Lecture 3:

Colors: Human Vision & Computer Vision

COMP 590/776: Computer Vision

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TA: Mykhailo (Misha) Shvets

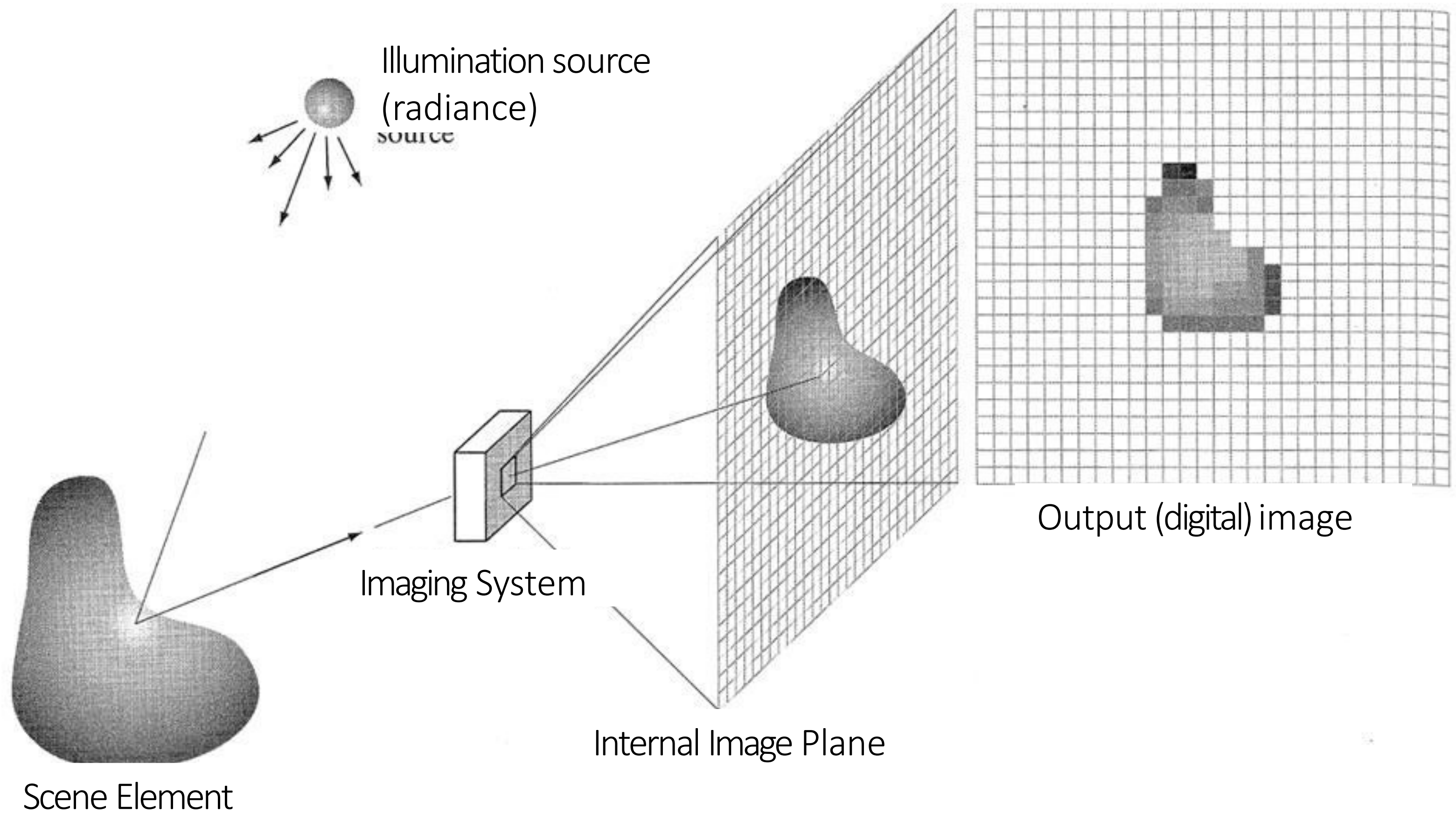
Etymology

PHOTOGRAPHY

light

drawing
/ writing

Camera = light-measuring device

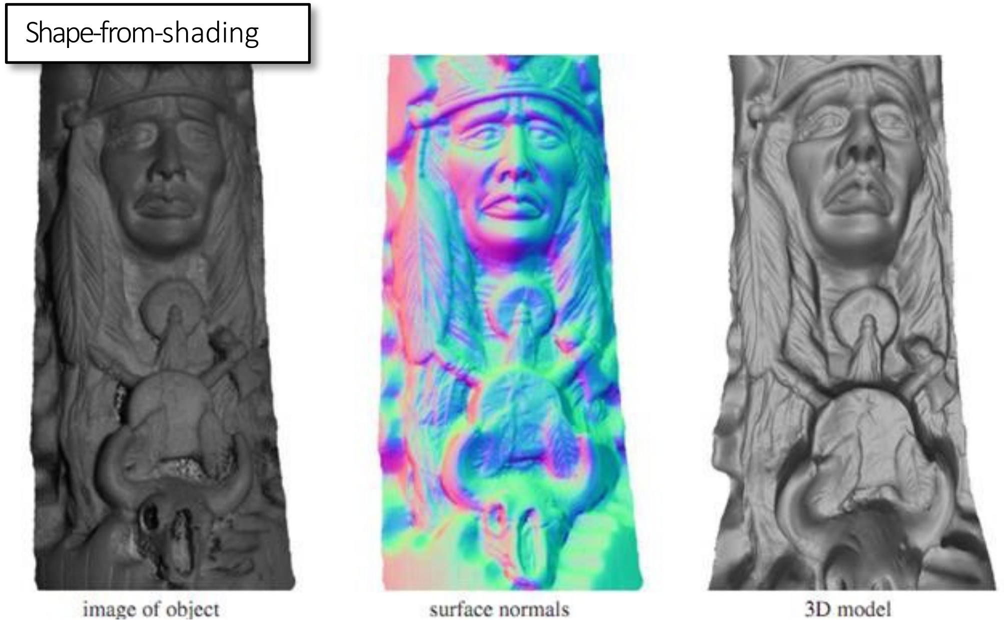


Simple models of a camera assumes an image is a "quantitative measurement" of scene radiance.

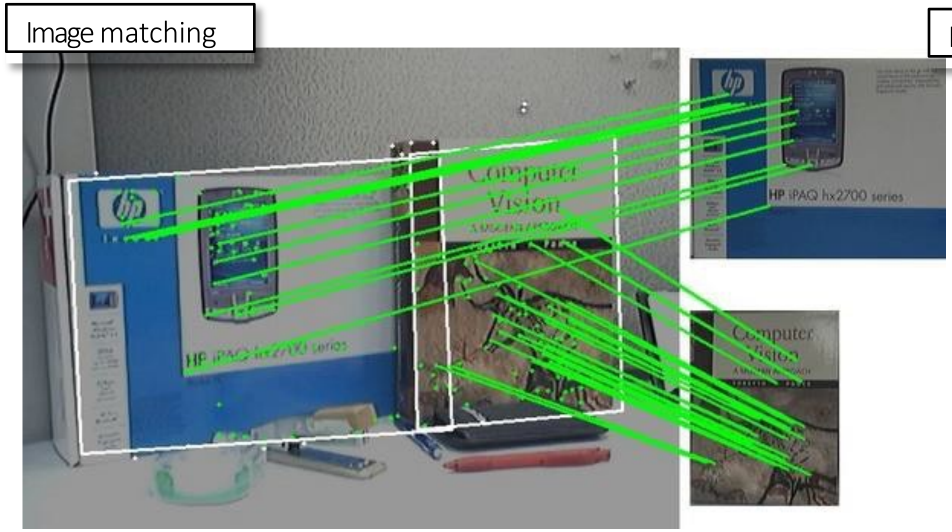
Figure from Digital Image Processing, Gonzales/Woods

This assumption is made often in computer vision

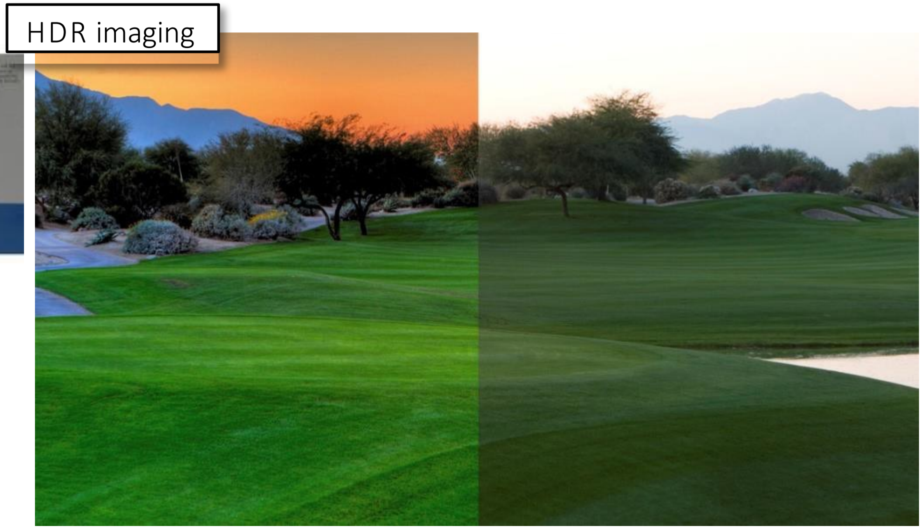
- Shape from shading
- HDR imaging
- Image matching
- Color constancy
- Applications relying on color
- Image delubrring
- Etc ...



From Lu et al, CVPR'10

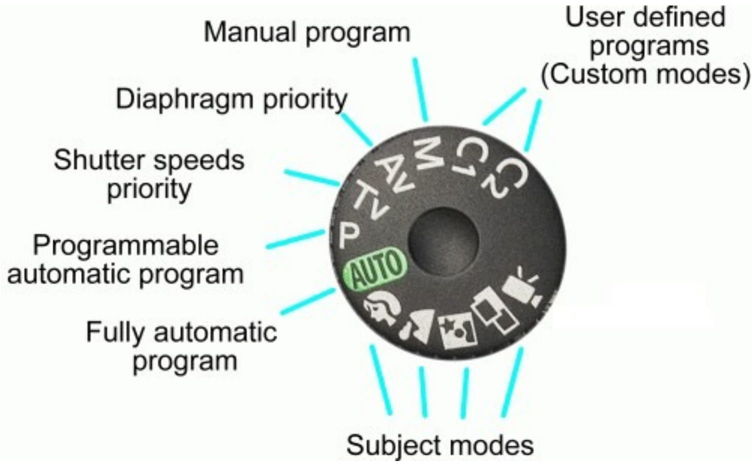


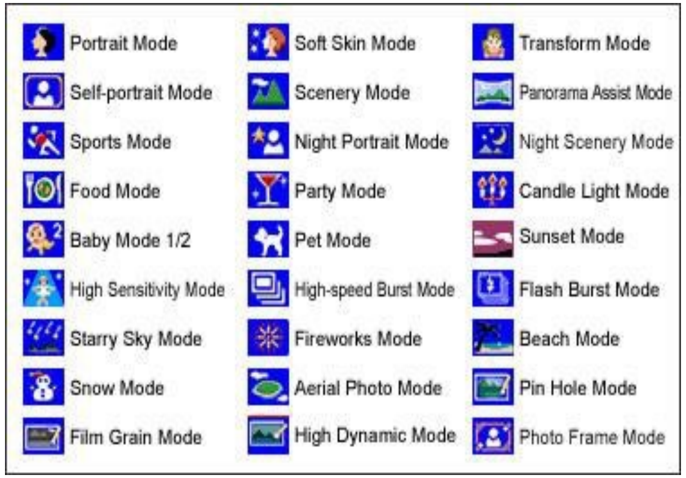
From Jon Mooser, CGIT Lab, USC



From O'Reilly's digital media forum

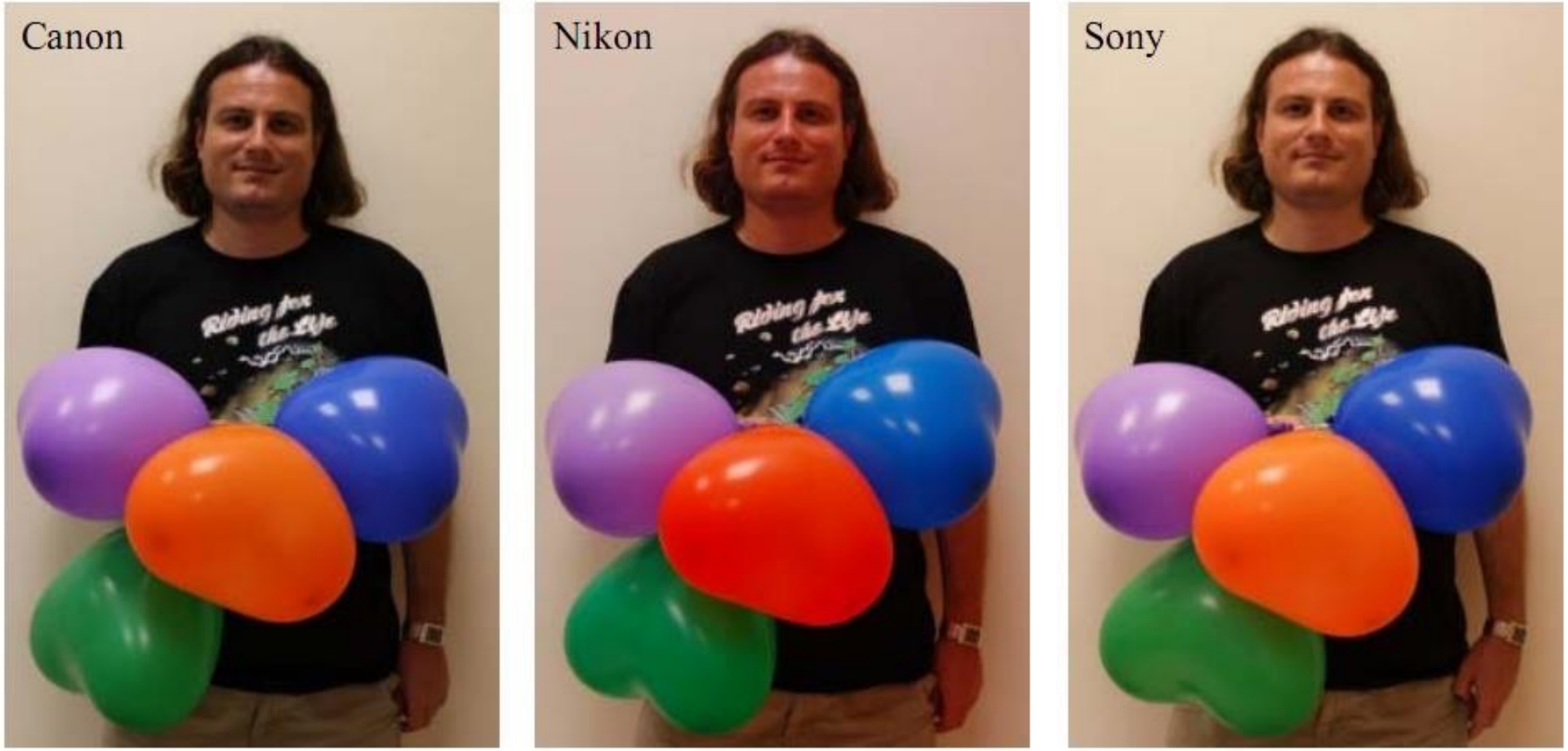
Camera = light-measuring device?





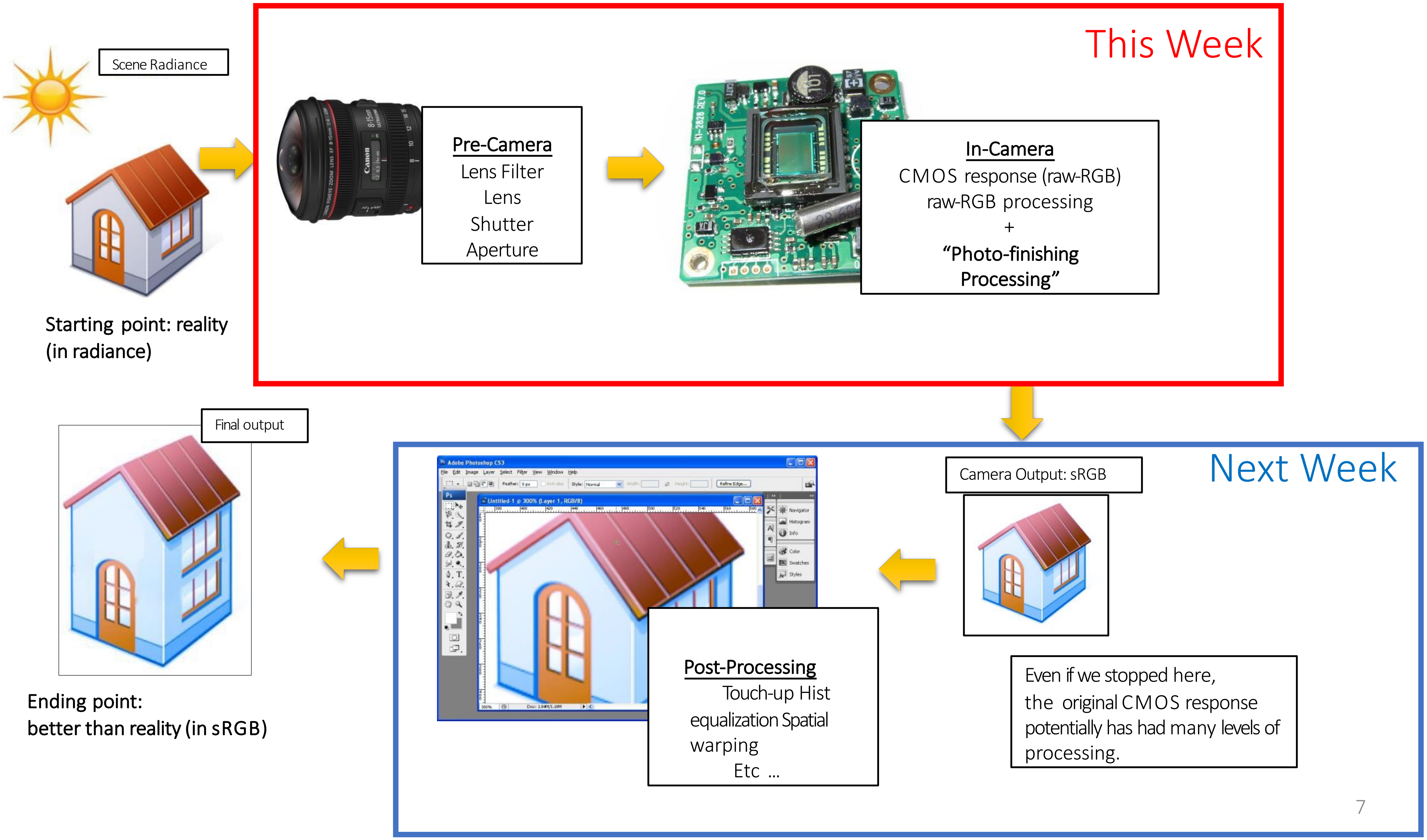
Camera pipeline photo-finishing routines

"Secret recipe" of a camera



Photographs taken from three different cameras with the same aperture, shutter speed, white-balance ,ISO, and picture style.

Modern photography pipeline



Digital cameras

- Digital cameras ***are not designed to be*** light-measuring devices
- They are designed to produce visually pleasing photographs
- There is a great deal of processing (photo-finishing) applied in the camera hardware

Today’s class

- Eye & Human Vision
- Pinhole Camera
- Perception of Color
- Quantifying Color
- Commonly Used Color Spaces
- Color Constancy

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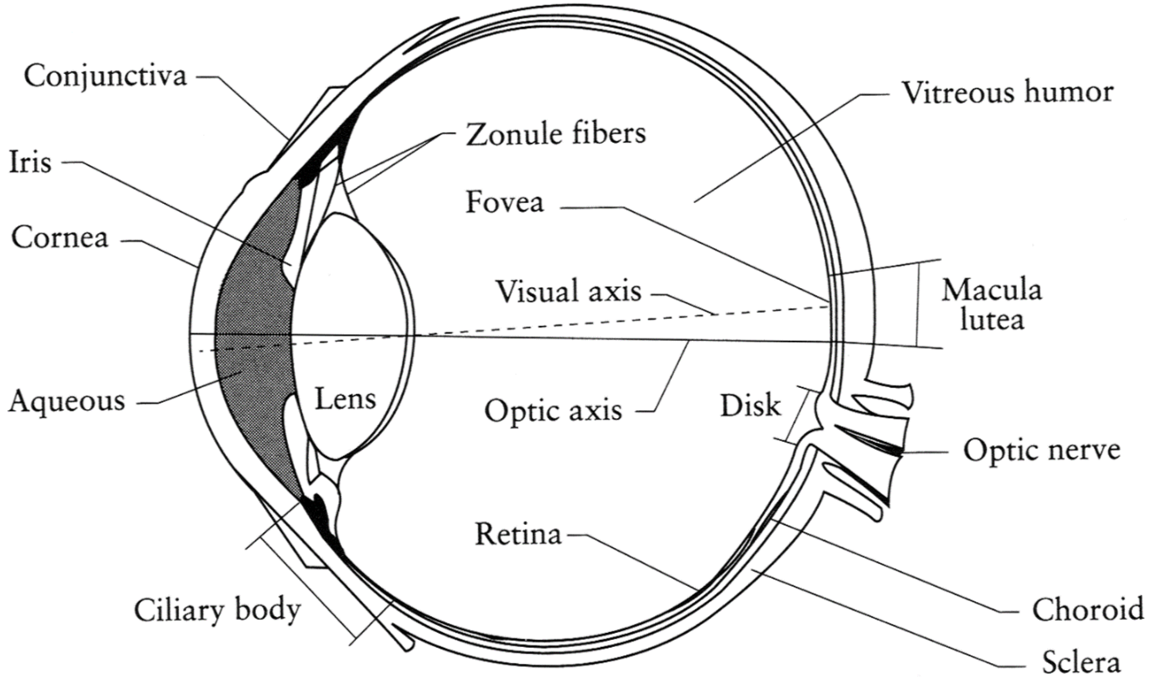
The Eye

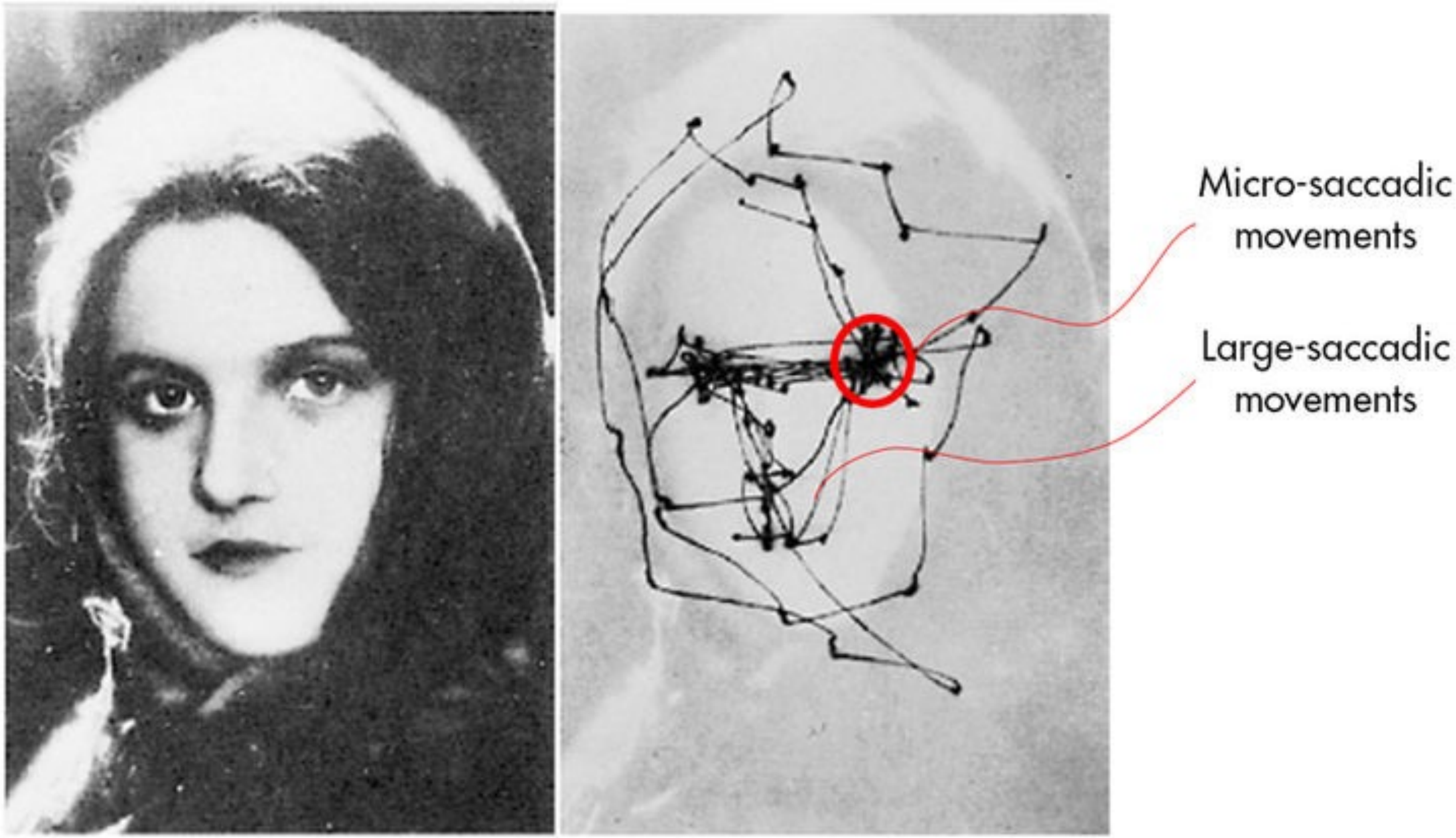


- The human eye is a camera!
  - **Iris** - colored annulus with radial muscles
  - **Pupil** - the hole (aperture) whose size is controlled by the iris
  - What's the "film"?
    - photoreceptor cells (rods and cones) in the **retina**

