# Color fundamentals and processing- Part I

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# Motivations

- Computation with reduced storage.
- Avoid overhead of entropy decoding and encoding.
- Exploit spectral factorization for improving the quality of result and speed of computation.

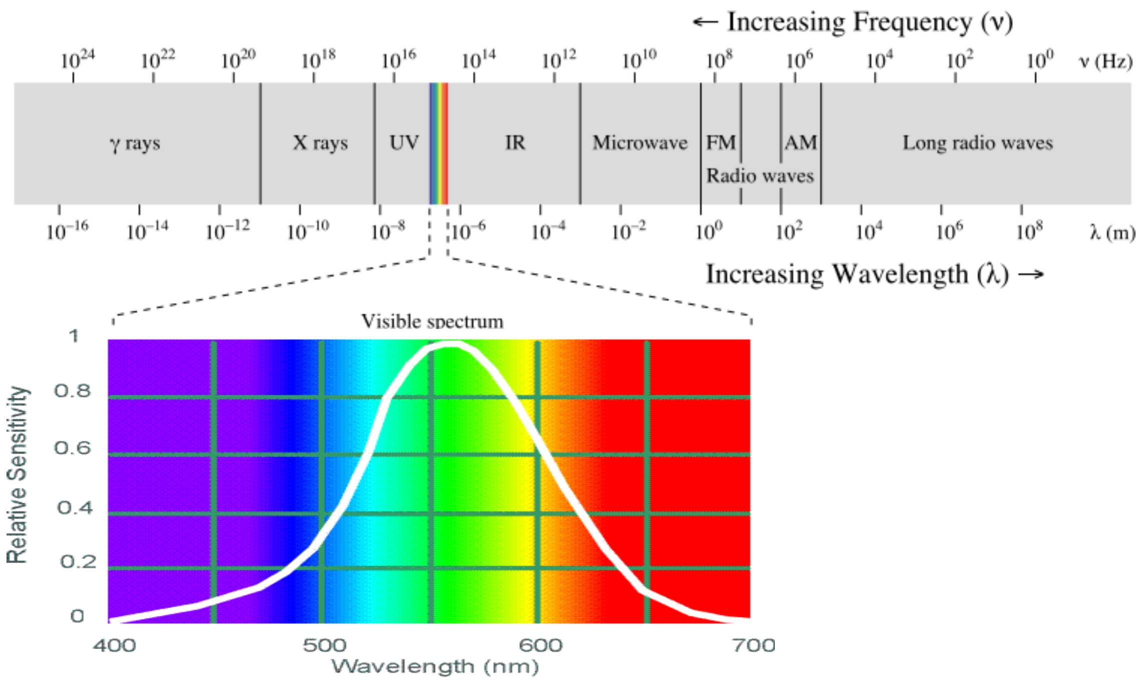
Wassily Kandinsky (1866-1944),
Murnau Street with Women, 1908

# 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 (S. Palmer, *Vision Science: Photons to Phenomenology*)
- Color is the result of interaction between physical light in the environment and our visual system

(S. Palmer, *Vision Science: Photons to Phenomenology*)

# Electromagnetic spectrum



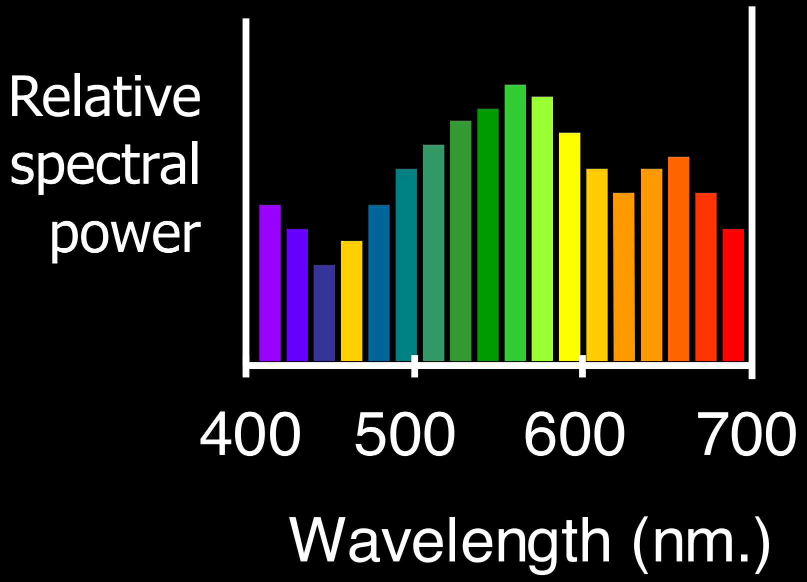

Human Luminance Sensitivity Function

Why do we see light at these wavelengths?

Because that's where the sun radiates electromagnetic energy.

