CMPE 362
Digital Image Processing

Color Perception and Color Spaces

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Why does a visual system need color? (an incomplete list…)

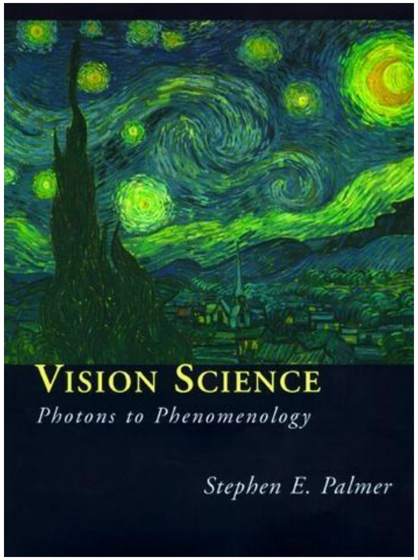
- To tell what food is edible
- To distinguish material changes from shading changes
- To group parts of one object together in a scene
- To find people's skin
- Check whether a person's appearance looks normal/healthy

Slide credit: W. Freeman

What is color?

- Color is the result of interaction between physical light in the environment and our visual system.

- Color is a psychological property of our visual experiences when we look at objects and lights, not a physical property of those objects or lights.



Slide credit: A. Efros

What color is the dress?

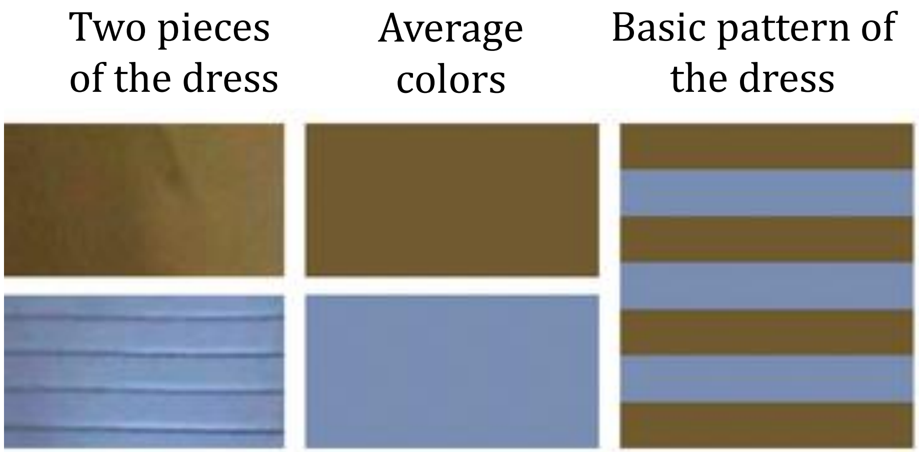
Poll 6

- white and gold ?
- blue and black ?

https://www.nytimes.com/interactive/2015/02/28/science/white-or-blue-dress.html?smid=pl-share

What color is the dress?

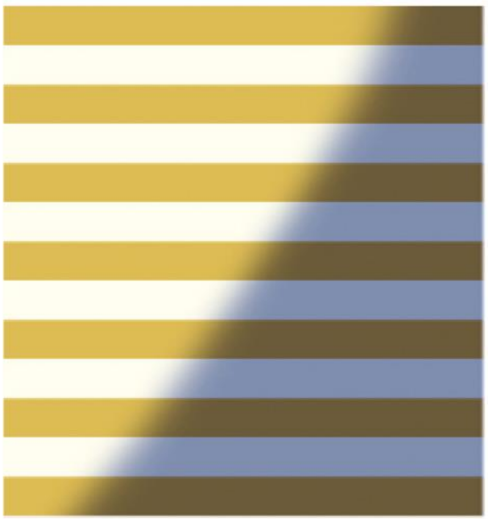
- Let us take some averages:



https://www.nytimes.com/interactive/2015/02/28/science/white-or-blue-dress.html?smid=pl-share

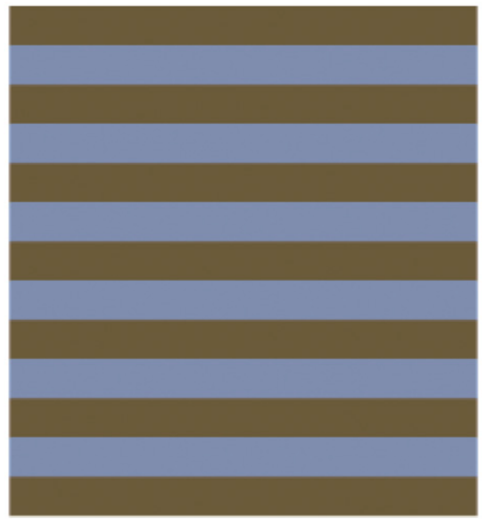
What color is the dress?

Is the dress in shadow?



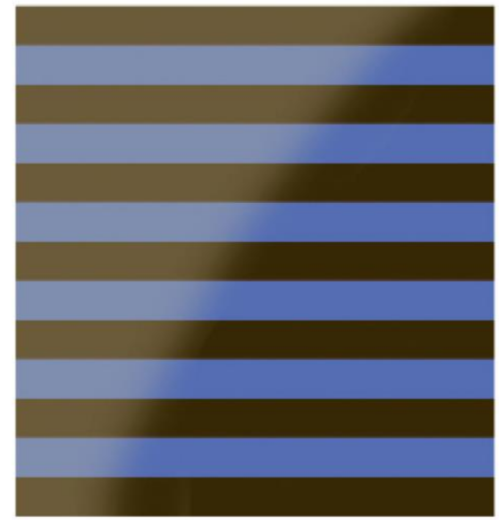
If you think the dress is in shadow, your brain may remove the blue cast and perceive the dress as being white and gold.

The dress in the photo



If the photograph showed more of the room, or if skin tones were visible, there might have been more clues about the ambient light.

Is the dress in bright light?



If you think the dress is being washed out by bright light, your brain may perceive the dress as a darker blue and black.

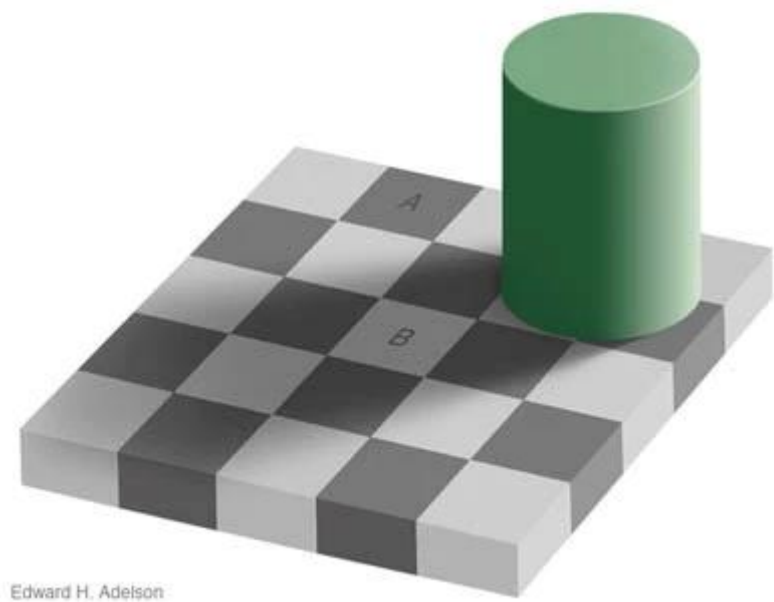
https://www.nytimes.com/interactive/2015/02/28/science/white-or-blue-dress.html?smid=pl-share

What color is the dress?

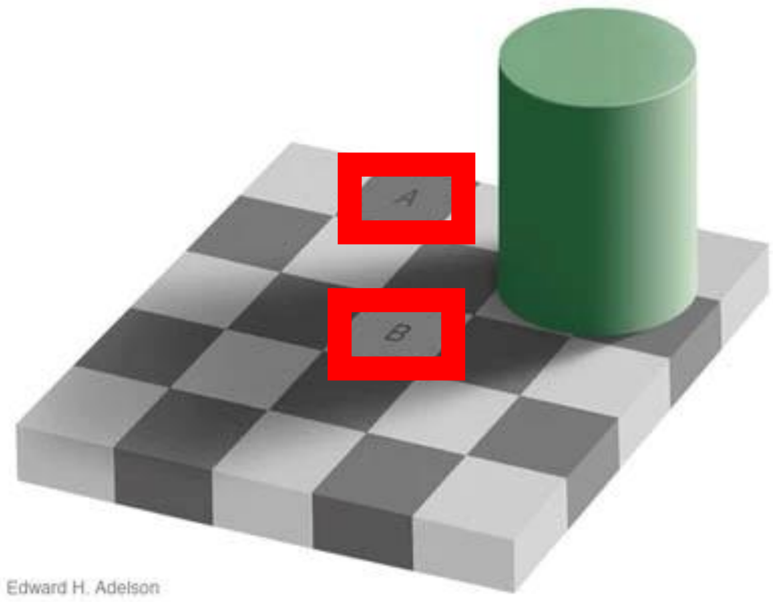
- Other photographs show that the dress is actually blue and black.

https://www.nytimes.com/interactive/2015/02/28/science/white-or-blue-dress.html?smid=pl-share

