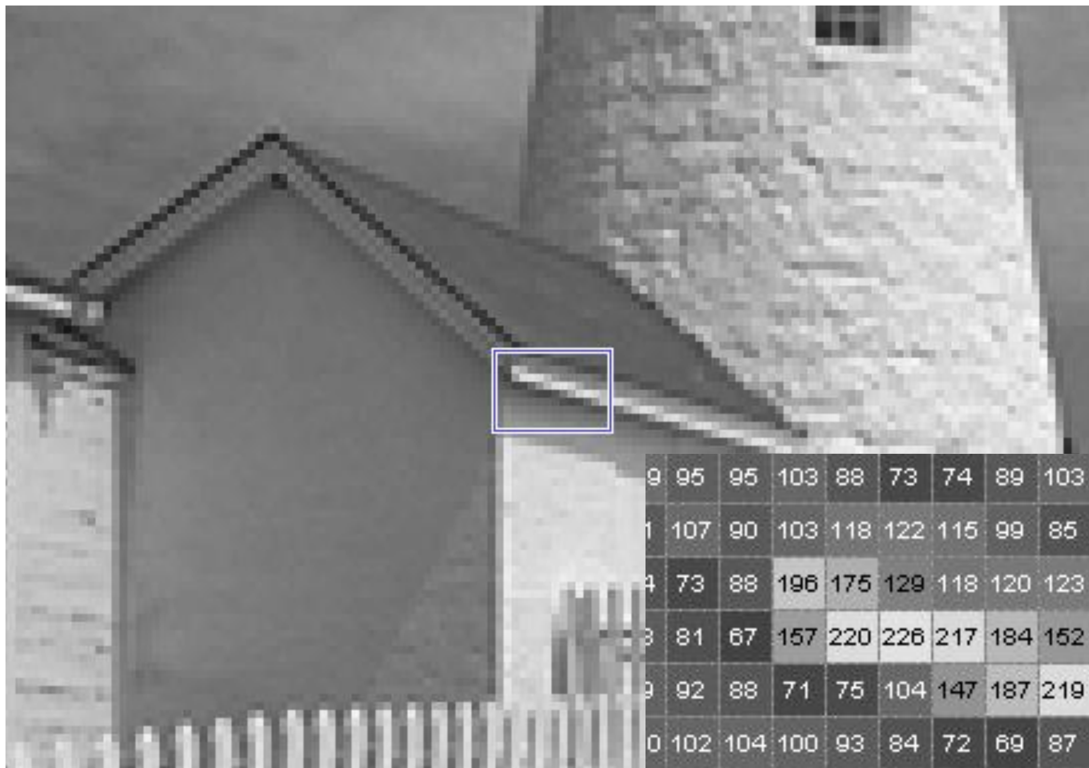
Digital Image: Representation and Acquisition

Jayanta Mukhopadhyay
Dept. of CSE,
IIT Kharagpur

How images are represented in a computer?



Width: 256
Height: 384

9	95	95	103	88	73	74	89	103	101	97	96	96	99	98	9
1	107	90	103	118	122	115	99	85	78	81	91	97	100	97	9
4	73	88	196	175	129	118	120	123	116	103	85	75	73	81	9
3	81	67	157	220	226	217	184	152	130	128	125	125	111	95	8
9	92	88	71	75	104	147	187	219	227	209	170	138	129	133	1
0	102	104	100	93	84	72	69	87	122	165	208	225	213	185	1
0	110	122	114	111	108	103	101	95	81	73	79	105	147	190	2
3	119	137	127	125	121	117	114	111	108	107	103	92	83	83	9
3	123	147	141	137	134	130	127	122	121	121	119	114	113	110	9
7	126	150	148	148	143	143	141	135	135	134	127	126	123	123	1

A 2D Array of integers

Color images

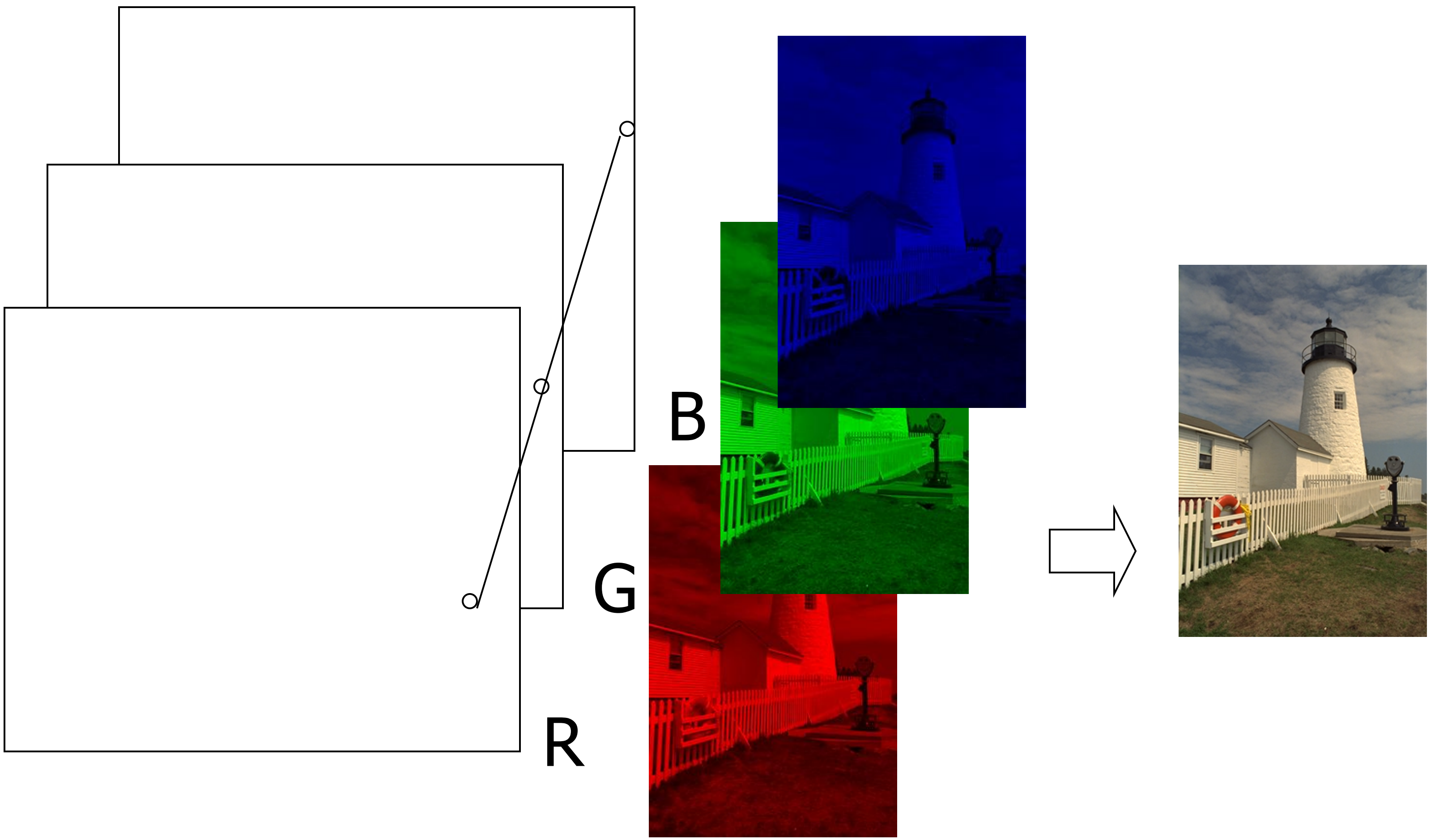
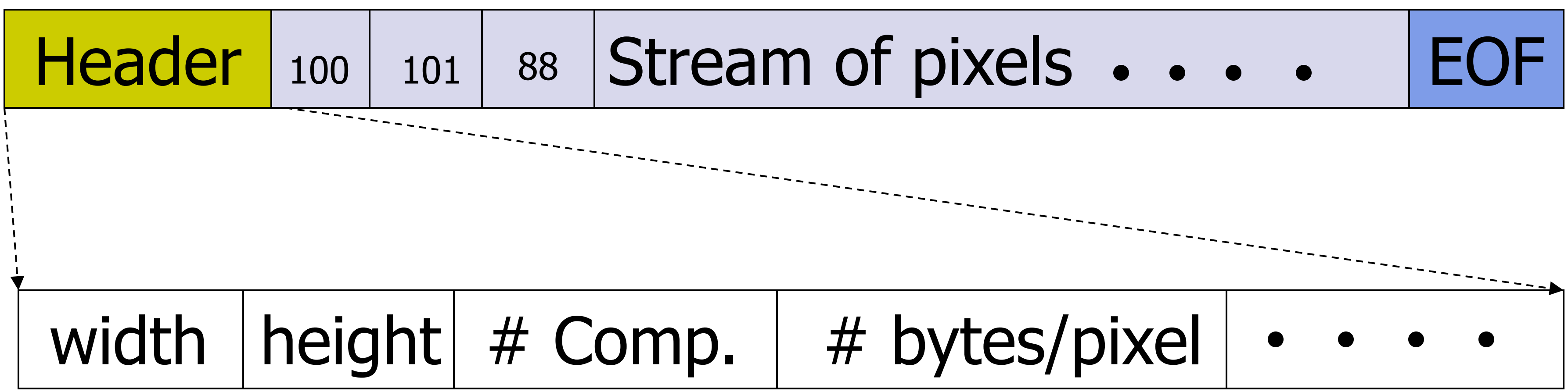
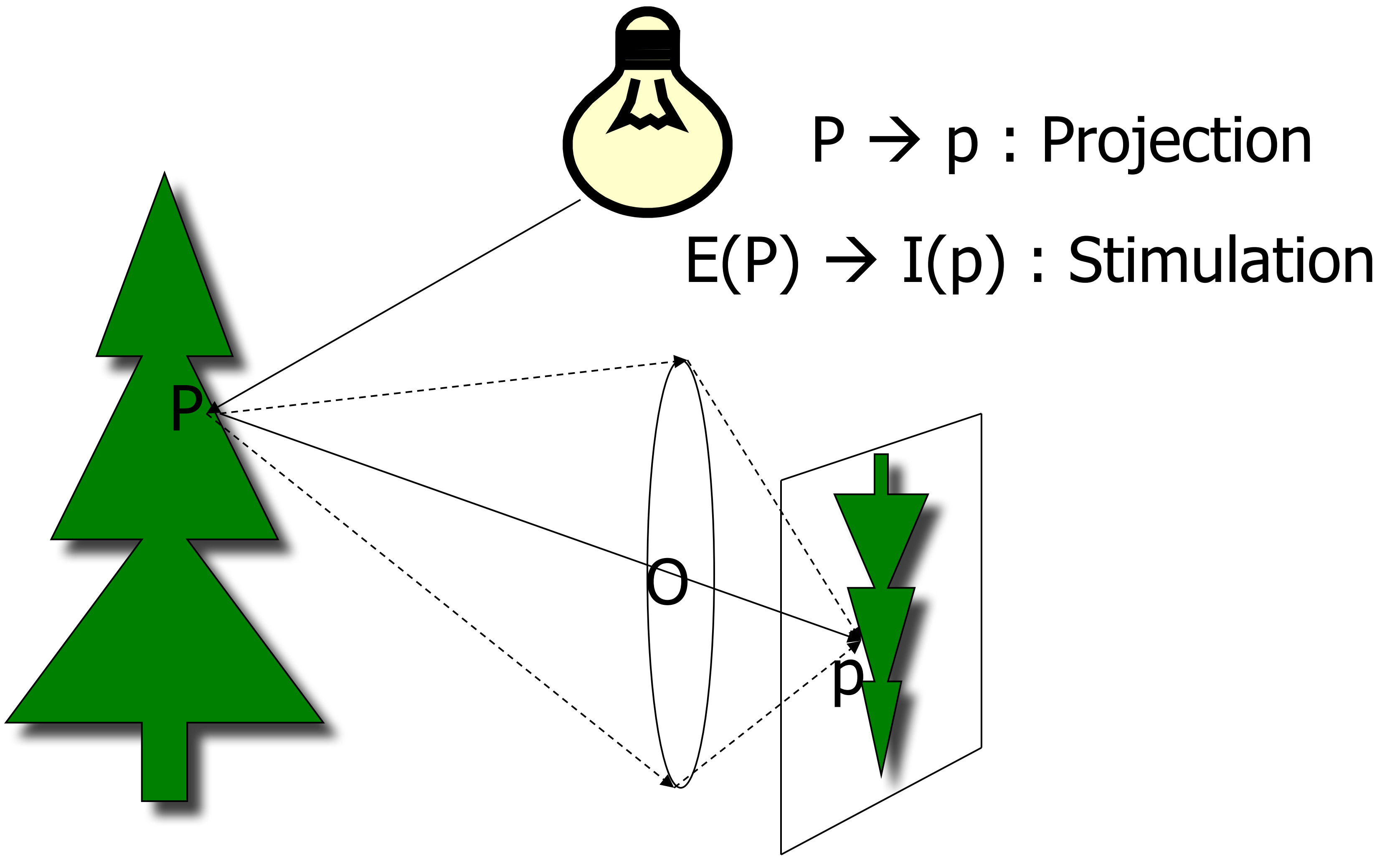


Image File



Standard File Formats:
TIFF, BMP, GIF, PGM, PPM, JPEG, DICOM, ….

