COSC579: Color and Perception

Jeremy Bolton, PhD
Assistant Teaching Professor

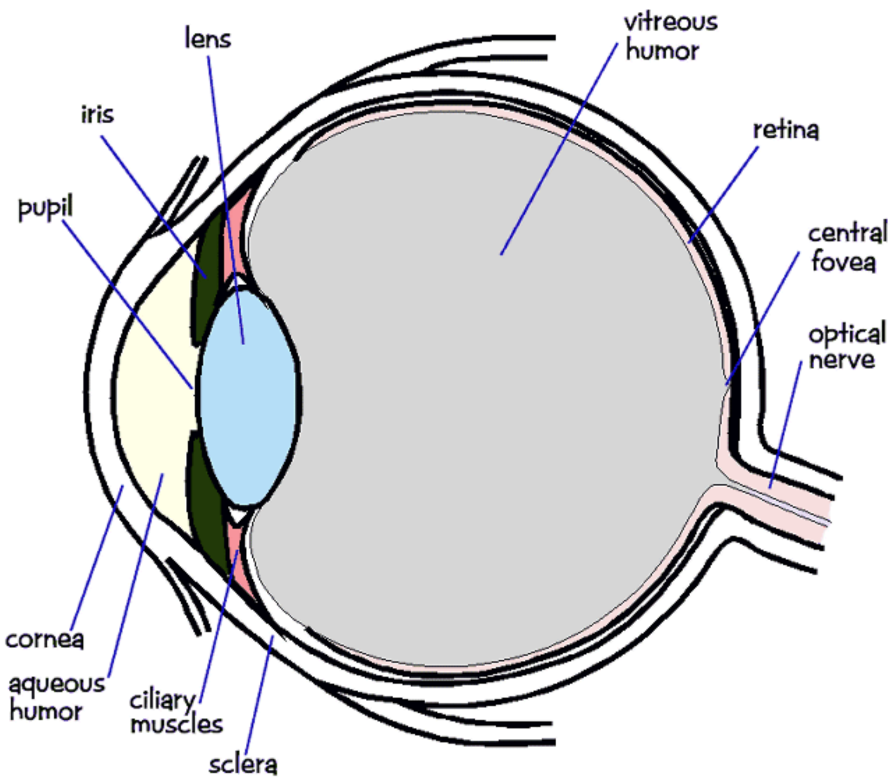
GEORGETOWN UNIVERSITY

Outline

I. Human perception of color.
II. Formalizing color?
III. Color Models

GEORGETOWN UNIVERSITY

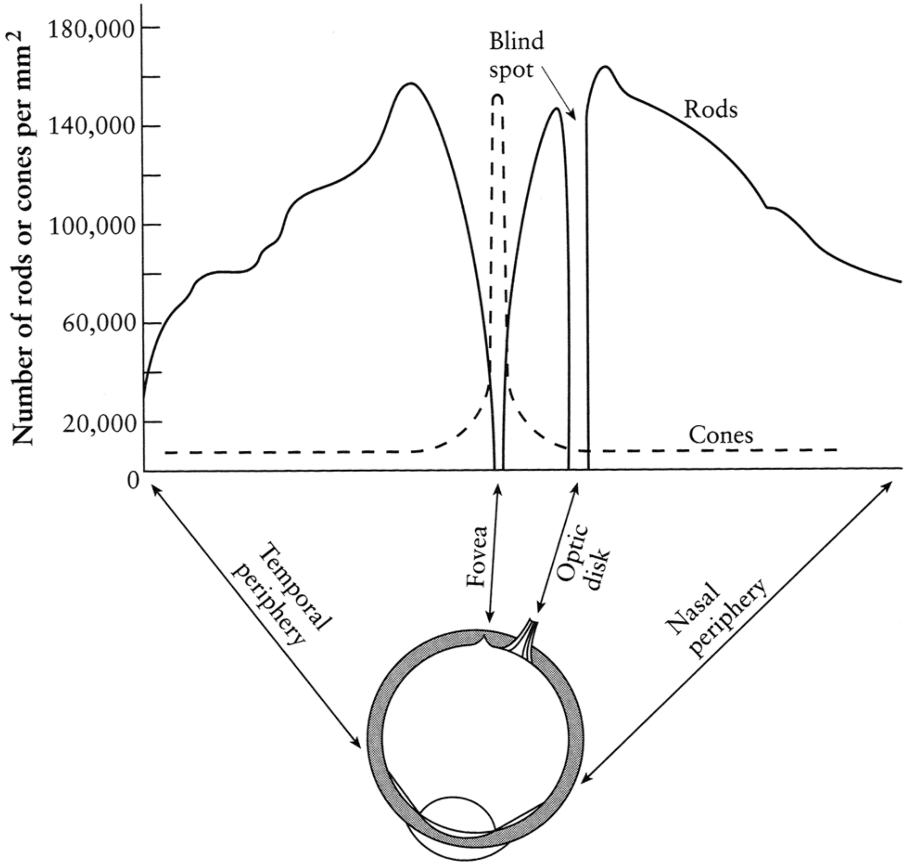
Capturing and Sensing Light: The human visual system



- Light and Color perception
  - Light hits the retina, which contains photosensitive cells
    - rods and cones
  - These cells convert the spectrum into a few discrete values

GEORGETOWN UNIVERSITY

Density of rods and cones



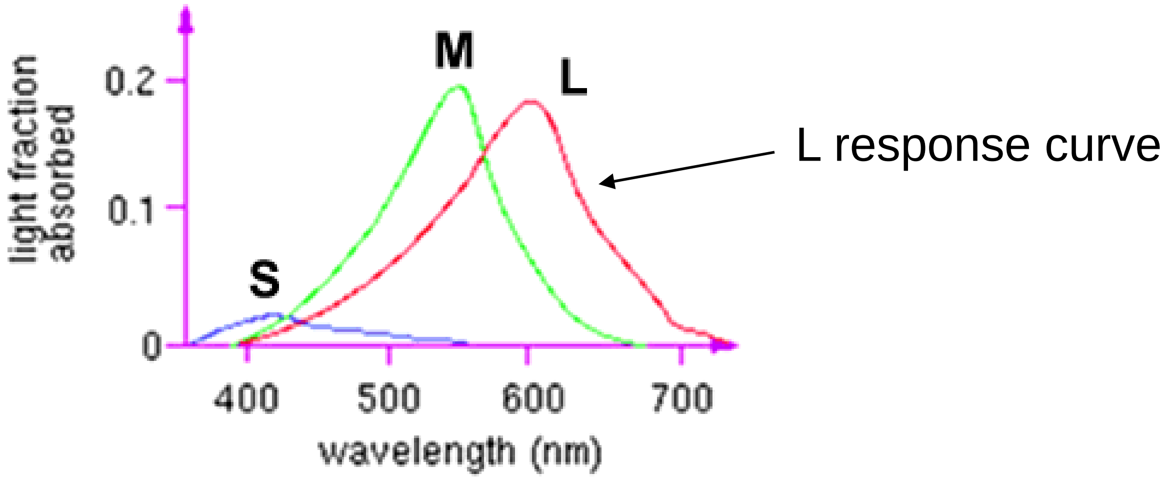
- Rods and cones are *non-uniformly* distributed on the retina
  - Rods responsible for intensity, cones responsible for color
  - **Fovea** - Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods).
  - Less visual acuity in the periphery—many rods wired to the same neuron

