

Color

# So far in the course

- Images formed by cameras
  - Image intensity related to scene brightness
  - 2D images related to 3D world by projection
- Image understanding/Computer vision is Inference
- Inference uses various cues
  - Geometry
  - Patterns in the distribution of intensities “Features”
- Extraction of “low-level” features
  - Edges, Corners, Texture
- Linear Filters
  - Fourier Analysis, Convolution
  - Noise smoothing
- Grouping of features

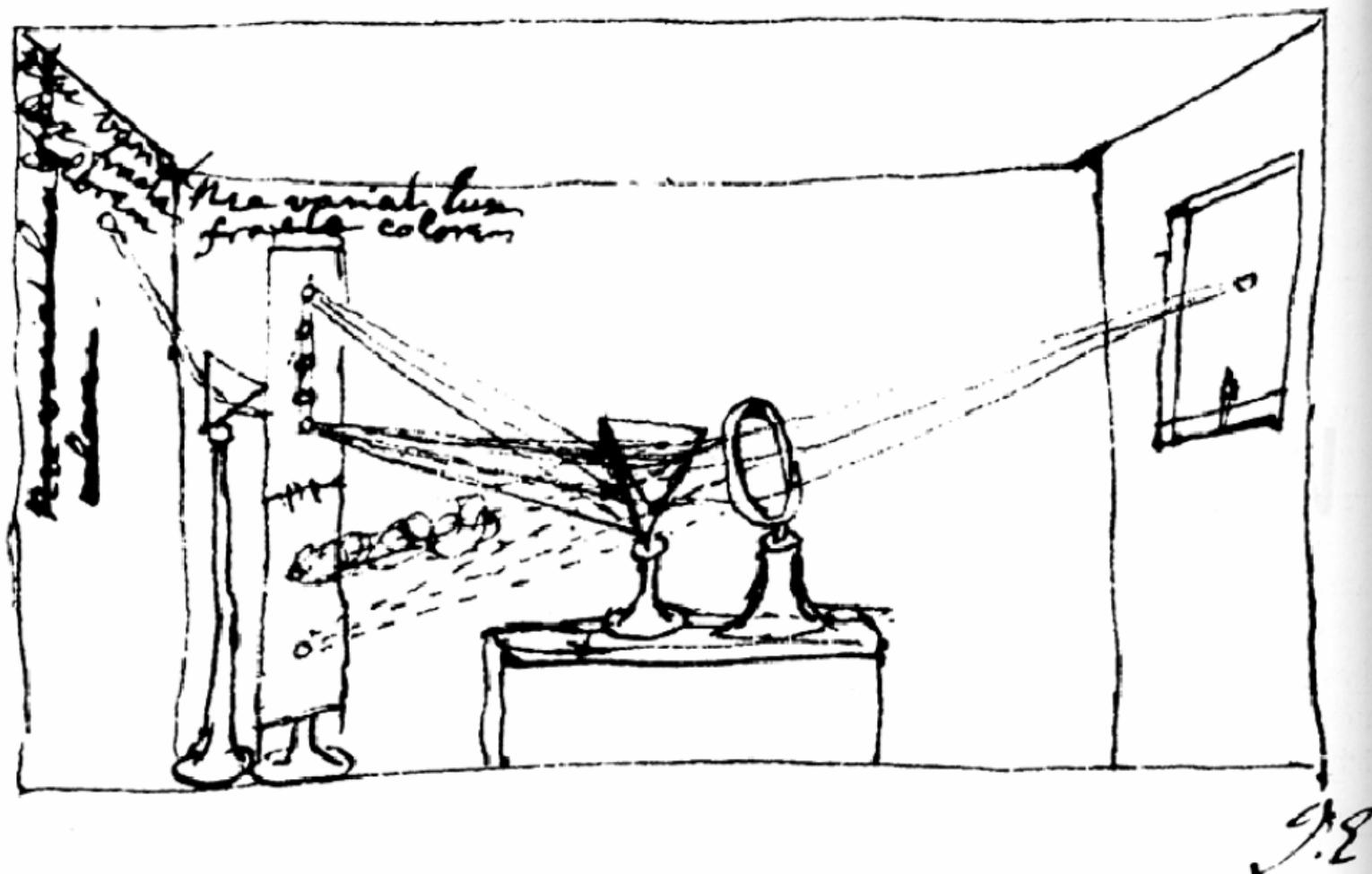
# Intensity/Grayscale images

- All analysis thus far has focused on grayscale images
- This class: color images
- Color is important for human perception of objects, for material identification, for determining the time of day, and even perhaps with psychological well-being!
- Color perception depends on both the physics of light and complex processing by the eye-brain which integrates properties of the stimulus with experience.
- With it becoming cheaper to capture color imagery and with faster processing, color information can be used effectively for machine vision.

# Why do we need color?

- Biological systems:
  - 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 someone's appearance looks normal/healthy.
  - To compress images
- Machine Systems
  - Color provides more information per pixel, enabling more inference to be done

# Color

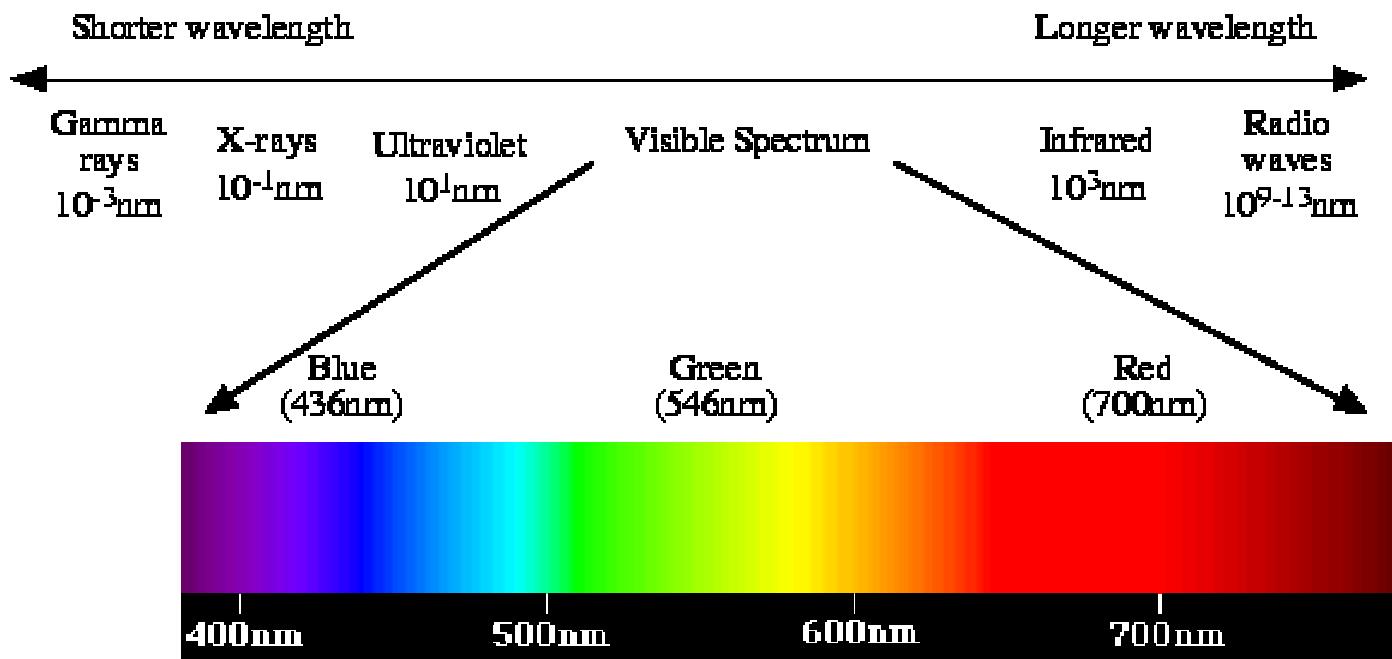


4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

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

# Electromagnetic Spectrum

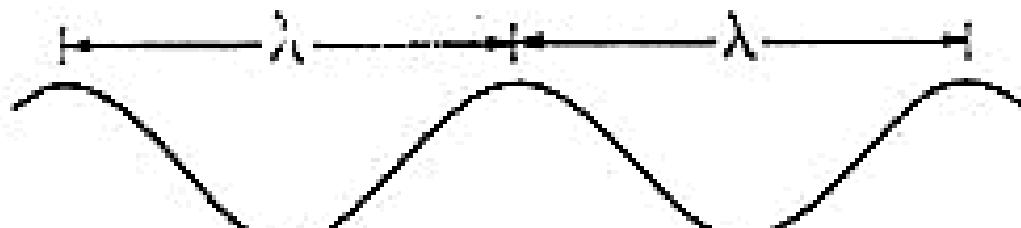
- Light is just one part of electromagnetic spectrum
- X rays 0.1 nanometer
- Radio waves 1 meter or more
- Light 380 to 770 nanometers (1000 nm = 1/100 paper sheet)



# *Waves*

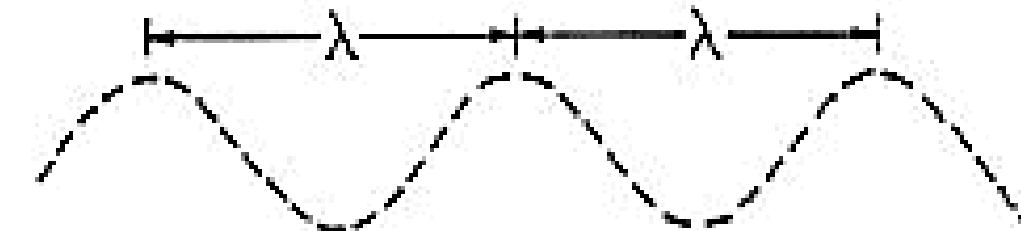
Red light:

$$\lambda = 680 \text{ nm}$$



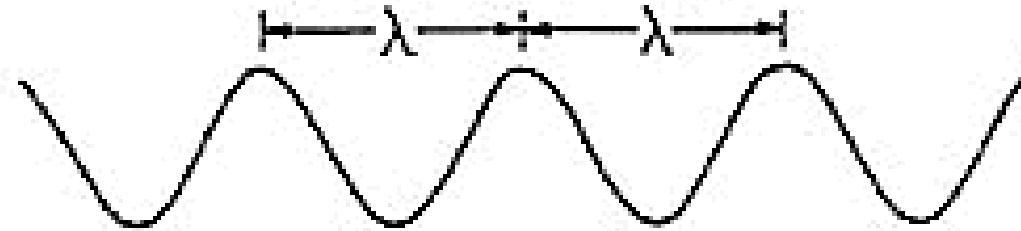
Yellow-green light:

$$\lambda = 550 \text{ nm}$$



Violet light:

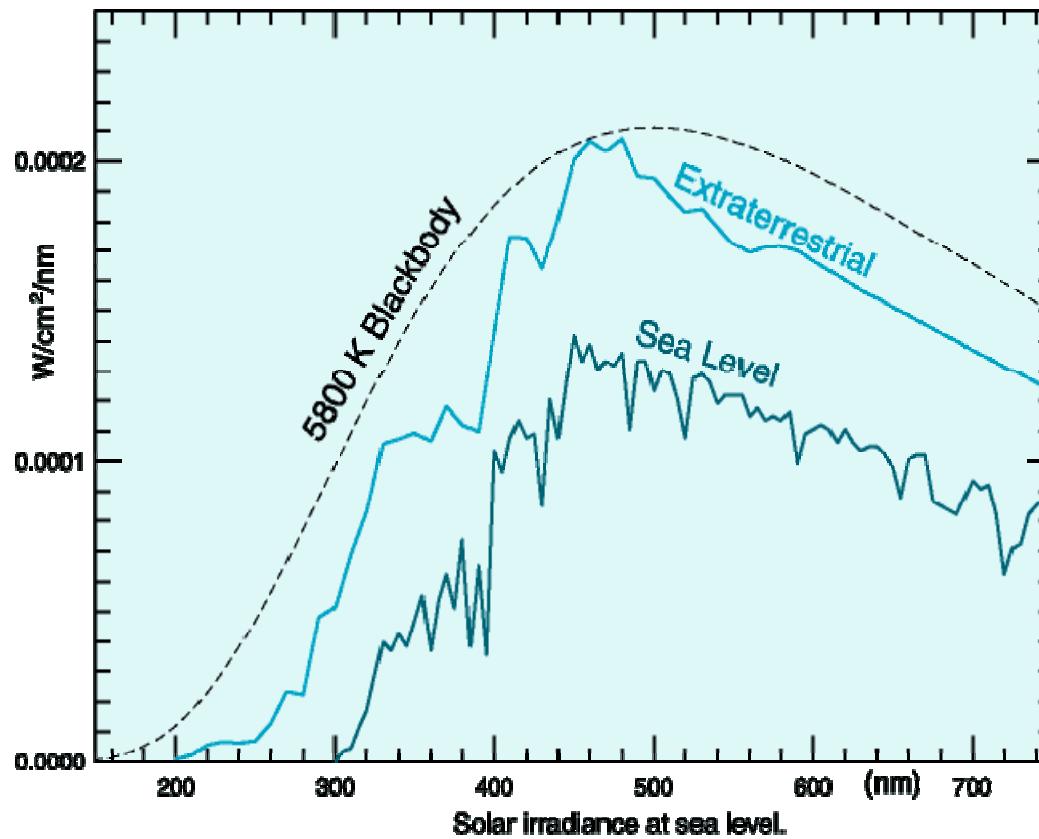
$$\lambda = 410 \text{ nm}$$



$\lambda = \text{wavelength}$

# Spectral Description of Light

- A light source can be described by its spectral power distribution
  - relative power emitted at each wavelength



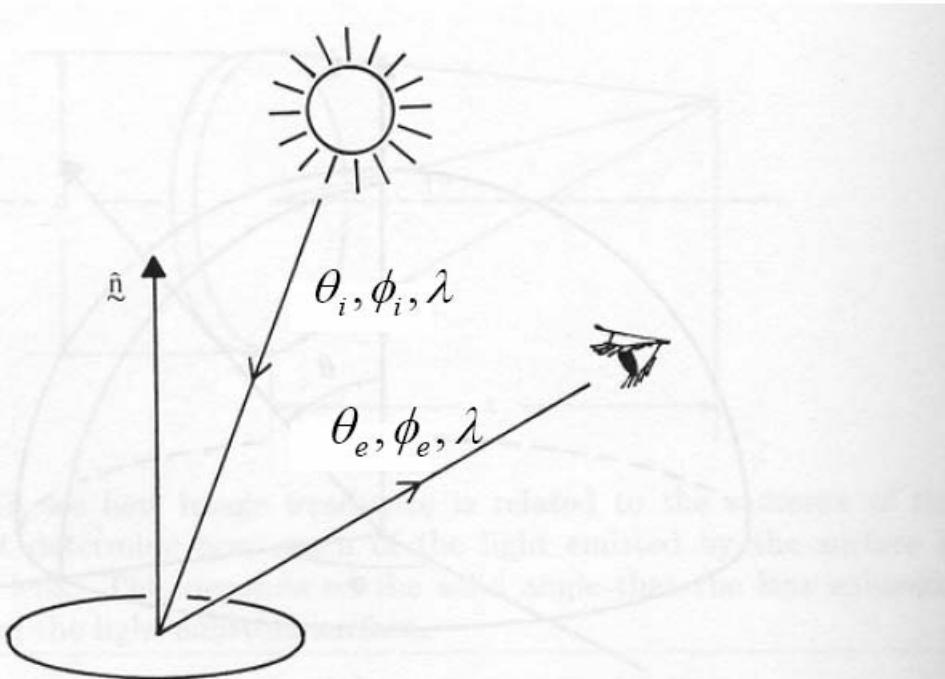
# Color

- So we know that the light coming off sources has a distribution of frequencies ...How about scattered light?
- Recall from Lecture 2
  - Pixel Intensity is related to scene brightness
- Same arguments follow ... except it is now “per unit wavelength”
- All units are now “per unit wavelength”
- All terms are now “spectral”
- Radiance becomes spectral radiance—watts per square meter per steradian per unit wavelength
- Irradiance becomes spectral irradiance—watts per square meter per unit wavelength

# Image Irradiance and Scene Radiance

$$E(\lambda) = \frac{\pi}{4} \left( \frac{D}{f} \right)^2 \cos^4 \alpha L(\lambda)$$

- Image irradiance  $E$  is proportional to scene radiance
- *Brighter scene points produce brighter pixels*
- Image irradiance is proportional to inverse of square of f-number ( $f/D$ ), is larger for small f-number
- What about color?
- This relation now applies on a per-color basis



Horn, 1986

**Figure 10-7.** The bidirectional reflectance distribution function is the ratio of the radiance of the surface patch as viewed from the direction  $(\theta_e, \phi_e)$  to the irradiance resulting from illumination from the direction  $(\theta_i, \phi_i)$ .