Brightness perception



Brightness perception



Color perception

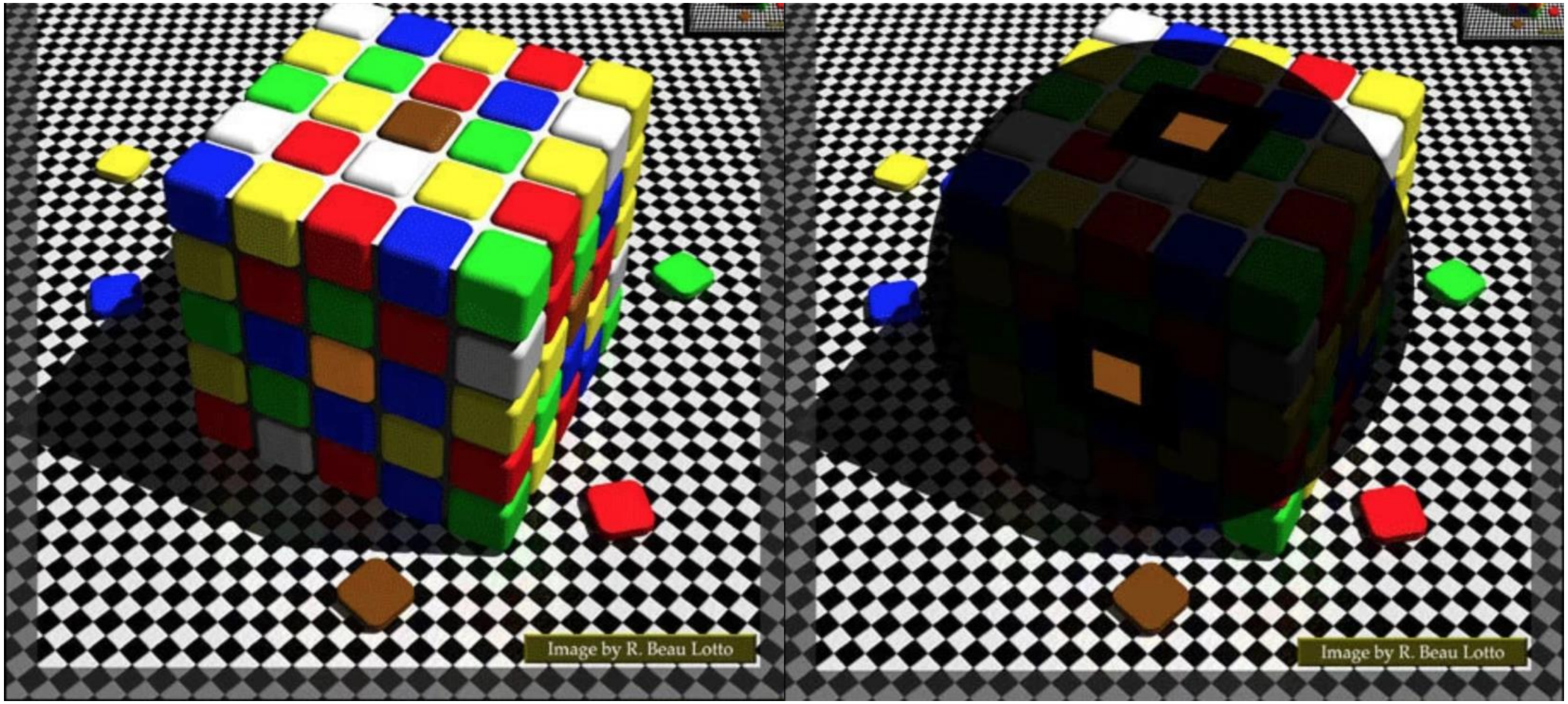


Image credit: Beau Lotto

Color perception

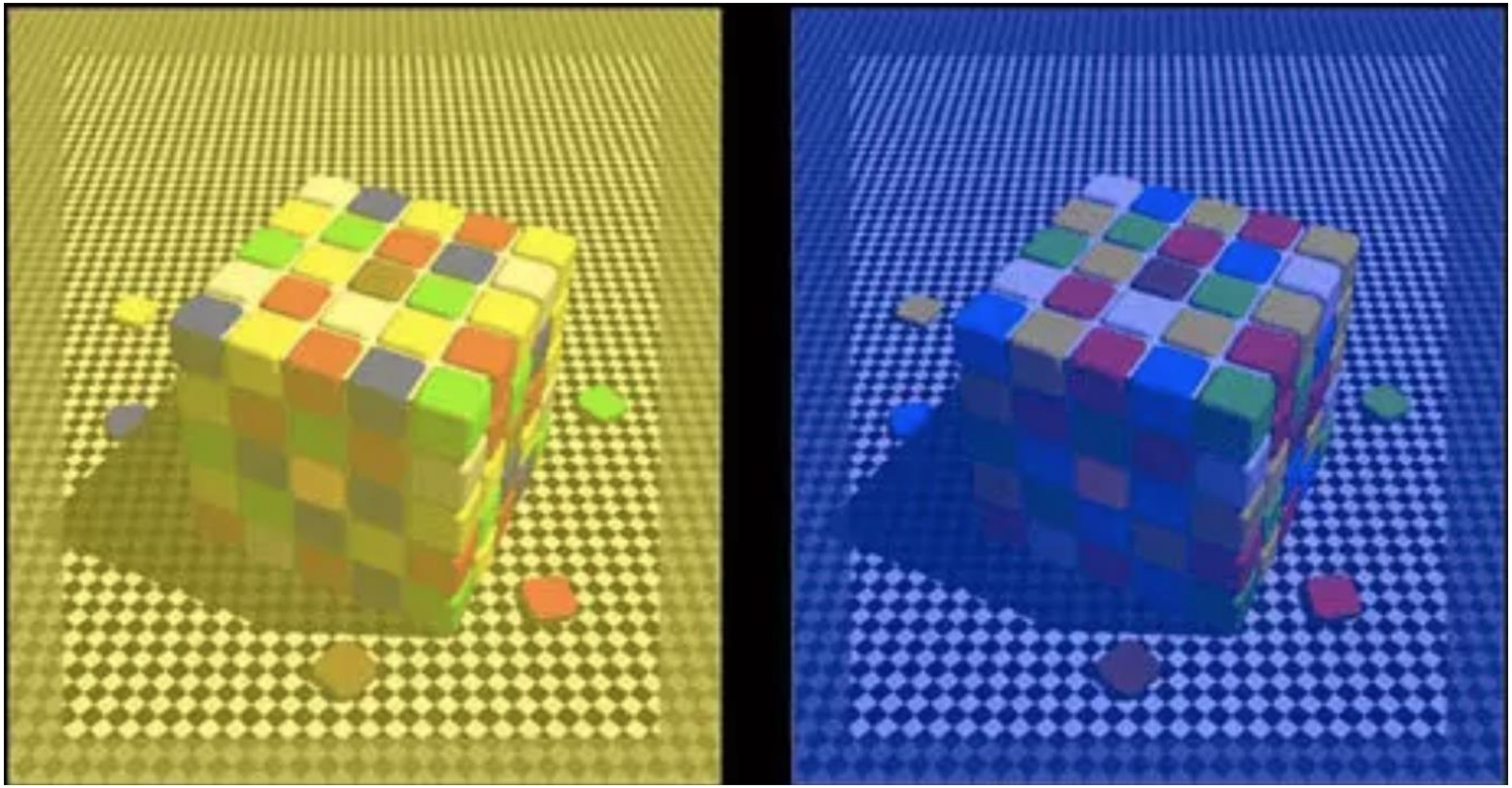


Image credit: Beau Lotto

Color perception

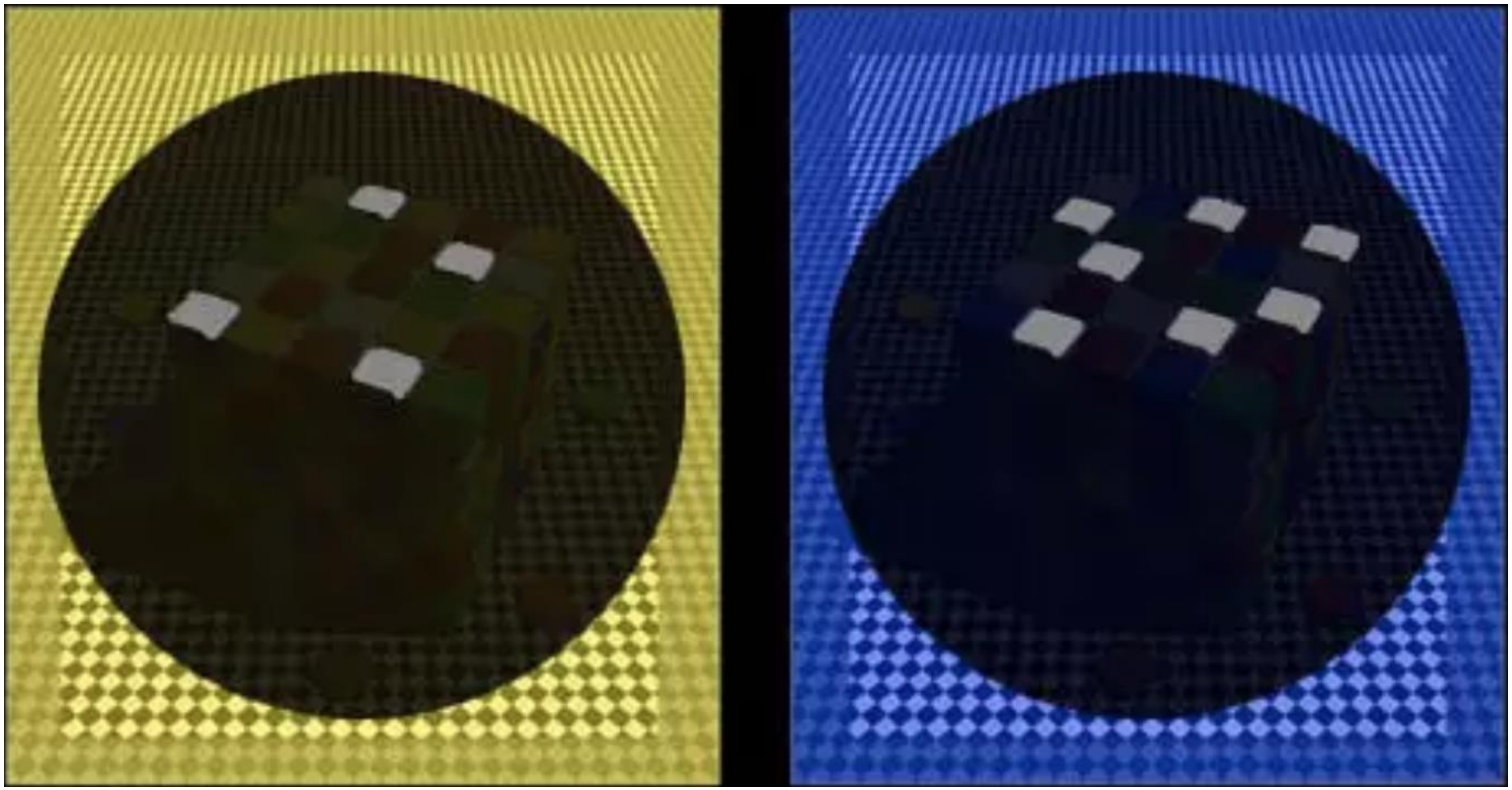


Image credit: Beau Lotto

Color perception

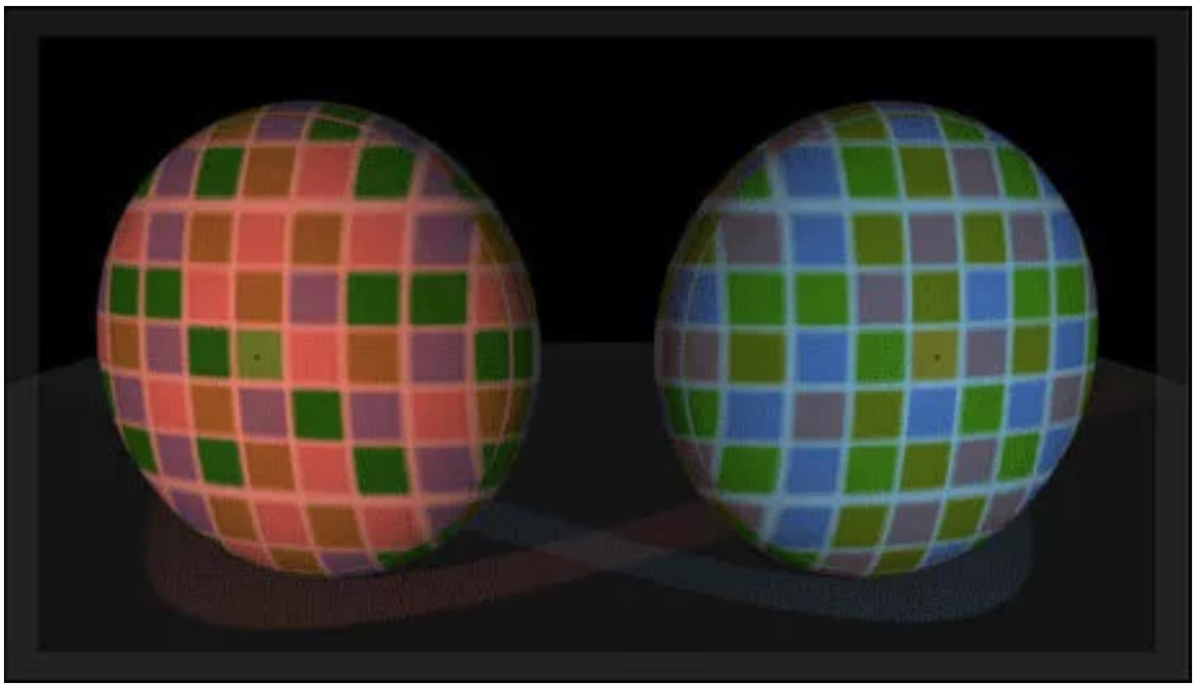


Image credit: Beau Lotto

Color perception

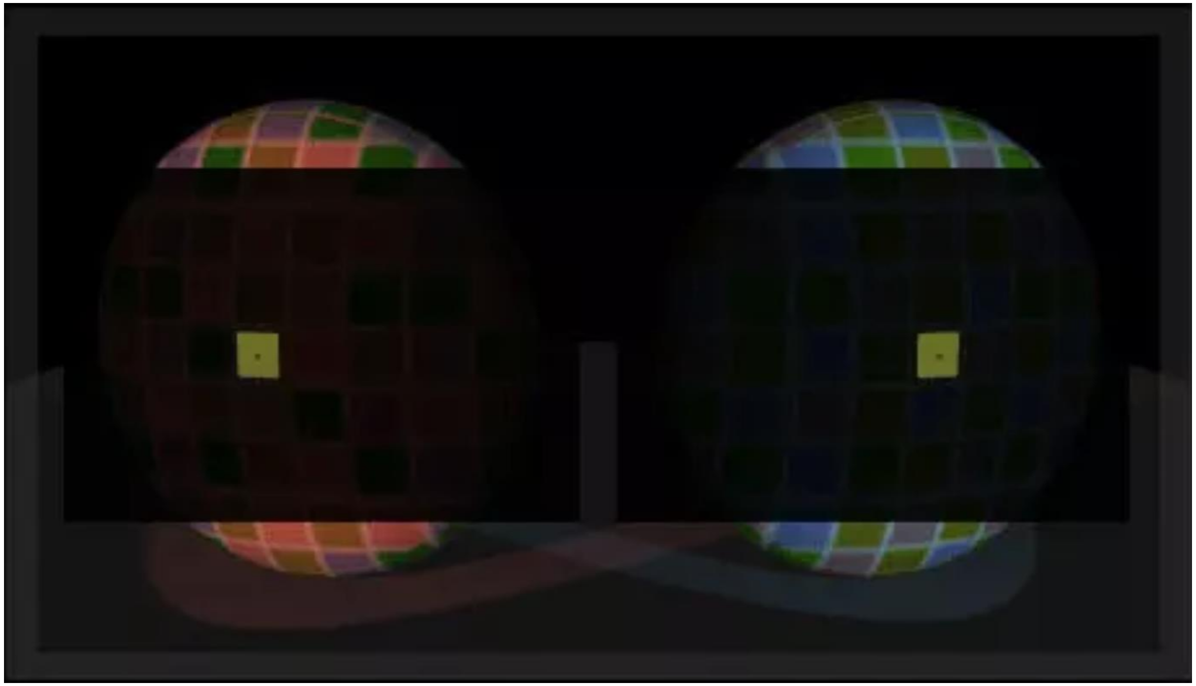


Image credit: Beau Lotto

Color constancy

- We filter out illumination variations.
  - The perceived color of objects remains relatively constant under varying illumination conditions.

Color and light

- Color of light arriving at camera depends on
  - Spectral radiance of light falling on that patch
  - Spectral reflectance of the surface that light is leaving

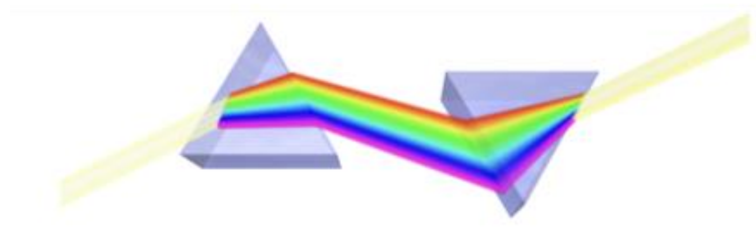
- Color perceived depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

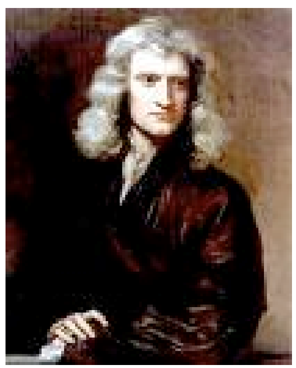
- Color is a phenomenon of human perception; it is not a universal property of light.