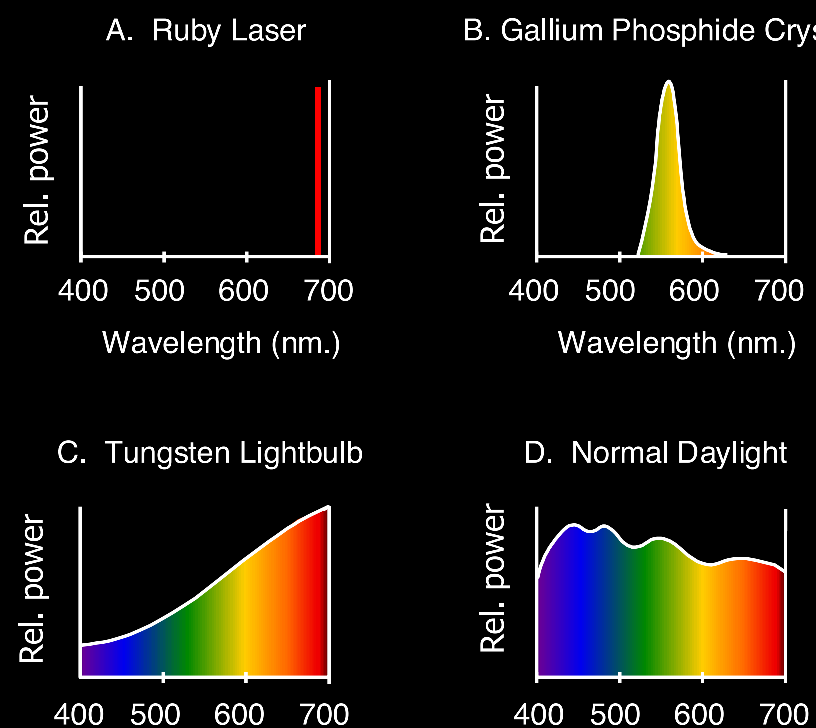
# The Physics of Light

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



# The Physics of Light

## Some examples of the spectra of light sources



# Black body radiators

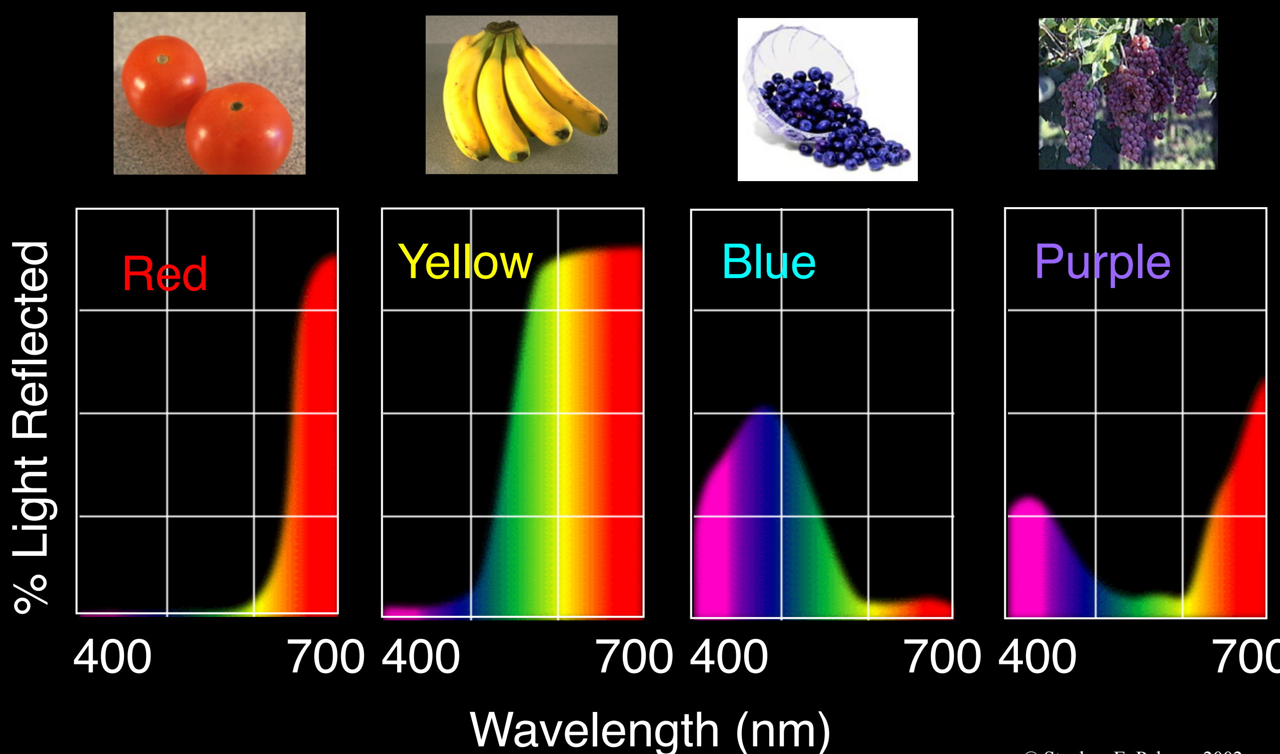
- Construct a hot body with near-zero albedo (black body)
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature

$$E(\lambda) \propto \left(\frac{1}{\lambda^5}\right)\left(\frac{1}{\exp\left(hc/k\lambda T\right)-1}\right)$$

- This leads to the notion of color temperature
  - the temperature of a black body that would look the same.

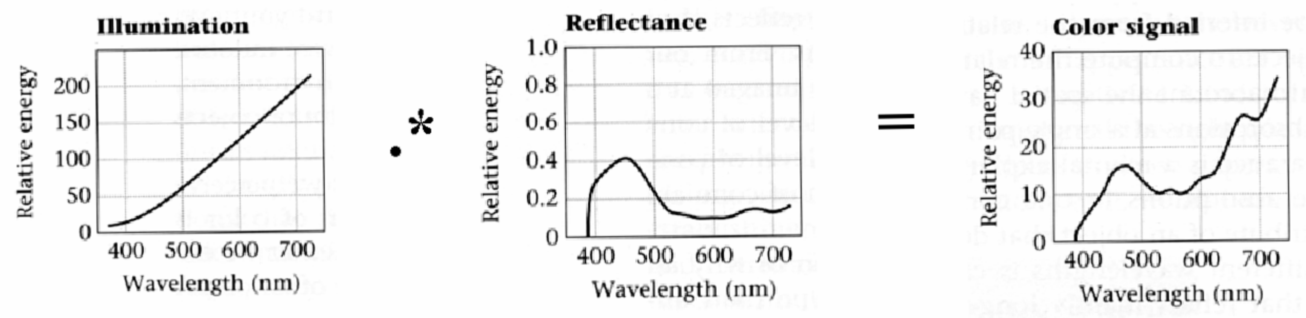
# The Physics of Light

Some examples of the reflectance spectra of surfaces

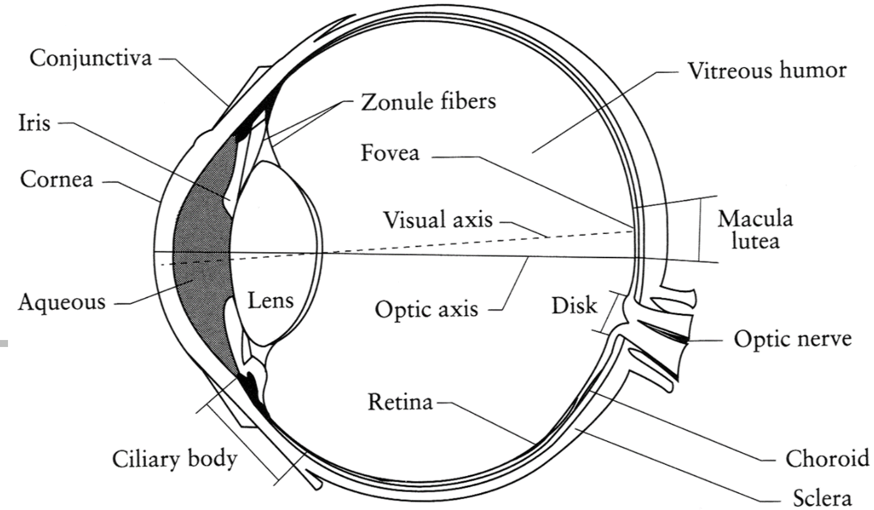


# Interaction of light and surfaces

- Observed color is the result of interaction of light source spectrum with surface reflectance
- Spectral radiometry
  - All definitions and units are now “per unit wavelength”
  - All terms are now “spectral”



# The Eye

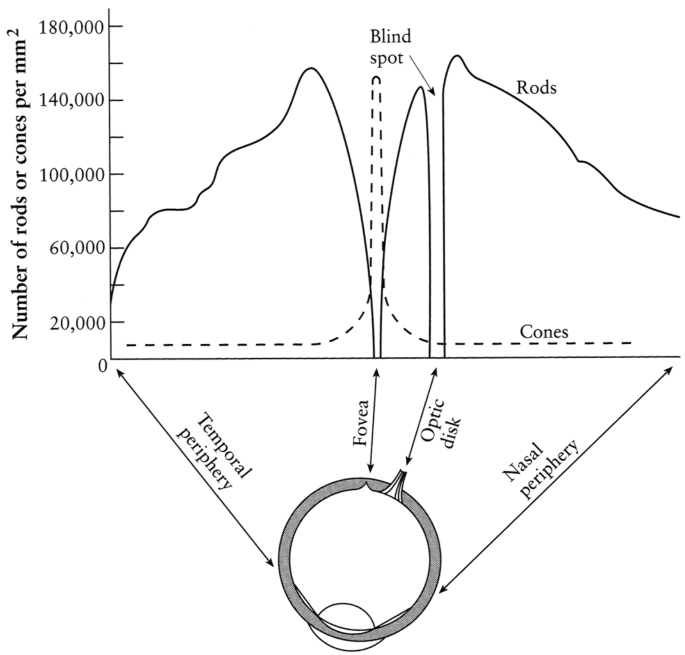


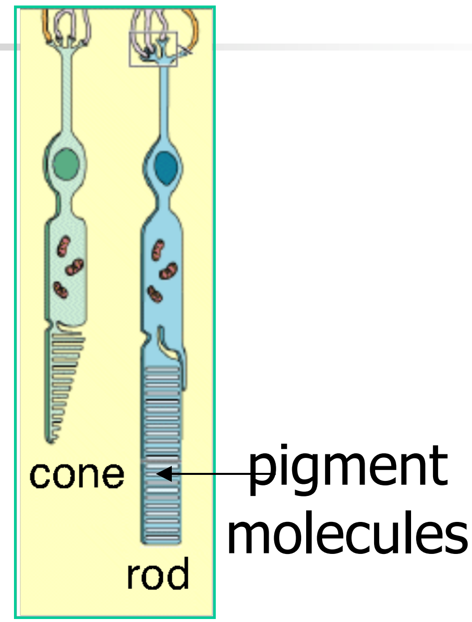

The human eye is a camera!

