Human Vision
Light, Color, Eyes, etc.

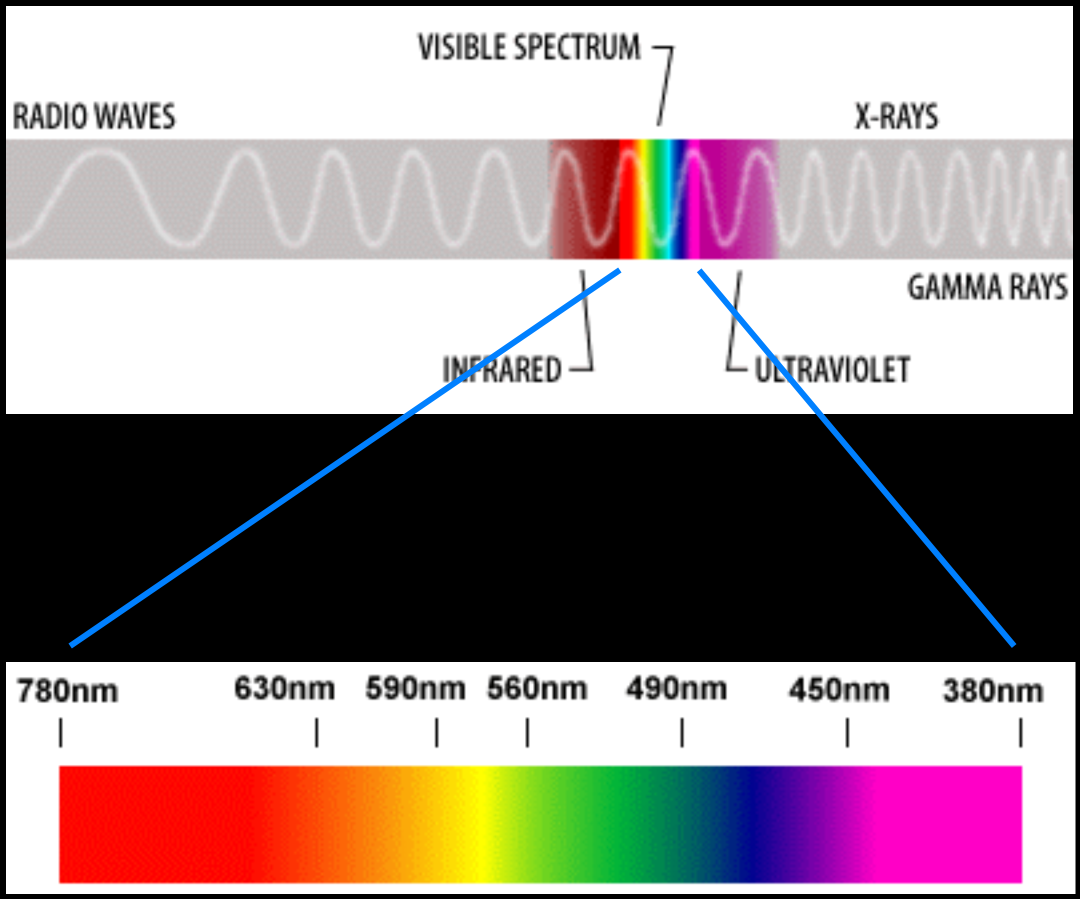
Photo of a ray of light striking a glass table top by Phil Ruthstrom

What's Color?

- It's an attribute of an object (or thing) like texture, shape, smoothness
- It depends upon
  - Spectral characteristics of the light illuminating the object
  - Spectral properties of the object (reflectance)
  - Spectral characteristics of the sensors of the imaging device (e.g. the human eye or a camera)
  - Reflectance relative to other things in environment?
  - Reflectance relative to our expectations?
    - Food court example.

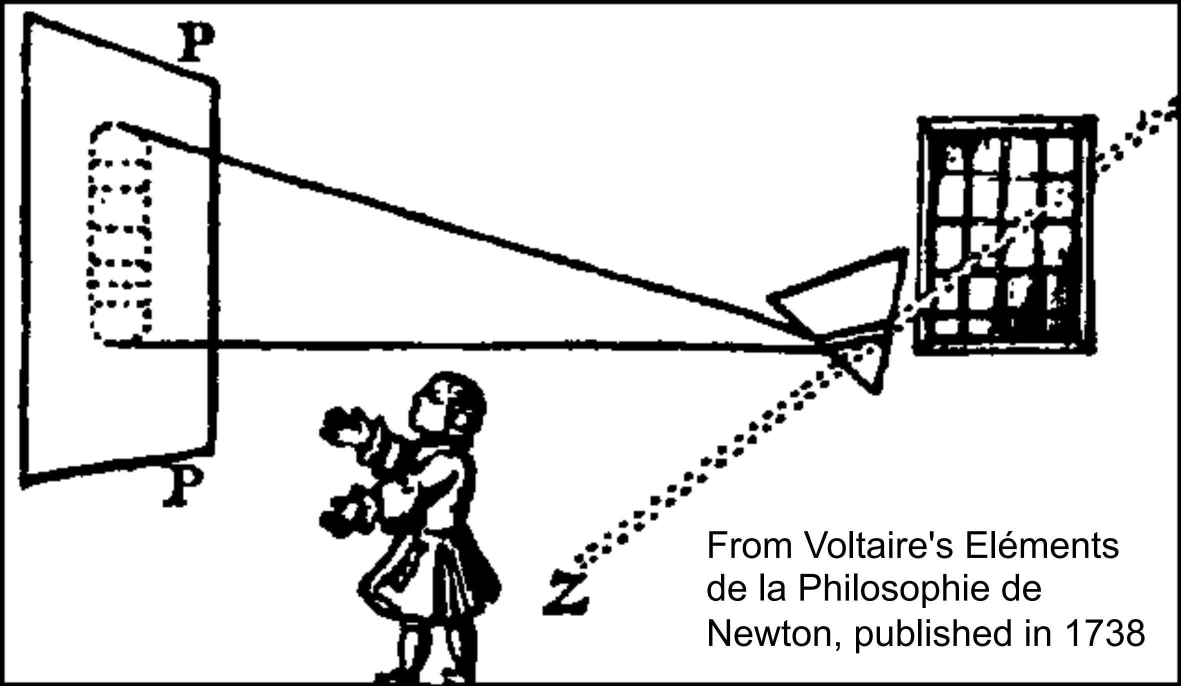
Light: EM Spectrum

Electromagnetic Spectrum



'Visible' Spectrum

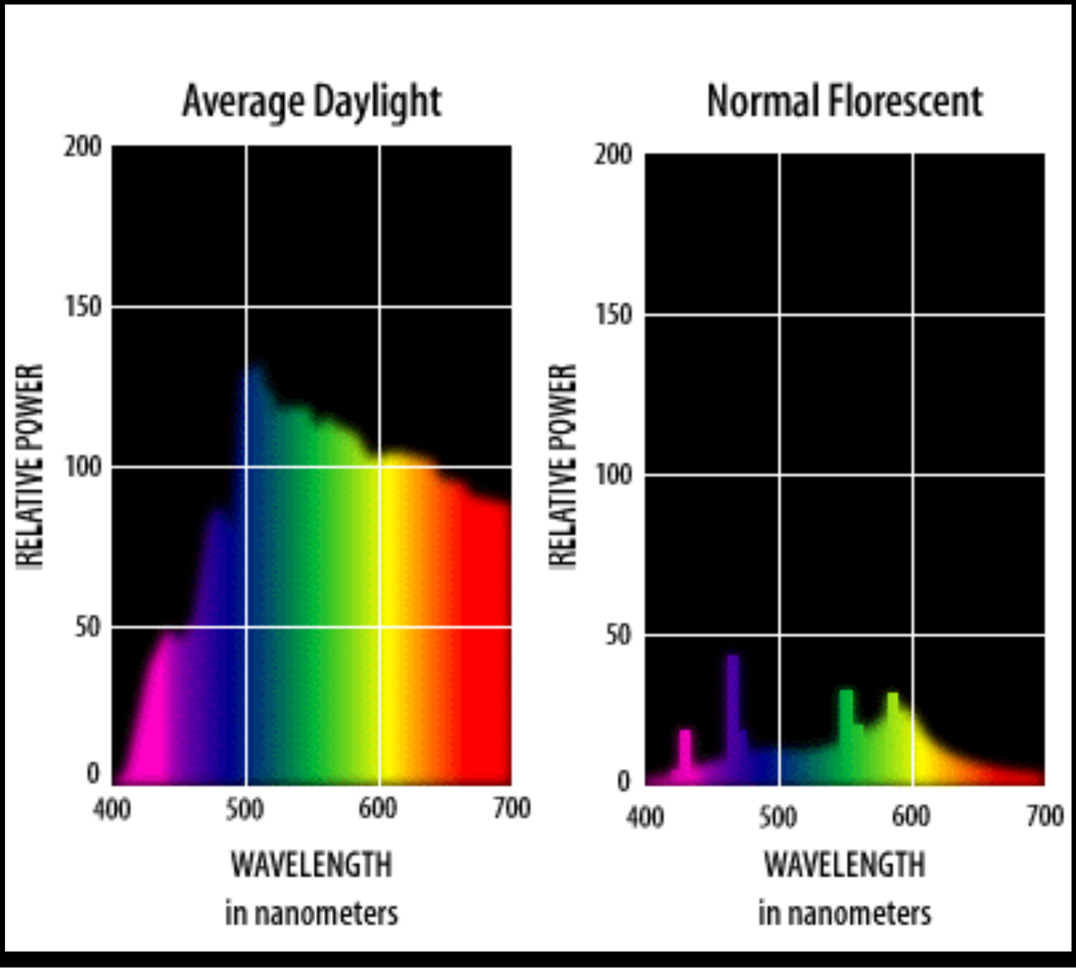
Newton 1666



From Voltaire's Eléments de la Philosophie de Newton, published in 1738

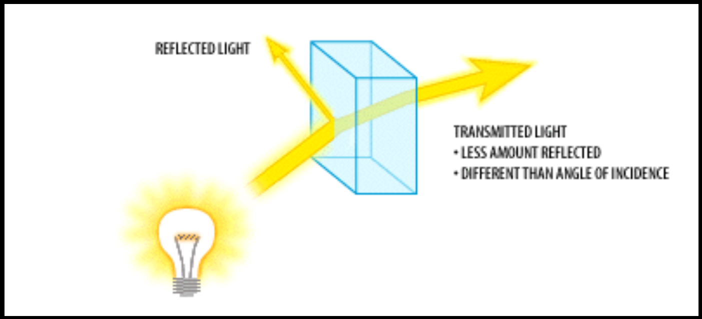
Spectral Distributions

- Spectral distributions show the ‘amount’ of energy at each wavelength for a light source; e.g.



Interaction of Light and Matter

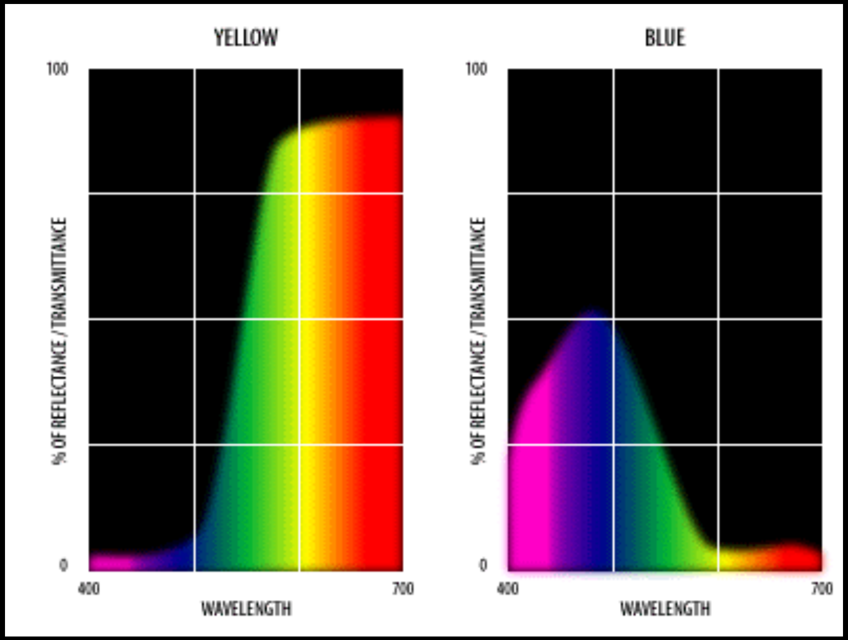
- When light strikes an object,
  - It will be wholly or partly transmitted.
  - It will be wholly or partly reflected.
  - It will be wholly or partly absorbed.
  - Physical surface properties dictate what happens

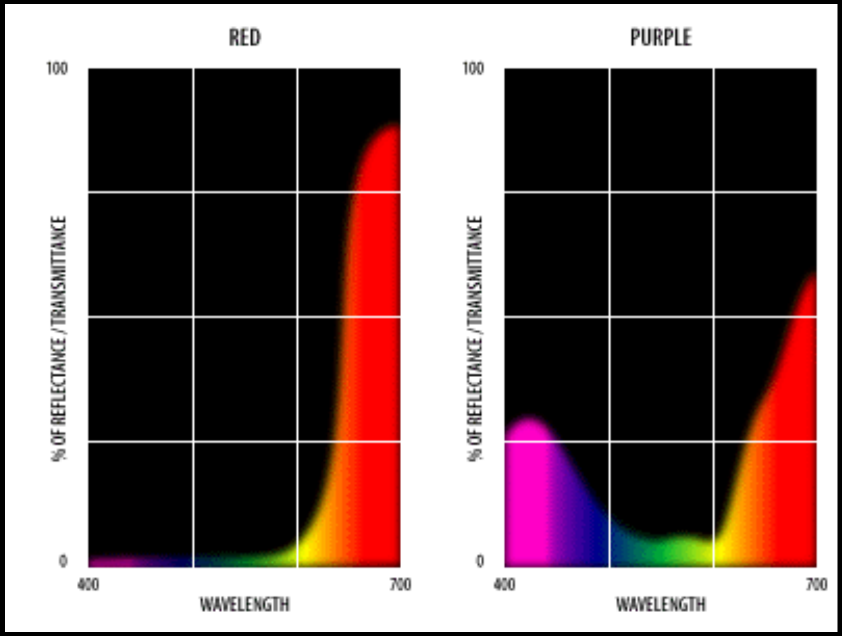


- When we see an object as blue or red or purple,
  - what we're really seeing is a partial reflection of light from that object.
  - The color we see is what's left of the spectrum after part of it is absorbed by the object.

Spectral Reflectance Curves

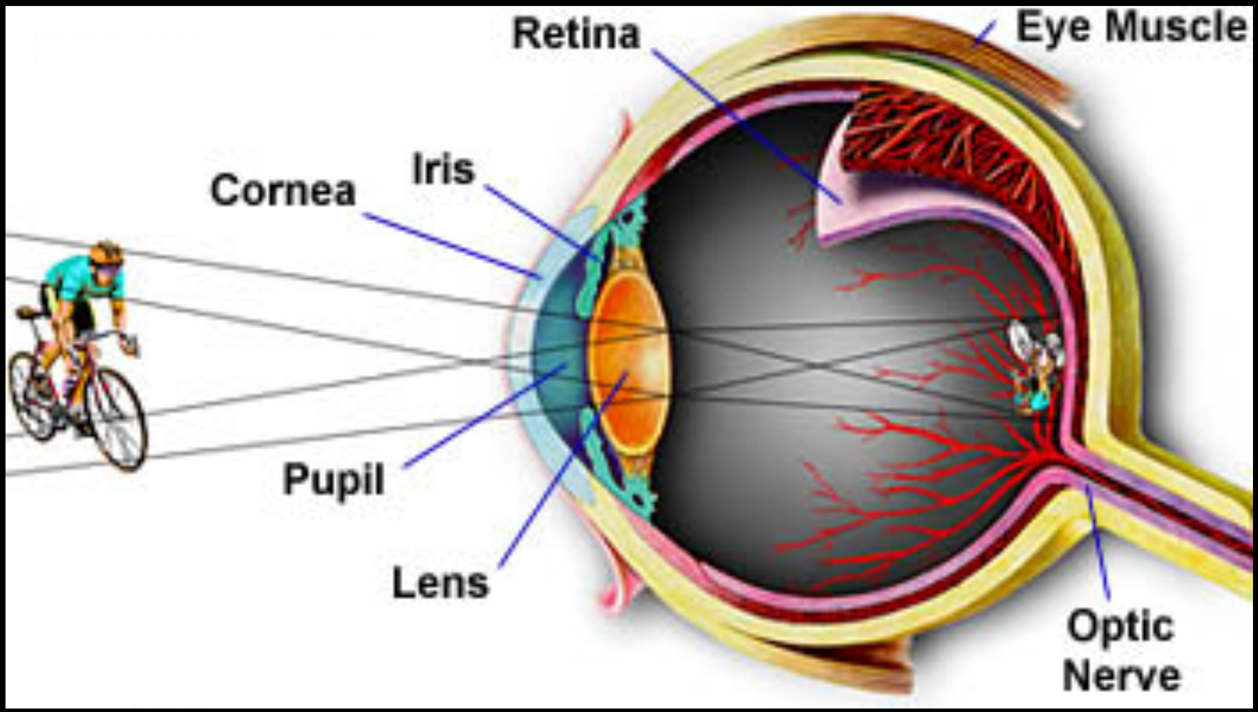
- Reflectance curves for objects that appear to be:





The wavelengths reflected or transmitted from or through an object determine the stimulus to the retina that provokes the optical nerve into sending responses to our brains that indicate color.