Spectral radiance

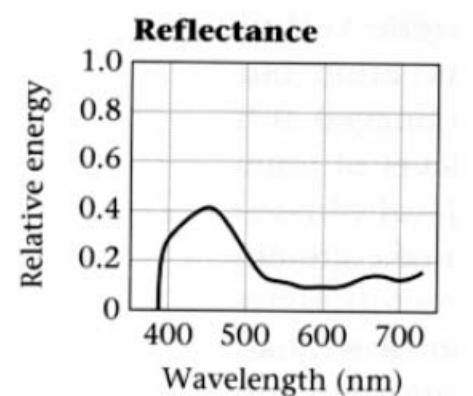
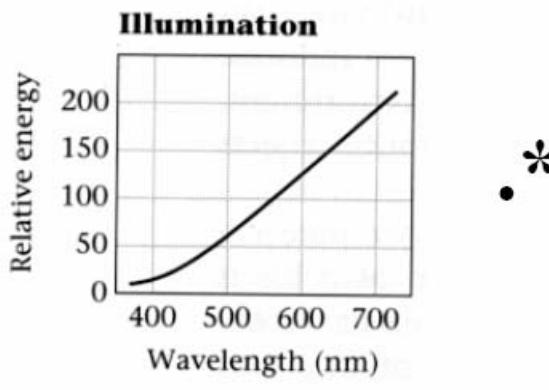
$$BRDF = f(\theta_i, \phi_i, \theta_e, \phi_e, \lambda) = \frac{L(\theta_e, \phi_e, \lambda)}{E(\theta_i, \phi_i, \lambda)}$$

Spectral irradiance

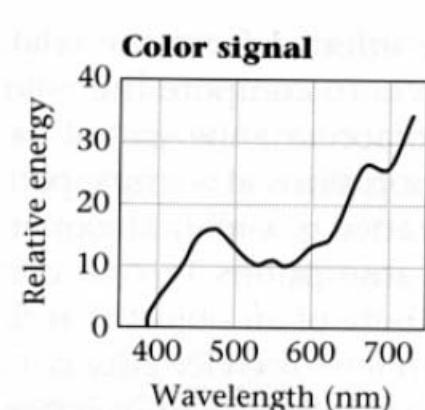
# Simplified rendering models: reflectance



Often are more interested in relative spectral composition than in overall intensity, so the spectral BRDF computation simplifies a wavelength-by-wavelength multiplication of relative energies.

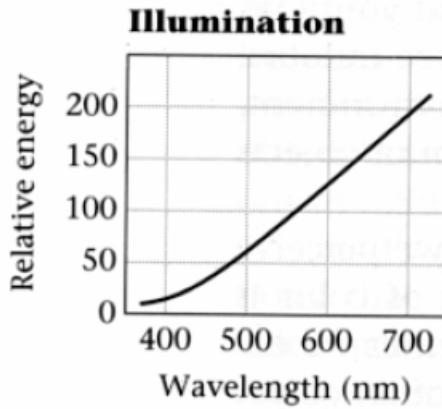
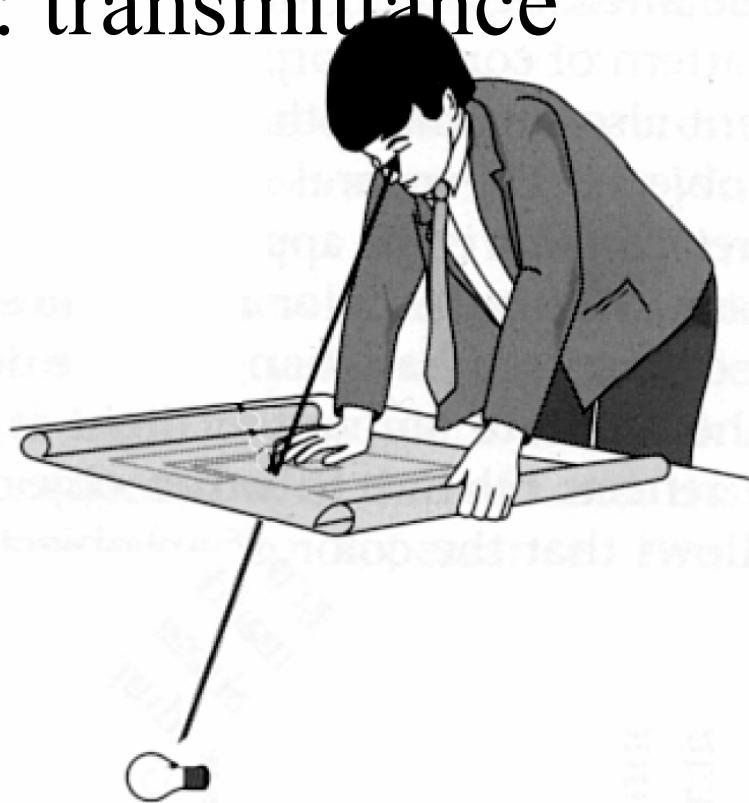


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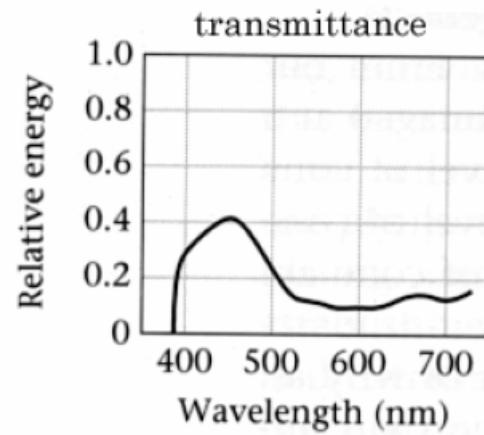


# Simplified rendering models: transmittance

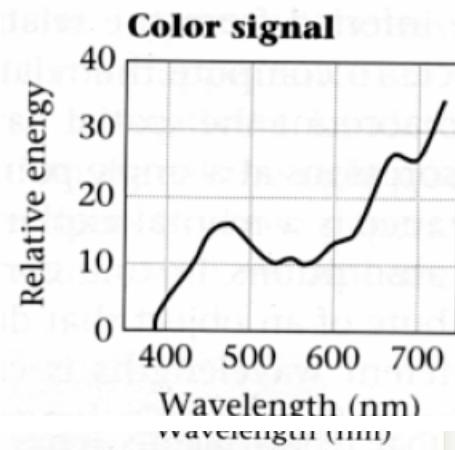
These models give us the spectral composition of the light reaching the eye after interacting with objects



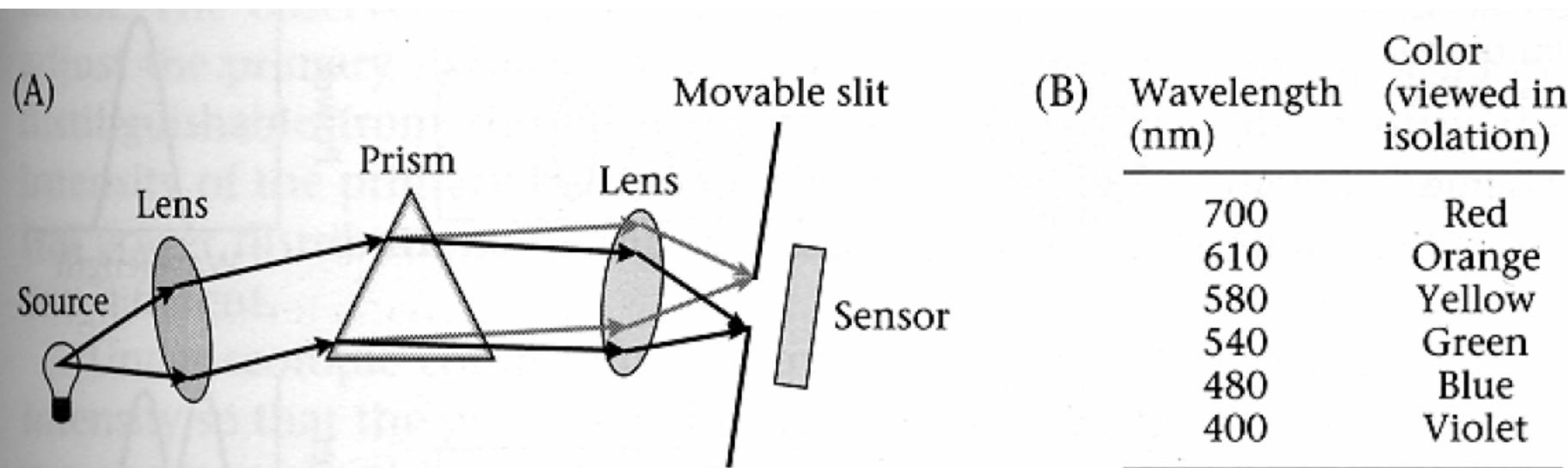
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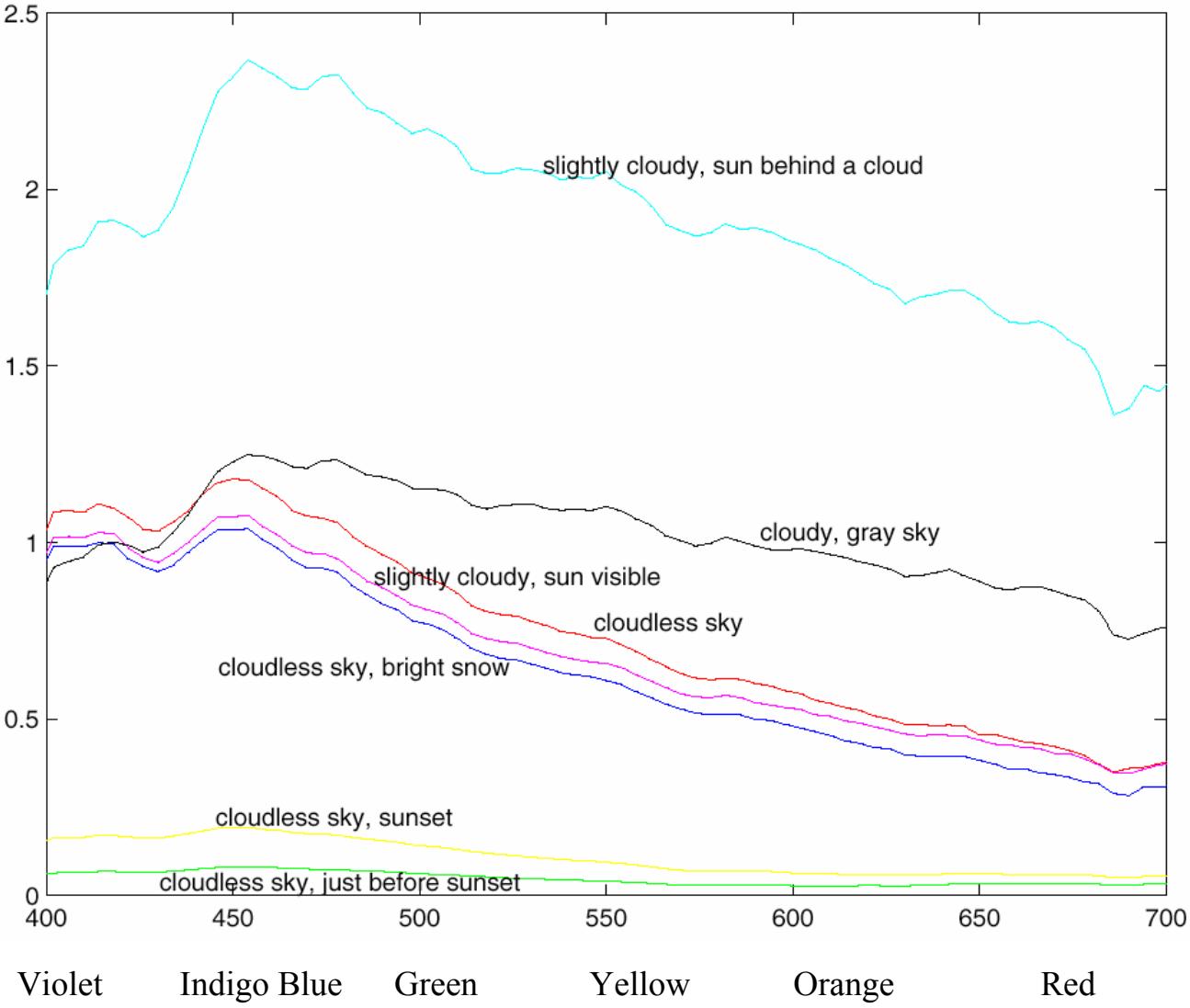
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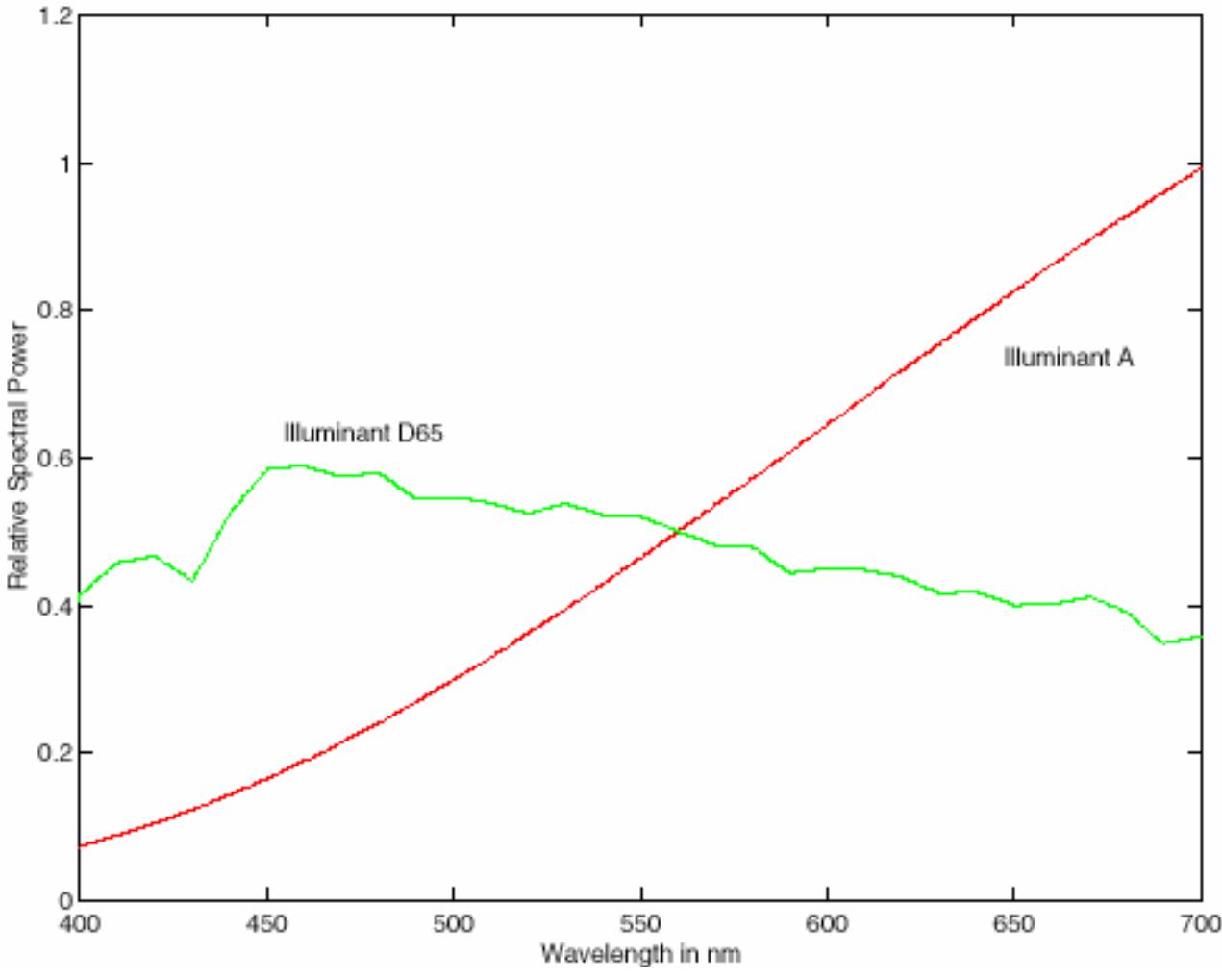
# Spectrophotometer: measures source characteristics



4.2 A SPECTRORADIOMETER is used to measure the spectral power distribution of light. (A) A schematic design of a spectroradiometer includes a means for separating the input light into its different wavelengths and a detector for measuring the energy at each of the separate wavelengths. (B) The color names associated with the appearance of lights at a variety of wavelengths are shown. After Wyszecki and Stiles, 1982.



