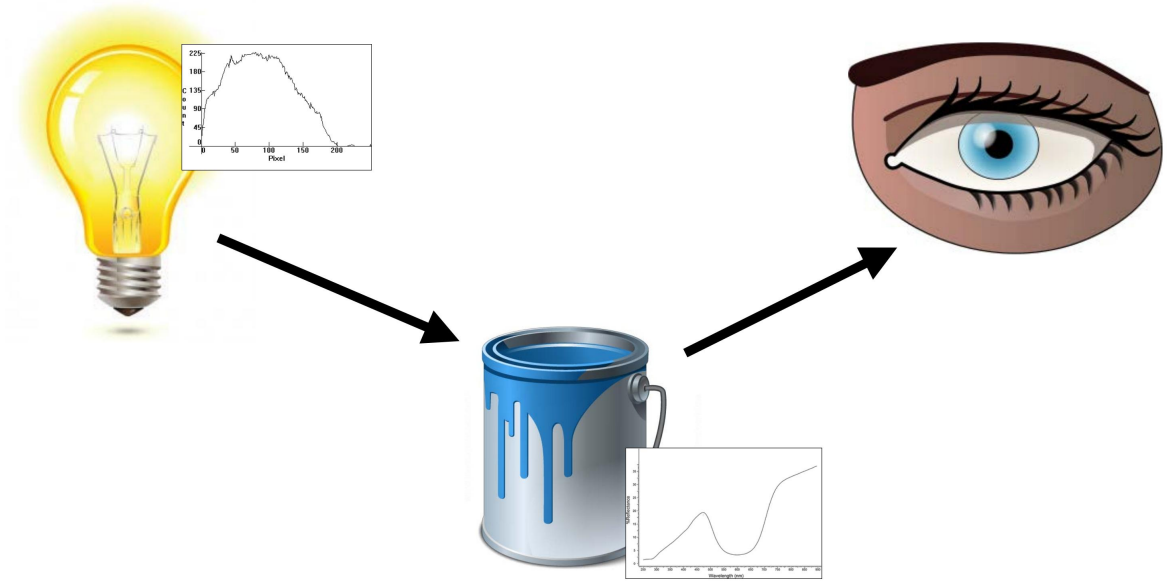
f(ν)g(ν)



Slide credit: Ren Ng

Color Reproduction is Hard

- Color clearly starts to get complicated as we start combining emission and absorption/refection (real-world challenge!)

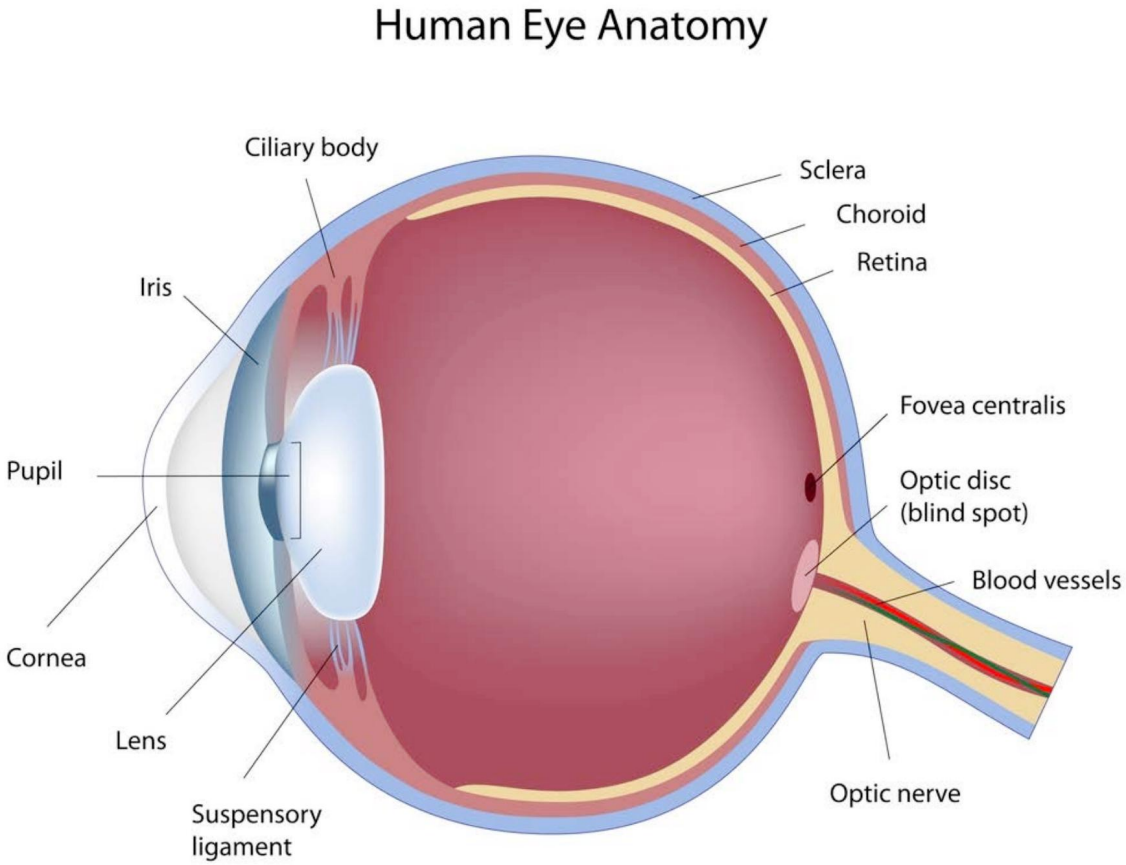


What color ink should we use to get the desired appearance?