GEORGETOWN UNIVERSITY

Light response is nonlinear

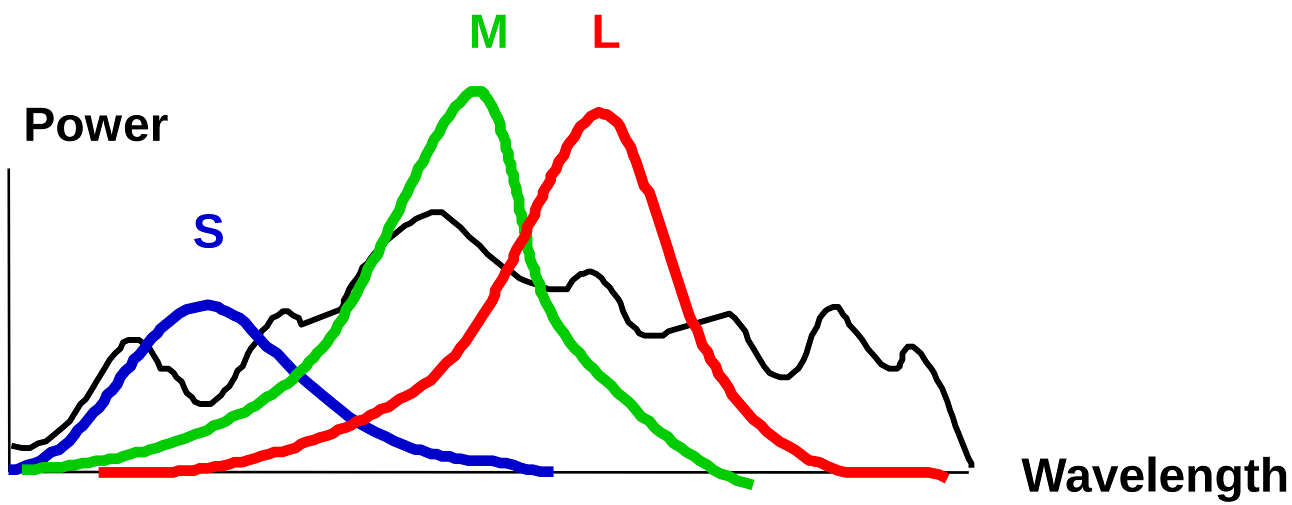
- Our visual system has a large *dynamic range*
  - We can resolve both light and dark things at the same time
  - One mechanism for achieving this is that we sense light intensity on a *logarithmic scale*
    - an exponential intensity ramp will be seen as a linear ramp
  - Another mechanism is *adaptation*
    - rods and cones adapt to be more sensitive in low light, less sensitive in bright light.

Color perception



- Three types of cones
  - Each is sensitive in a different region of the spectrum
    - but regions overlap
    - Short (S) corresponds to blue
    - Medium (M) corresponds to green
    - Long (L) corresponds to red
  - Different sensitivities: we are more sensitive to green than red
  - Colorblindness—deficiency in at least one type of cone

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
  - Q: How can we represent an entire spectrum with 3 numbers?
  - A: We can't! Most of the information is lost.
    - As a result, two different spectra may appear indistinguishable
      - » such spectra are known as **metamers**
      - » http://www.cs.brown.edu/exploratories/freeSoftware/repository/edu/brown/cs/exploratories/applets/spectrum/metamers_guide.html

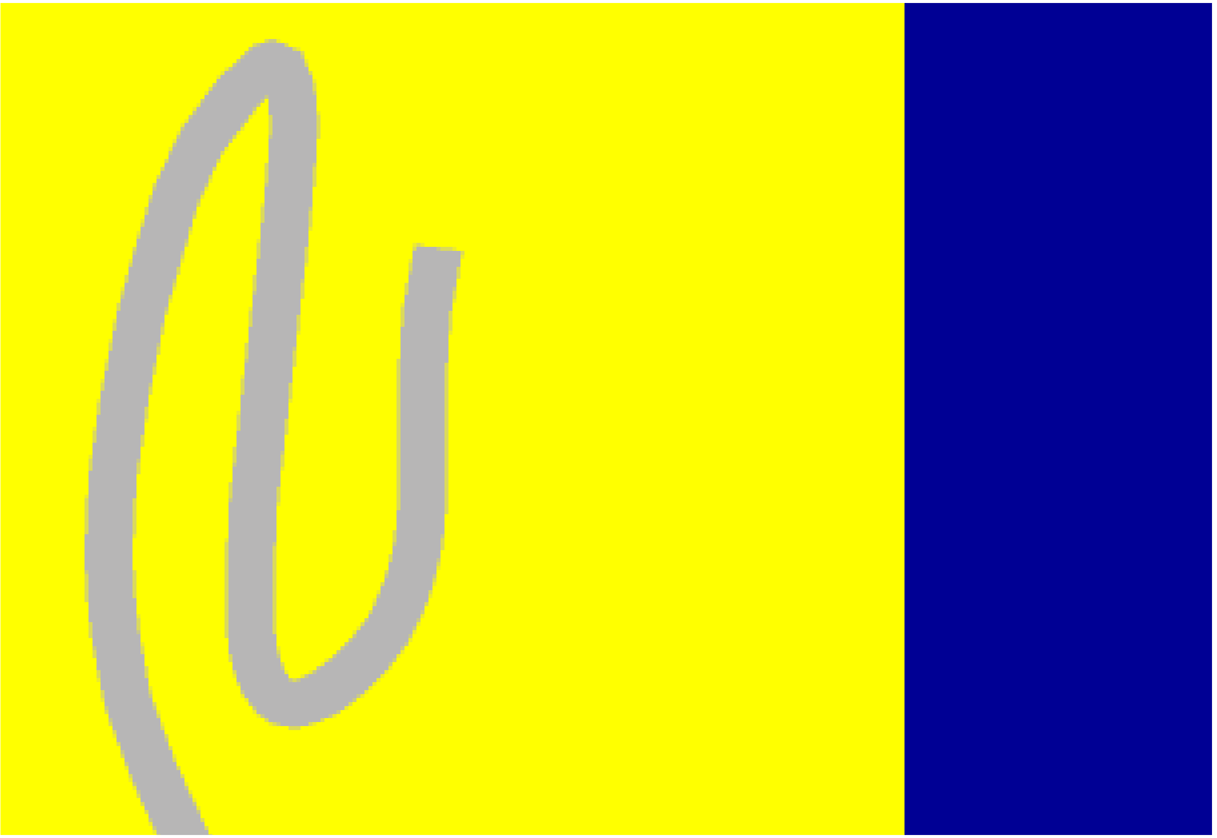
The appearance of colors

- Color appearance is based on the sensing mechanism
  - As we have discussed … it has been shown, it is possible to match almost all colors, viewed in film mode using only three primary sources - the principle of **trichromacy**.