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- What's the "film"?

–photoreceptor cells (rods and cones) in the **retina.**

# Density of rods and cones



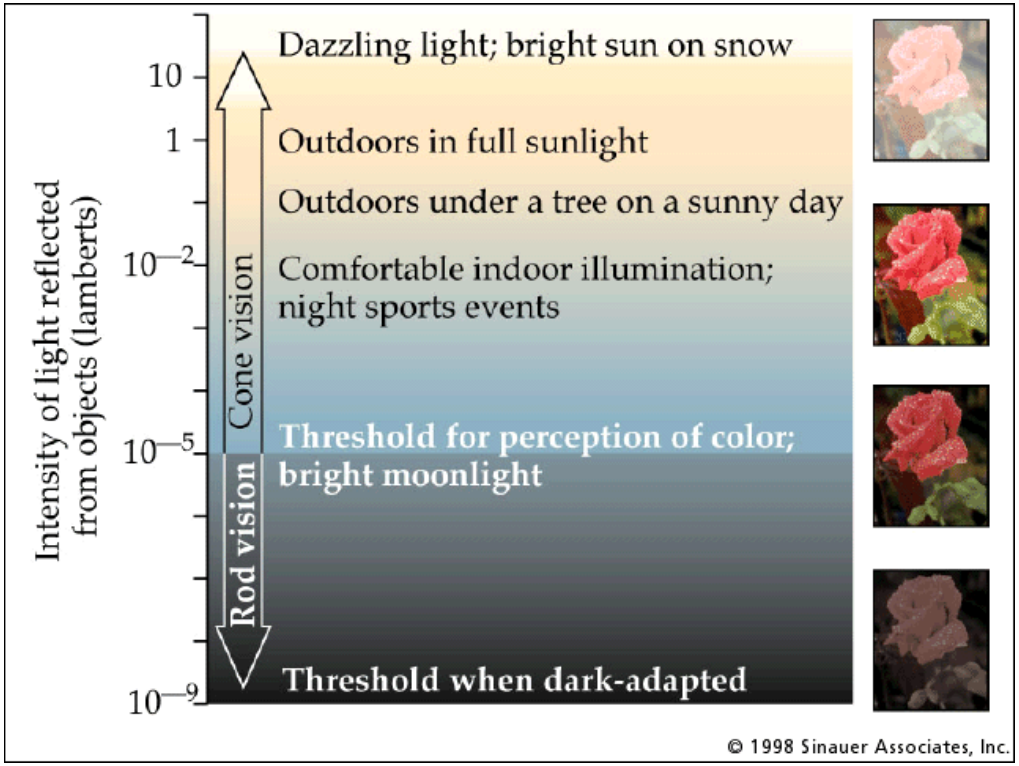

Rods and cones are *non-uniformly* distributed on the retina

- 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 $540 \times 10^{12}$ hertz and that has a radiant intensity in that direction of $^{1}/_{683}$ watt per steradian.



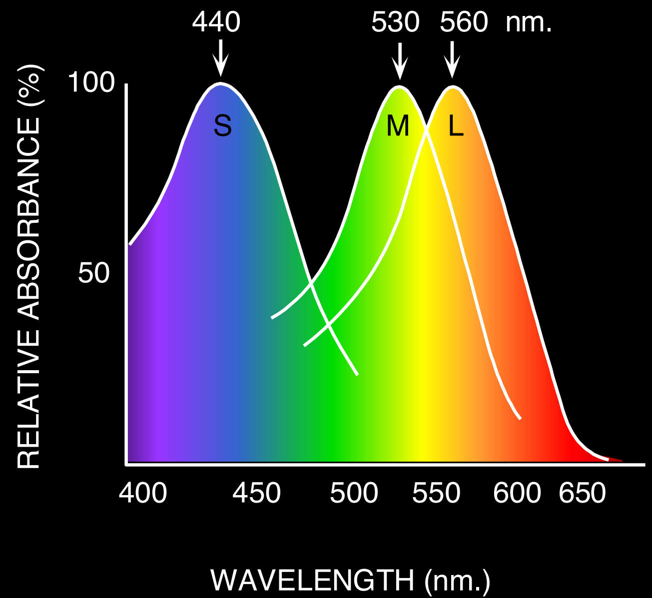

1 lambert (L) = $\frac{1}{\pi}$ candela per square centimetre (0.3183 cd/cm²) or $\frac{10^4}{\pi}$ cd $m^{-2}$

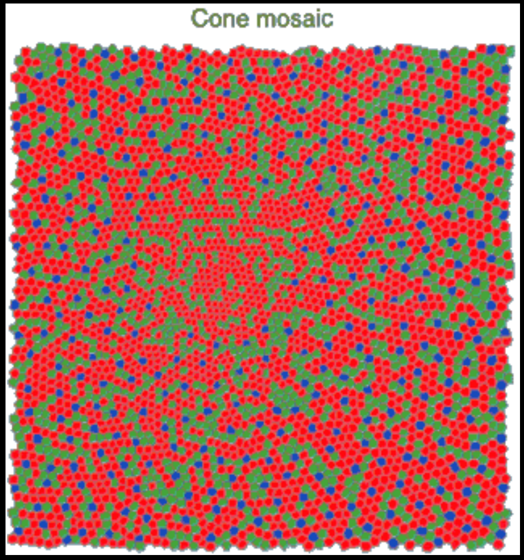
Why can't we read in the dark?

Slide by A. Efros

# Physiology of Color Vision

Three kinds of cones:



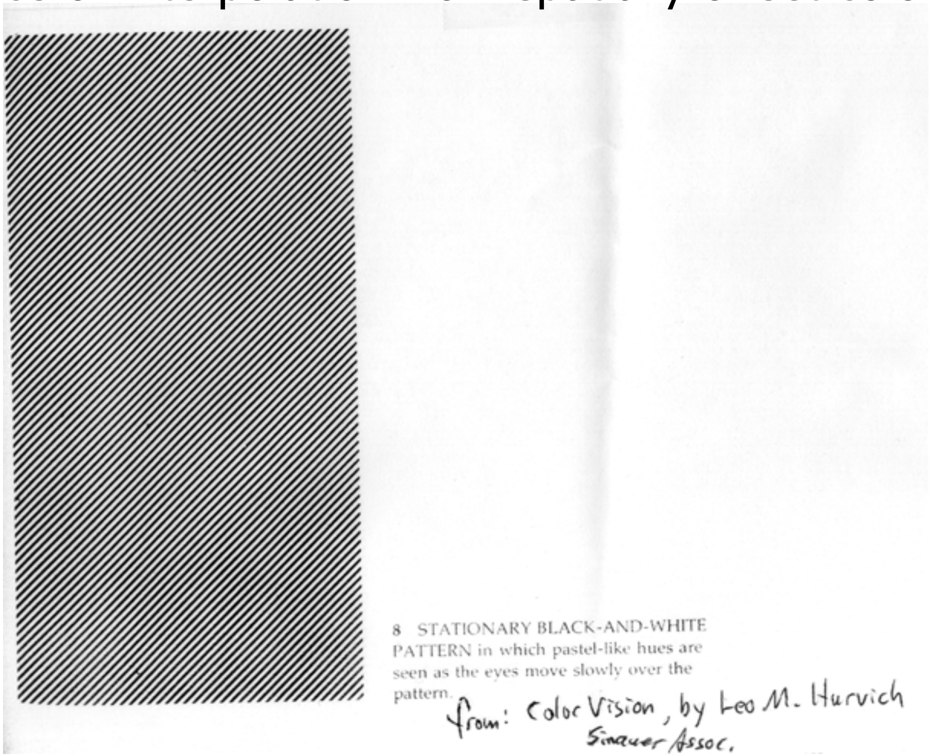




- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

# Color interpolation in human visual system

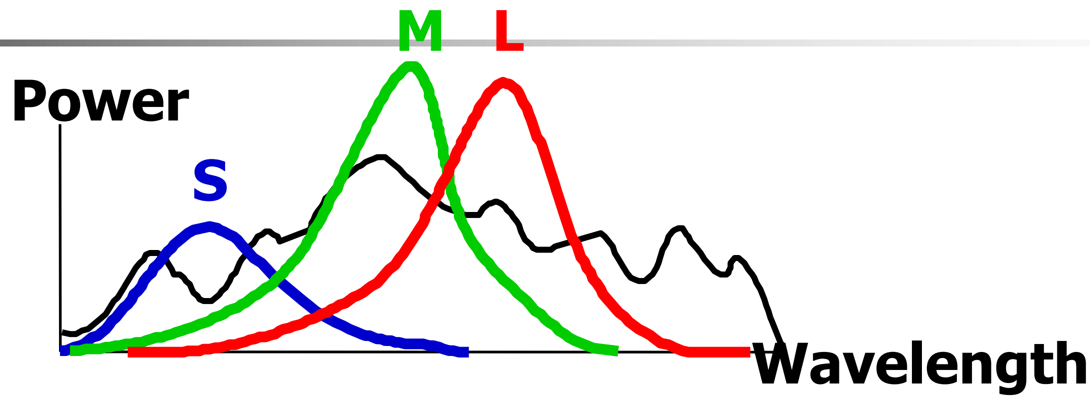
Brewster's colors: evidence of interpolation from spatially offset color samples

Scale relative to human photoreceptor size: each line covers about 7 photoreceptors




Source: F. Durand

# Color perception




Each cone yields one number

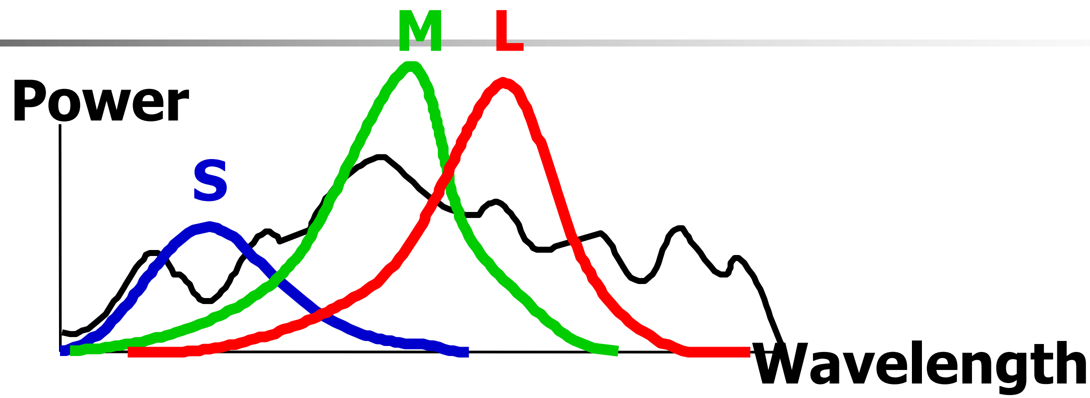
Rods and cones act as filters on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths.

- Q: How can we represent an entire spectrum with 3 numbers?
- A: We can't! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable
    - » such spectra are known as **metamers**

Slide by Steve Seitz

# Color perception

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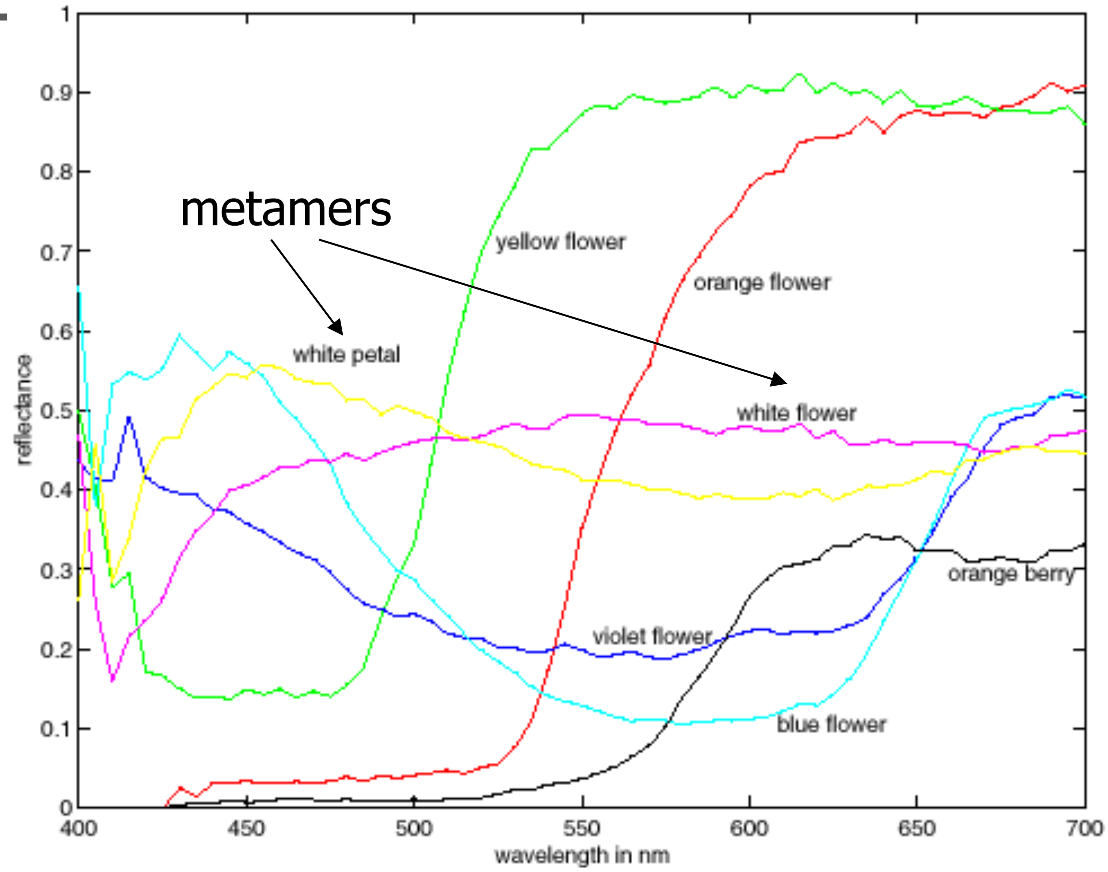
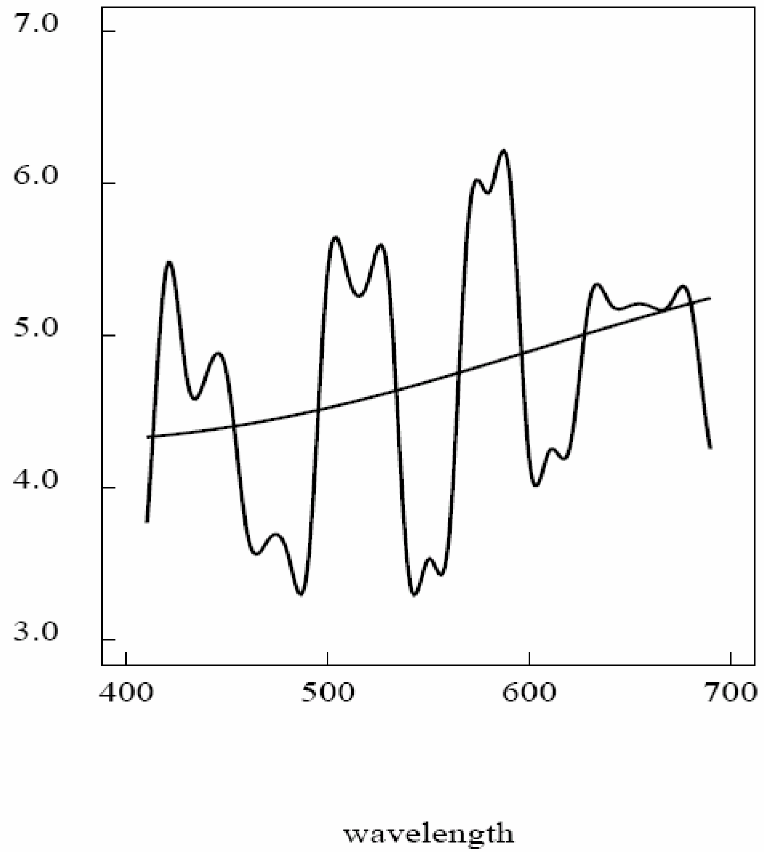
Slide by Steve Seitz