Slide by Steve Seitz

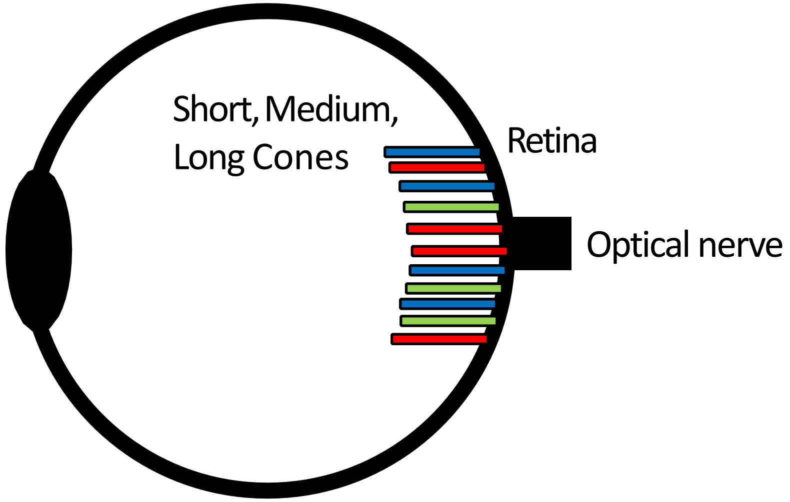
Saccadic eye movement

Saccadic eye movement

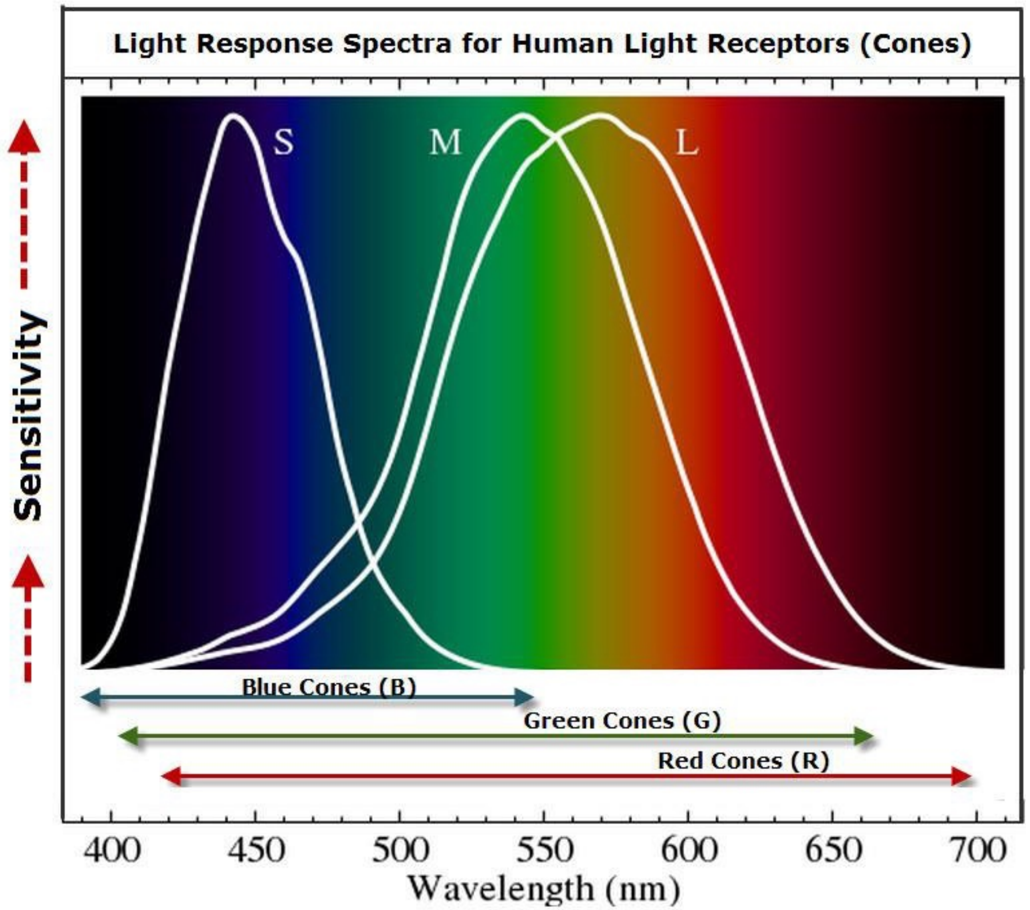


Biology of color sensations

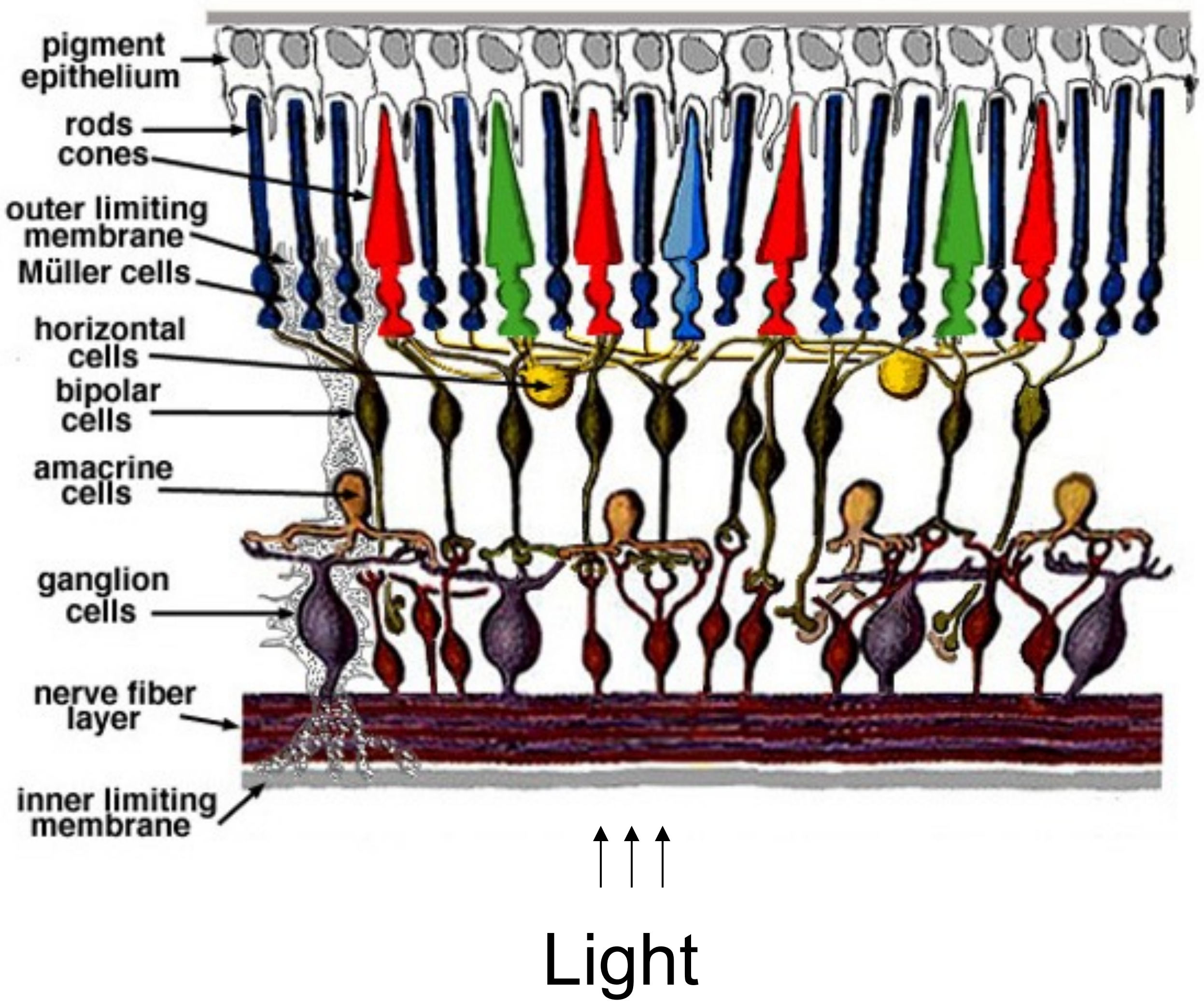
- Our eye has three receptors (cone cells) that respond to visible light and give the sensation of color



Eye



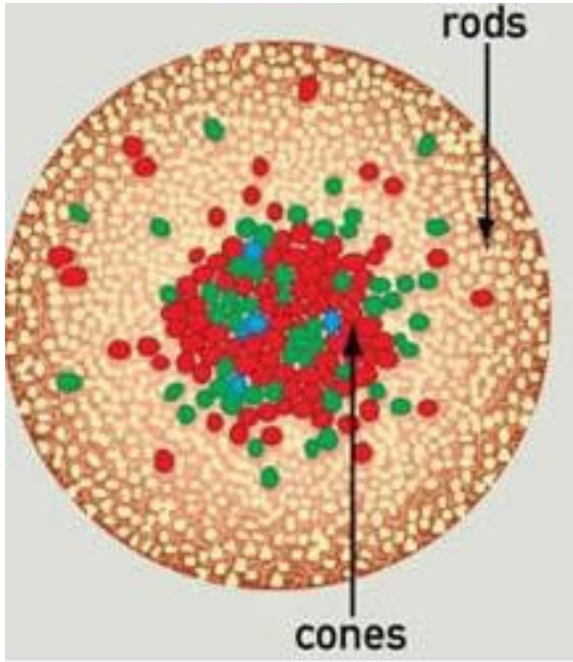
Retina up-close

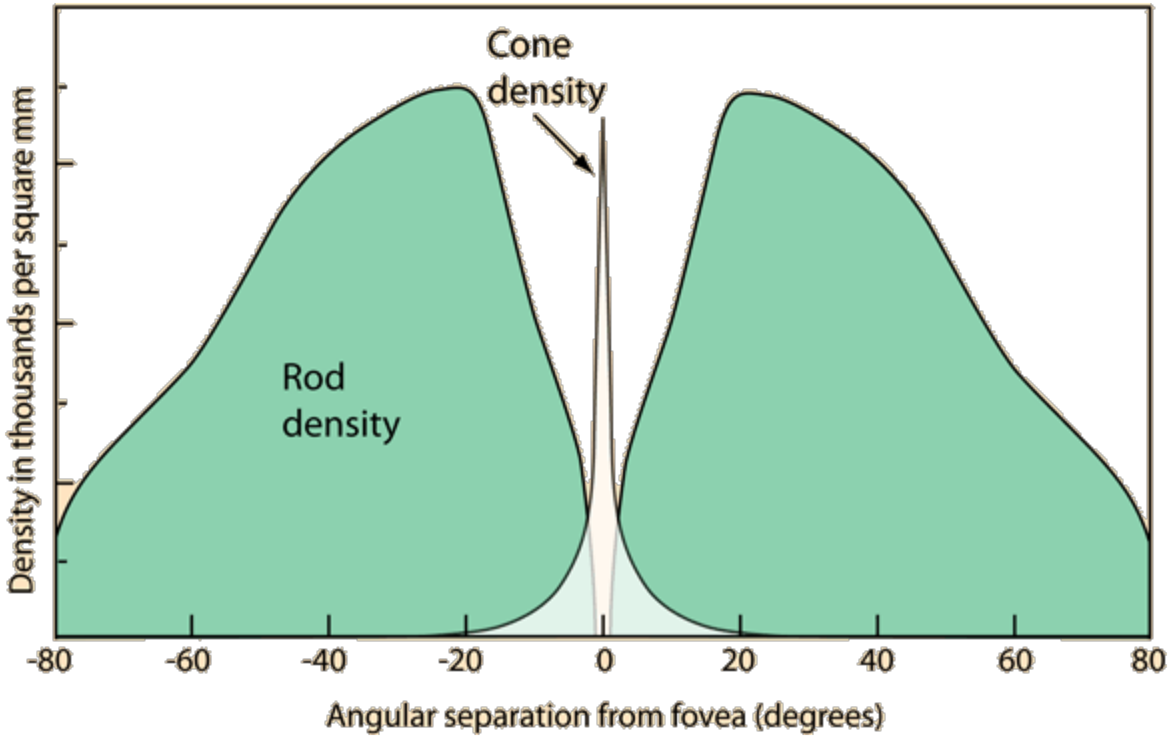


Cones and rods

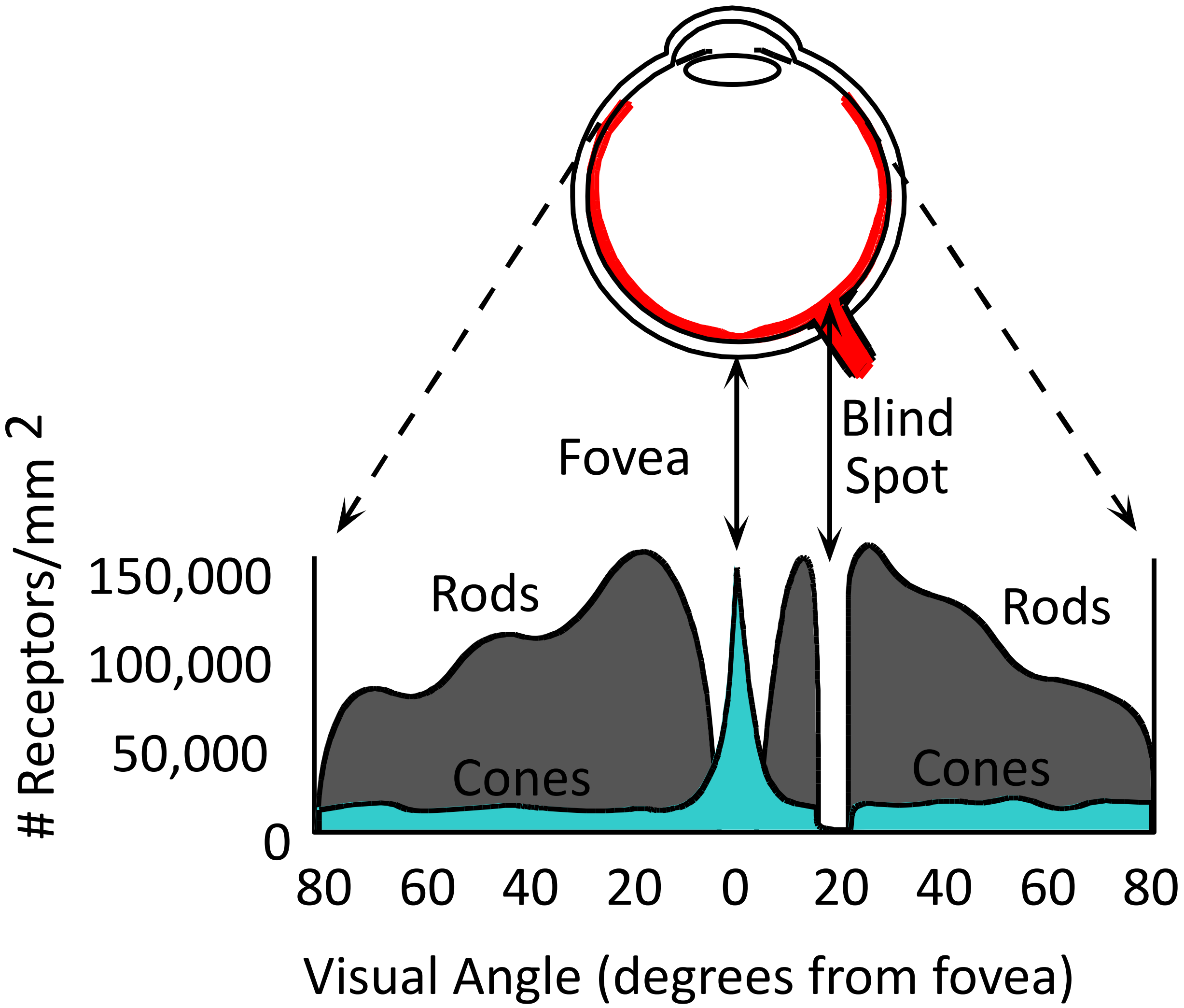
- We have additional light sensitive cells called *rods* that are not responsible for color.
- Rods are used in low-light vision.
- Cone cells are most concentrated around the fovea of the eye

Fovea = region of retina where visual activity is the highest, responsible for central vision.



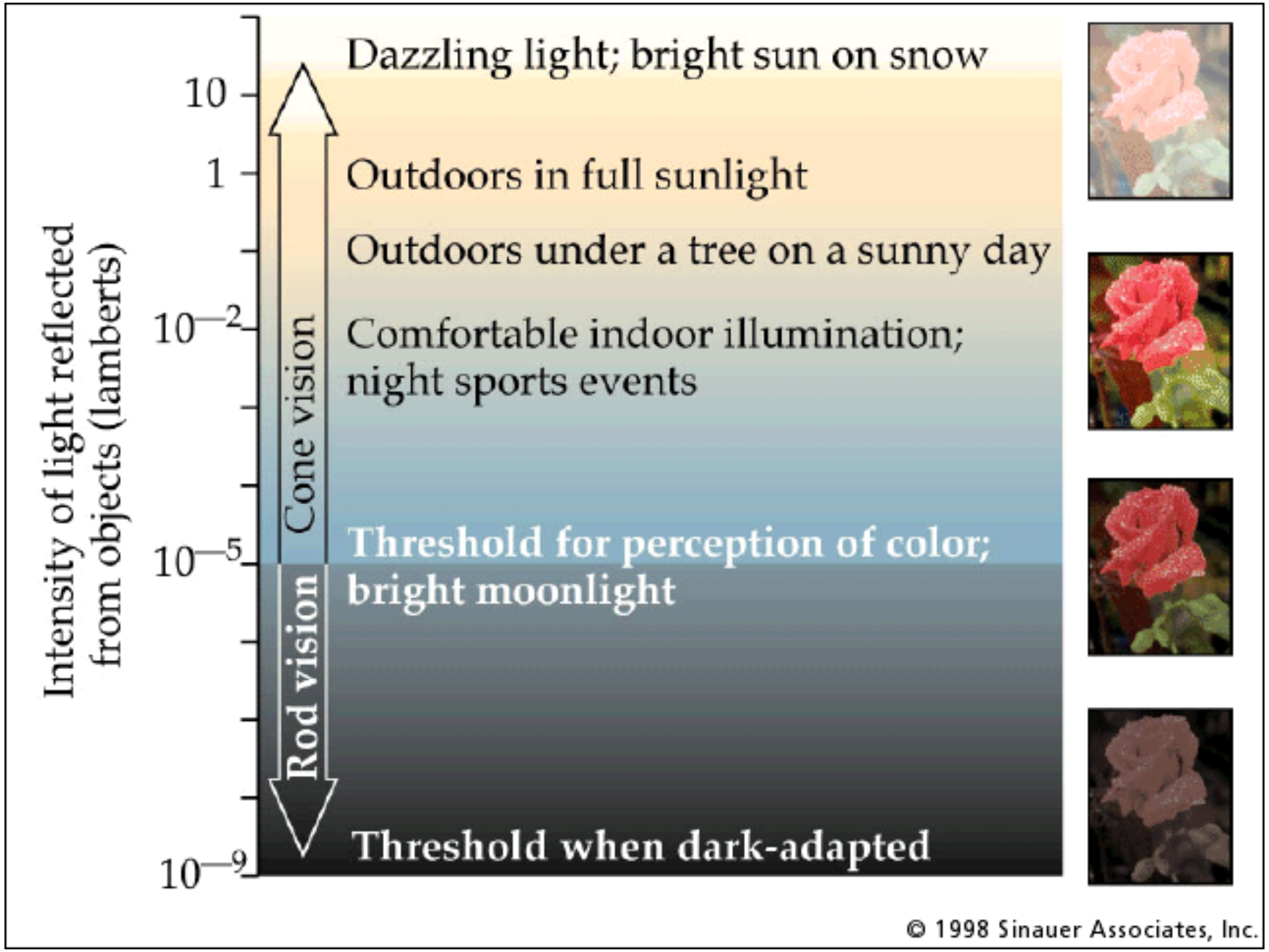


Distribution of Rods and Cones



Night Sky: why are there more stars off-center?

Rod / Cone sensitivity



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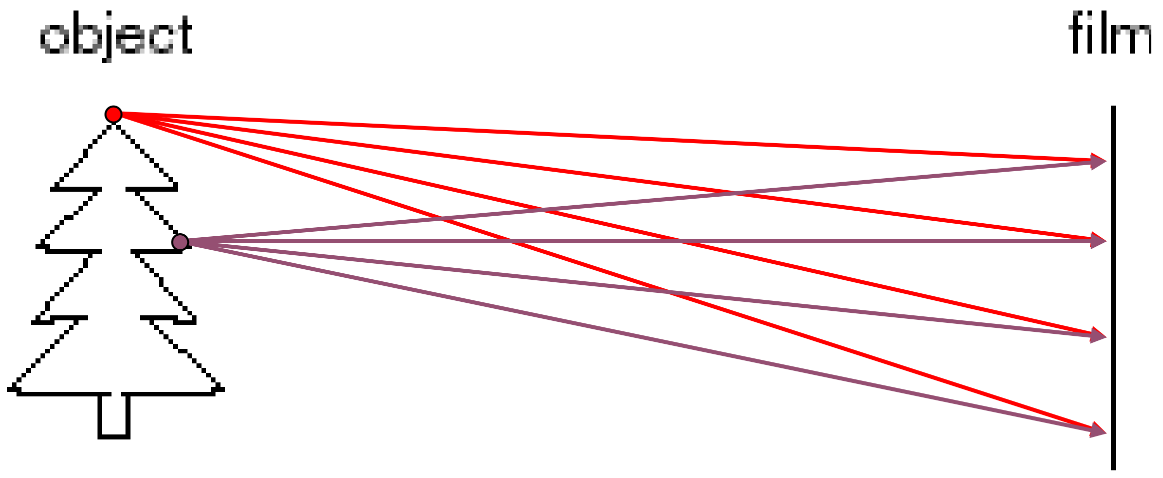
Projection

Steve Seitz

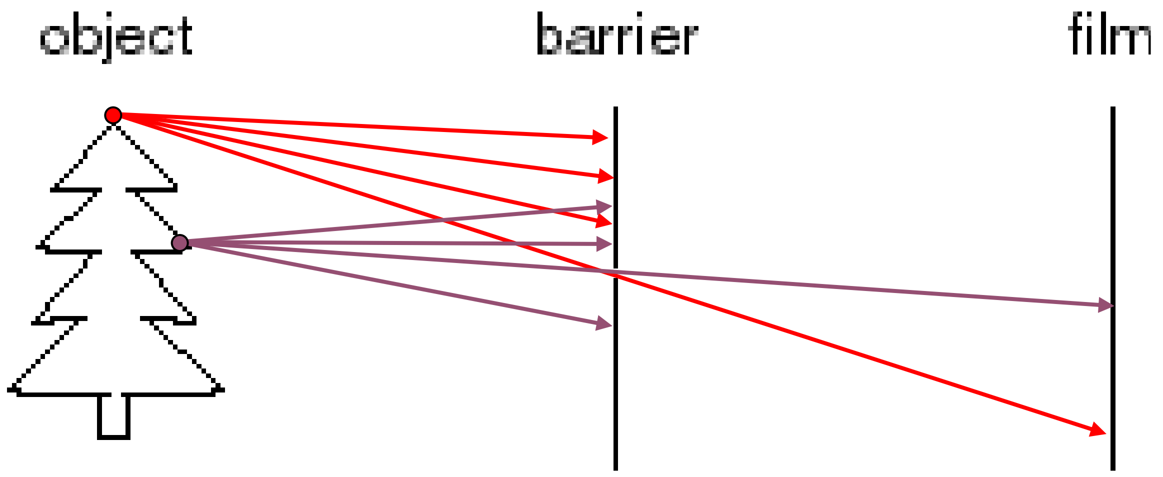
Image formation



Let's design a camera

- Idea 1: put a piece of film in front of an object
- Do we get a reasonable image?
- No. This is a bad camera.

Pinhole camera



Add a barrier to block off most of the rays

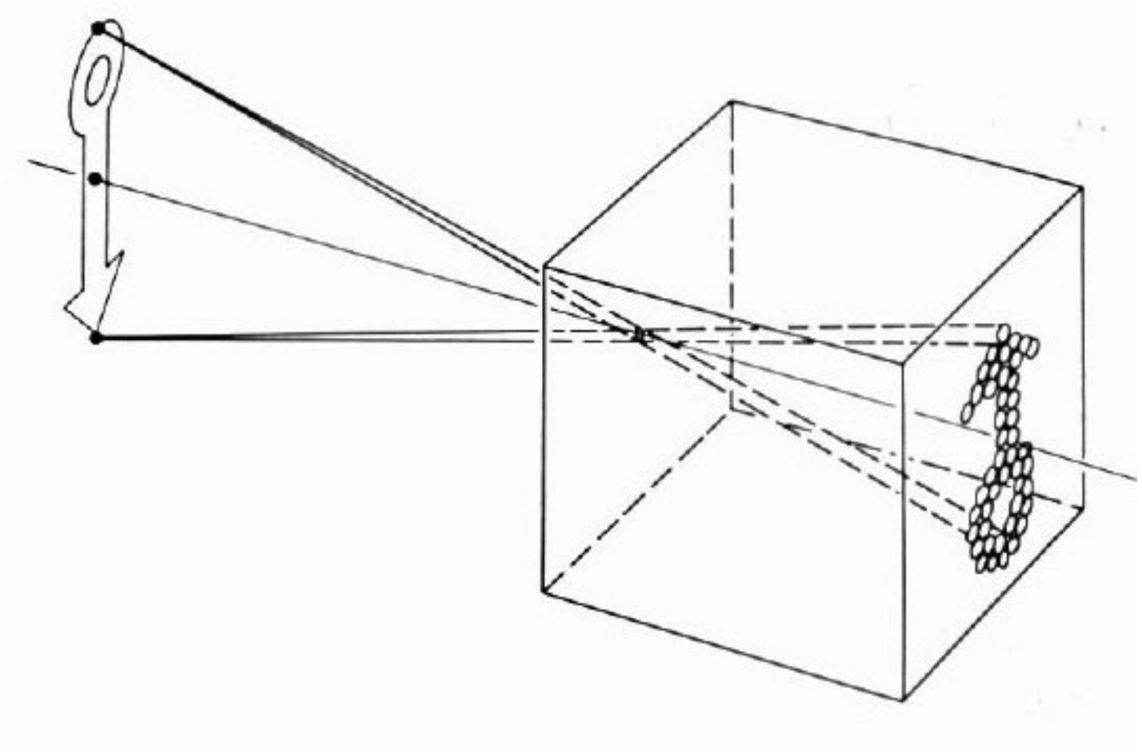
- This reduces blurring
- The opening known as the **aperture**
- How does this transform the image?

Camera Obscura

- Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Source: A. Efros

Camera Obscura



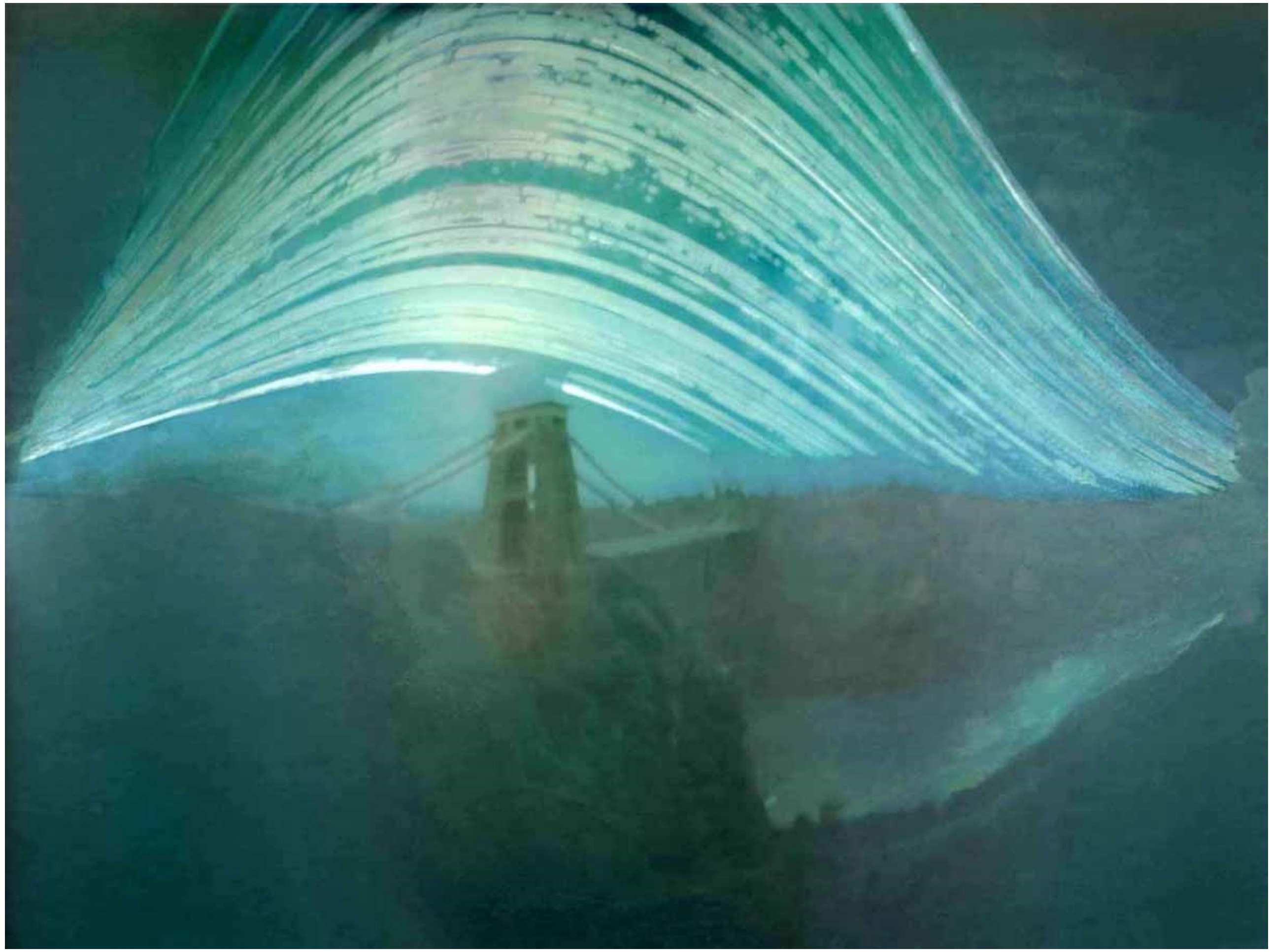
Home-made pinhole camera

Why so blurry?