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”.

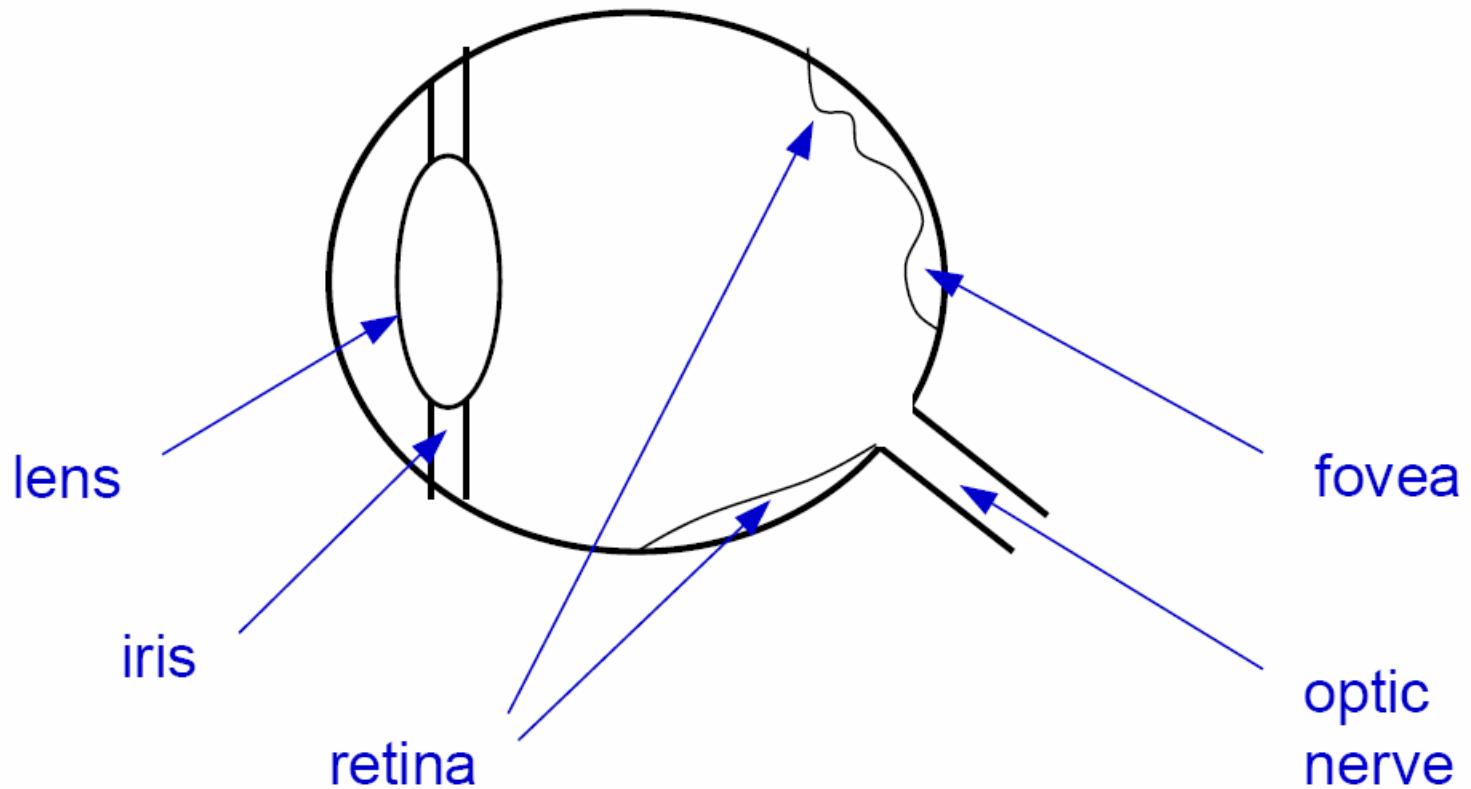


Violet      Indigo Blue      Green      Yellow      Orange      Red

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”.

# How do we see color?

- Our sensors do not return frequency vs. intensity relationships
  - Would require too many sensors.
  - Recall the structure of the eye



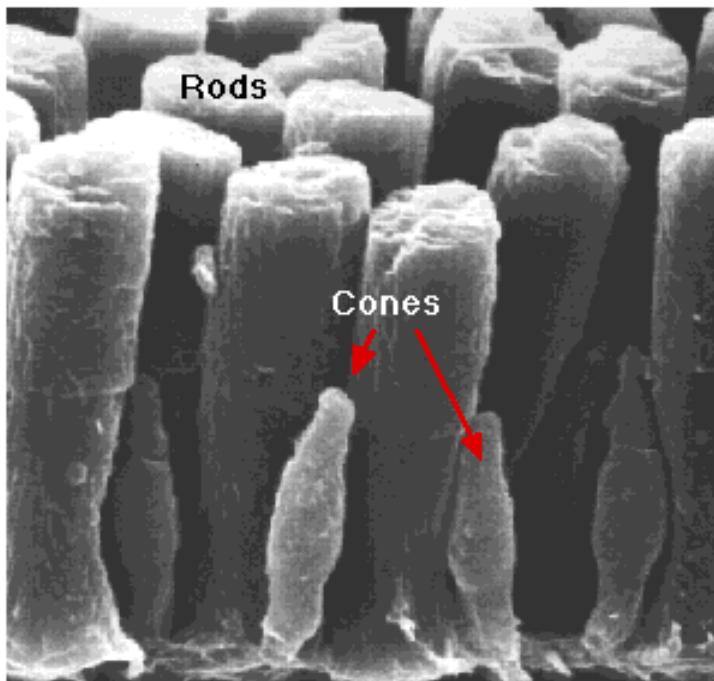
# The Eye

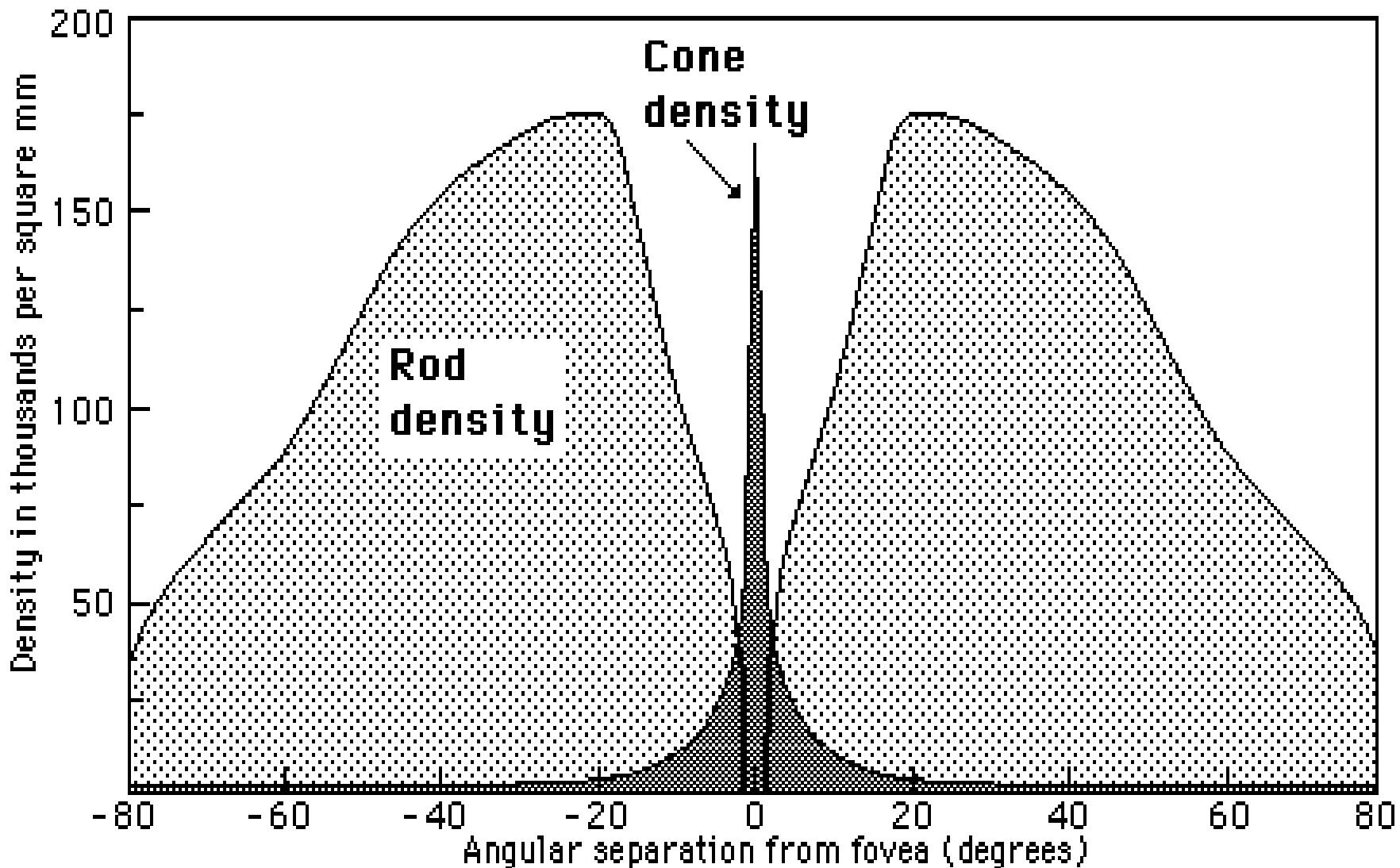
- Light is an electromagnetic wave
  - with wavelength of 350nm to 780nm that stimulates human visual response
- Expressed as spectral energy distribution  $I(\lambda)$ 
  - visual system operates on 10 orders of magnitude of illumination range

# *Two Types of Photoreceptors*

- *Retina has Two Types of Photoreceptors*
- Rods
  - long and thin
  - large quantity ( $\sim 100$  million)
  - provide *scotopic* vision (i.e., at low illumination)
  - only extract luminance information
- Cones
  - short and thick, densely packed in fovea (center of retina)
  - much fewer ( $\sim 6.5$  million) and less sensitive
  - provide *photopic* vision (i.e., at higher illumination)
  - responsible for color vision
- Mesopic vision
  - *provided at intermediate illumination by both rod and cones*

# Cones and Rods



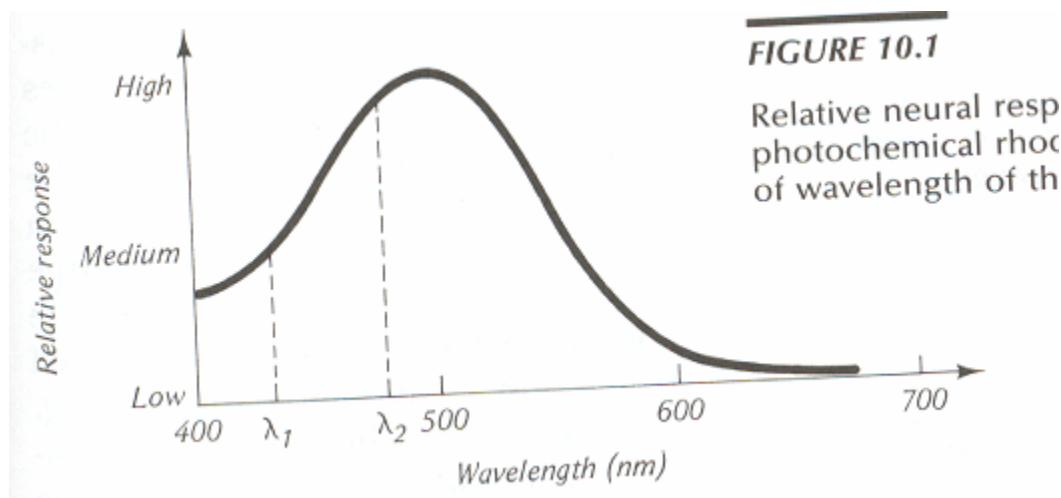


# Sensitivity

- **Cones:** slow, fine grain, like color film.
  - Need high level of light (photopic condition, day)
  - High density, high resolution.
- **Rods:** fast, coarse grain, black & white film
  - Low level of light (scotopic condition, at night)
- No color is obvious.
- **Adaptation:** Changing of retina sensitivity.
- The **fovea** defines the center of the retina, and is the region of highest visual acuity. The fovea is directed towards whatever object you wish to study most closely - this sentence, at the moment. In the fovea there are almost exclusively cones, and they are at their highest density.

# How do we see color?

- There is only one type of rod. It can only tell the intensity of the light, not its color.



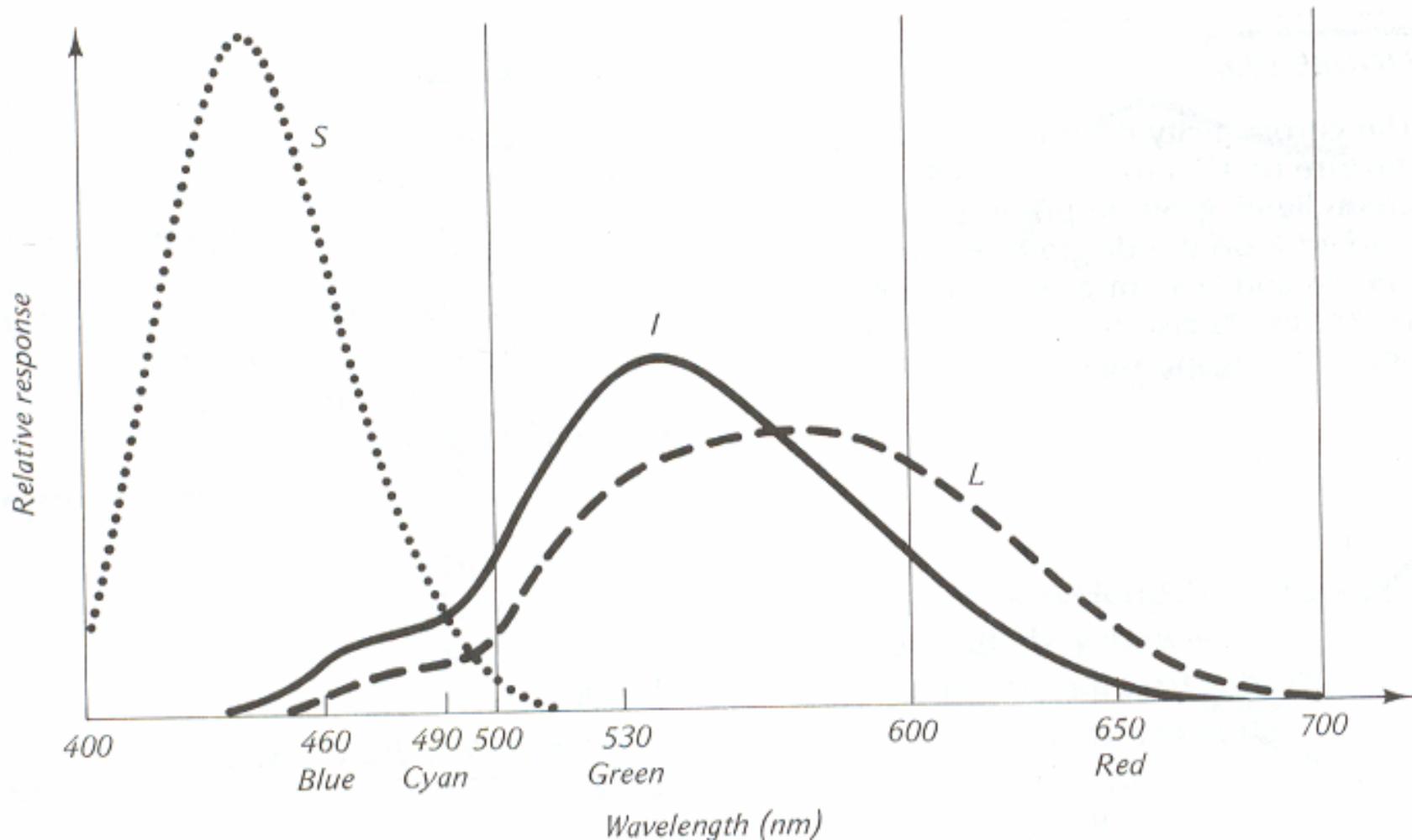
One cannot see color under scotopic conditions

# Three types of cones?

- Because the cones can differentiate colors, there must be more than one type of cones.
- Thomas Young (1801) postulated three types of cones --- **Trichromacy**, based on the three attributes of color: hue, saturation, lightness.
  - need three inputs to get three outputs
- Von Helmholtz postulated three response curves for the three types of cones:
  - **S-cones**: has the best response to short wavelength of light
  - **L-cones**: .... to long wave length of light
  - **I-cones**: ..... to the intermediate wavelength of light.
- Different colors correspond to different patterns of responses in these cones.