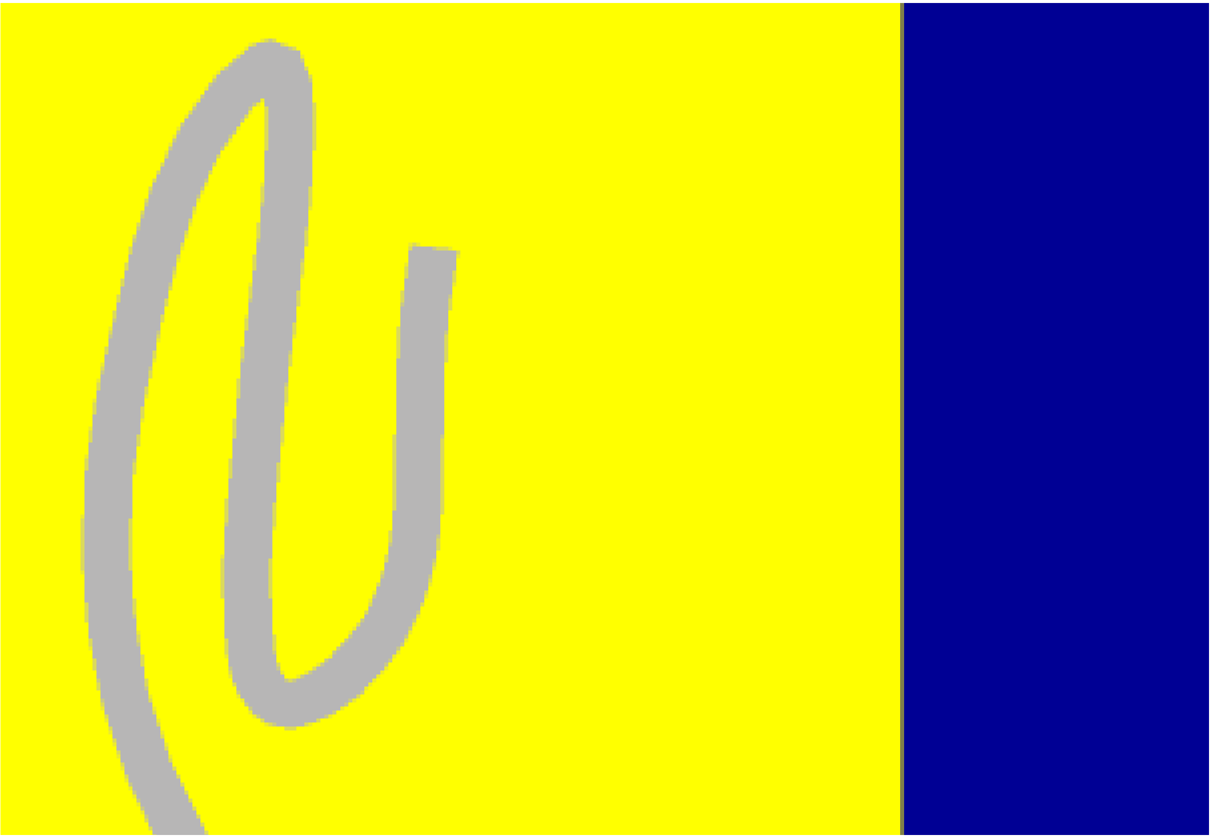
- Color appearance is affected by the “compression” and “post processing” of an objects albedo
  - “Post processing” in visual cortex is complex process
  - Hering, Helmholtz: Color appearance is strongly affected by other nearby colors, by adaptation to previous views, and by “state of mind”
  - Adaptation phenomena

- See neuroscience related research by Poggio et al.


XXXXXX
GREEN
XXXXXX
BLUE
XXXXXX
YELLOW
XXXXXX
PURPLE
XXXXXX
ORANGE
XXXXXX
RED
XXXXXX
WHITE
XXXXXX
PURPLE
XXXXXX
ORANGE
XXXXXX
BLUE
XXXXXX
RED
XXXXXX
GREEN