The Human Eye

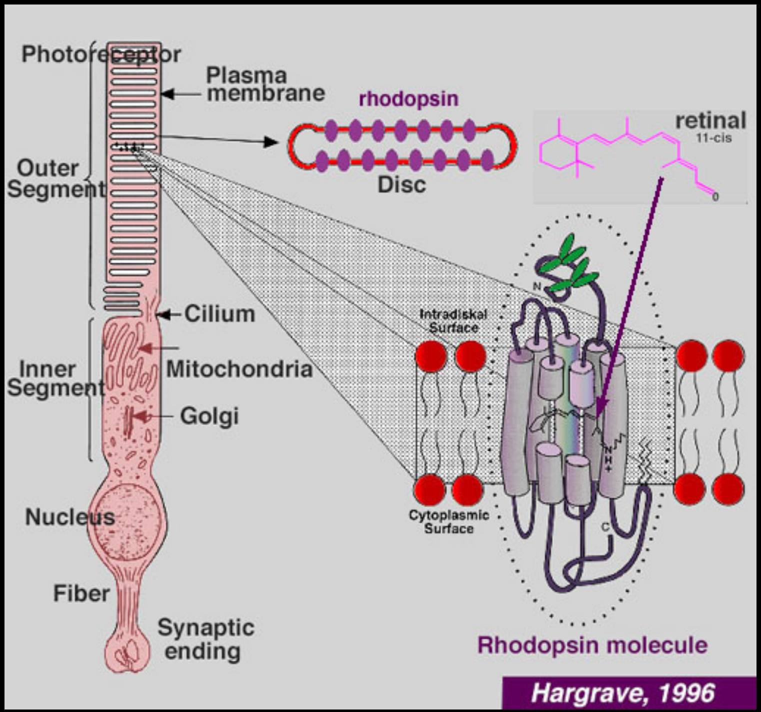


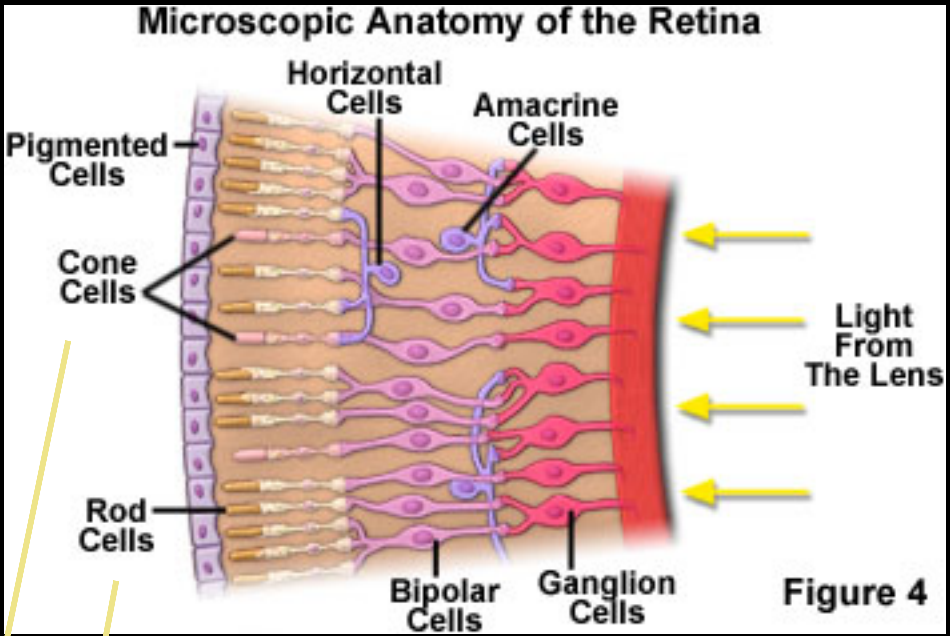
Pupil -	The opening through which light enters the eye - size from 2 to 8 mm in diameter
Iris -	The colored area around the pupil that controls the amount of light entering the eye.
Lens -	Focuses light rays on the retina.
Retina -	The lining of the back of the eye containing nerves that transfer the image to the brain.
Rods -	Nerve cells that are sensitive to light and dark.
Cones -	Nerve cells that are sensitive to a particular primary color.

Questions

- Why don’t we see things upside down?
- Why is black and white TV “normal” feeling.
- Why is it hard to notice our blind spot?

Photoreceptor

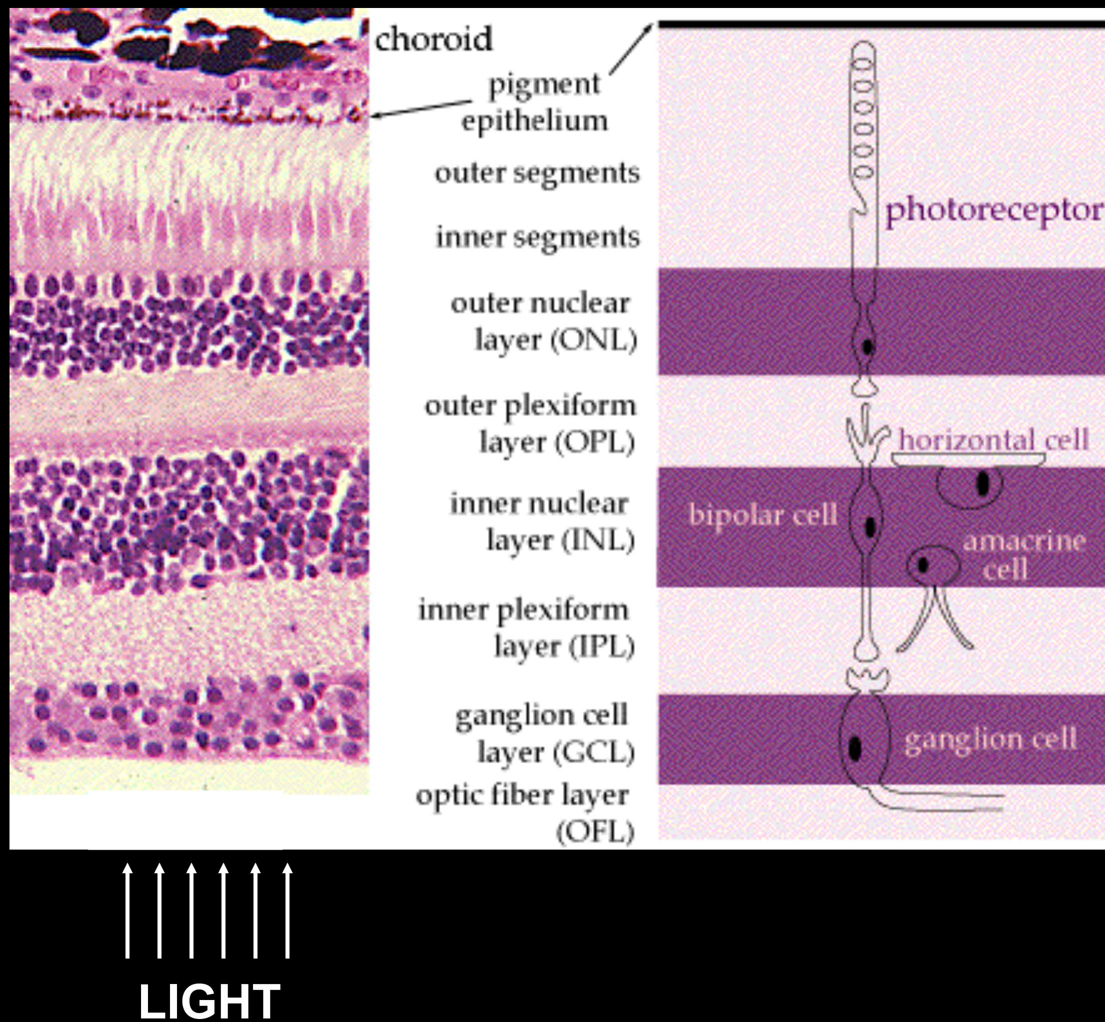




Low light receptors: ~125 million

Color receptors: 5-7 million

Retinal Tissue



Rods and Cones

- Cones are located in the fovea and are sensitive to color.
  - Each one is connected to its own nerve end.
  - Cone vision is called photopic (or bright-light vision).
- Rods give a general, overall picture of the field of view and are not involved in color vision.
  - Several rods are connected to a single nerve and are
  - Sensitive to low levels of illumination (scotopic or dim-light vision).

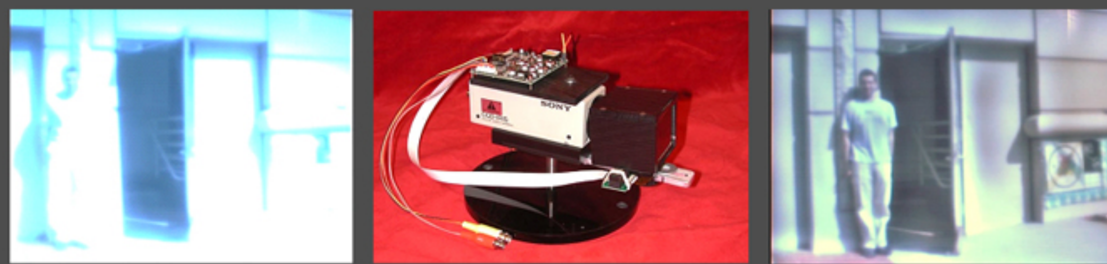
Human Vision is "Multi-modal"

- Separate color vs. black-and-white detectors.
- Separate motion sensitive sensors (different time sampling properties).
- Uneven spatial sampling rates.

- Modern high-tech camera systems starting to use these ideas (see Shree Nayar's Laboratory):
  - High resolution slow-speed camera coupled with low resolution high speed.
  - Interleaved sensors with different dynamic range for high dynamic range

Dynamic Range

Adaptive Dynamic Range Imaging



Conventional Camera Output | ADR Camera | ADR Camera Output

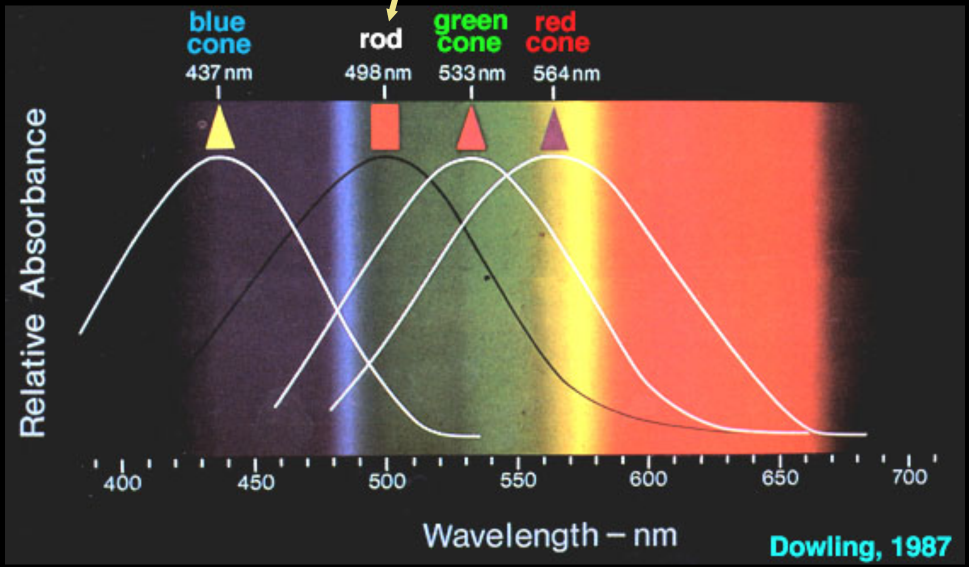
This project is focused on the development of a new approach to imaging that significantly enhances the dynamic range of an imaging system. The key idea is to adapt the exposure of each pixel on the detector based on the radiance value of the corresponding scene point. This adaptation is done in optical domain, that is, during image formation. In practice, this is achieved using a two-dimensional spatial light modulator, whose transmittance function can be varied with high resolution over space and time.

A real-time control algorithm has been developed that uses a captured image to compute the optimal transmittance function for the spatial modulator. The captured image and the corresponding transmittance function are used to compute a very high dynamic range image that is linear in scene radiance.

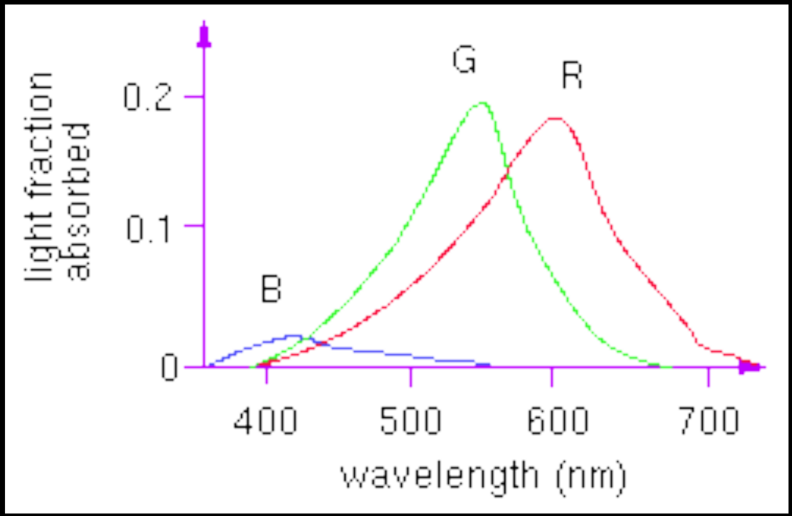
Extensive simulations and experiments have been conducted to demonstrate this concept of adaptive dynamic range imaging. The simulation results show the ability of the control algorithm to produce stable, high quality images even when the scene changes with time. We have implemented a video-rate adaptive dynamic range (ADR) camera that consists of a color CCD detector and a controllable liquid crystal light modulator. Experiments have been conducted in a variety of scenarios with complex and harsh lighting conditions. The results indicate that adaptive imaging can impact vision applications such as monitoring, tracking, recognition and navigation.

Absorption Curves

Rods: achromatic vision

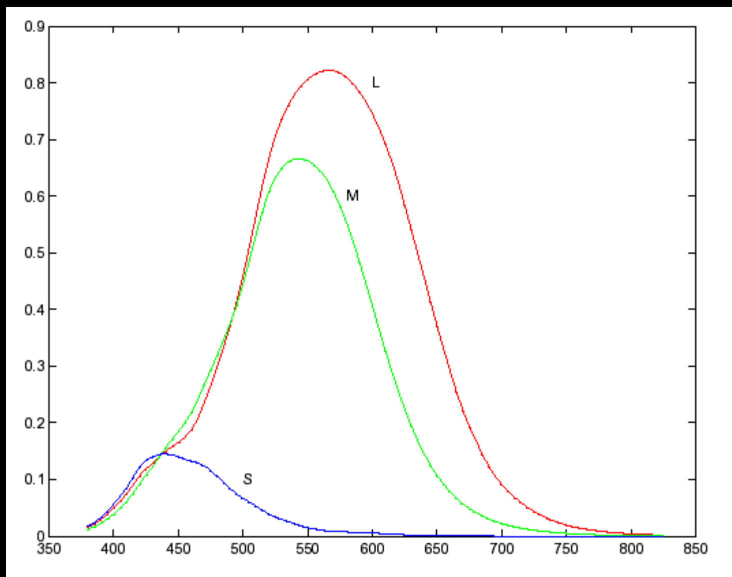


The different kinds of cells have different spectral sensitivities



Peak sensitivities are located at approximately 437nm, 533nm, and 610nm for the "average" observer.

Responses



Cone sensitivity curves

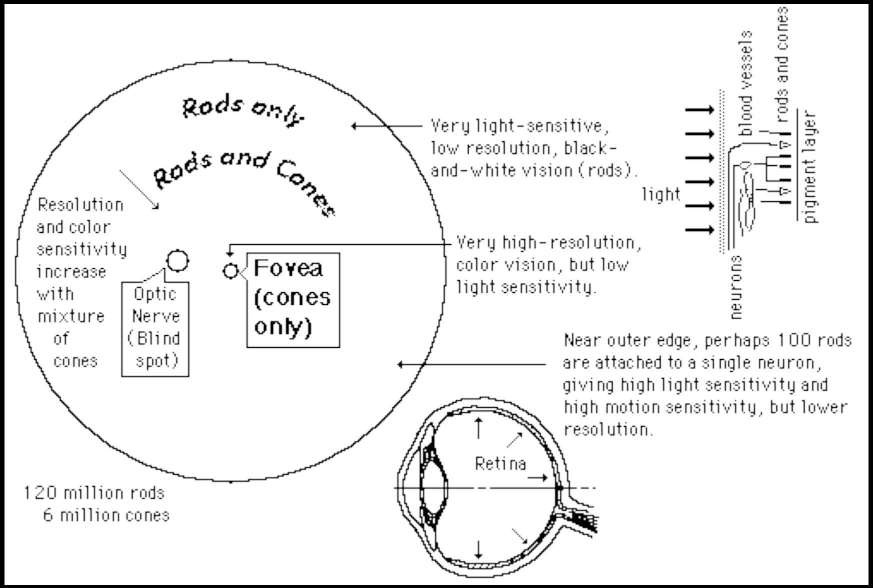
Response from i-th cone type:

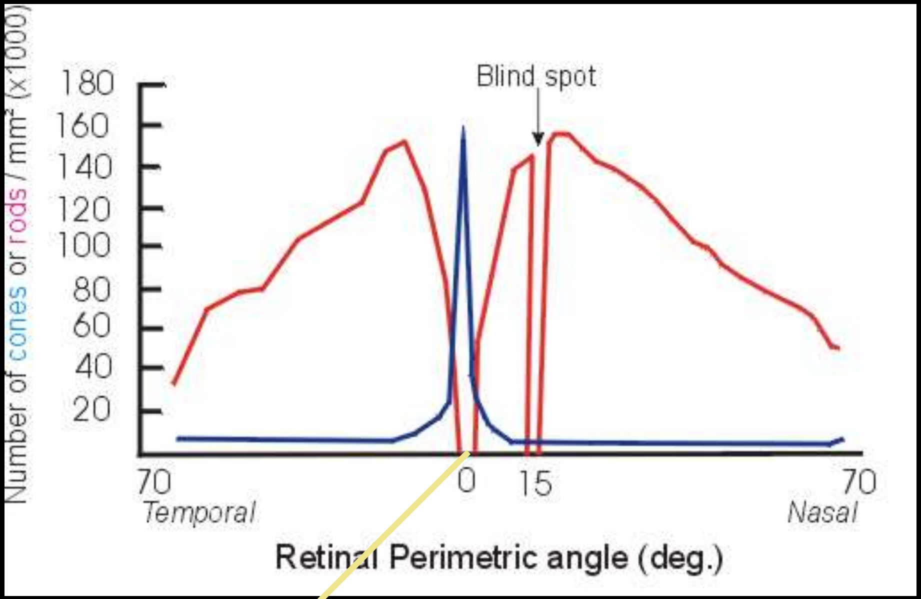
$$c_i = \int s_i(\lambda)t(\lambda)d\lambda$$

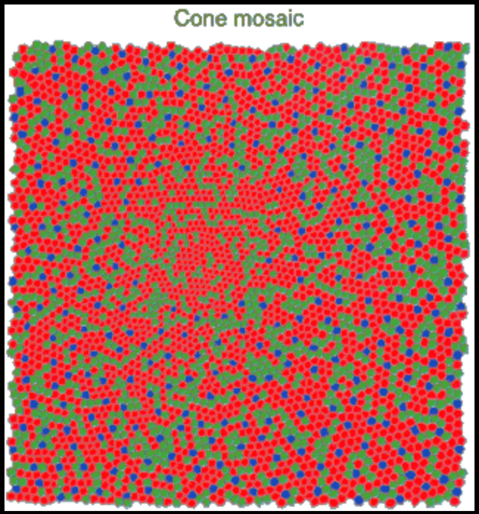
s_i(l) = sensitivity of i-th cone
t(l) = spectral distribution of light
l= wavelength

How can we find color equivalents?

Distribution







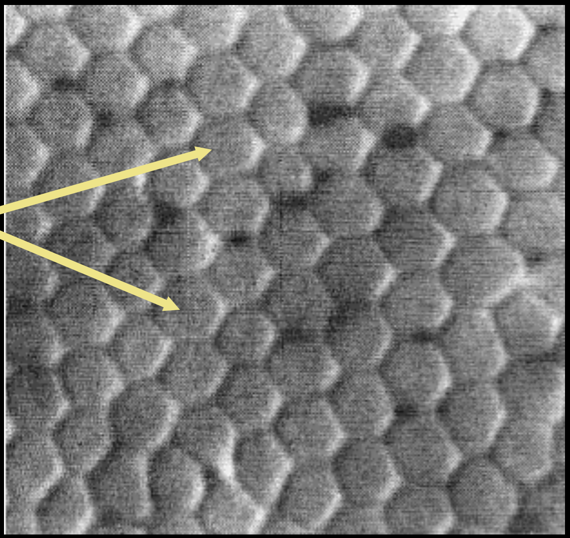
Why don't we notice blind spots?