# Cone responses

- Color sensation arises from 3 types of neurochemical sensors in retina, the cones
  - Each with own response curve to light spectrum

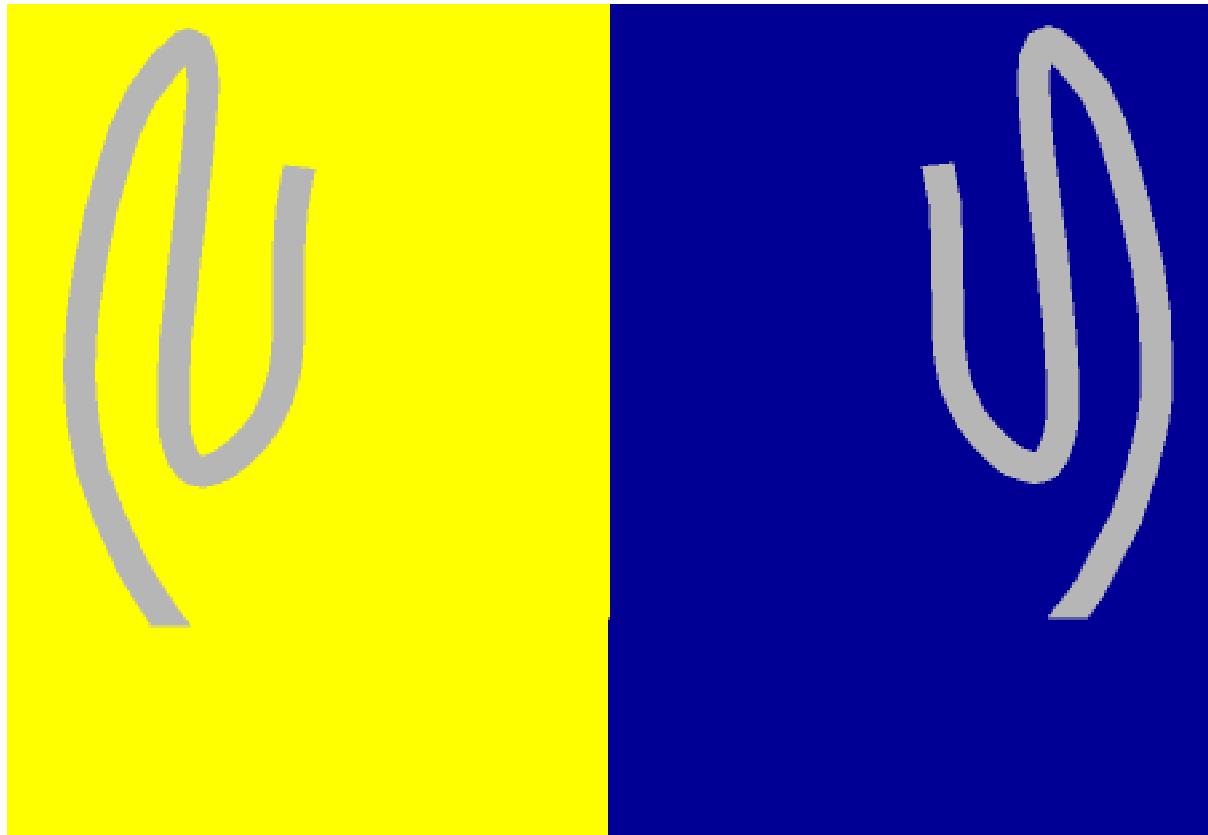


# Seeing with three sensors

- Color response is essentially due to a combination of the output from the three sensors
- If the same sensor output is achieved by different input colors, we will perceive the same color!
- Further, the sensitivity of the sensors changes with context ... and our perception also does
- Finally, mood, and higher functions also affect perceived color

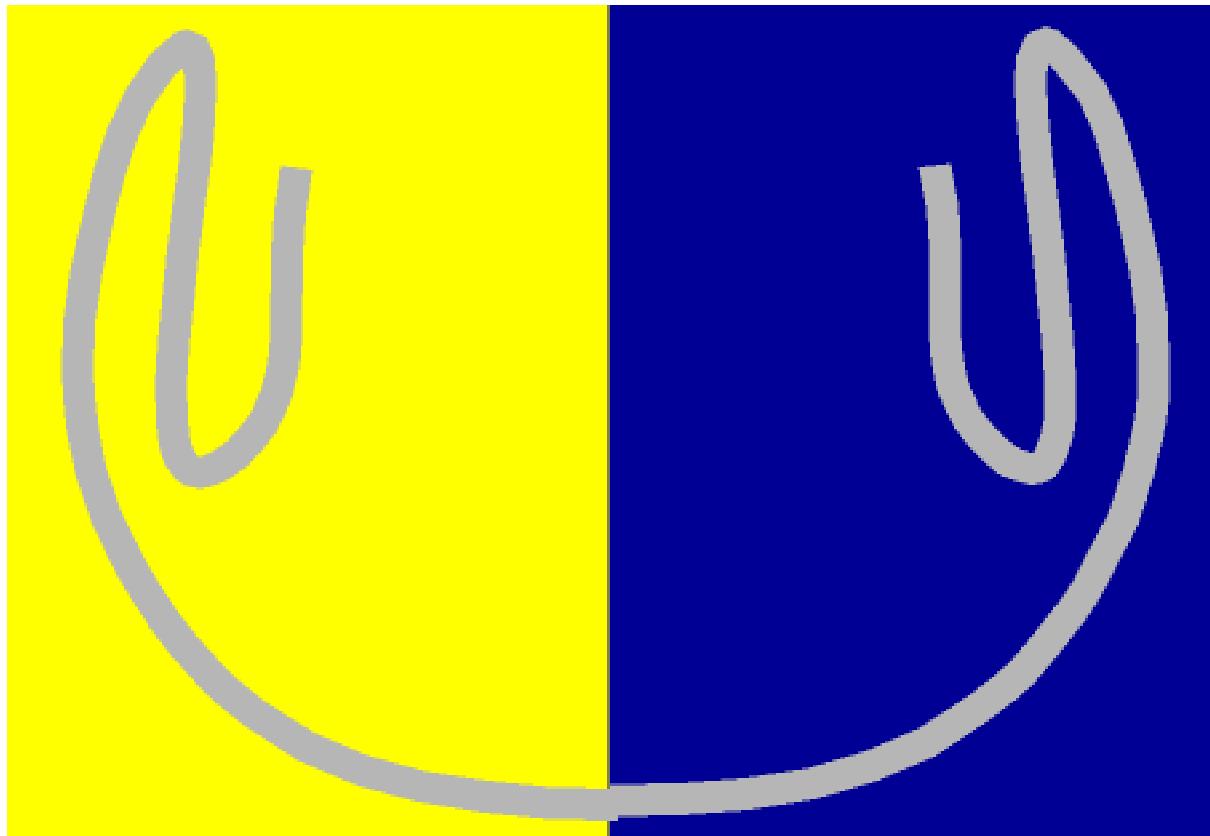
XXXXXX	GREEN	GREEN
XXXXXX	BLUE	BLUE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	RED	RED
XXXXXX	WHITE	WHITE
XXXXXX	PURPLE	PURPLE
XXXXXX	ORANGE	ORANGE
XXXXXX	BLUE	BLUE
XXXXXX	RED	RED
XXXXXX	GREEN	GREEN
XXXXXX	WHITE	WHITE
XXXXXX	YELLOW	YELLOW
XXXXXX	PURPLE	PURPLE
XXXXXX	RED	RED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

Are the two colors the same?



Previous Slide: The Stroop effect

Read all about it at <http://faculty.washington.edu/chudler/words.html>



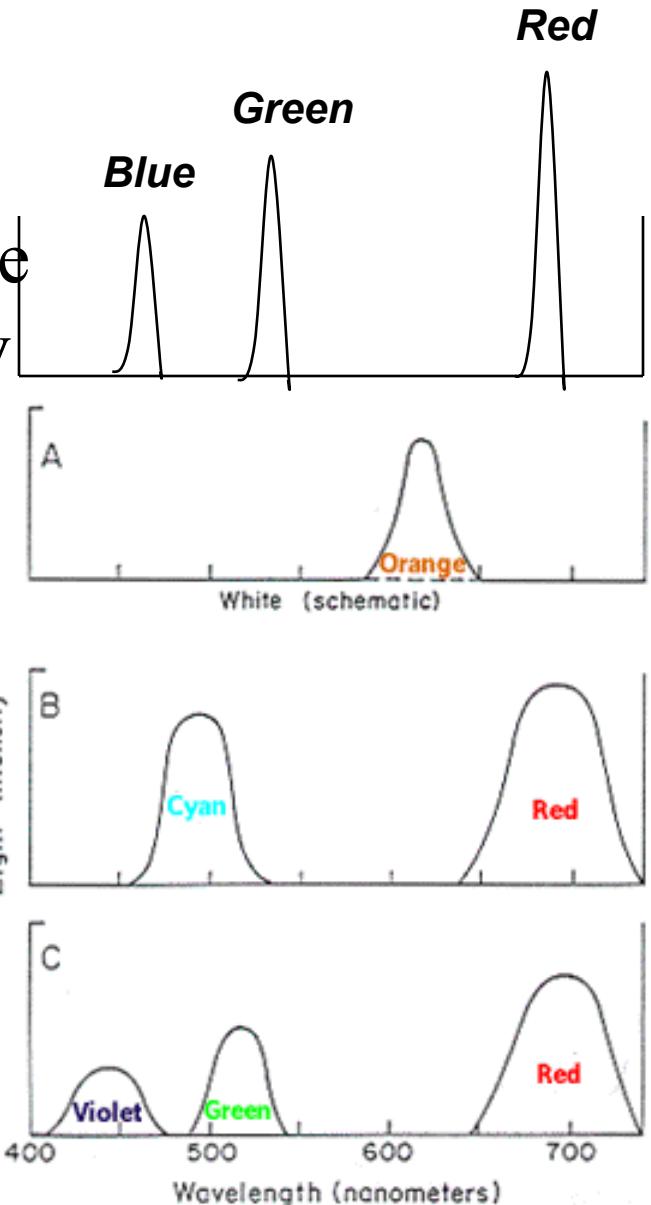
The colors are the same!

# Color models

- Can we take advantage of this mechanism of seeing colors?
- Yes ... we can take standard inputs and mix them in different proportions that reproduce all (or significant portions of) the types of output the sensors can achieve
- We can also use these to represent color images
- Choice of inputs are called “Color Models”
  - Red Green Blue
  - Hue Saturation Value

# Metameric colors

- Different light spectra can produce the same color impressions if they produce the same rod and cone firings
- Surprisingly, sensation of almost all colors can be recreated by weighting 3 color-function approximations

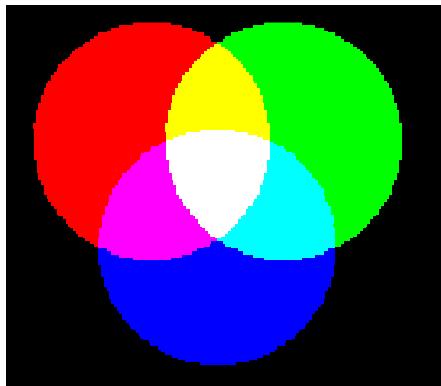


# Color Models

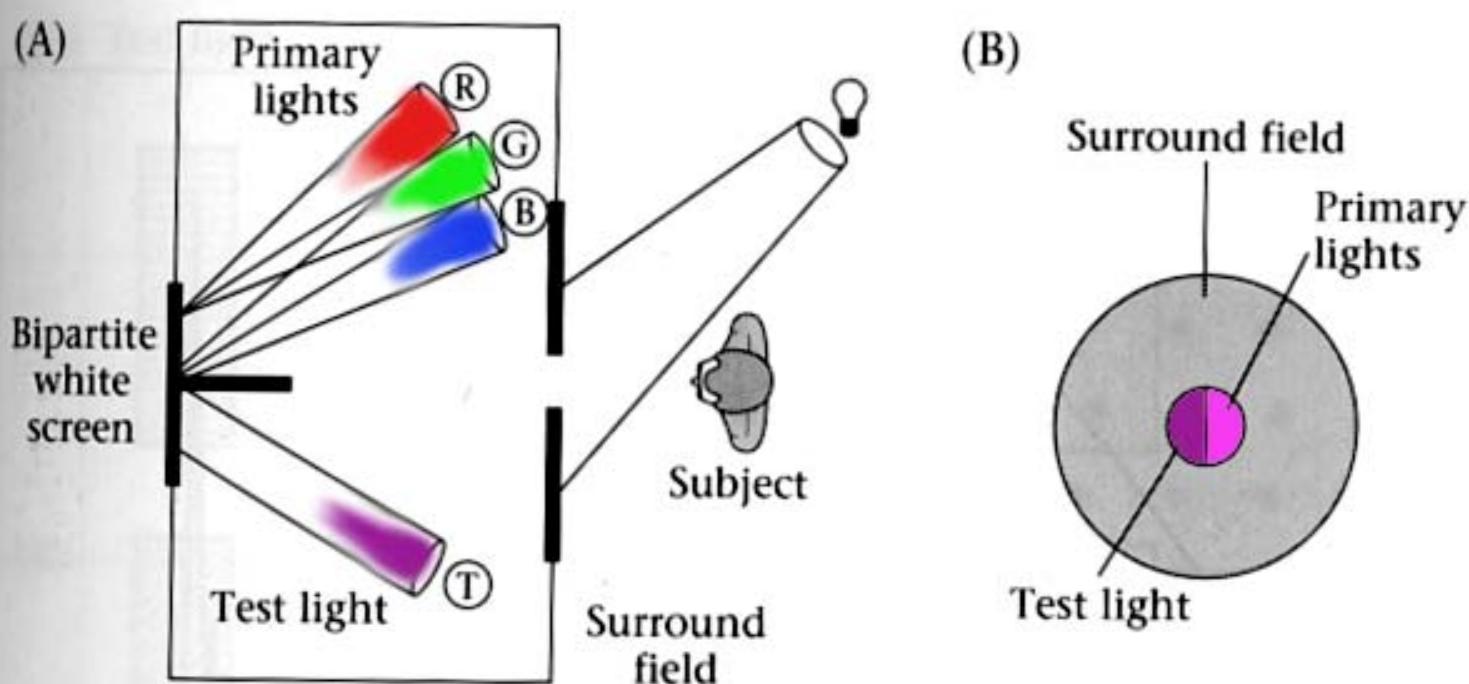
- Color Models are useful for driving hardware that generate or capture images
  - Monitors, TVs, video cameras
  - Color printers
- Since color sensation can be reproduced by combination of pure colors, it is simpler to use phosphors and CCD elements that have sharp and narrow spectra rather than combine overlapping spectra.
- Color models describe in what proportion to combine these spectra to produce different color impressions.