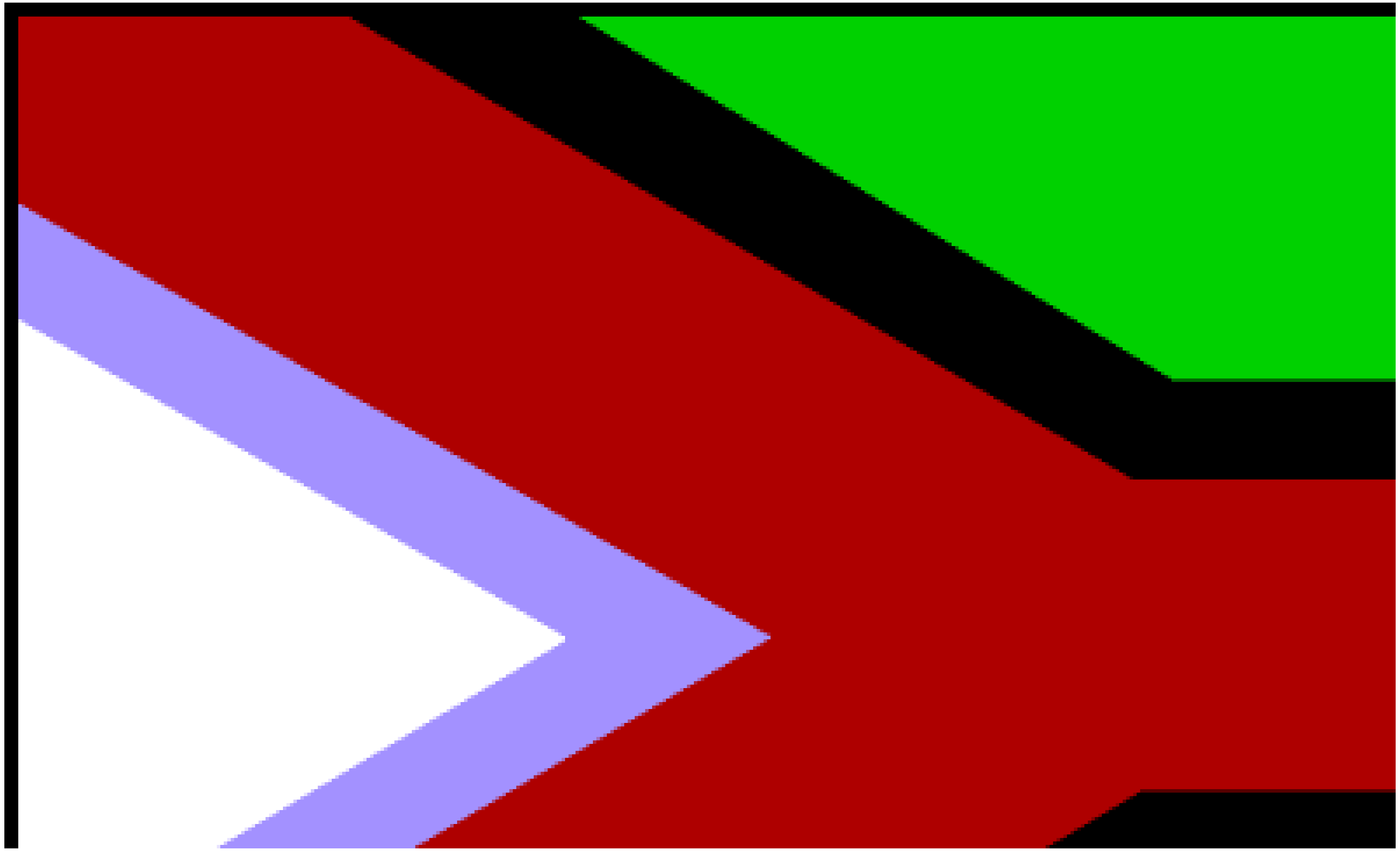


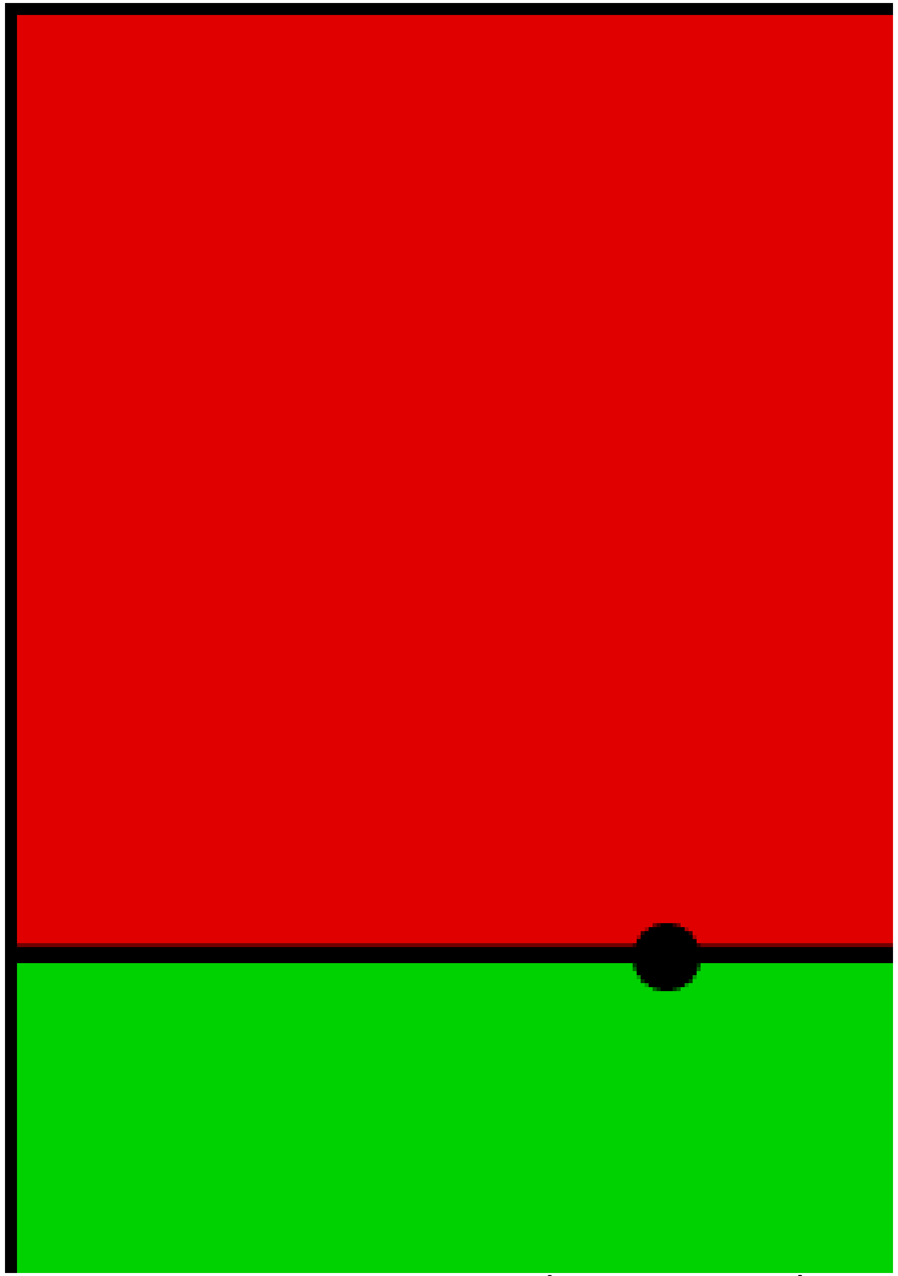
GEORGETOWN UNIVERSITY



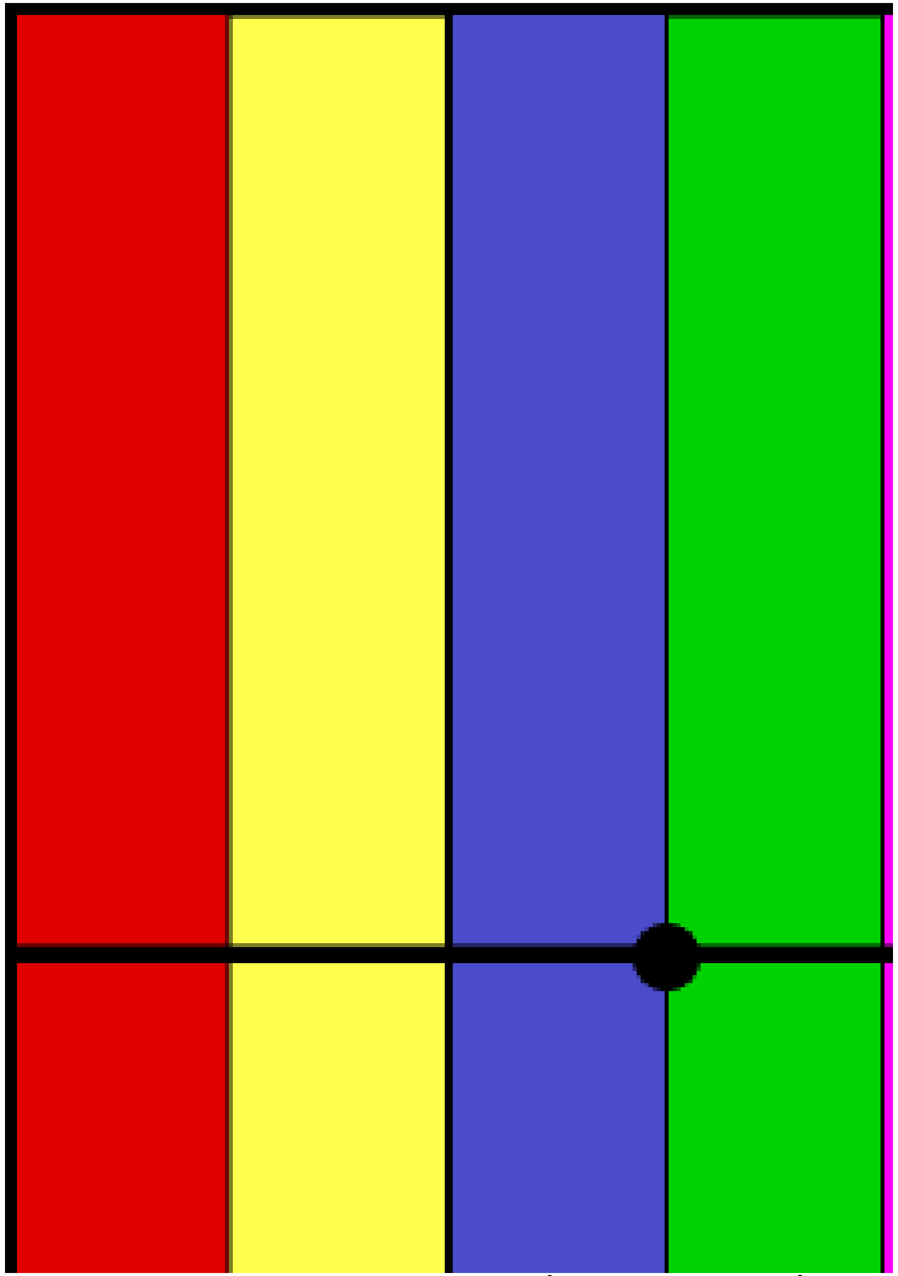
Adaptation phenomena

- The response of your color system depends both on spatial contrast and what it has seen before (adaptation)
- This seems to be a result of coding constraints --- receptors appear to have an operating point that varies slowly over time, and to signal some sort of offset. One form of adaptation involves changing this operating point.
- Common example: walk inside from a bright day; everything looks dark for a bit, then takes its conventional brightness.