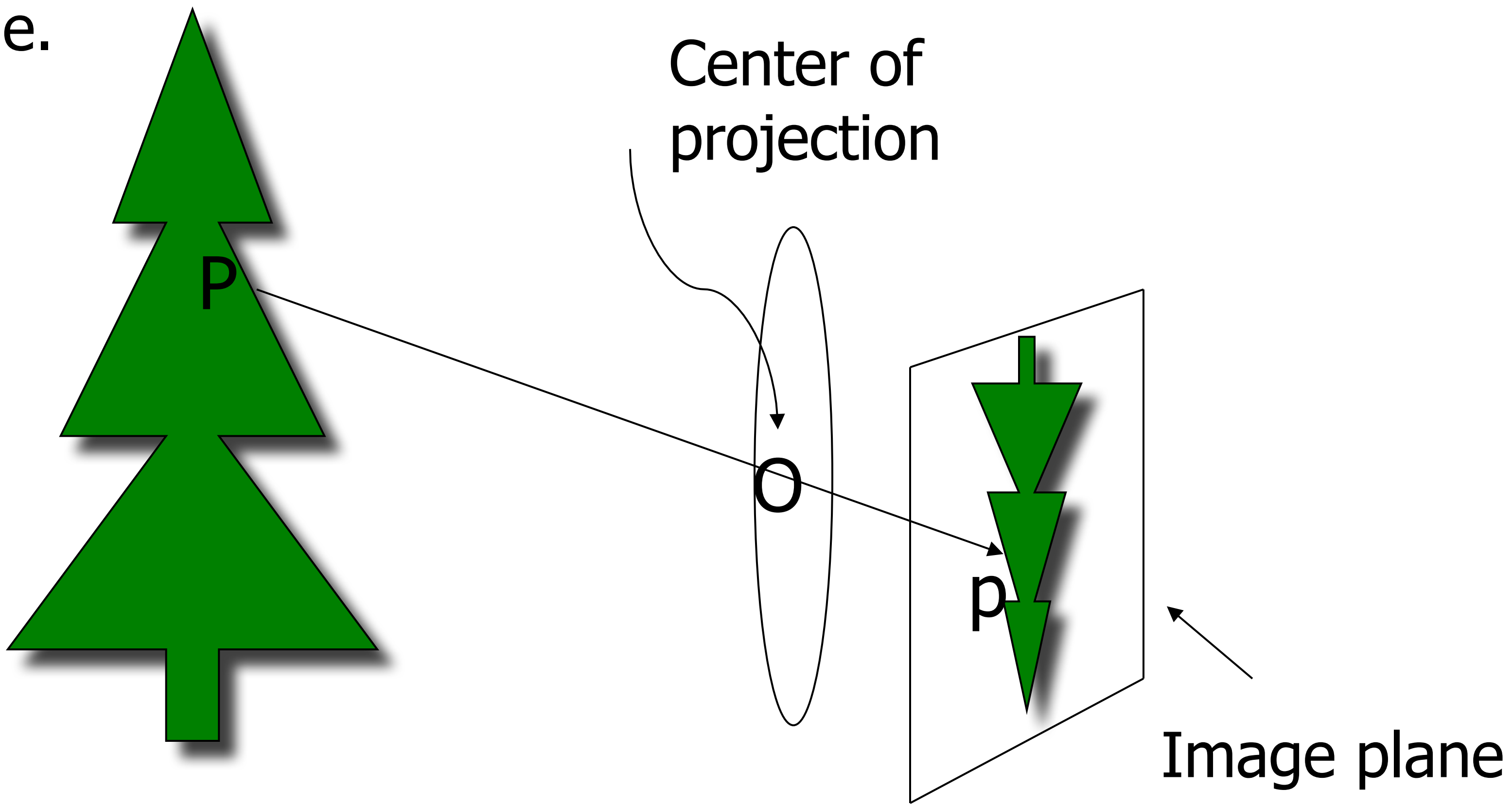
Image formation in optical camera



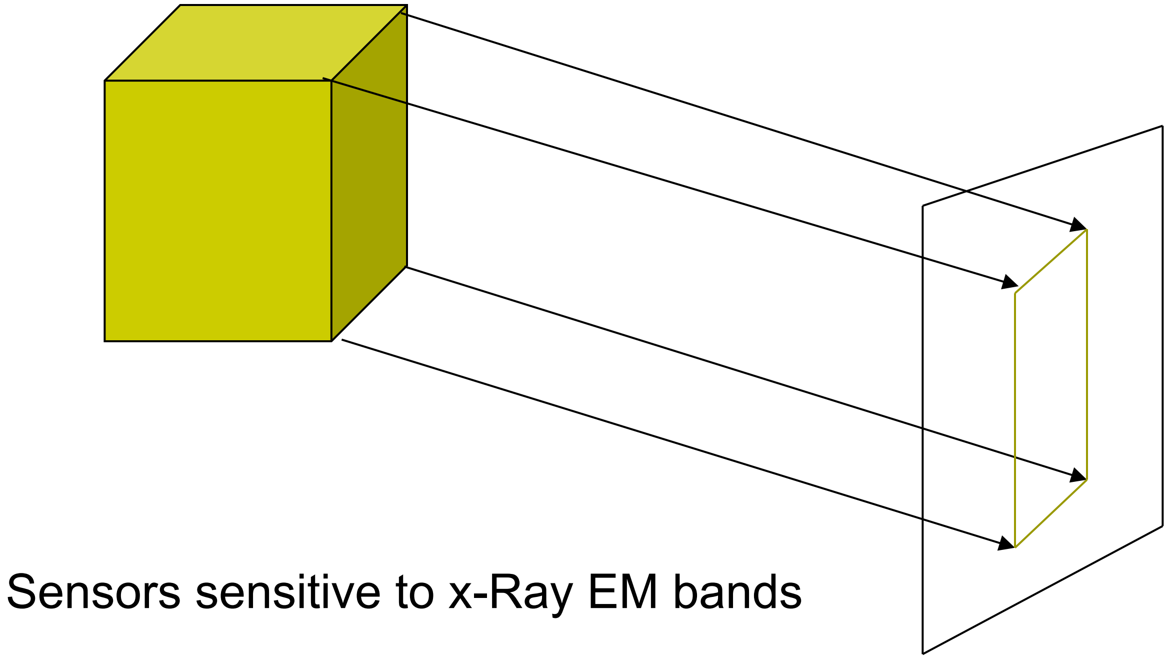
Rules of projection

Perspective projection

Image points formed by intersection of the ray from a point P passing through the center of projection O with the image plane.



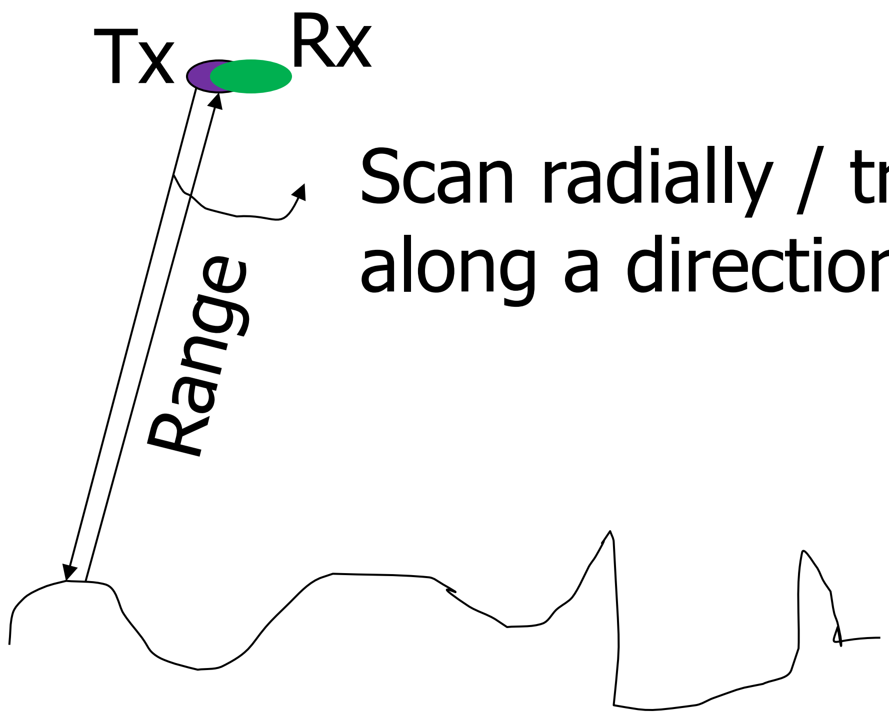
Other imaging principle: Xray imaging



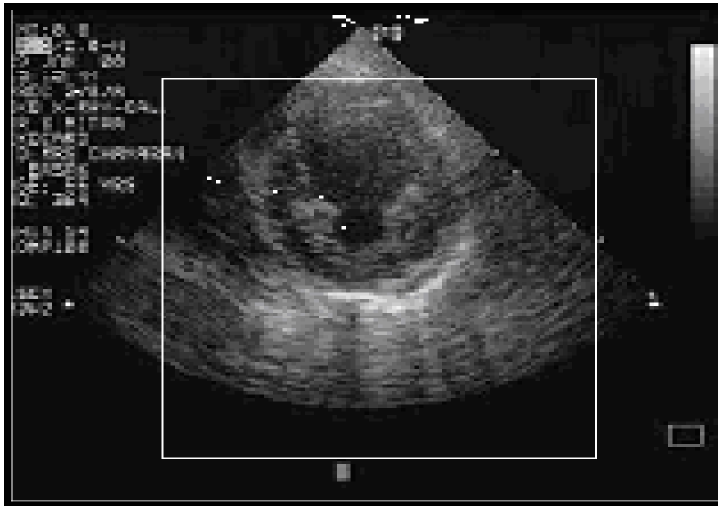
Parallel projection

Image points formed by intersection of parallel rays with the image plane.

Other imaging principle: Ultra-Sound Imaging



Scan radially / translating Tx-Rx along a direction.



What is an image?

- Impression of the physical world.
- Spatial distribution of a measurable quantity, encoding the geometry and material properties of objects.