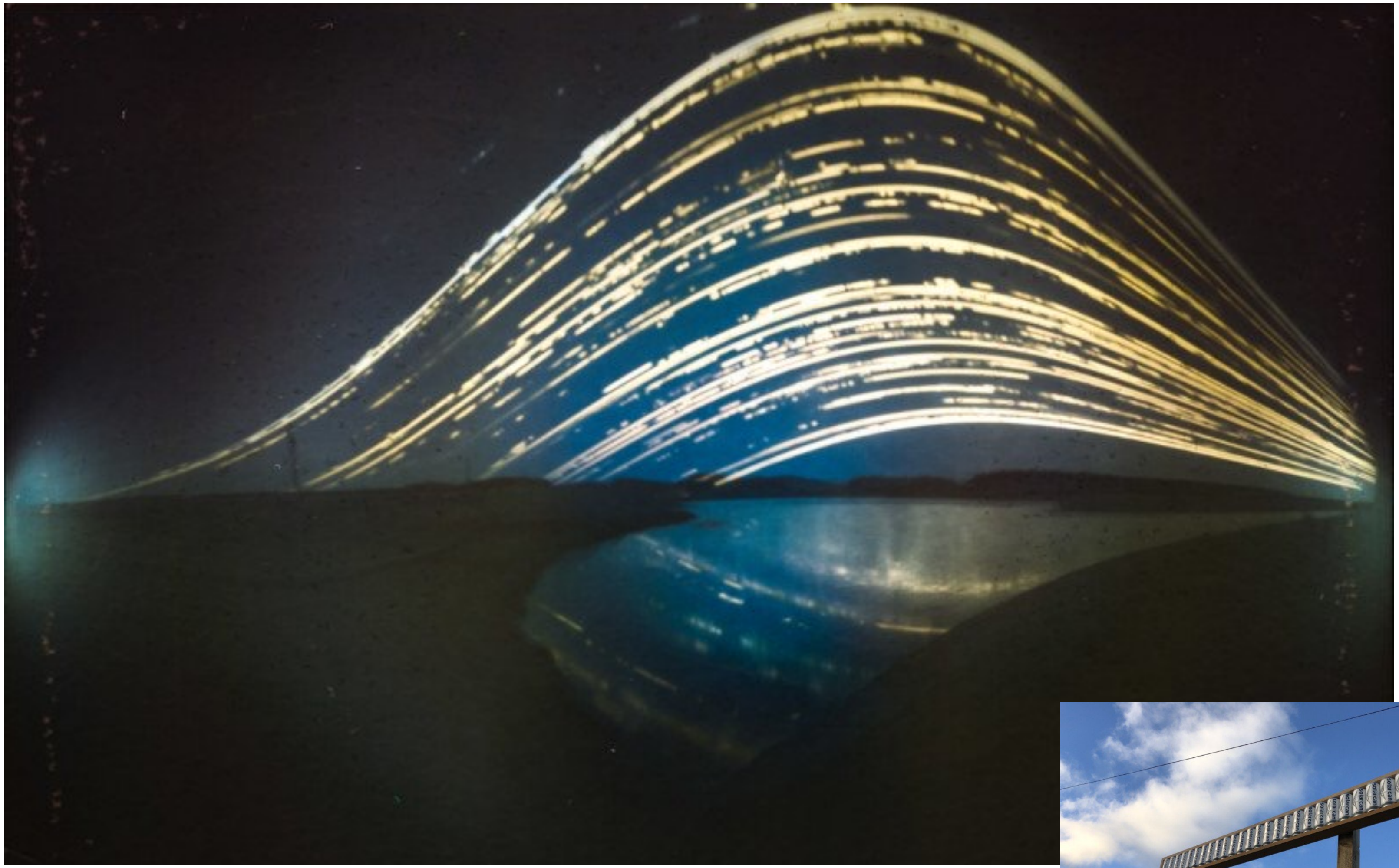
Slide by A. Efros

http://www.debevec.org/Pinhole/

Pinhole photography

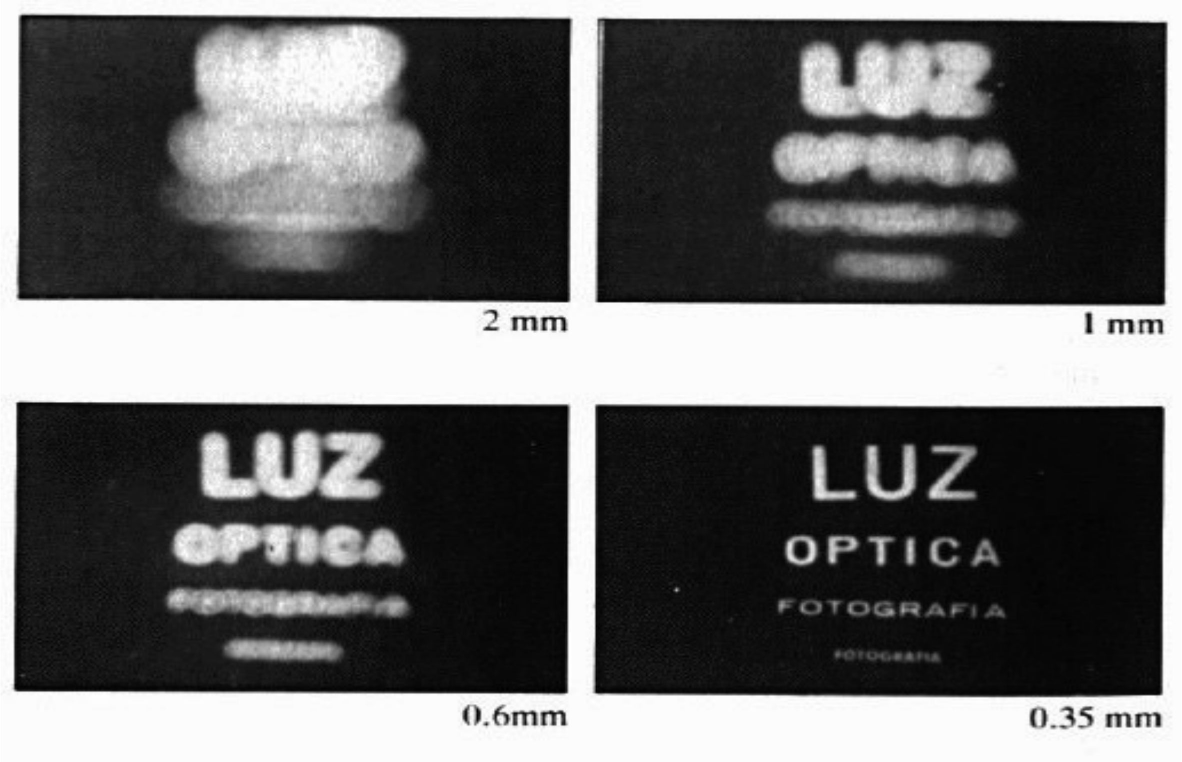


Justin Quinnell, The Clifton Suspension Bridge. December 17th 2007 - June 21st 2008
***6-month* exposure**



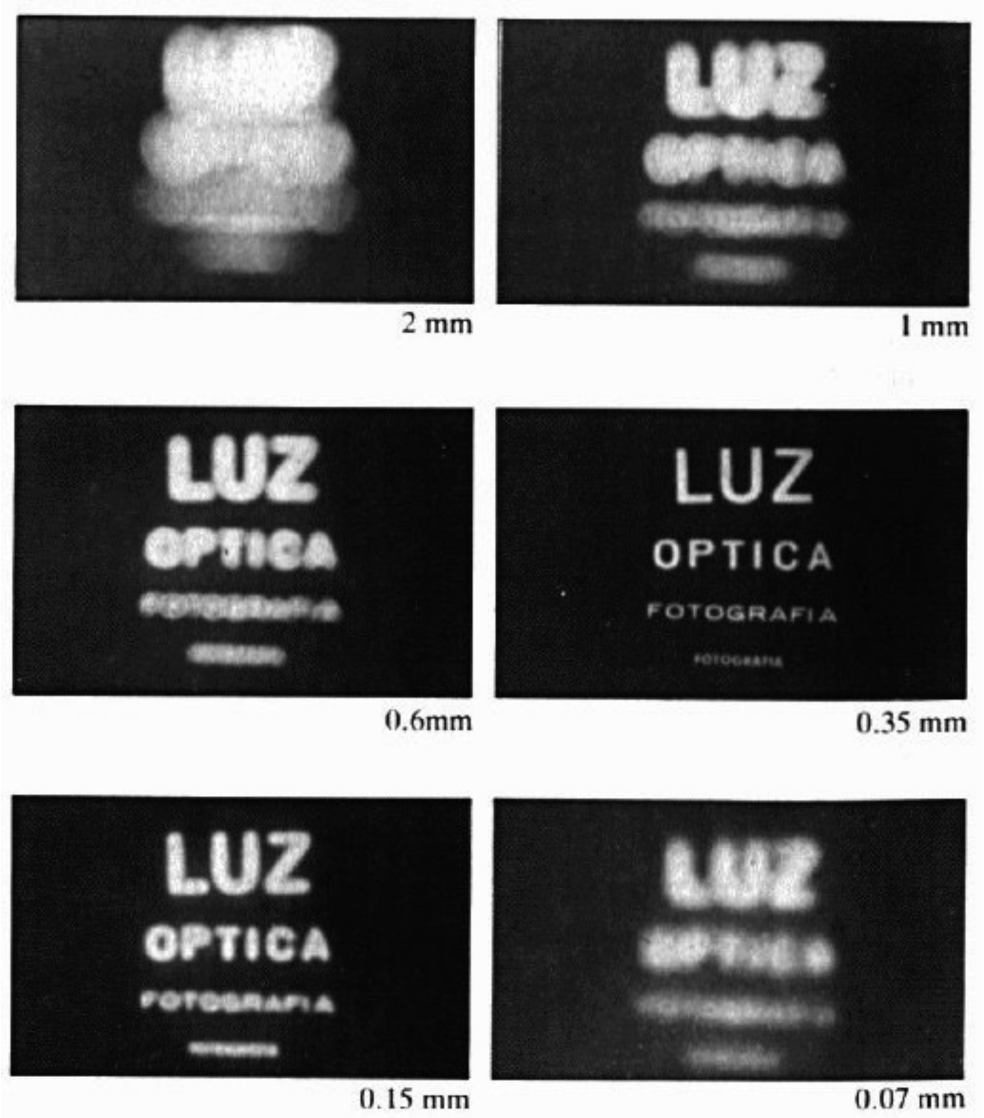
https://petapixel.com/2019/07/17/this-is-the-worlds-first-solargraphy-timelapse/

Shrinking the aperture

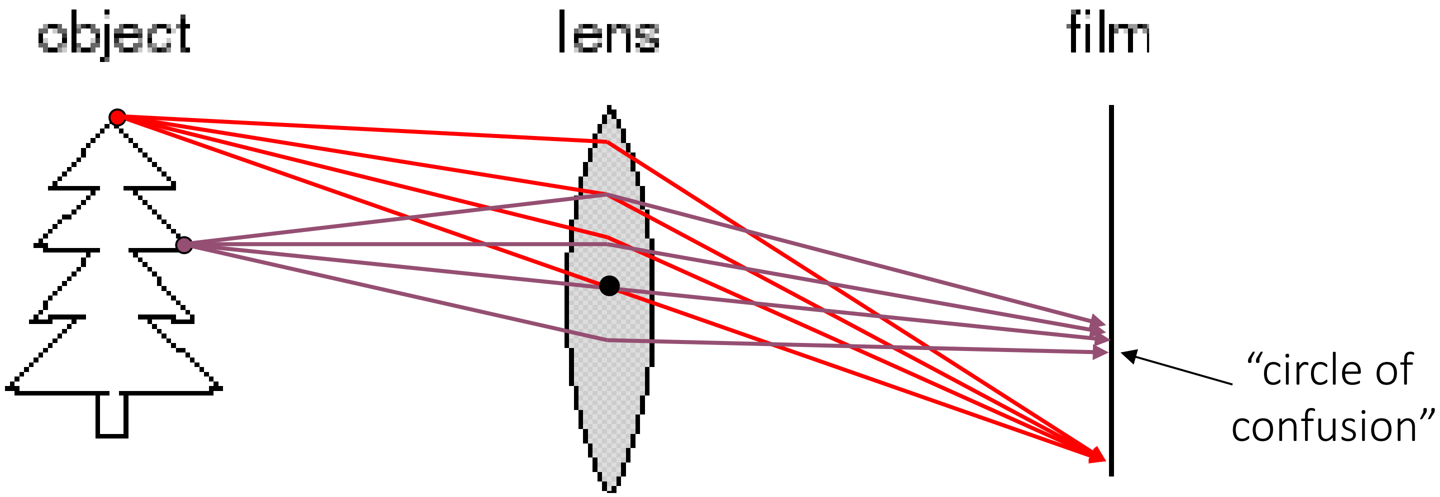


- Why not make the aperture as small as possible?
  - Less light gets through
  - *Diffraction* effects...

Shrinking the aperture



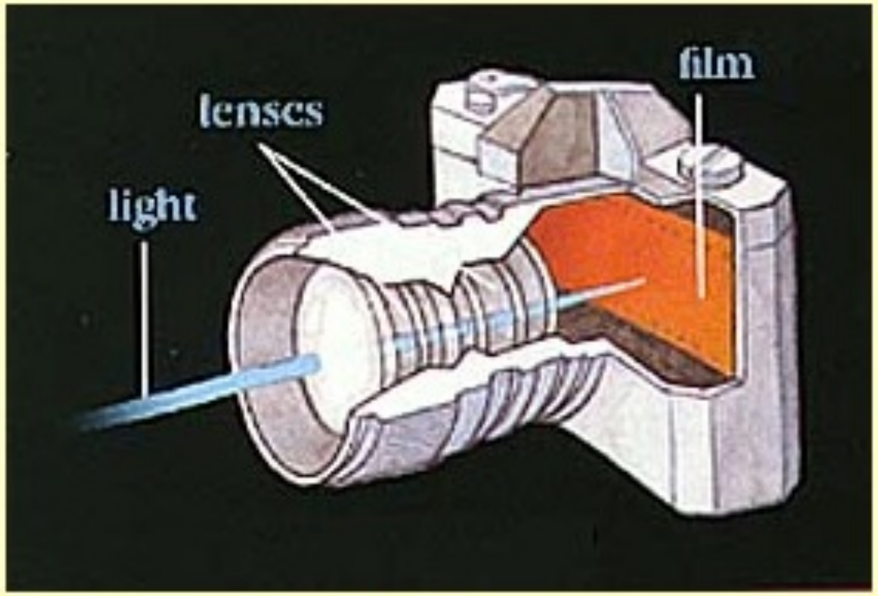
Adding a lens



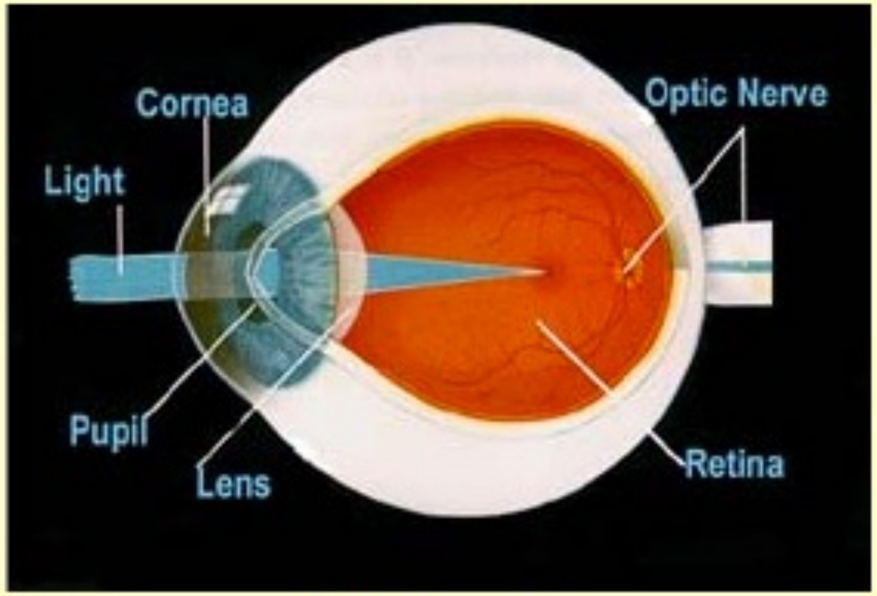
A lens focuses light onto the film

- There is a specific distance at which objects are “in focus”
  - other points project to a “circle of confusion” in the image
- Changing the shape of the lens changes this distance

Eye vs Camera



The Camera



The Human Eye

	Human Eye	Camera
How does light enter?	Pupil	Aperture
What controls the amount of light?	Iris	Diaphragm
What interprets the image?	Retina	Film
How is the light focused?	Lens	Lens

Credits: https://slideplayer.com/slide/6029035/ & https://www.knowswhy.com/similarities-between-camera-and-human-eye/

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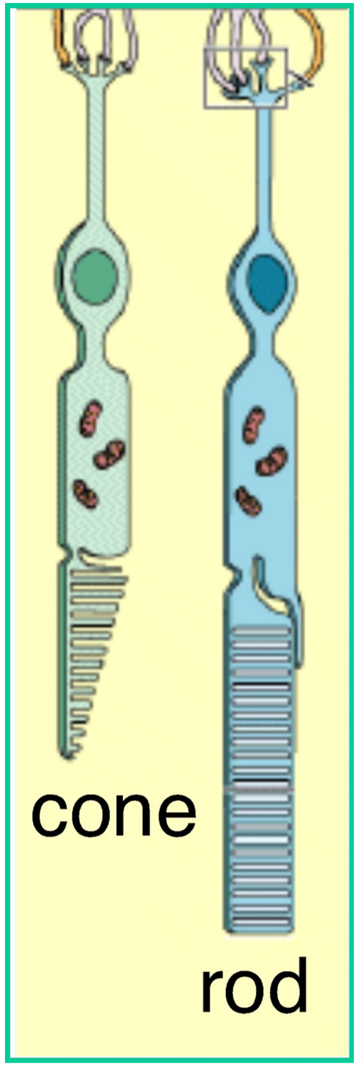
Two types of light-sensitive receptors

Cones

- cone-shaped
- less sensitive
- operate in high light
- color vision

Rods

- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision



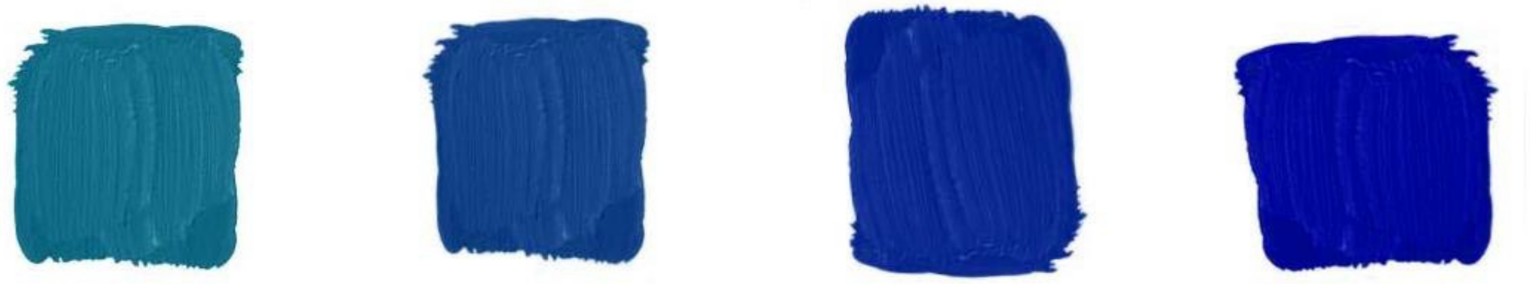
Color

Def *Color* (noun):The property possessed by an object of producing different sensations on the eye as a result of the way it reflects or emits light.

Oxford Dictionary

Color is perceptual

- **Color is not** a primary *physical* property on an object
- Red, Green, Blue, Pink, Orange, Atomic Tangerine, Baby Pink, etc., are just words we assign to human color sensations

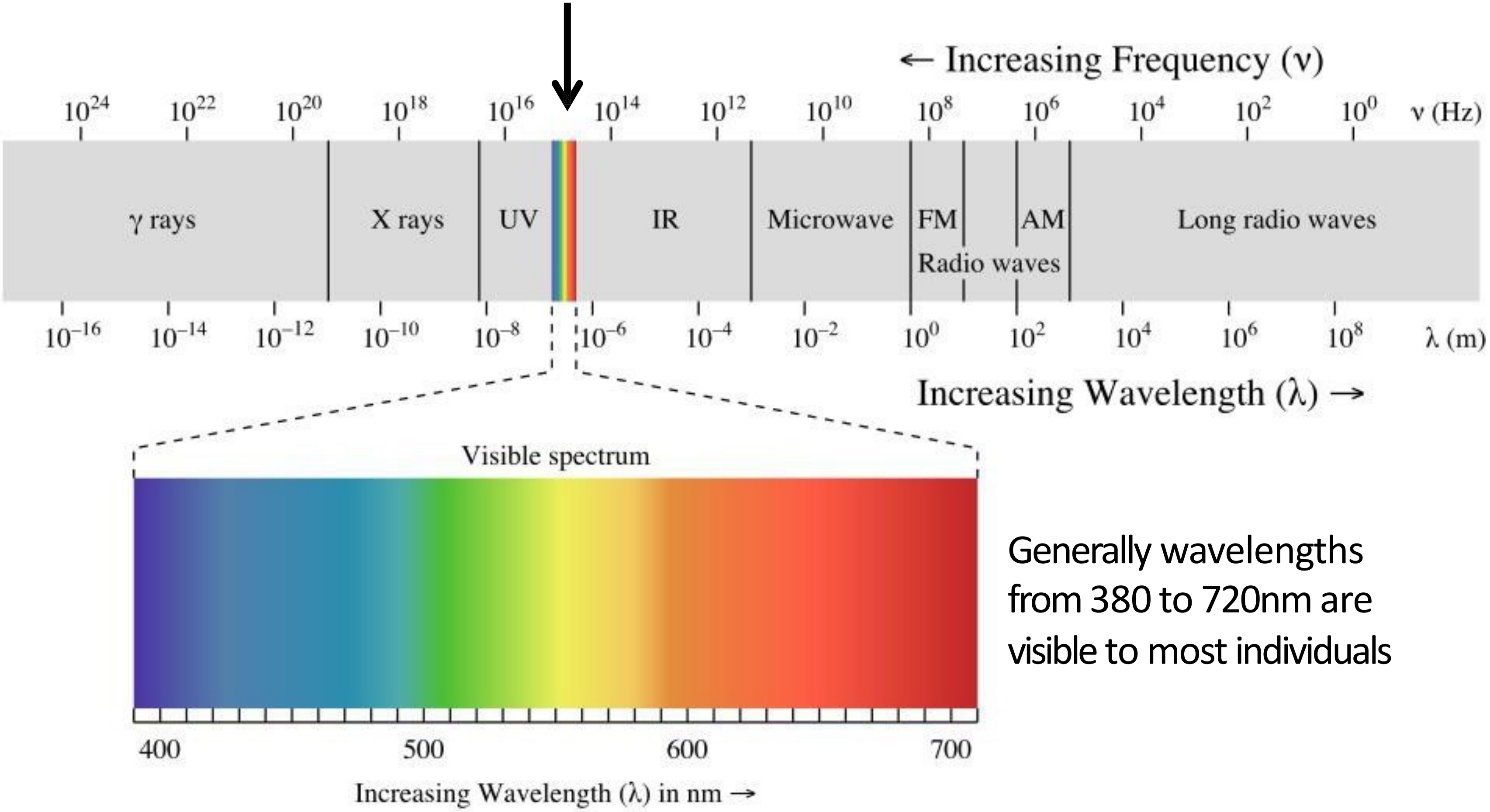


Which is the "true blue"?

http://en.wikipedia.org/wiki/List_of_colors

Where do “color sensations” come from?

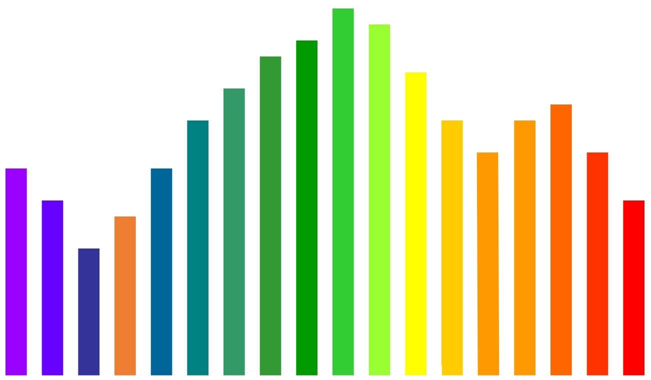
A *very* small range of electromagnetic radiation



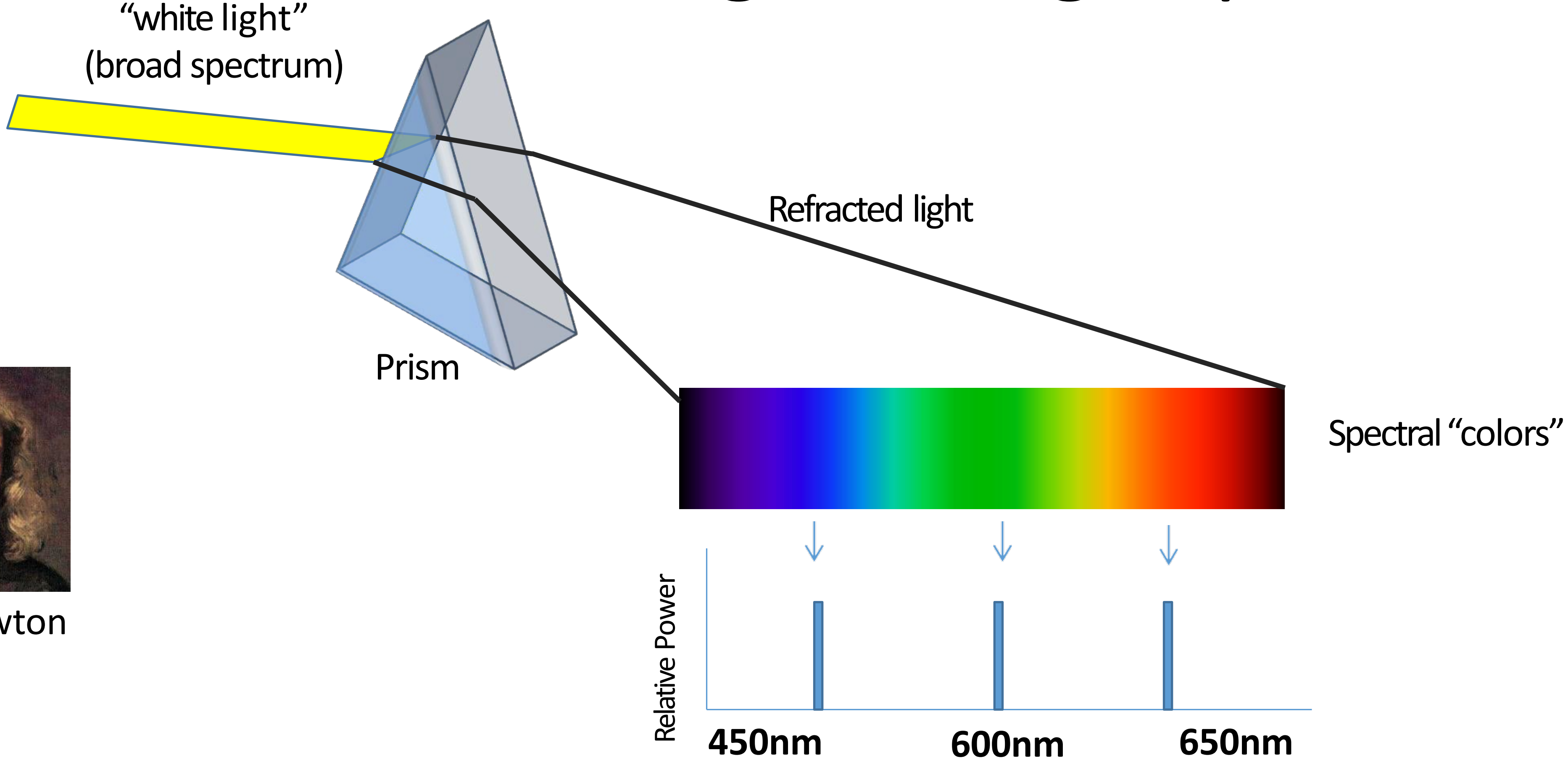
Generally wavelengths from 380 to 720nm are visible to most individuals

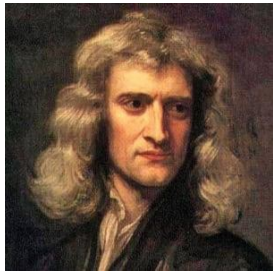
The Physics of Light

Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.