Slide credit: K. Grauman, S. Marschner

Color

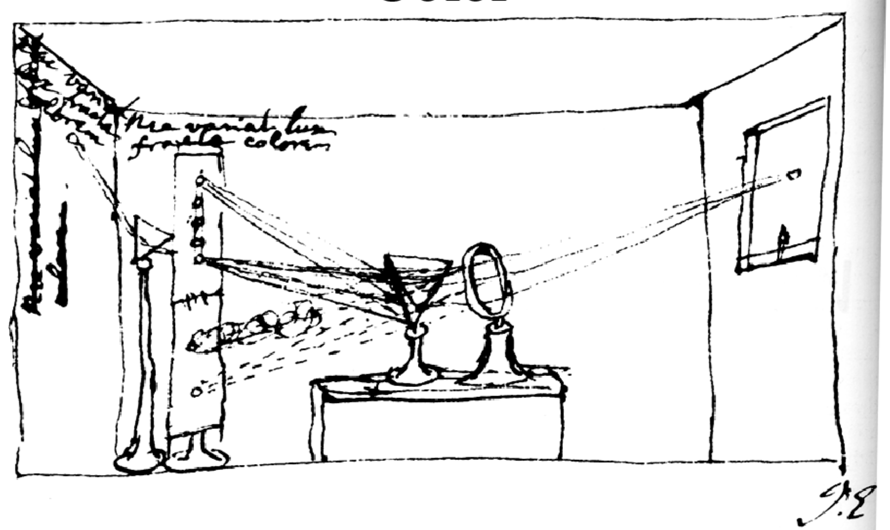
White light: composed of about equal energy in all wavelengths of the visible spectrum





Newton

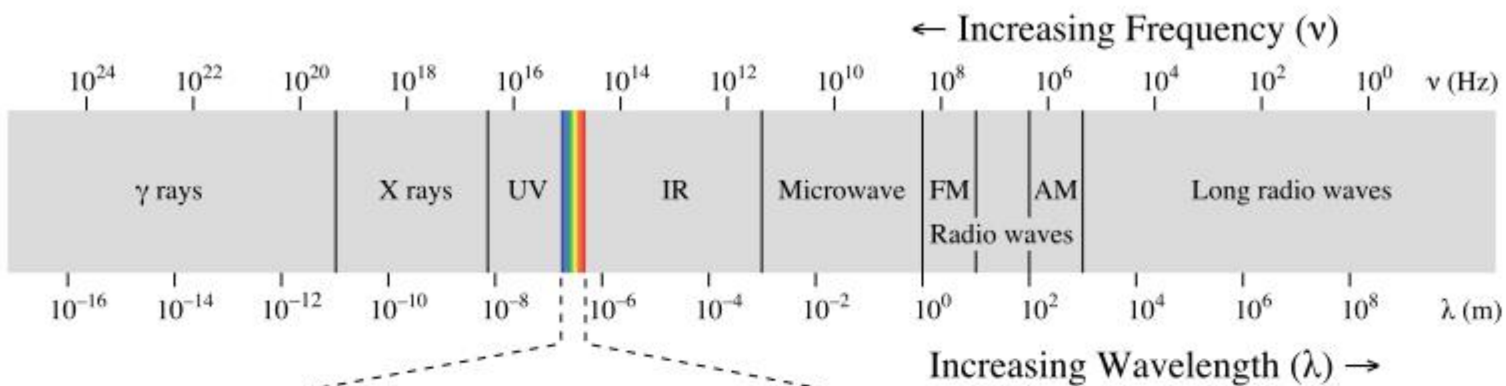
Color

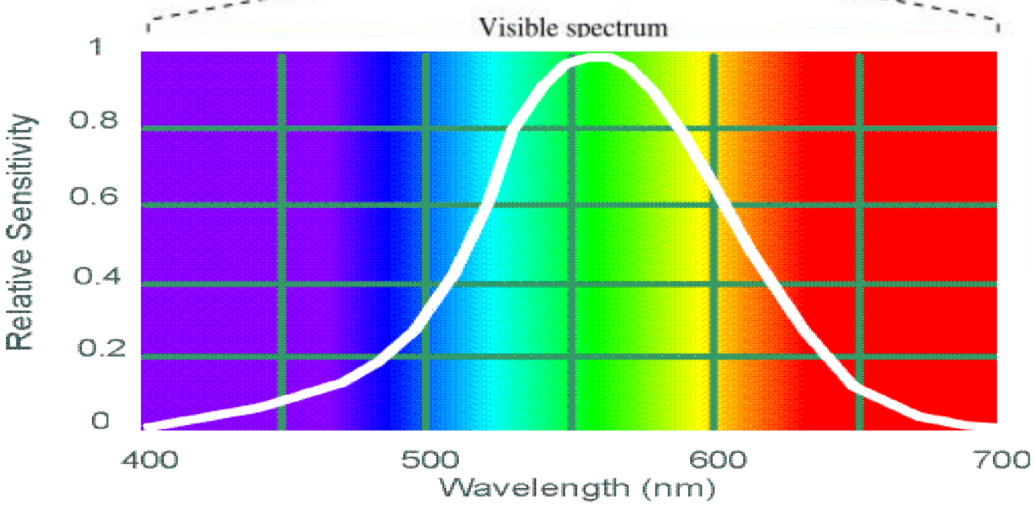


4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

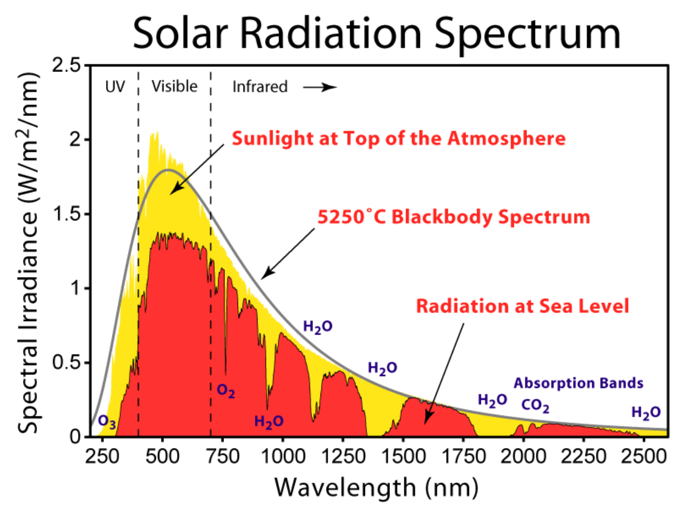
From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Electromagnetic spectrum





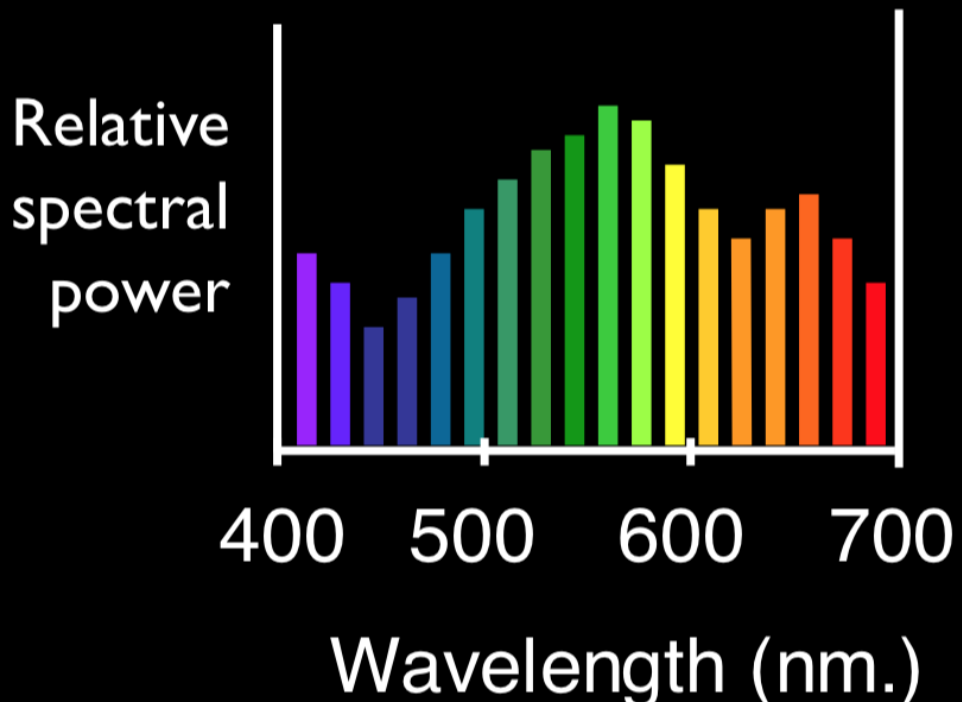
Human Luminance Sensitivity Function



Slide by Svetlana Lazebnik

The Physics of light

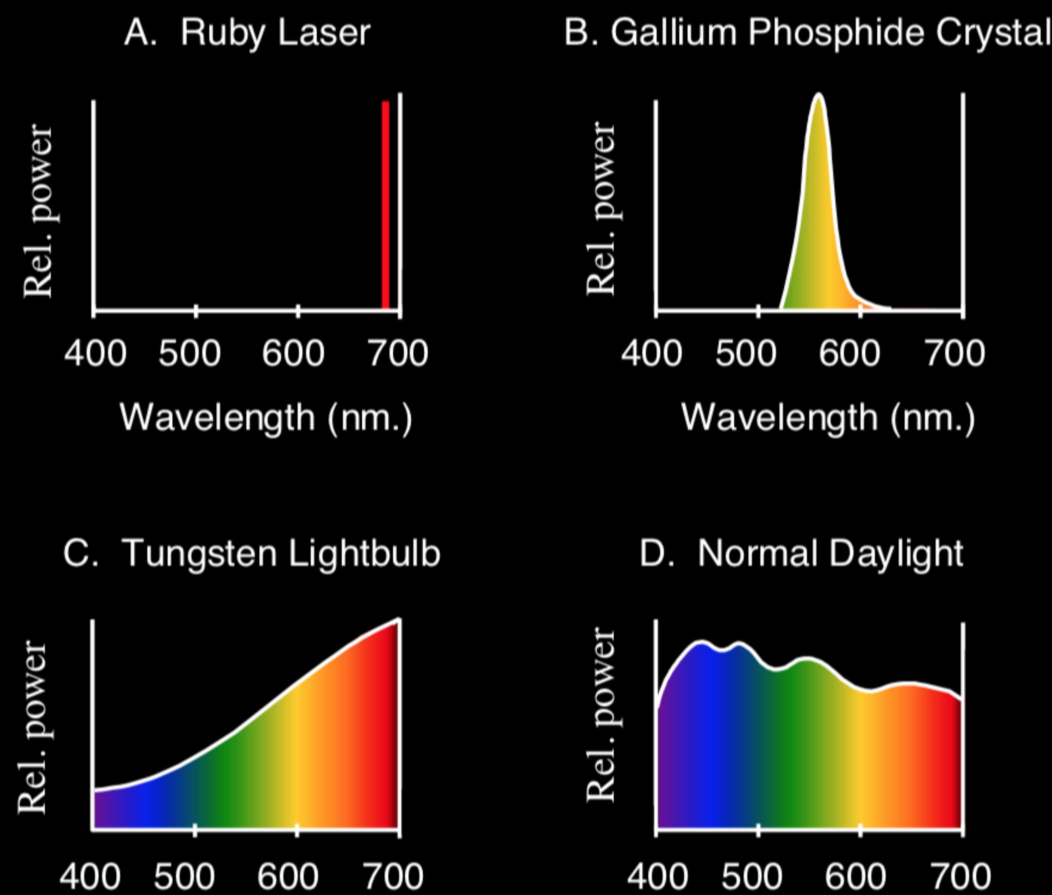
Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.