# Spectra of some real-world surfaces

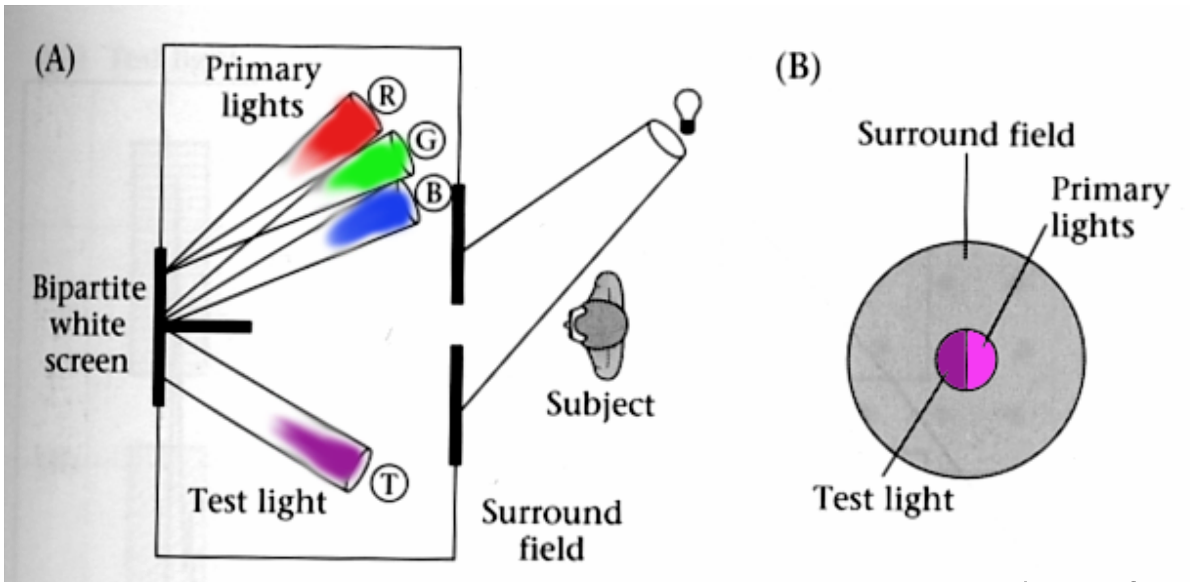


# Metamers



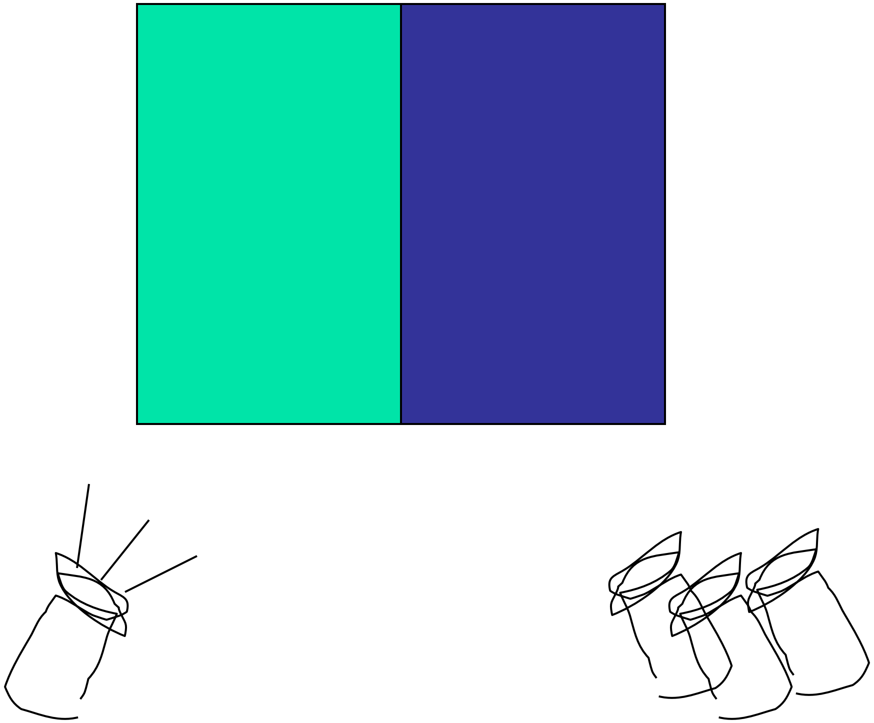
# Standardizing color experience

- We would like to understand which spectra produce the same color sensation from people under similar viewing conditions
- Color matching experiments