Slide credit: Stanford CS148

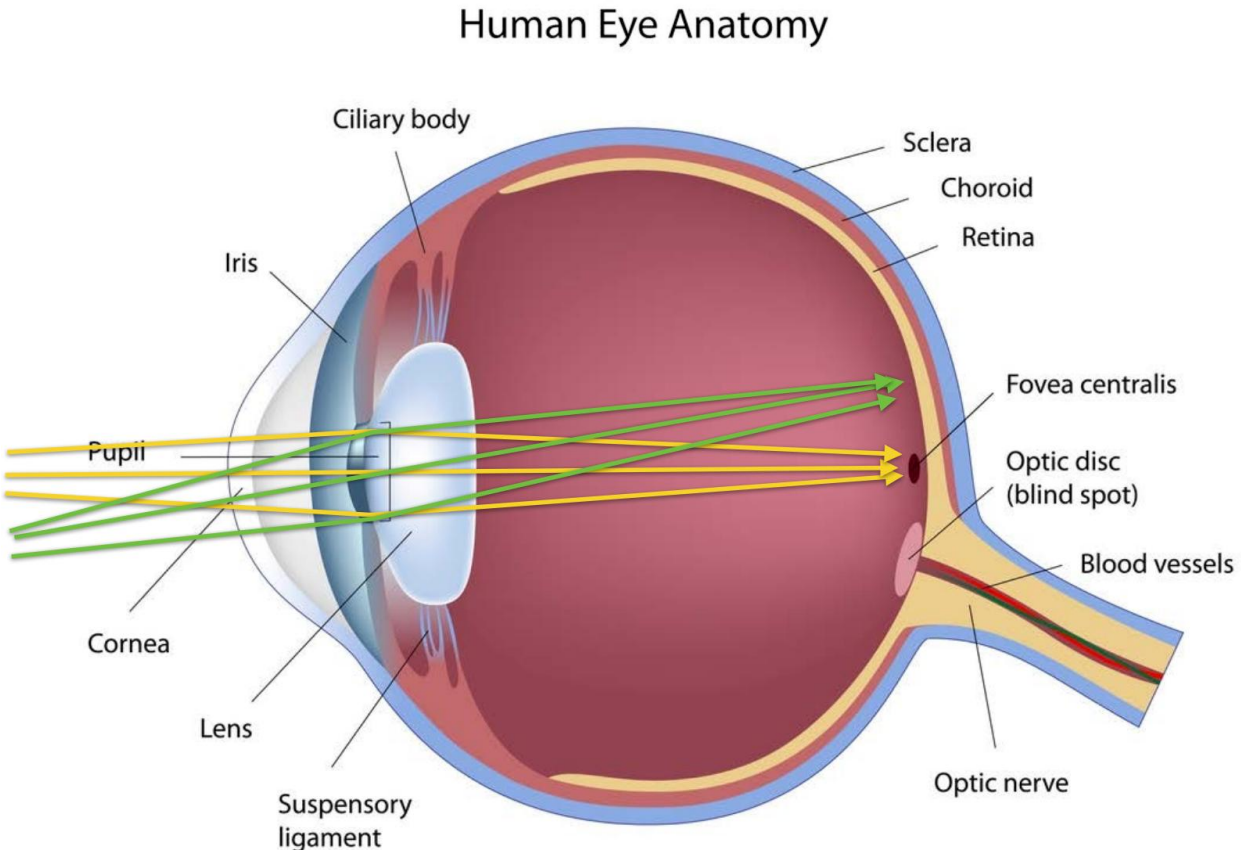
Biological Basis of Color

Human Eye



Slide credit: https://infiniteeyecare.ca/basic-eye-anatomy/

Human Eye (Optics)



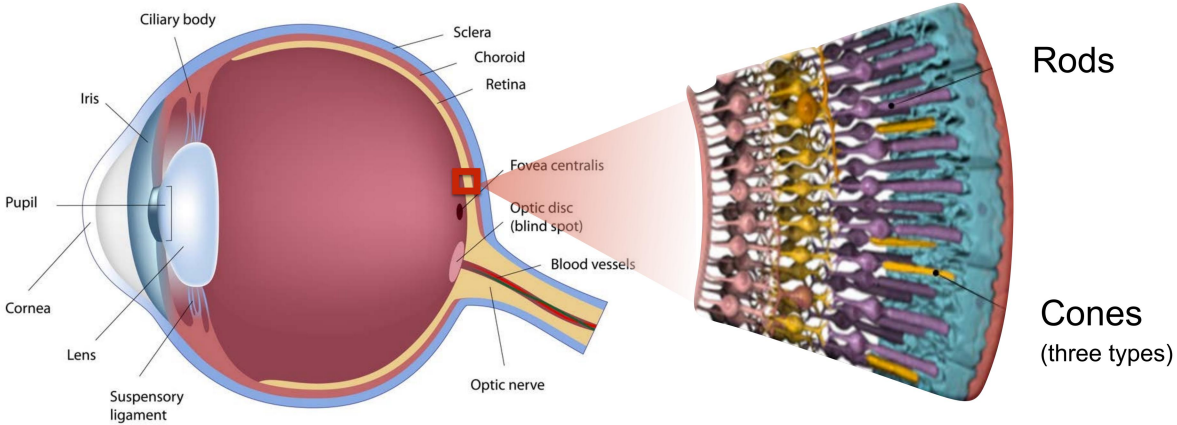
Slide credit: https://infiniteeyecare.ca/basic-eye-anatomy/

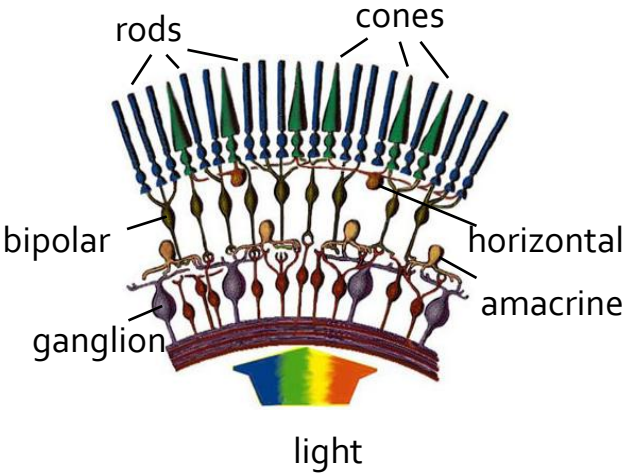
Photosensor Response (Eye, Camera, …)