Other "Blind Spots"

- Hemi-neglect
- Prosopagnosia
- The difference between zero and nothing.

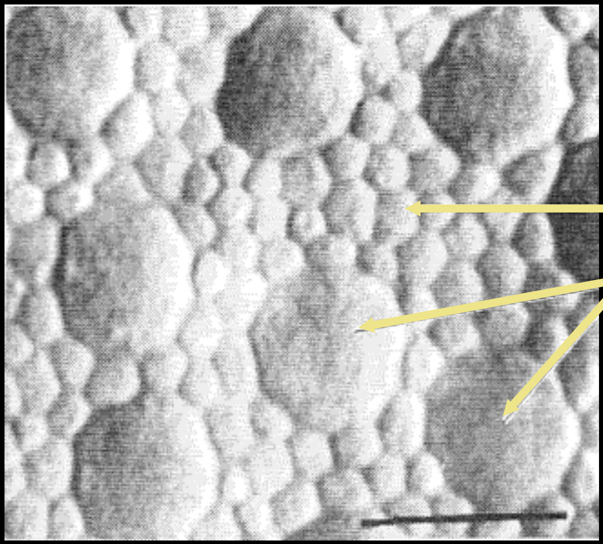
Retina

Cones in the fovea

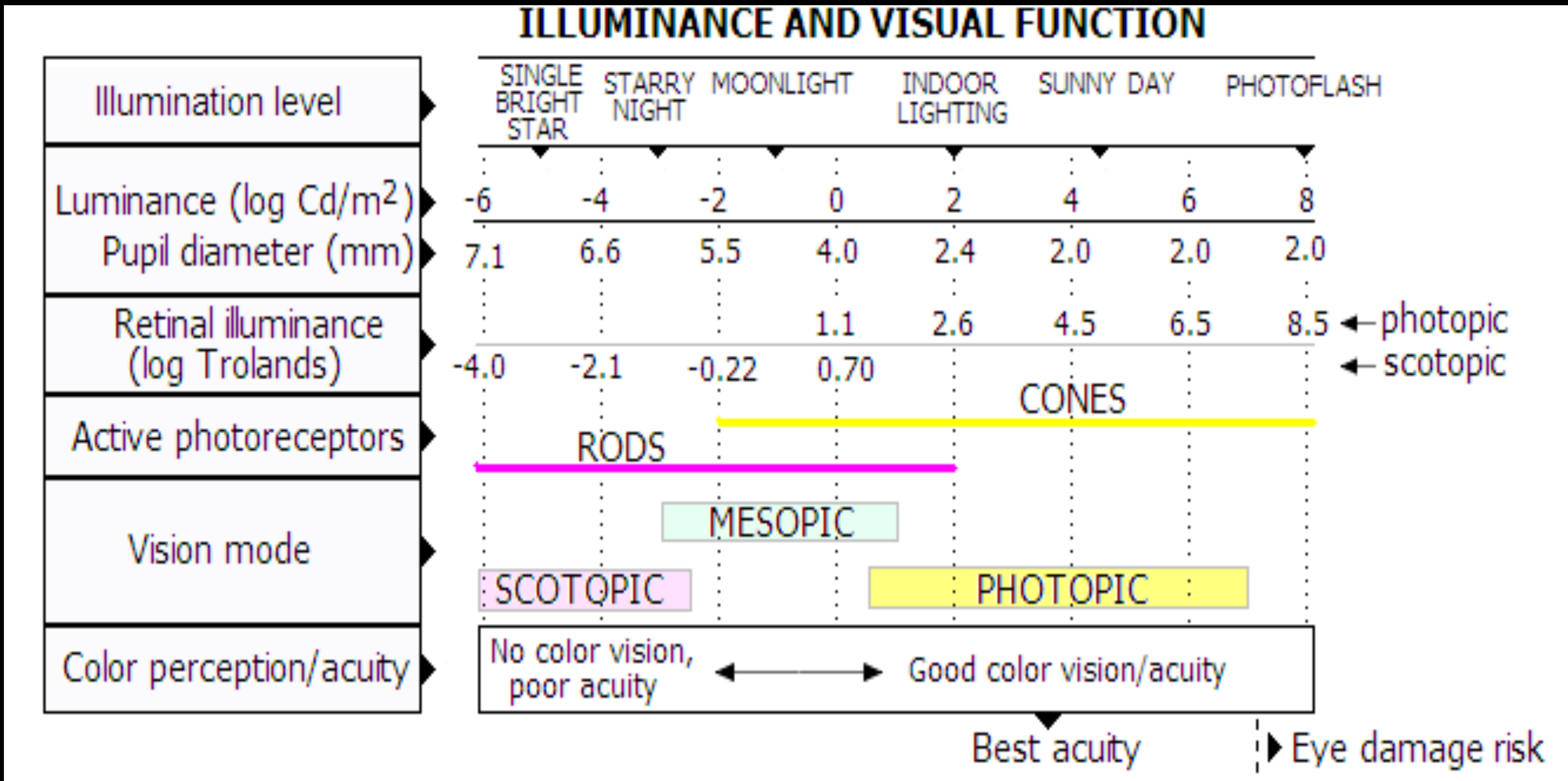


All of them are cones!

Moving outward from fovea



Sensitivity



Flux and intensity

- Luminous flux vs. radiant flux
  - Radiant flux is related to total amount of radiation within certain frequency bands
  - Luminous flux weights the radiant flux by average visibility to humans.
    - Example: since humans can't see infrared, it doesn't contributed to luminous flux.

Candela

- The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that directoin of 1/683 watt per steradian.
- About one candle.

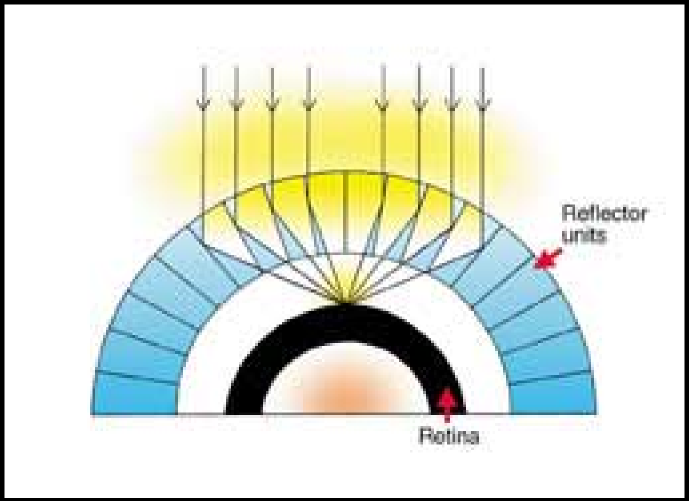
Sensitivity redux

Photopic and *Scotopic* Vision

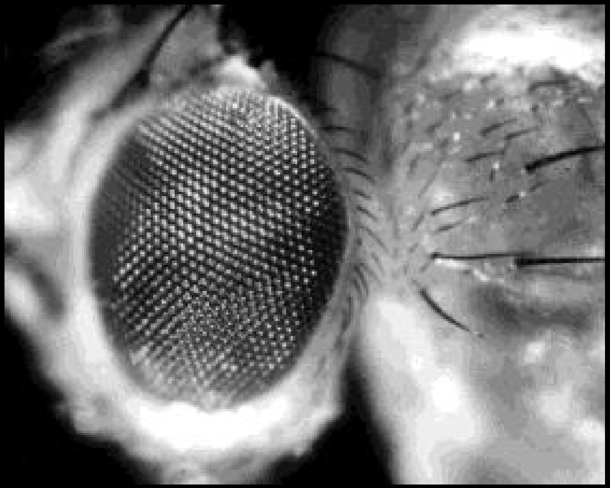
Sun's surface at noon	10^{10}	**Damaging**
	10^{9}	
	10^{8}	
Tungsten filament	10^{7}	
	10^{6}	
	10^{5}	**Photopic**
White paper in sunlight	10^{4}	
	10^{3}	
	10^{2}	
Comfortable reading	10	
Mixed	1	
	10^{-1}	
White paper in moonlight	10^{-2}	**Scotopic**
	10^{-3}	
White paper in starlight	10^{-4}	

Other eyes

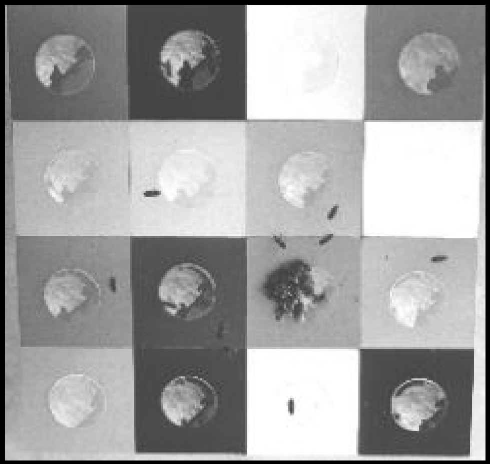
- Lobsters, crayfish
  - X-ray focusing



- "Compound eyes"
  - Flies

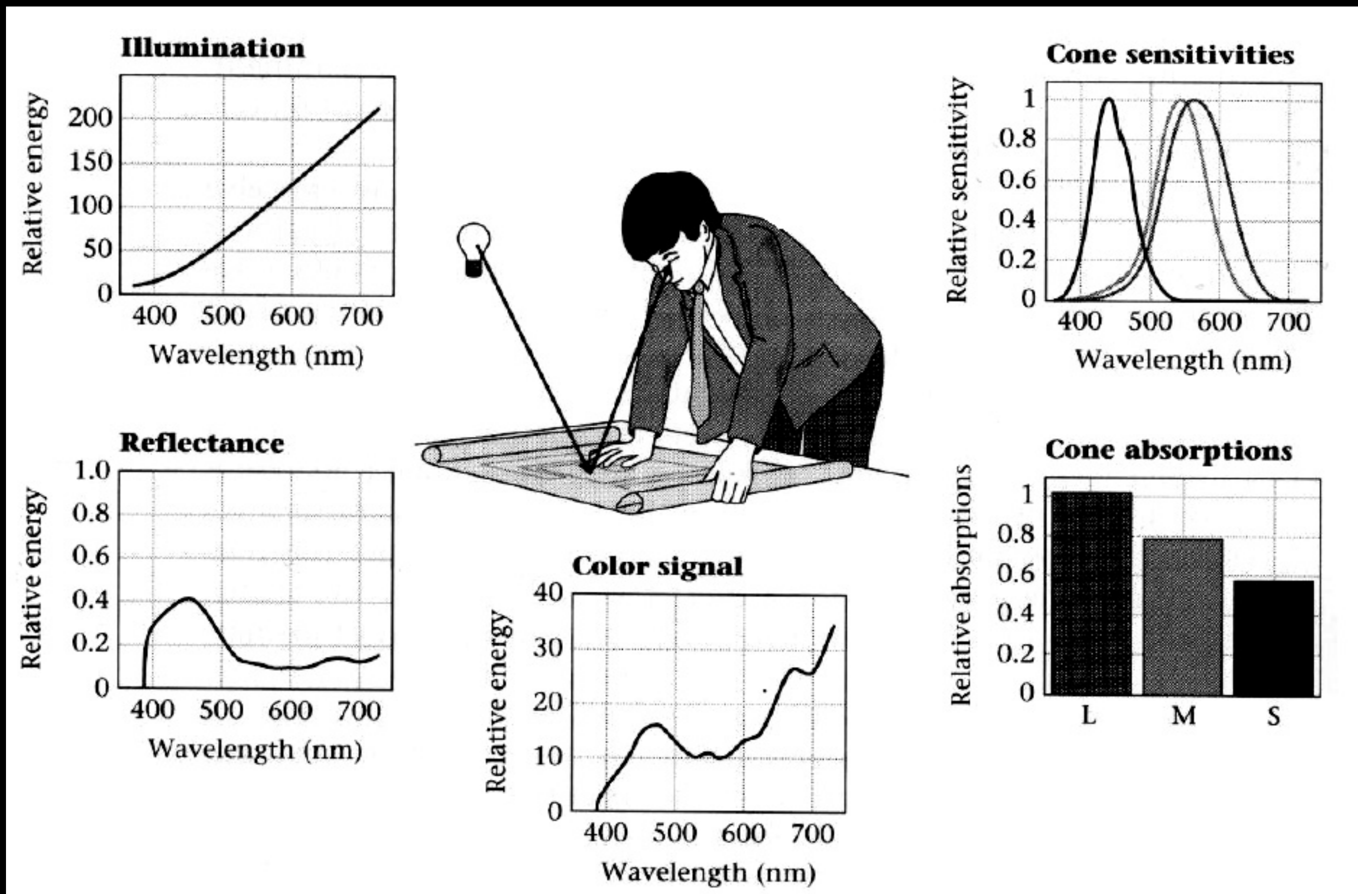


The Eye of a Fly



What Do We 'See' ?

Light Sources
Surface Reflectance
Eye sensitivity

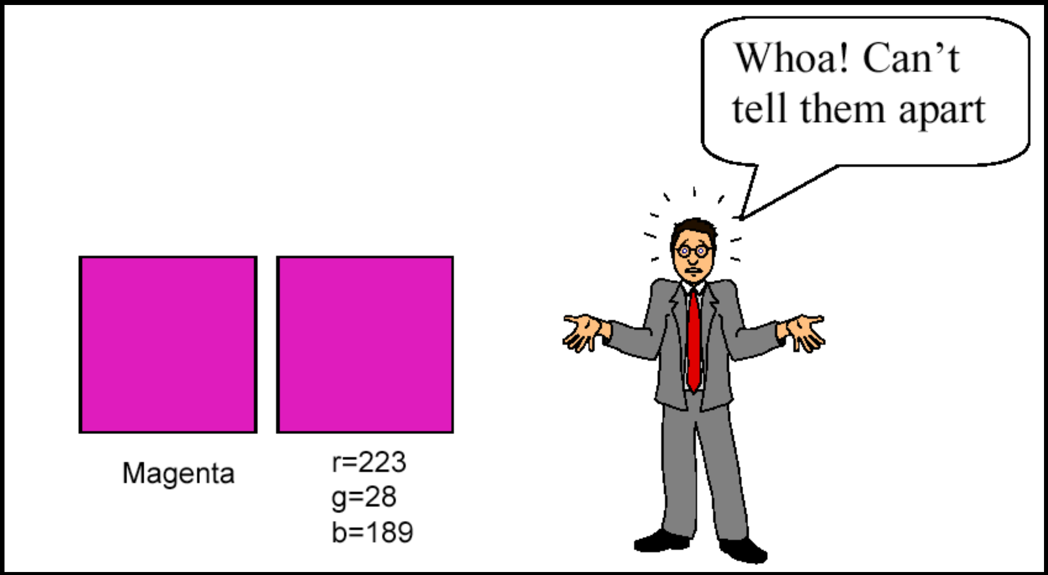


Tristimulus Theory

- Two light sources S1 and S2 may have very different spectral distribution functions and yet appear identical to the human eye.
- The human retina has three types of receptors.
- The receptors have different responses to light of different frequencies.
- Two sources S1 and S2 will be indistinguishable if they generate the same response in each type of receptor.
  - same observer
  - same light conditions
  - called metamerism

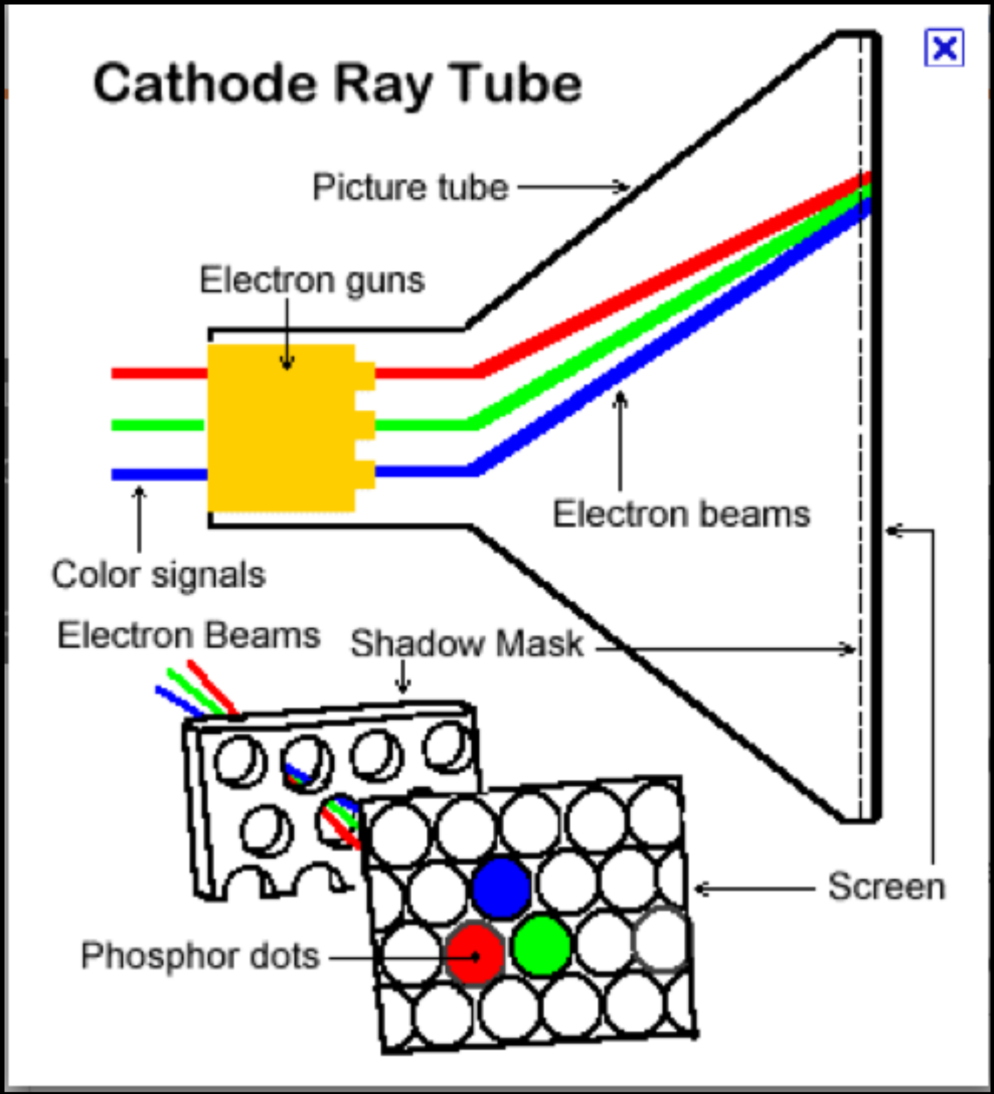
Grassman's Law (1835)

- 1st Law: Any color stimulus can be matched exactly by a combination of three primary lights.
  - The match is independent of intensity
- Basis of many color description systems



- 2nd Law: adding another light to both of these stimuli changes both in the same way.