# Additive Color Models

- In monitors, 3 electron beams illuminate phosphors of 3 colors that act as additive light sources
- The powers of these beams are controlled by the components of colors described by the R,G,B model

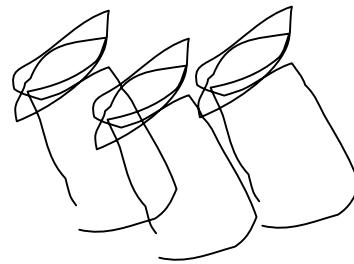
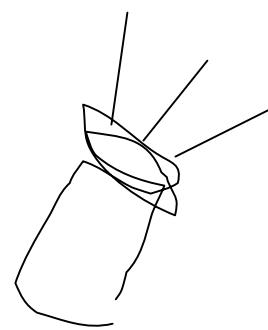
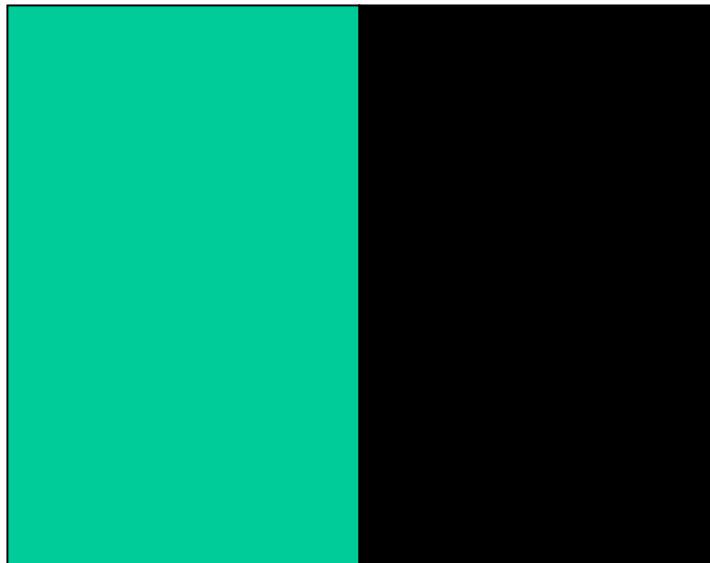


# Color matching experiment

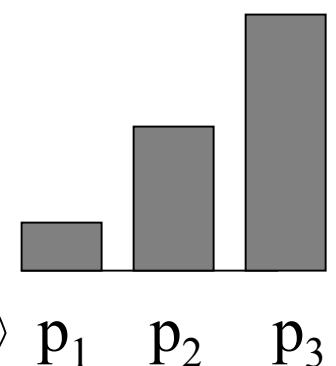
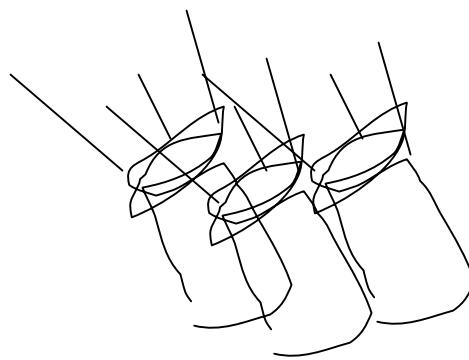
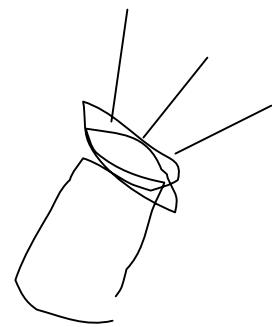
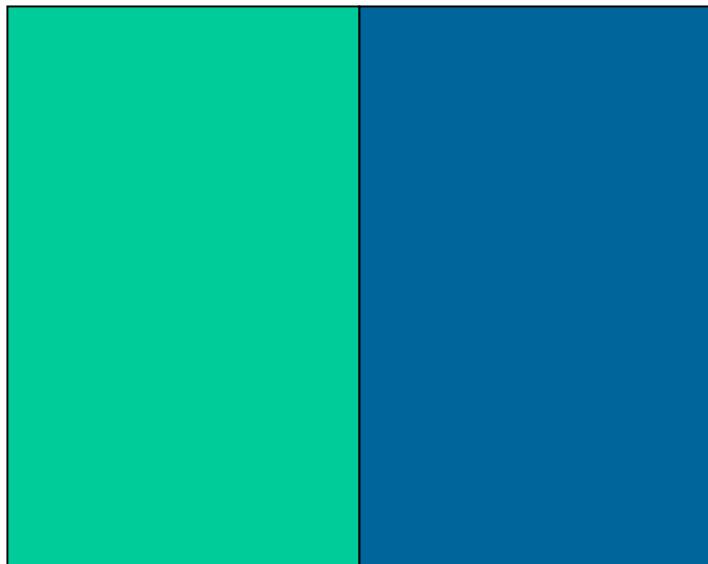


**4.10 THE COLOR-MATCHING EXPERIMENT.** The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

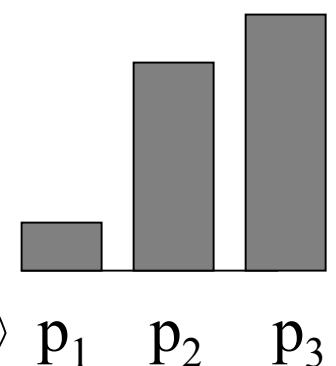
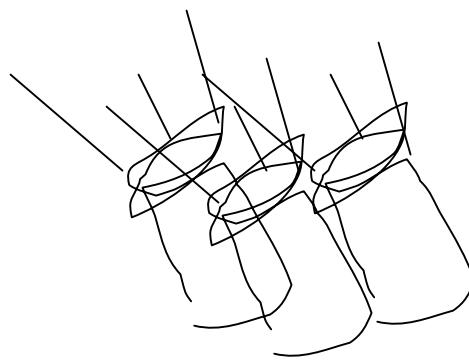
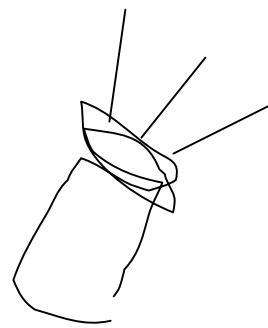
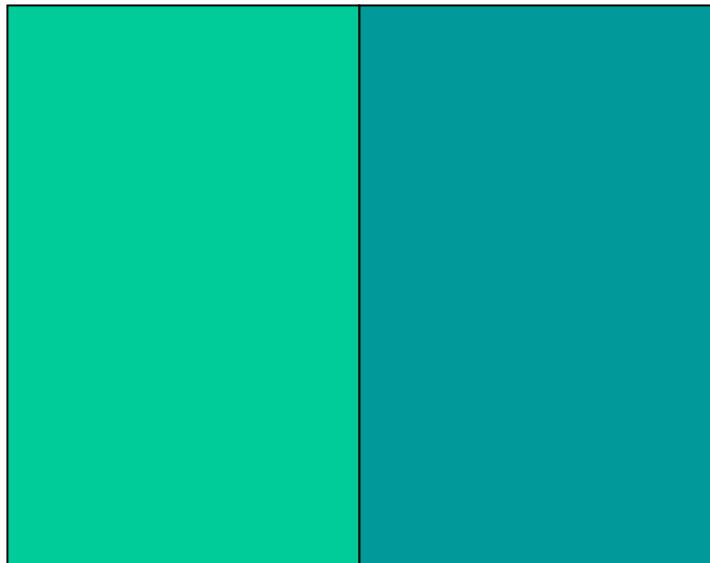
# Color matching experiment 1



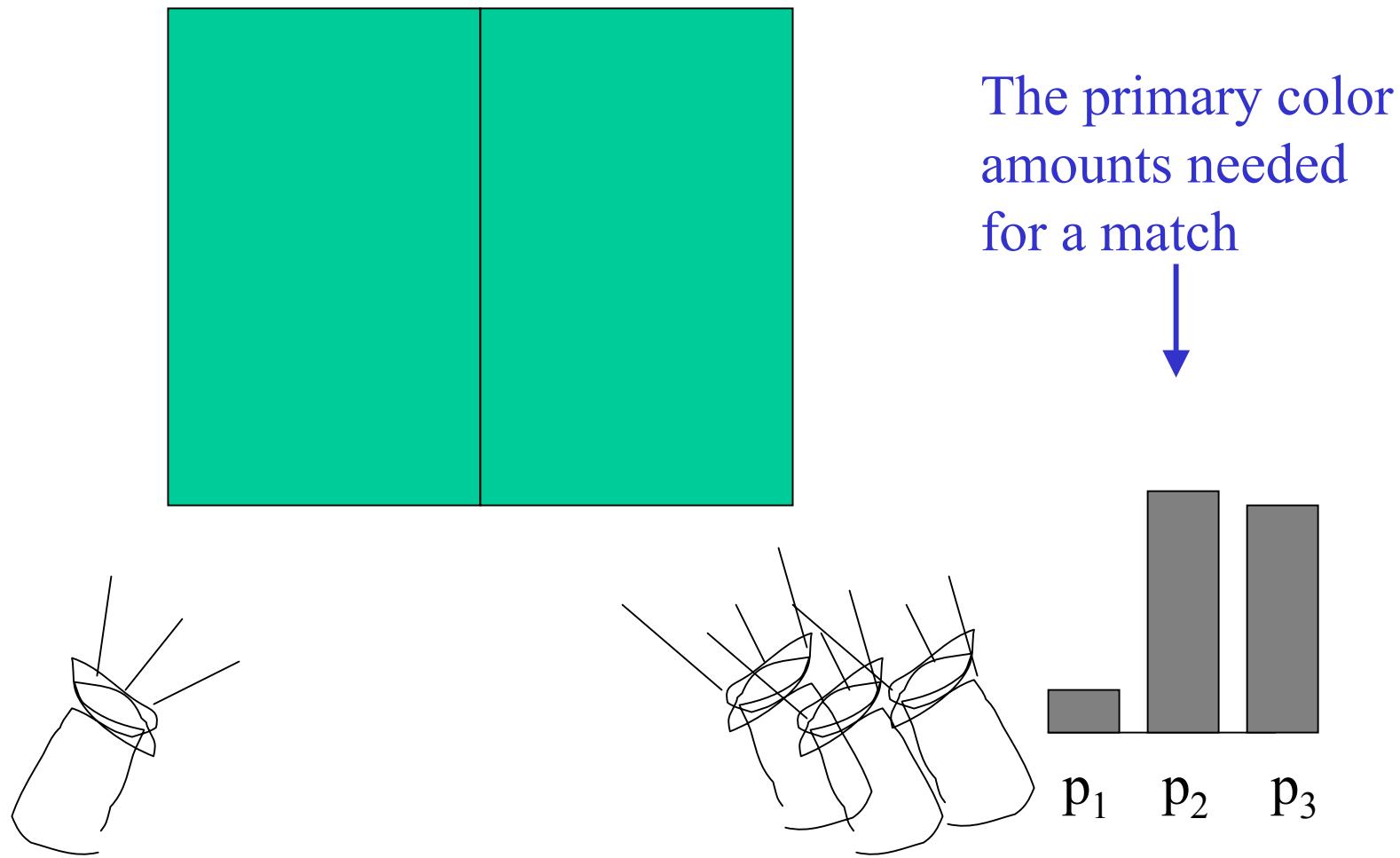
# Color matching experiment 1



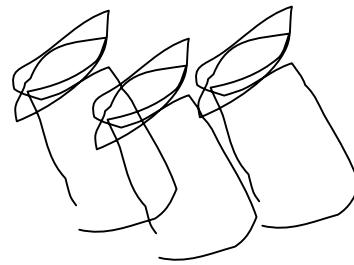
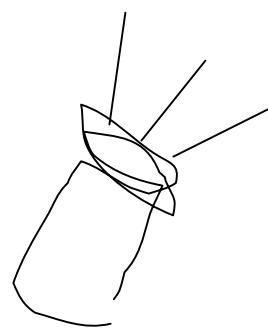
# Color matching experiment 1



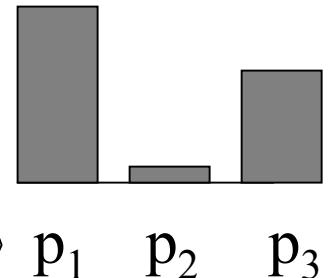
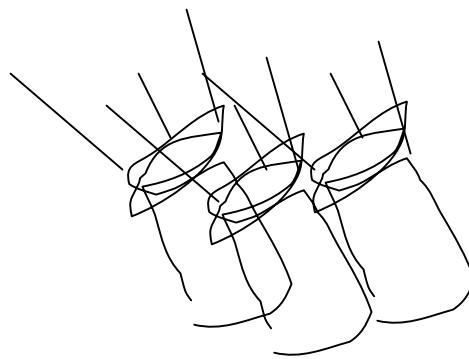
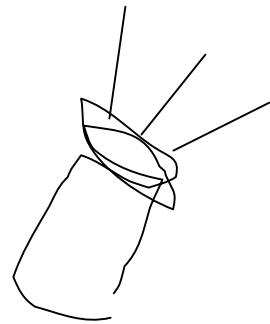
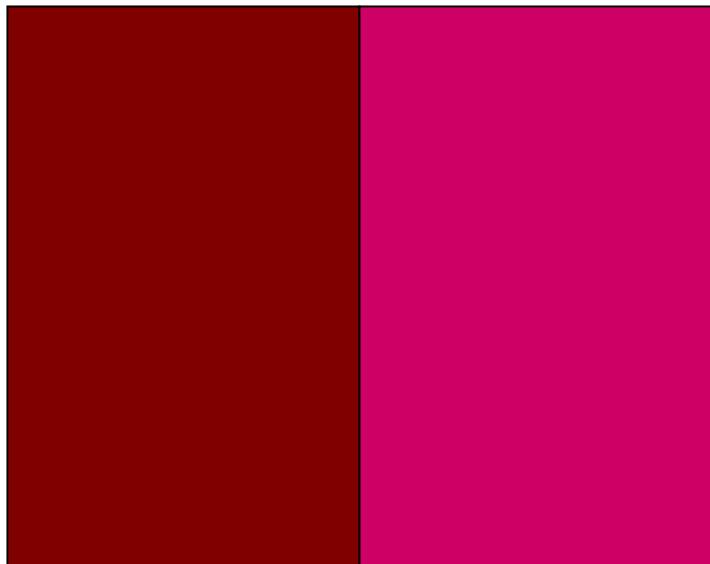
# Color matching experiment 1



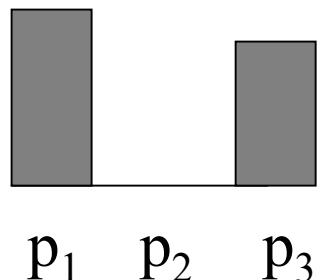
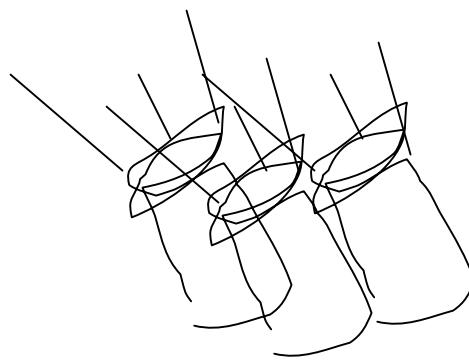
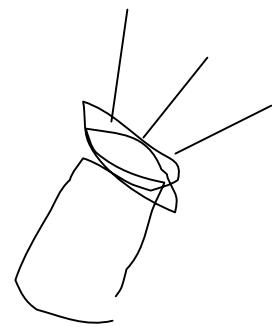
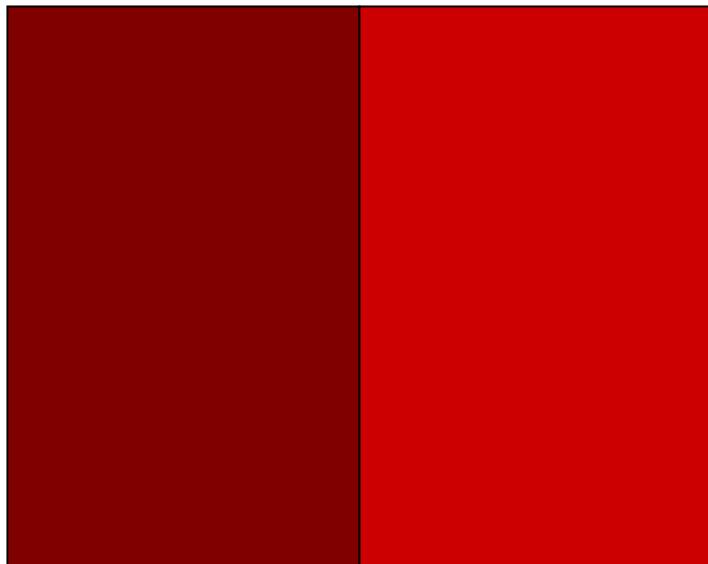
# Color matching experiment 2