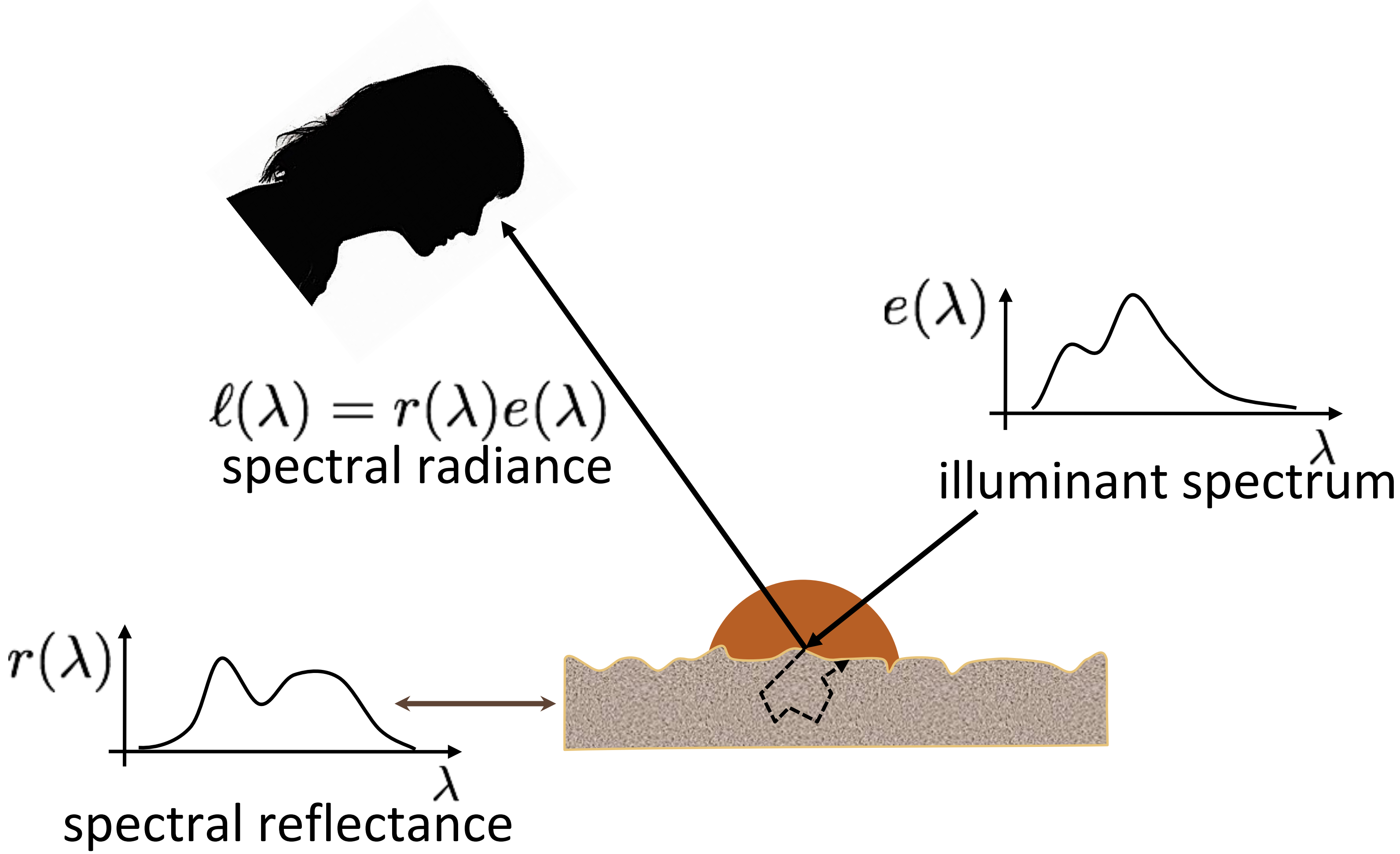
White light through a prism



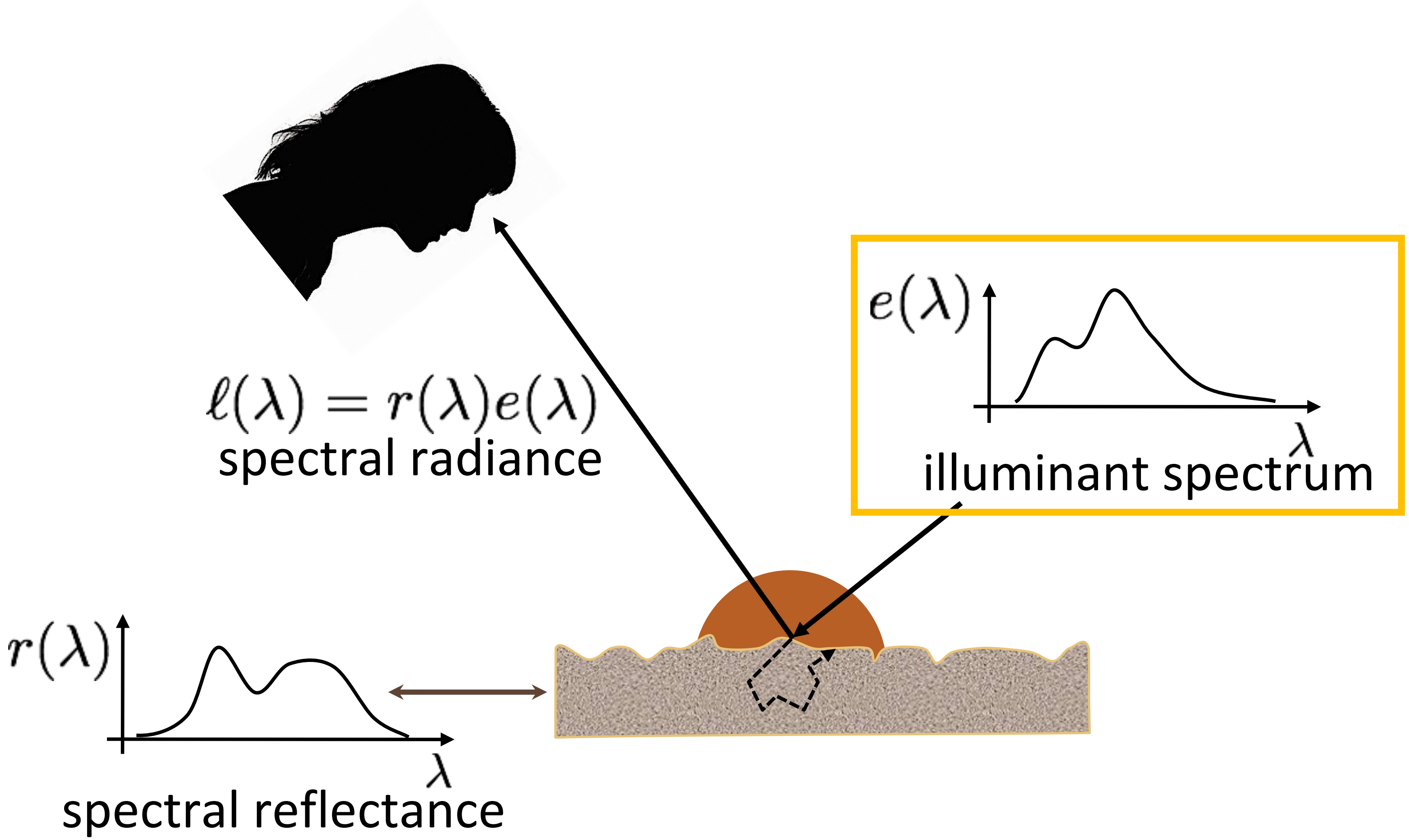

Isaac Newton

Light is separated into “monochromatic” light at different wave lengths.

Light-material interaction



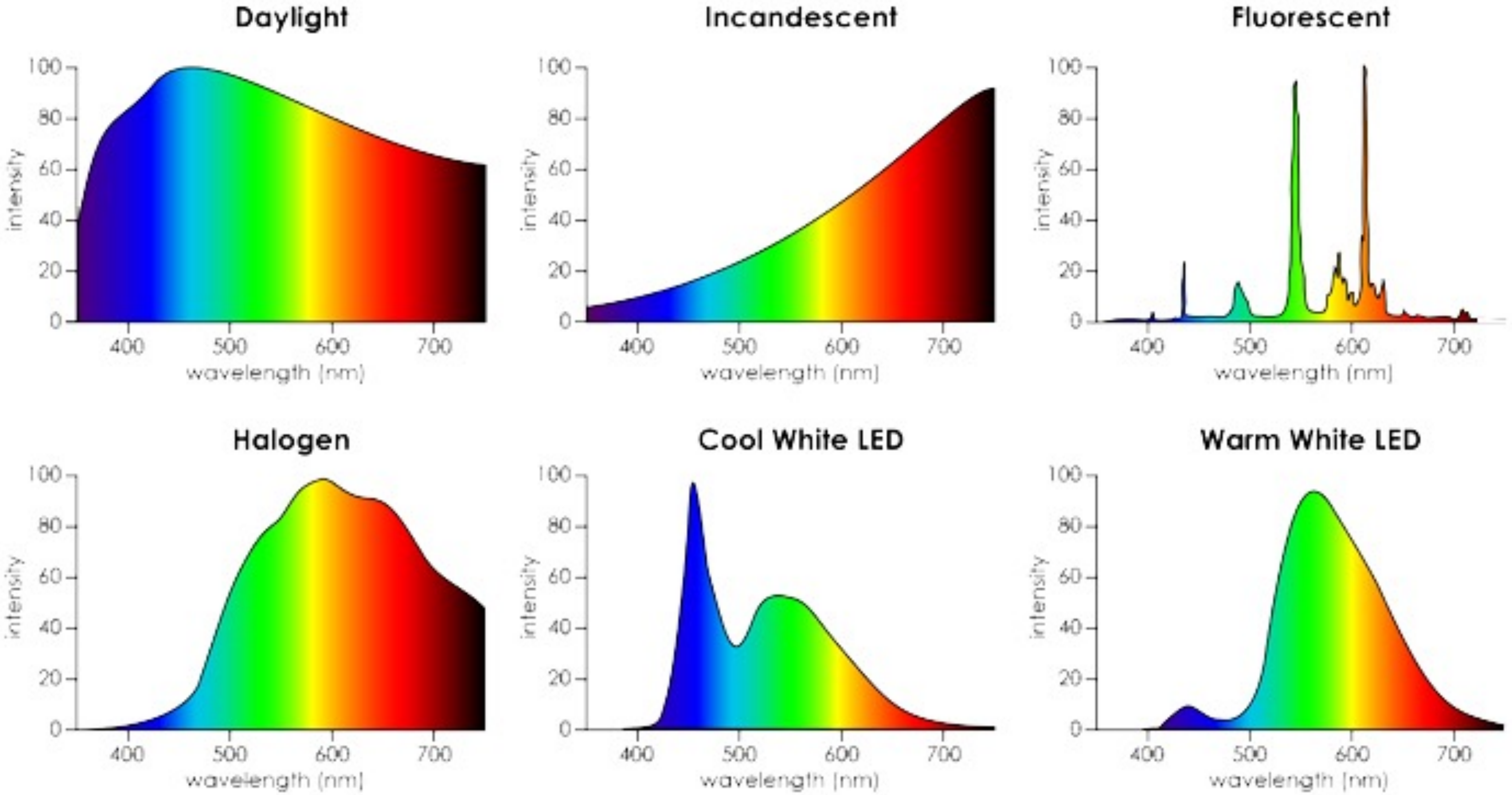
Light-material interaction



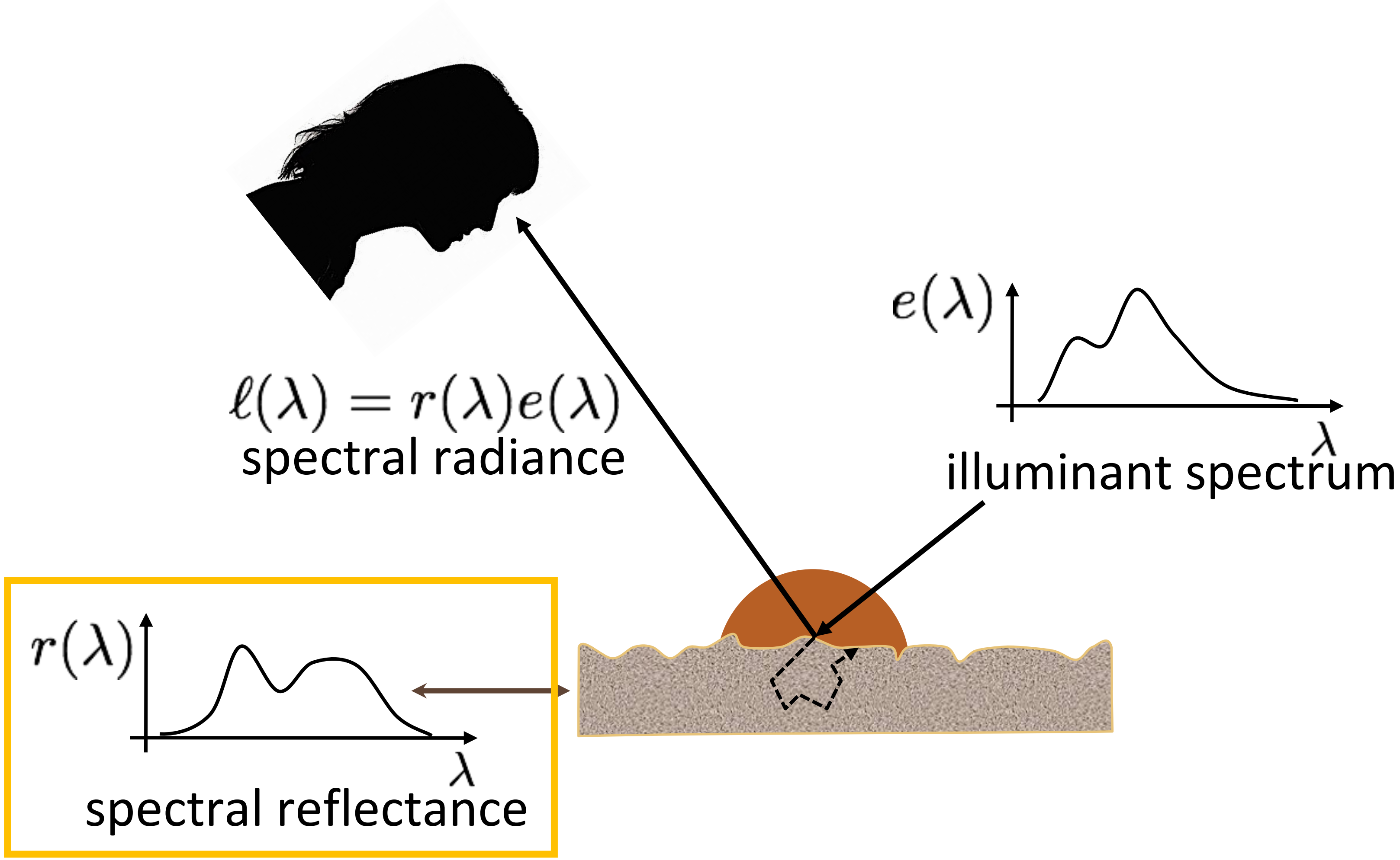
Illuminant Spectral Power Distribution (SPD)

- Most types of light “contain” more than one wavelengths.
- We can describe light based on the distribution of power over different wavelengths.

We call our sensation of all of these distributions “white”.

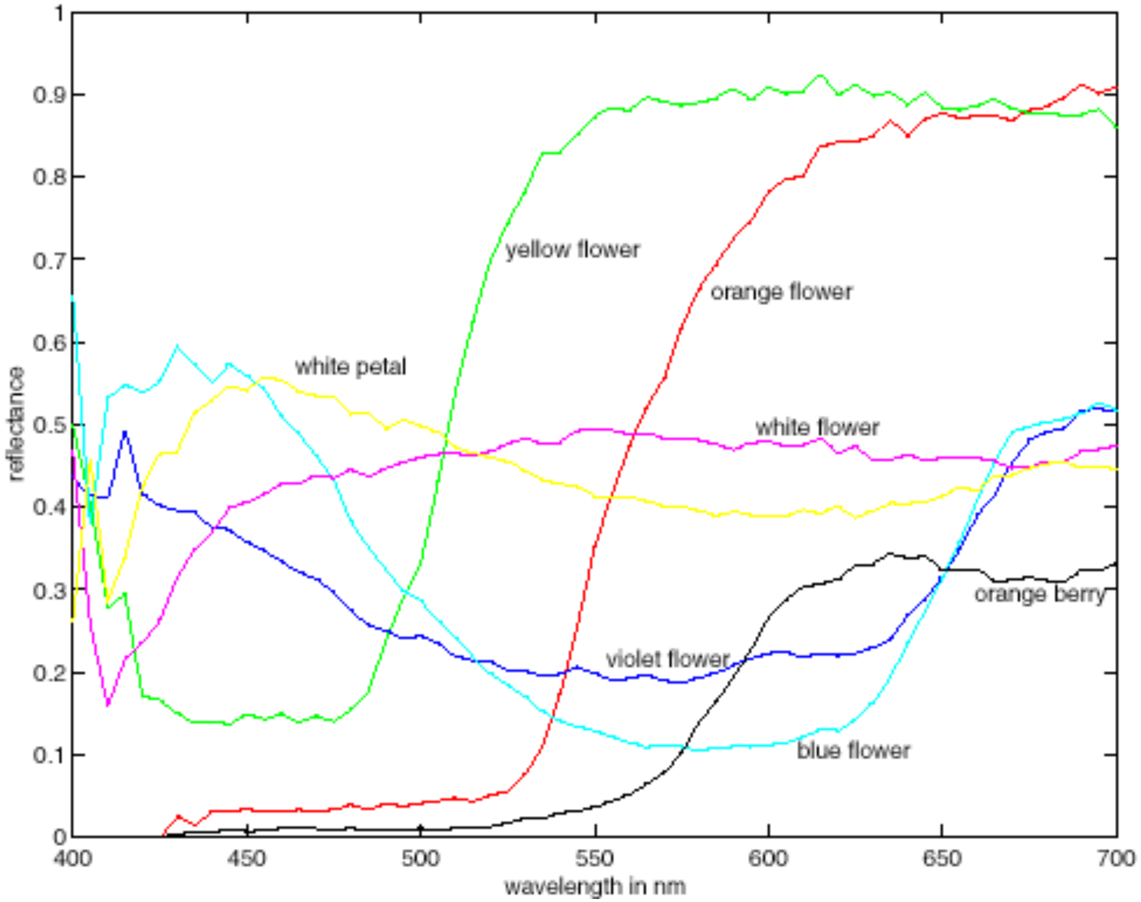


Light-material interaction

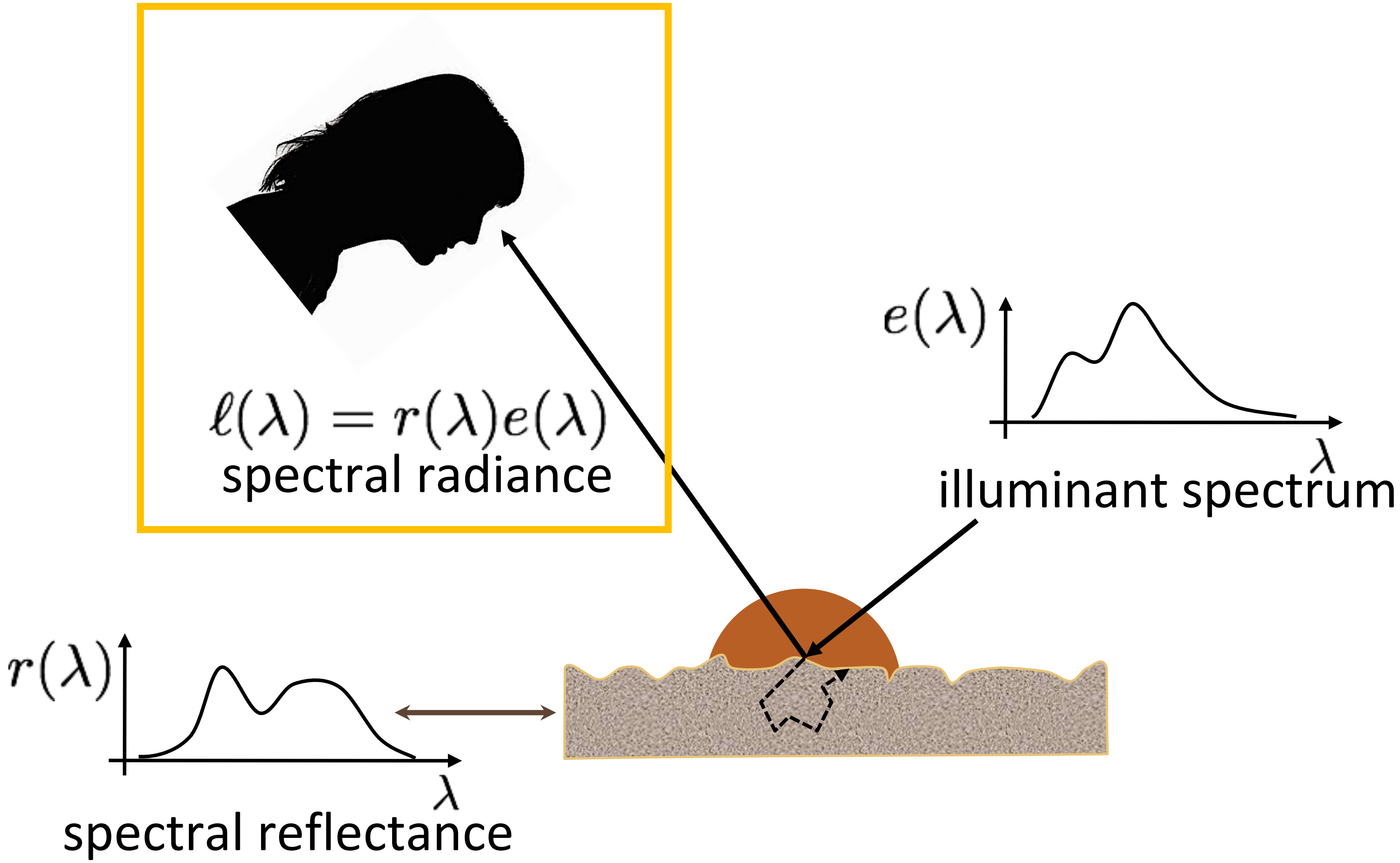


Spectral reflectance

- Most materials absorb and reflect light differently at different wavelengths.
- We can describe this as a ratio of reflected vs incident light over different wavelengths.

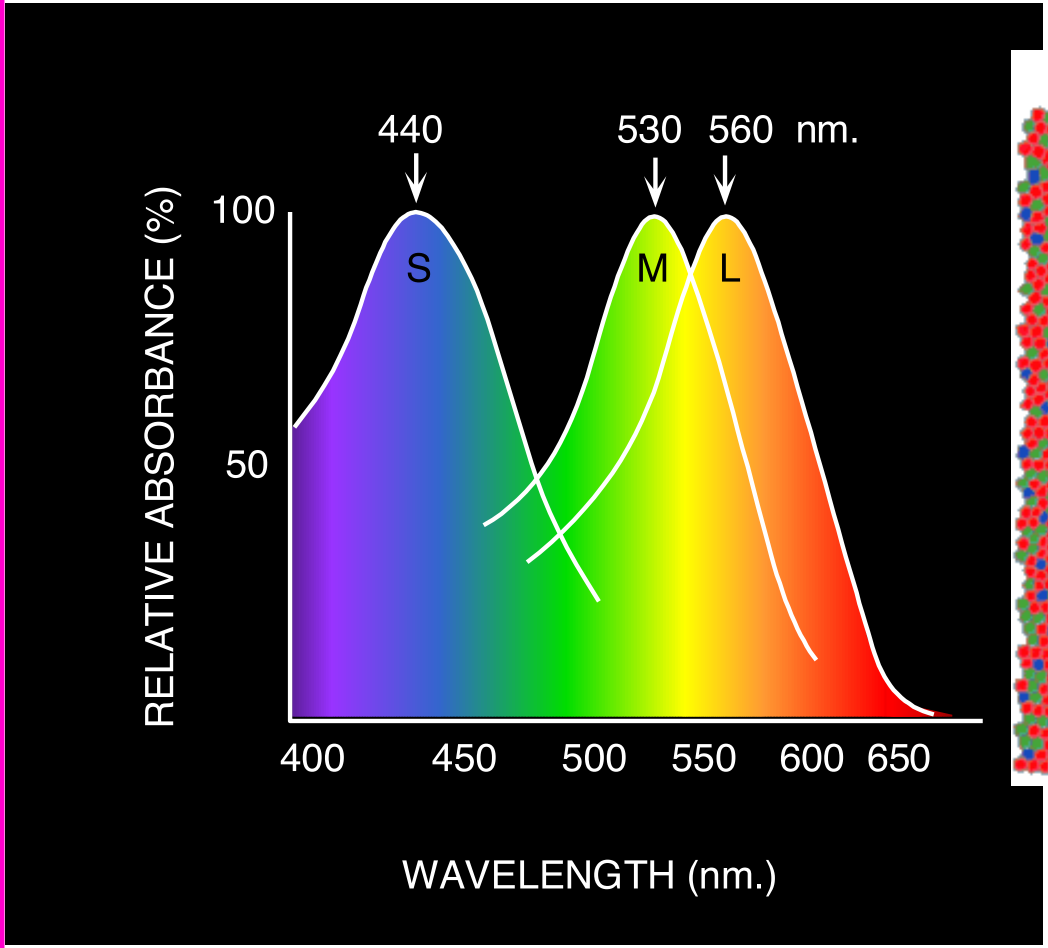


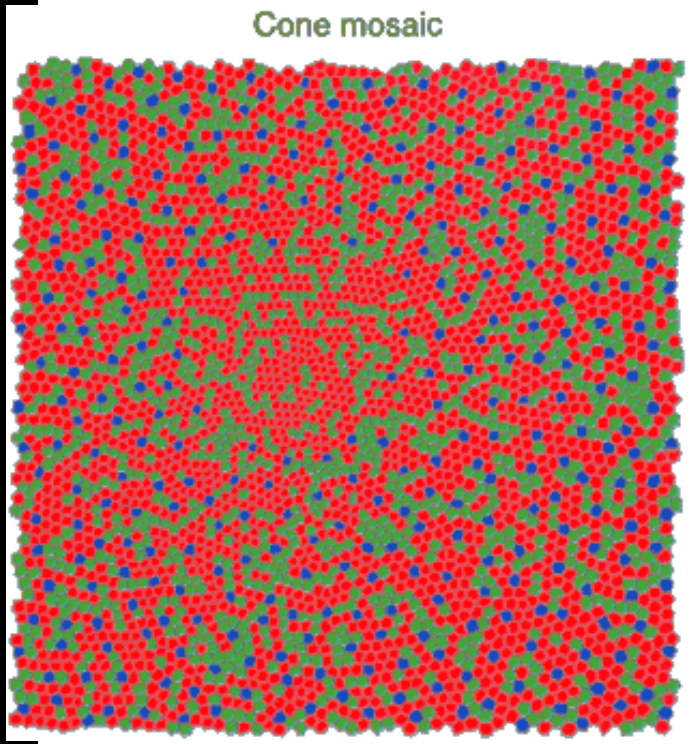
Light-material interaction



Physiology of Color Vision

Three kinds of cones:



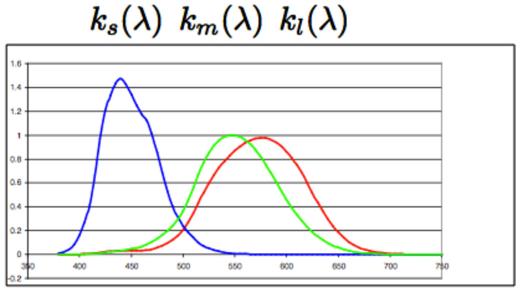


Human color vision

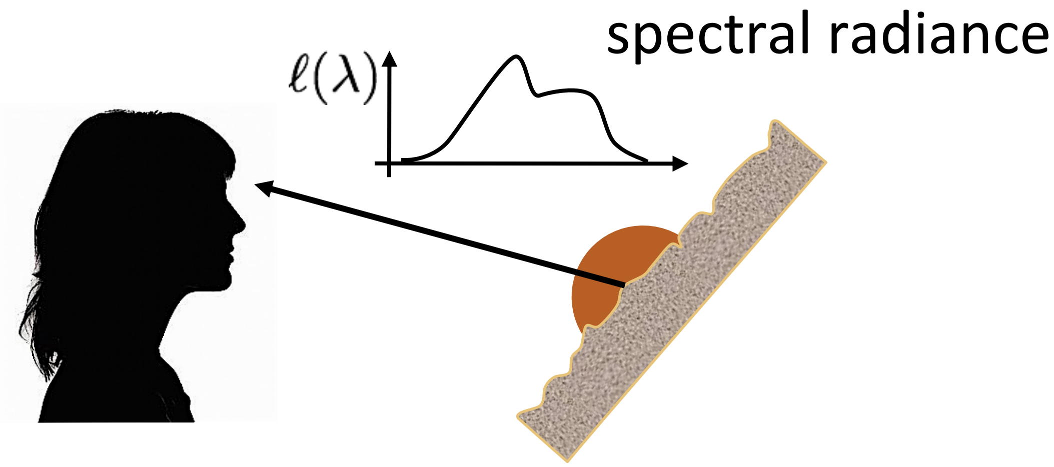
retinal color

$$\mathbf{c}(\ell(\lambda)) = (c_s, c_m, c_l)$$

$$c_s = \int k_s(\lambda)\ell(\lambda)d\lambda$$



LMS senstivity functions



perceived color

object color

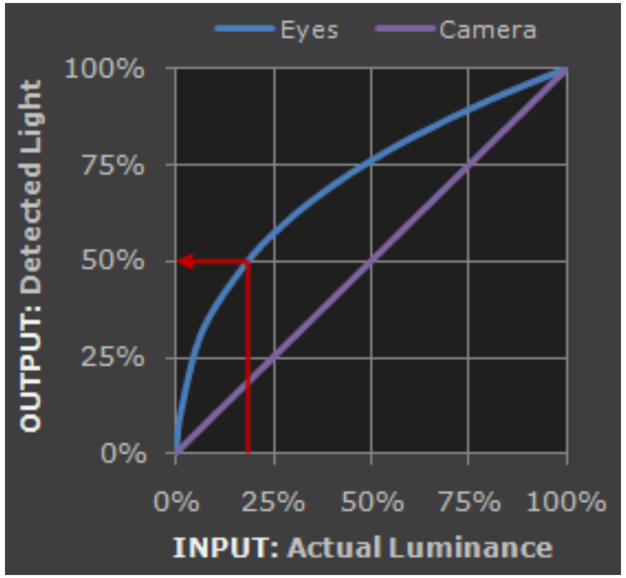
color names

Retinal vs perceived color

Retinal vs perceived color.

This is known as Color Constancy: more later in this lecture

Perceived vs measured brightness by human eye



Human-eye *response* (measured brightness) is linear.

However, human-eye *perception* (perceived brightness) is *non-linear*:

- More sensitive to dark tones.
- Approximately a Gamma function.