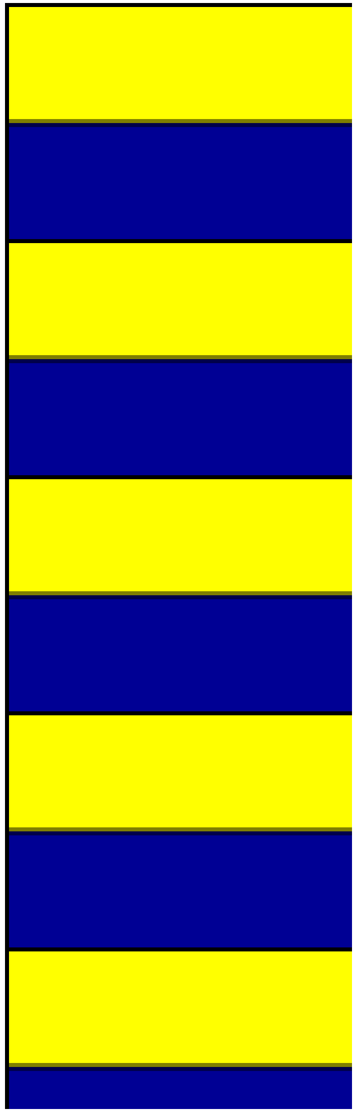


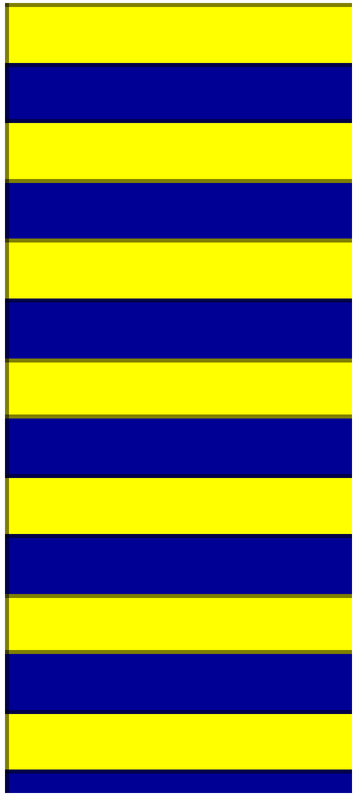


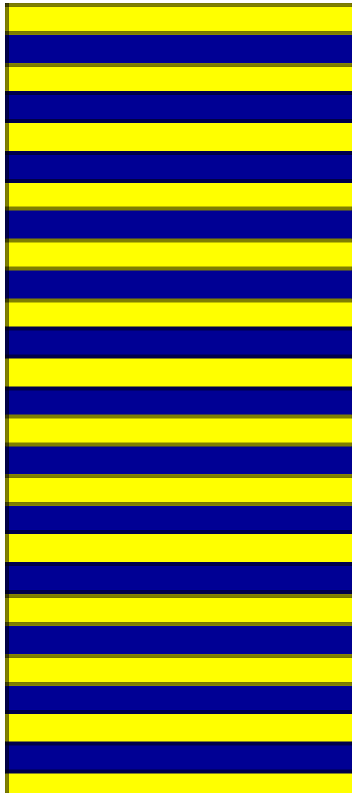
GEORGETOWN UNIVERSITY

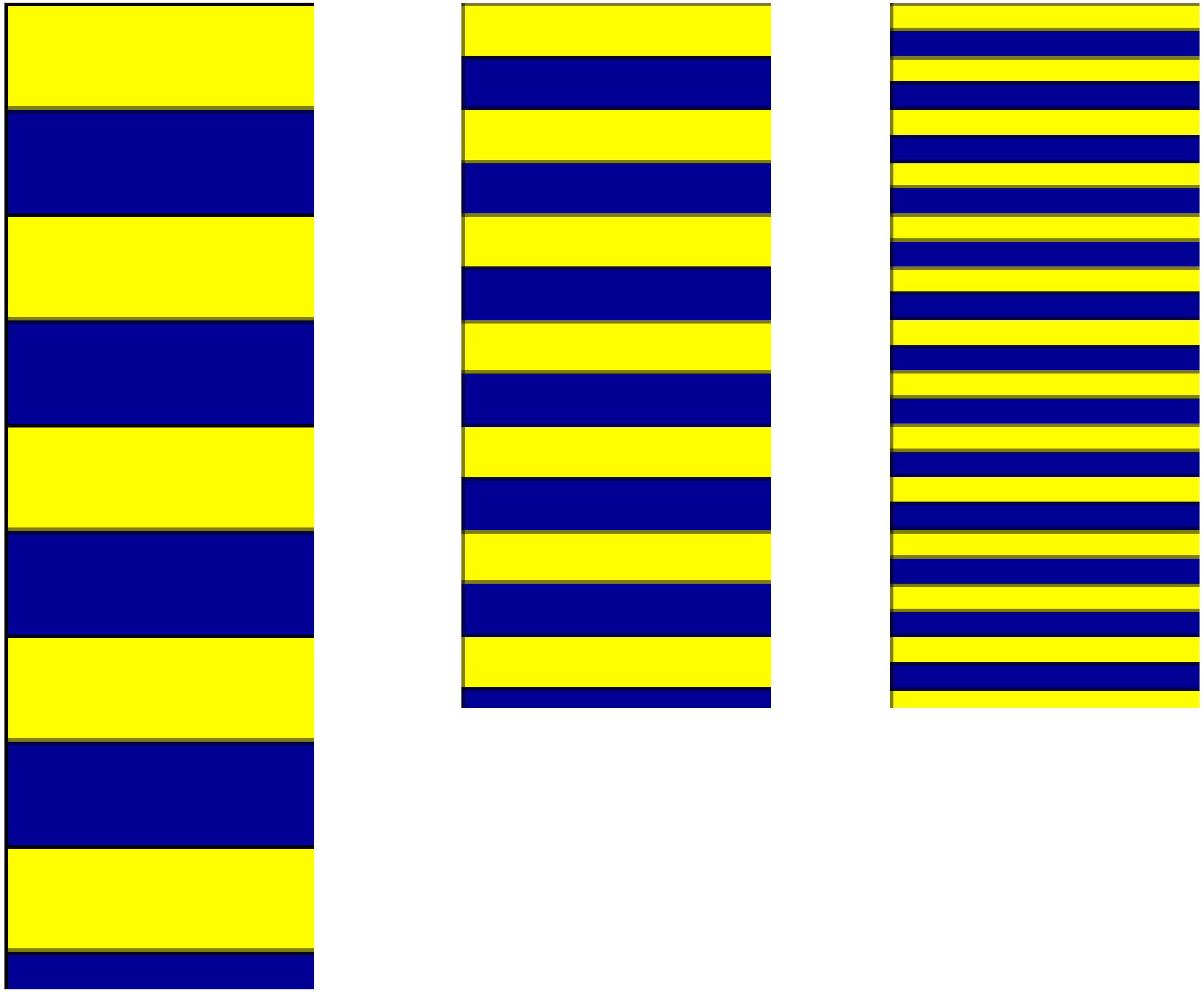


GEORGETOWN UNIVERSITY









Perception summary

- The mapping from radiance to perceived color is quite complex!
  - We throw away most of the data
  - We apply a logarithm
  - Brightness affected by pupil size
  - Brightness contrast and constancy effects
  - Afterimages

- The same is true for cameras
  - But we have tools to correct for these effects
    - Coming soon….

Outline

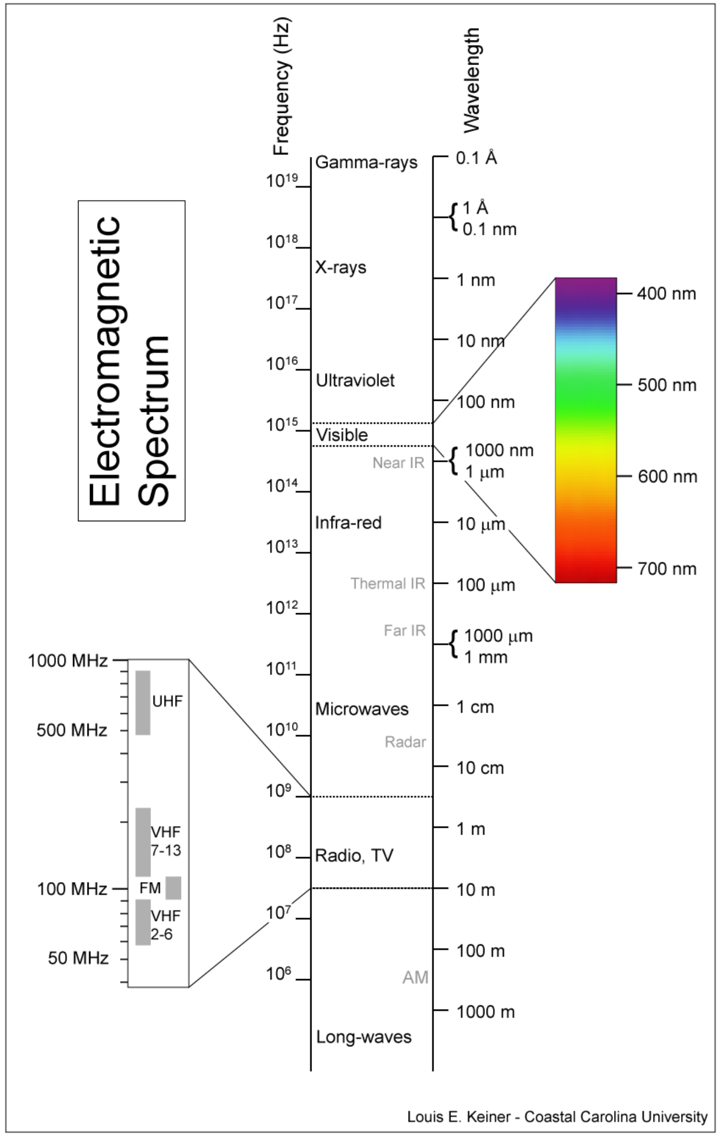
I. Human perception of color
II. Formalizing Color
III. Color Models

So why specify color numerically?