# Color matching experiment 2

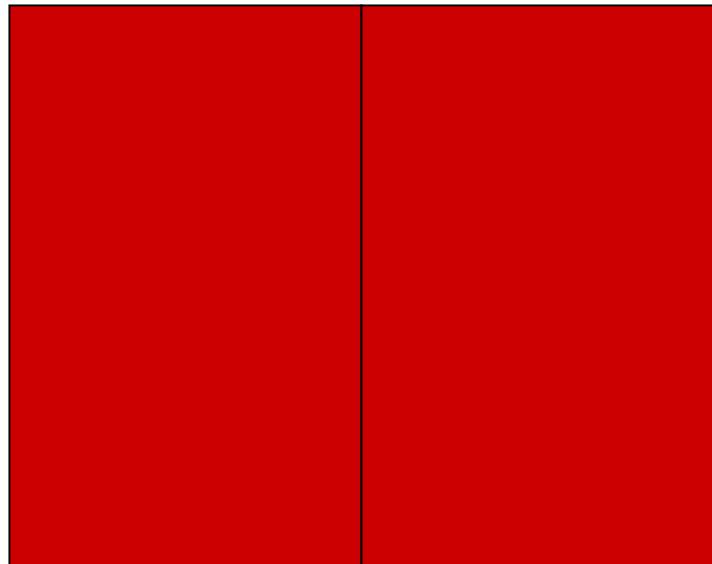


# Color matching experiment 2

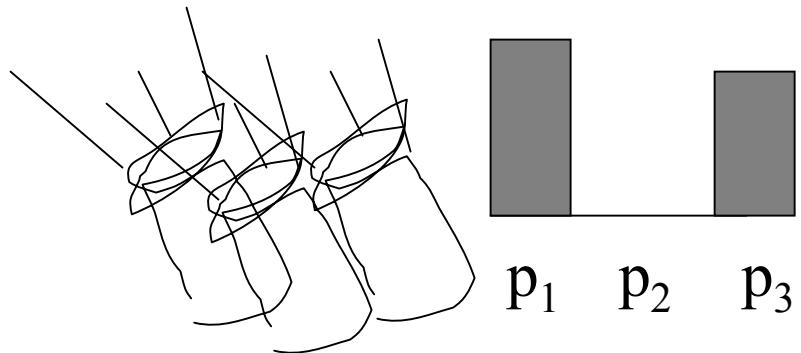
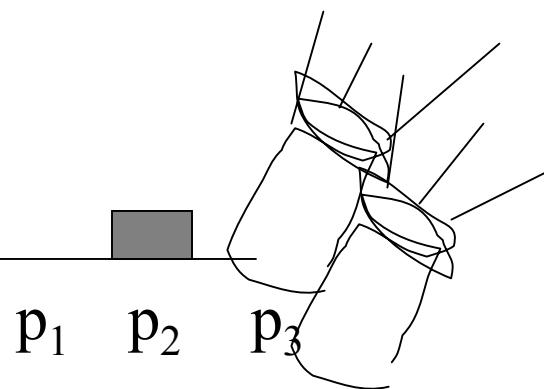
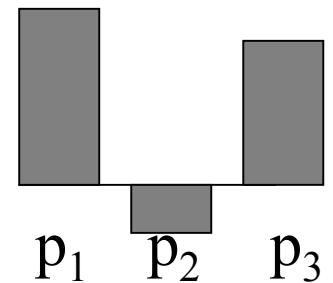


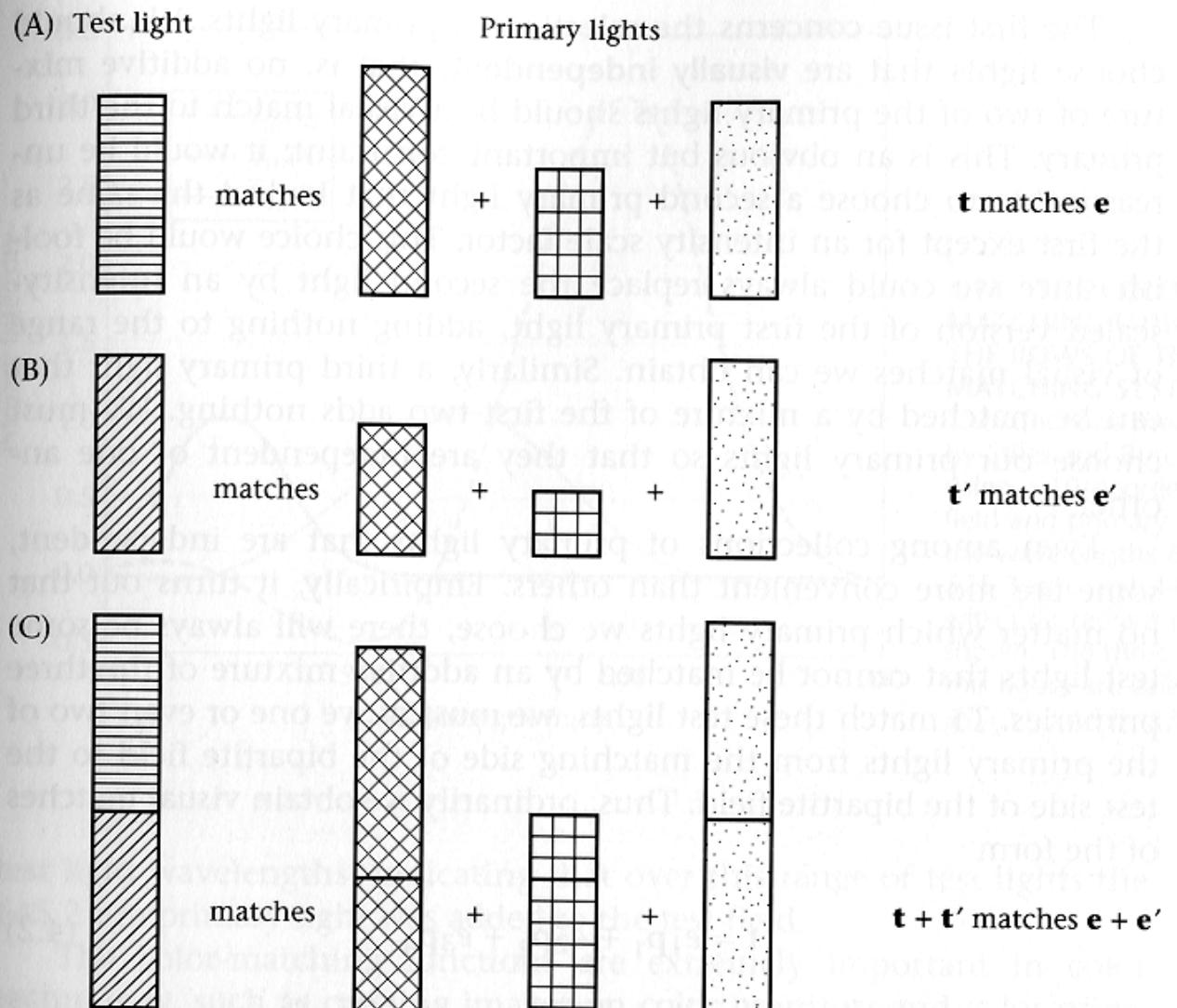
# Color matching experiment 2

We say a “negative” amount of  $p_2$  was needed to make the match, because we added it to the test color’s side.



The primary color amounts needed for a match:





**4.12 THE COLOR-MATCHING EXPERIMENT SATISFIES THE PRINCIPLE OF SUPERPOSITION.** In parts (A) and (B), test lights are matched by a mixture of three primary lights. In part (C) the sum of the test lights is matched by the additive mixture of the primaries, demonstrating superposition.

# Measure color by color-matching paradigm

- Pick a set of 3 primary color lights.
- Find the amounts of each primary,  $e_1$ ,  $e_2$ ,  $e_3$ , needed to match some spectral signal,  $t$ .
- Those amounts,  $e_1$ ,  $e_2$ ,  $e_3$ , describe the color of  $t$ . If you have some other spectral signal,  $s$ , and  $s$  matches  $t$  perceptually, then  $e_1$ ,  $e_2$ ,  $e_3$  will also match  $s$ .

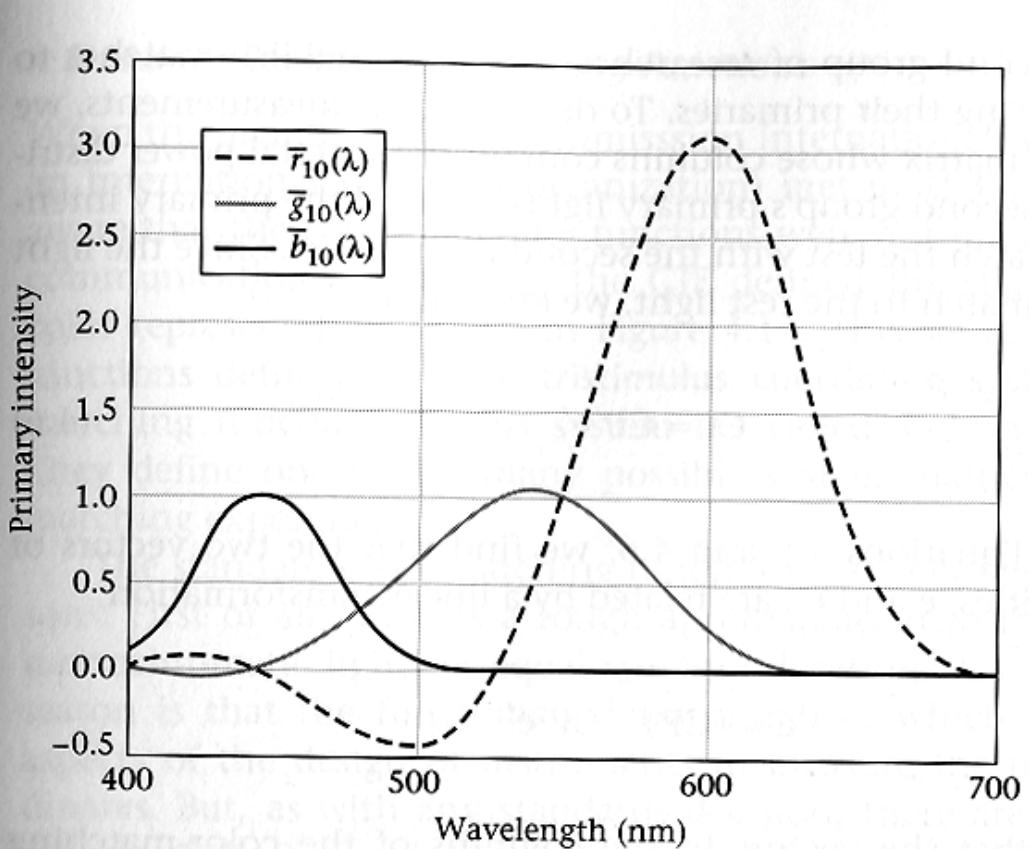
# Grassman's Laws

- For colour matches made in film colour mode:
  - symmetry:  $U=V \Leftrightarrow V=U$
  - transitivity:  $U=V \text{ and } V=W \Rightarrow U=W$
  - proportionality:  $U=V \Leftrightarrow tU=tV$
  - additivity: if any two (or more) of the statements  
 $U=V,$   
 $W=X,$   
 $(U+W)=(V+X)$  are true, then so is the third
- These statements are as true as any biological law. They mean that color matching in film color mode is linear.  
Implies that we can use linear algebra to transform colors

# How to do this, mathematically

- Pick a set of primaries.
- Measure the amount of each primary needed to match monochromatic light at each spectral wavelength (pick some spectral step size).

# Color matching functions for a particular set of monochromatic primaries



- $\textcolor{red}{\blacksquare} p_1 = 645.2 \text{ nm}$
- $\textcolor{green}{\blacksquare} p_2 = 525.3 \text{ nm}$
- $\textcolor{blue}{\blacksquare} p_3 = 444.4 \text{ nm}$

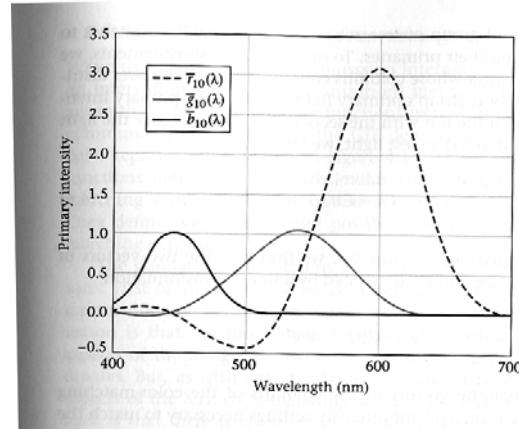
## 4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX.

The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called  $\bar{r}_{10}(\lambda)$ ,  $\bar{g}_{10}(\lambda)$ , and  $\bar{b}_{10}(\lambda)$ .

# Using the color matching functions to predict the primary match for a new spectral signal

Store the color matching functions in the rows of the matrix, C

$$C = \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$



Let the new spectral signal to be characterized be the vector t.

$$\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$

Then the amounts of each primary needed to match t are:

$$C\vec{t}$$

# How do you translate colors between different systems of primaries?

$$\text{p}_1 = (0 \ 0 \ 0 \ 0 \ 0 \dots \ 0 \ 1 \ 0)^T$$

$$\text{p}_2 = (0 \ 0 \dots \ 0 \ 1 \ 0 \dots \ 0 \ 0)^T$$

$$\text{p}_3 = (0 \ 1 \ 0 \ 0 \dots \ 0 \ 0 \ 0 \ 0)^T$$

Primary spectra, P

Color matching functions, C

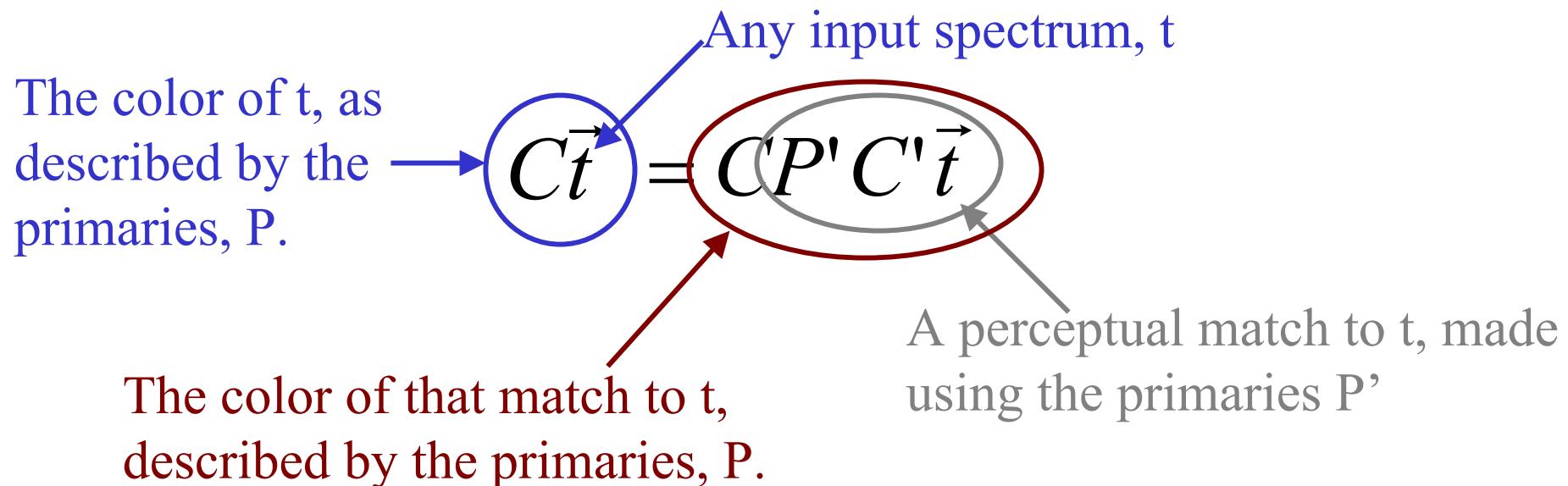
$$\text{p}'_1 = (0 \ 0.2 \ 0.3 \ 4.5 \ 7 \dots \ 2.1)^T$$

$$\text{p}'_2 = (0.1 \ 0.44 \ 2.1 \dots \ 0.3 \ 0)^T$$

$$\text{p}'_3 = (1.2 \ 1.7 \ 1.6 \dots \ 0 \ 0)^T$$

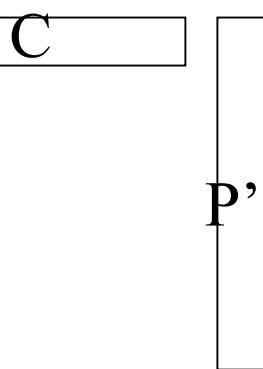
Primary spectra, P'