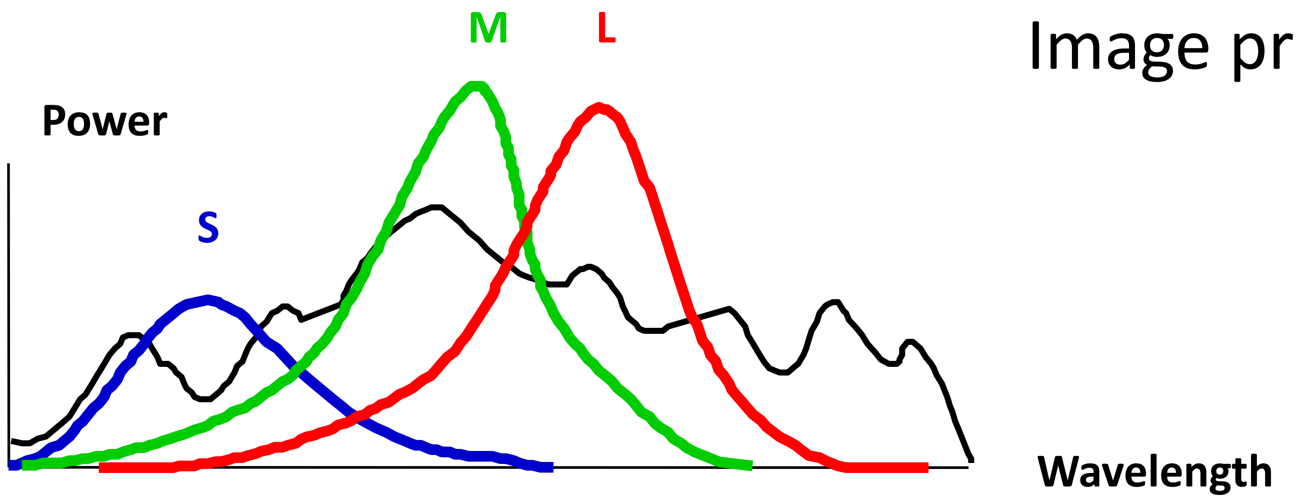
Not everyone is trichromat

- Types of color blindness:
  - Deuteranopia: missing M cones
  - Protanopia: missing L cones
  - Tritanopia: missing S cones
- “M” and “L” on the X-chromosome
  - Why men are more likely to be color blind
  - “L” has high variation, so some women are tetrachromatic
- Some animals have
  - 1 (night animals)
  - 2 (e.g., dogs)
  - 4 (fish, birds)
  - 5 (pigeons, some reptiles/amphibians)
  - 12 (mantis shrimp)

http://en.wikipedia.org/wiki/Color_vision

Trichromacy

Cone primaries = L, M, S
Image primaries = R, G, B



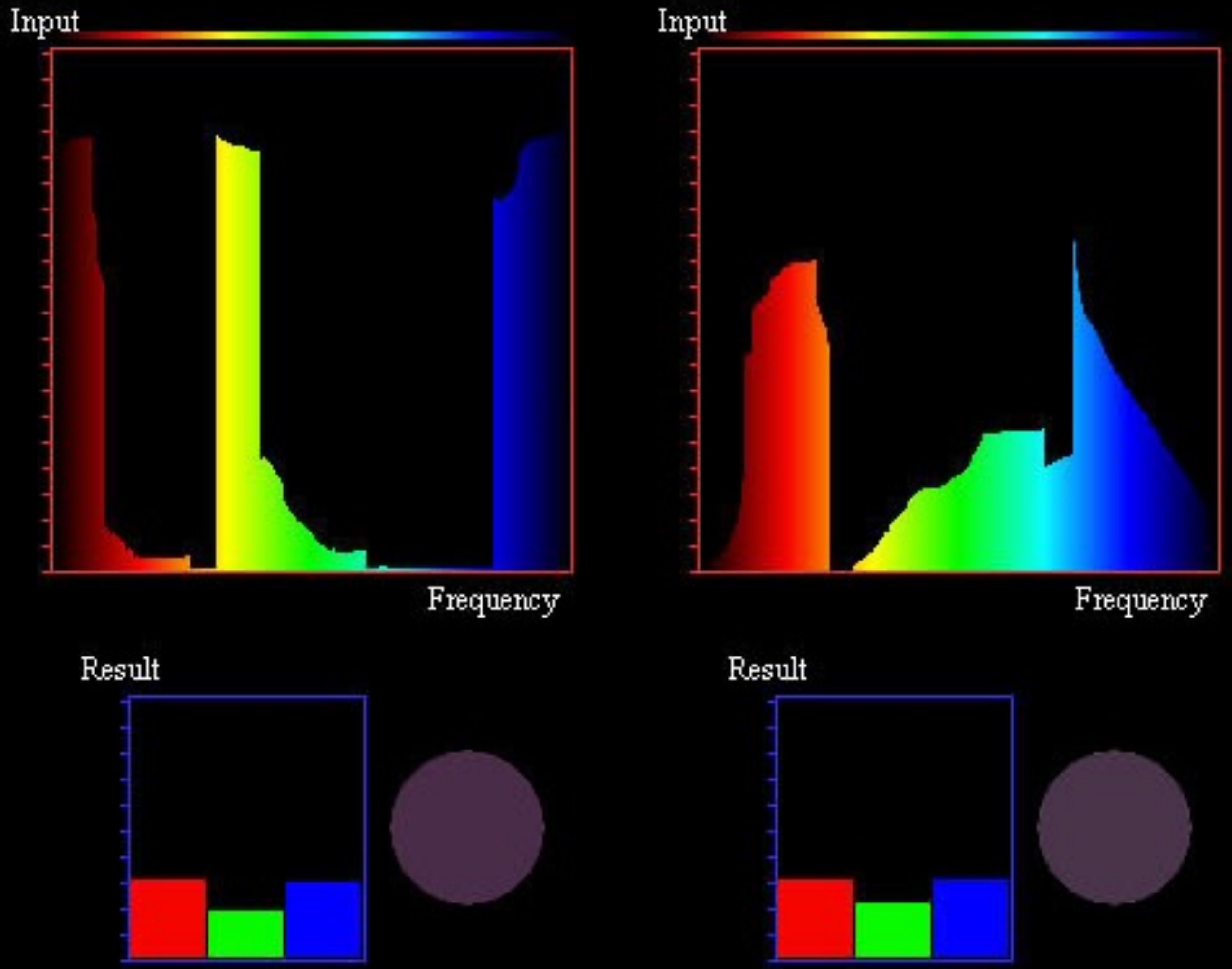
Rods and cones act as *filters* on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

- How can we represent an entire spectrum with 3 numbers?
- We can't! Most of the information is lost
  - As a result, two different spectra may appear indistinguishable
    - » such spectra are known as **metamers**

Slide by Steve Seitz

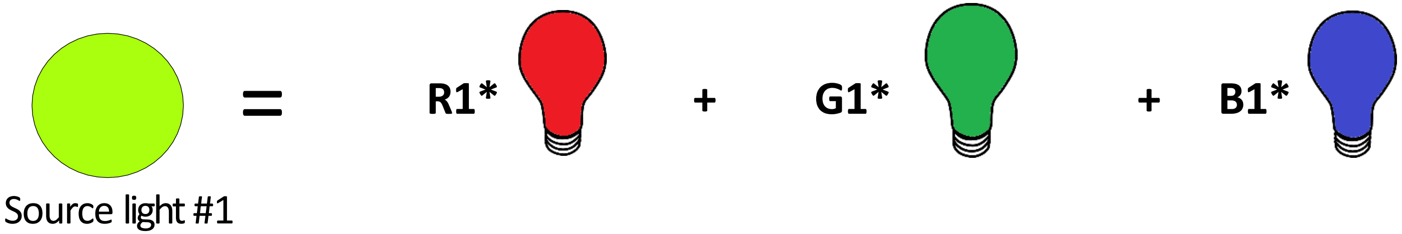
Metamers



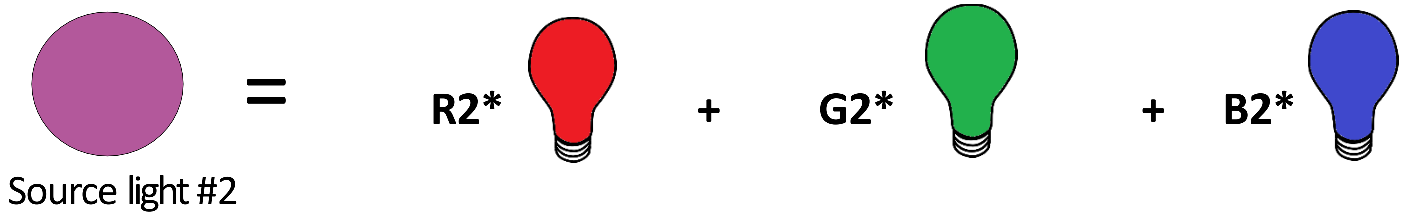
by Jeff Beall, Adam Doppelt and John F. Hughes

Tristimulus color theory

Grassman's Law states that a source color can be matched by a **linear** combination of three independent "primaries".



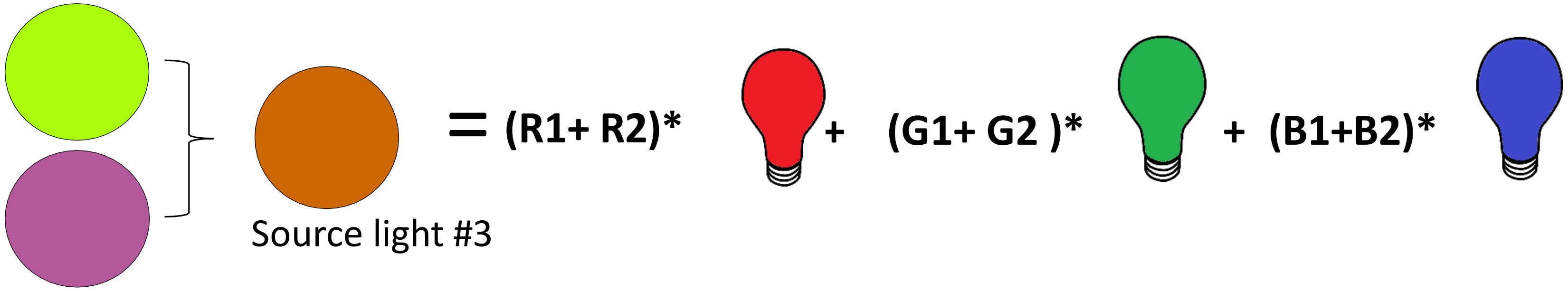
Three lights (shown as lightbulbs) serve as primaries. Each light has intensity, or weights, R1, G1, B1 to match the source light #1 perceived color.



Same three primaries and the weights (R2, G2, B2) of each primary needed to match the source light #2 perceived color

If we combined source lights 1 & 2 to get a new source light 3

The amount of each primary needed to match the new source light #3 is the sum of the weights that matched lights sources #1 & #2.



This may seem obvious now, but discovering that light obeys the laws of linear algebra was a huge and useful discovery.

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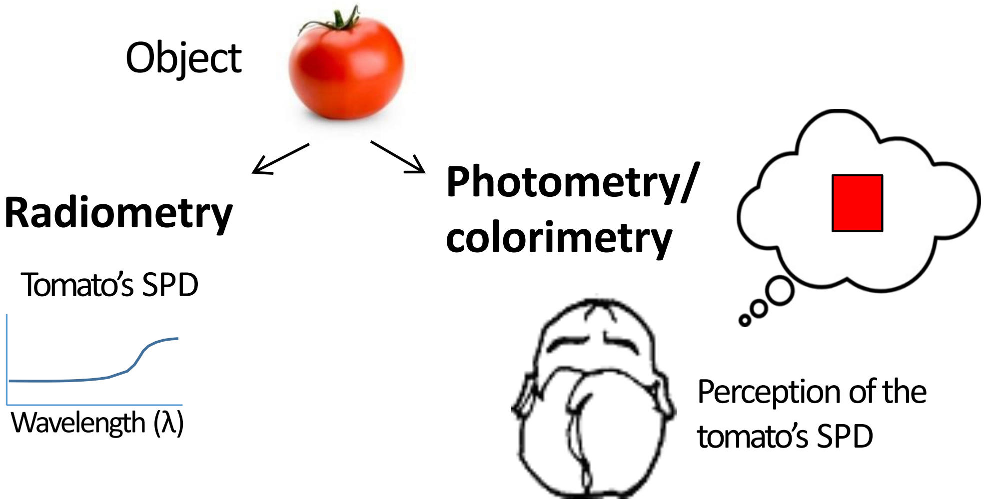
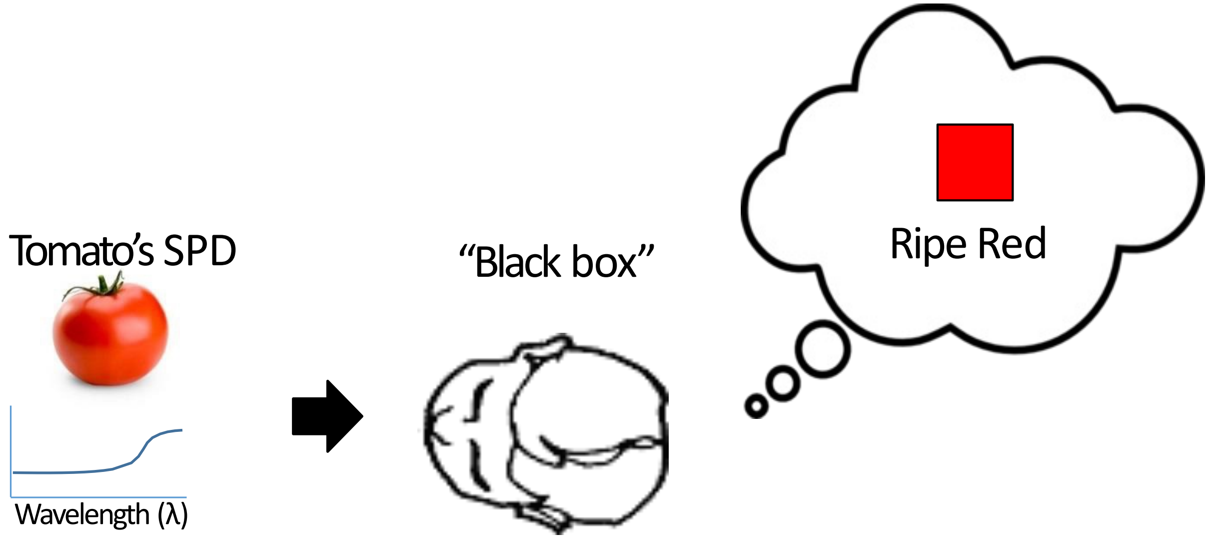
Radiometry vs. photometry

- **Radiometry**
  - Quantitative measurements of radiant energy
  - Often shown as spectral power distributions (SPD)
  - Measures either light coming from a source (radiance) or light falling on a surface (irradiance)
- **Photometry/ colorimetry**
  - Quantitative measurement of **perceived** radiant energy based on human's sensitivity to light
  - Perceived in terms of "brightness" (photometry) and color (colorimetry)

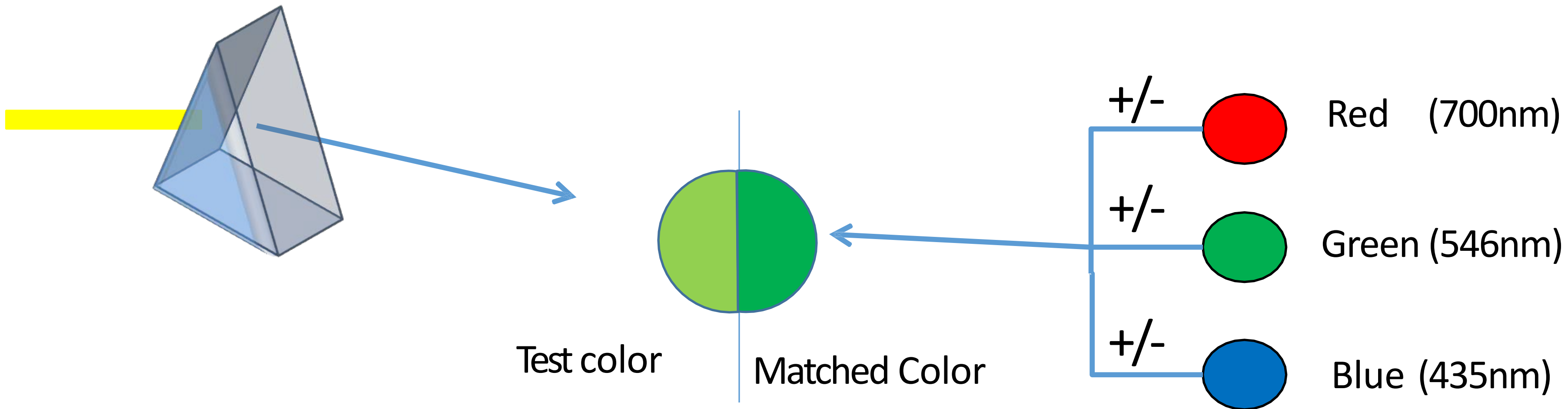


Quantifying color

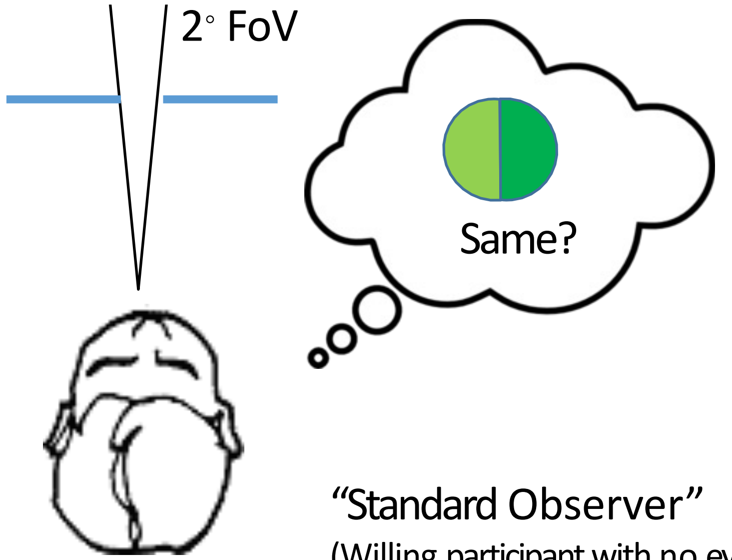
- We still need a way to quantify color & brightness
- SPDs go through a "black box" (human visual system) and are perceived as color
- The only way to quantify the "black box" is to perform a human study



CIE RGB color matching



Human subjects matched test colors by add or subtracting three primaries.

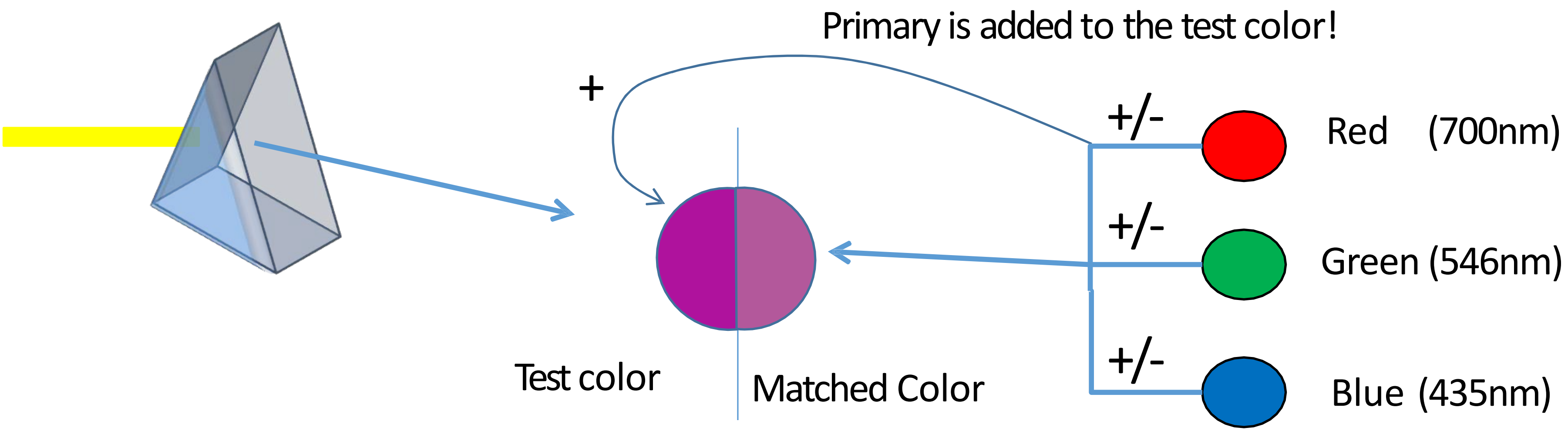


Field of view was 2-degrees (where color cones are most concentrated)

"Standard Observer"
(Willing participant with no eye disease)

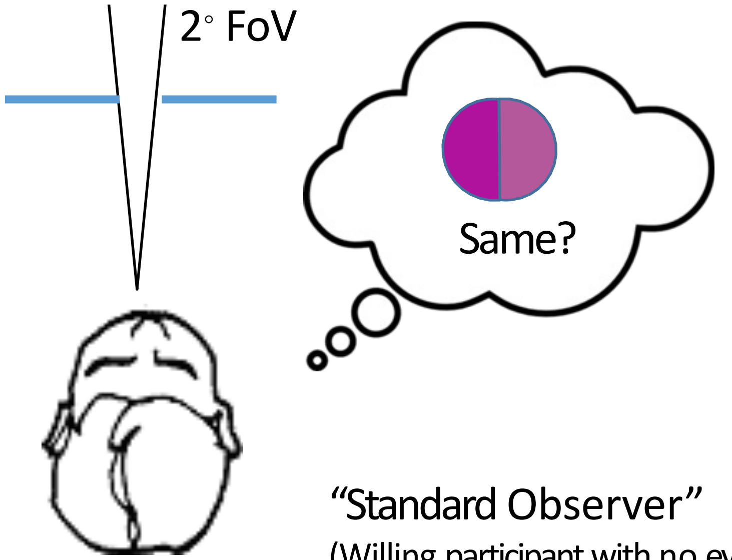
Experiments carried out by
W. David Wright (Imperial College) and John Guild (National Physical Laboratory, London) – Late 1920s

CIE RGB color matching



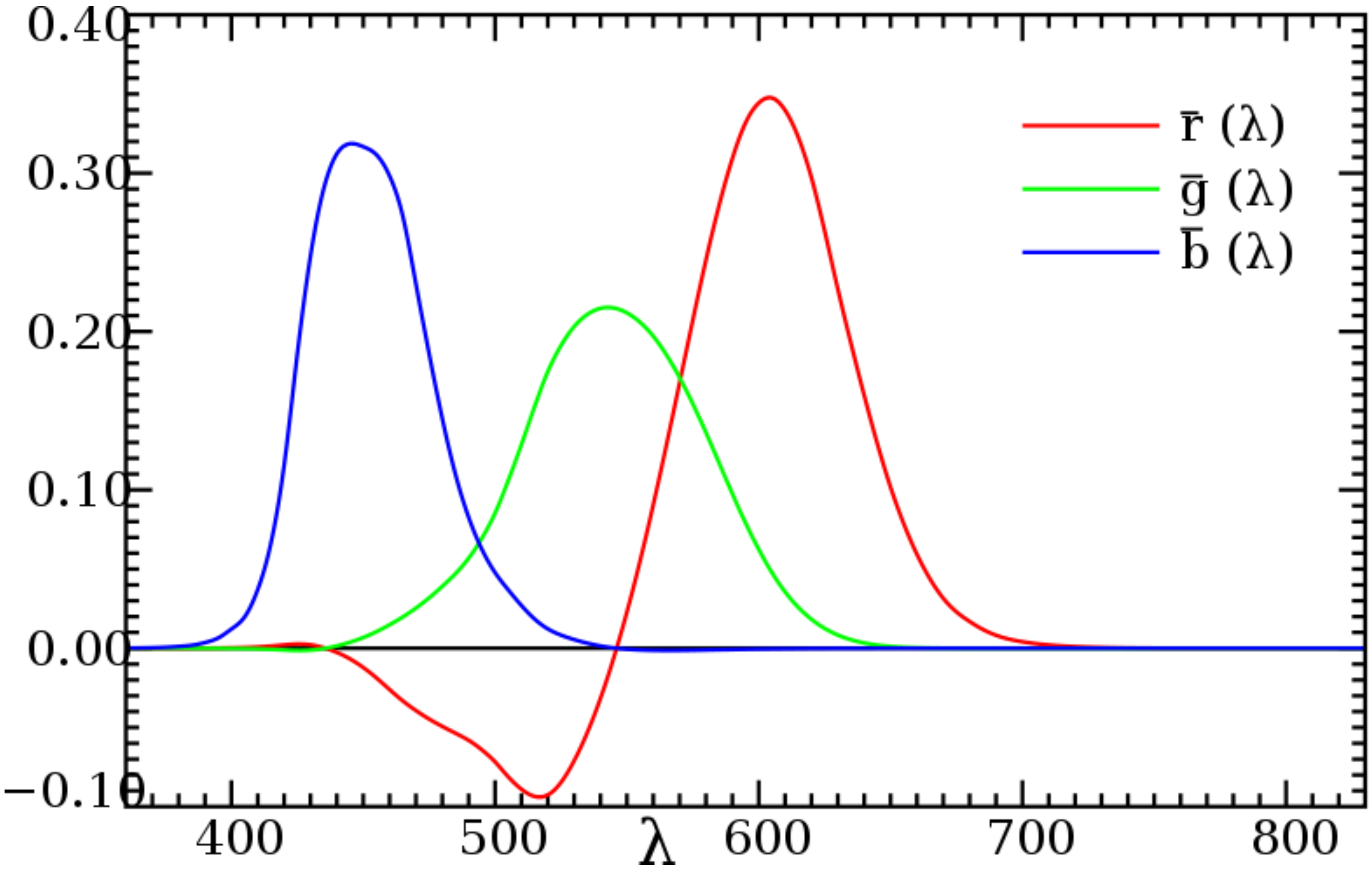
For some test colors, no mix of the primaries could give a match! For these cases, the subjects were ask to add primaries to the test color to make the match.

This was treated as a negative value of the primary added to the test color.



"Standard Observer"
(Willing participant with no eye disease)

CIE RGB results

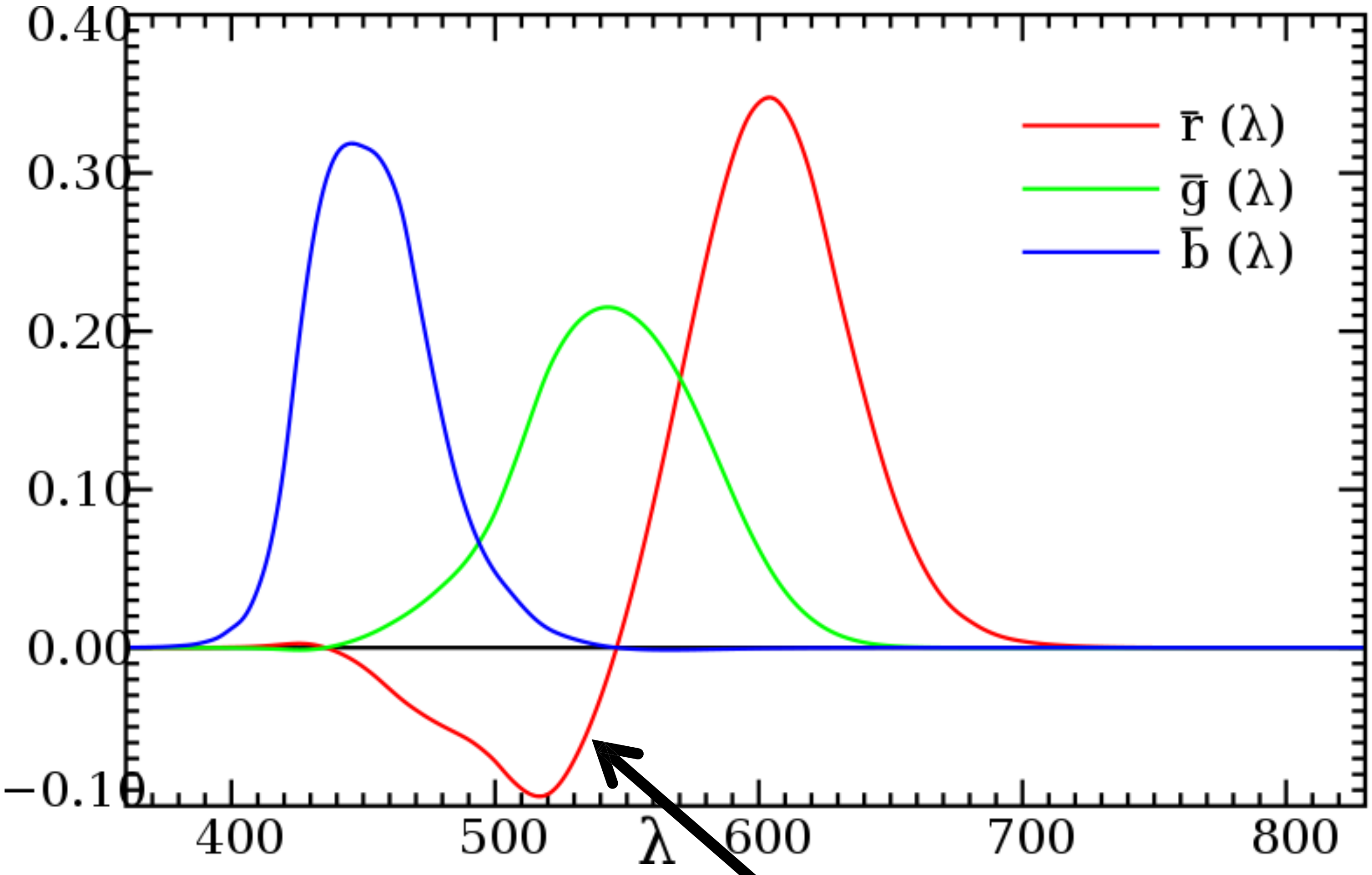


Plots are of the mixing coefficients of each primary needed to produce the corresponding monochromatic light at that wavelength.