Cathode Ray Tubes

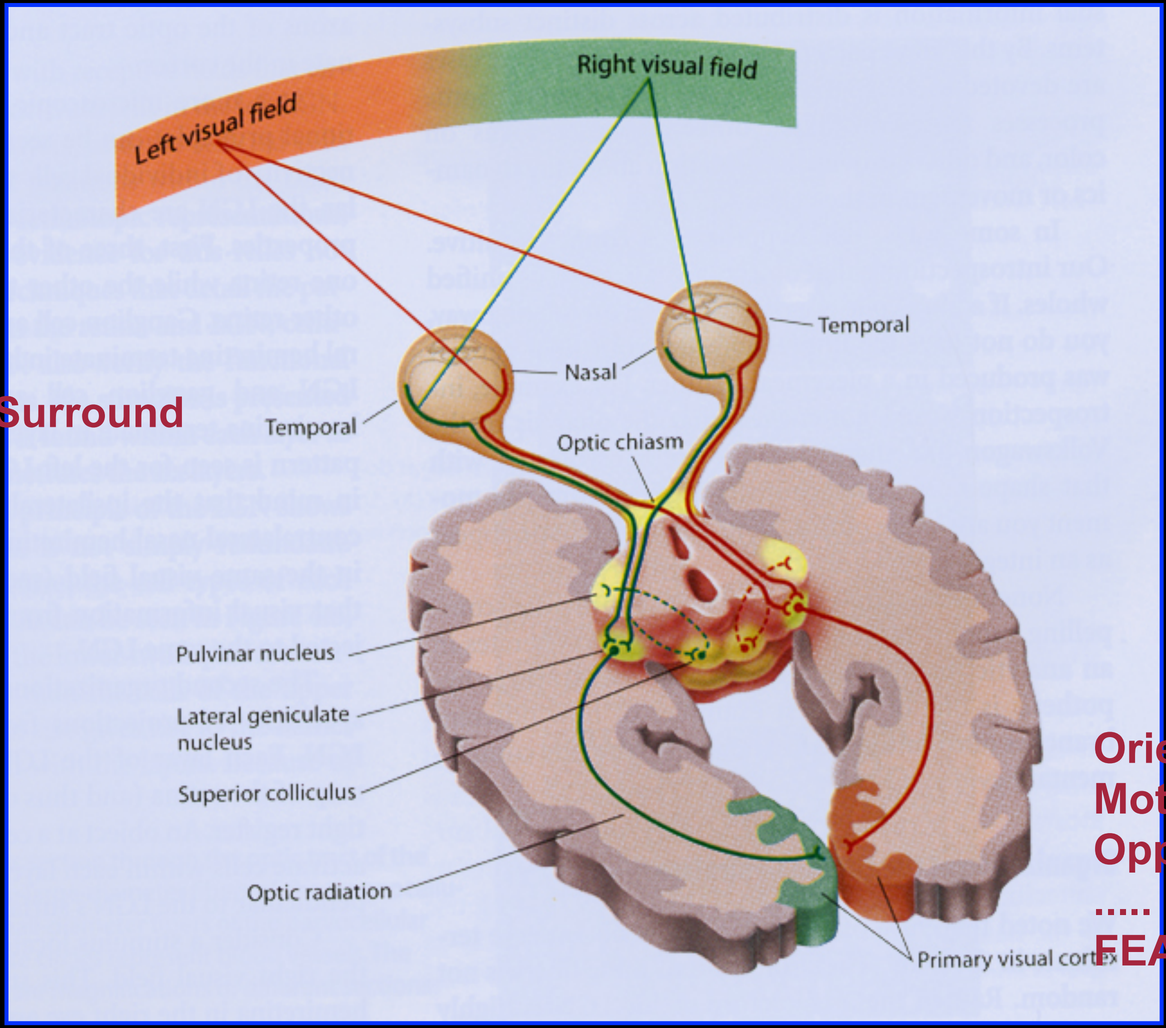


Visual Pathways

- Past the eye, visual signals move through different processing stages in the brain.
- There appear to be two main pathways
  - Magnocellular: low-resolution, motion sensitive, and primarily achromatic pathway
  - Parvocellular: high-resolution, static, and primarily chromatic pathway

Primary Visual Pathway

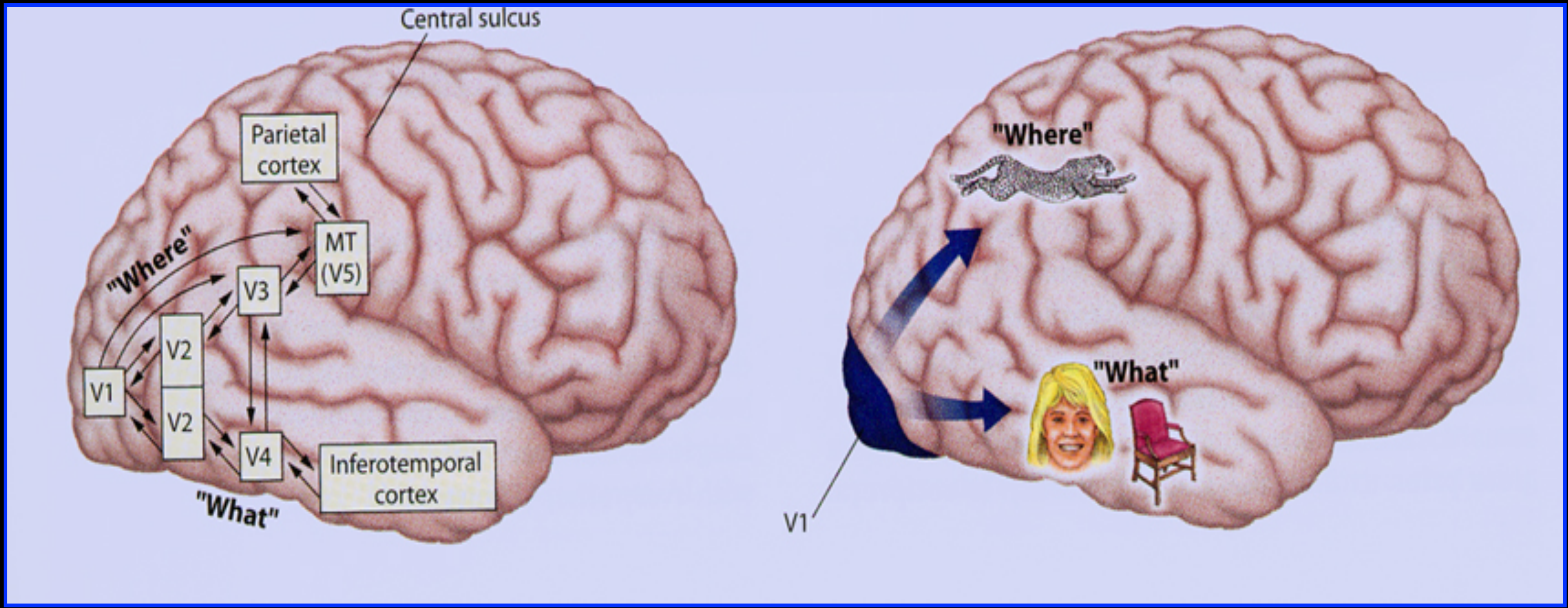
Monocular Visual Field: 160 deg (w) X 175 deg (h)
Binocular Visual Field: 200 deg (w) X 135 deg (h)



Center Surround

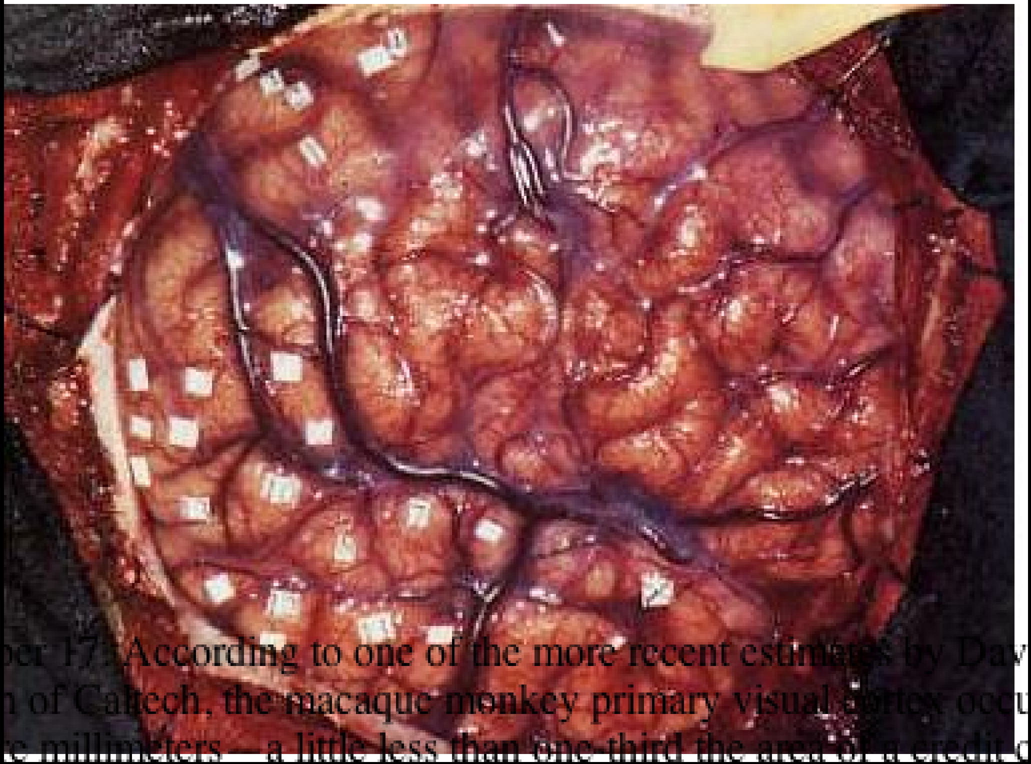
Orientation sensitive
Motion sensitive
Opponent Colors
.....
FEATURES

Processing Streams

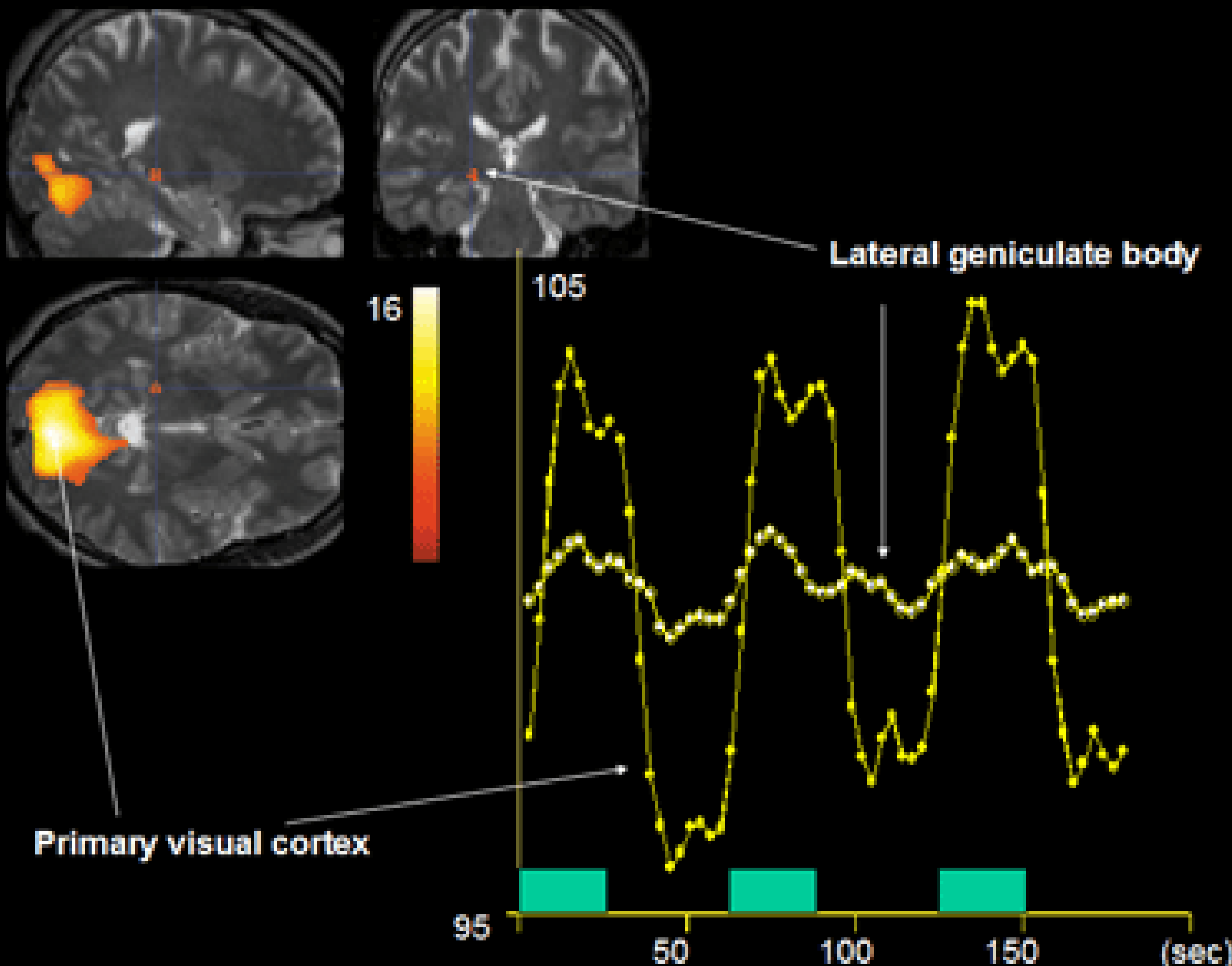


Probing the Brain

- Electrode insertion
- Brain surface measurements
- Functional MRI



Functional MRI



Describing Color

- Color is a very complex phenomenon
  - physical
  - psychological
- Following description only skims the surface
  - important details omitted
  - simplified mathematics
  - ‘leaps of faith’

Terminology (Rough)

- Hue: dominant wavelength of light entering the eye
- Saturation: inversely proportional to amount of white light mixed with pure color
  - Red - fully saturated
  - pink - partially saturated
  - white - fully unsaturated
- Luminance: intensity of light entering the eye
  - Lightness: luminance of a reflecting object
  - Brightness: luminance of a light source (radiance)
- Chromaticity: hue and saturation (not luminance)

Color and Independence

- Which representation of color is “most natural”?
- Brain seems to try to sort things into “independent” quantities.
  - More useful for prediction?
  - More efficient information representation?
- Independence in artificial intelligence.
- Are the responses of red, green, and blue detectors independent?
- Are hue, saturation, and luminance independent?

Brightness and Luminance

- *Question*: What is the difference between luminance and brightness?
- *Answer:* Luminance of an object is its absolute intensity. Brightness is its perceived luminance, which depends on the luminance of the surrounding.
- *Question:* Why are luminance and brightness different?
- *Answer*: because our perception is sensitive to luminance contrast rather than absolute luminance.

Example: car headlights bother car driver much more at night (when it's dark) than in the day time.
Luminance of headlights is the same, it's only the perceived luminance (brightness) that differs from night (dark) to daytime (light).

Brightness Adaptation

- Range of light intensity levels to which HVS (human visual system) can adapt: on the order of 10^{10}.
- Brightness as perceived by the HVS is a logarithmic function of the light intensity incident on the eye.
- The HVS cannot operate over such a range simultaneously.
- For any given set of conditions, the current sensitivity level of HVS is called the brightness adaptation level.

Brightness Adaptation

- The eye also discriminates between changes in brightness at any specific adaptation level.

$$\frac{\Delta I_c}{I} \blacklozenge \text{ Weber ratio}$$

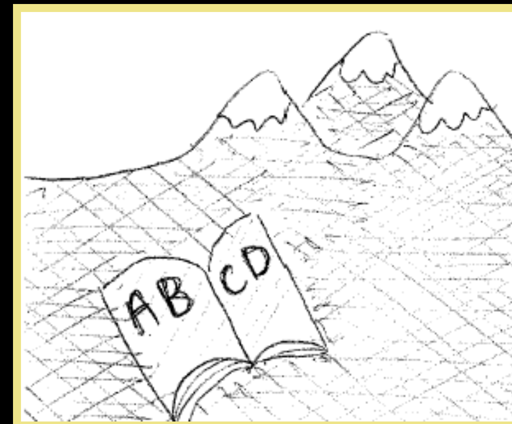
DI_c: the increment of illumination discriminable 50% of the time and

I : background illumination

- Small values of Weber ratio mean good brightness discrimination (and vice versa).
- At low levels of illumination brightness discrimination is poor (rods) and it improves significantly as background illumination increases (cones).
- The typical observer can discern one to two dozen different intensity changes (major caveats here).

Contrast vs. Intensity

- We care about surface reflectance, not light intensity. Why?
- Contrast is proportional to reflectance.