Radiometric factors of image formation

Spectral response of a sensor

- Three factors of image formation:

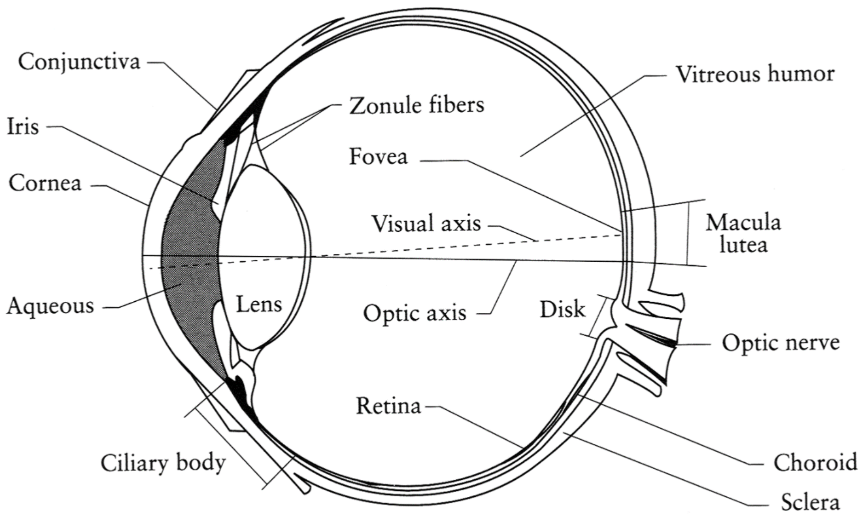
$$I(x) = \int_{\lambda} E(\lambda) R^{X}(\lambda) S(\lambda) d\lambda$$

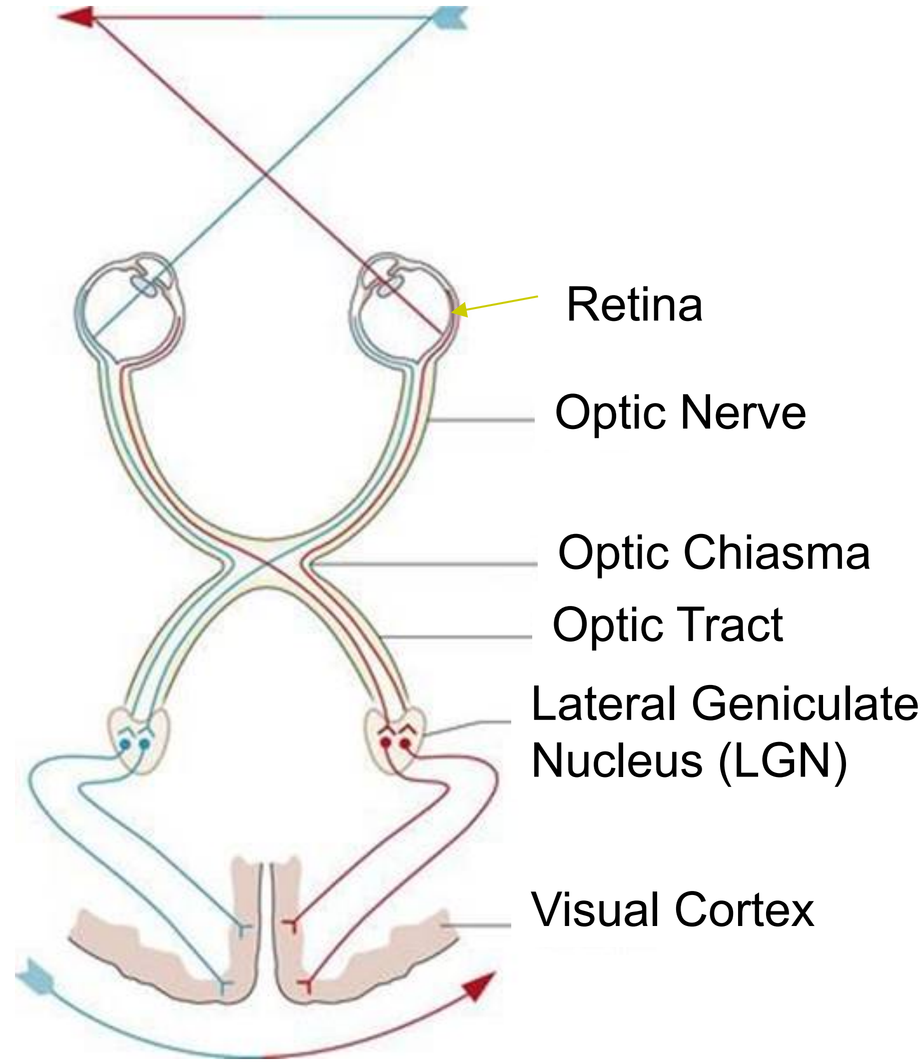
Spectral power distribution

Surface reflectance spectrum

- Objects present in the scene.
- Spectral Energy of Light Sources.
- Spectral Sensitivity of sensors.
  - For color images three different types of sensors used
  - More number of components for multispectral / hyperspectral imaging systems in remote sensing applications

Visual Information Processing





- Visual information enters the primary visual cortex via the lateral geniculate nucleus
  - smaller pathways also exist
    - a pathway to the superior colliculus (SC).

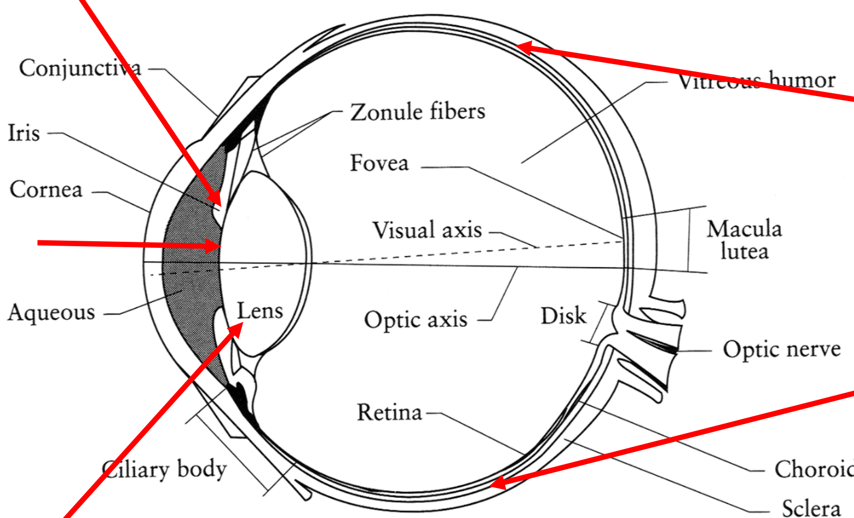
Adapted from slides by Steve Seitz.

taitravenab.blogspot.com

The Eye: A Camera!

Iris - colored annulus with radial muscles

Pupil - the hole (aperture), size controlled by the iris.



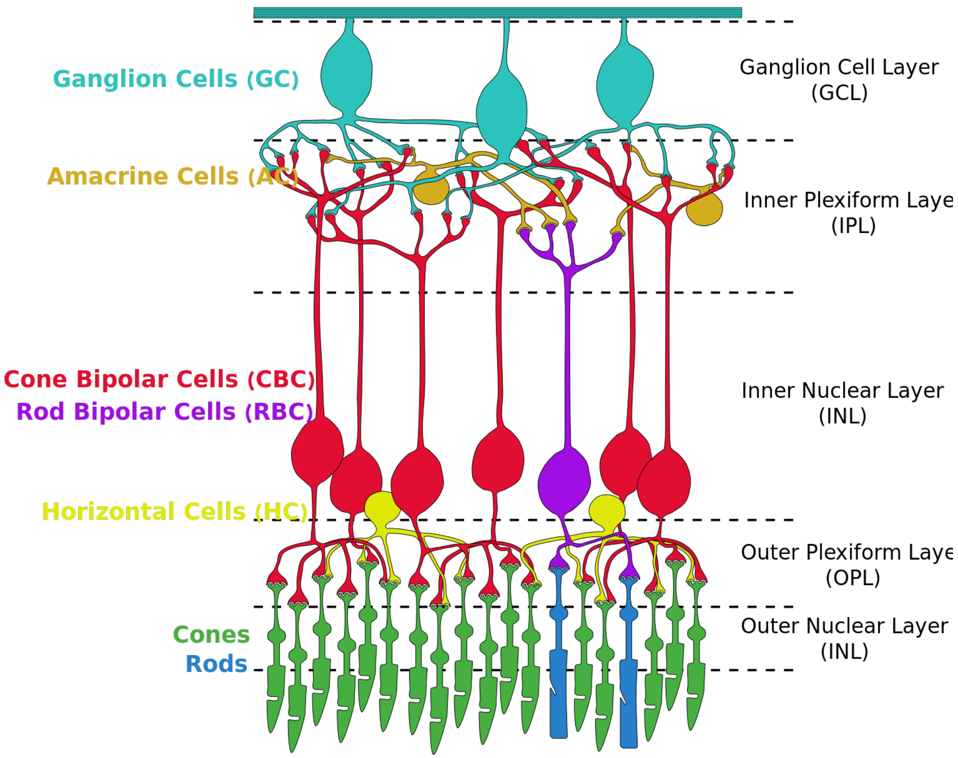
Retina -photoreceptor cells (rods and cones) acting like the film or array of sensors of a camera.

Lens - changes shape by using ciliary muscles for focusing on objects of interest.

Adapted from slides by Steve Seitz.

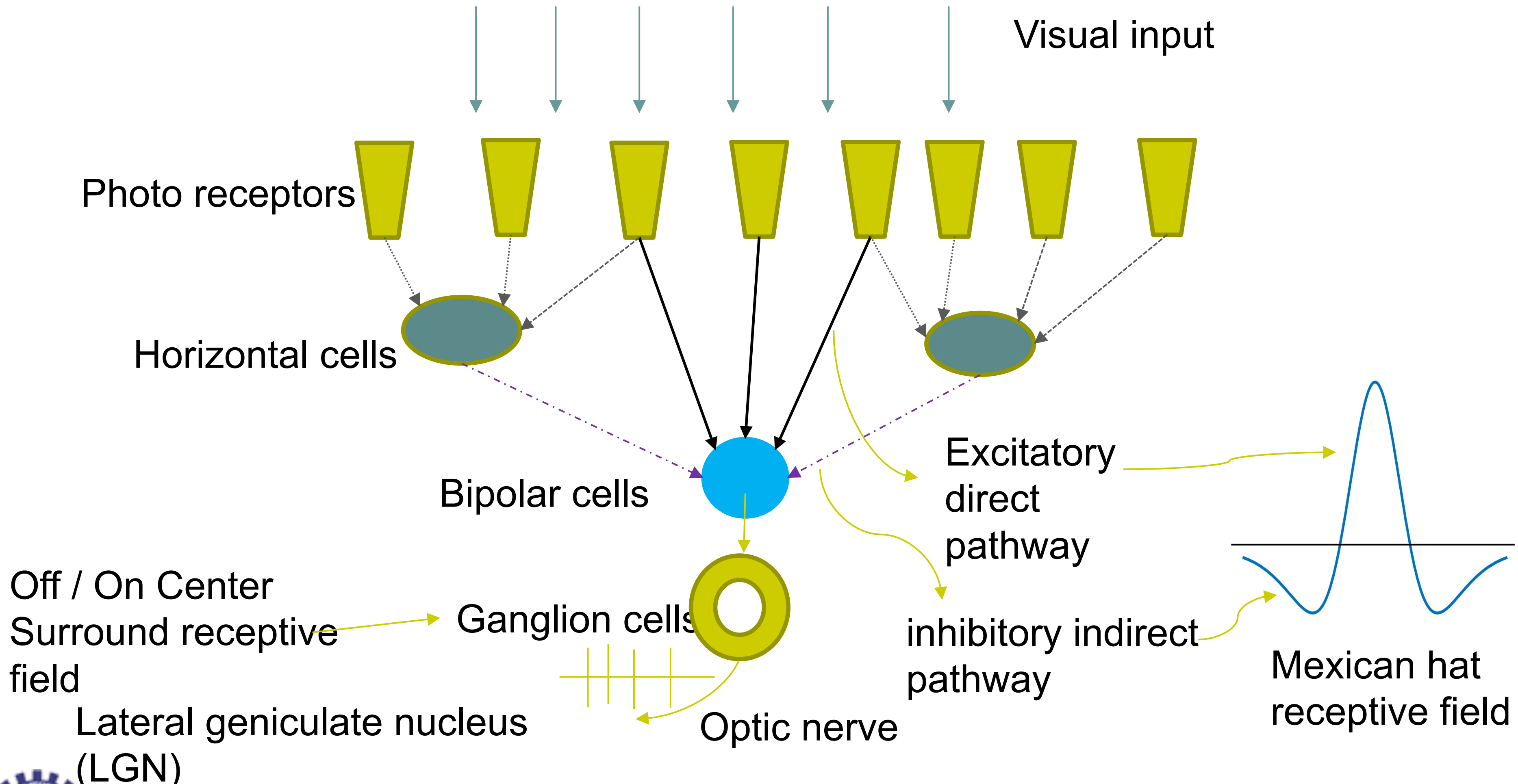
Rods, Cones and Synapse

Rods: Low illumination scene
Cone: Color perception
Trichromacy theory
Color opponency
G-R
B – (G+R)
Color constancy