Note that these functions have been scaled such that area of each curve is equal.

CIE RGB 2-degree Standard Observer
(based on Wright/Guild's data)

CIE RGB results



Negative values -- the three primaries used did not span the full range of perceptual colors.

CIE 1931 XYZ

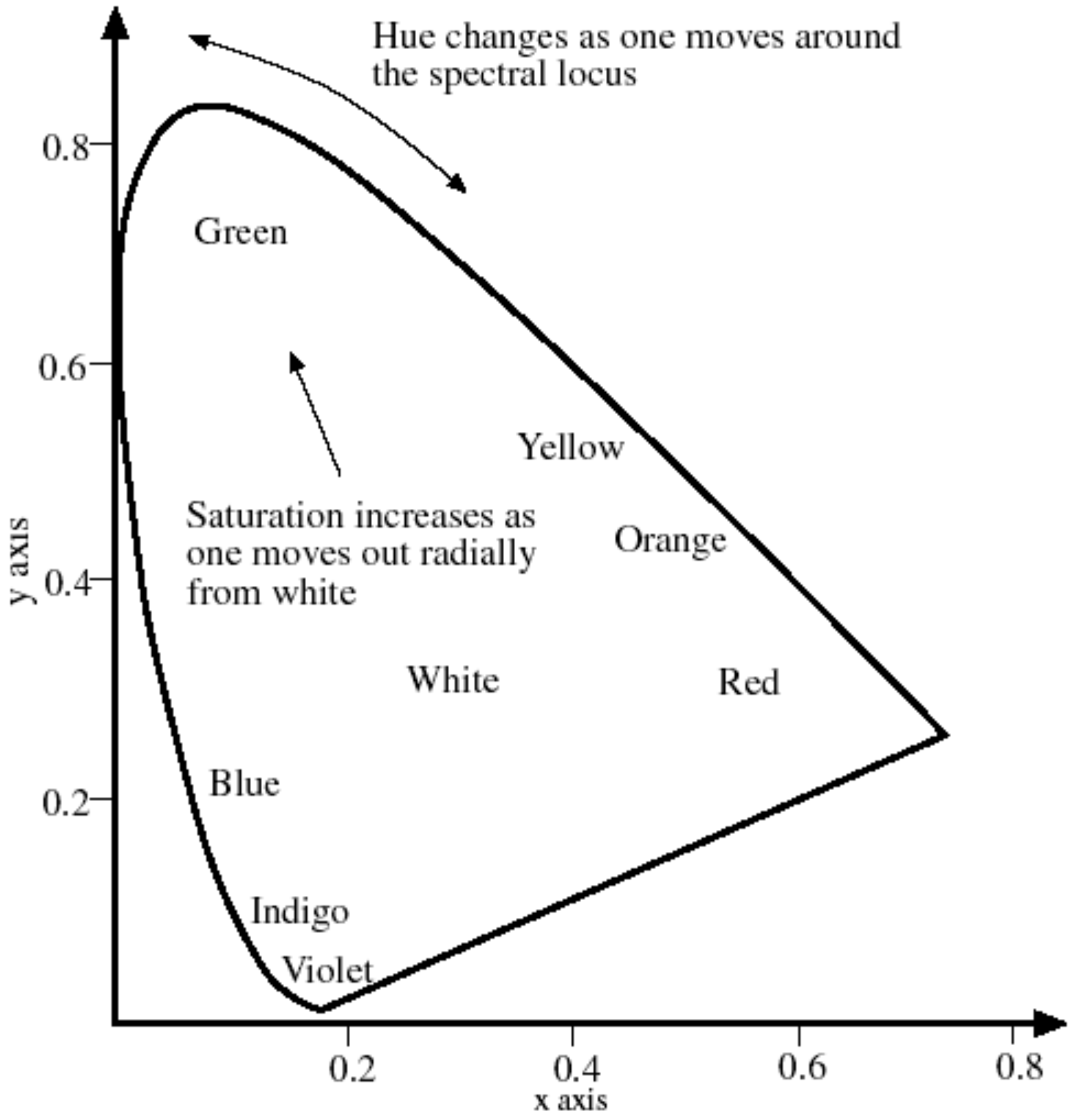
- In 1931, the CIE met and approved defining a new canonical basis, termed XYZ that would be derived from Wright-Guild's CIE RGB data
- Properties desired in this conversion:
  - White point defined at X=1/3, Y=1/3, Z=1/3
  - Y would be the luminosity function ($V(\lambda)$)
  - Quite a bit of freedom in selecting these XYZ basis
  - In the end, the adopted transform was:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4887180 & 0.3106803 & 0.2006017 \\ 0.1762044 & 0.8129847 & 0.0108109 \\ 0.0000000 & 0.0102048 & 0.9897952 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE 1931 RGB

Nice article see: Fairman et al "How the CIE 1931 Color-Matching Functions Were Derived from Wright–Guild Data", Color Research & Application, 1997

CIE xy (chromaticity)



$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$(X, Y, Z) \longleftrightarrow (\underbrace{x, y}_{\text{chromaticity}}, Y)$$

luminance/brightness

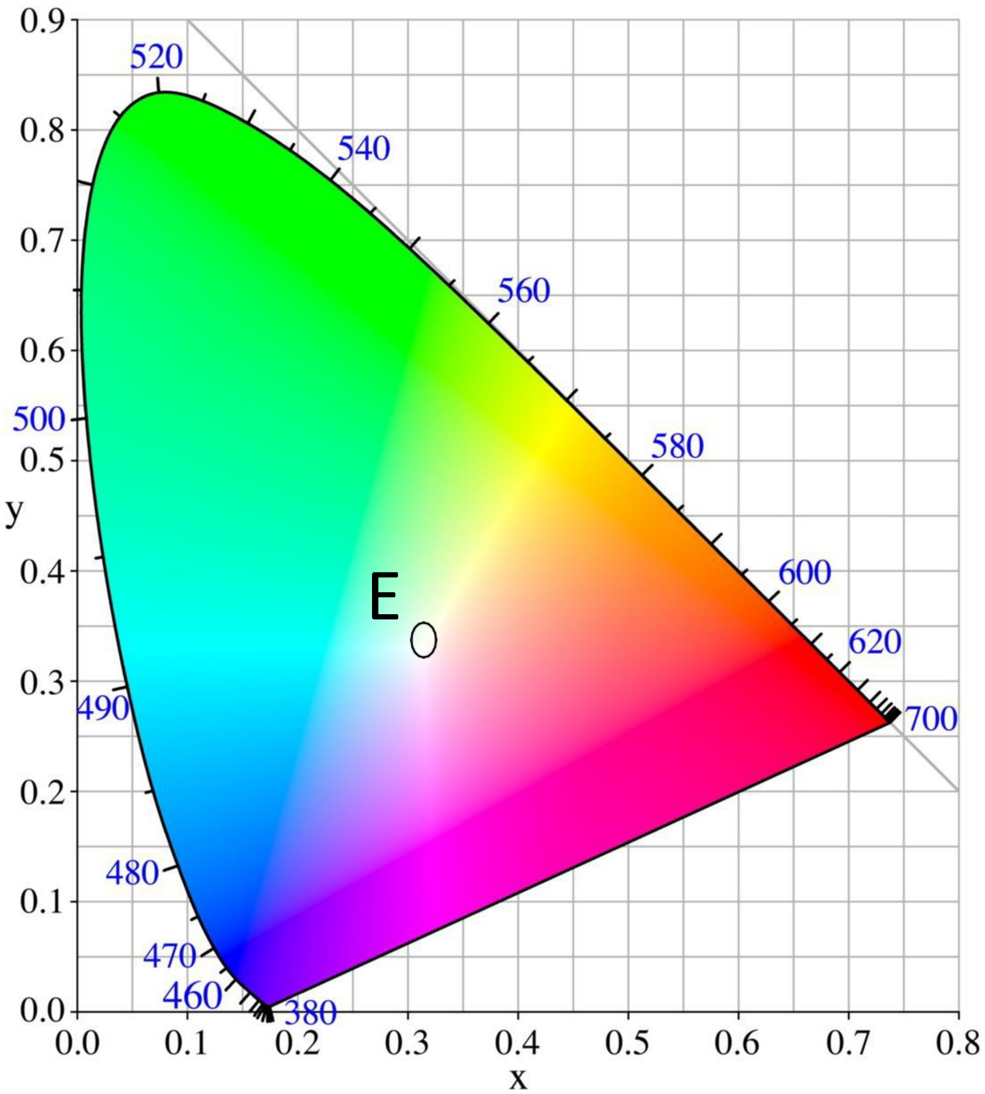
Perspective projection of 3D retinal color space to two dimensions.

CIE xy chromaticity diagram

This gives us the familiar horseshoe shape of visible colors as a 2D plot. Note the axis are x & y.

Point "E" represents where X=Y=Z have equal energy (X=0.33,Y=0.33, Z=0.33)

CIE XYZ "white point"



In the 1930s, CIE had a bad habit of over using the variables X,Y. Note that x,y are chromaticity coordinates, x,y (with the bar above) are the matching functions, and X,Y are the imaginary SPDs of CIE XYZ.

Fast forward 80+ years

- CIE 1931 XYZ, CIE 1931 xyY (2-degree standard observer) color spaces have stood the test of time
- Many other studies have followed (most notably - CIE 1965 XYZ 10- degree standard observer), …
- But in the literature (and in this tutorial) you'll find CIE 1931 XYZ color space remains the preferred standard

What is perhaps most amazing?

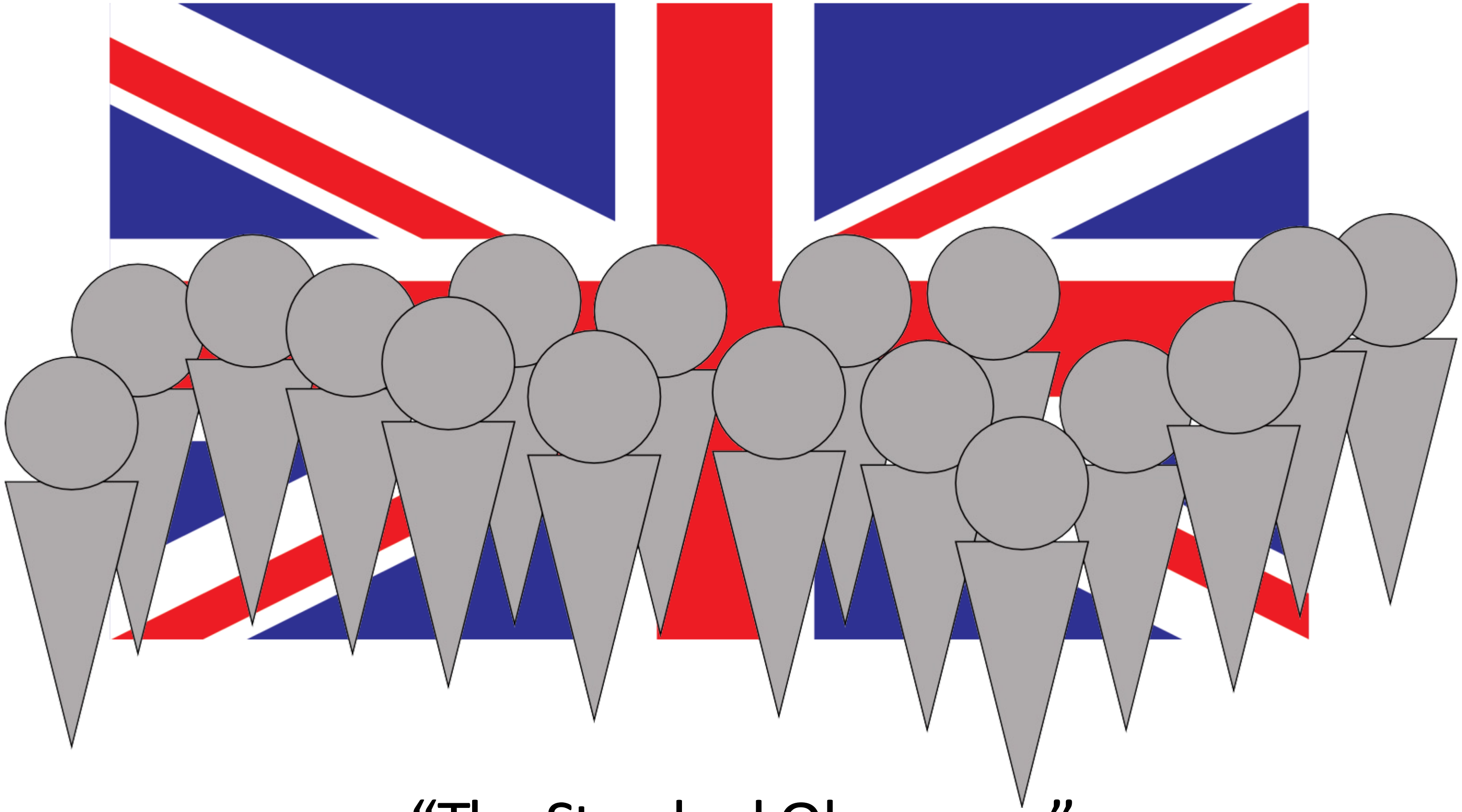
- 80+ years of CIE XYZ and it is all based on the experiments by the "standard observers"

- How many standard observers were used? 100, 500, 1000?

A Standard Observer

CIE XYZ is based on 17 standard observers

10 by Wright, 7 by Guild



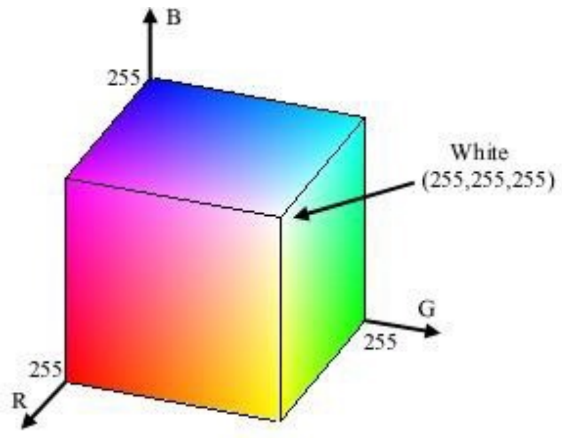
"The Standard Observers"

Today’s class

- Eye & Human Vision
- Pinhole Camera
- Perception of Color
- Quantifying Color
- Commonly Used Color Spaces
- Color Constancy

CIE XYZ and RGB

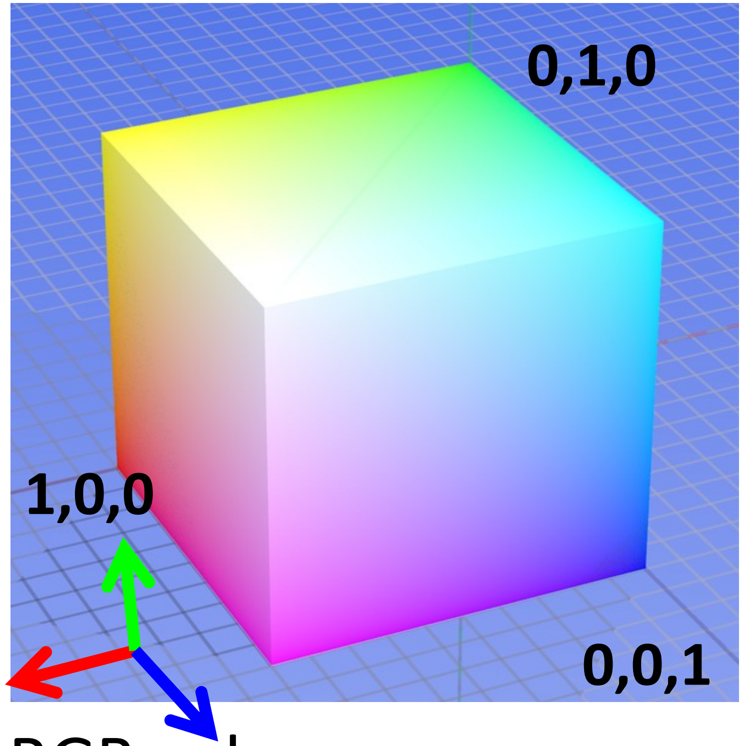
- While CIE XYZ is a canonical color space, images/devices rarely work directly with XYZ
- XYZ are not real primaries
- RGB primaries dominate the industry
- We are all familiar with the RGB color cube



But by now, you should realize that Red, Green, Blue have no quantitative meaning. We need to know their corresponding SPDs or CIE XYZ values.

Color spaces: RGB

Default color space



RGB cube

- Easy for devices
- But not perceptual

R
(G=0,B=0)

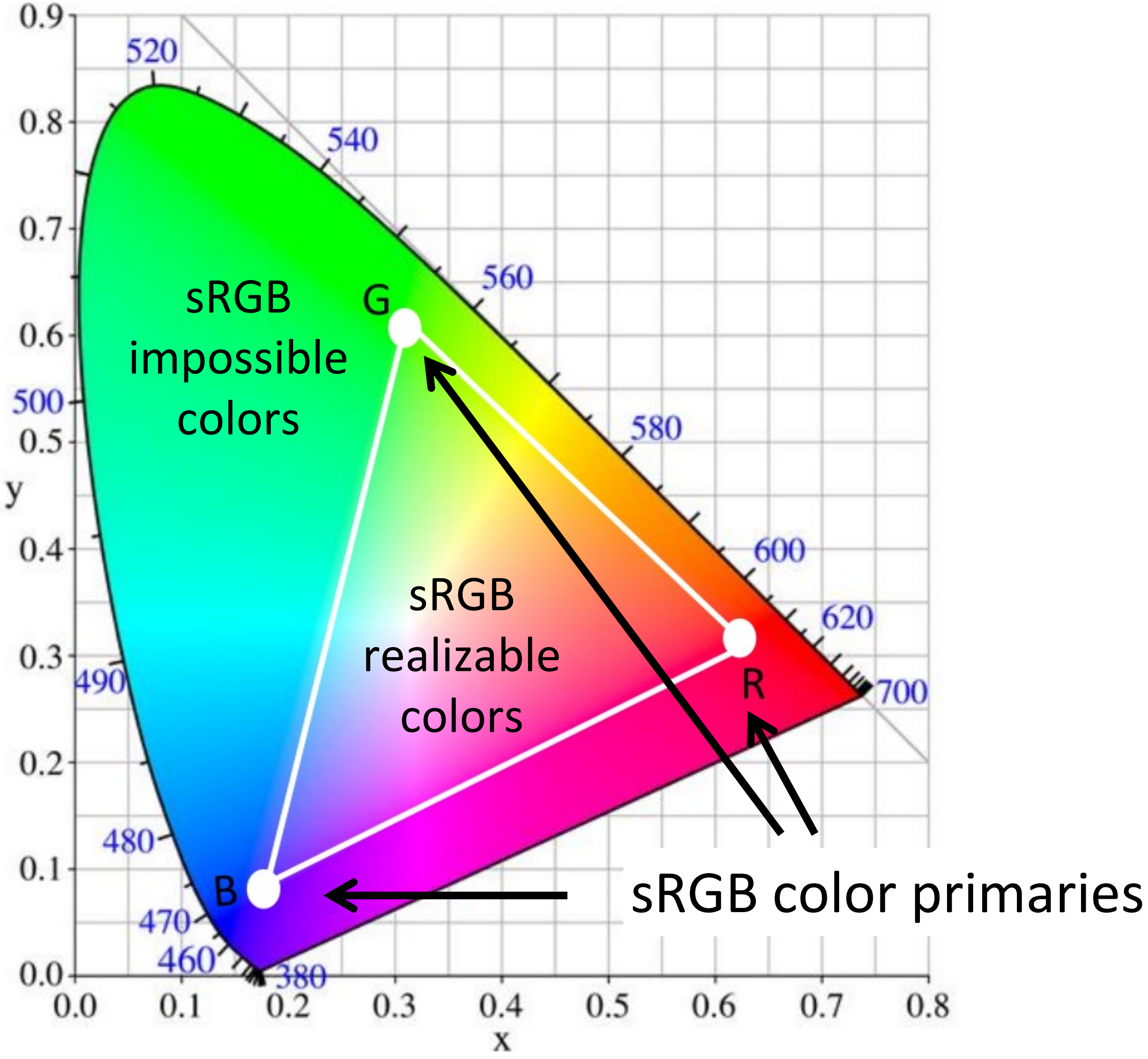
G
(R=0,B=0)

B
(R=0,G=0)

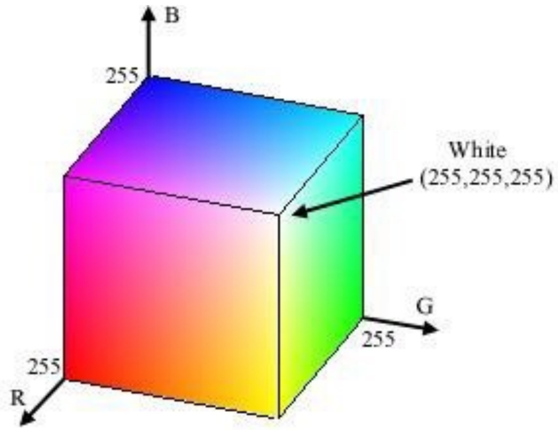
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

Color gamuts

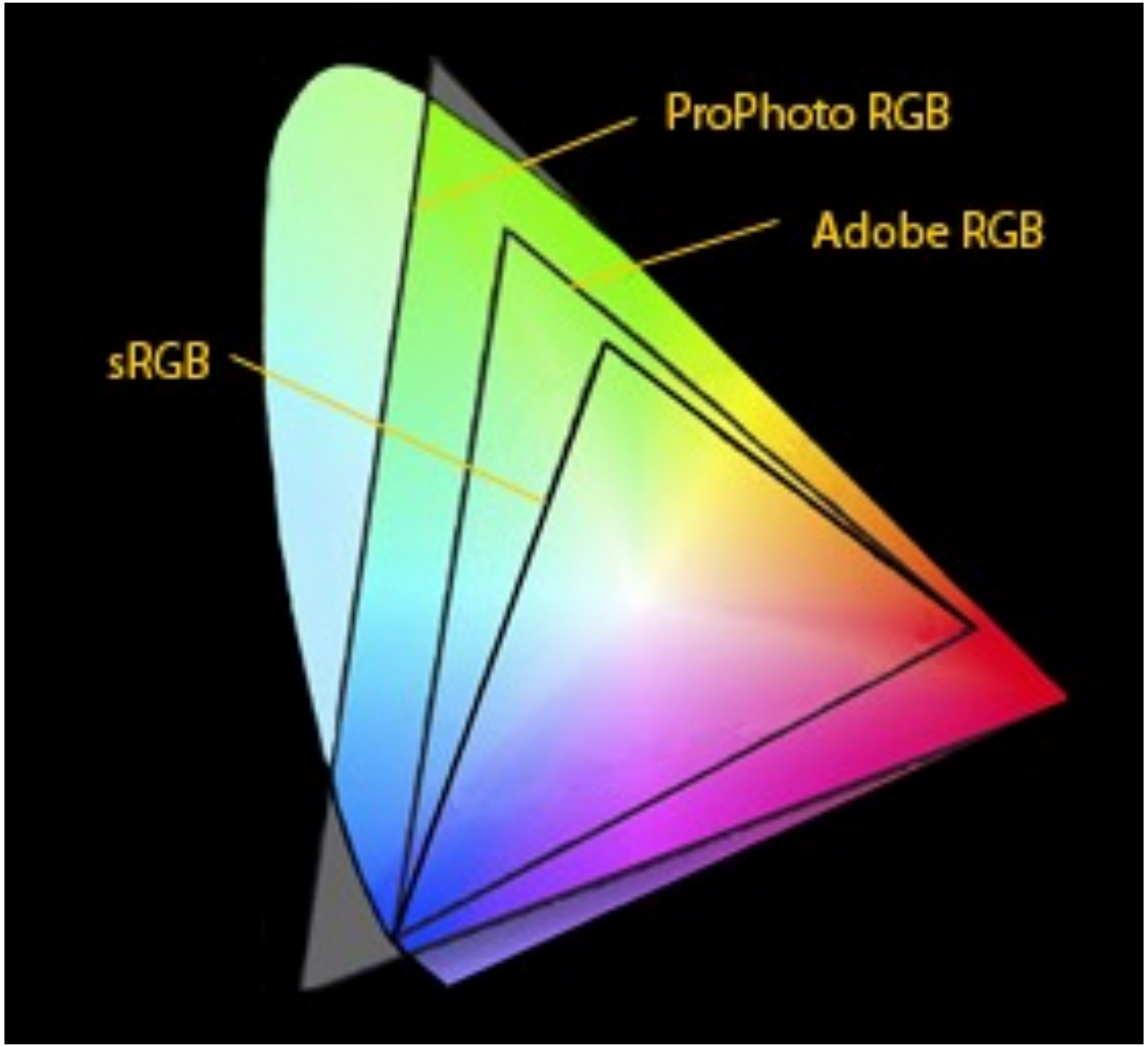
sRGB color gamut



The RGB values span a subspace of CIE-XYZ to define the devices gamut.



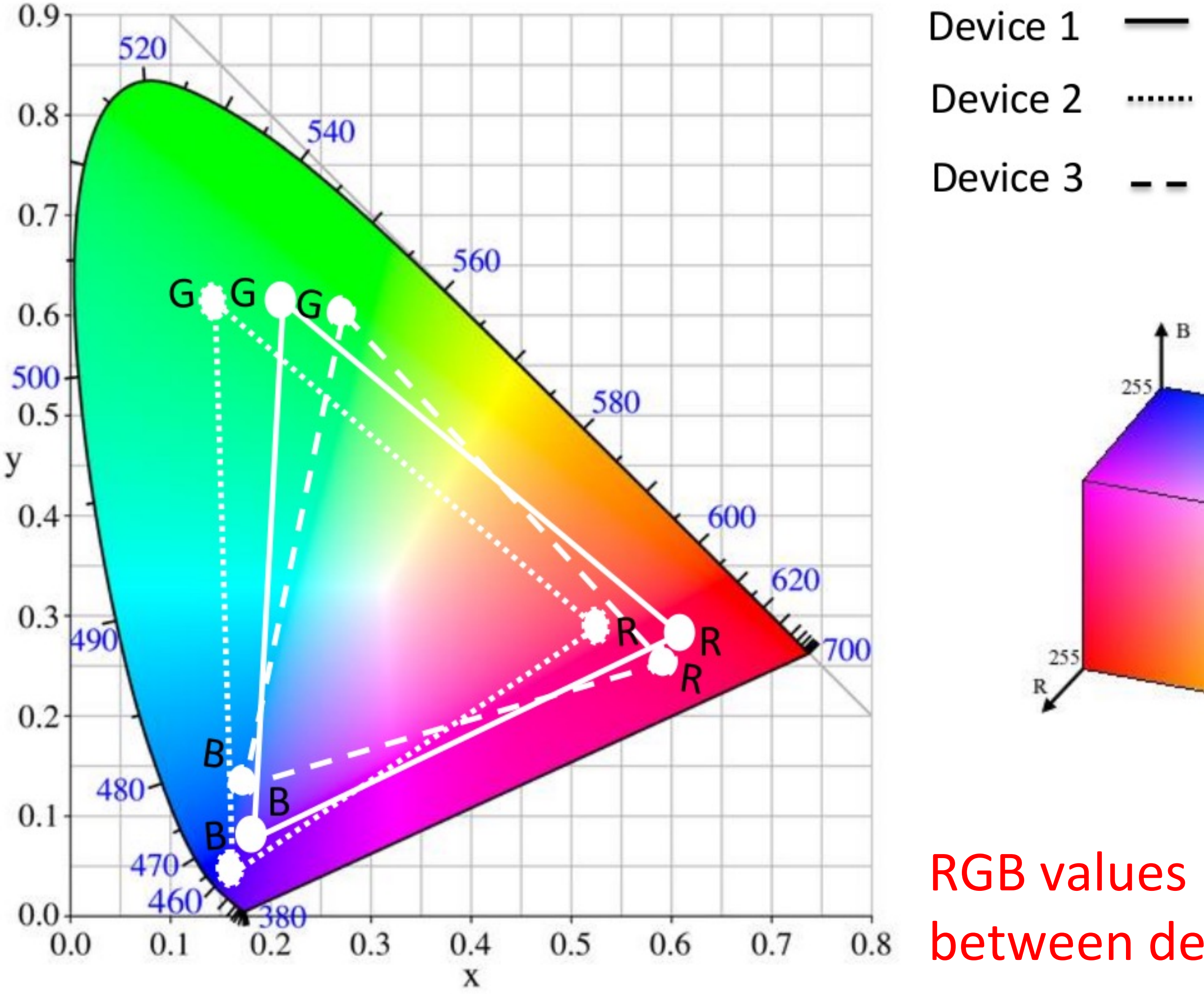
Color gamuts

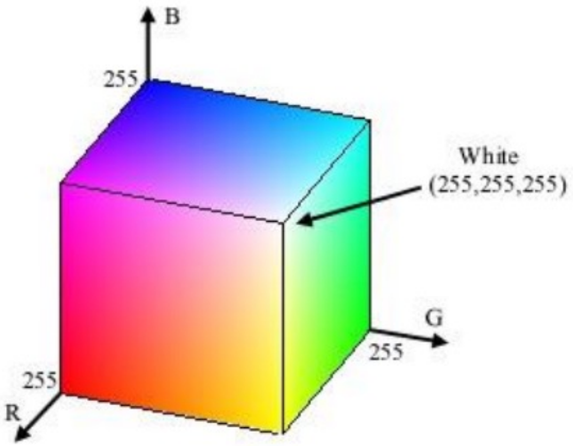


If you have RGB values, they are specific to a particular device .