	Reflectance	Intensity I at noon (1000000 W)	Intensity I at dusk (1000 W)	Local contrast c at noon (1000000 W)	Local contrast c at dusk (1000 W)
Snow	90%	900000 W	900W	1.25	1.25
Grass	40%	400000 W	400 W	0	0
Paper	80%	800000 W	800 W	1	1
Ink	10%	100000 W	100 W	-0.75	-0.75
Mean	40%	400000 W	400 W	0	0

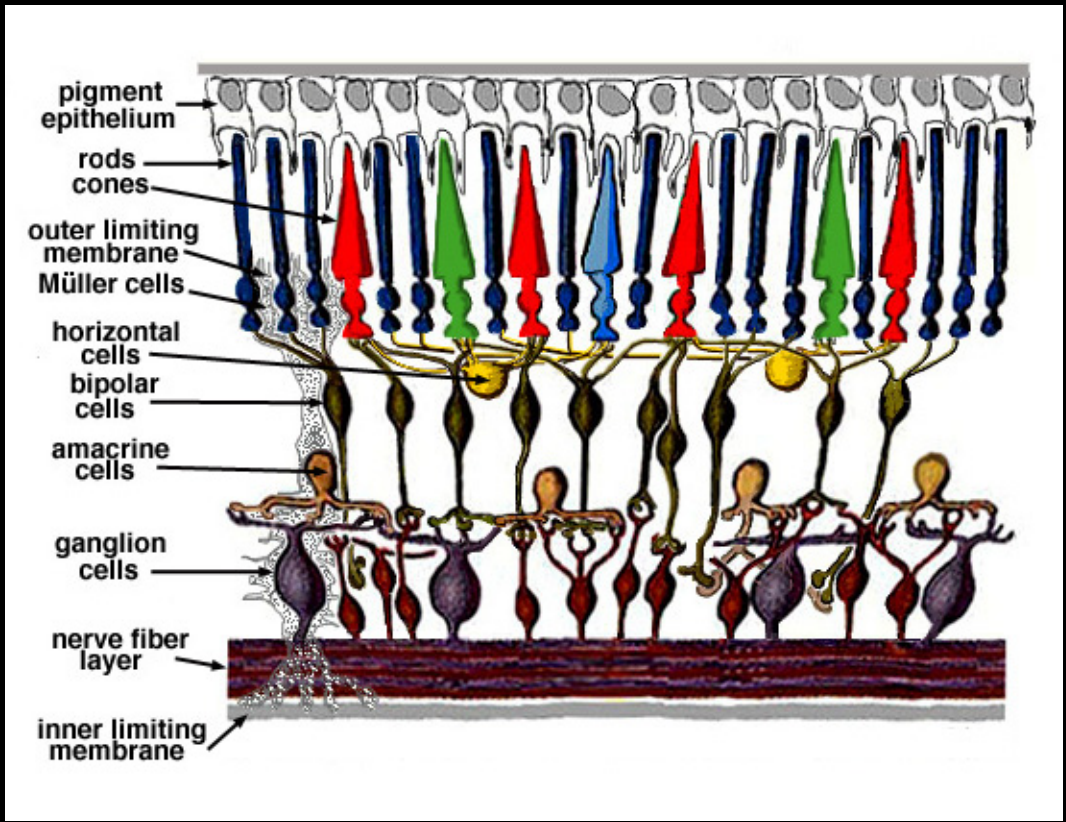
Intensity is reflectance*illumination
Local contrast is c = (I-Imean)/Imean

The Retina

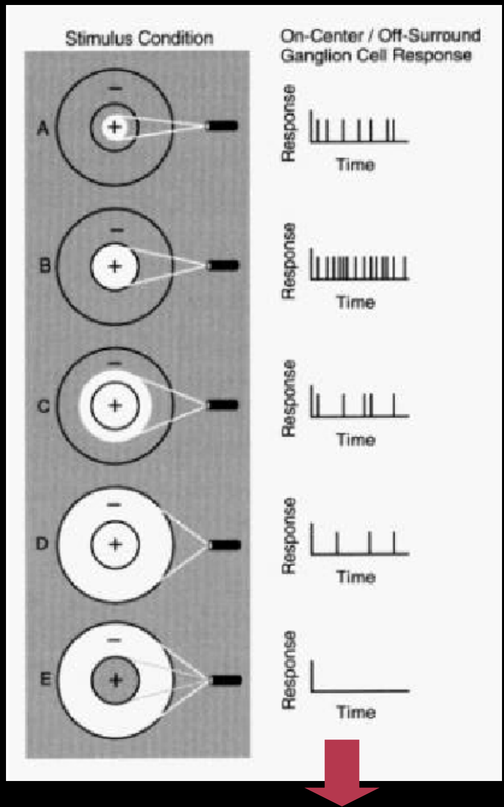
- "The retina is part of the brain." What???
  - David H. Hubel

Retinal Processing

130 million sensors -> 10 million nerve fibers



Processing at retinal level: center surround receptive fields

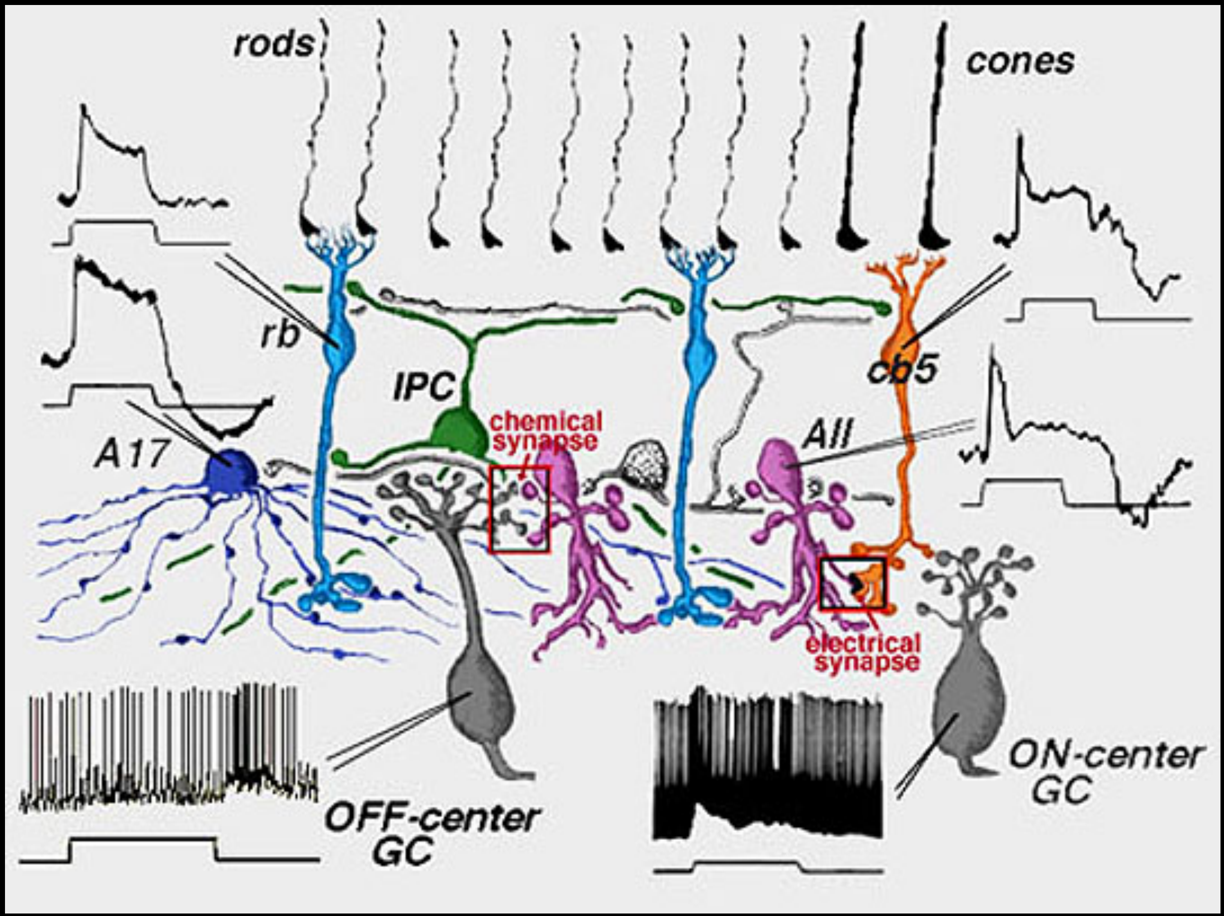


This is what is sent down the optic nerve fibers

Center Surround

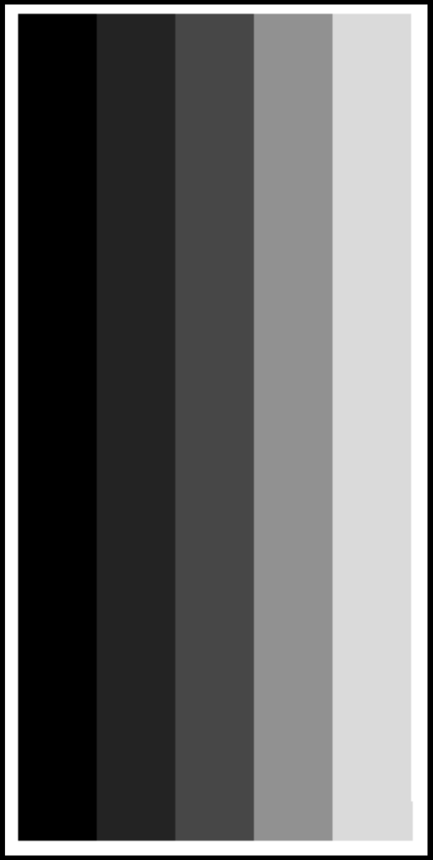
- Why might the optic nerve send center surround signals?
  - Invariance to brightness changes
  - Independence of signals.
    - Spatial derivatives carry more "independent" information.

Rod Pathways

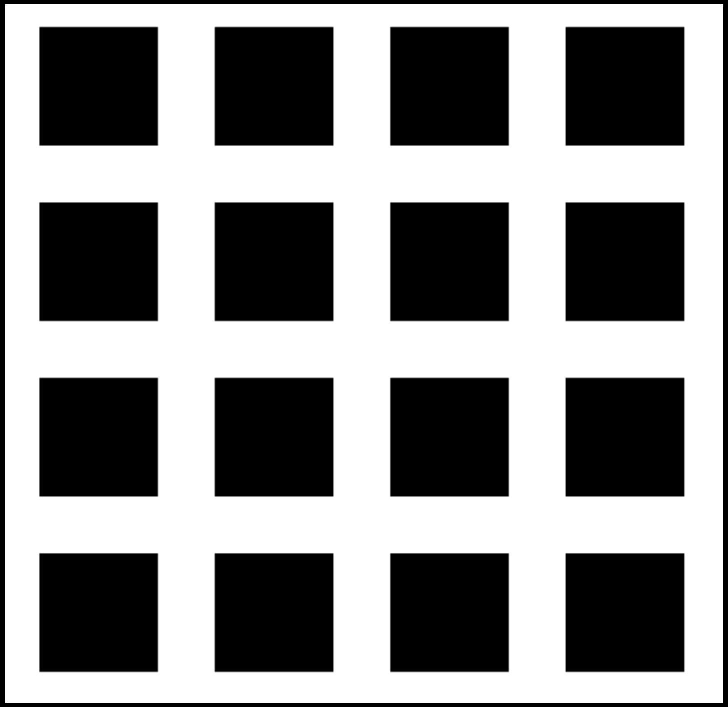


Illusions

Center surround operators can be used to explain several ‘illusions’

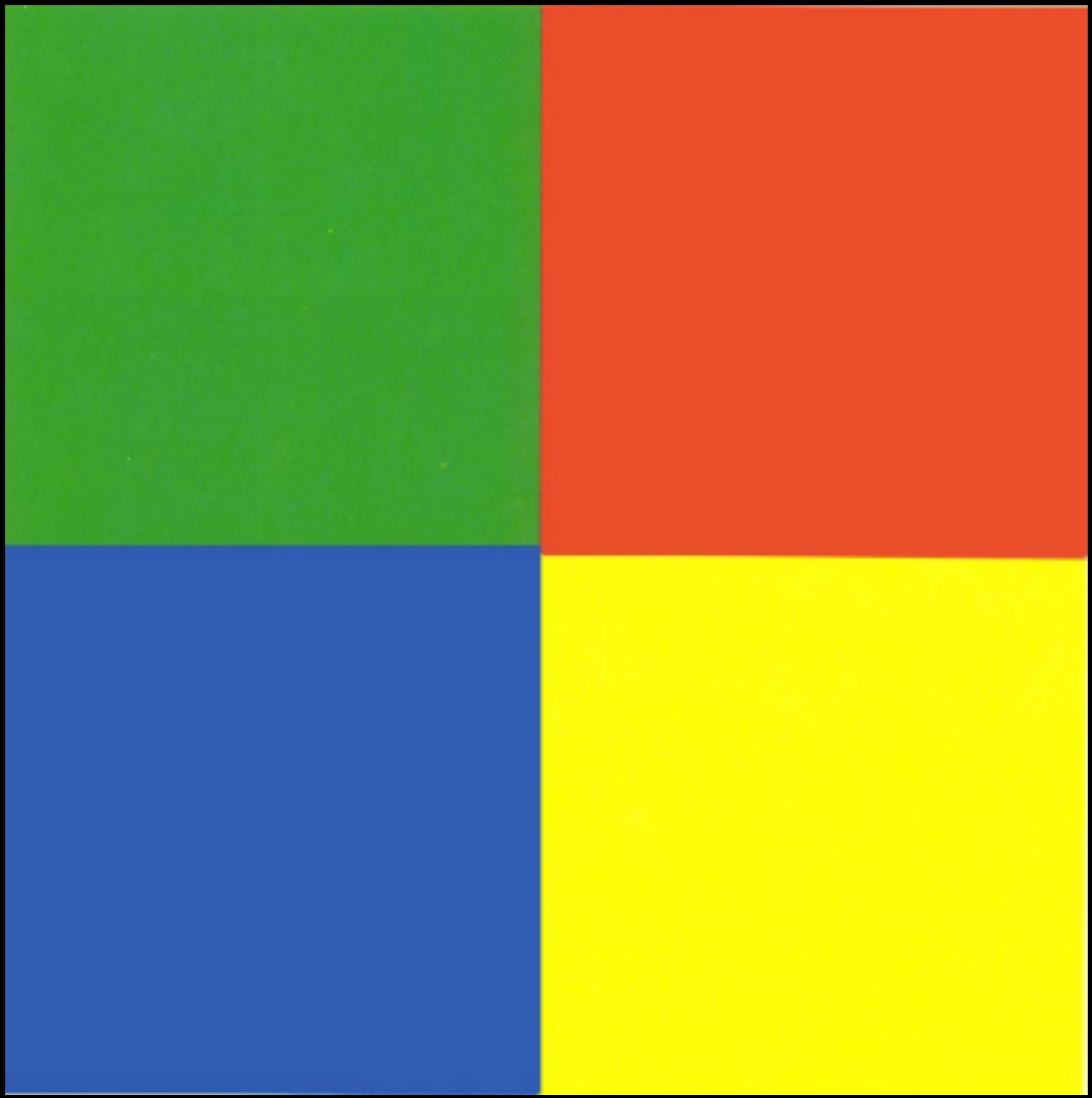


Mach Bands



Herring Grid

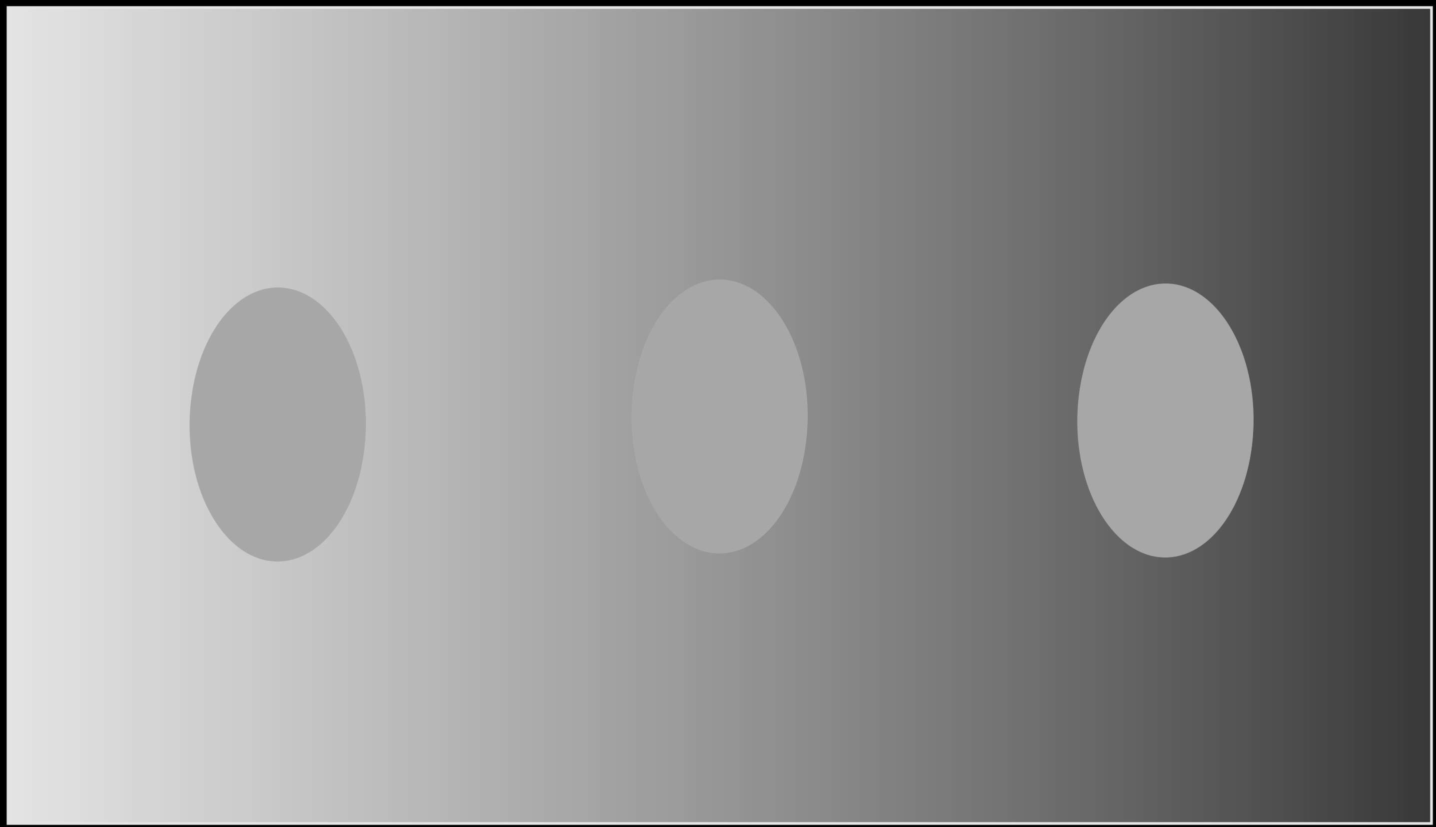
Sensor Depletion



Sensor Depletion

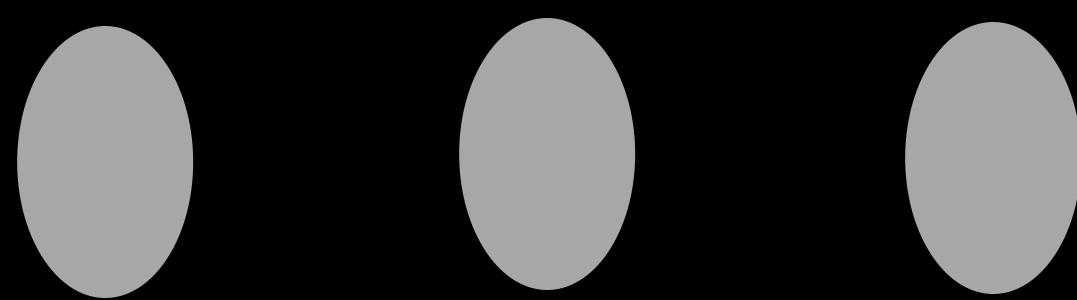
Local Adaptation

- Ellipses are the same gray level



Local Adaption

- Ellipses are the same gray level



The eye / brain combination is NOT a camera!

Color Constancy

- If color is just a light of a certain wavelength, then why does a yellow object always look yellow under different lighting (e.g. fluorescent versus sunlight)
- This is the phenomenon of 'color constancy'
- Colors are constant under different lighting because the brain tends to respond to ratios of the R, G, B cones signals, and not absolute magnitudes
- Note that camera film, video cameras, etc DO NOT exhibit color constancy!