- Photosensor input: light
  - Electromagnetic power distribution over wavelengths:Φ(λ)
- Photosensor output: a "response" … a number
  - e.g., encoded in electrical signal
- Spectral response function:
  - Sensitivity of sensor to light of a given wavelength
  - Greater f(λ) corresponds to more a efficient sensor (when f(λ) is large, a small amount of light at wavelength λ will trigger a large sensor response)
- Total response of photosensor:

$$R = \int_{\lambda} \Phi(\lambda) f(\lambda) d\lambda$$

Retinal Photoreceptor Cells: Rods and Cones



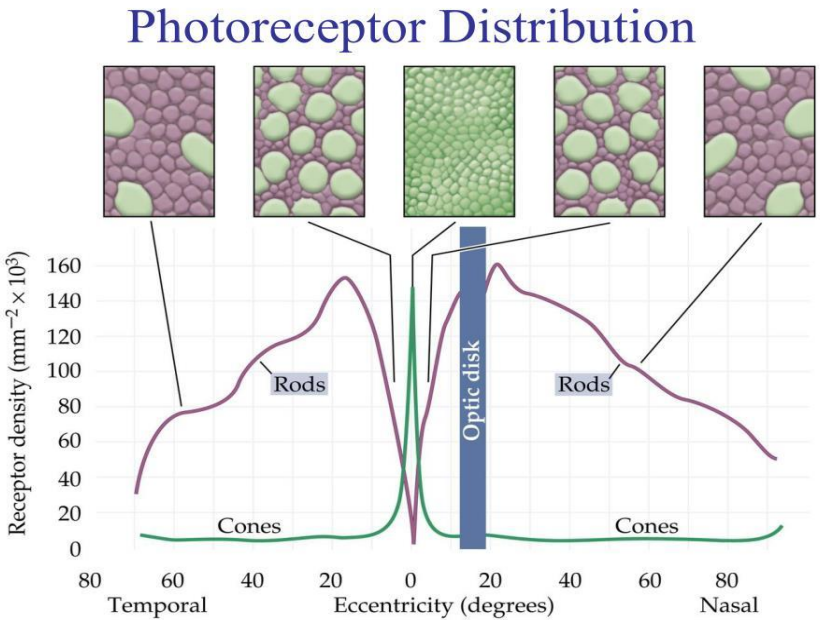


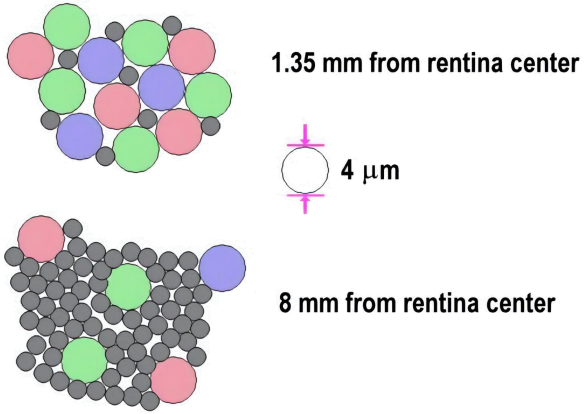
- Rods are primary receptors under dark viewing conditions (Scotopic vision)
  - Approx. 120 million rods in human eye (500nm)
- Cones are primary receptors under high-light viewing conditions (Photopic vision)
  - Approx. 6-7 million cones in human eye (555nm)
- Each of the three types of cone feature a different spectral response. This will be critical to color vision

Source: Wikipedia

Retinal Cone Cell Response Functions (L, M, S types)

- Highest density of cones is in fovea (best color vision at center of where human is looking)
- Note "blind spot" due to optic nerve



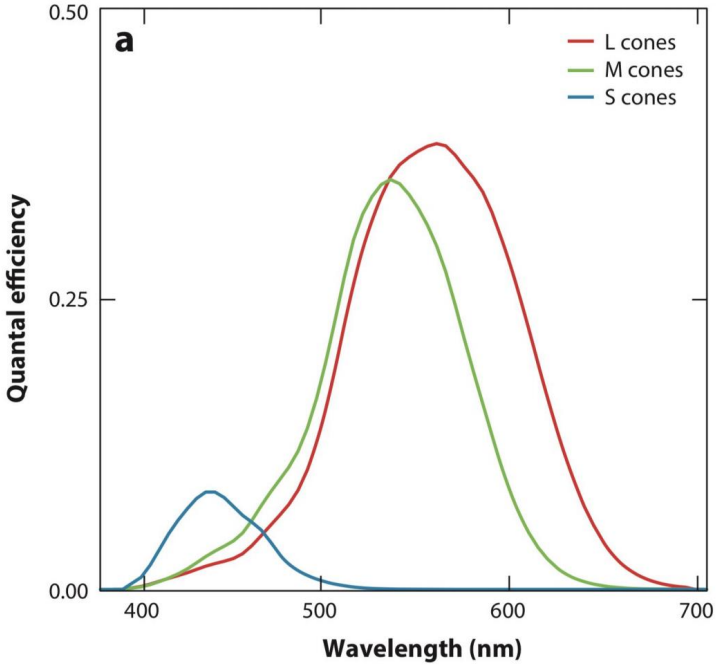


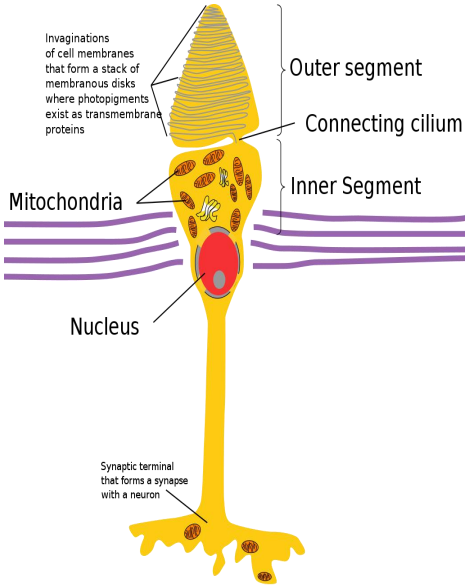
https://www.slideserve.com/file-download/5160399, Figure2 credit:Idit Haran

Retinal Cone Cell Response Functions (L, M, S types)

- Three types of cone cells: S, M, and L (corresponding to peak response at short, medium, and long wavelengths)