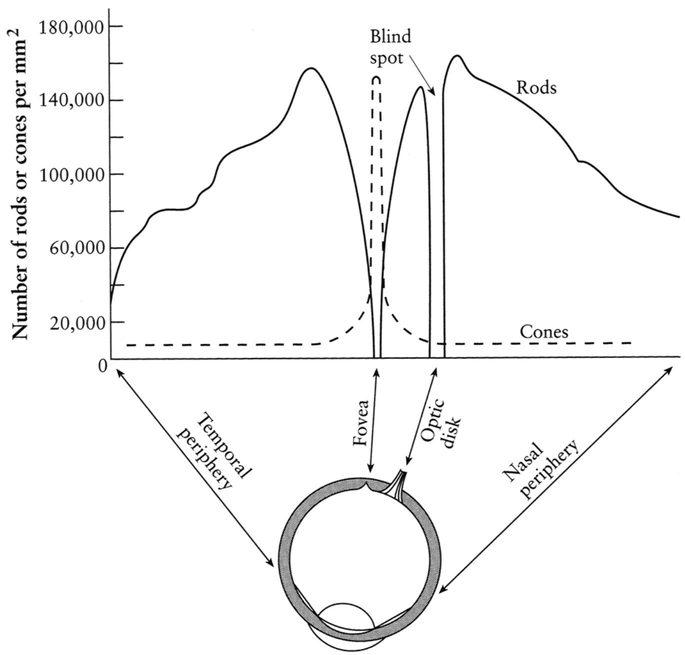


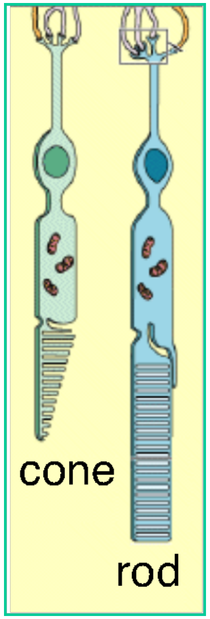
https://commons.wikimedia.org/wiki/File:Rods_Cones_Synapse.svg

Cells in retina



Density of rods and cones





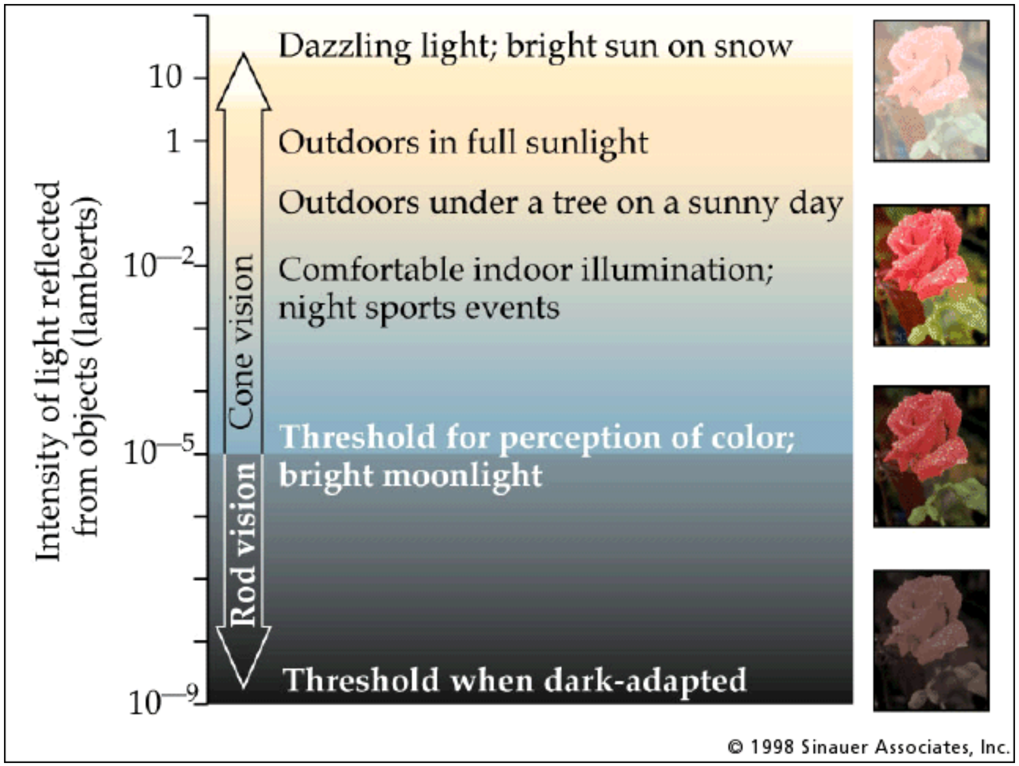
Rods and cones are *non-uniformly* distributed on the retina

- 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

Slide by Steve Seitz

Rod / Cone sensitivity

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 direction of $^{1}/_{683}$ watt per steradian.



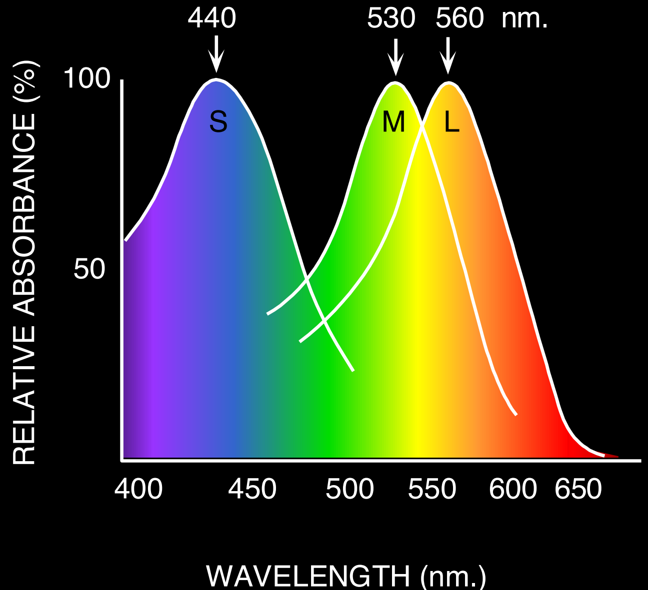
1 lambert (L) = $\frac{1}{\pi}$ candela per square centimetre (0.3183 cd/cm²) or $\frac{10^4}{\pi}$ cd m^{-2}

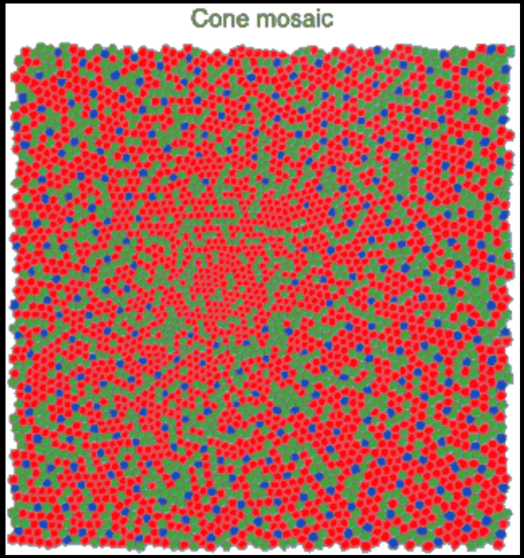
As cone vision is not activated in low illumination, we are unable to read.

Adapted from slides by A. Efros

Physiology of Color Vision

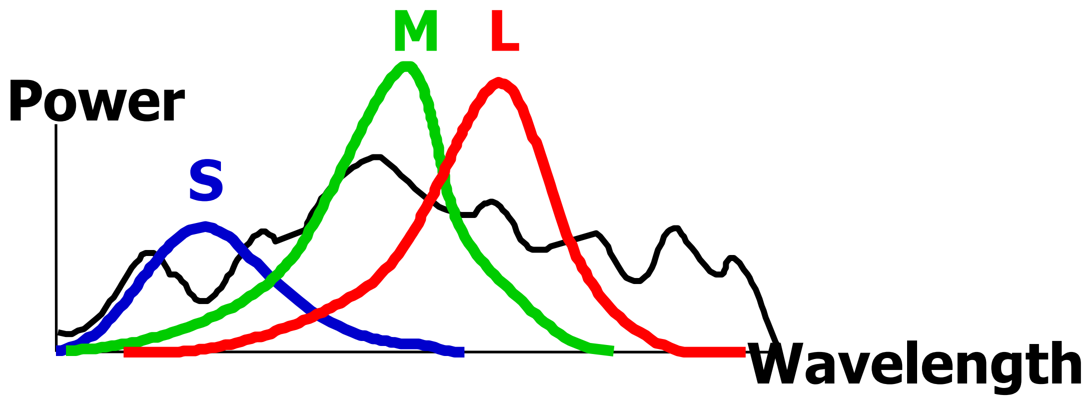
Three kinds of cones:





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

Color perception

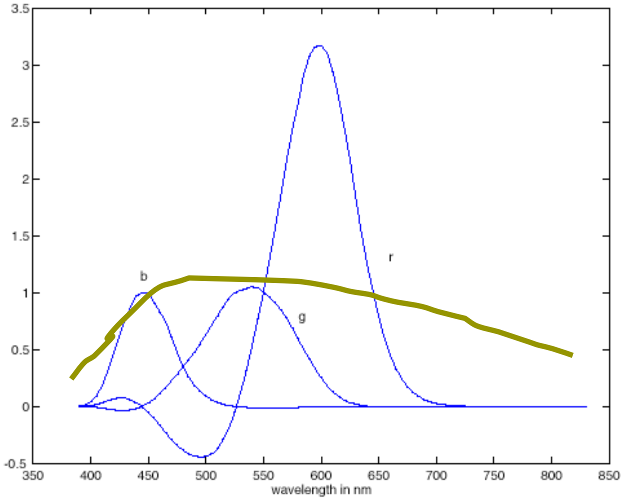


- Entire spectrum (of reflected energy from an object or energy of an illuminant) represented by 3 numbers.
- Even different spectra may have same representation and thus indistinguishable.
    - such spectra called **metamers.**

Adapted from slides by Steve Seitz.

What is Color?

- A psychological property of our visual experiences when we look at objects and lights.
  - Not a physical property of those objects or lights.
  - The result of interaction between physical light in the environment and our visual system.



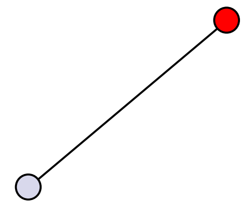
- Can be represented by 3 numbers.
  - Trichromatic Theory
  - Color rendition as a Mixture of three primary colors

Grassman's Laws

- Color matching appears to be linear.
- If two test lights can be matched with the same set of weights, then they match each other:
  - If $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = u_1 P_1 + u_2 P_2 + u_3 P_3$. Then $A = B$.
- If we mix two test lights, then mixing the matches will match the result:
  - If $A = u_1 P_1 + u_2 P_2 + u_3 P_3$ and $B = v_1 P_1 + v_2 P_2 + v_3 P_3$. Then $A+B = (u_1+v_1)\ P_1 + (u_2+v_2)\ P_2 + (u_3+v_3)\ P_3$.
- If we scale the test light, then the matches get scaled by the same amount:
  - If $A = u_1 P_1 + u_2 P_2 + u_3 P_3$, then $kA = (ku_1)\ P_1 + (ku_2)\ P_2 + (ku_3)\ P_3$.

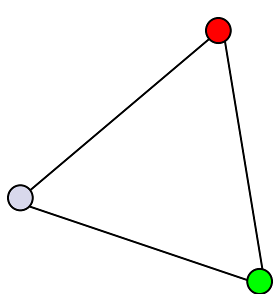
Adapted from W. Freeman

Linear color spaces



mixing two lights produces colors that lie along a straight line in color space.

- Defined by a choice of three primaries
- The coordinates of a color are given by the weights of the primaries used to match it.
- *Matching functions*: weights required to match single-wavelength light sources.

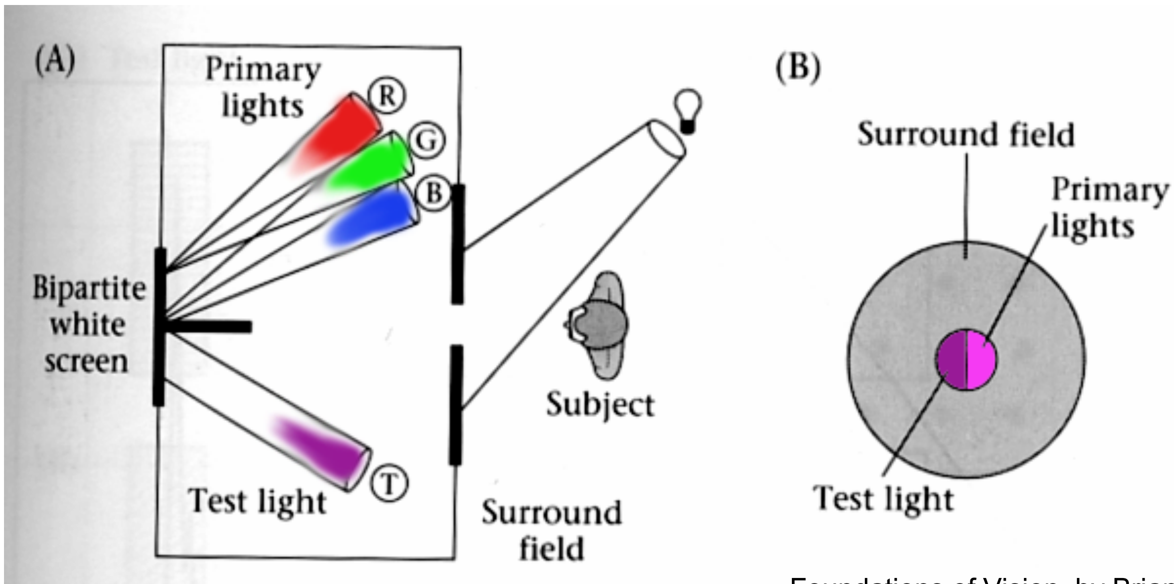


mixing three lights produces colors that lie within the triangle they define in color space.