Slide credit: A. Efros

The Physics of light

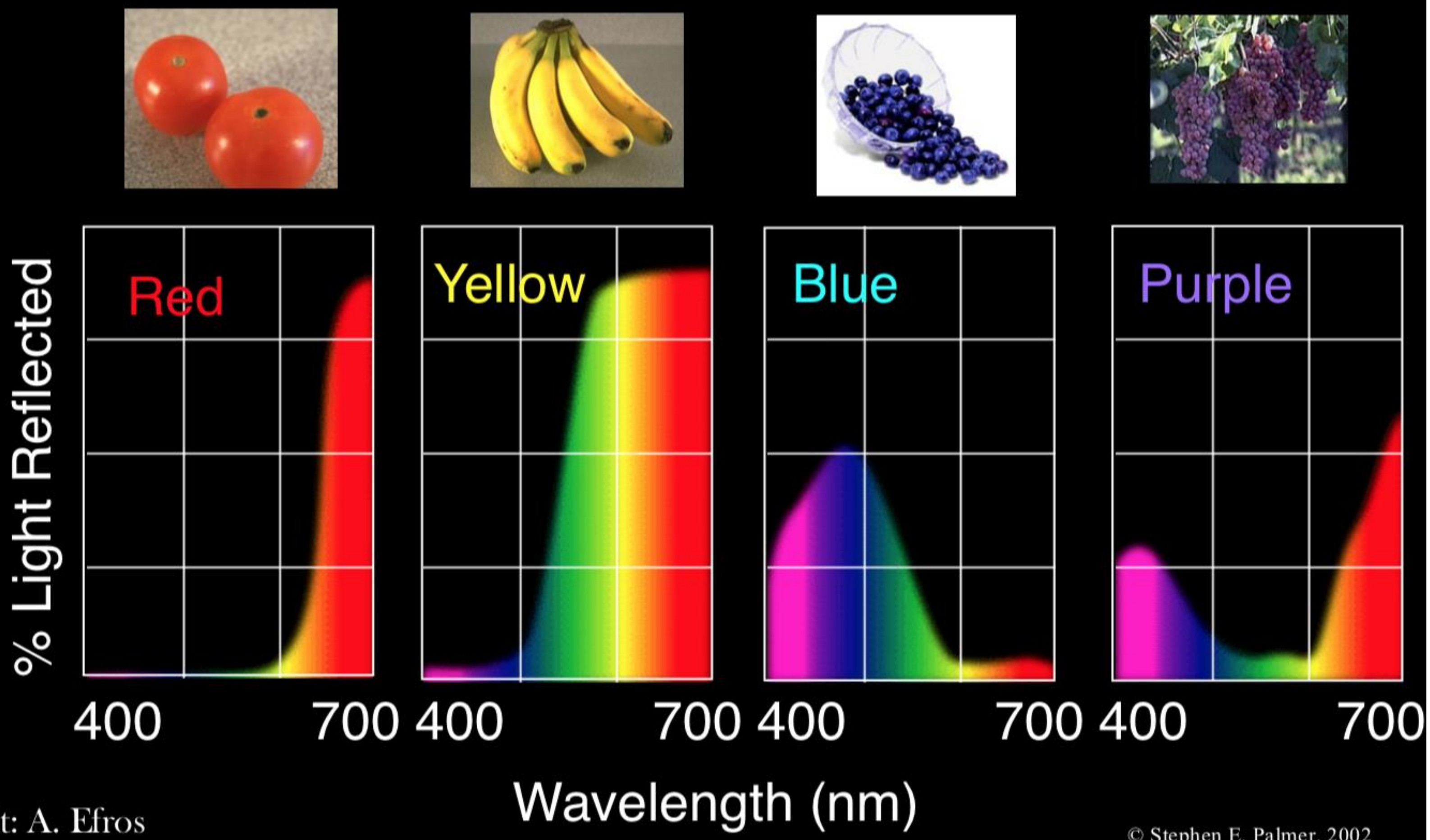
Some examples of the spectra of light sources



Slide credit: A. Efros

The Physics of light

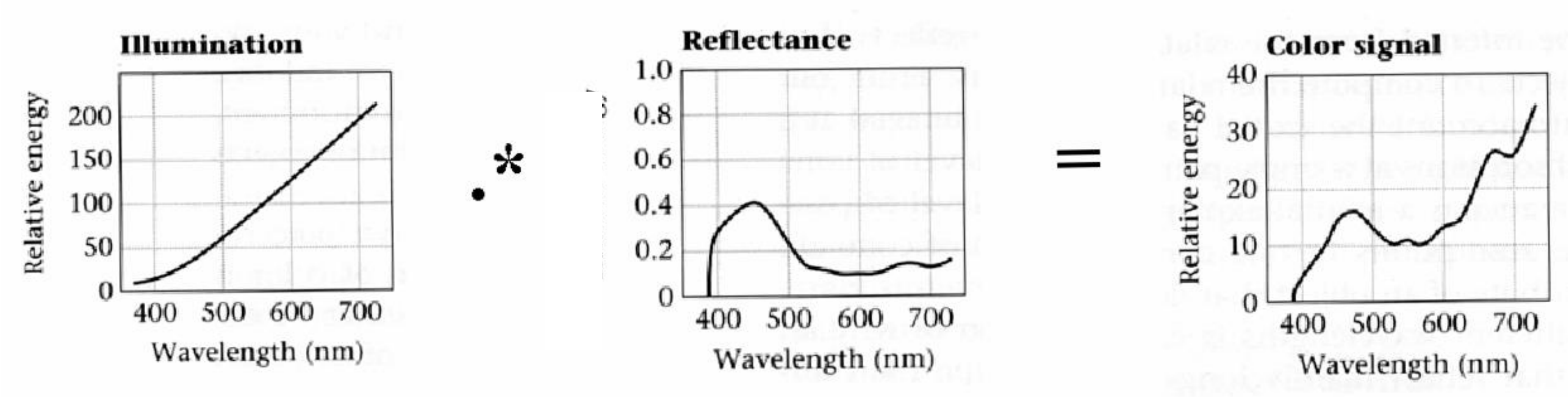
Some examples of the reflectance spectra of surfaces



Slide credit: A. Efros

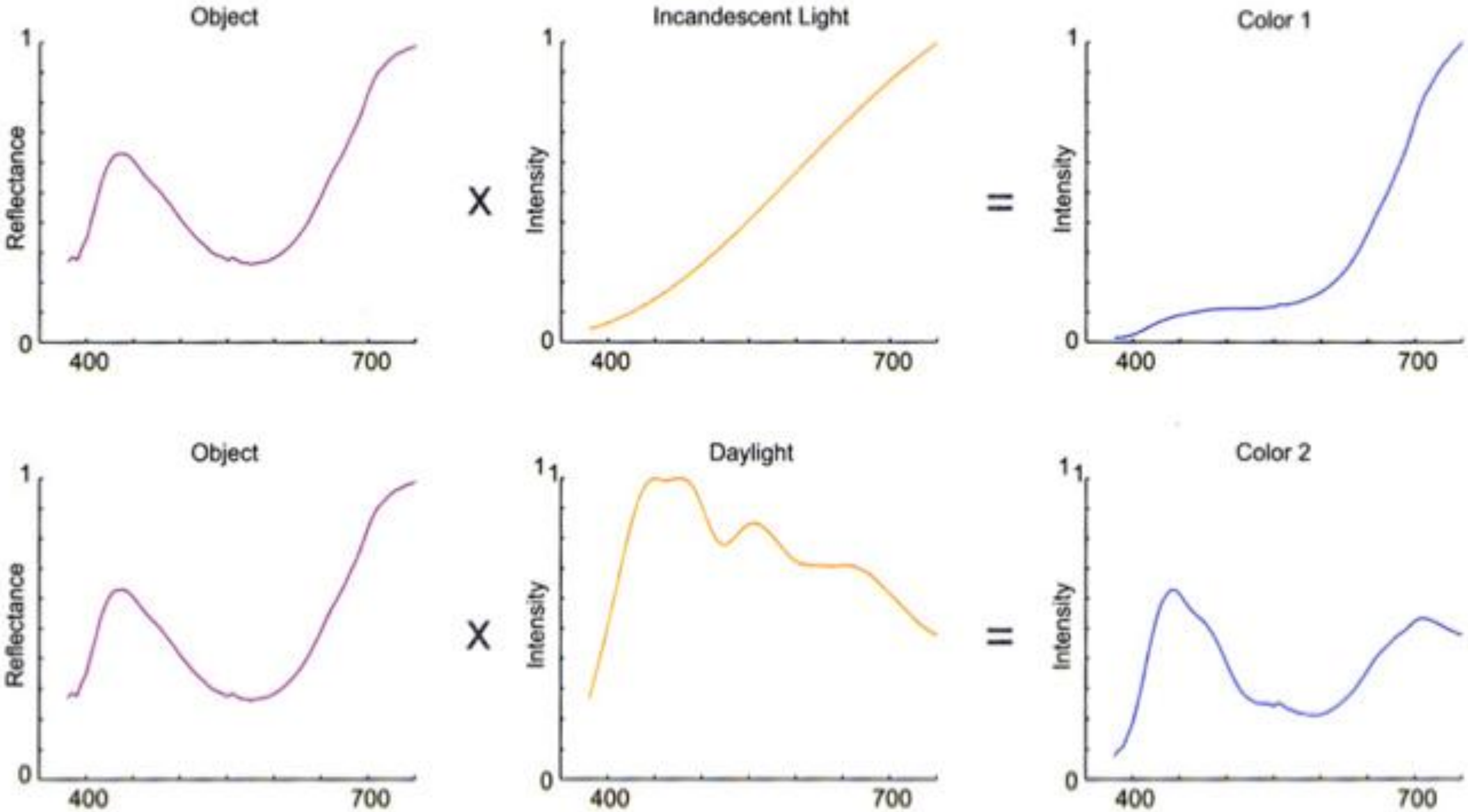
Interaction of light and surfaces

Reflected color is the result of interaction of light source spectrum with surface reflectance



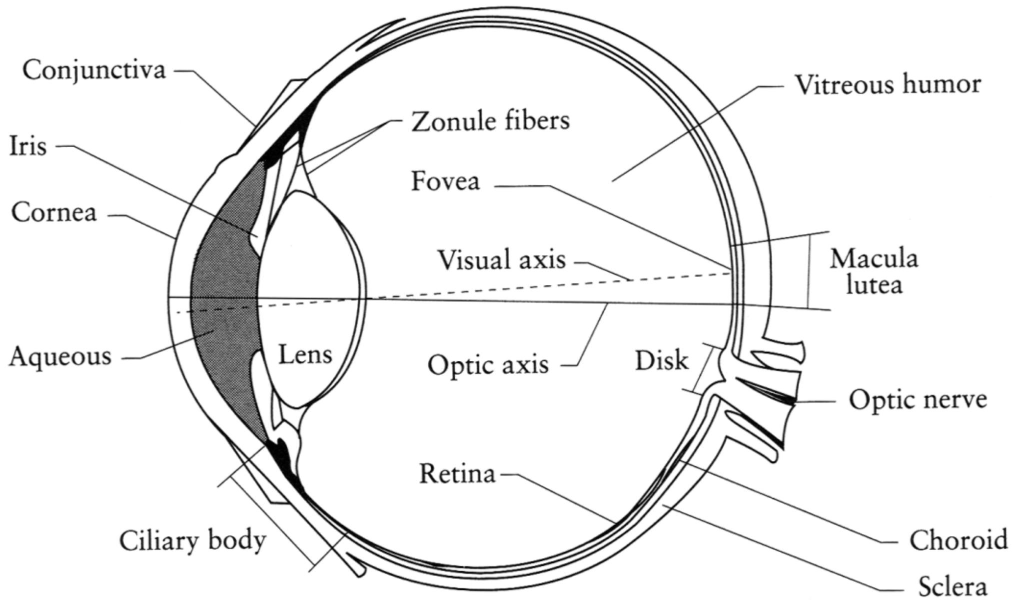
Slide credit: A. Efros

Reflection from colored surface



Slide credit: S. Marschner

The eye

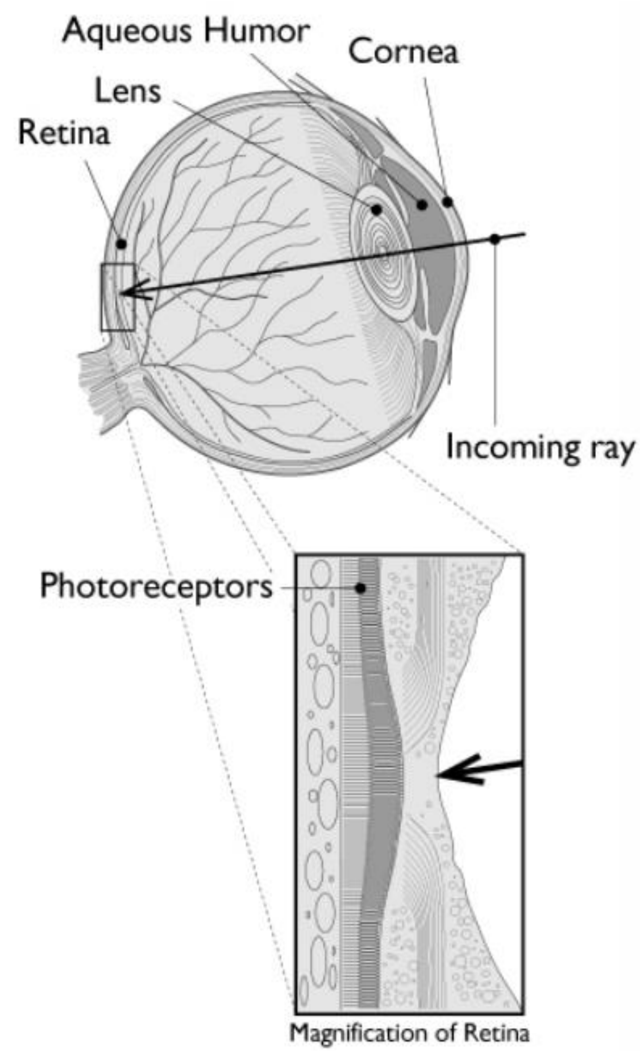


- Iris: colored annulus with radial muscles
- Pupil: the hole (aperture) whose size is controlled by the iris
- Lens: changes shape by using ciliary muscles (to focus on objects at different distances)
- Retina: photoreceptor cells