Color matching functions, C'



# So color matching functions translate like this:

From previous slide  $C\vec{t} = CP'C'\vec{t}$  But this holds for any input spectrum,  $t$ , so...



$$C = \underbrace{CP'C'}_{}$$

a 3x3 matrix

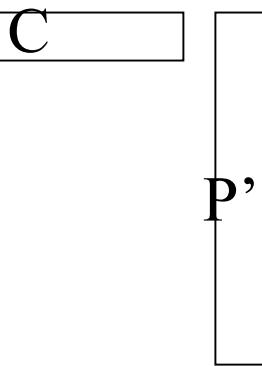
$P'$  are the old primaries

$C$  are the new primaries' color matching functions

How do you translate from the color in one set of primaries to that in another?

$$e = CP'e'$$

the same 3x3 matrix



$P'$  are the old primaries

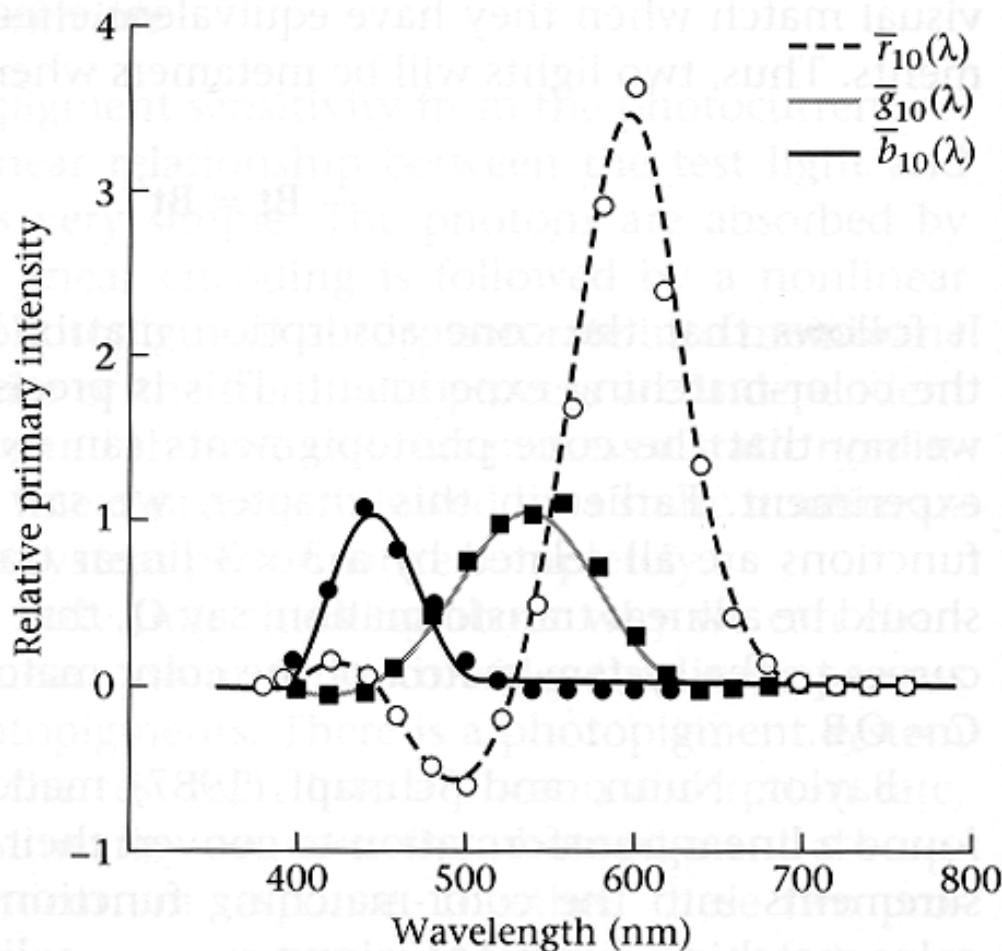
$C$  are the new primaries' color matching functions

# CIE XYZ color space

- Commission Internationale d'Eclairage, 1931
- “...as with any standards decision, there are some irritating aspects of the XYZ color-matching functions as well...no set of physically realizable primary lights that by direct measurement will yield the color matching functions.”
- “Although they have served quite well as a technical standard, and are understood by the mandarins of vision science, they have served quite poorly as tools for explaining the discipline to new students and colleagues outside the field.”

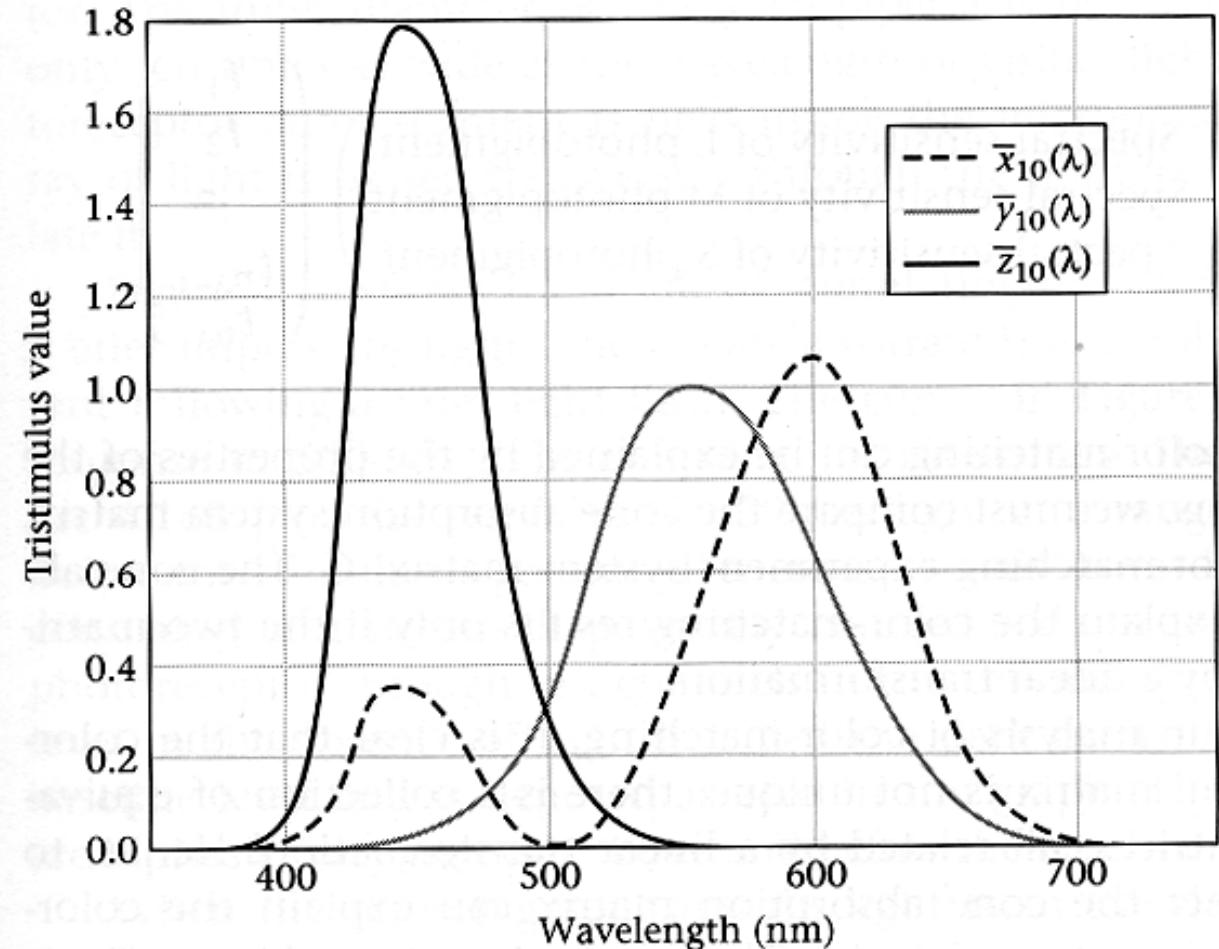
# Comparison of color matching functions with best 3x3 transformation of cone responses

**4.20 COMPARISON OF CONE PHOTOCURRENT RESPONSES AND THE COLOR-MATCHING FUNCTIONS.** The cone photocurrent spectral responsivities are within a linear transformation of the color-matching functions, after a correction has been made for the optics and inert pigments in the eye. The smooth curves show the Stiles and Burch (1959) color-matching functions. The symbols show the matches predicted from the photocurrents of the three types of macaque cones. The predictions included a correction for absorption by the lens and other inert pigments in the eye. Source: Baylor, 1987.



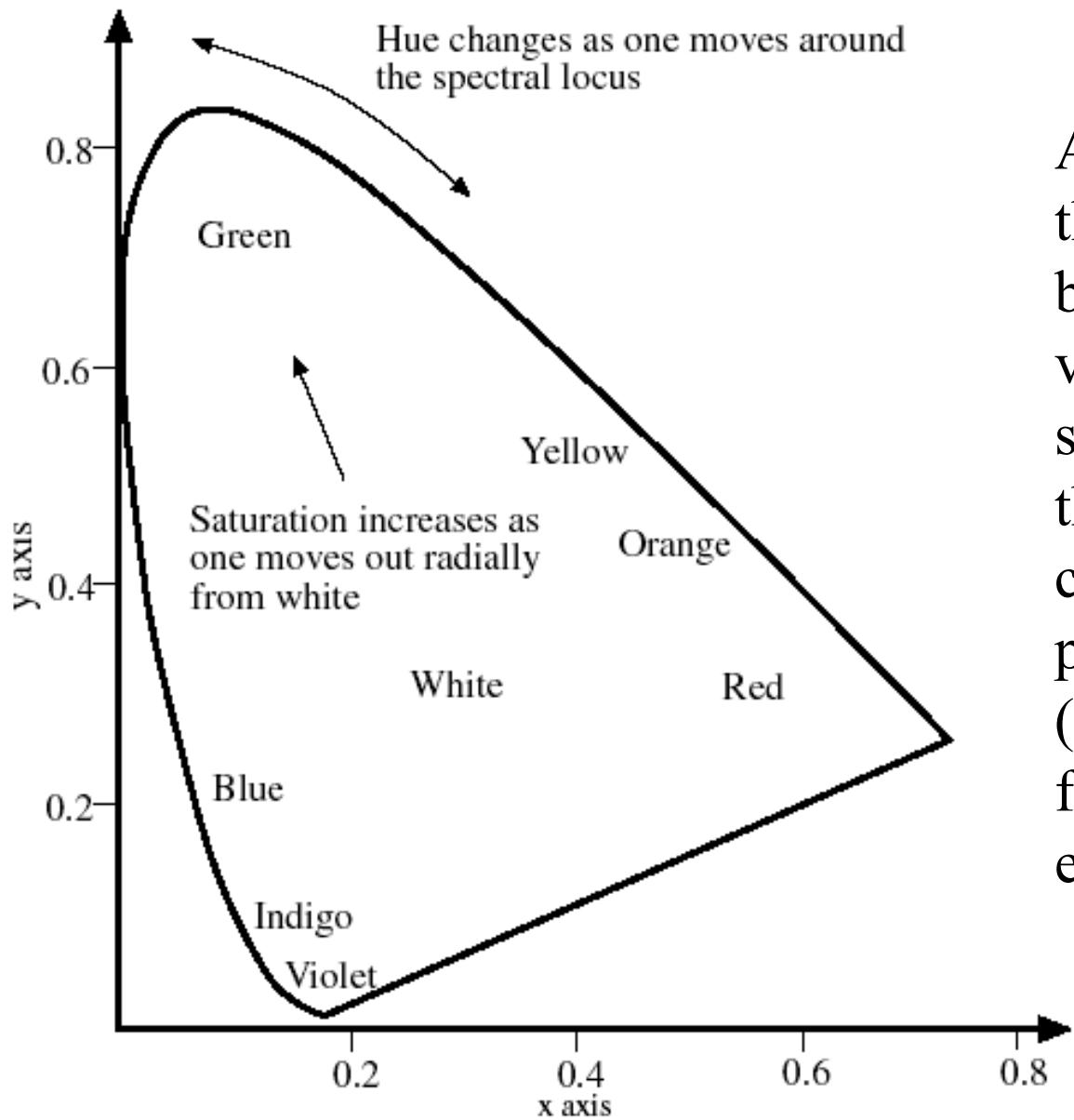
Since we can define colors using almost any set of primary colors, let's agree on a set of primaries and color matching functions for the world to use...

**4.14 THE XYZ STANDARD COLOR-MATCHING FUNCTIONS.** In 1931 the CIE standardized a set of color-matching functions for image interchange. These color-matching functions are called  $\bar{x}(\lambda)$ ,  $\bar{y}(\lambda)$ , and  $\bar{z}(\lambda)$ . Industrial applications commonly describe the color properties of a light source using the three primary intensities needed to match the light source that can be computed from the XYZ color-matching functions.