Adapted from W. Freeman

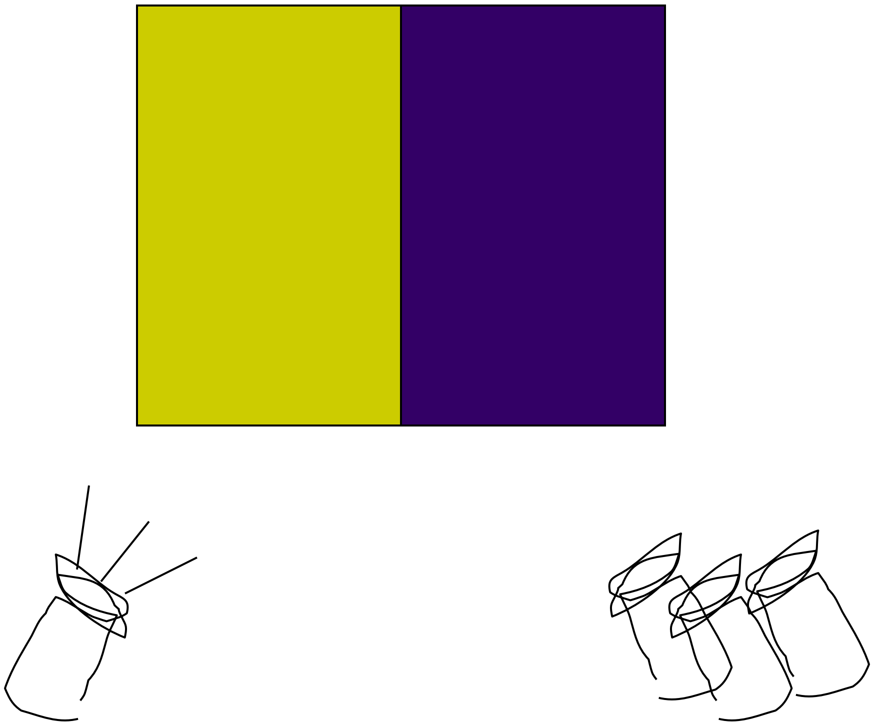
Standardizing color experience

- To understand which spectra produce the same color sensation under similar viewing conditions.
- Color matching experiments.



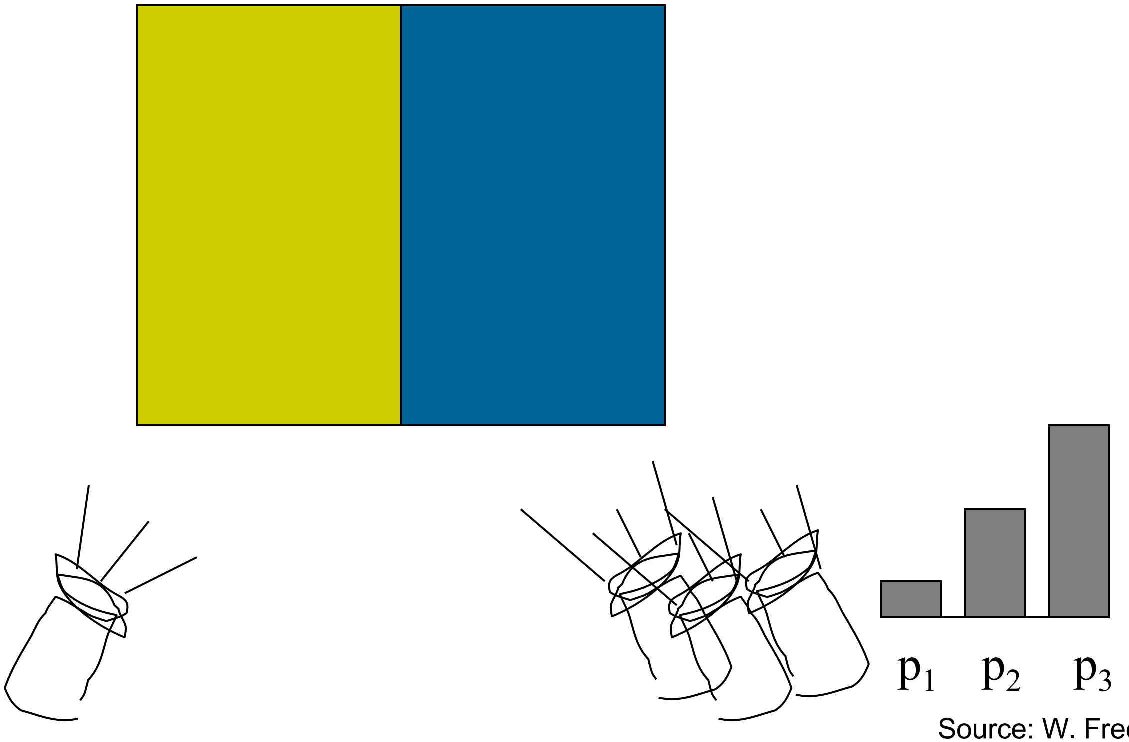
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Color matching experiment 1