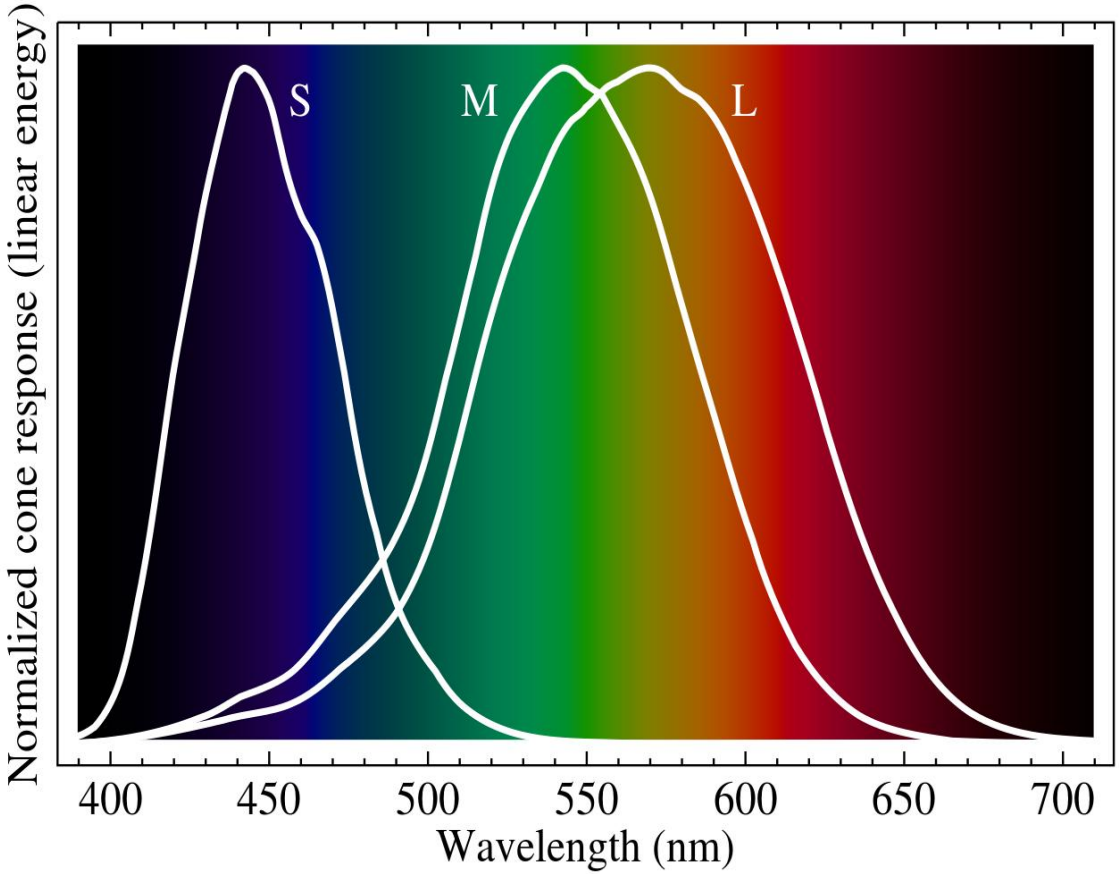
Probability that a photon will cause a photopigment isomerization





Wikipedia/Brainard, Color and the Cone Mosaic, 2015

Response of Cones to Conochromatic Light



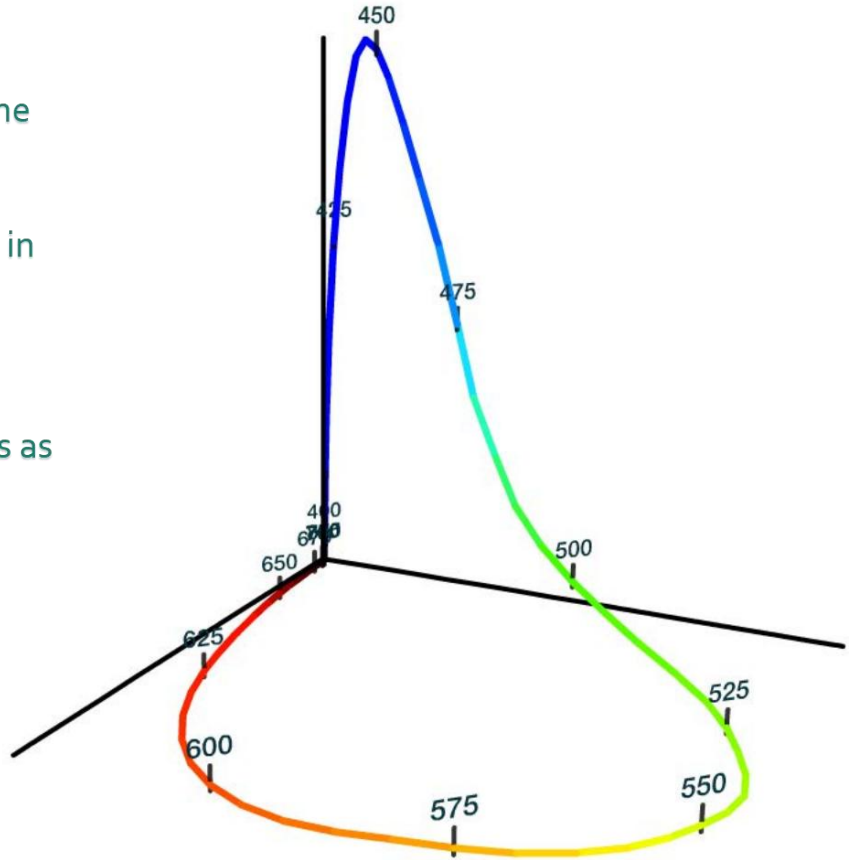
Source: Wilipedia

Retinal Cone Cell Response (L, M, S in 3D)

Visualization of "spectral locus" of human cone cells' response to monochromatic light (light with energy in a single wavelength) as points in 3D space.

This is a plot of the S, M, L response functions as a point in 3D space.