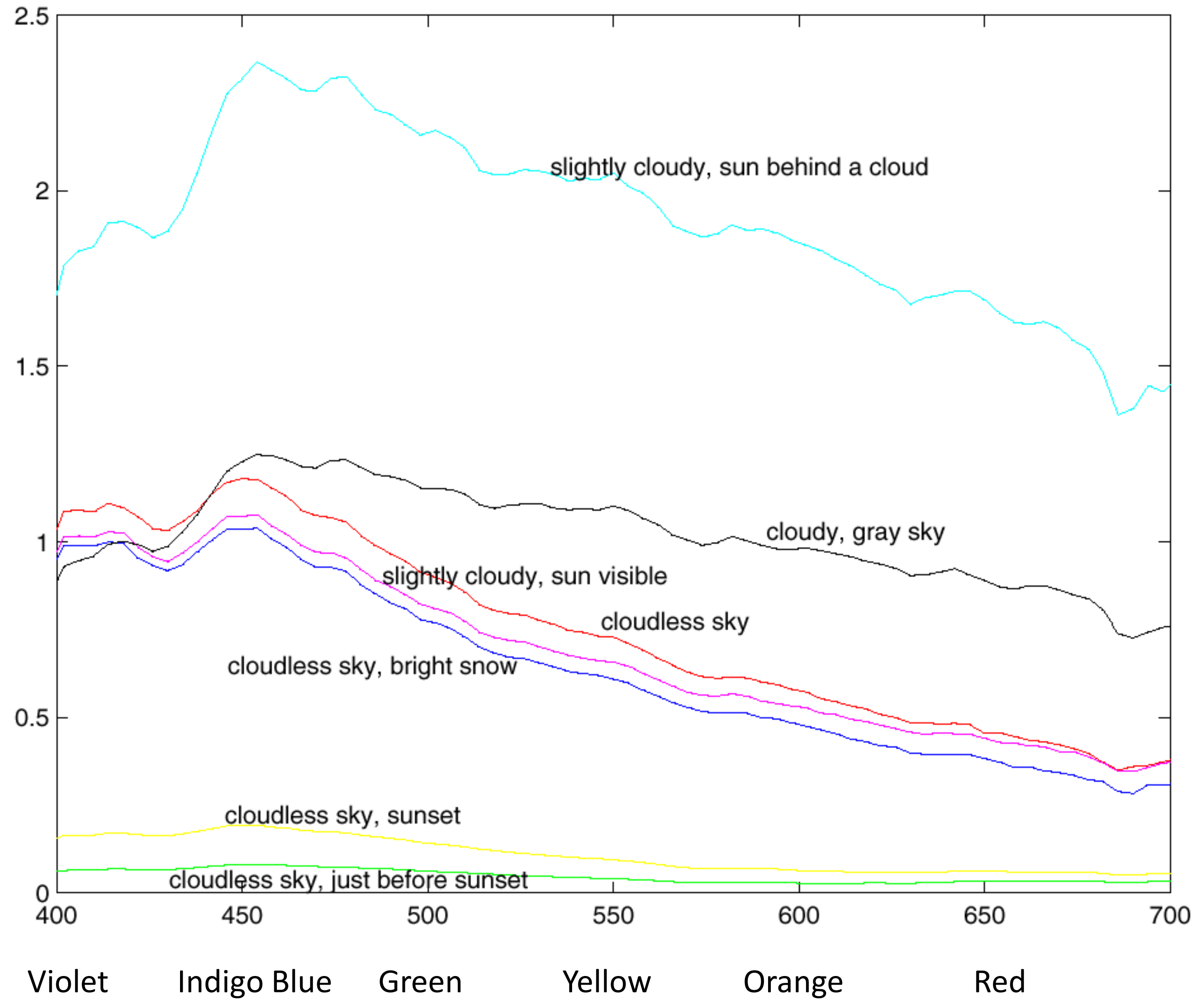
- Accurate color reproduction is commercially valuable
  - Many products are identified by color (“golden” arches;
- Few color names are widely recognized by English speakers -
  - About 10; other languages have fewer/more, but not many more.
  - It’s common to disagree on appropriate color names.
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  - How do we ensure that everyone sees the same color?

Visible light

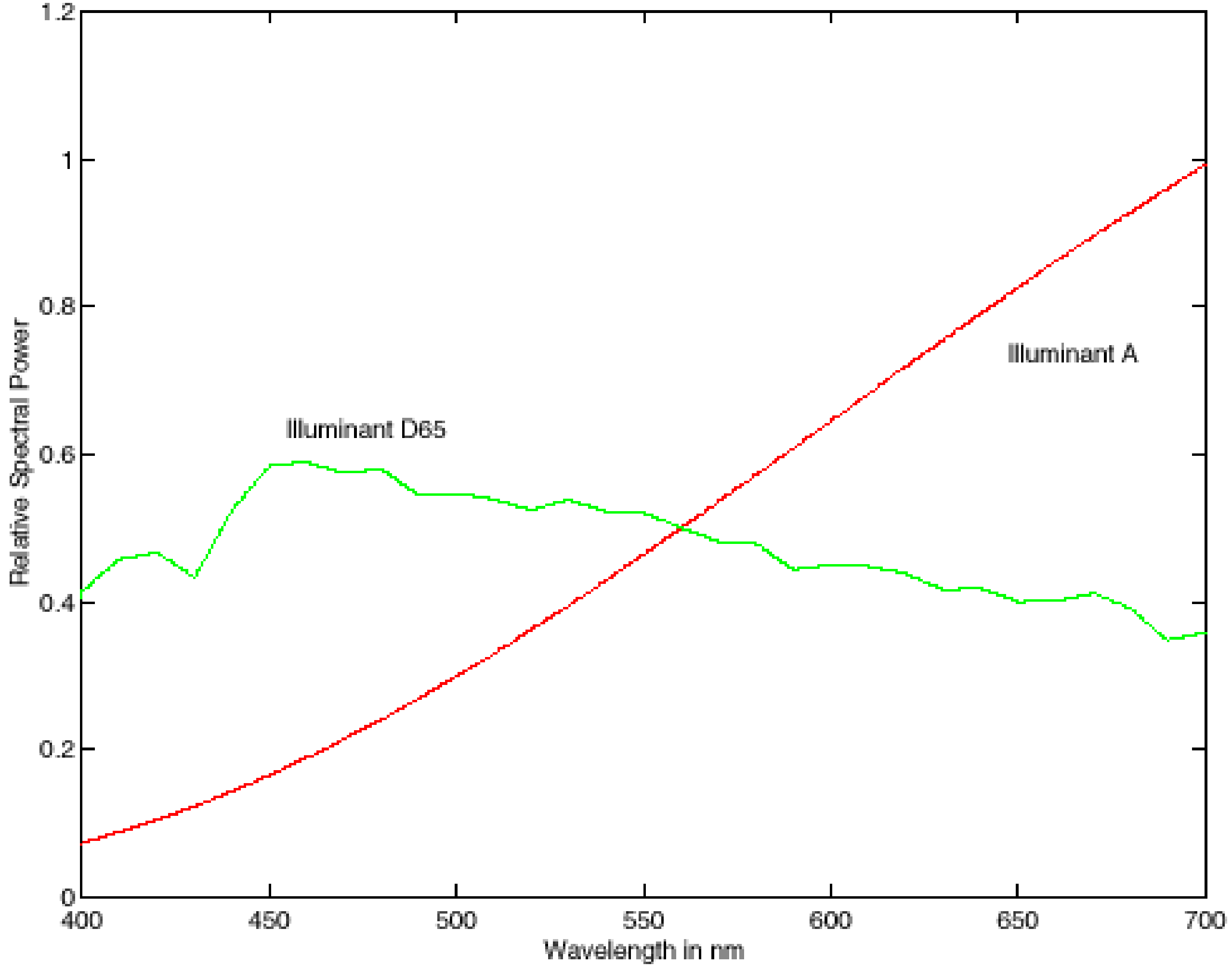
- This physics-based phenomenon is quantifiable