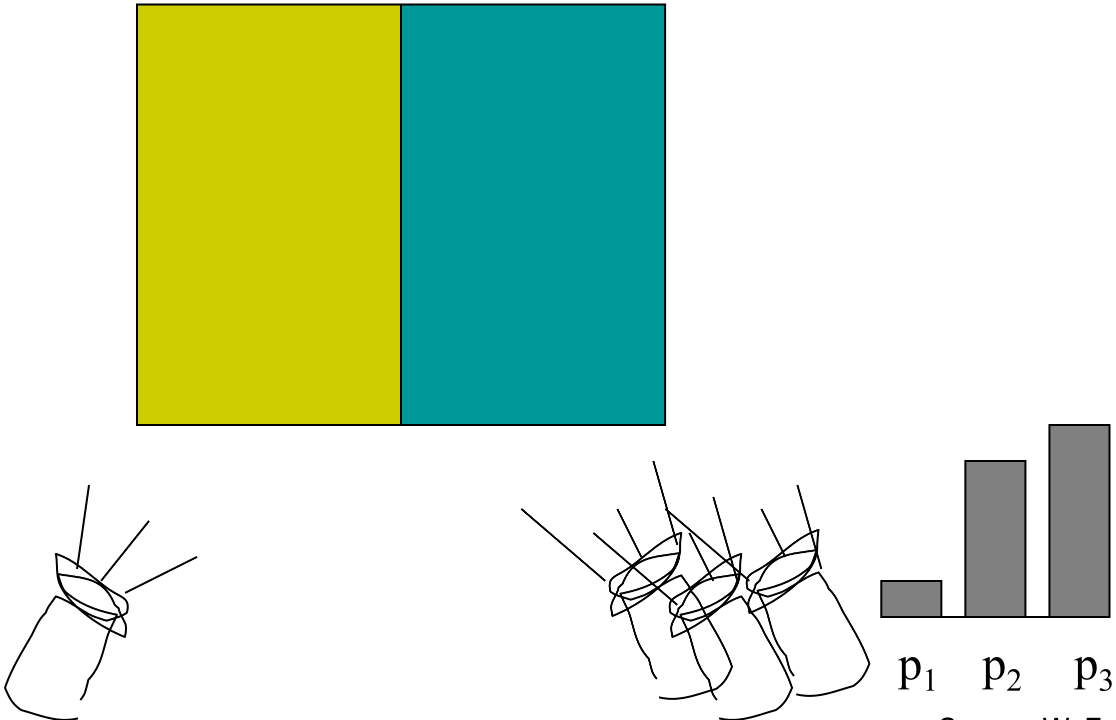
Source: W. Freeman

Color matching experiment 1



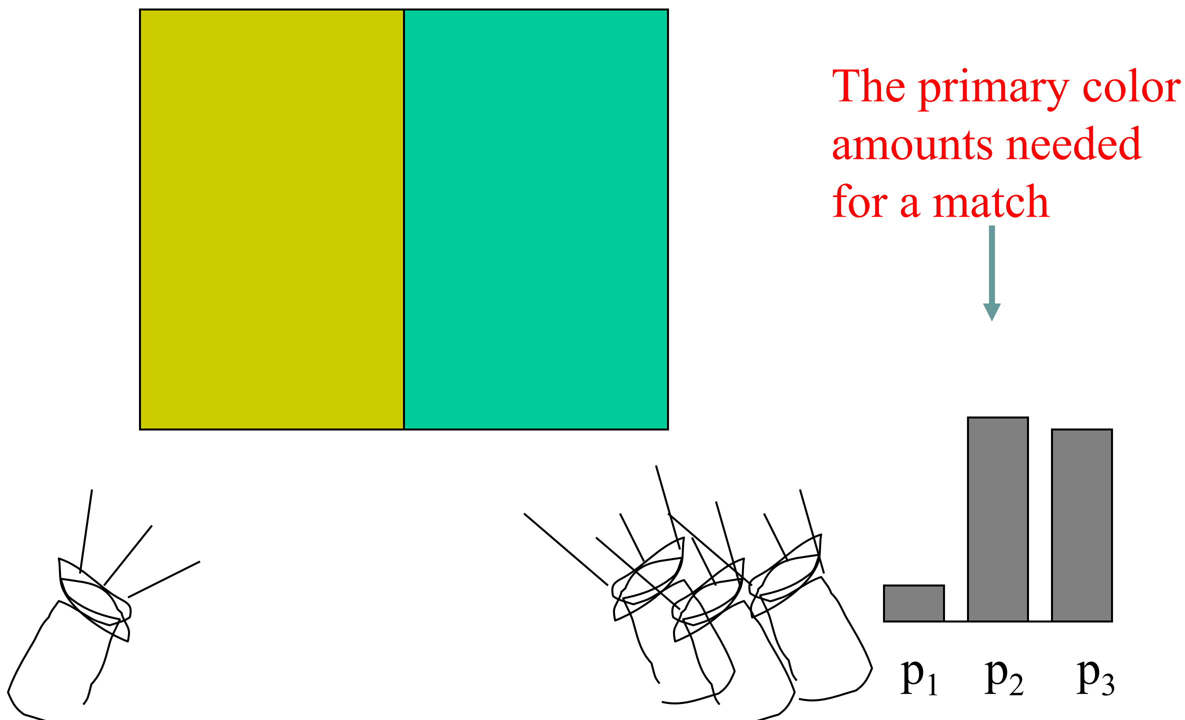
Source: W. Freeman

Color matching experiment 1



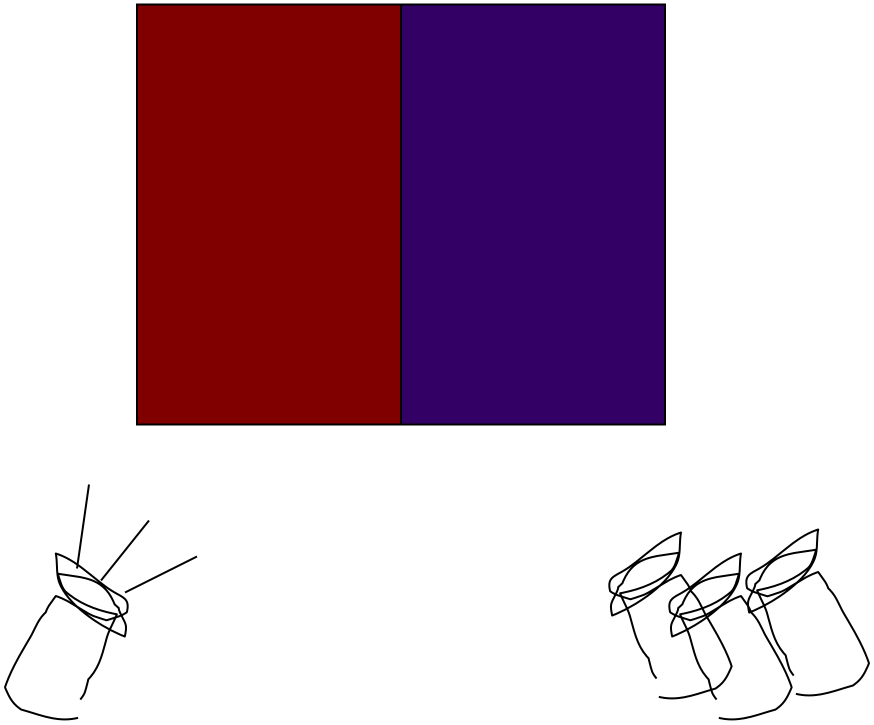
Source: W. Freeman

Color matching experiment 1



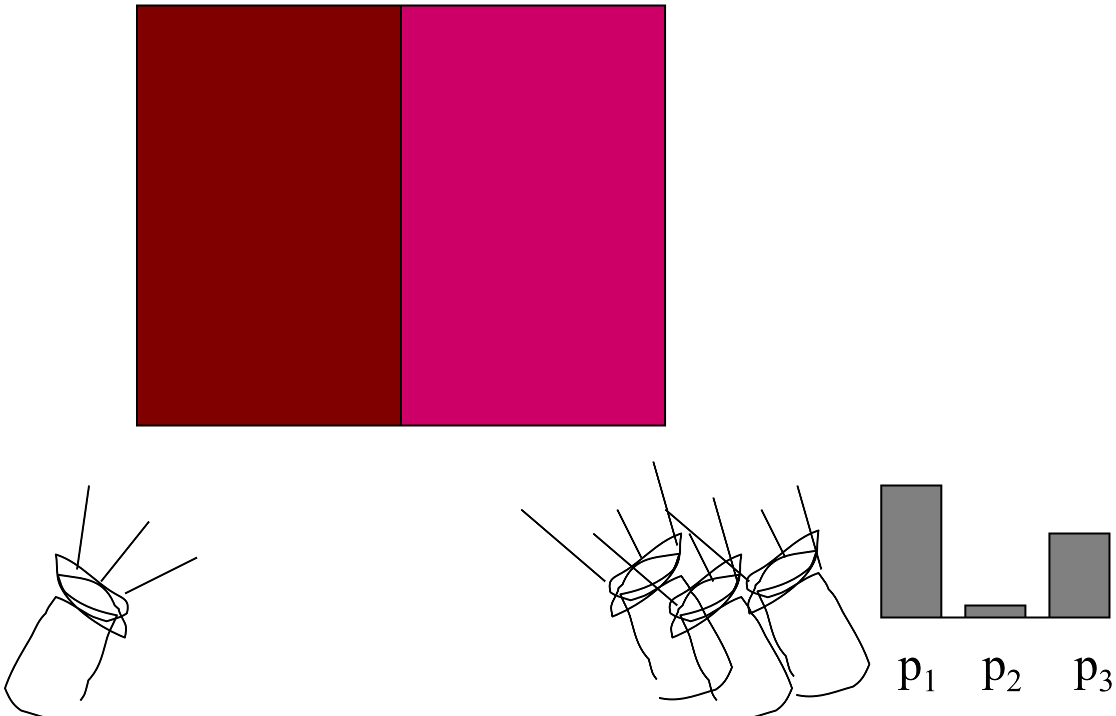
Source: W. Freeman

Color matching experiment 2



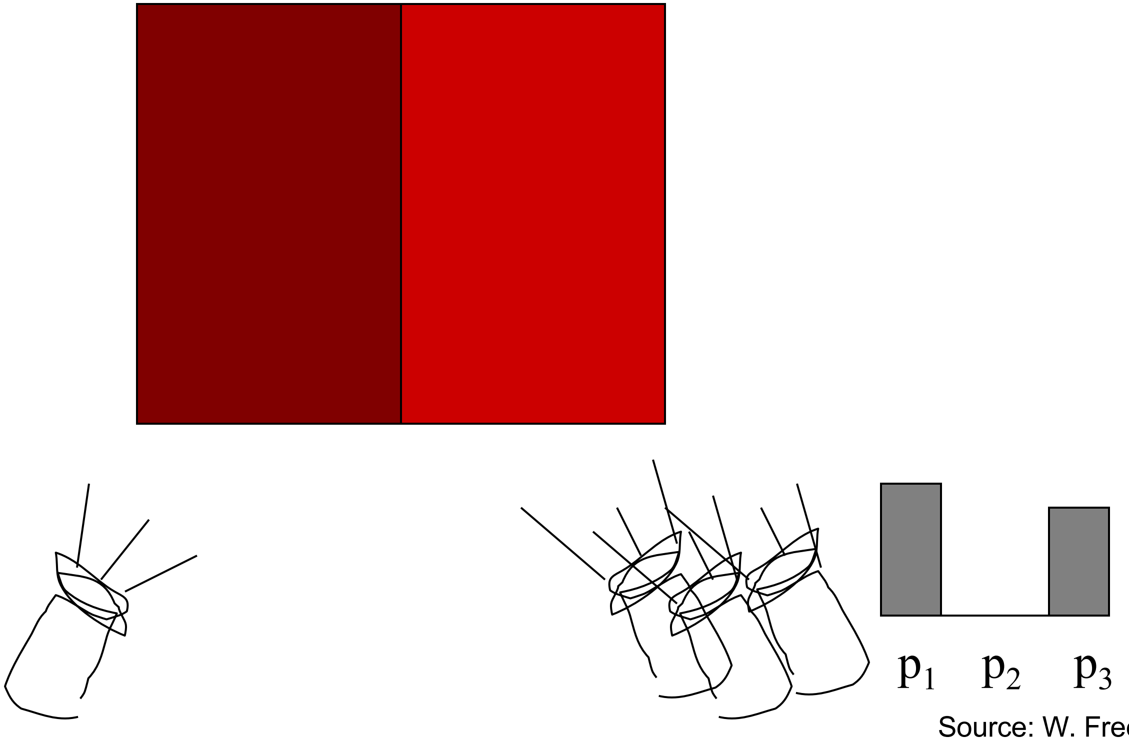
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

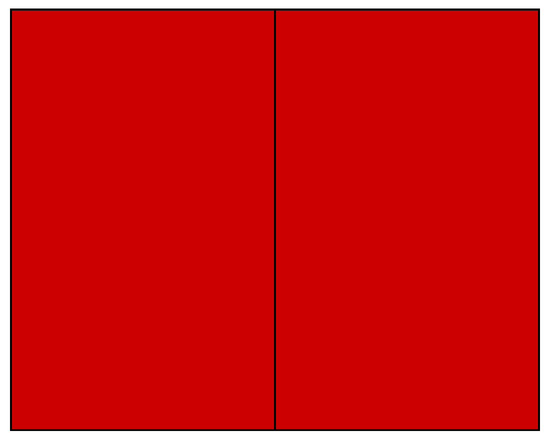
Color matching experiment 2



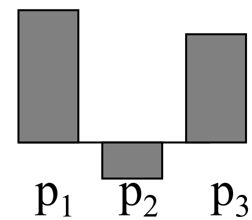
Source: W. Freeman

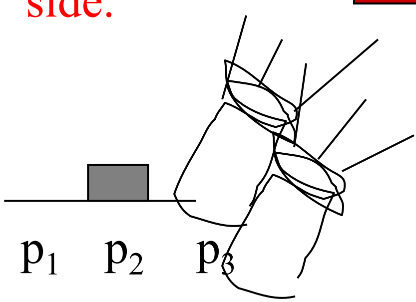
Color matching experiment 2

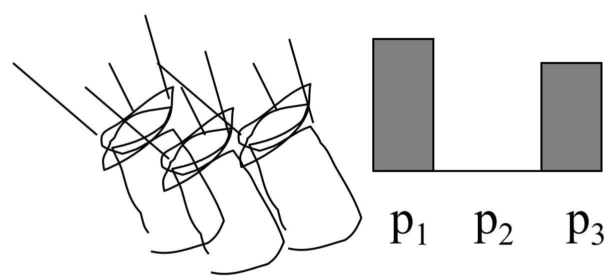
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.



The primary color amounts needed for a match:



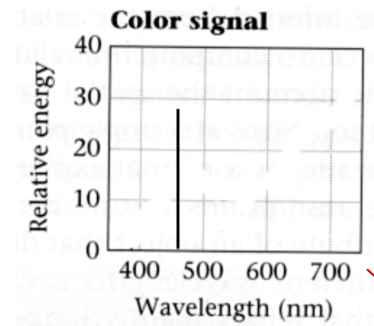


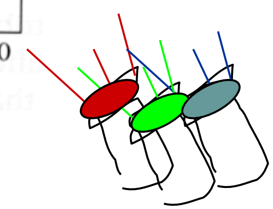


Source: W. Freeman

Using color matching functions to predict the matches for a new spectral signal

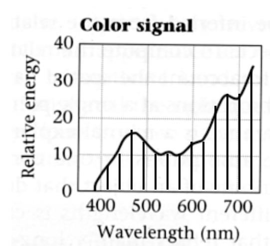
A monochromatic light of λ_i wavelength will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.





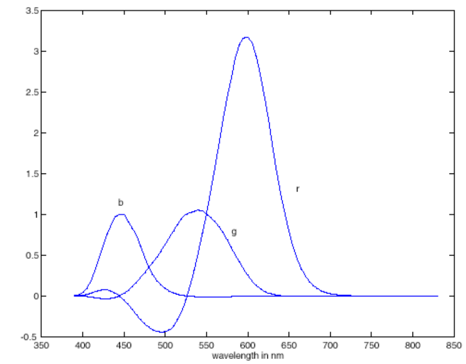
And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

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



Source: W. Freeman

Using color matching functions to predict the primary match to 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 be described by the vector *t*.

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

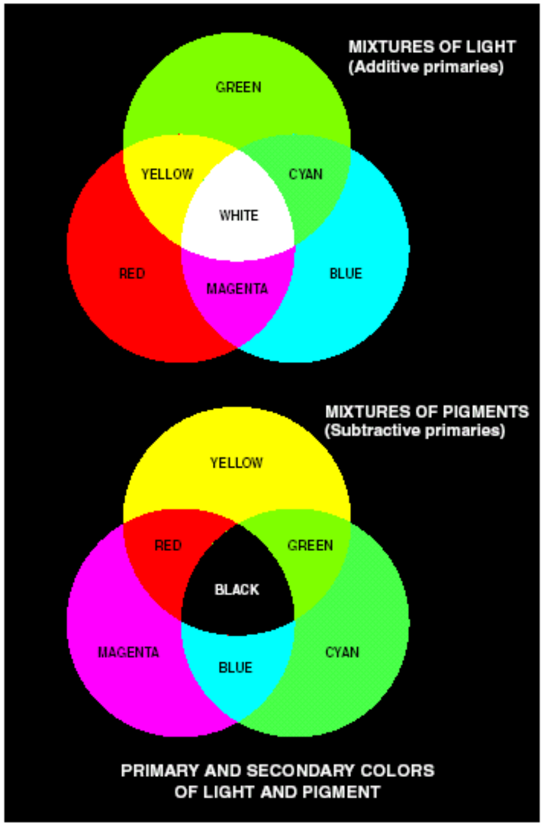
Then the amounts of each primary needed to match t are:

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

The components 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* (by Grassman's Laws)

Source: W. Freeman

Additive and subtractive colors



a
b

FIGURE 6.4 Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lamp Business Division.)

Adapted from Gonzales and Woods

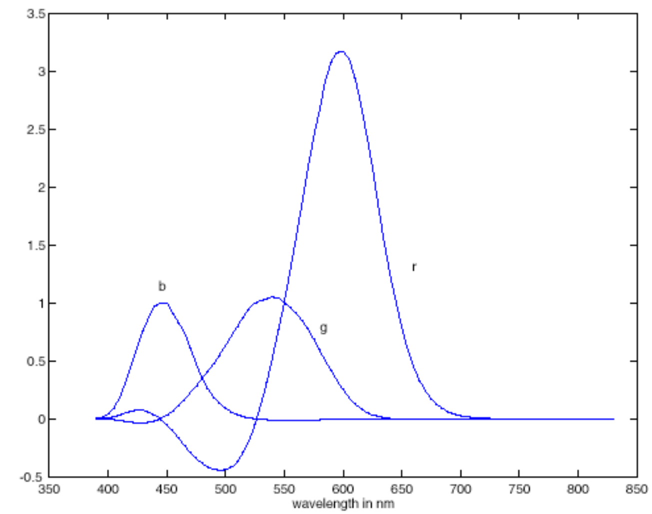
Linear color spaces: RGB

$p_1 = 645.2$ nm

$p_2 = 525.3$ nm

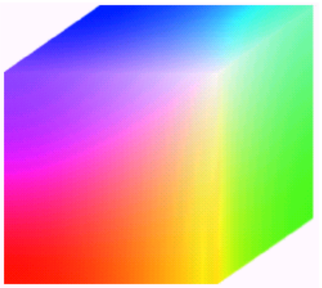
$p_3 = 444.4$ nm

- Primaries are monochromatic lights (for monitors, they correspond to the three types of phosphors).
- *Subtractive matching* required for some wavelengths.