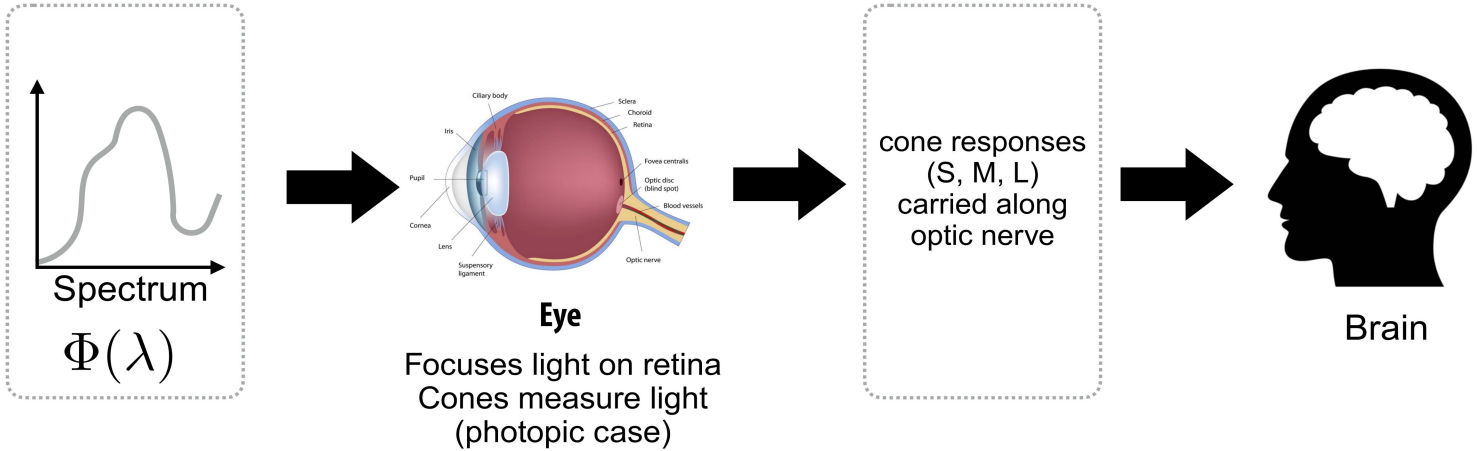
Space of all possible responses are positive linear combinations of points on this curve.



Slides Credit: Marc Leovy

The Human Visual System

- Human eye does not directly measure the spectrum of incoming light
  - a.k.a. the brain does not receive "a spectrum" from the eye
- The eye measures three response values = (S, M, L).
- The result of integrating the incoming spectrum against response functions of S, M, L-cones



Slide credit: Unknown

Metamerism

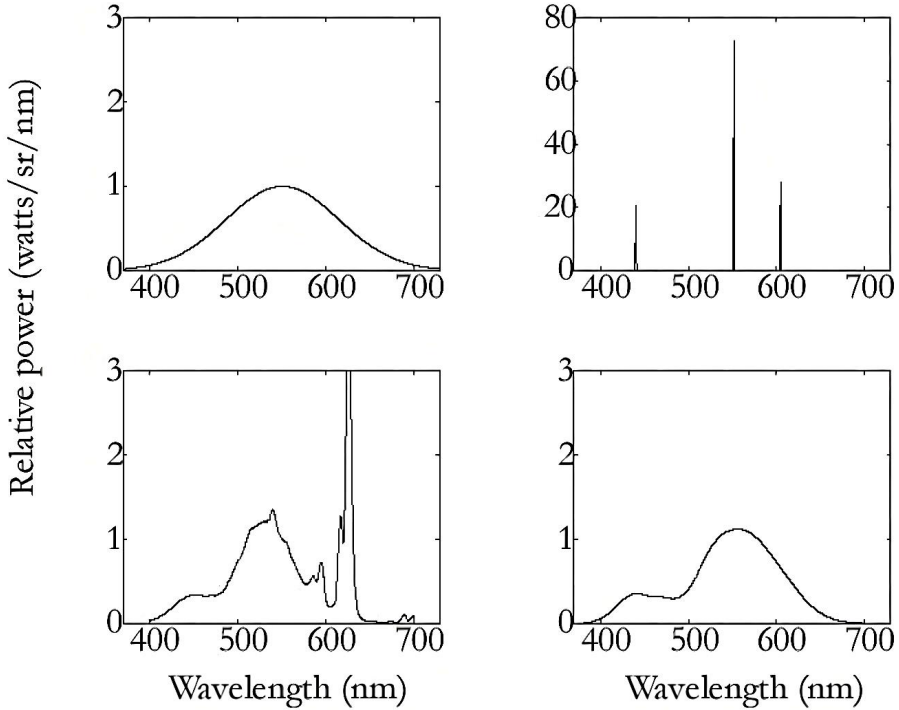
Metamers

- Metamers = two different spectra that integrate to the same (S,M,L) response! (Two lights that appear the same visually.)

- The existence of metamers is critical to color reproduction
- It means a compute display does not have to reproduce the full spectrum of a real world scene for it to be perceived to look like the scene
- Luckily！ A metamer can reproduce the perceived color of a real-world scene on a display with pixels of only **three colors**

Metamerism is a big effiect

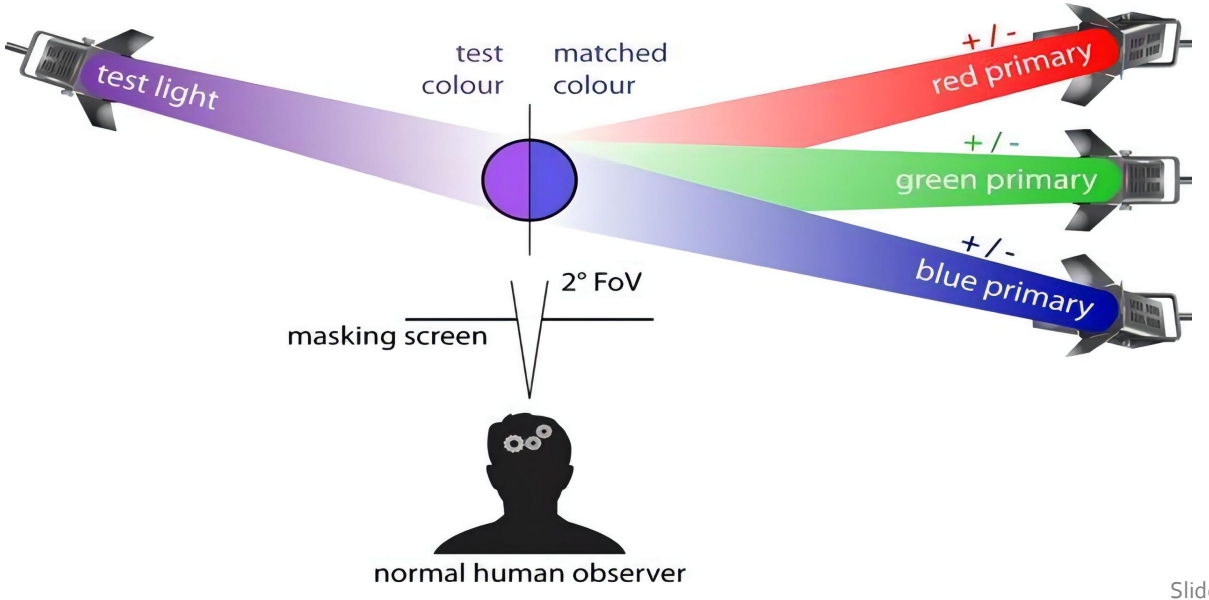
- These four different spectrum are metamers (they produce the same response)