Introduction to

Computer Vision

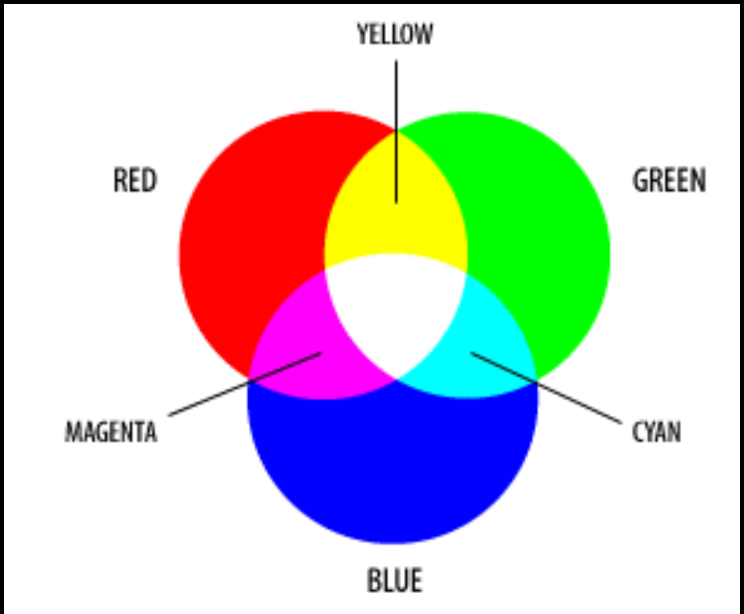
Color Flows

Color Models

- Many different color models have been developed
- Usually application specific
- Most are linear transforms of the XYZ space

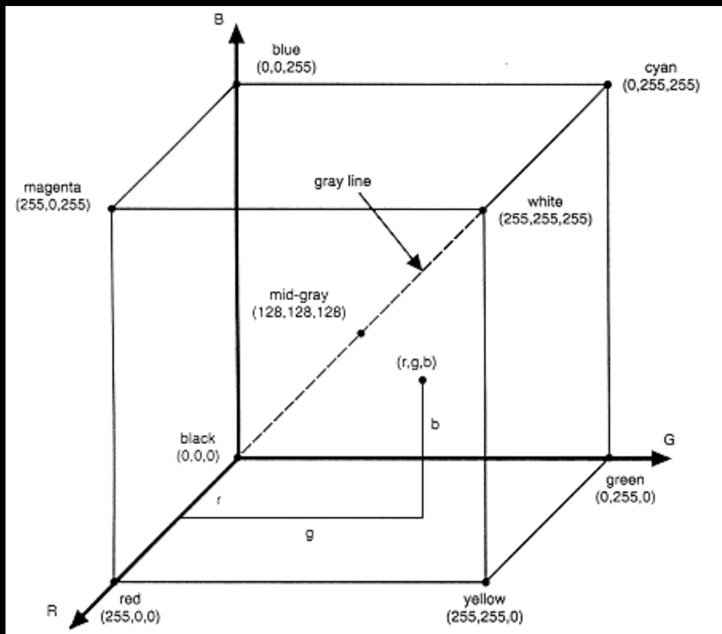
RGB Space

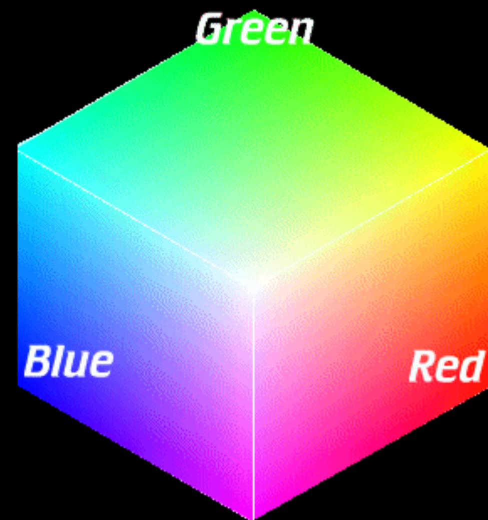
- Red, green, and blue are
  - the primary stimuli for human color perception
  - the primary additive colors
  - RGB is the basic color model used in television receivers or any other medium that projects color.
  - cannot be used for print production (why?)

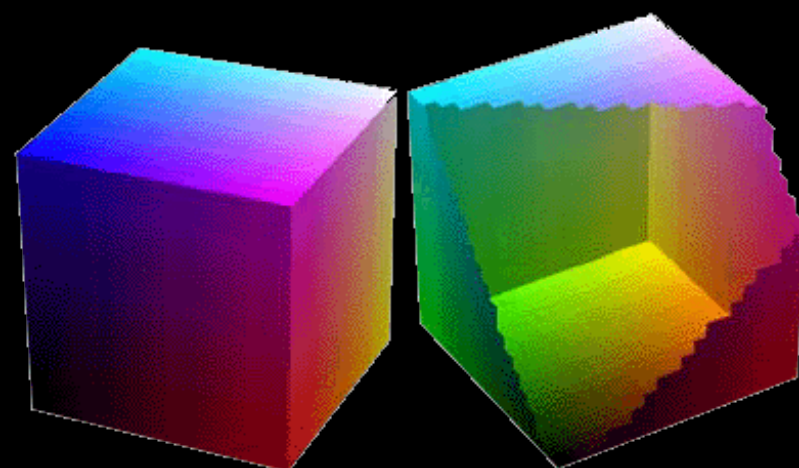


The secondary colors of RGB, cyan, magenta, and yellow, are formed by the mixture of two of the primaries and the exclusion of the third.

RGB Color Space

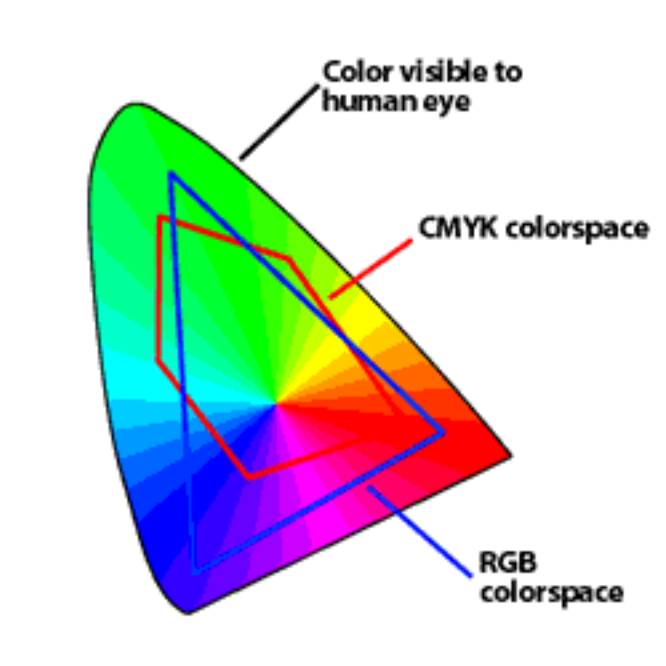






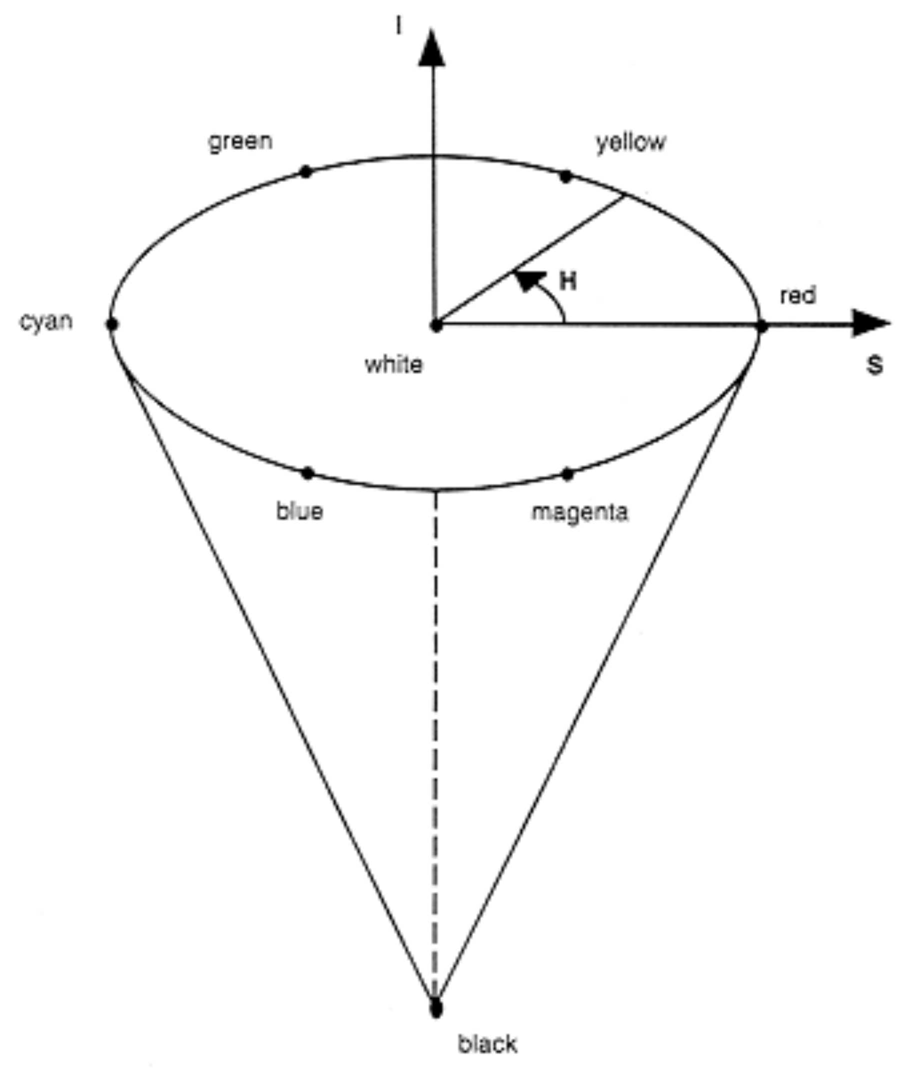
RGB and XYZ

[R] = [2.739 -1.145 -0.424] [X]
[G] = [-1.119 2.029 0.033] [Y]
[B] = [0.138 -0.333 1.105] [Z]



Gamuts don't match!

HSI Color Space



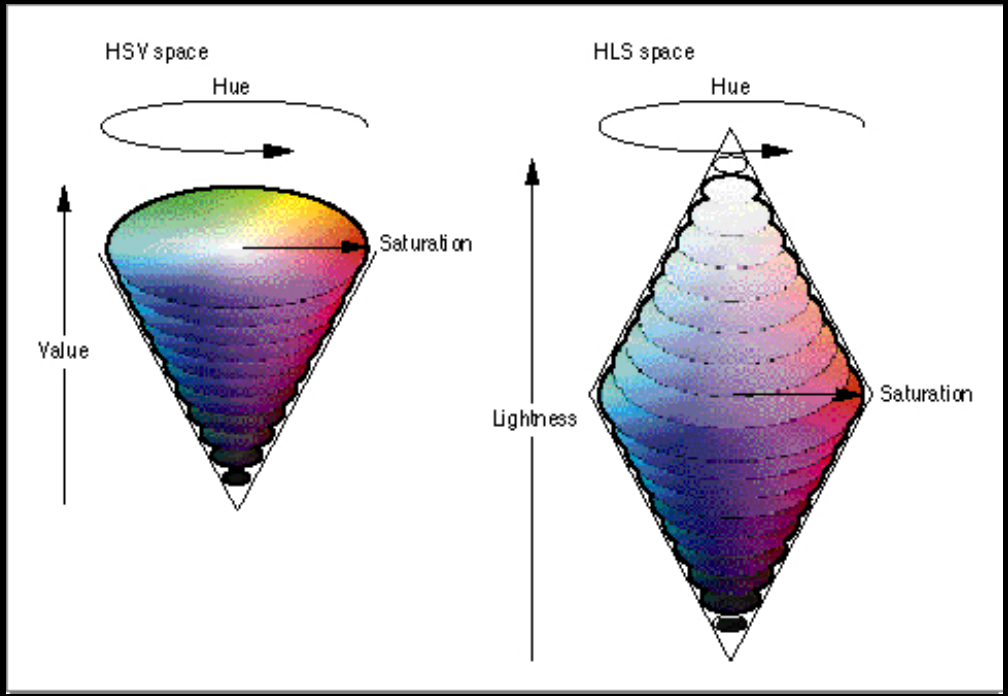
$$I = \frac{1}{3}(R + G + B)$$

$$S = 1 - \frac{3}{R + G + B}\left[\min(R, G, B)\right]$$

$$H = \cos^{-1}\left[\frac{\frac{1}{2}\left[(R - G) + (R - B)\right]}{\sqrt{(R - G)^2 + (R - B)(G - B)}}\right]$$

If B is greater than G, then
$H = 360^{o} - H$.

HSI and HSV



- Viewing the RGB color cube down the greyscale axis yields HSV & HLS color spaces
- HSV & HLS differ in where pure colors lie and how intensity relates to saturation
- These spaces are designed to be intuitive for color picking
- Very useful for computer vision

Color Enhancement

- One form of color enhancement: increase color saturation
- Moves colors towards boundary of visible region on CIE diagram, for example

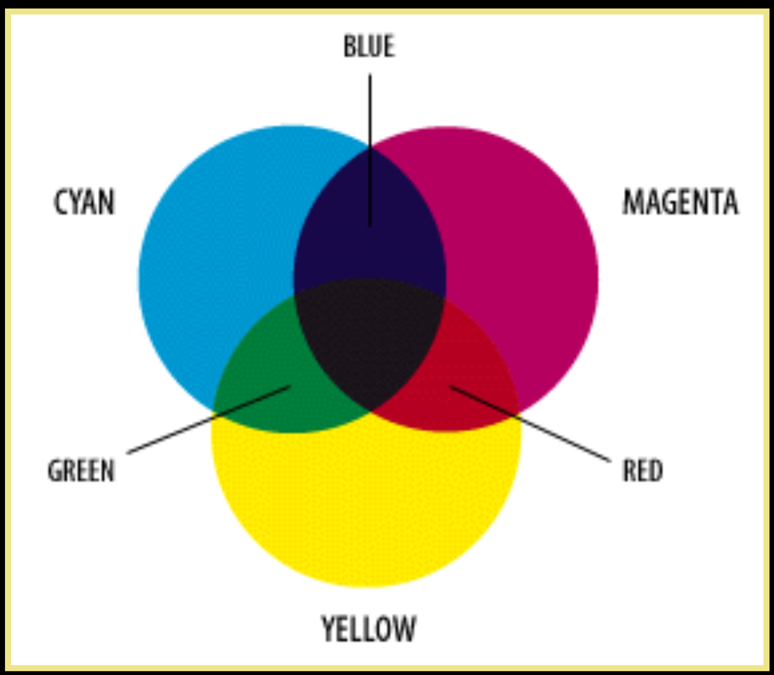
Unsaturated

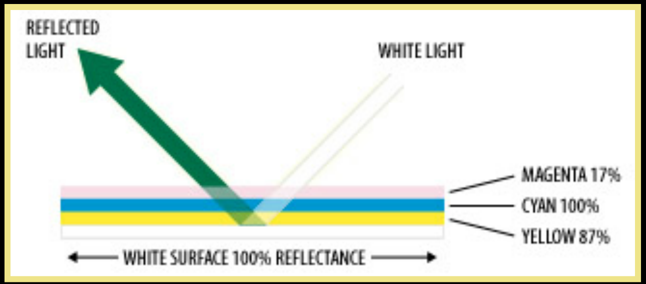
More Saturated

Hue has not changed!

CMY(K) Space

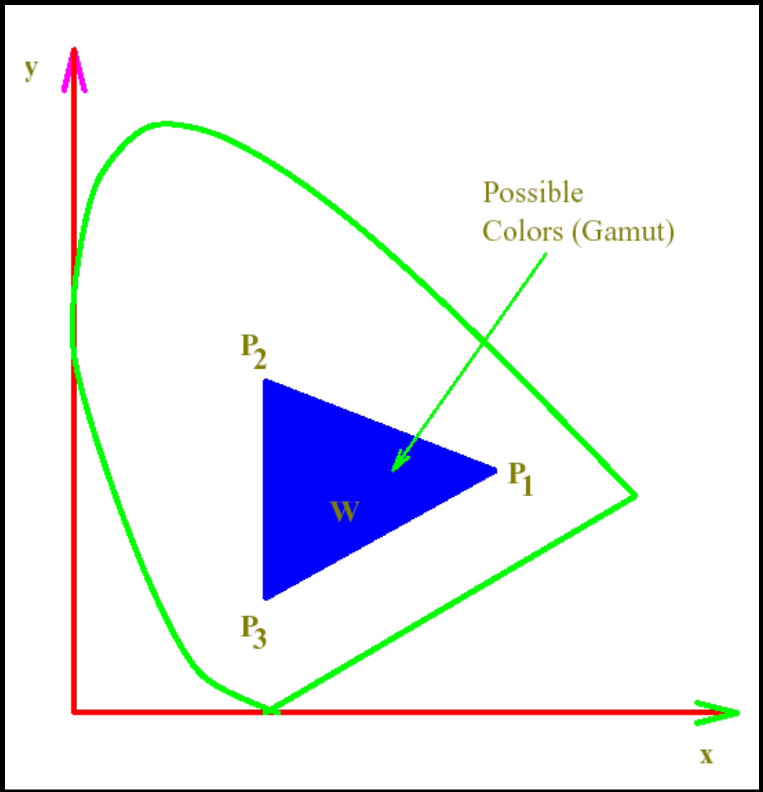
- Cyan, magenta, and yellow correspond roughly to the primary colors in art production: blue, red, and yellow.
  - used primarily in printing
  - the primary subtractive colors
  - black is sometimes added (K) to achieve a true black





Printing Color: CMYK

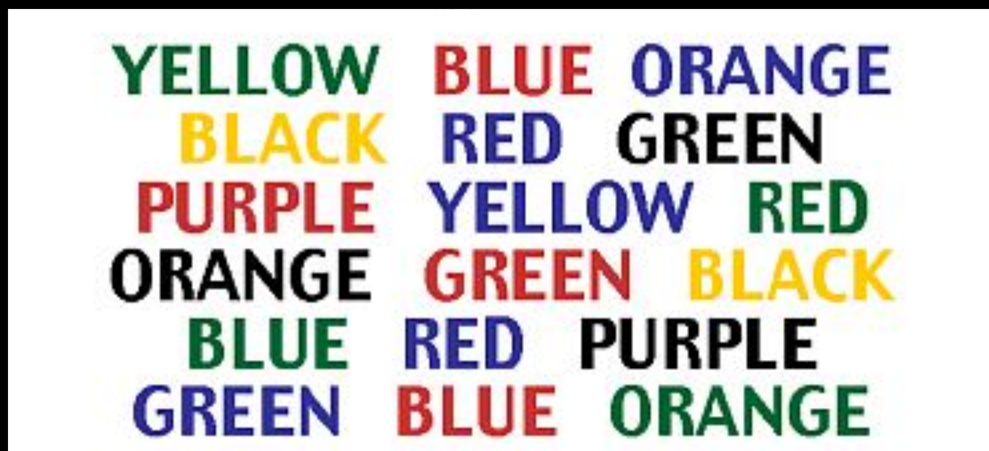
Color Gamuts



- Not every color output device is capable of generting all visible colors in the CIE diagram
- Usually color is generated as an affine combination of three primaries P_1, P_2, and P_3
- Colors that the device can generate are bounded by a triangle whose vertices are these primaries
- This region of the CIE diagram is called the device gamut