GEORGETOWN UNIVERSITY

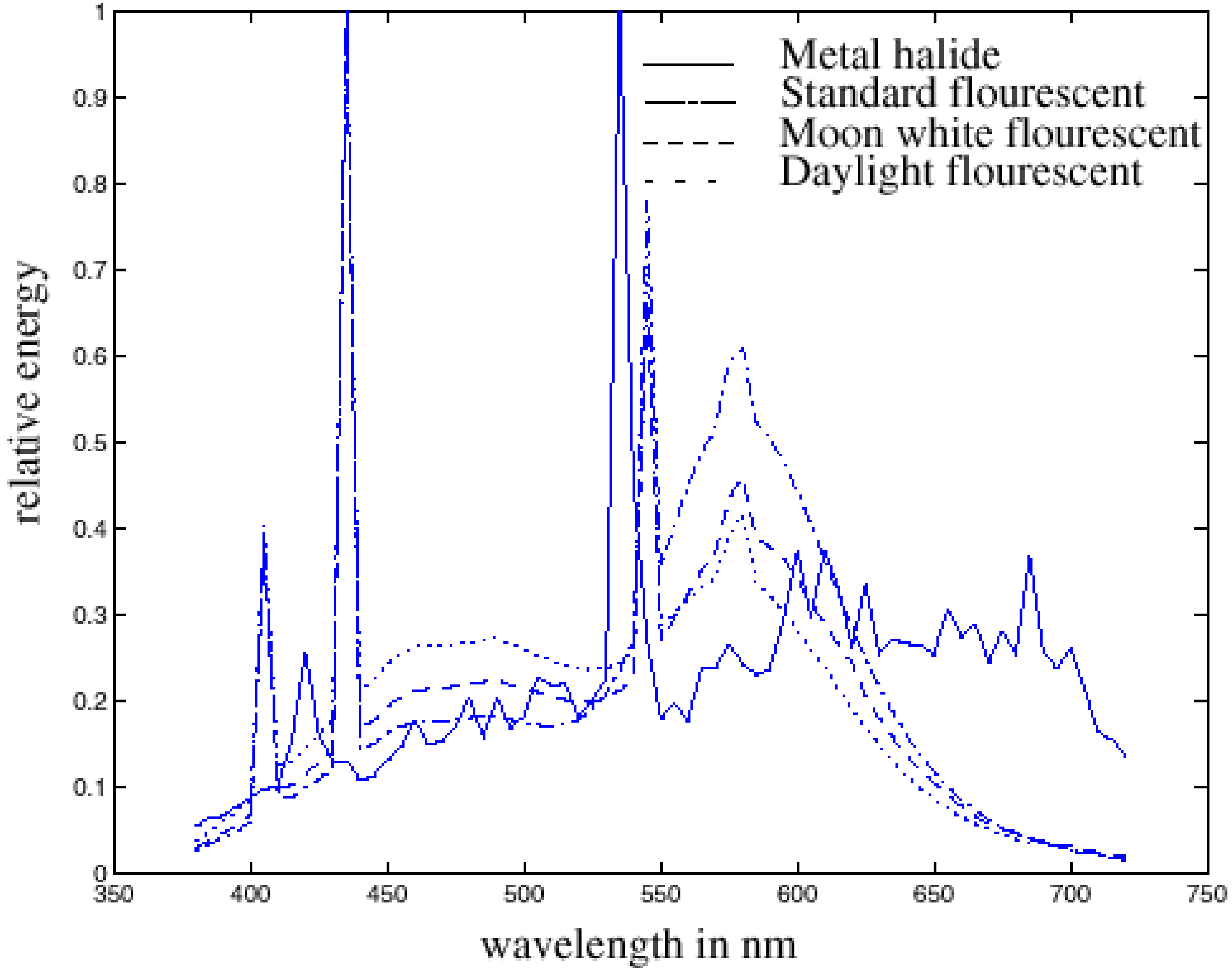


Measurements of relative spectral power of sunlight, made by J. Parkkinen and P. Silfsten. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the “colors of the rainbow”. Mnemonic is “Richard of York got blisters in Venice”.