Slide credit: S. Seitz

The eye as a measurement device

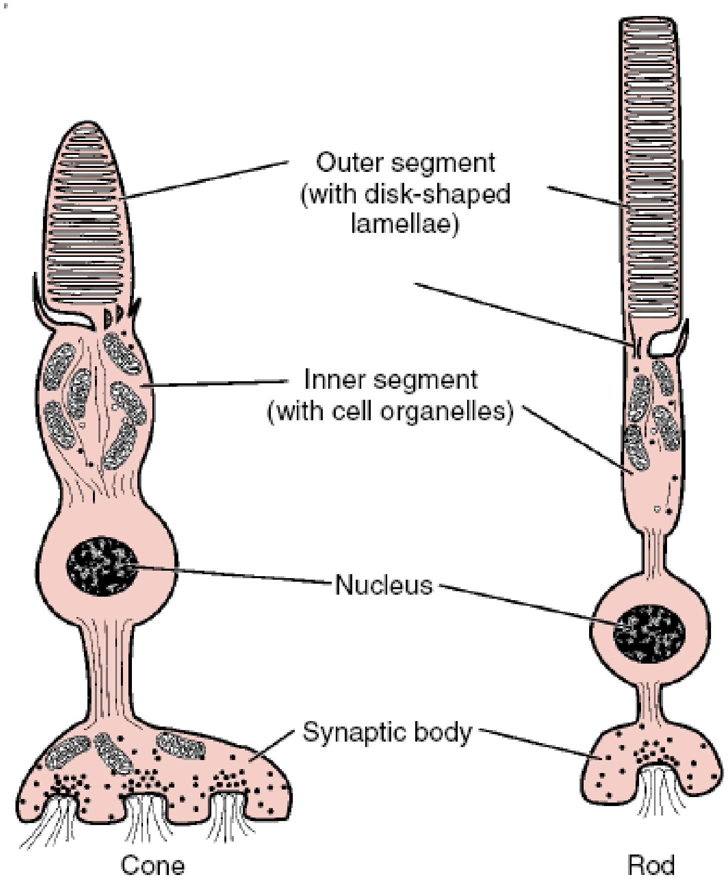
- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
  - its optics are much like a camera
  - its detection mechanism is also much like a camera
- Light is measured by the *photoreceptors* in the retina
  - they respond to visible light
  - different types respond to different wavelengths
- **The human eye is a camera!**



Slide credit: S. Marschner

Two types of light-sensitive receptors

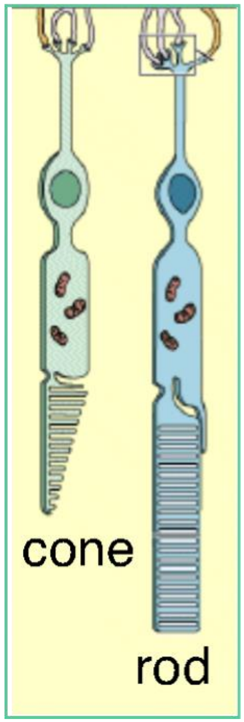
- Cones
  - Cone-shaped
  - Less sensitive
  - Operate in high light
  - Color vision
- Rods
  - Rod-shaped
  - Highly sensitive
  - Operate at night
  - Gray-scale vision

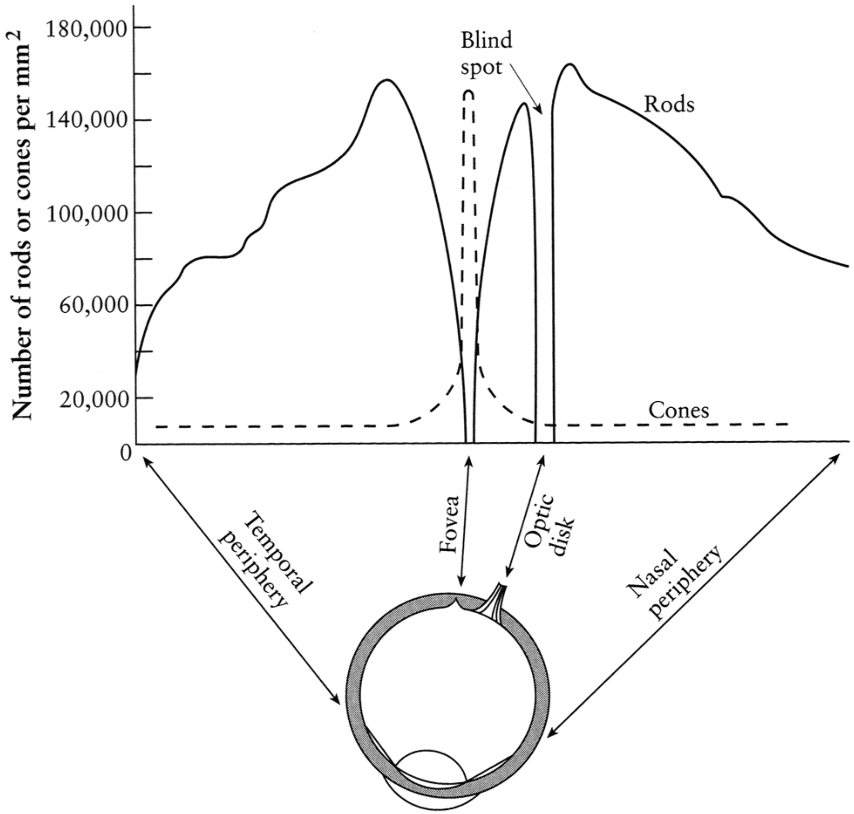


Images by Shimon Ullman

Slide credit: A. Efros

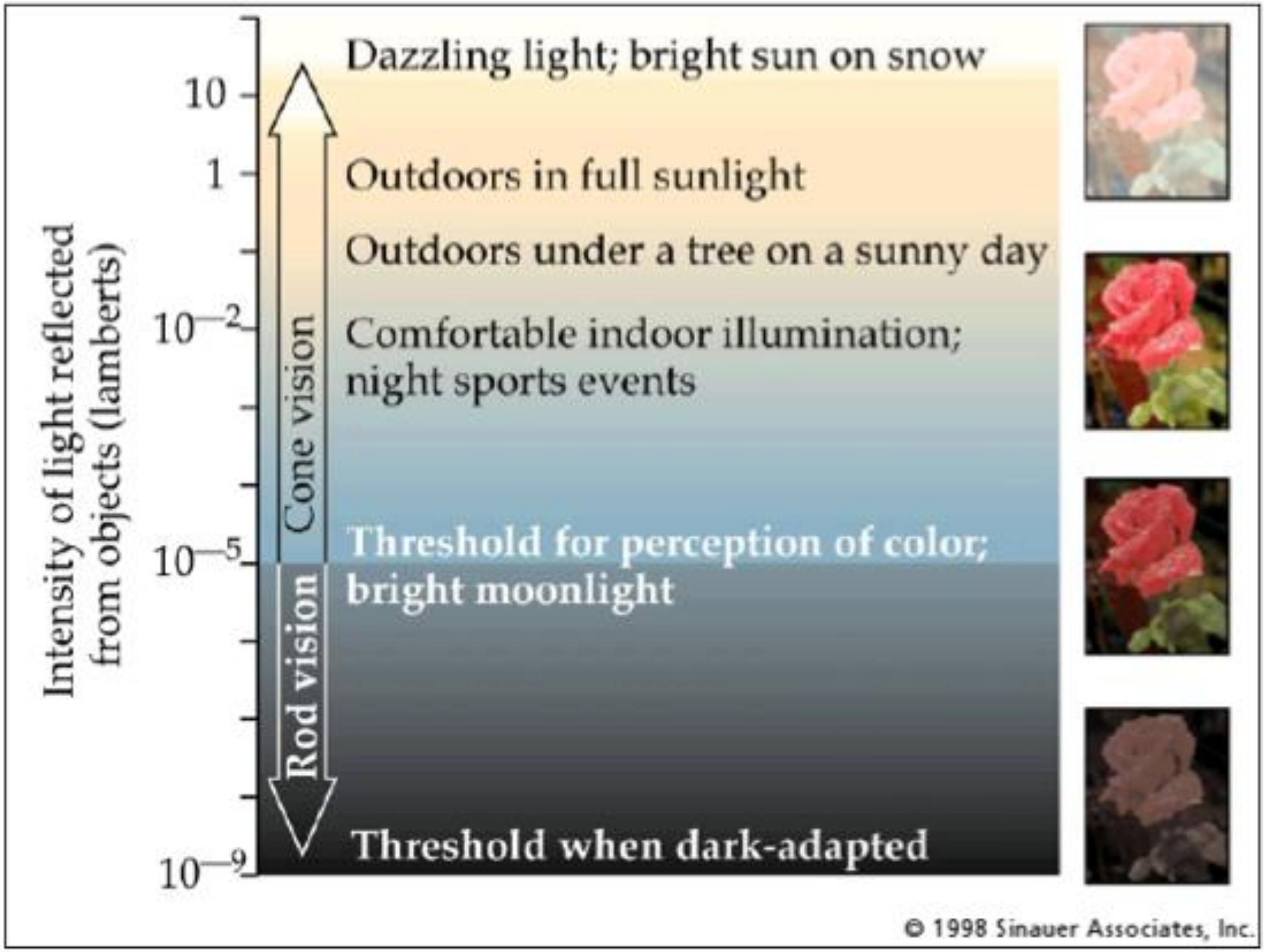
Rodes and cones





- Rods are responsible for intensity, cones for color perception.
- Rods and cones are non-uniformly distributed on the retina.
  - Fovea (small region at the center of the visual field) contains the highest density of cones (and no rods).

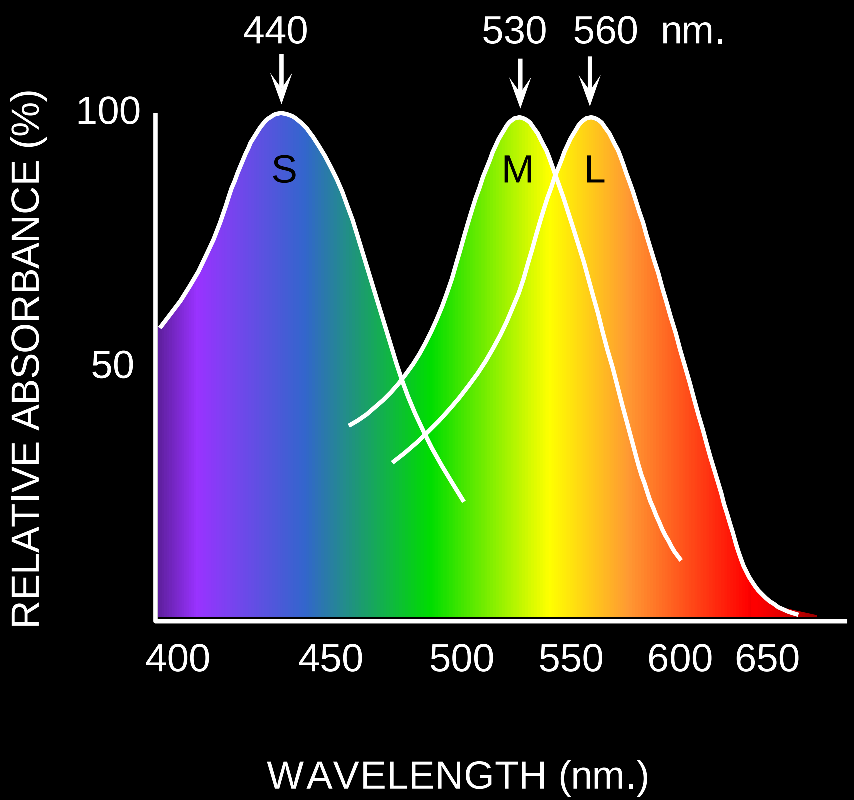
Sensitivity of rodes and cones

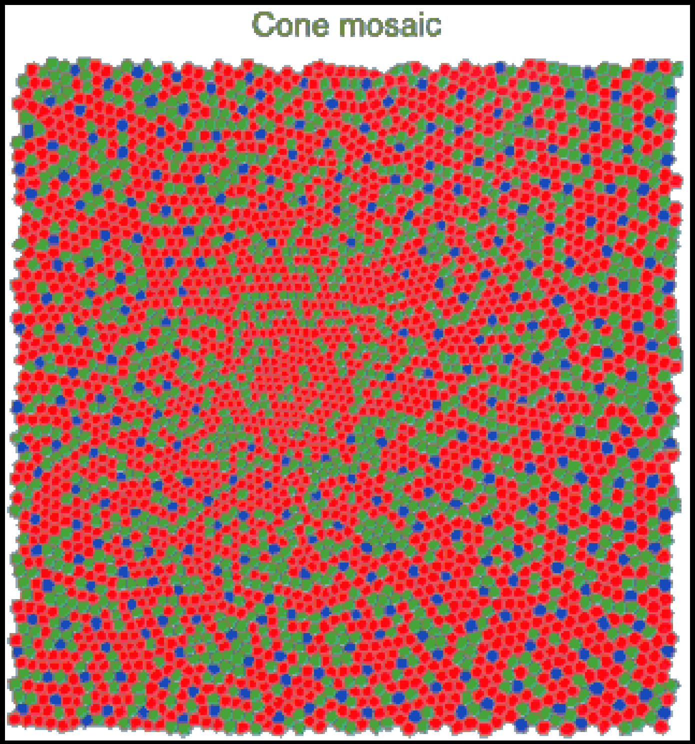


Slide credit: A. Efros

Physiology of Color Vision

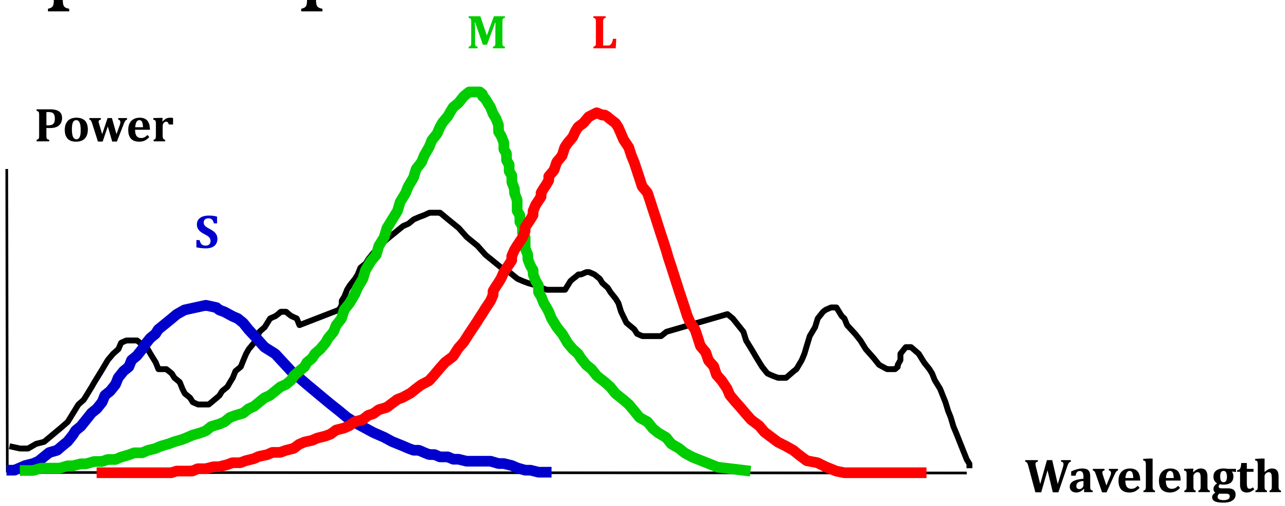
Three kinds of cones:





- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

Color perception



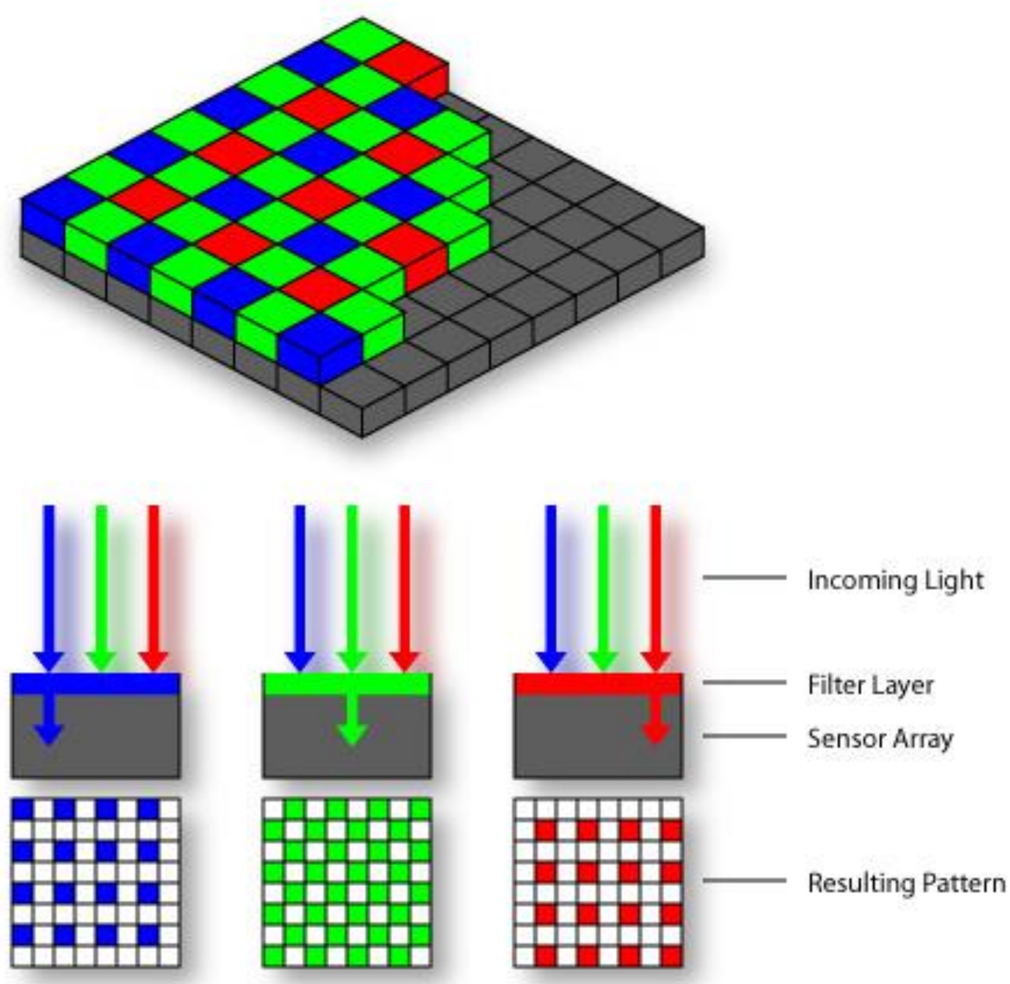
Rods and cones act as *filters* on the spectrum

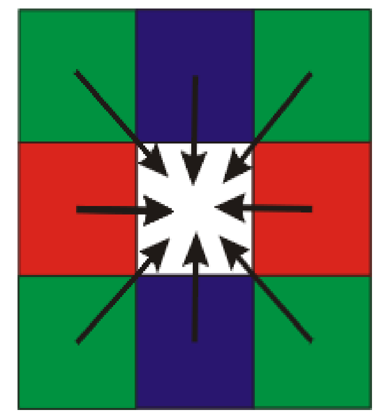
- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

- How can we represent an entire spectrum with 3 numbers?
- We can not! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable.

Slide by Steve Seitz

Color images: Bayer grid





Estimate RGB at G cells from neighbouring values

Slide credit: S. Seitz

Digital color images

Color images
RGB color space

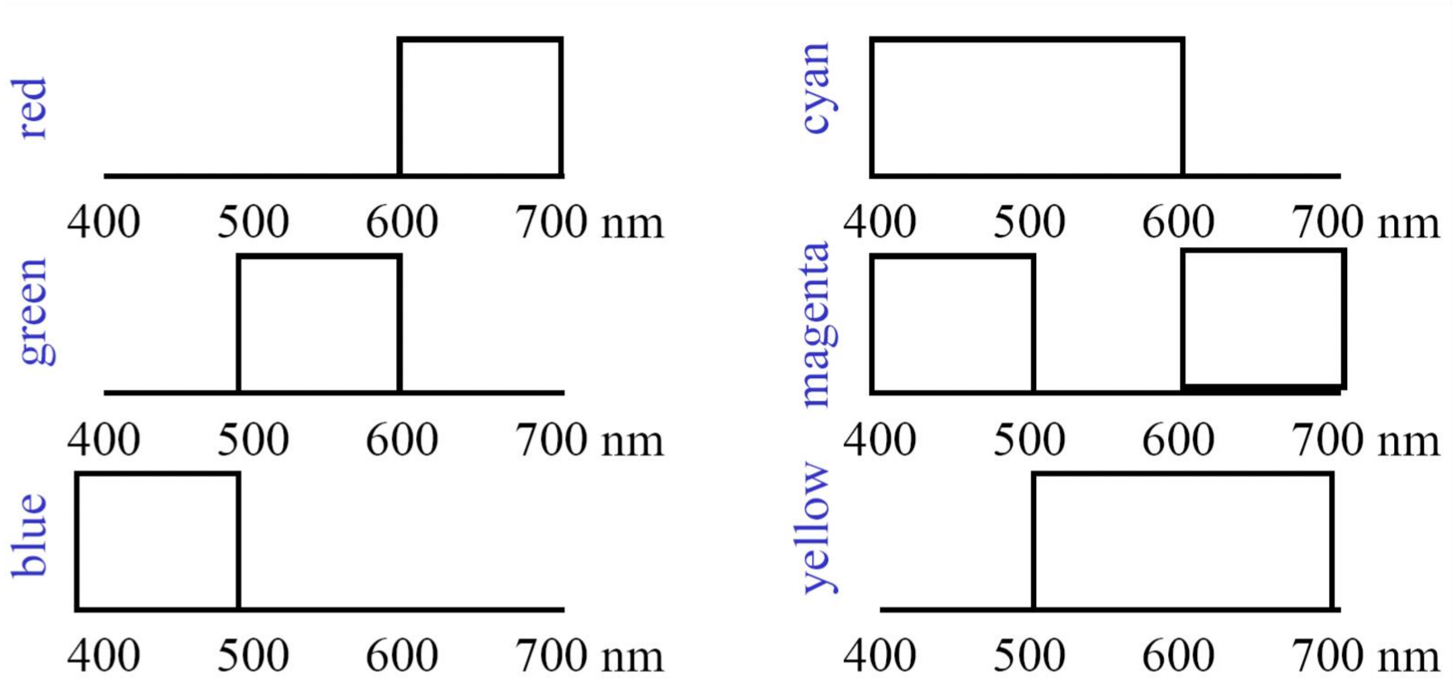
R

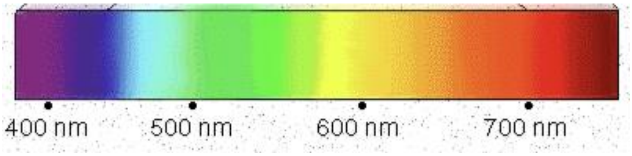
G

B

Color mixing

Cartoon spectra for color names:





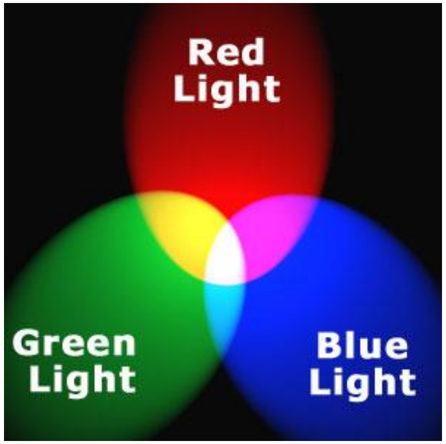
Credit: W. Freeman

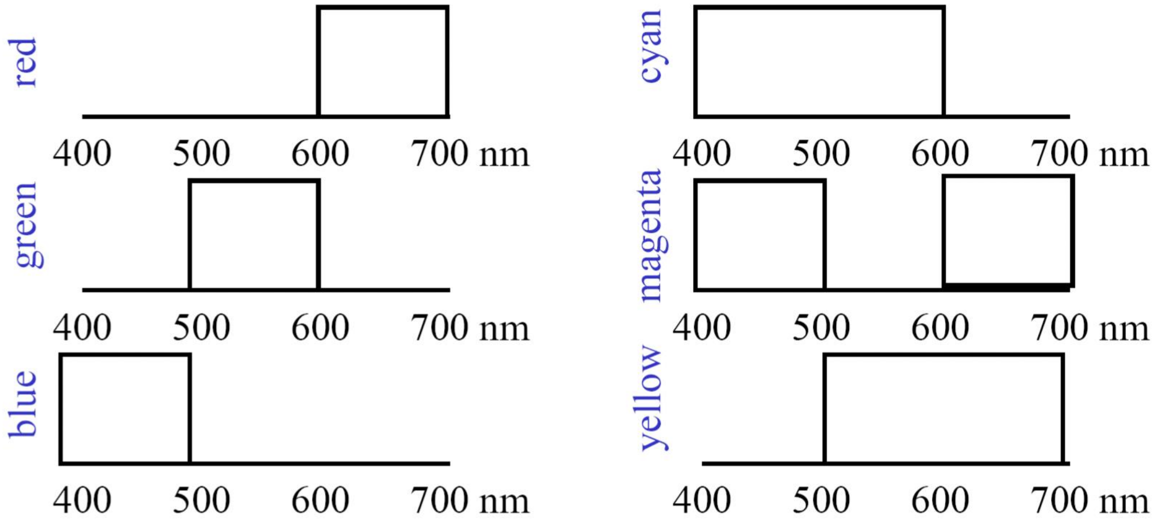
Examples of additive color systems

- Projectors
- Monitors

Additive color mixing

Colors combine by adding color spectra.





Light adds to black.

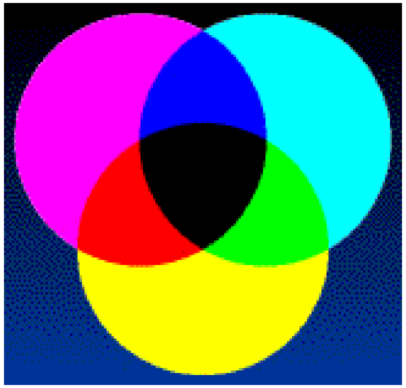
Credit: W. Freeman

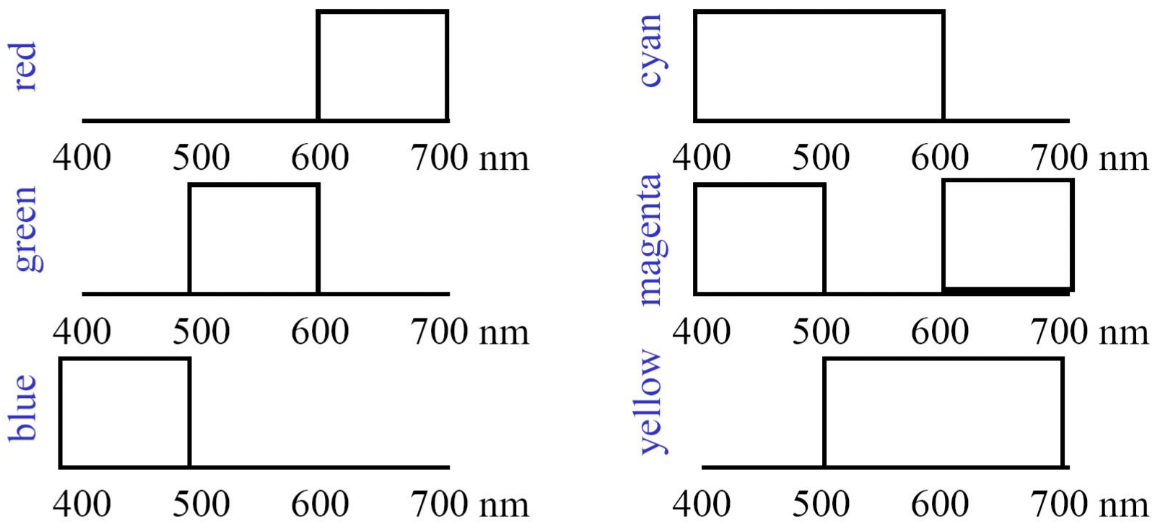
Examples of subtractive color systems

- Printing

Subtractive color mixing

Colors combine by multiplying color spectra.