Slide credit: Ren Ng

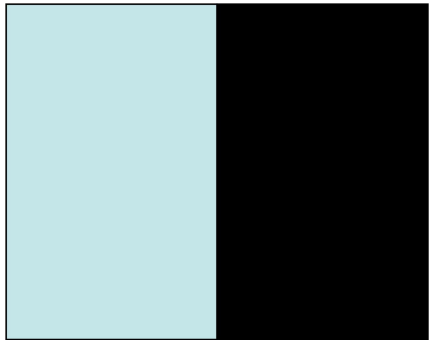
Color Matching Experiment

- Show test light spectrum on left
- Mix "primaries" on right until they match
- The primaries need not be RGB



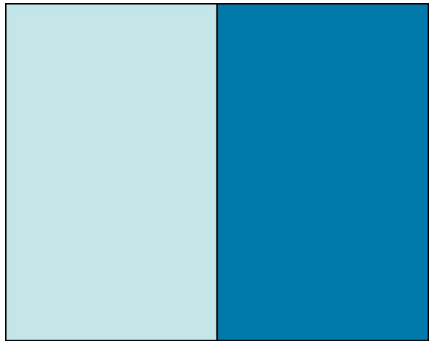
Slide credit: Geert J J Verhoeven

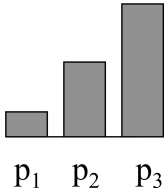
Color Matching Experiment



Out of gamut target

Color Matching Experiment





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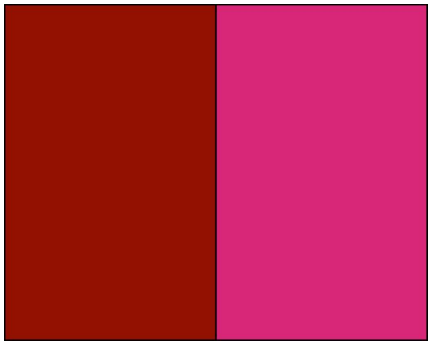
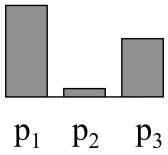
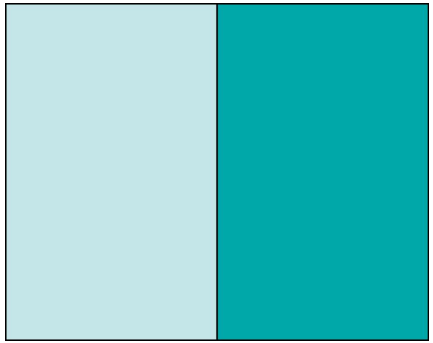
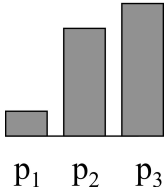




Slide credit: Ren Ng

Color Matching Experiment





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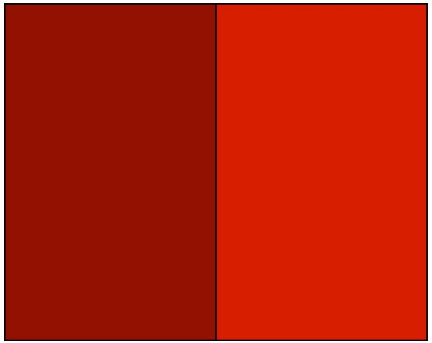
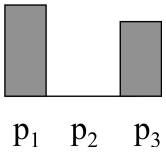
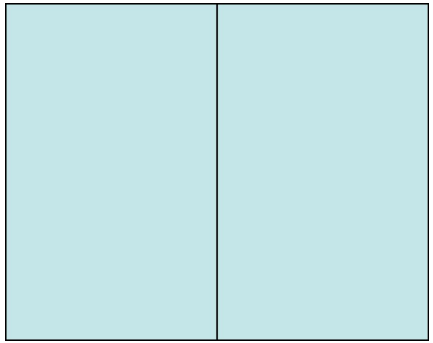
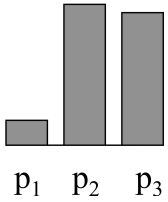