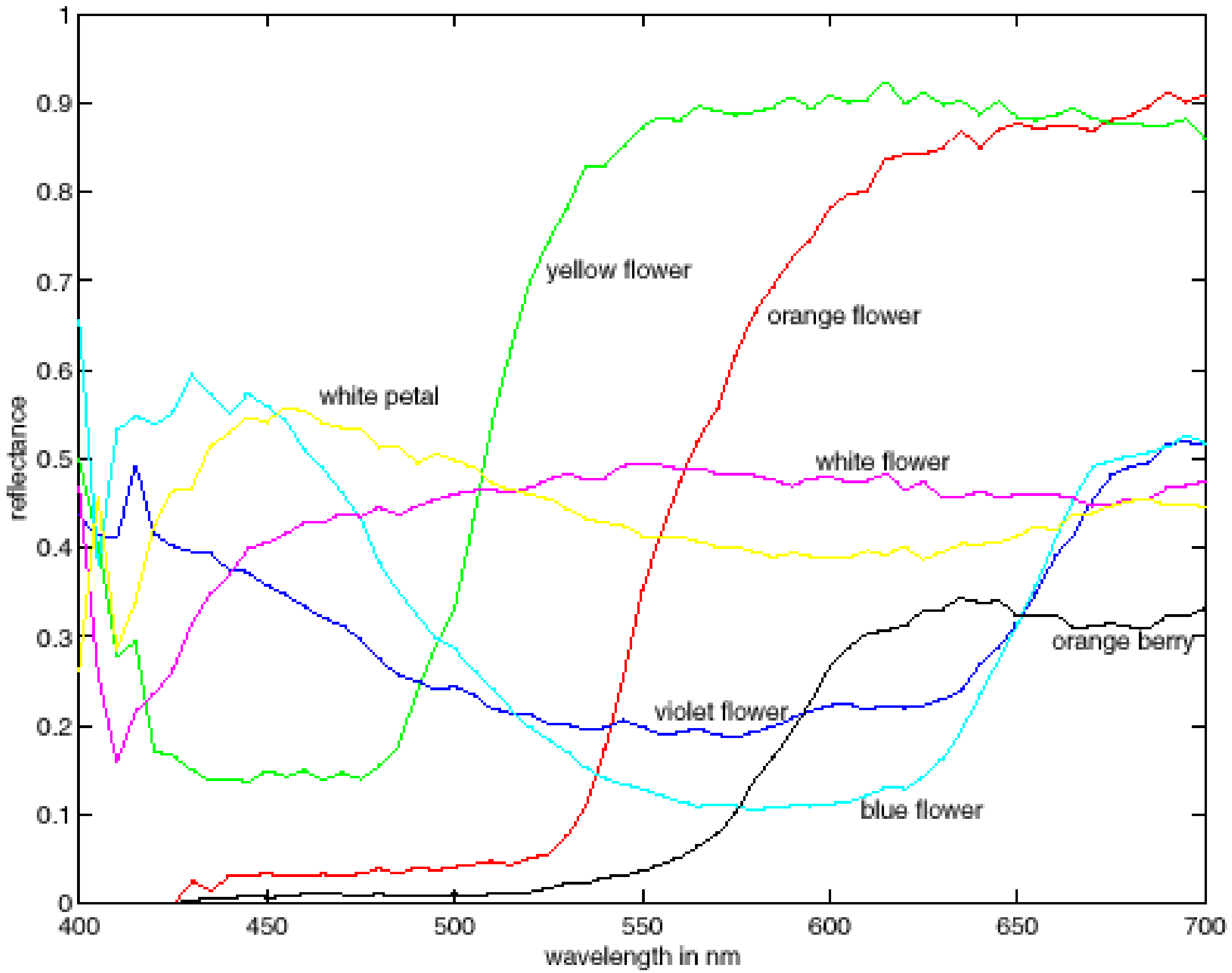


Violet Indigo Blue Green Yellow Orange Red

Relative spectral power of two standard illuminant models --- D65 models sunlight,and illuminant A models incandescent lamps. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength --- the "colors of the rainbow".



Measurements of relative spectral power of four different artificial illuminants, made by H.Sugiura. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm.



Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Quantifying Color

- “Visible” can be characterized by a spectral signature

- A spectral signature is a mapping from wavelength to observed intensity

Outline

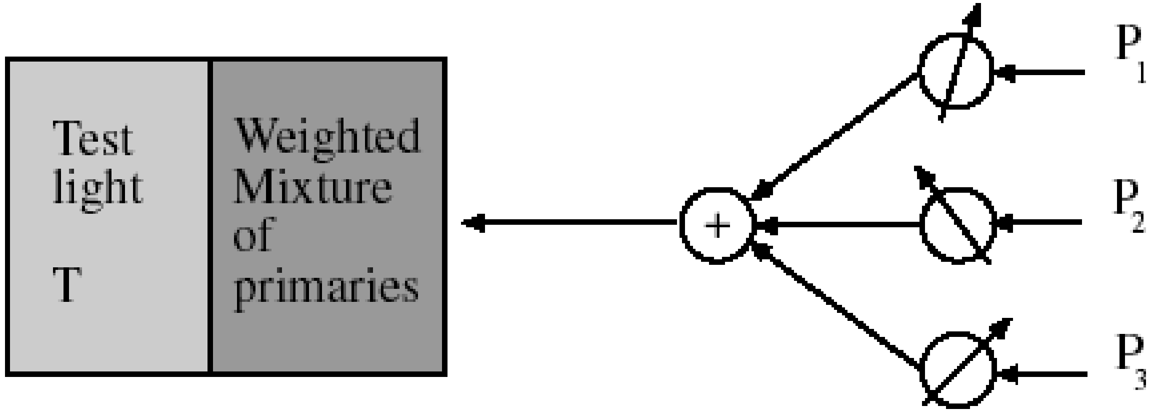
I. Human perception of color
II. Formalizing Color
III. Color Models

GEORGETOWN UNIVERSITY

Why specify color numerically?

- Accurate color reproduction is commercially valuable
  - Many products are identified by color (“golden” arches;
- Few color names are widely recognized by English speakers -
  - About 10; other languages have fewer/more, but not many more.
  - It’s common to disagree on appropriate color names.
- Color reproduction problems increased by prevalence of digital imaging - eg. digital libraries of art.
  - How do we ensure that everyone sees the same color?

Color matching experiments - I



- Show a split field to subjects; one side shows the light whose color one wants to measure, the other a weighted mixture of primaries (fixed lights).

Color matching experiments - II

- Many colors can be represented as a mixture of A, B, C
- write

  M=a A + b B + c C

  where the = sign should be read as “matches”
- This is **additive** matching.
- Gives a color description system - two people who agree on A, B, C need only supply (a, b, c) to describe a color.

Subtractive matching

- Some colors can't be matched like this: instead, must write

M+a A = b B+c C

- This is **subtractive** matching.
- Interpret this as (-a, b, c)
- Problem for building monitors: Choose R, G, B such that positive linear combinations match a large set of colors

Color Matching

- Additive and Subtractive Models
  - Note: Colors are not “created” by combining (adding and subtracting) wavelengths

- But I thought primary colors can be used to create all colors?
  - Based on human visual system.
  - Recall the eye has 3 types of cones (which respond to different portions of color spectrum) used to perceive all visible color.

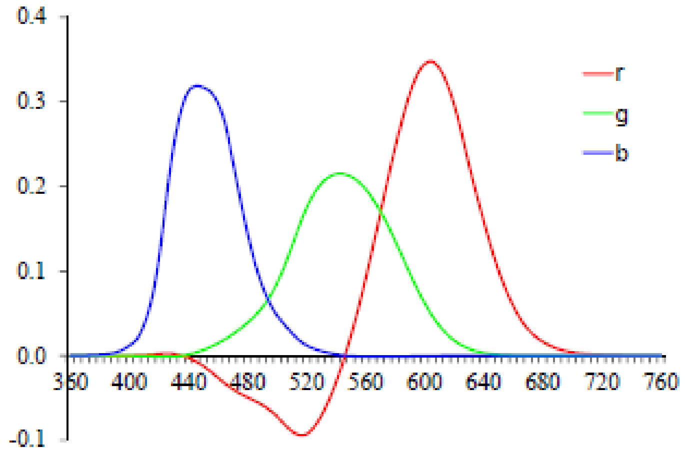
- Although color can be technically specified by wavelength, it is often considered to be “in your head” – based on perception.

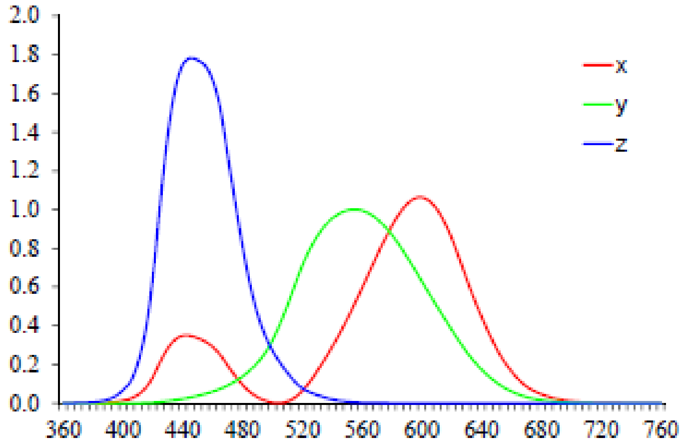
Common Color Spaces

- Color spaces are therefore often based on mixtures of 3 primaries.
  –

- RGB Color Space: Given the nature of these mixings, the chosen primary spectra may have negative components
  – For example: to correctly perceive colors in the blue-green range, some “red” is often subtracted.

- XYZ Color Space is non-negative.





GEORGETOWN UNIVERSITY

Color Vectors

- Thus each point or pixel is a 3-d spectral vector (or 3-tuple)
- Note: we can transform from RGB to XYZ

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

- The pixels may be unnormalized. Normalize to get a unit color vector.

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}$$

Summary

- Color appearance is a complex process.

- Color can be quantified using albedo or spectral signatures.

- Color Models:
  - Additive or Subtractive Models
  - Color Space Models
    - RGB
    - XYZ

- The illusion of color monitors
  - https://jakubmarian.com/the-illusion-of-rgb-screens/

Appendix

Jeremy Bolton, PhD
Assistant Teaching Professor

GEORGETOWN UNIVERSITY