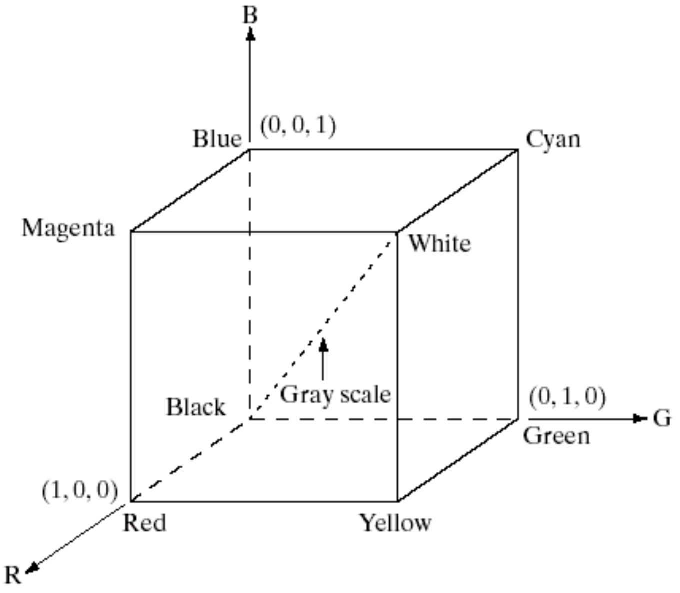


RGB matching functions

RGB model



- Additive model.
- An image consists of 3 bands, one for each primary color.
- Appropriate for image displays.



Adapted from Gonzales and Woods

CMY model

Inks: Cyan=White-Red, Magenta=White-Green, Yellow=White-Blue.

- Cyan-Magenta-Yellow is a subtractive model which is good to model absorption of colors.
- Appropriate for paper printing.

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CIE chromaticity model

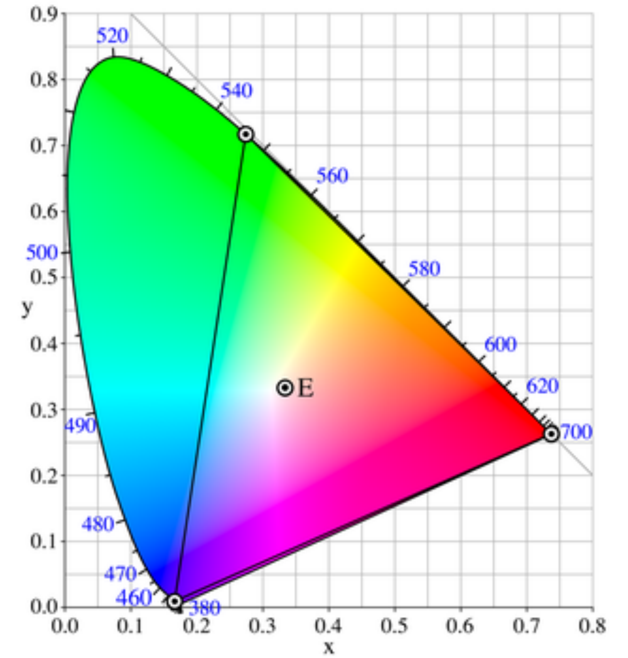
- The Commission Internationale de l'Eclairage (estd. 1931) defined 3 standard primaries: X, Y, Z that can be added to form all visible colors.
- Y was chosen so that its color matching function matches the sum of the 3 human cone responses.

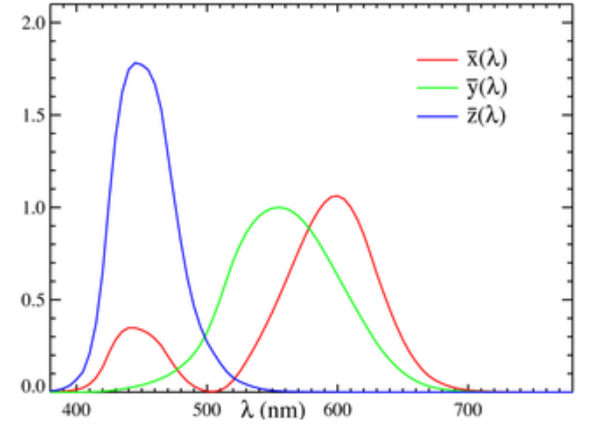
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.6067 & 0.1736 & 0.2001 \\ 0.2988 & 0.5868 & 0.1143 \\ 0.0000 & 0.0661 & 1.1149 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.9107 & -0.5326 & -0.2883 \\ -0.9843 & 1.9984 & -0.0283 \\ 0.0583 & -0.1185 & 0.8986 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Adapted from Octavia Camps, Penn State

CIE XYZ: Linear color space

- Primaries are imaginary, but matching functions are everywhere positive
- 2D visualization: draw (x,y), where
  $x = X/(X+Y+Z)$
  $y = Y/(X+Y+Z)$





Matching functions

http://en.wikipedia.org/wiki/CIE_1931_color_space

CIE chromaticity model

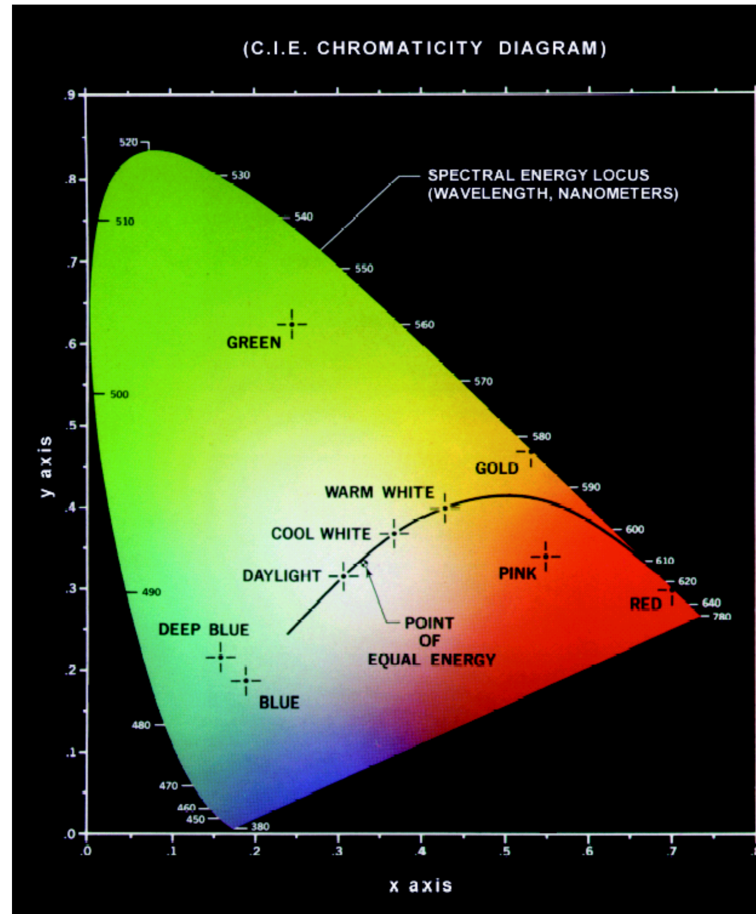
- x, y, z normalize X, Y, Z such that

  $$x + y + z = 1.$$

- Actually only x and y are needed because

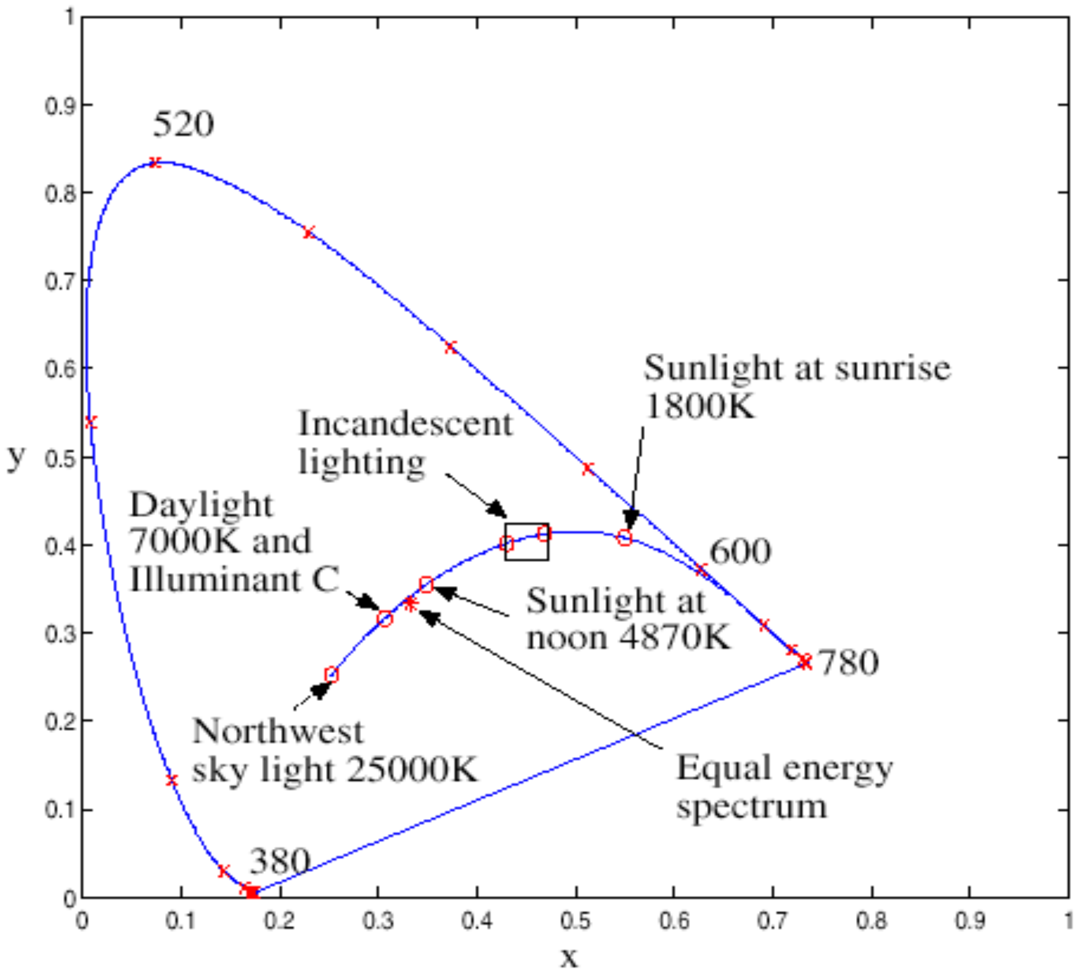
  $$z = 1 - x - y.$$

- Pure colors are at the curved boundary.
- White is (1/3, 1/3, 1/3).