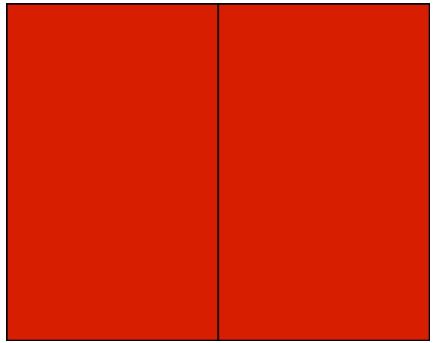
Slide credit: Ren Ng

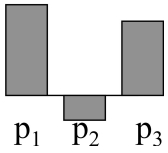
Color Matching Experiment





Out of gamut target



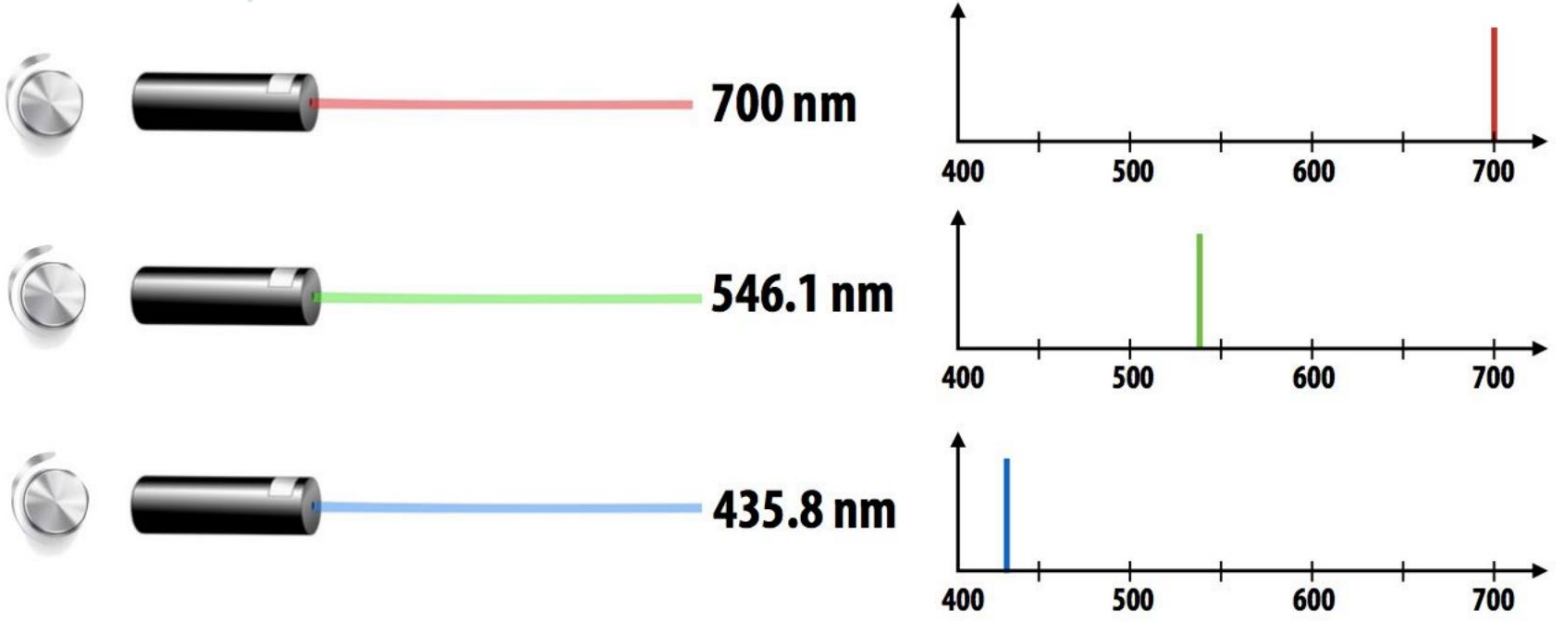


A “negative” amount of p_2 was needed to make the match, as we added it to the test color’s side.

Slide credit: Ren Ng

CIE RGB Color Matching Experiment

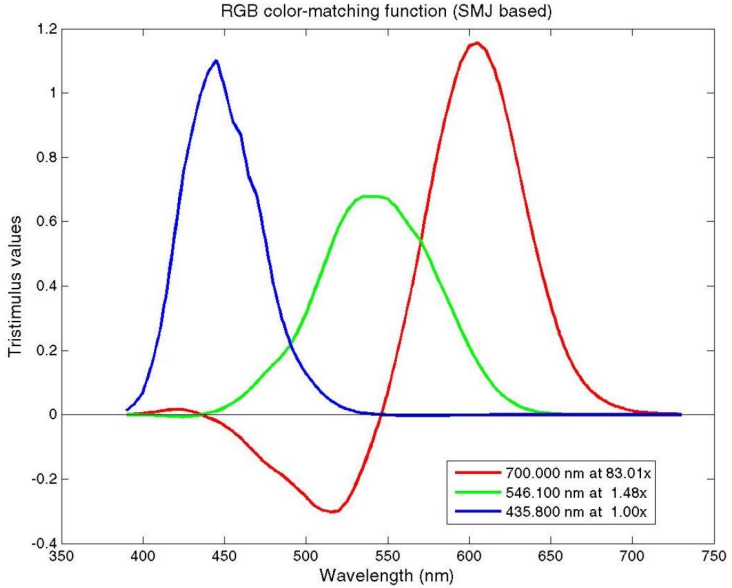
- Same setup as additive color matching before, but primaries are monochromatic light (single wavelength) of the following wavelengths defined by CIE RGB standard



Slide credit: Unknow

CIE RGB Color Matching Functions

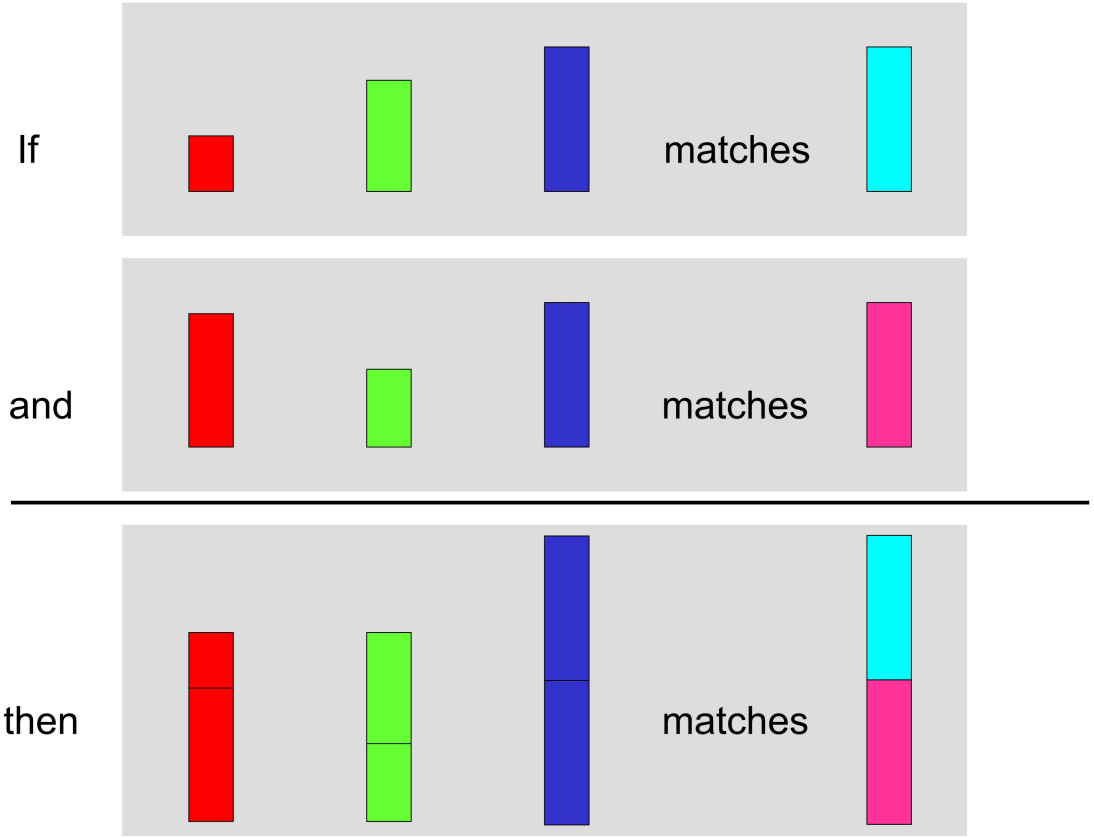
- This graph plots how much of each CIE RGB primary light must be combined to match the appearance of a monochromatic light of the wavelength given on x-axis