Pigments remove color from incident light (white).

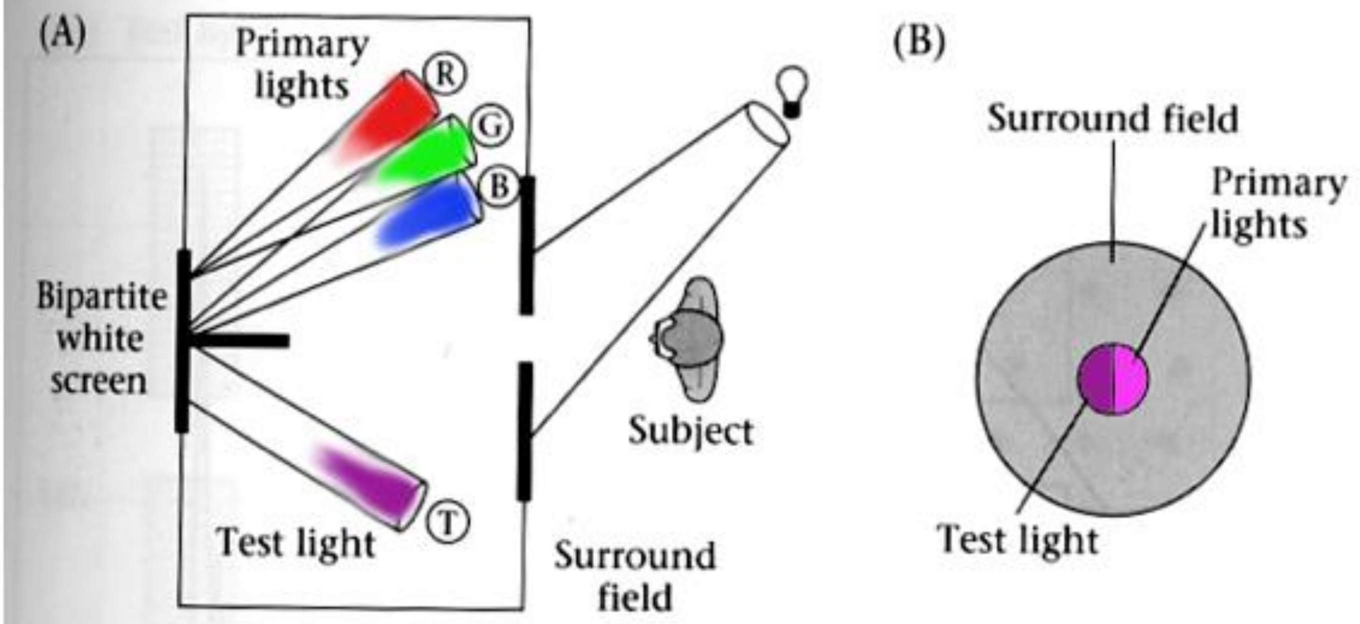
Credit: W. Freeman

Color spaces

- How to represent color?

Color matching experiment

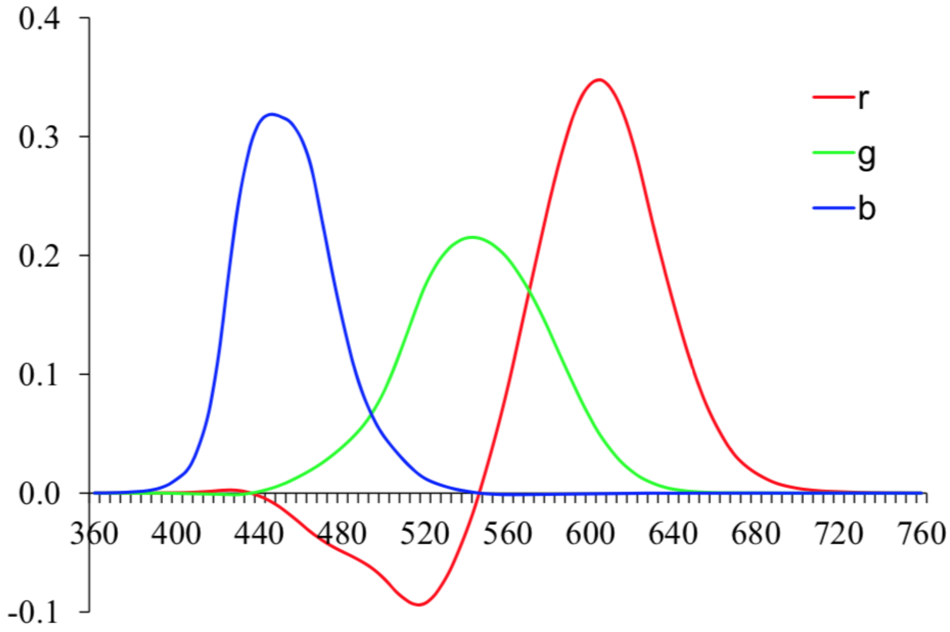
R = 700.0nm, G = 546.1nm, and B = 435.8nm primaries



4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

Slide credit: B. Freeman

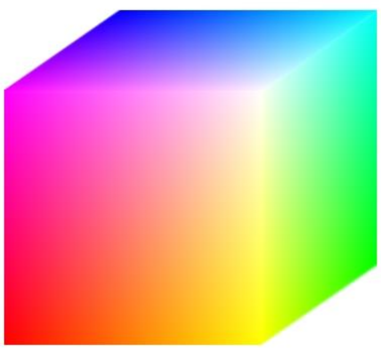
CIE RGB

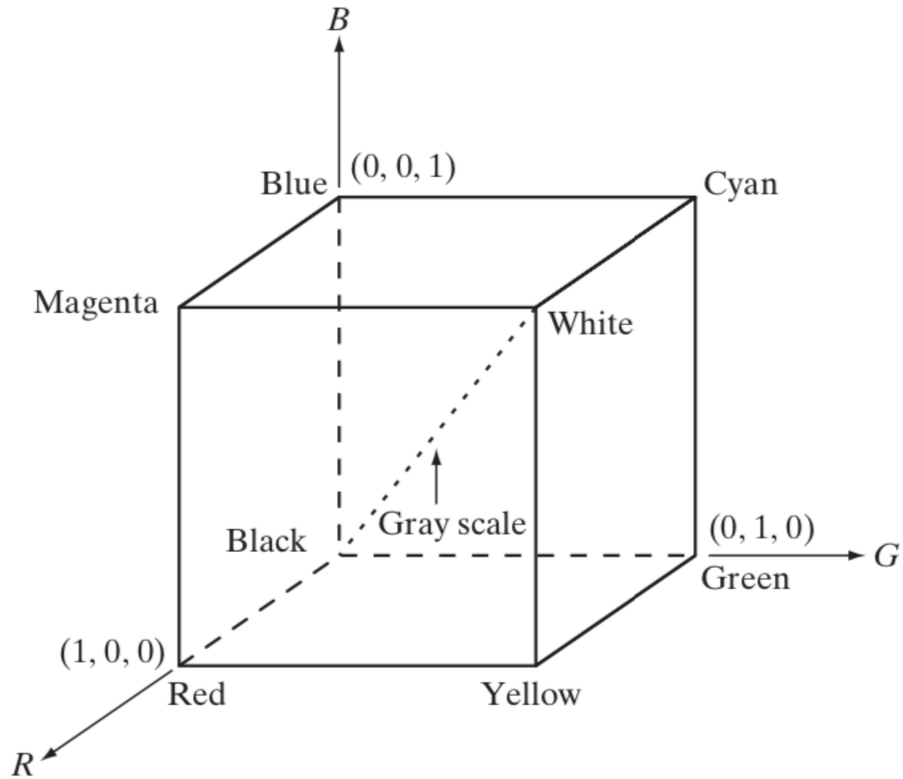


Standard CIE color matching functions: r (λ), g (λ), b(λ) color spectra obtained from matching pure colors to R = 700.0nm, G = 546.1nm, and B = 435.8nm primaries

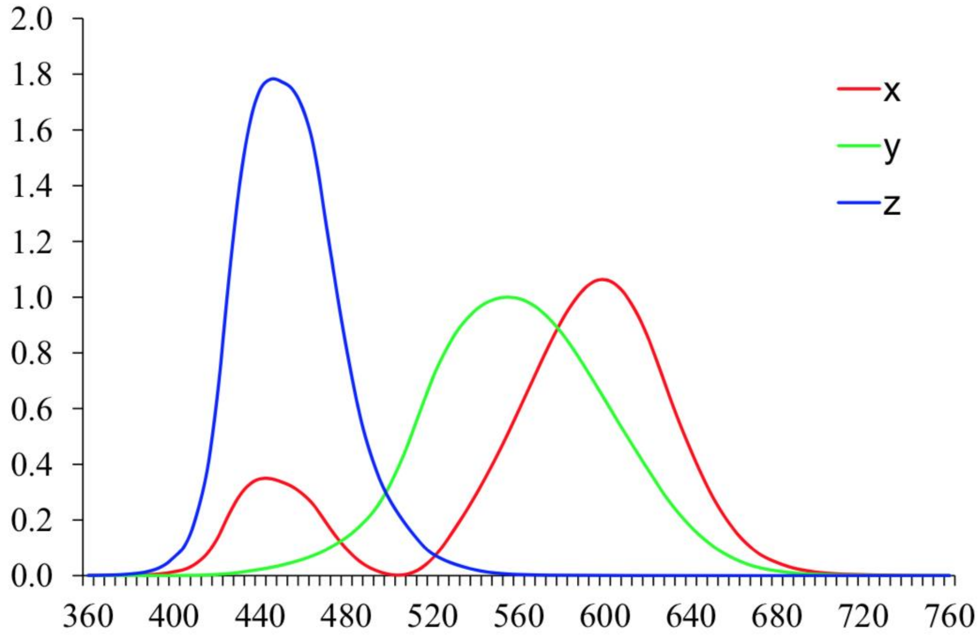
RGB color cube

FIGURE 6.7 Schematic of the RGB color cube. Points along the main diagonal have gray values, from black at the origin to white at point (1, 1, 1).





CIE XYZ

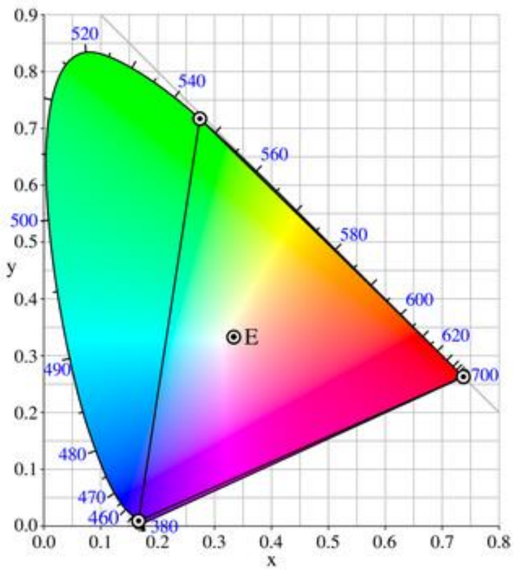


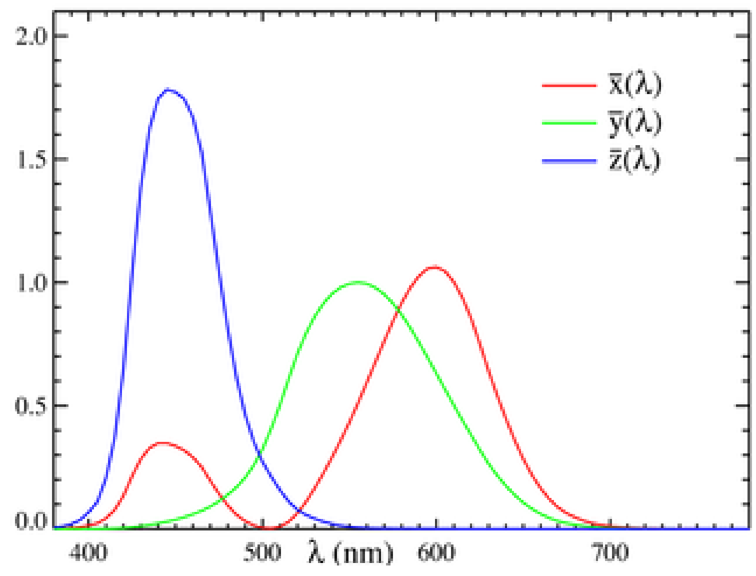
Standard CIE color matching functions: x (λ), y (λ), z (λ) color matching functions, which are linear combinations of the (r (λ), g (λ), b(λ)) spectra.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE XYZ

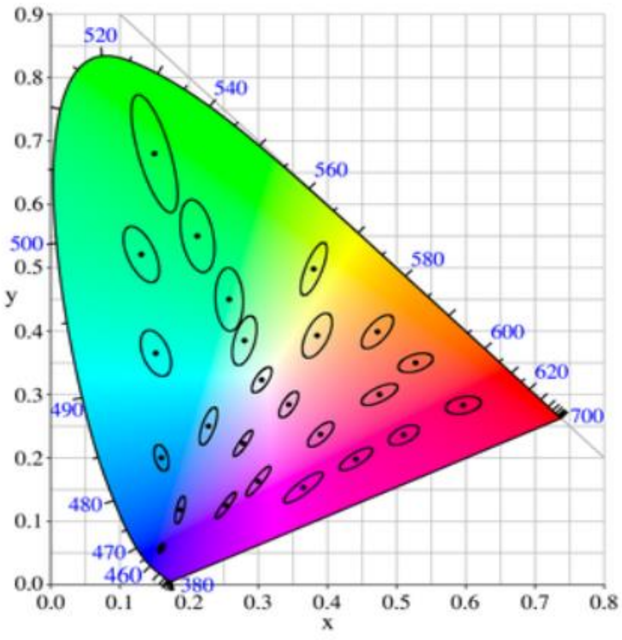
- Primaries are *imaginary*, but matching functions are positive everywhere
- The Y parameter corresponds to brightness or *luminance* of a color
- 2D visualization: draw (x,y), where $x = X/(X+Y+Z)$, $y = Y/(X+Y+Z)$





Distances in color space

- Are distances between points in a color space perceptually meaningful?
  - Not necessarily: CIE XYZ is not a uniform color space, so magnitude of differences in coordinates are poor indicator of color “distance”.