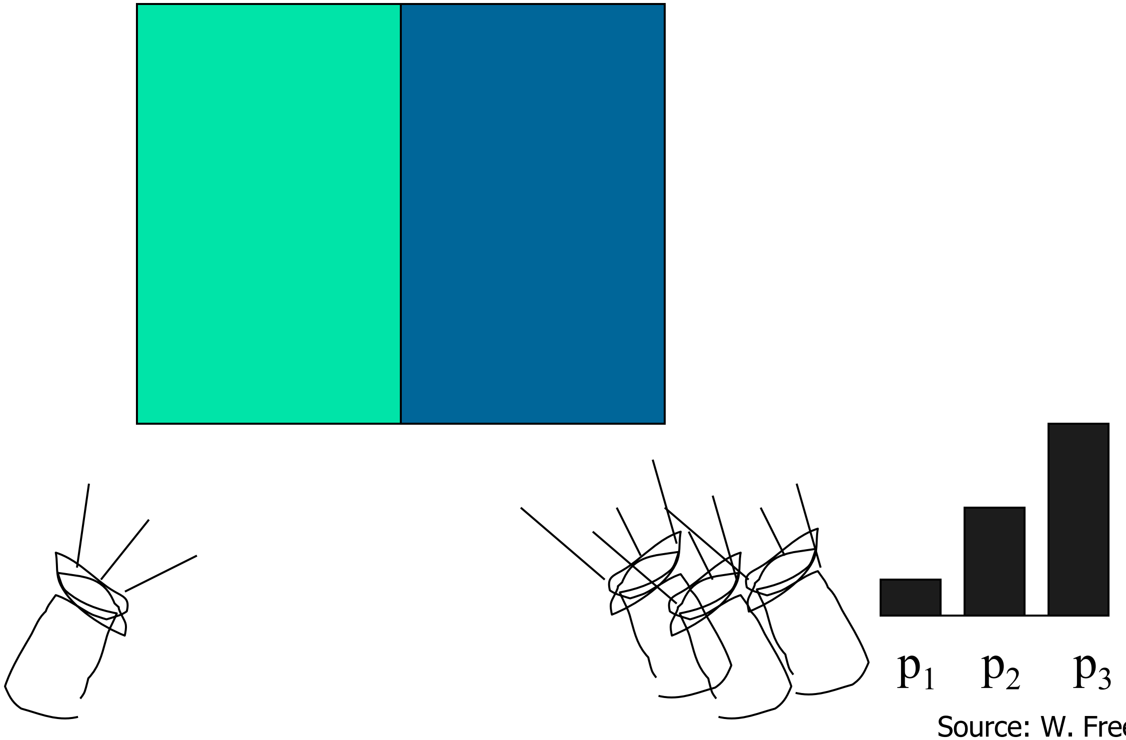

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 19

# Color matching experiment 1



Source: W. Freeman

# Color matching experiment 1




Source: W. Freeman

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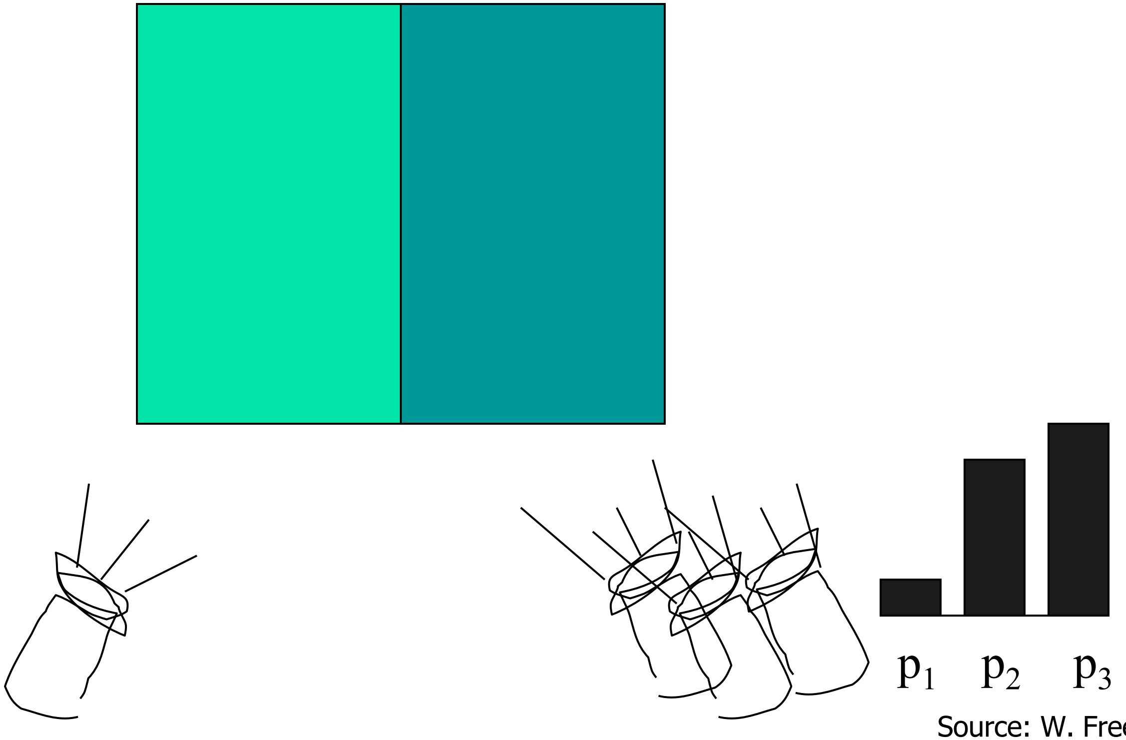


Source: W. Freeman

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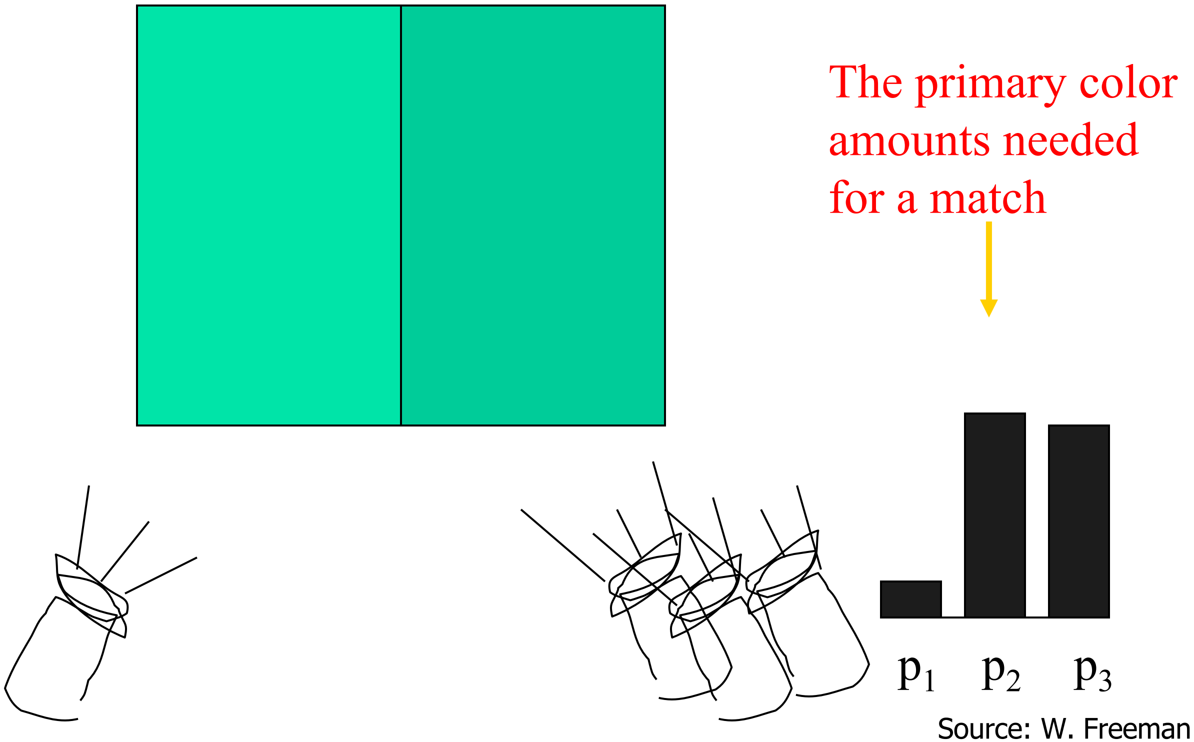
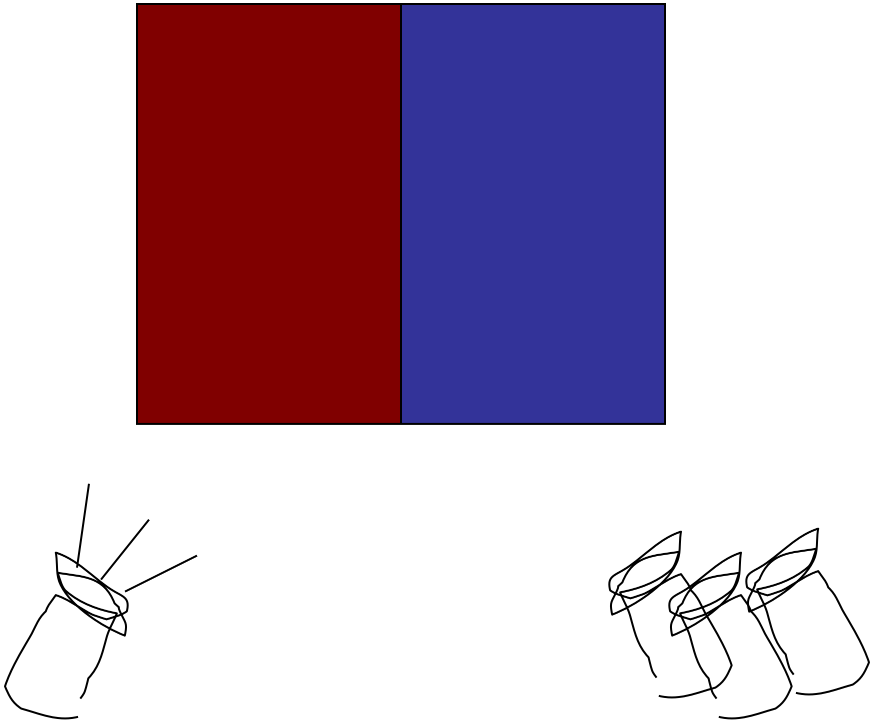