Gamuts of various common industrial RGB spaces

The problem with RGBs visualized in chromaticity space





RGB values have no meaning if the primaries between devices are not the same!

HSV: Perceptual Color Space

Hue
Name of the color
(yellow, red, blue, green, ...)

Value/Lightness/Brightness
How light or dark a color is.

Saturation/Chroma/Color Purity
How "strong" or "pure" a color is.

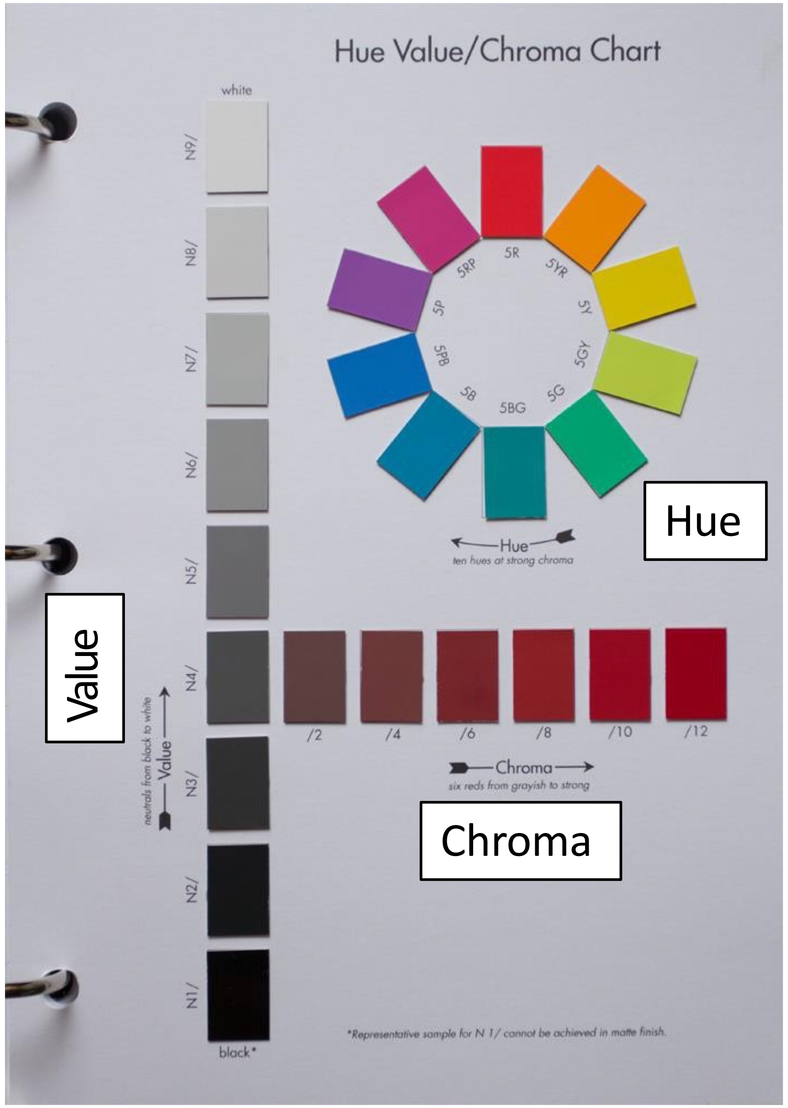
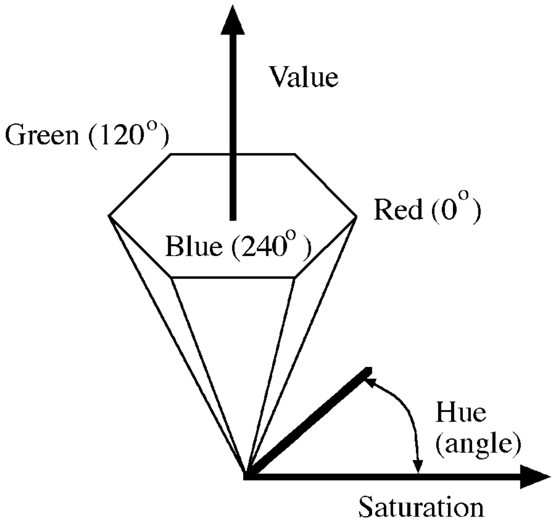
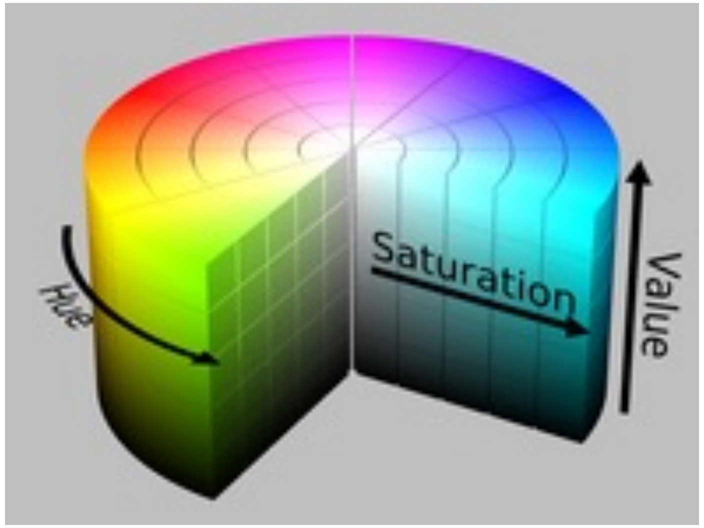


Image from Benjamin Salley
A page from a Munsell Student Color Set

HSV



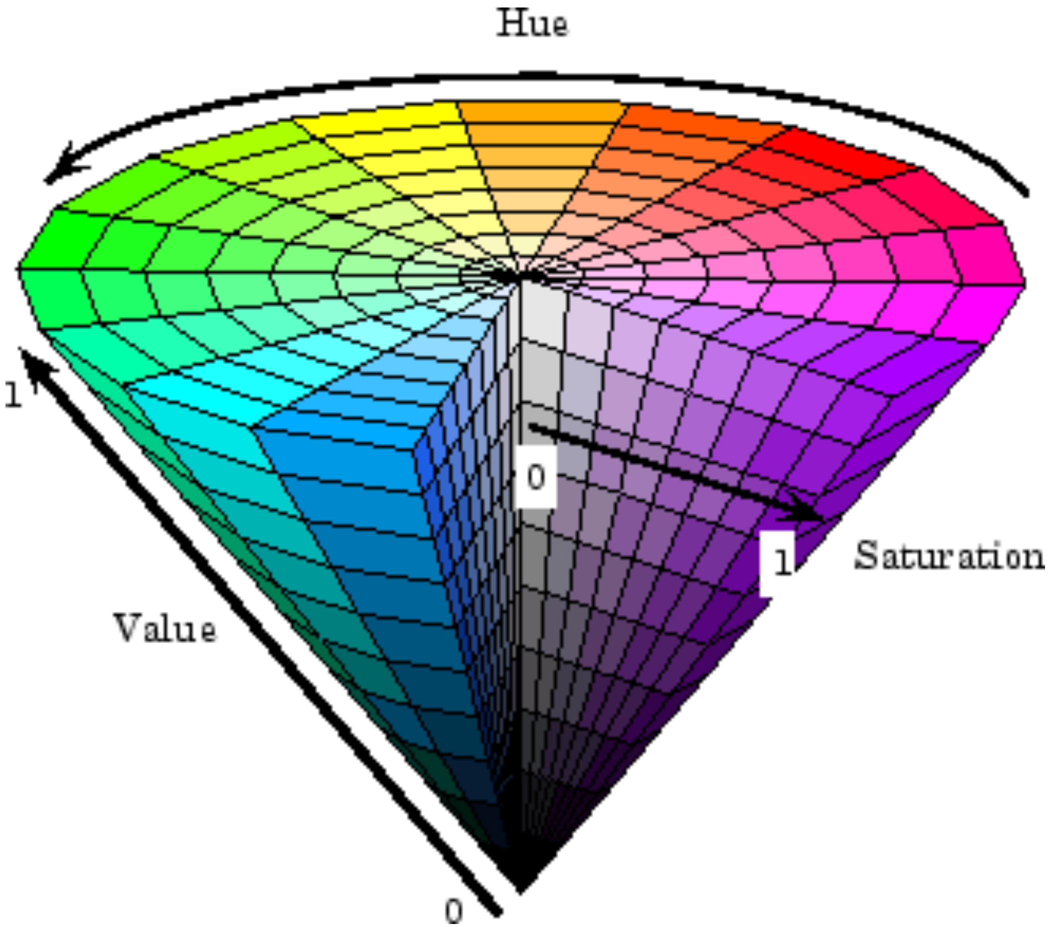


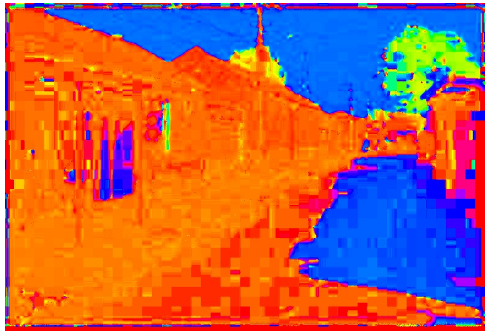
- Perceptual dimensions of color:
- **Hue**: the “kind” of color, regardless of its attributes
- **Saturation**: Purity, “colorfulness”
- **Value** (or lightness): total amount of light
- Use rgb2hsv() and hsv2rgb() in Matlab, in Python w/skimage

Slide from Steve Seitz / Ren Ng

Color spaces: HSV

Intuitive color space





H

(S=1,V=1)

S

(H=1,V=1)

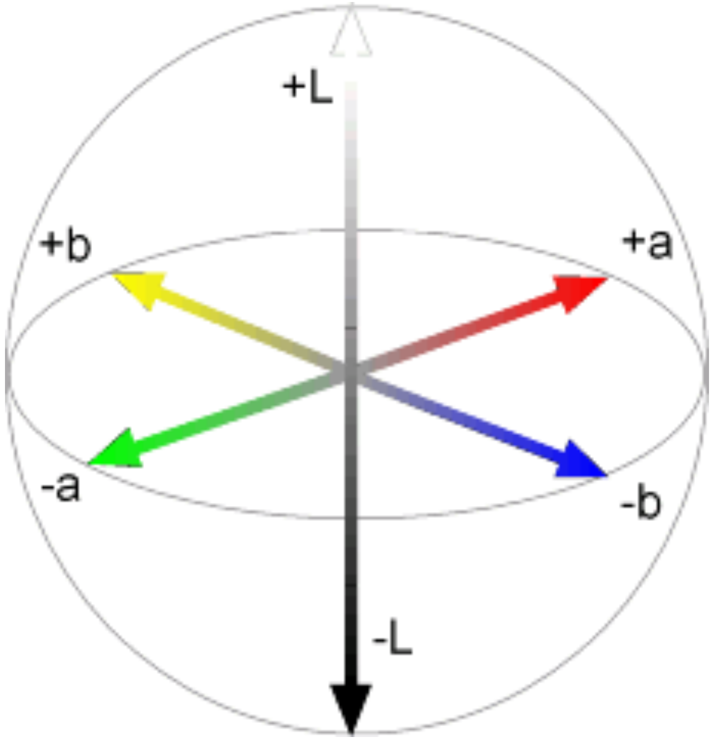
V

(H=1,S=0)

Color spaces: L*a*b*

"Perceptually uniform"* color space

L = Luma (Lightness)
a = Red to Green
b = Blue to yellow



L
(a=0,b=0)

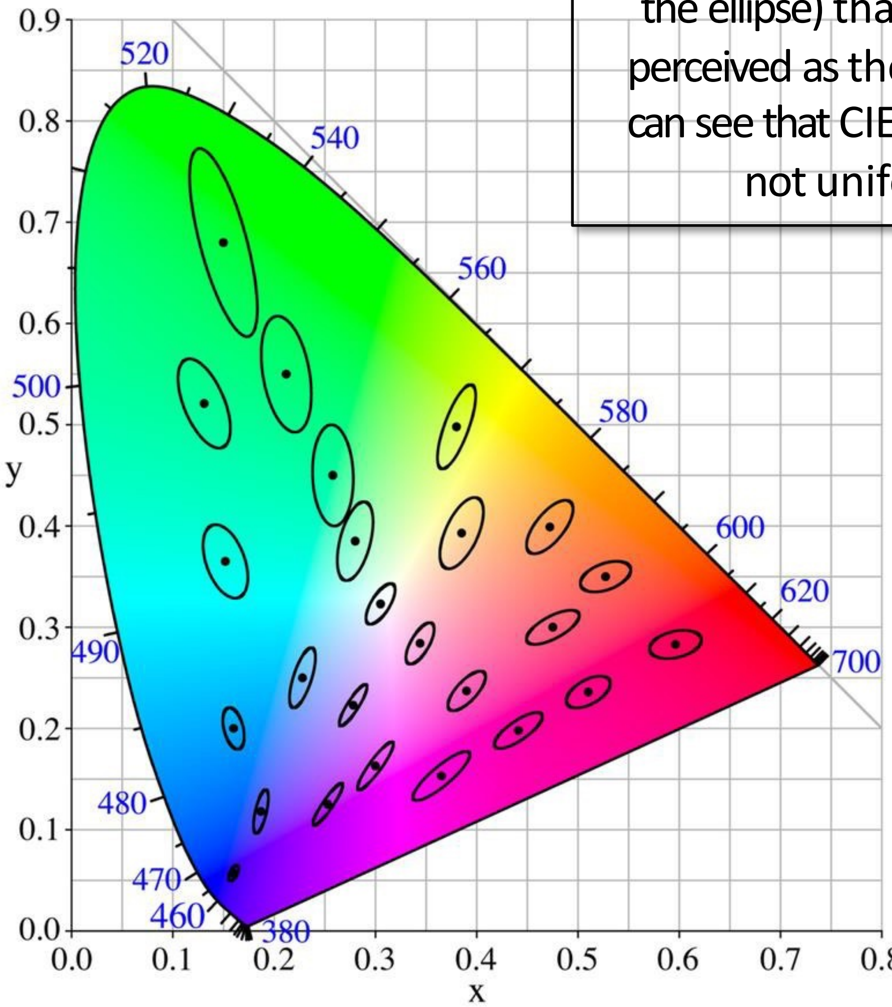
a
(L=65,b=0)

b
(L=65,a=0)

CIE LAB space

- CIE LAB space (also written as CIE $L^*a^*b^*$) was introduced as a perceptually uniform color space
- **Why?**
  - CIE XYZ provides a means to map between a physical SPD (radiometric measurement) to a colorimetric measurement (perceptual)
  - However, a uniform change in CIE XYZ space does result in an uniform change in perceived color difference (see diagram)
- CIE Lab transforms CIE to a new space where color (and brightness) differences are more uniform.

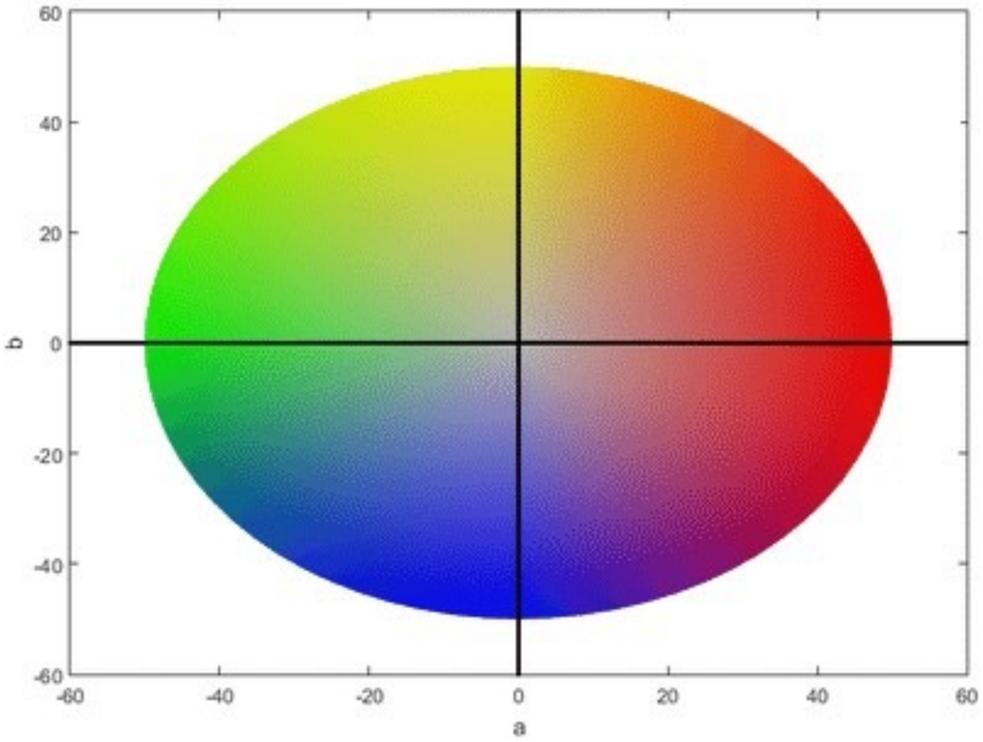
The ellipses shows the range of colors (around the center of the ellipse) that would be perceived as the same. We can see that CIE XYZ this is not uniform.



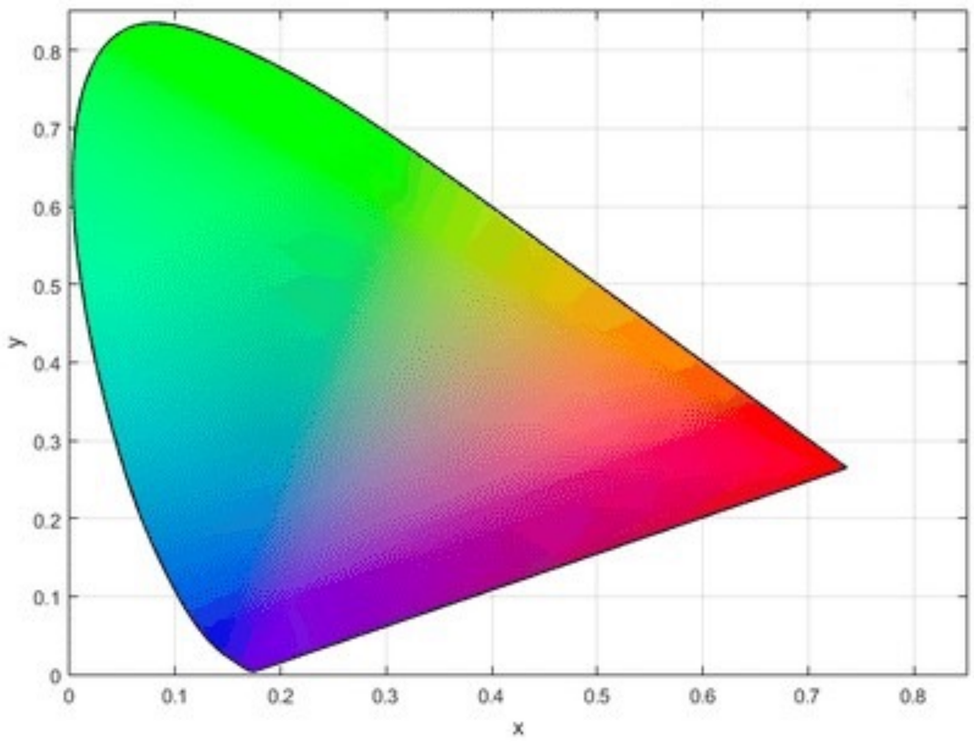
David MacAdam performed experiments into color perception. This plot is known as the MacAdam ellipses.

CIE LAB

CIE-L*ab space



CIE-xyY space



Chromaticity comparison's between CIE LAB and CIE XYX

Image from Bagdasar et al ICSTCC'17

I want to train Deep Learning algorithms, why should I care beyond RGB color spaces?

- If you are training ML systems to do object recognition, detection, etc, you shouldn't care.
- But if you are solving different Image Processing & Computational Photography tasks, you should!
- CIE Lab color space is commonly used for tasks like:
  - Image Colorization
  - Intrinsic Image Decomposition
  - Reflectance Estimation
- Many papers often use other color spaces instead of RGB. It can help in easier learning.

Color error metric – CIE 2000 Delta E (ΔE)

- The CIE defined a color error metric in 2000 based on the CIE LAB space. This returns a color error between 0-100.
- You will see this referred to as CIEDE2000, CIEDE, ΔE, Delta E, DE, ..
- Delta E 2000 interpretation:

Delta E	Perception
<= 1.0	Not perceptible by human eyes.
1 - 2	Perceptible through close observation.
2 - 10	Perceptible at a glance.
11 - 49	Colors are more similar than opposite
100	Colors are exact opposite

In general, DE of 2 or less is considered to be very good. It means a standard observer could not tell that two colors are different unless they observed them very closely.

Table from
https://zschuessler.github.io/DeltaE/learn/

Color error metric – CIE 2000 Delta E (ΔE)

- How do you use this in practice?
  - As a metric or loss function to measure color/chromaticity of the reconstructed image w.r.t. GT image.

"Measure Albedo in the Wild: Filling the Gap in Albedo Evaluation", ongoing work in my group which uses this metric to evaluate a Deep Learning algorithm's ability to estimate 'true' color of an object.

Today’s class

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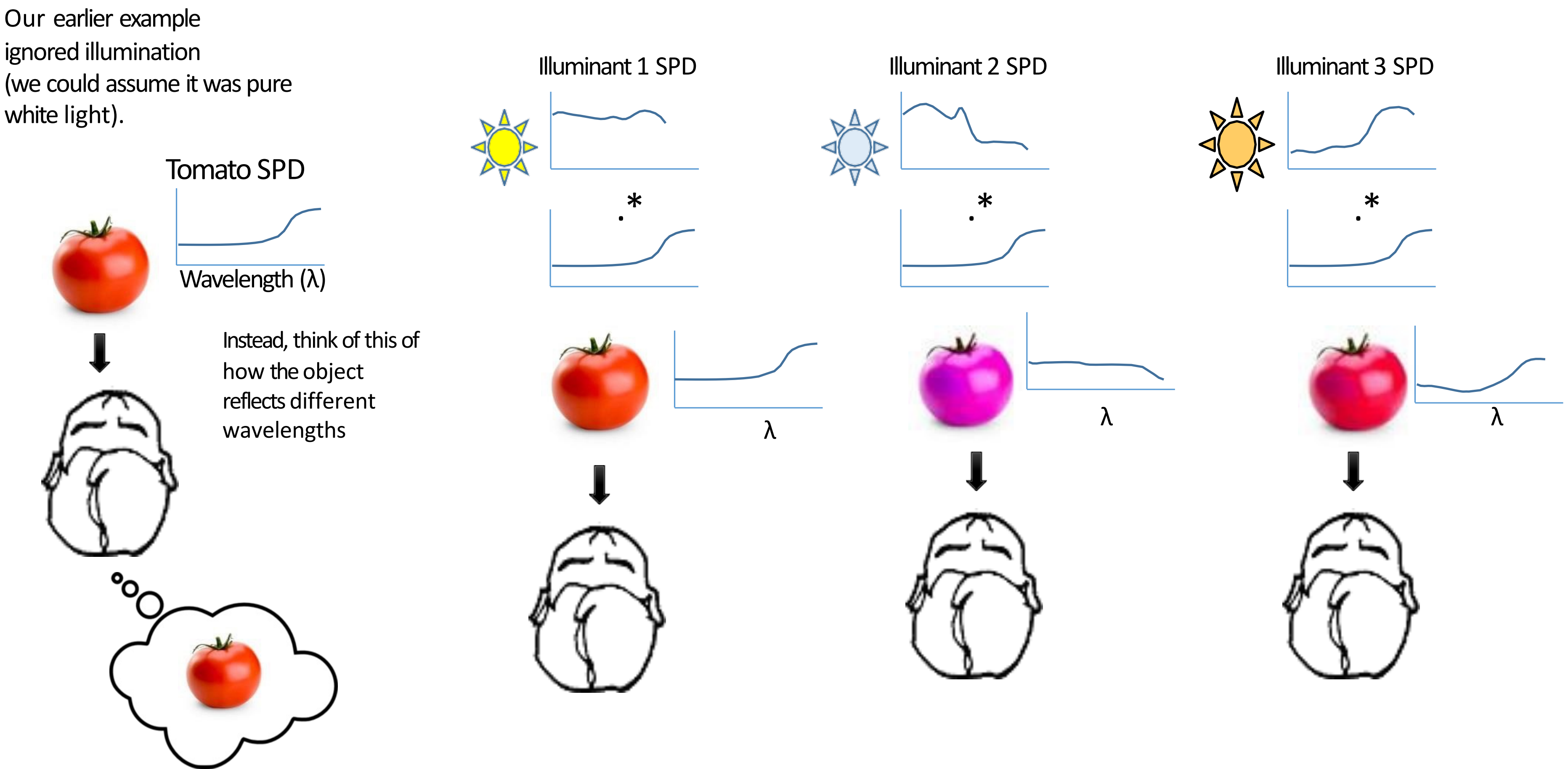
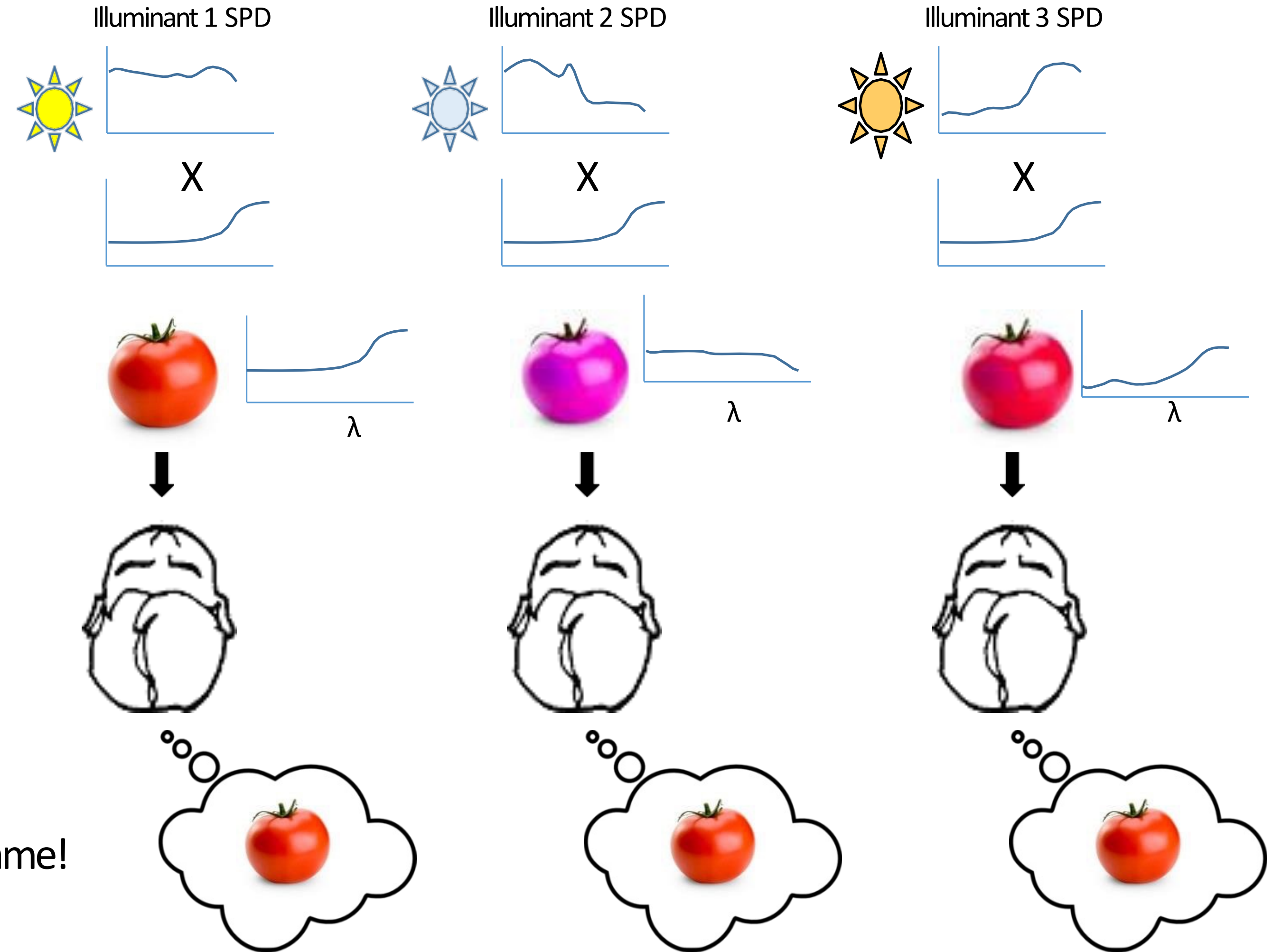
An object's SPD

- In a real scene, an object's SPD is a combination of the its reflectance properties **and** scene illumination



Color constancy

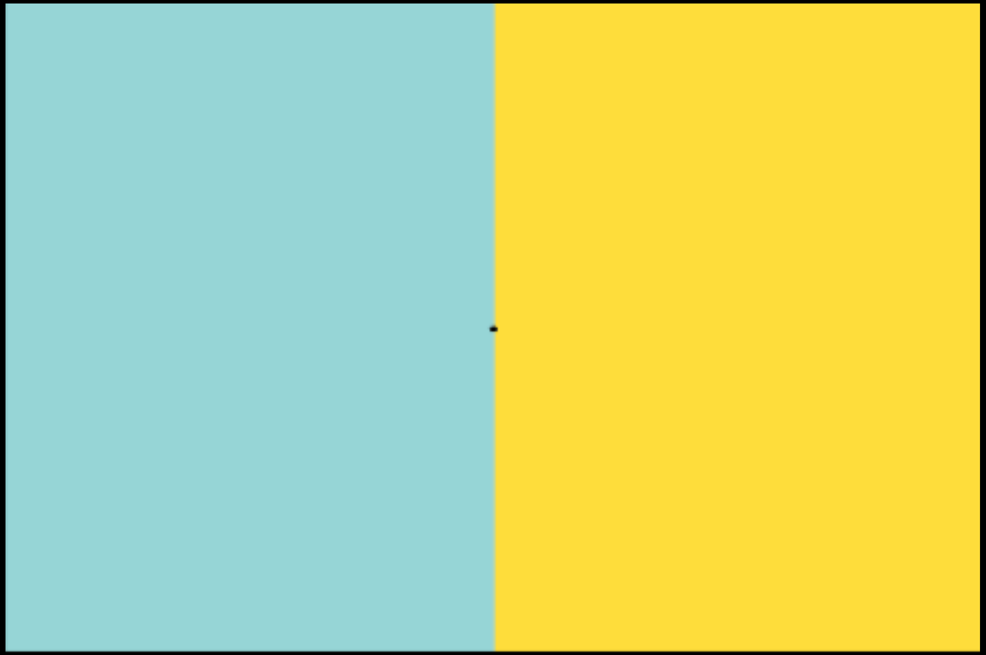
- Our visual system is able to compensate for the illumination



Looks the same!