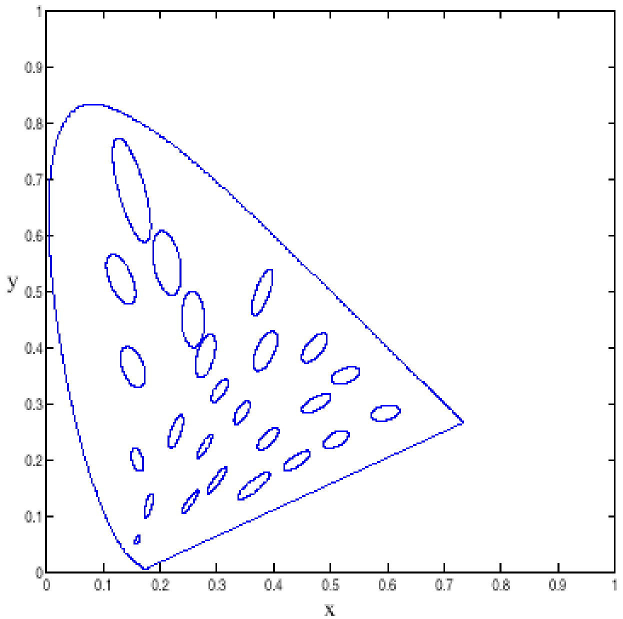


McAdam ellipses:
Just noticeable differences in color

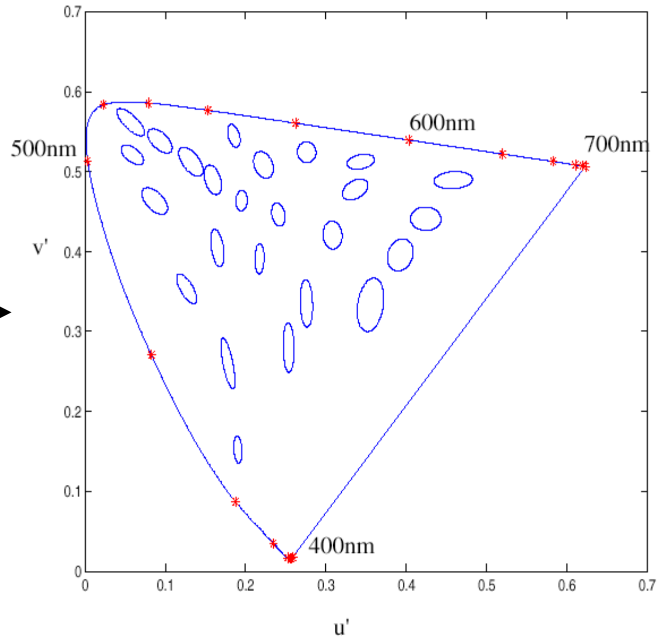
Slide credit: K. Grauman

Uniform color spaces

- Attempt to correct this limitation by remapping color space so that just noticeable differences are contained by circles → distances more perceptually meaningful.
  - Examples: CIE L*u*v*, CIE L*a*b*



CIE XYZ

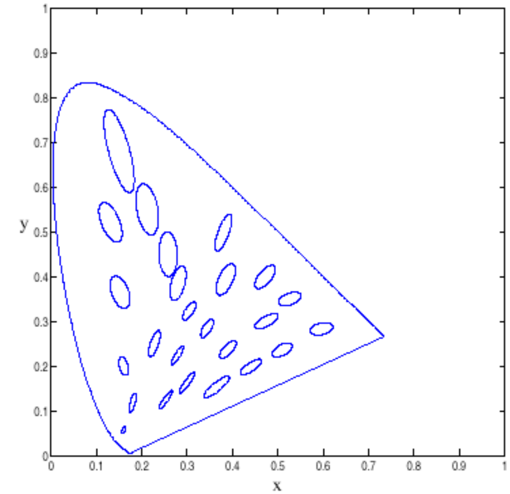


CIE L*u*v*

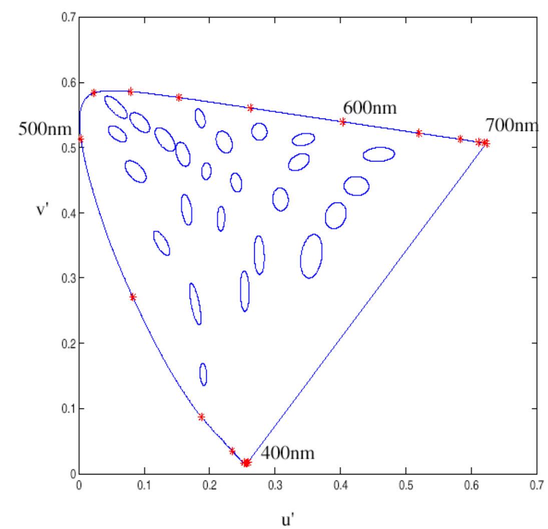
Slide credit: K. Grauman

Perceptually uniform spaces

- CIE L*u*v and CIE L*a*b* are two major spaces standardized by CIE
  - designed so that equal differences in coordinates produce equally visible differences in color
  - by remapping color space so that just noticeable differences are contained by circles → distances more perceptually meaningful
  - L*u*v*: earlier, simpler space
  - L*a*b*: more complex but more uniform
  - both separate luminance from chromaticity



CIE XYZ

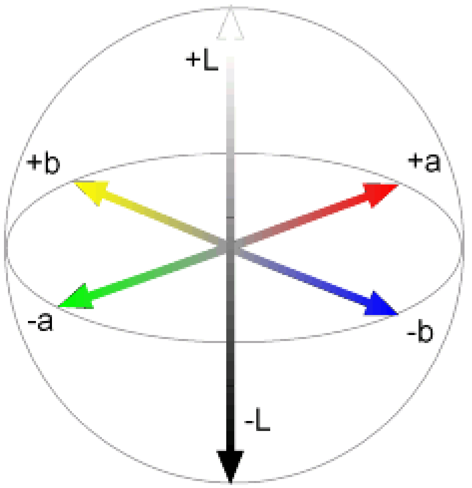


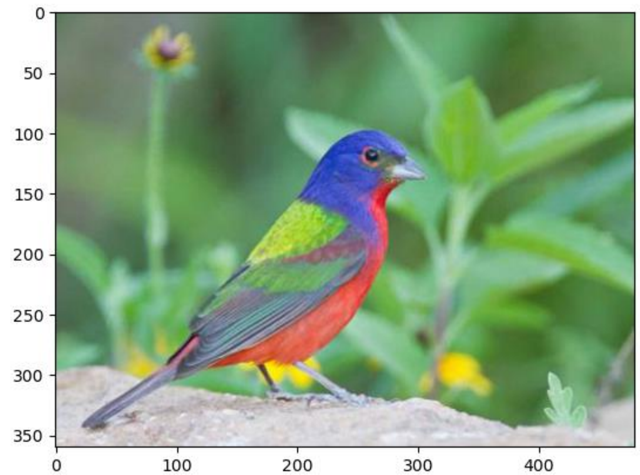
CIE L*u*v*

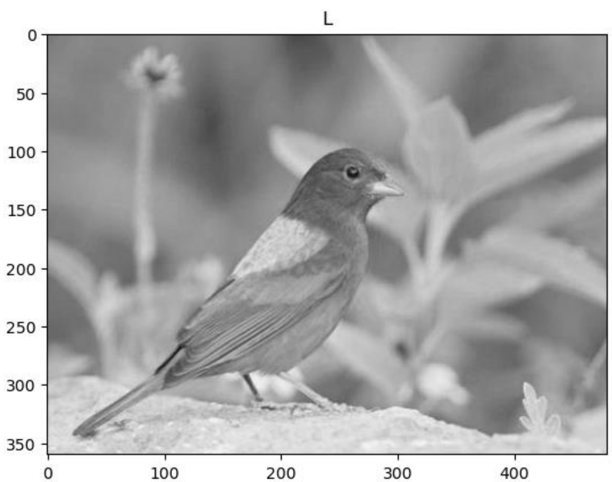
Slide credit: K. Grauman, S. Marschner

CIE L*a*b*

- Perceptually uniform color space

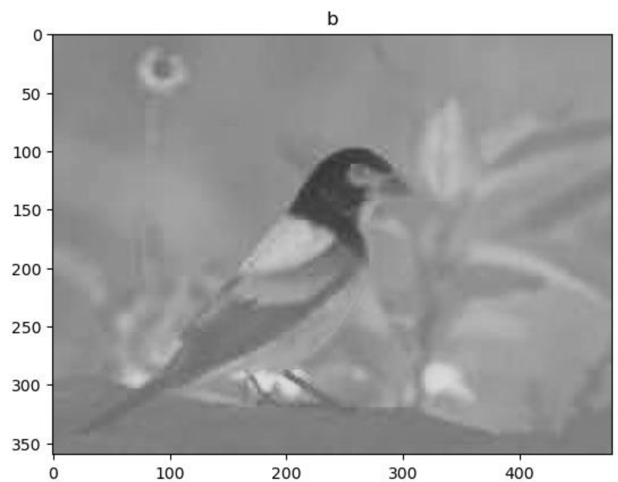






L*

a*



b*

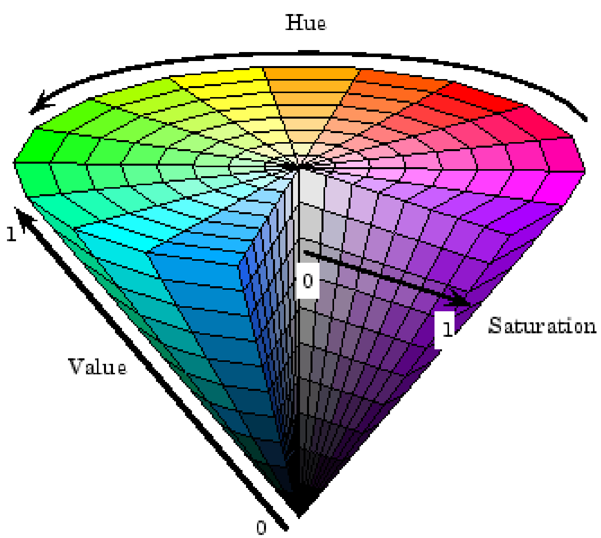
Perceptual dimensions of color

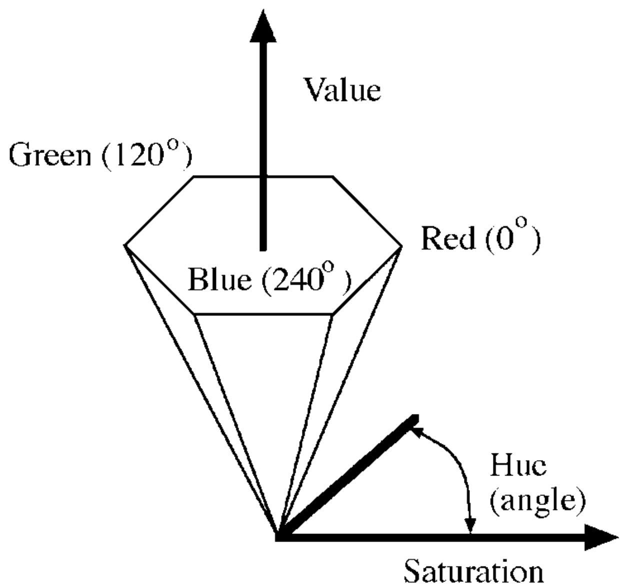
- Hue
  - the kind of color, regardless of attributes
  - colorimetric correlate: dominant wavelength
  - artist's correlate: the chosen pigment color
- Saturation
  - the colorfulness
  - colorimetric correlate: purity
  - artist's correlate: fraction of paint from the colored tube
- Lightness (or value)
  - the overall amount of light
  - colorimetric correlate: luminance
  - artist's correlate: tints (mixture with white) are lighter, shades (mixture with black) are darker

Slide credit: S. Marschner

HSV color space

- Hue, Saturation, Value
- Nonlinear: reflects topology of colors by coding hue as an angle





Slide credit: K. Grauman

Week 02 – Hands on activitiy

- Prepare and submit a Jupyter Notebook file containing the codes and the results for:
  - Reading a colored RGB image that you choose and displaying its R, G and B channels.
  - Converting the RGB image into HSV color space and displaying its H, S and V channels.
  - Converting the RGB image into Lab color space and displaying its L, a, and b channels.