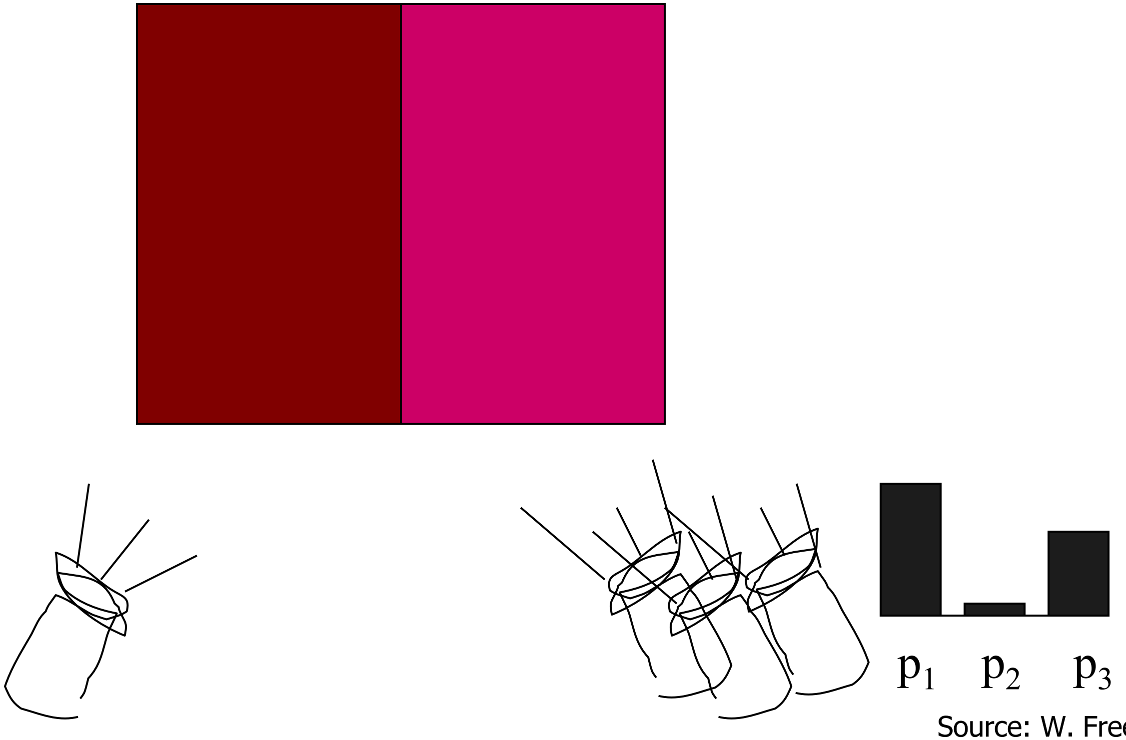

Source: W. Freeman

# Color matching experiment 2



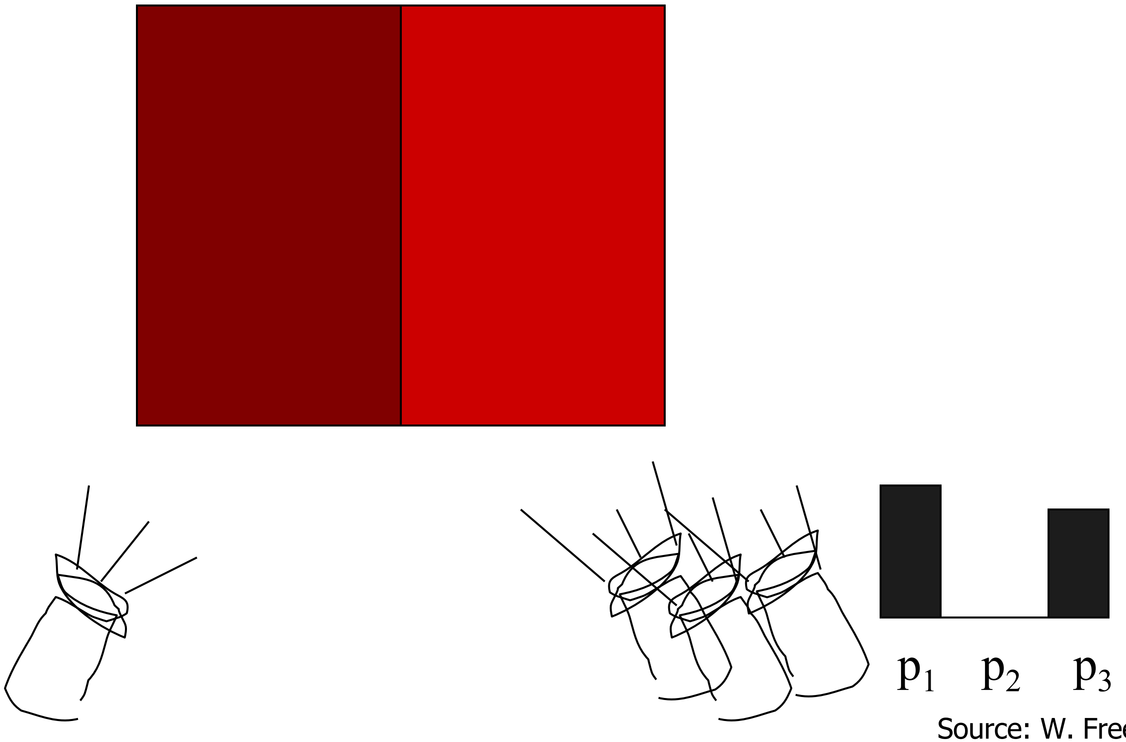
Source: W. Freeman

# Color matching experiment 2




Source: W. Freeman

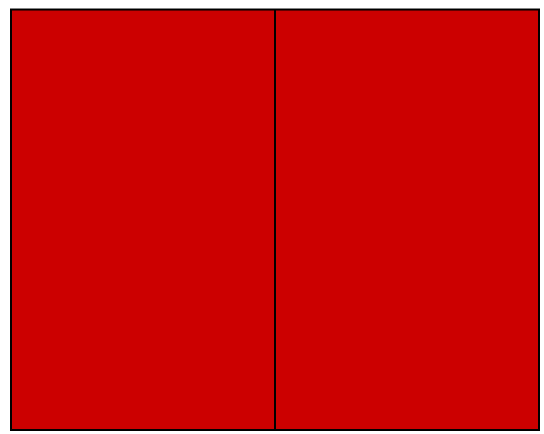
# Color matching experiment 2



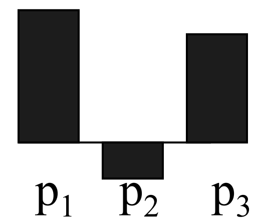

Source: W. Freeman

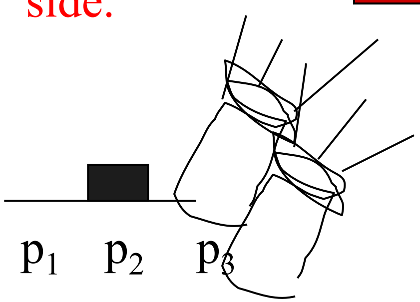
# Color matching experiment 2

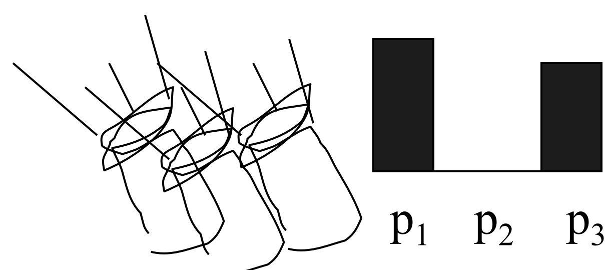
We say a "negative" amount of $p_2$ was needed to make the match, because we added it to the test color's side.