Careful: these graphs are color matching curves, not response curves or primary spectra!

Slide credit: Ren Ng

The Color Matching Experiment is Linear



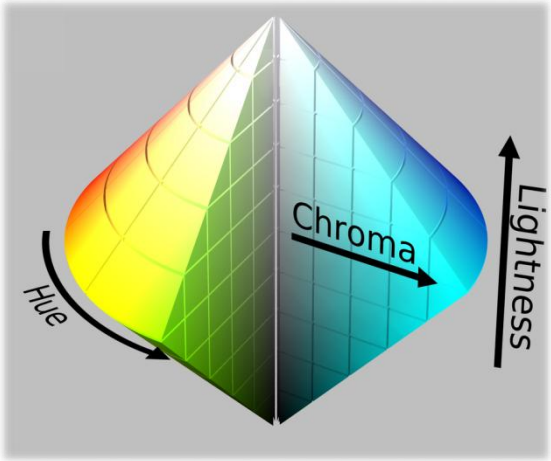
Slide credit: Brain Wandell

Color Perception:

Hue, Saturation, Brightness

Hue, Saturation, and Brightness

- Hue: where a color lies around a color wheel: red, green, yellow, blue-green, etc.
- Saturation: the "purity" of a color; a fully-saturated color has no white mixed with it, in paint terms
- Brightness: light, dark, or in between?
- Most people probably are thinking of hue when they speak of color



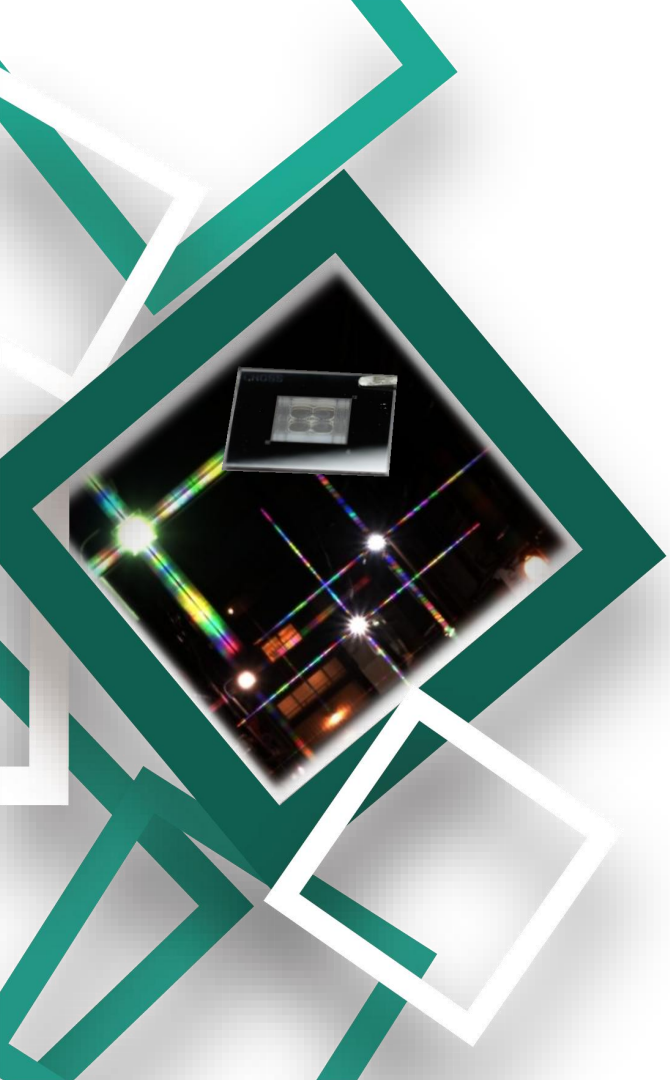
Slide credit: Idit Haran

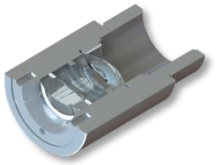
Grassmann's law

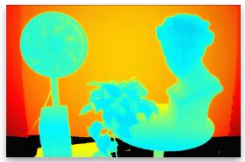
- **First law:** Two colored lights appear different if they differ in either dominant wavelength, luminance or purity.
- **Second law:** The appearance of a mixture of light made from two components changes if either component changes.
- **Third law:** There are lights with different spectral power distributions but appear identical.
- **Fourth law:** The intensity of a mixture of lights is the sum of the intensities of the components. This is also known as Abney's law.

Wikipedia

- Introduction to Color
- What's Color
- Spectral Power Distribution
- Biological Basis of color
  - Human Eye
  - Photosensor Response
  - Cone Cell Response (L, M, S)
- CFA Array Response
- Metamerism
  - Primary Light
  - Color Matching
- Color Perception: Hue, Saturation, Brightness







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Thank You!

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