Chromatic adaptation example

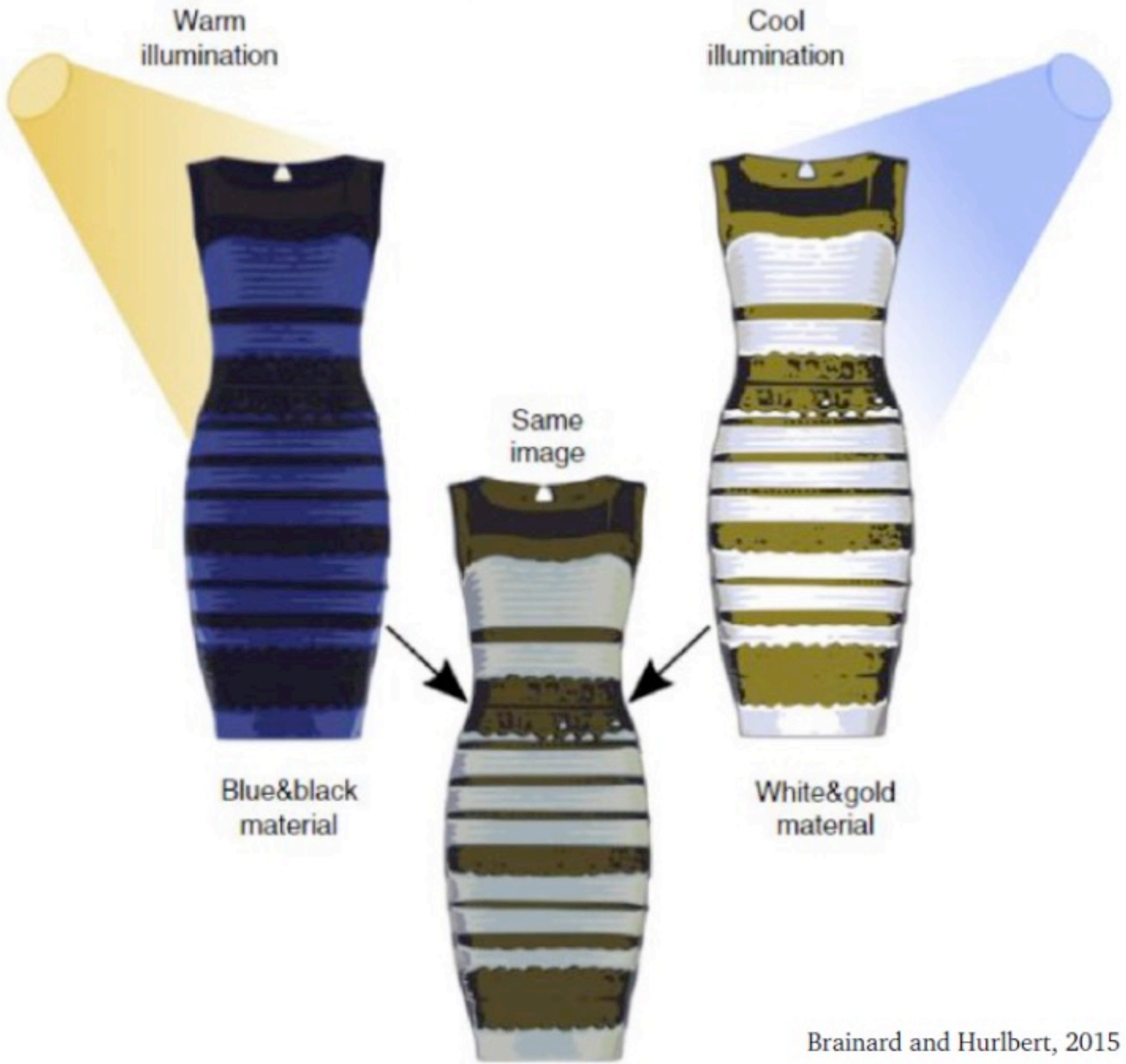
Chromatic adaptation example



What color is the "The Dress"?

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

Two Scene Interpretations of #thedress



Brainard and Hurlbert, 2015

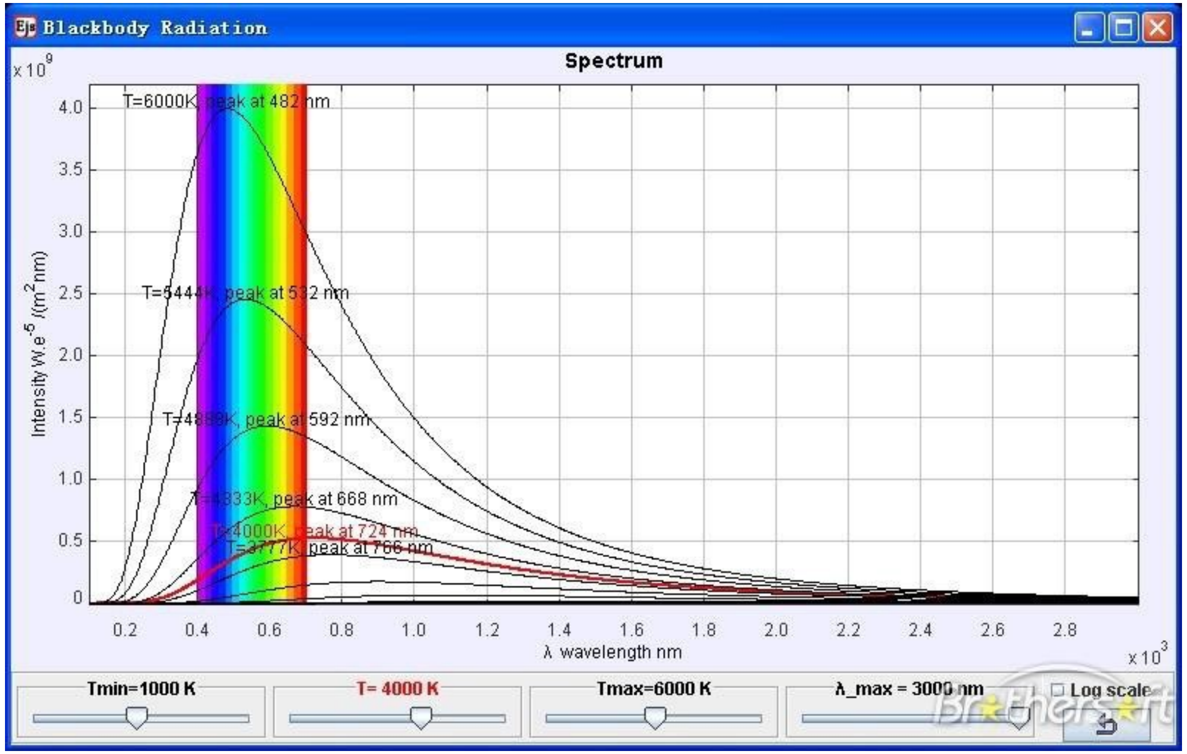
Color constancy/chromatic adaptation

- Color constancy (also called *chromatic adaptation*) is the ability of the human visual system to adapt to scene illumination
- This ability is not perfect, but it works fairly well
- Image sensors do not have this ability (it must be performed as a processing step, i.e. "white balance")

Note: Our eyes do not adjust to the illumination in the photograph -- we adjust to the viewing conditions of the scene we are viewing the photograph!

Color temperature

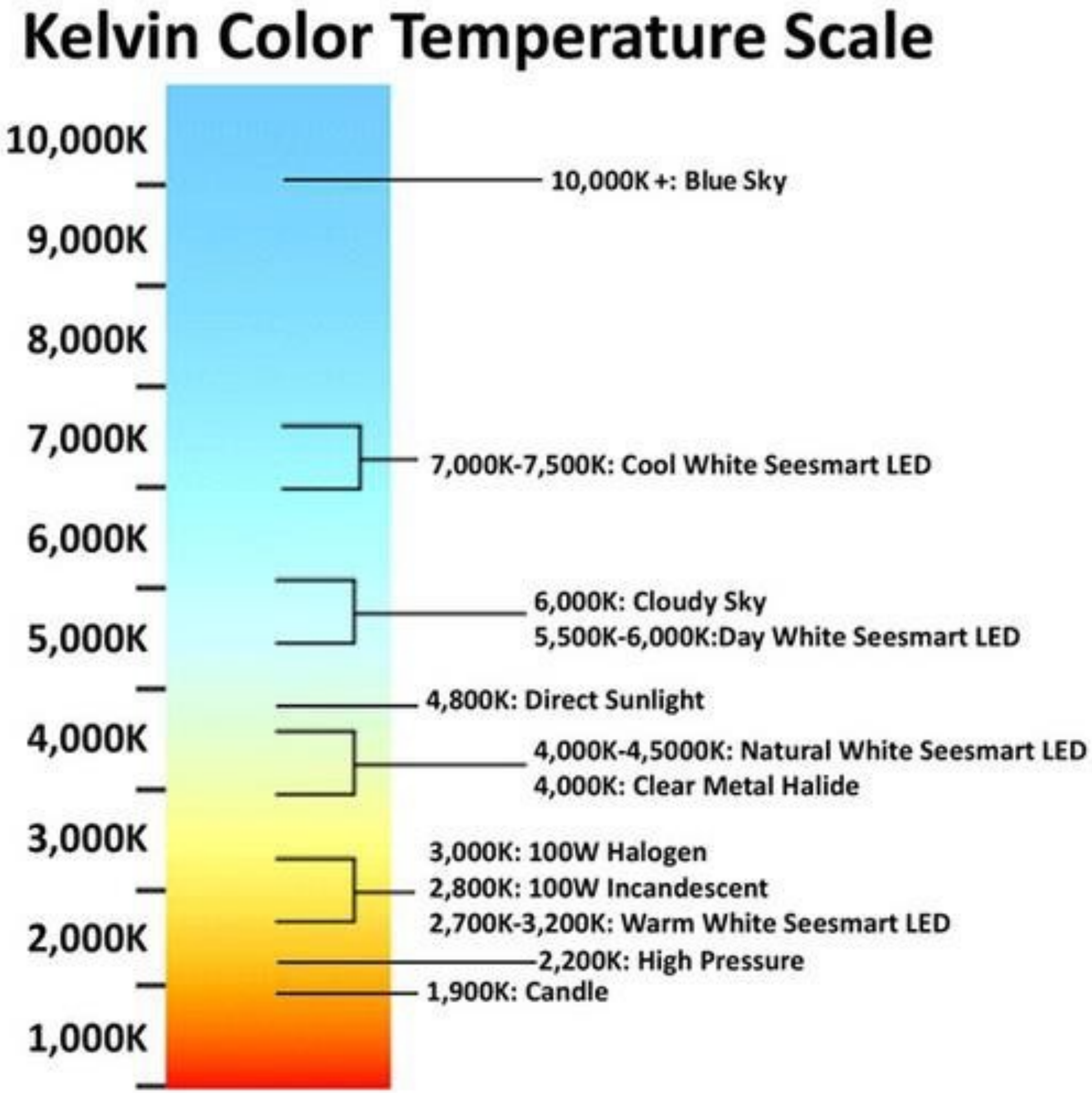
- Illuminants are often described by their "color temperature"
- This mapping is based on theoretical "blackbody radiators" that produce SPDs for a given temperature -- expressed in Kelvin (K)
- We map light sources (both real and synthetic) to their closest color temperature (esp in Photography/Video production)



$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

Plank's law
Spectral density of electromagnetic radiation emitted by a blackbody radiator at a given temperature T.

Color temperature



Typical description of color temperature used in photography & lighting sources.

From B&H Photo

Lighting industry uses color temperature

Usage of color temperature in these ads relate to the perceived color of the bulb's light.The heat output of a typical LED bulb is between 60C-100C (~333-373K).

White point

- A white point is a CIE XYZ or CIE xyY value of an ideal "white target" or "white reference"
- The idea of chromatic adaptation is to make white points the same between scenes.

Color constancy (at its simplest)

Johannes von Kries

- (Johannes) *Von Kries* transform
- Compensate for each channel corresponding to the L, M, S cone response

$$\begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} = \begin{bmatrix} 1/L_{1w} & 0 & 0 \\ 0 & 1/M_{1w} & 0 \\ 0 & 0 & 1/S_{1w} \end{bmatrix} \begin{bmatrix} L_1 \\ M_1 \\ S_1 \end{bmatrix}$$

L_2, M_2, S_2 is the new LMS response with the illuminant divided "out". In this case white is equal to [1,1,1]

L_{1w}, M_{1w}, S_{1w} is the LMS response to "white" under this illuminant

L_1, M_1, S_1 are the input LMS space under an illuminant.

Illuminant to illuminant mapping

- More appropriate would be to map to another illuminant's LMS response (e.g. in the desired viewing condition)
- $(LMS)_1$ under an illuminant with white-response (L_{1w}, M_{1w}, S_{1w})
- $(LMS)_2$ under an illuminant with white-response (L_{2w}, M_{2w}, S_{2w})

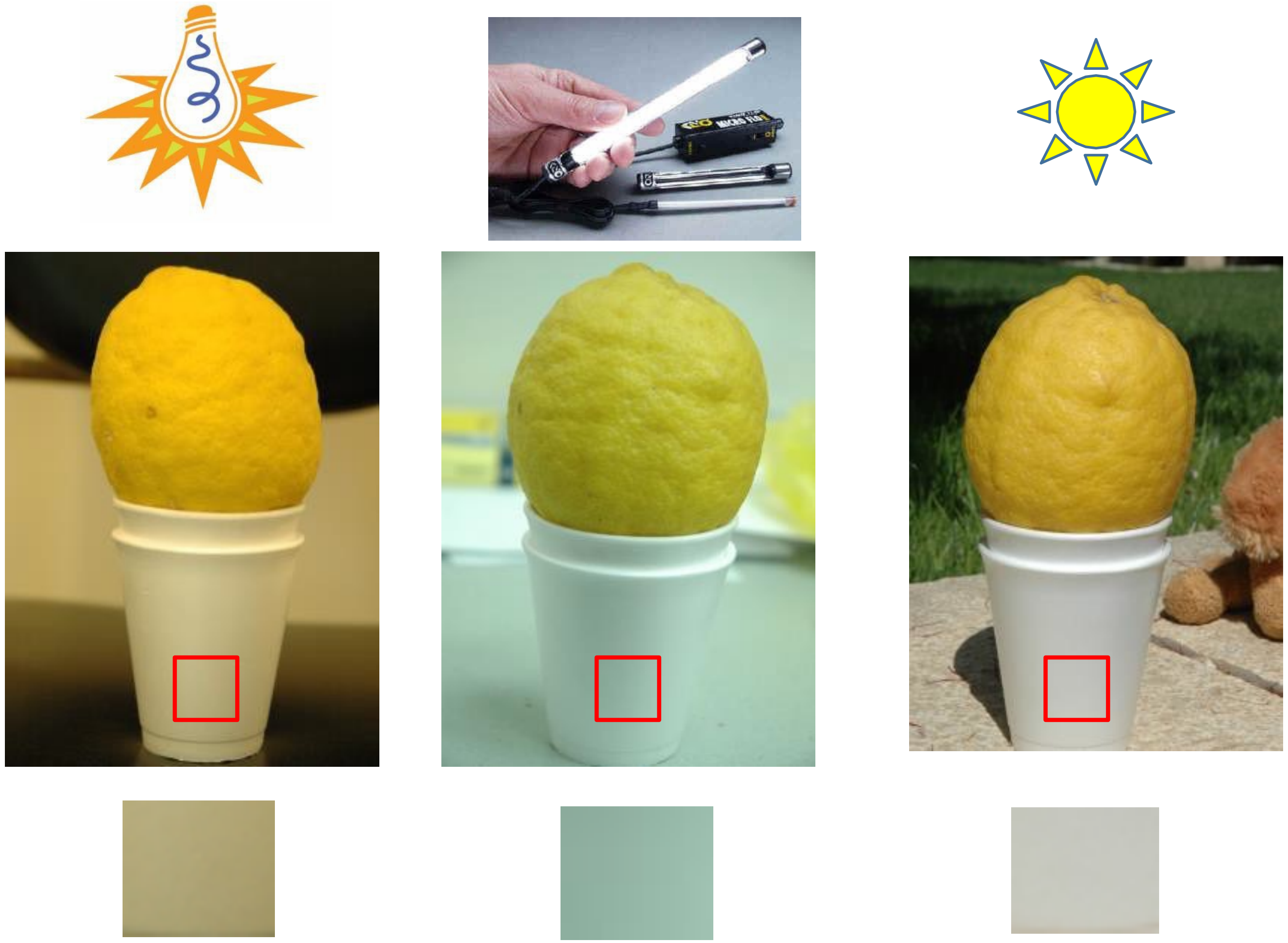
$$\begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} = \begin{bmatrix} L_{2w}/L_{1w} & 0 & 0 \\ 0 & M_{2w}/M_{1w} & 0 \\ 0 & 0 & S_{2w}/S_{1w} \end{bmatrix} \begin{bmatrix} L_1 \\ M_1 \\ S_1 \end{bmatrix}$$

L_2, M_2, S_2 is the new LMS response with the illuminant divided "out" and scaled to LMS_2 illuminant

L_{1w}, M_{1w}, S_{1w} is the LMS response to "white" the input illuminant, L_{2w}, M_{2w}, S_{2w} response to "white" of output illuminant

L_1, M_1, S_1 are the input LMS space under an illuminant.

Example

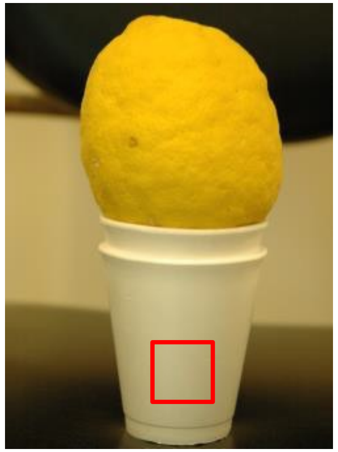


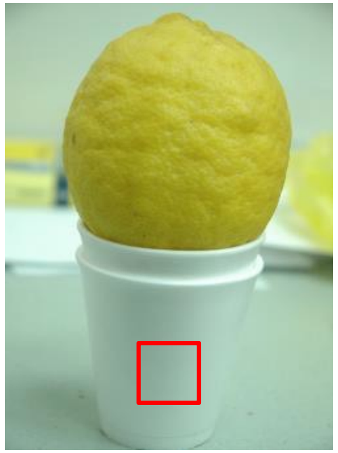
Simulation of different "white points" by photographing a "white" object under different illumination.

Images courtesy of Sharon Albert (Weizmann Institute)

Example

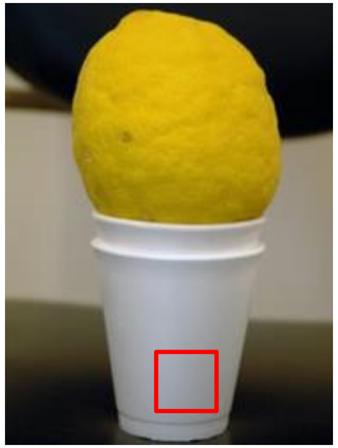
Input

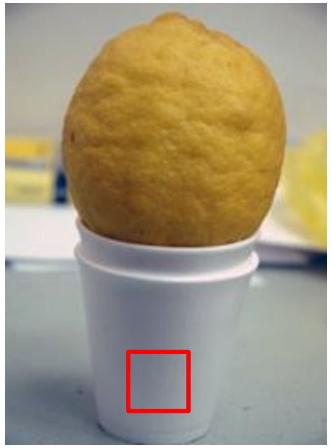


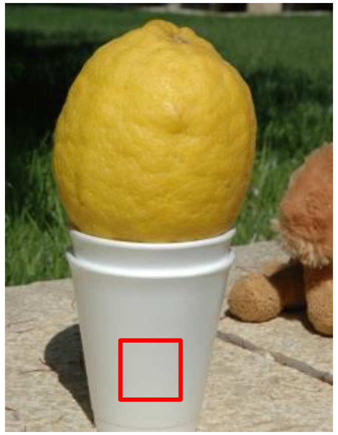


Here, we have mapped the two input images to one below to mimic chromatic adaptation. The "white" part of the cup is shown before and after to help show that the illumination falling on white appears similar after the "chromatic adaptation".

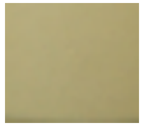
Adapted to "target" illuminant







Before



After

Before

After

Target Illumination

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- Eye & Human Vision
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- Perception of Color
- Quantifying Color
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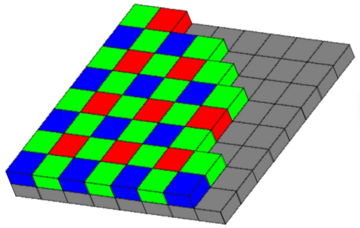
- Color Constancy

Next Class: A typical color imaging pipeline



Sensor with color filter array (CFA)
(CCD/CMOS)

ISO gain and raw-image processing

RGB Demoasicing

Noise Reduction

White-Balance & Color Space Transform (CIE XYZ)

Color Manipulation (Photo-finishing)

Mapping to sRGB output

JPEG Compression

Save to file

NOTE:This diagram represents the steps applied on a typical consumer camera pipeline. ISPs may apply these steps in a different order or combine them in various ways. A modern camera ISP will undoubtedly be more complex, but will almost certainly implement these steps in some manner.

Watch these 5 min videos!

- Color in 5 min: https://youtu.be/6tTNgvAl1y4
- Displays in 5 min: https://youtu.be/1albYPL9Cfg
- Pinhole Camera in 5 min: https://youtu.be/F5WA26W4JaM

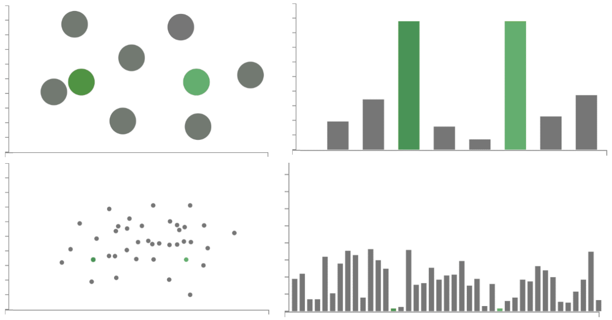
Additional Reading

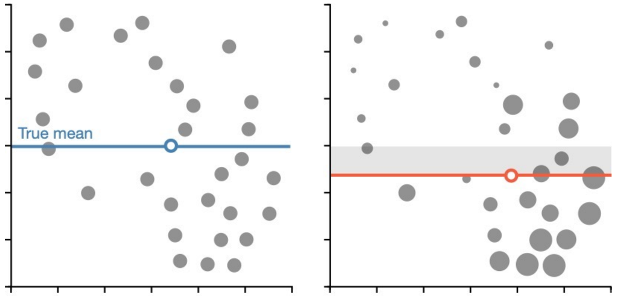
Sec 3.1, 3.2, 3.3 from Forsyth & Ponce

Interested in Color & Perception of Color in Data Visualization?

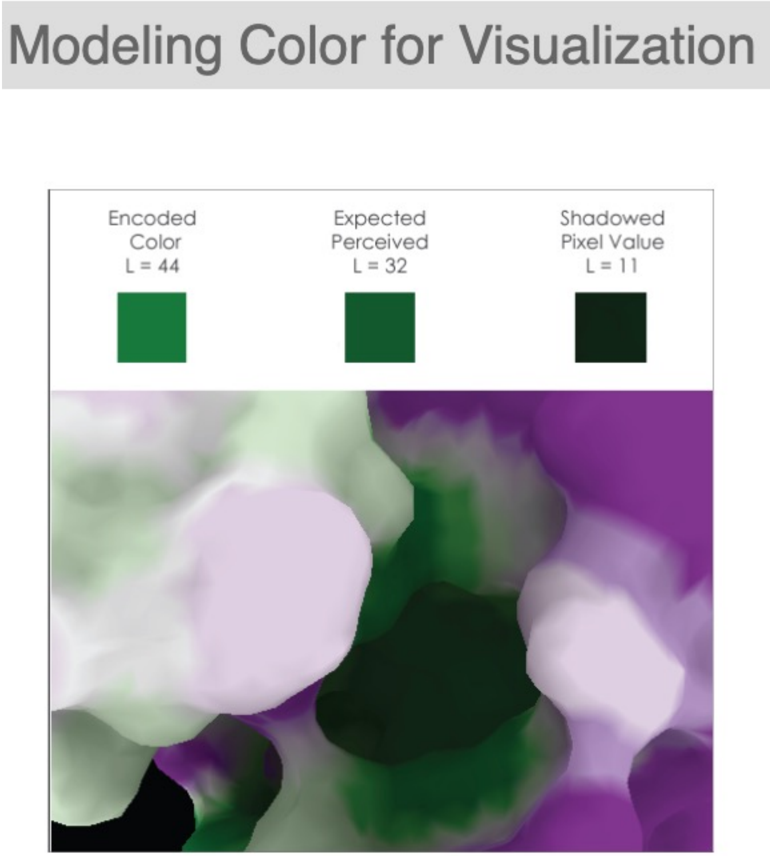
UNC VisuaLab

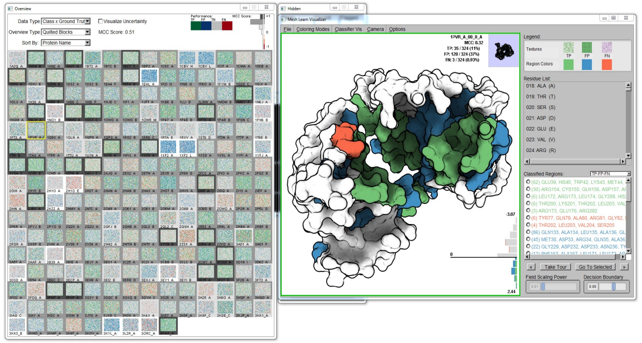
danielle.szafir@cs.unc.edu | https://cu-visualab.org/

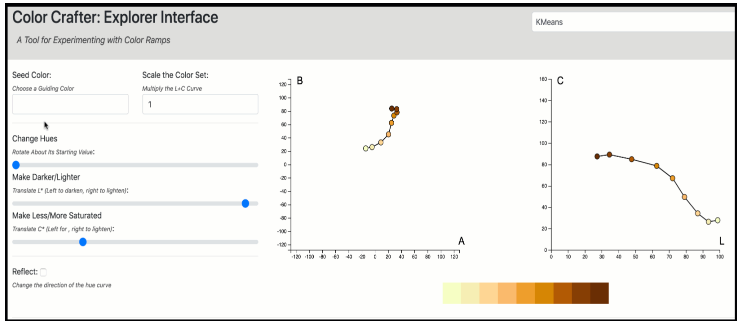




Measure color & other aspects of perception in data visualization







Use models of perception to create tools for data science

Slide Credits

- **“Understanding Color and the In-Camera Image Processing Pipeline for Computer Vision”, by Michael S. Brown, ICCV 2019 tutorial.**
- CS 194-26/294-26: Intro to Computer Vision and Computational Photography, **UC Berkeley, by Alyosha Efros.**
- **CS 15-463, 663, 862, CMU, by Computational Photography, Ioannis Gkioulekas.**