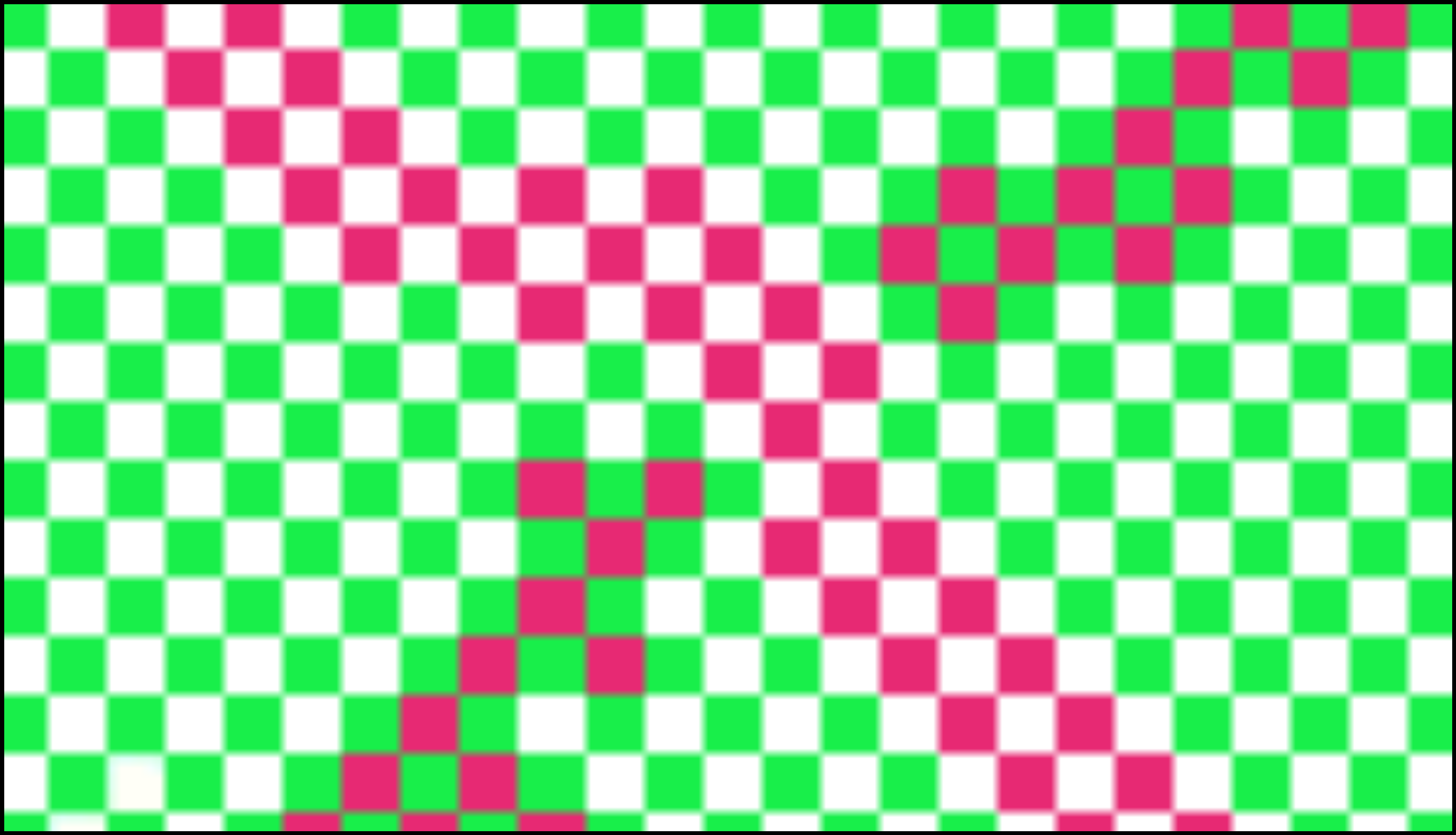
Interesting Experiment

- Look at the chart and say the color, not the word:

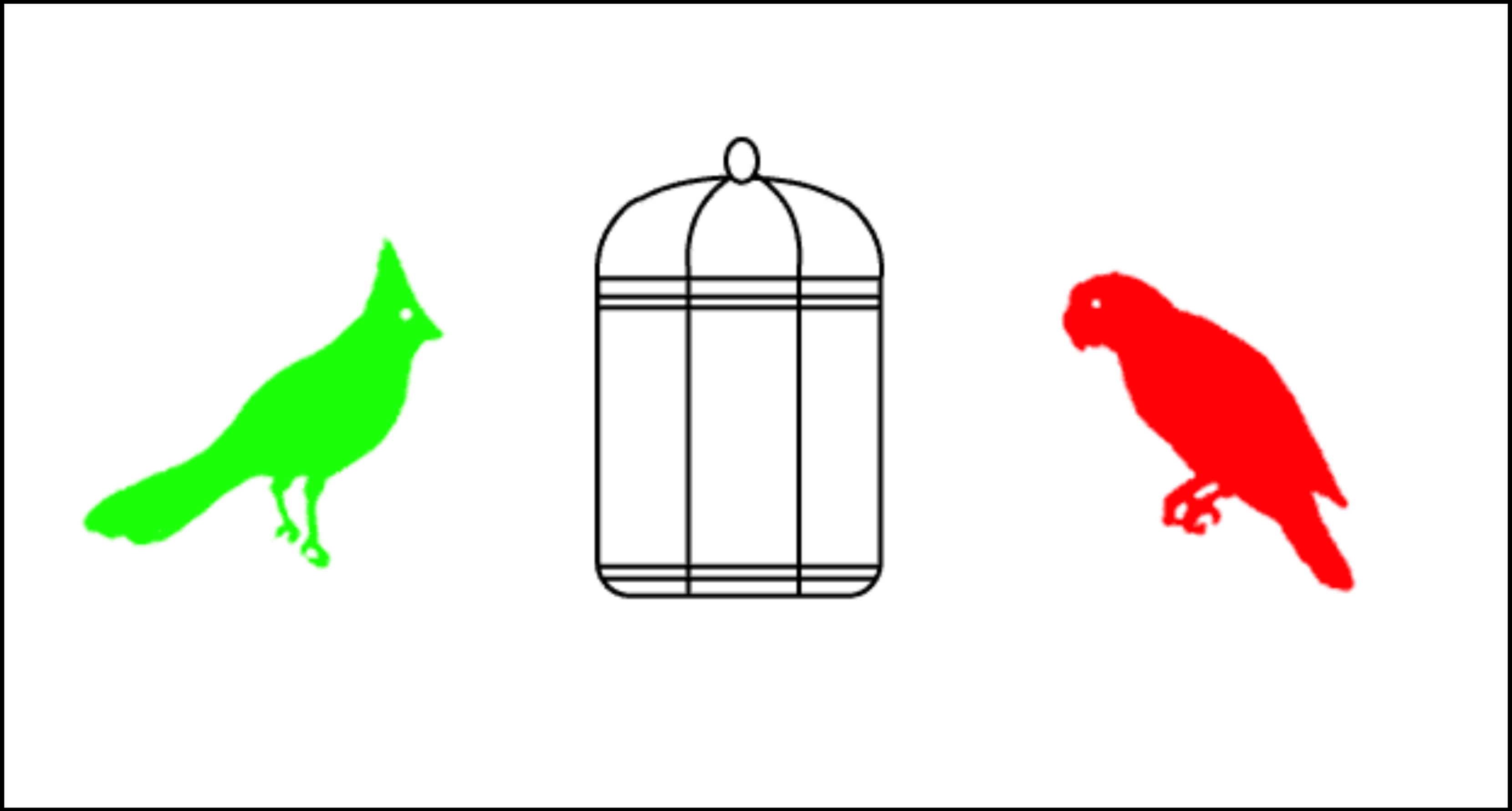


- Left brain - right brain conflict?

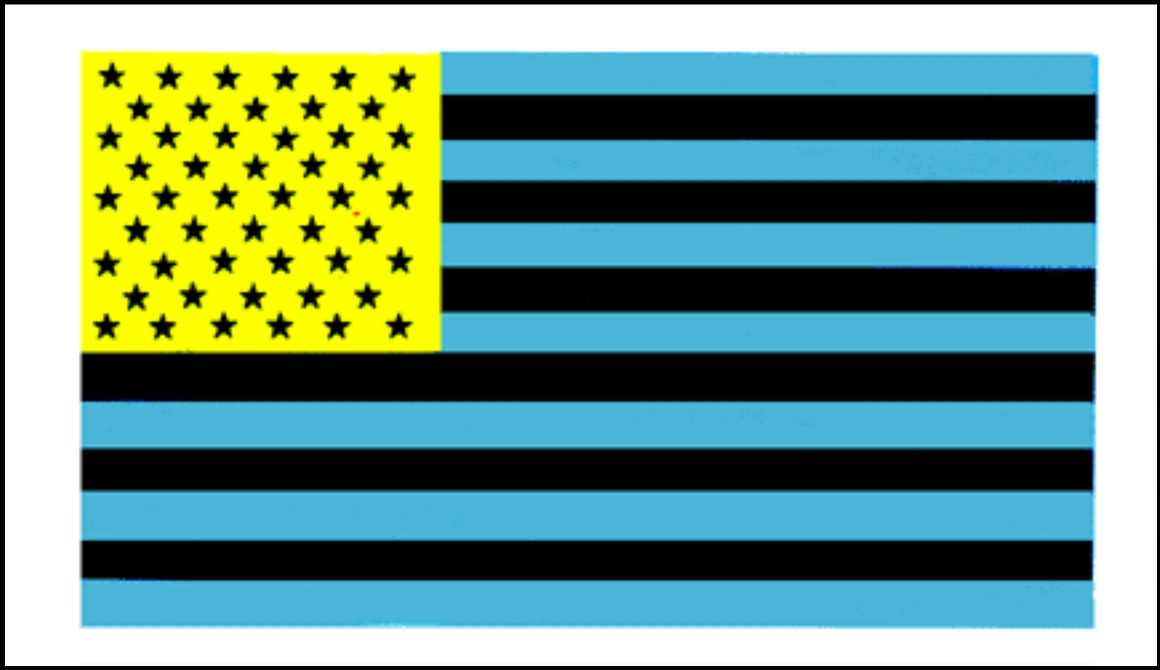
Illusions



Illusions



Illusions

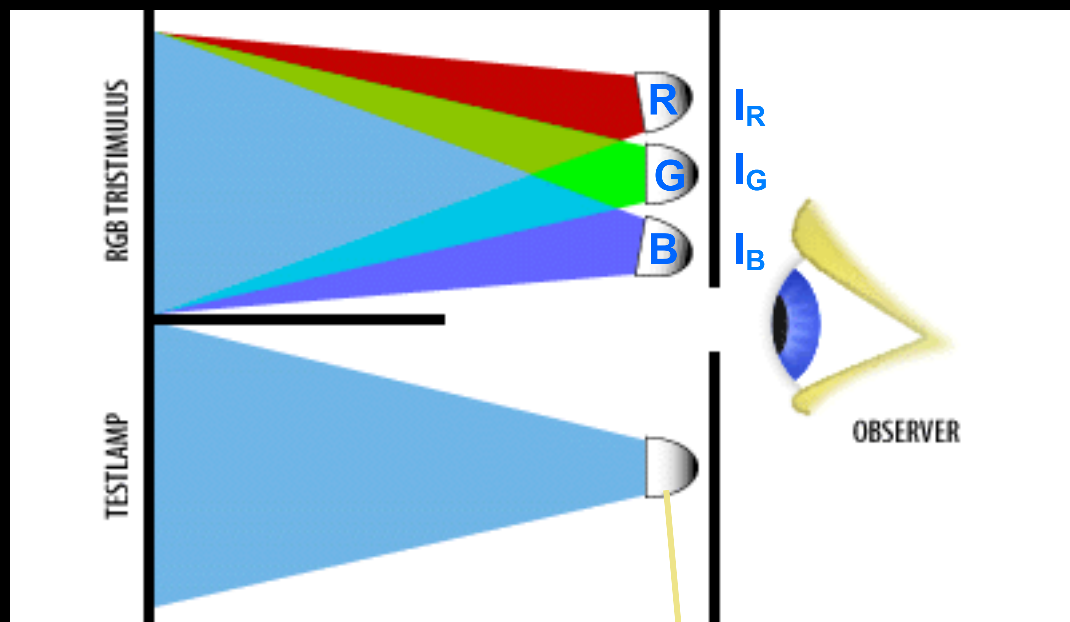


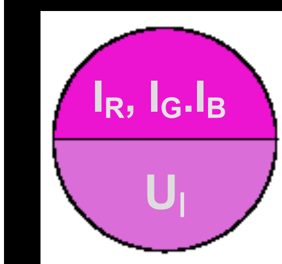
Color Matching Experiments

Controllable standard sources -
e.g. a, b, and g are user determined

Controllable mix

Unknown color





Monochromatic light of constant intensity U_l

Following few slides adapted from Paul Avery, Univ. of Florida

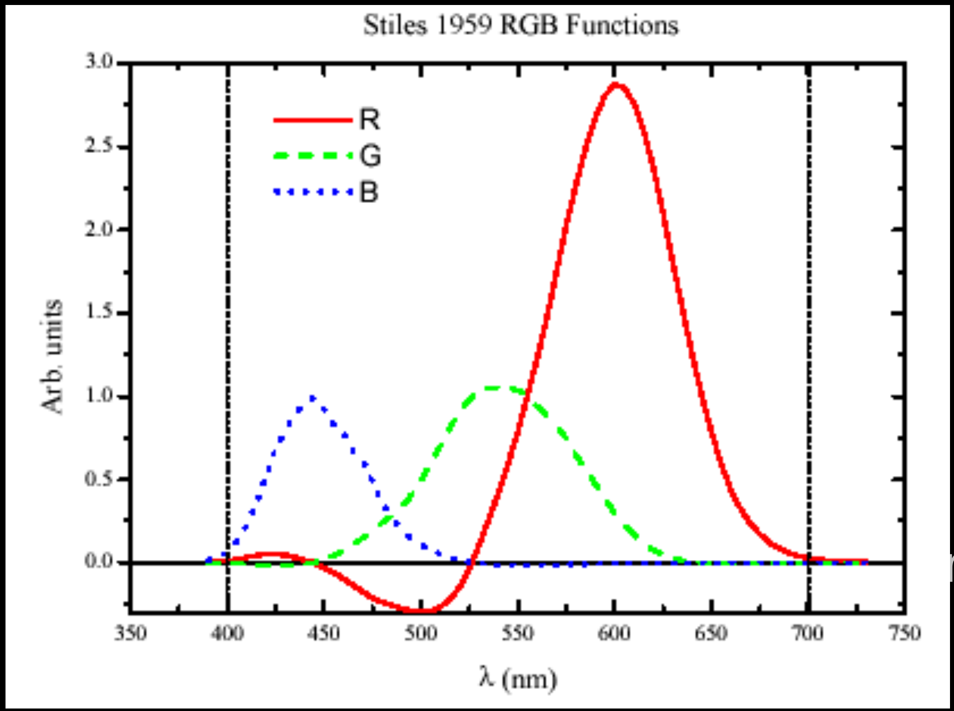
Procedure

- Upper part of field illuminated by adjustable monochromatic lights of wavelengths l_R, l_G, l_B
- l_R = 645 nm, l_G= 526 nm, l_B = 444 nm
- Lower part of field illuminated by a single monochromatic light of constant intensity U_l
- Adjust RGB intensities until perfect match
- Record intensities ($\mathbf{I_R}$, $\mathbf{I_G}$, $\mathbf{I_B}$) for that wavelength
- Shift wavelength l=l+Dl
- Repeat

What do we get?

Color Matching Functions

- Recorded values of (I_R, I_G, I_B) define color matching functions for the three light sources



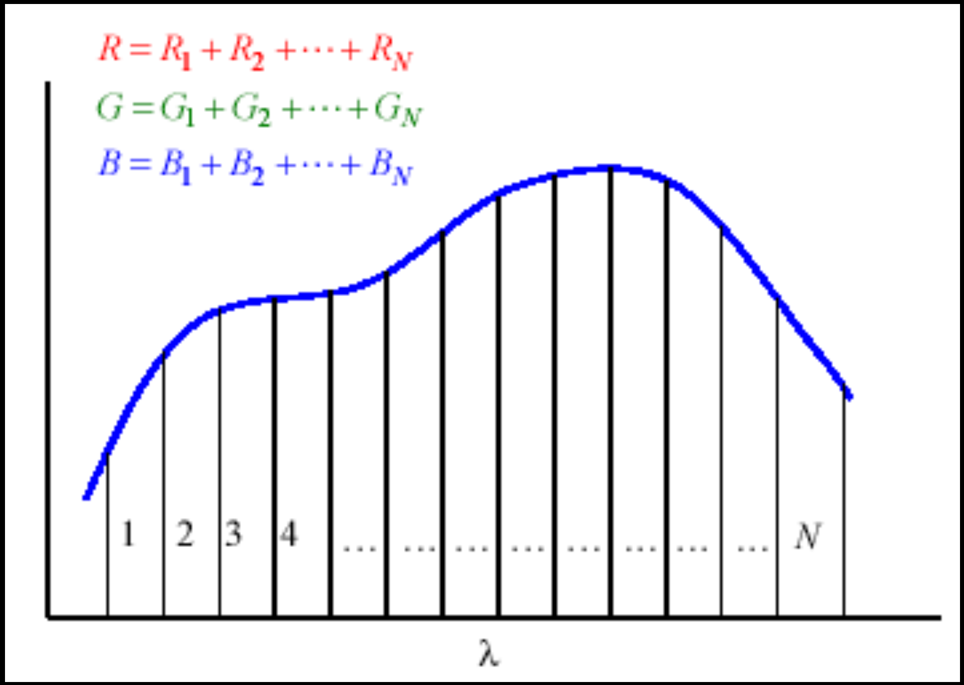
Example:
match unit intensity at 500 nm

Use curves to get values
I_R=-0.30, I_G=0.50, I_B=0.10

r one of the lights, add the

Matching a spectrum

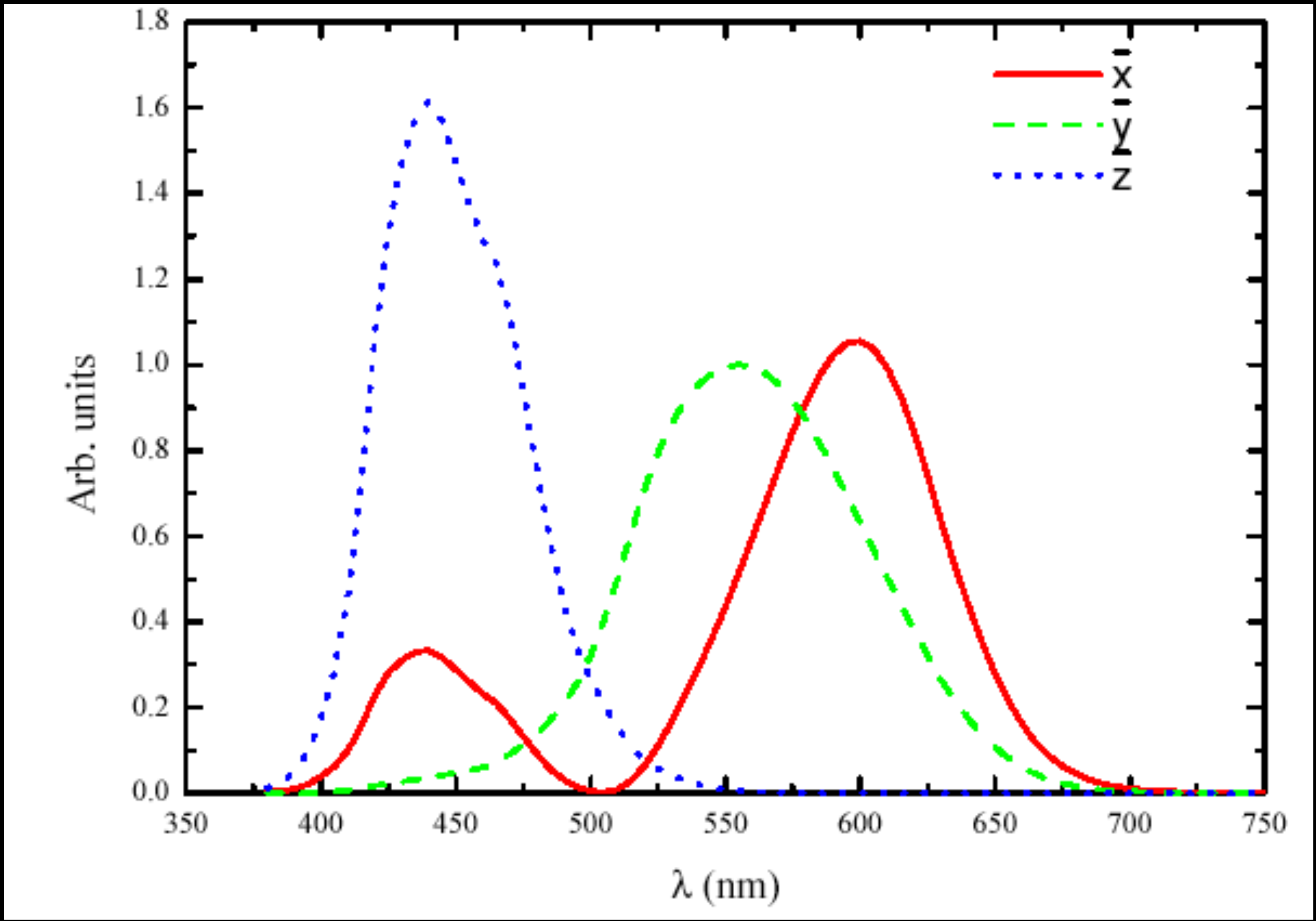
- Any spectrum can be matched this way
  - break spectrum into n discrete samples
  - for each sample, calculate (Ri, Gi, Bi) as before
  - Add all (Ri, Gi, Bi) to get final (R, G, B) value
  - Simple!