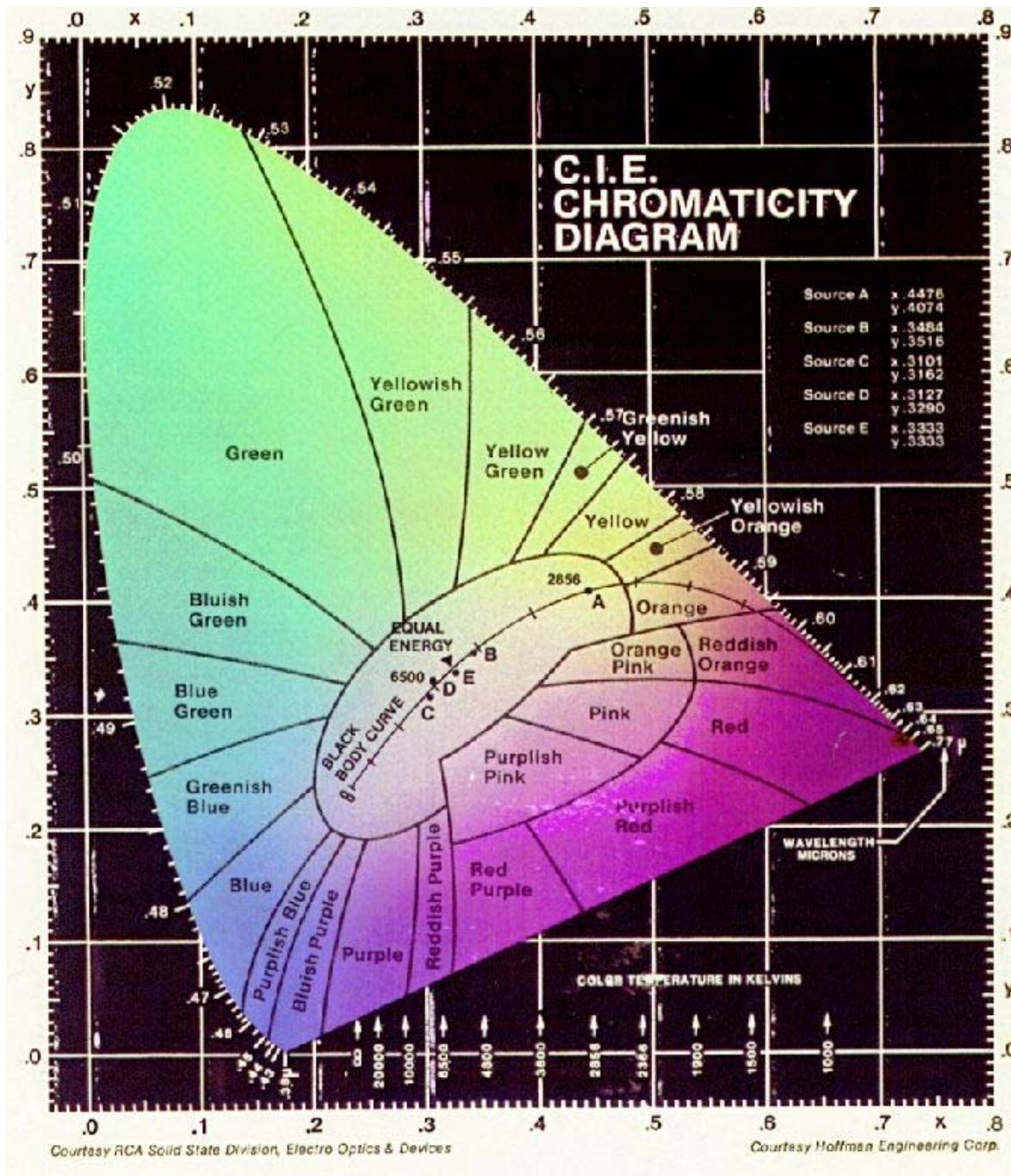


CIE XYZ: Color matching functions are positive everywhere, but primaries are imaginary. Usually draw x, y, where  $x=X/(X+Y+Z)$

$$y=Y/(X+Y+Z)$$



A qualitative rendering of the CIE (x,y) space. The blobby region represents visible colors. There are sets of (x, y) coordinates that don't represent real colors, because the primaries are not real lights (so that the color matching functions could be positive everywhere).



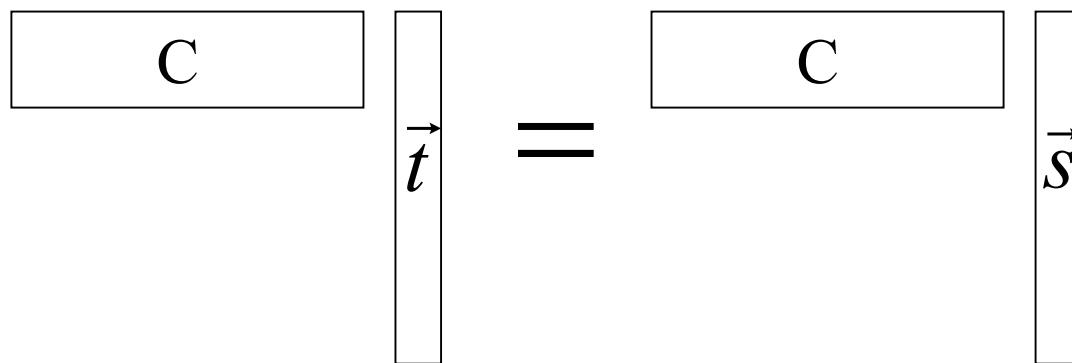
# Color metamerism

Two spectra,  $t$  and  $s$ , perceptually match when

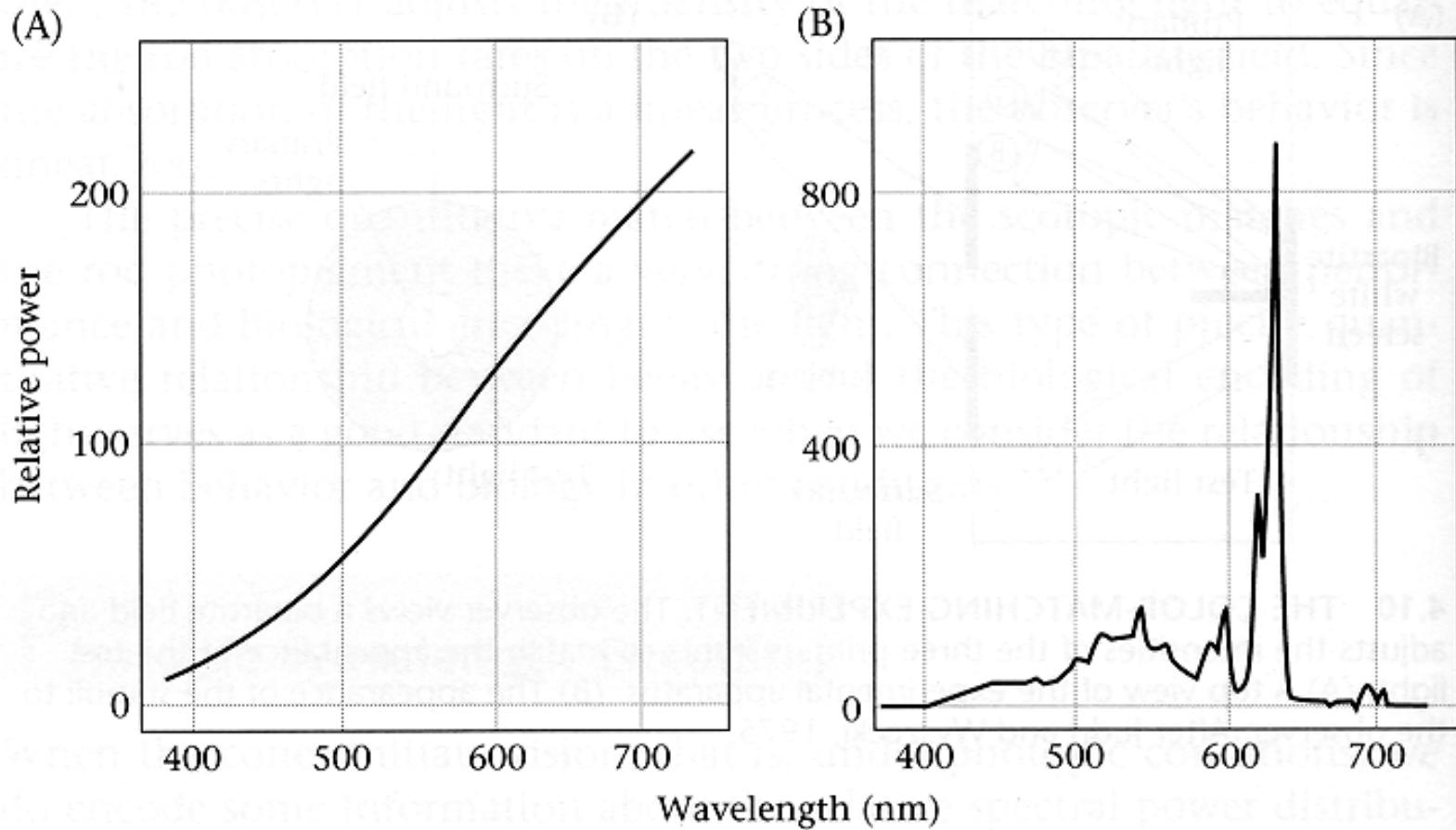
$$C\vec{t} = C\vec{s}$$

where  $C$  are the color matching functions for some set of primaries.

Graphically,



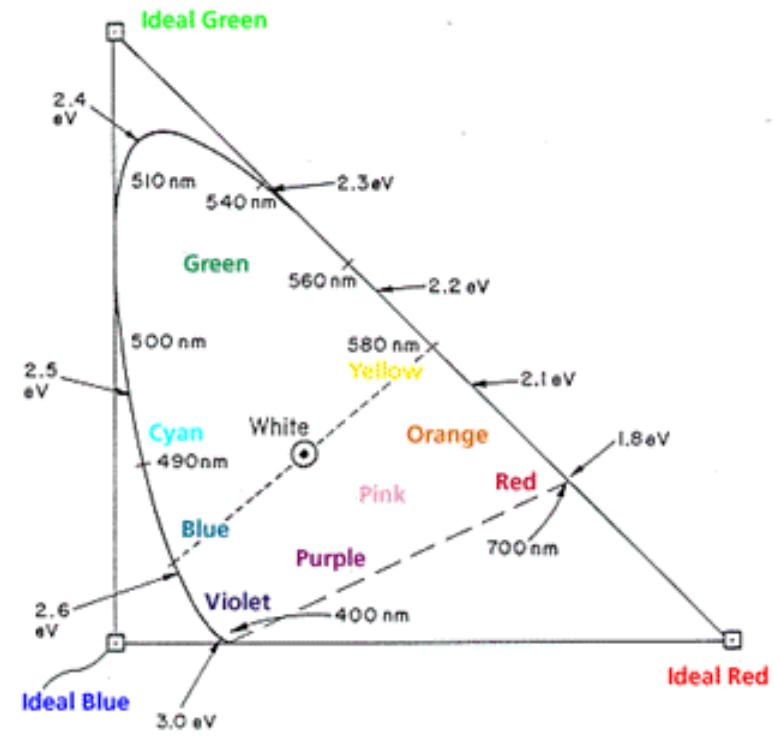
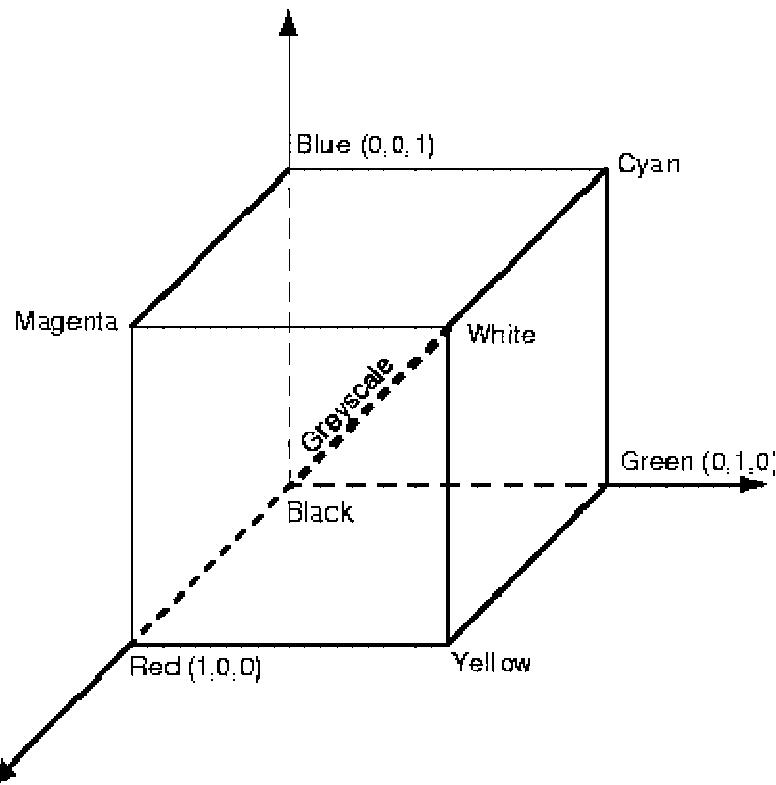
# Metameric lights



**4.11 METAMERIC LIGHTS.** Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.

# Color Models

- R, G, B cube
- 2D diagram ( $R/R+G+B$ ,  $G/R+G+B$ ), related to the CIE chromaticity diagram (see Pokorny)

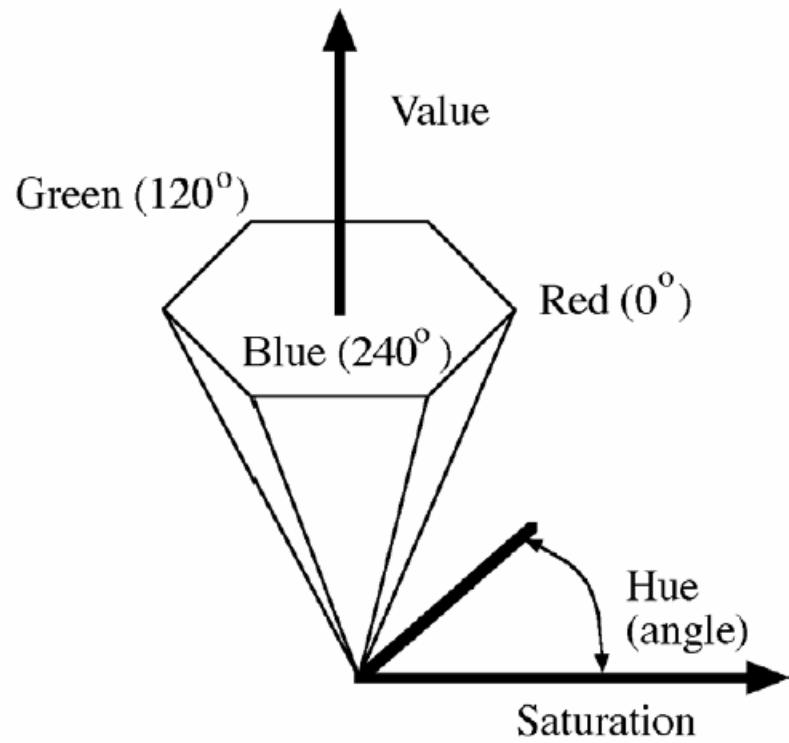
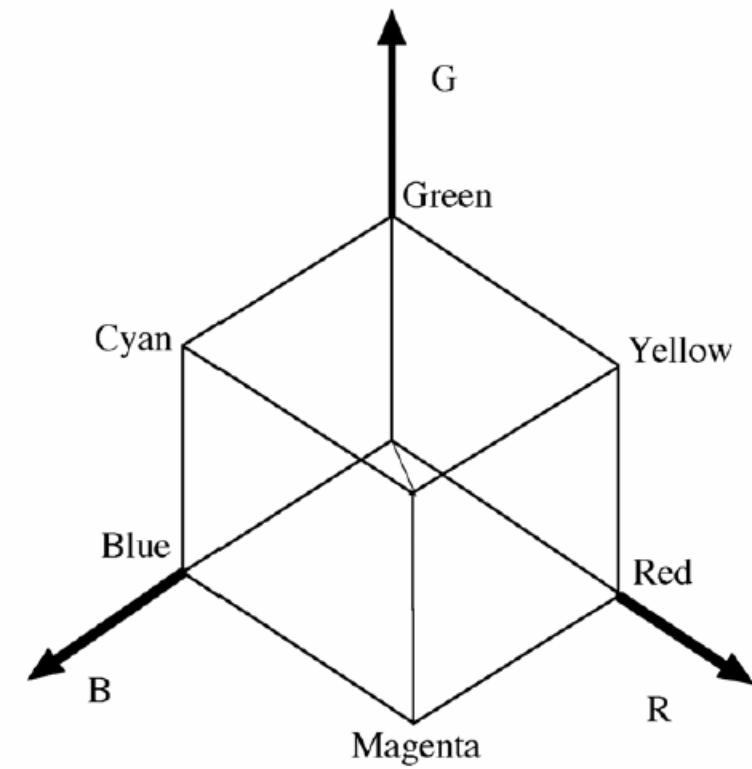


# Other Color Models

Beyond the eyes, the brain may have its own color space. For image compression, it is important to understand which part of color information is important to people and which is not. It is intuitive to describe a color impression by saying

- what the dominant color is: *hue* is mode of spectrum
- How washed out by white light the color is: *saturation* is related to variance (red vs. pink)
- how bright or dim the light is: *intensity* is area of the light spectral distribution

# HSV hexcone



# Intensity-Saturation-Hue Color Models

- Find a new coordinate system that reflects these three quantities
  - YIQ, linear transformation

$$\begin{pmatrix} Y \\ I \\ Q \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

- IHS space:
  - Diagonal (1,1,1) of RGB space is intensity axis
  - Saturation (*chroma*) is distance from that axis
  - Hue is angle about that axis

There are many more models

# Color Constancy

- Objects tend to retain the same perceived color even though the coloration of the overall illumination may change.
  - A biological necessity.
  - Comes from lateral inhibition.
- The color constancy is not perfect. It depends on the state of adaptation.