Adapted from Octavia Camps, Penn State

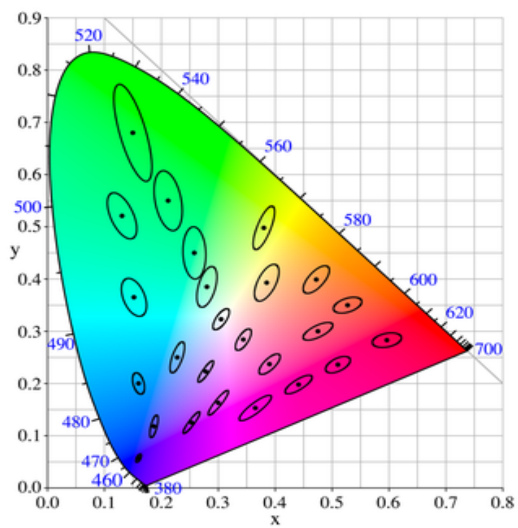
Spectral locus of monochromatic lights and the heated black-bodies

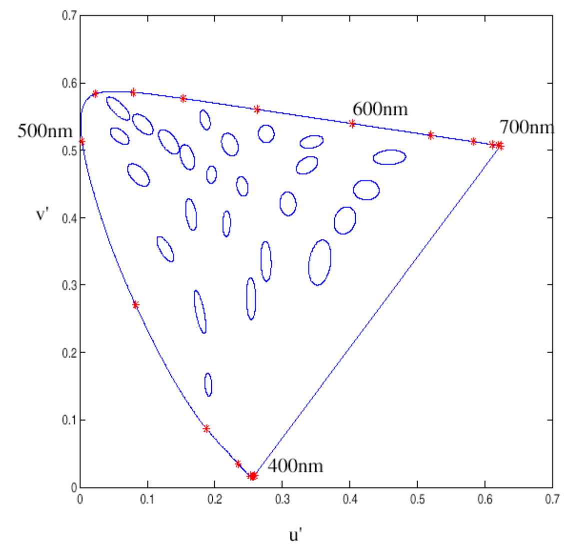


Uniform color spaces

- Differences in x,y coordinates do not reflect perceptual color differences.
- CIE u'v' is a projective transform of x,y to make the ellipses more uniform.

$$(u', v') = \left(\frac{4X}{X + 15Y + 3Z}, \frac{9Y}{X + 15Y + 3Z}\right)$$

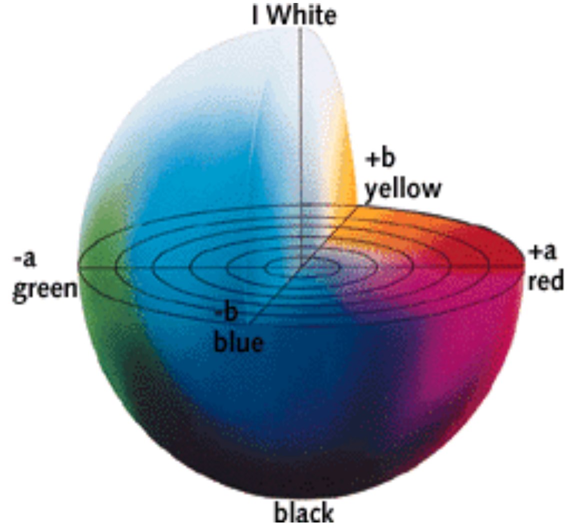




McAdam ellipses:
Just noticeable differences in color

CIE Lab ($L*a*b$) model

- One luminance channel ($L*$) and two color channels ($a*$ and $b*$).
- In this model, the color differences which we perceive correspond to Euclidean distances in CIE Lab.
- The a axis extends from green (-a) to red (+a) and the b axis from blue (-b) to yellow (+b). The brightness (L) increases from the bottom to the top of the 3D model.



$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right]$$

X_n, Y_n and Z_n are the reference white in XYZ space.

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

Adapted from Linda Shapiro, U of Washington

YIQ model

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.532 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Have better compression properties.
- Luminance Y is encoded using more bits than chrominance values I and Q (humans are more sensitive to Y than I and Q).
- Luminance used by black/white TVs.
- All 3 values used by color TVs.

Adapted from Octavia Camps, Penn State

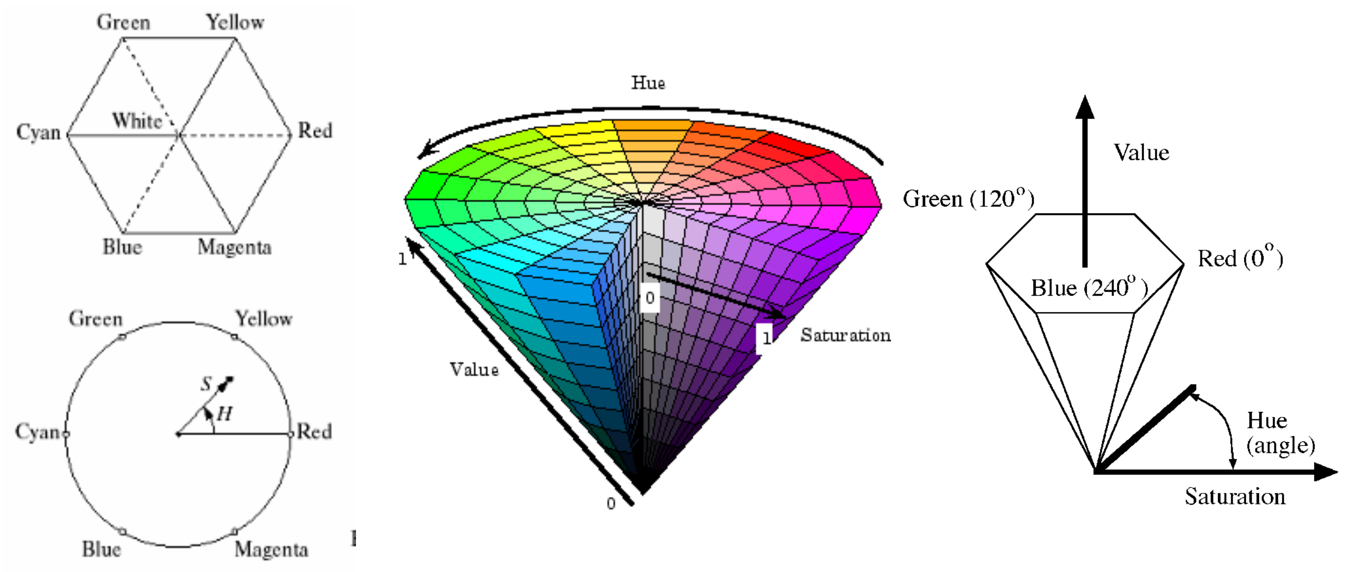
YCbCr space

$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.256 & 0.502 & 0.098 \\ -0.148 & -0.290 & 0.438 \\ 0.438 & -0.366 & -0.071 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 0 \\ 128 \\ 128 \end{bmatrix}$$

- Have better compression properties. Used in image and video compression schemes.
- Y represents the luminance, and Cb and Cr are chrominance parts.
- Not a linear transformation, affine.
- Cb and Cr translated to bring them within the range of 0 to 240 assuming ranges of R, G and B are 0 to 255.

Adapted from Octavia Camps, Penn State

Nonlinear color spaces: HSV



- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)

Adapted from Linda Shapiro, U of Washington

HSV model

- HSV: Hue, saturation, value are non-linear functions of RGB.
- Hue relations are naturally expressed in a circle.

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

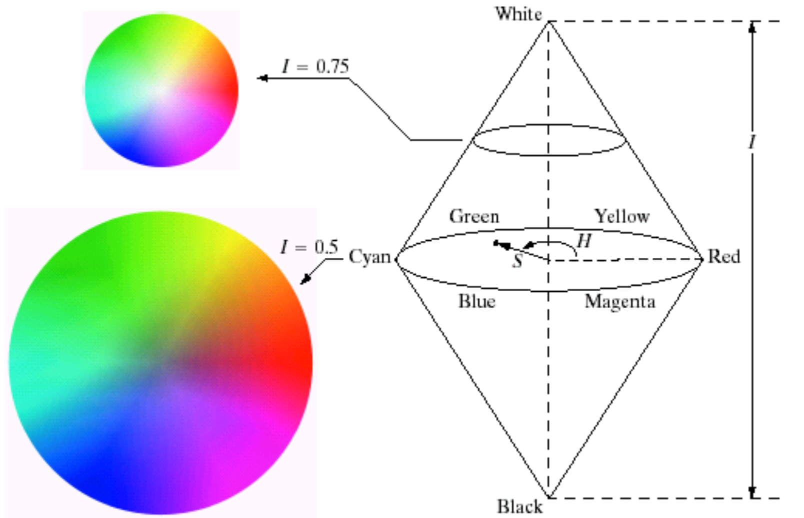
$$S = 1 - \frac{\min(R, G, B)}{I}$$

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

$$H = 360 - \cos^{-1}\left\{\frac{1/2[(R-G)+(R-B)]}{\sqrt{\left[(R-G)^2 + (R-B)(G-B)\right]}}\right\} \text{if} \quad B>G$$

HSV model

- Uniform: equal (small) steps give the same perceived color changes.
- Hue is encoded as an angle (0 to 2π).
- Saturation is the distance to the vertical axis (0 to 1).
- Intensity is the height along the vertical axis (0 to 1).



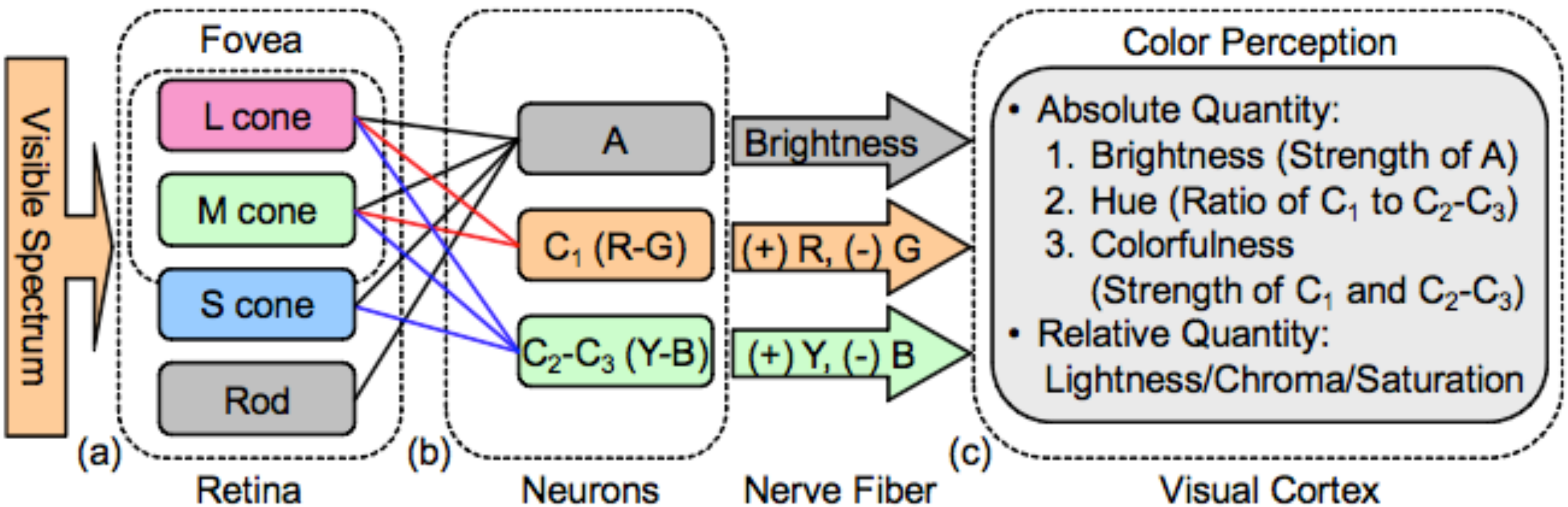
Adapted from Gonzales and Woods

Opponent Color Processing

- The color **opponent process:** A theory proposed on perception of color by processing signals from cones and rods in an antagonistic manner.
- Overlapping spectral zone of three types of cones (L for long, M for medium and S for short).
- The visual system considered to record *differences* between the responses of cones, rather than each type of cone's individual response.
  - People don’t perceive reddish-greens, or bluish-yellows.

Opponent Color Processing

- The opponent process theory accounts for mechanisms that receive and process information from cones.



Opponent Color Processing

- Three opponent channels:

  Red vs. Green, (G-R)

  Blue vs. Yellow, (B-Y) or (B-(R+G)) and

  Black vs. White, (Luminance: e.g. (R+G+B)/3).

$$\begin{bmatrix} Y \\ Cb-128 \\ Cr-128 \end{bmatrix} = \begin{bmatrix} 0.256 & 0.502 & 0.098 \\ -0.148 & -0.290 & 0.438 \\ 0.438 & -0.366 & -0.071 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Y-Cb′-Cr′ follows opponent color space representation.

Summary

- Images are formed by projection.
  - through sensing reflected energy from the respective surface point.
  - spectral sensitivity of sensor determines the color of the component.
- Human perception of color follows trichromacy law.
  - Three types of cones in our retina with spectral responses in different zones of optical band
- Color is captured in the RGB color space.
  - Not suitable for direct interpretation of color components such as Hue and Saturation.
  - Not all colors are representable in positive half of RGB color space.
- CIE Chromaticity Chart provides color matching functions.
  - expresses in 2-D normalized x-y chromaticity space.
- Various other color spaces used for processing.

Thank You