CIE Color Model

- CIE 1931 Standard model
- Negative values were consider undesirable for an international standard
  - couldn't use with RGB monitors, for example (came later)
- Introduced three new(imaginary primaries X, Y, Z so that all tristimulus values are positive
- Can relate R, G, B to X, Y, Z mathematically, so no problem
- Called x(l), y(l), z(l) functions → XYZ values
- Independent of initial choice of l_R, l_G, l_B values!

1978 CIE CMFs

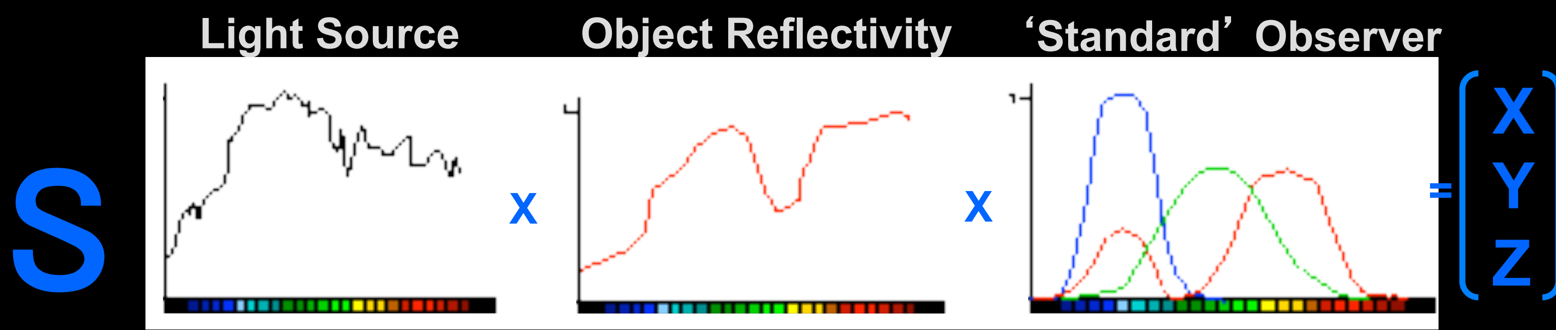


Other Properties

- Middle curve y set to match brightness sensitivity of eye
- Thus Y is a measure of overall brightness
- Normalized so that 'flat' spectrum yields X=Y=Z=100
- 0£Y £ 100 always

- XYZ called the 'tristimulus value'
  - every color has it own (XYZ) value
  - two colors with the same (XYZ) appear identical
    - 'Metameric pair'

Computing XYZ Values



- Sample spectrum into n discrete wavelengths
- Sample i has wavelength l_i, illuminance I_i, reflectance $\mathcal{R}_i$, color matching function CMF_i
- $(X_i\ Y_i\ Z_i)$ for each l_i computed by multiplying

  Illuminance x reflectance x CMFs
- Total XYZ obtained by adding up all $(X_i\ Y_i\ Z_i)$
- Scale so that 100% reflectance gives Y = 100

Mathematically

$$X = k \sum_{i} I_i(\lambda_i)\, \mathcal{R}_i(\lambda_i)\, \bar{x}_i(\lambda_i)$$

$$Y = k \sum_{i} I_i(\lambda_i)\, \mathcal{R}_i(\lambda_i)\, \bar{y}_i(\lambda_i)$$

$$Z = k \sum_{i} I_i(\lambda_i)\, \mathcal{R}_i(\lambda_i)\, \bar{x}_i(\lambda_i)$$

k is a normalization constant chose to make 100% reflectance (white) correspond to Y=100

$$k = 100 / Y$$

In continuous case, replace summation by integral

Example (Simple)

- Illuminant spectrum:
  - 2 units of light at 500 nm
  - 1 unit of light at 600 nm
- Object
  - Reflectance at 500 nm = 0.50
  - Reflectance at 600 nm = 0.60
- CMF values (from graph)
  - l = 500 nm x = 0.00, y=0.30, z=0.25
  - l = 600 nm x = 1.05, y=0.65, z=0.00
- Calculate k = 100/(2*0.30 + 1*0.65) = 80
- Then
  - X = 80(2*0.50*0.00 + 1*0.60*1.05) = 50.4
  - Y = 80(2*0.50*0.30 + 1*0.60*0.65) = 55.2
  - Z = 80(2*0.50*0.25 + 1*0.60*0.00) = 20.0

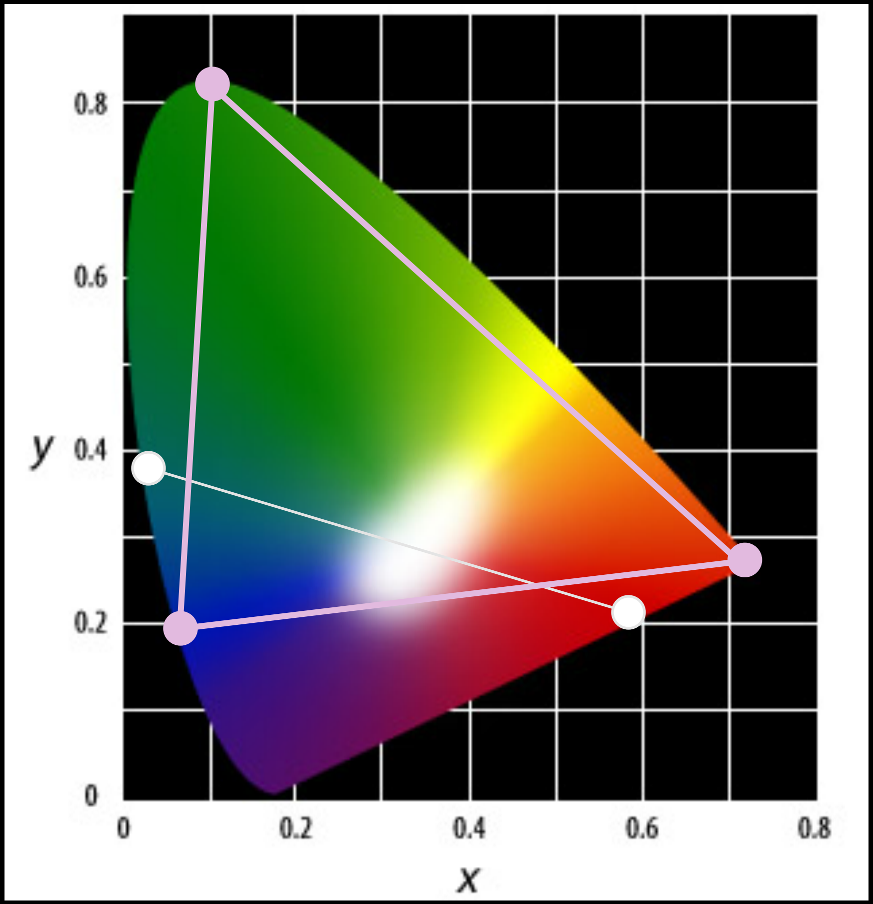
Chromaticity Coordinates

- Now normalize the X, Y, Z values
- e.g. $x = X/(X+Y+Z)$ etc.
- $x + y + z = 1$, so only two of these are independent
- Use (x,y,Y) to specify any color
- Use x and y to map colors - get the standard CIE chromaticity diagram
- Y is luminance and x and y correspond to hue and chroma (more on this later)

CIE Chromaticity Diagram

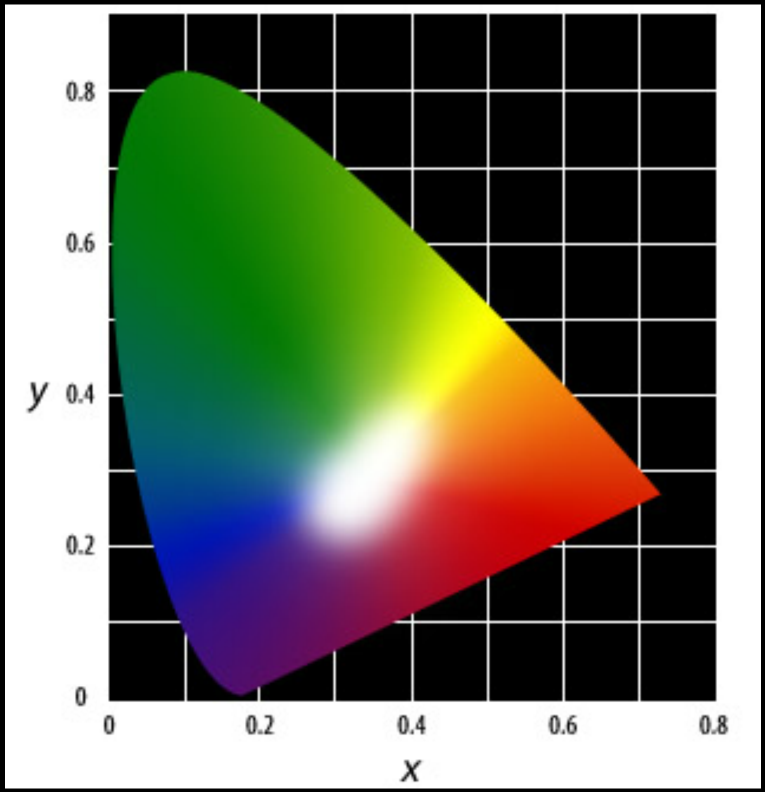
- Pure colors lie on the curved perimeter
- All visible colors lie in convex hull of curved perimeter

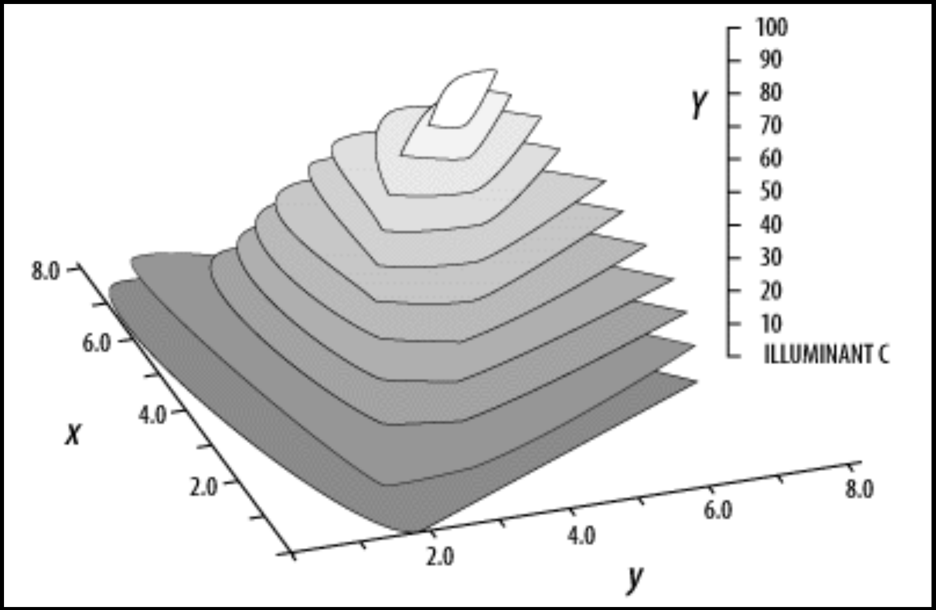
Only colors within the triangle can be constructed by mixing red, green, and blue



Complementary colors

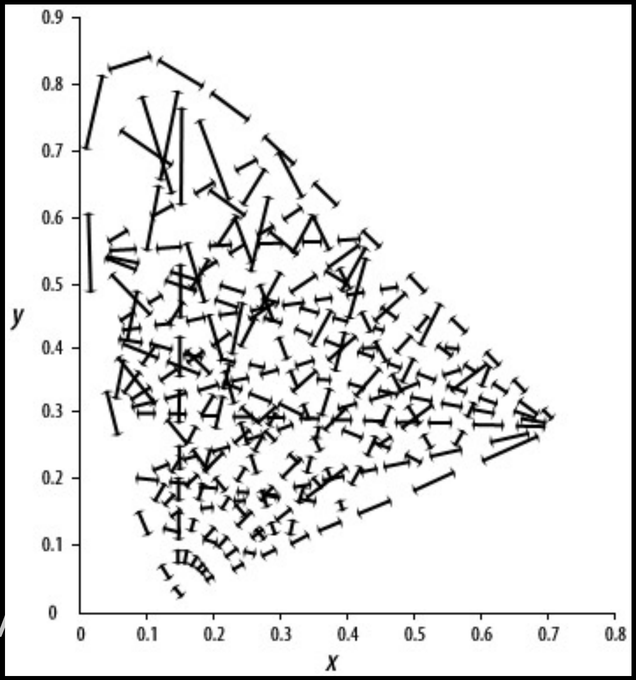
The 3rd Dimension





CIE Chromaticity Model

- NOT a model of human color perception:
  - distances in CIE diagram do not correspond to perceptual differences in color.

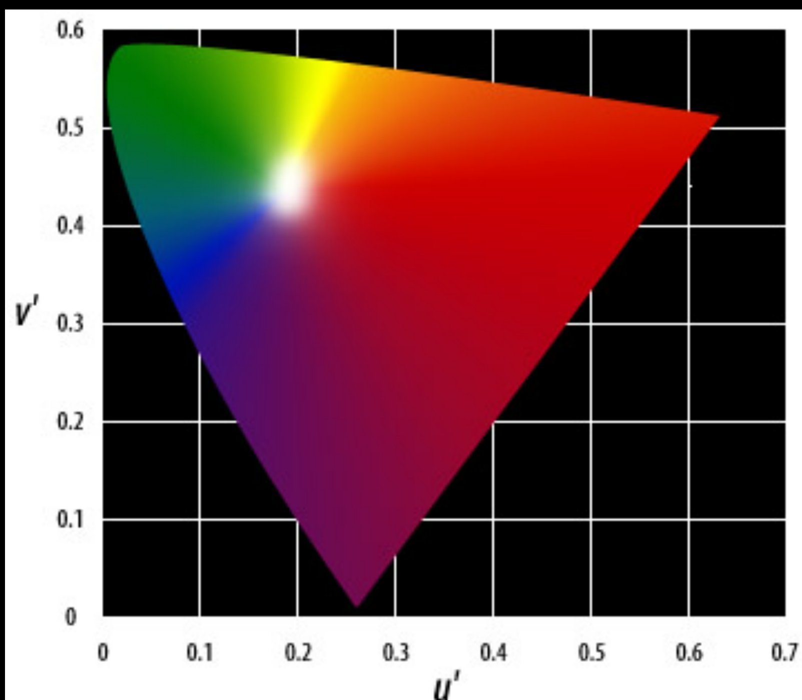


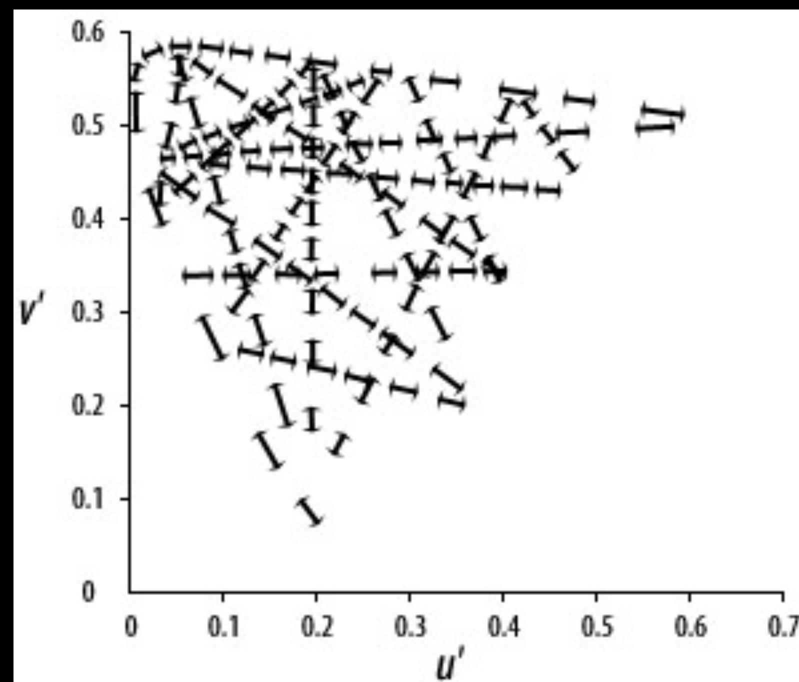
The distance between the end points of each line segment are perceptually the same according to the 1931 CIE 2° standard observer.

- CIELUV

CIE LUV Model

- Transform the XYZ values or x,y coordinates mathematically to a new set of values (u’,v’) that result in a visually more accurate two-dimensional model.





YIQ Color Space

- YIQ is used in color TV broadcasting
  - downward compatible with B/W TV where only Y is used.
- Y (luminance) is the CIE Y primary.

$$Y = 0.299R + 0.587G + 0.114B$$

- The other two vectors:

$$I = 0.596R - 0.275G - 0.321B$$

$$Q = 0.212R - 0.528G + 0.311B$$

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.274 & -0.322 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0.956 & 0.621 \\ 1 & -0.272 & -0.647 \\ 1 & -1.105 & 1.702 \end{bmatrix} \begin{bmatrix} Y \\ I \\ Q \end{bmatrix}$$

- The YIQ transform:
  - I is the red-orange axis, Q is roughly orthogonal to I.
- Eye is most sensitive to Y, next to I, next to Q.
  - In NTSC, 4 MHz is allocated to Y, 1.5 MHz to I, 0.6 MHz to Q.

Example YIQ Decomposition