The primary color amounts needed for a match:




Source: W. Freeman

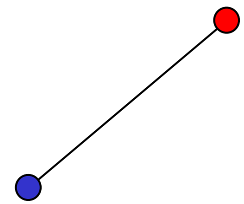
# Trichromacy

- In color matching experiments, most people can match any given light with three primaries
  - Primaries must be *independent*
- For the same light and same primaries, most people select the same weights
  - Exception: color blindness
- Trichromatic color theory
  - Three numbers seem to be sufficient for encoding color
  - Dates back to $18^{th}$ century (Thomas Young)

# Grassman's Laws

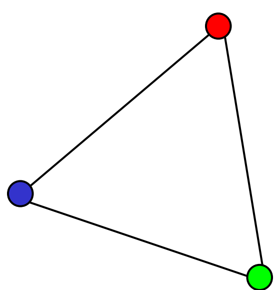
- Color matching appears to be linear.
- If two test lights can be matched with the same set of weights, then they match each other:
  - If $A = u_1P_1 + u_2P_2 + u_3P_3$ and $B = u_1P_1 + u_2P_2 + u_3P_3$. Then $A = B$.
- If we mix two test lights, then mixing the matches will match the result:
  - If $A = u_1P_1 + u_2P_2 + u_3P_3$ and $B = v_1P_1 + v_2P_2 + v_3P_3$.
    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 $A = u_1P_1 + u_2P_2 + u_3P_3$, then $kA = (ku_1)\ P_1 + (ku_2)\ P_2 + (ku_3)\ P_3$.

# Linear color spaces



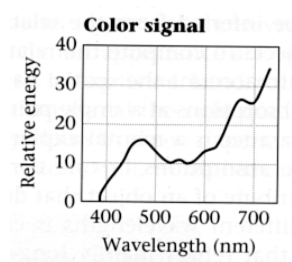
mixing two lights produces colors that lie along a straight line in color space

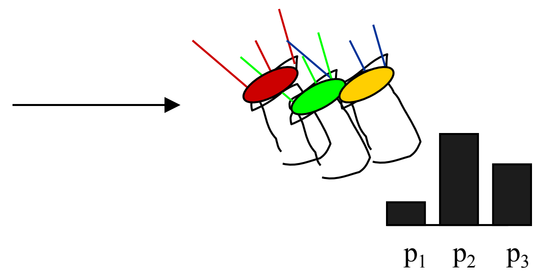
- Defined by a choice of three primaries
- The coordinates of a color are given by the weights of the primaries used to match it
- *Matching functions*: weights required to match single-wavelength light sources



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

# How to compute the color match for any color signal for any set of primary colors



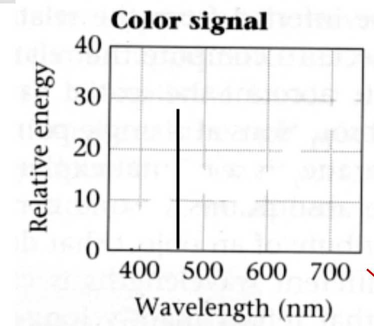



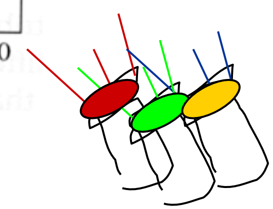

- Pick a set of primaries, $p_1(\lambda), p_2(\lambda), p_3(\lambda)$
- Measure the amount of each primary, $c_1(\lambda_0), c_2(\lambda_0), c_3(\lambda_0)$ needed to match a monochromatic light, $t(\lambda_0)$ at each spectral wavelength $\lambda_0$ (pick some spectral step size). These are the color matching functions.

Source: W. Freeman

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

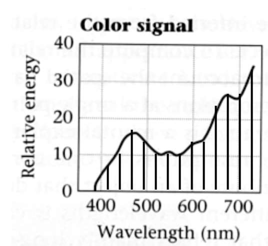
We know that a monochromatic light of wavelength $\lambda_i$ will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.



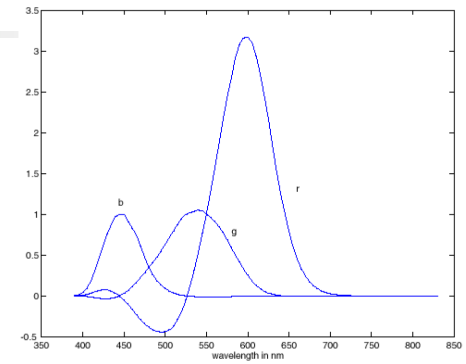
And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

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




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*.

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

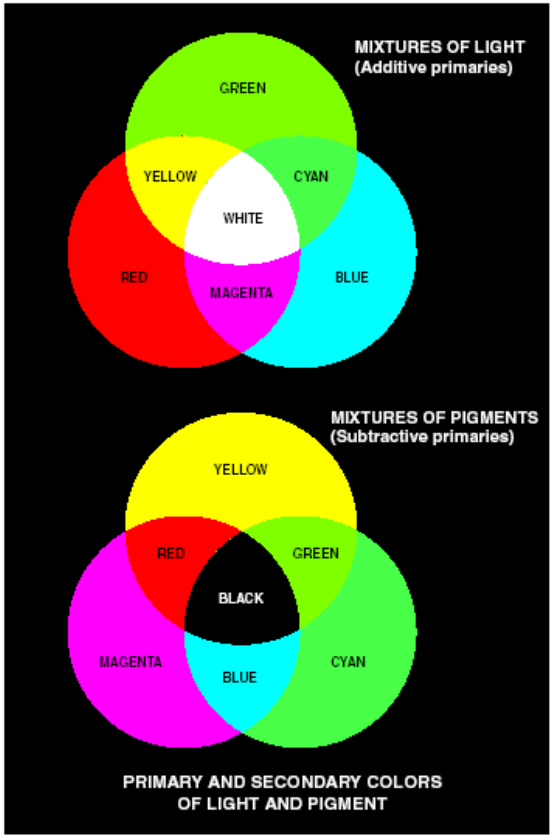
Then the amounts of each primary needed to match t are:

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

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

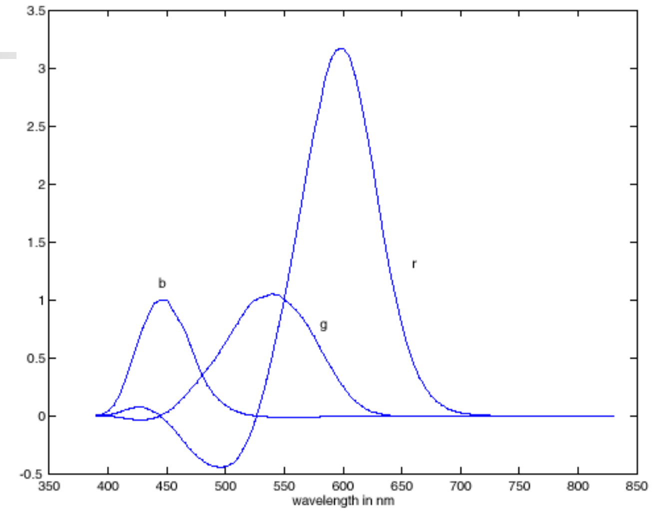
**FIGURE 6.4** Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lamp Business Division.)

Adapted from Gonzales and Woods

# Linear color spaces: RGB

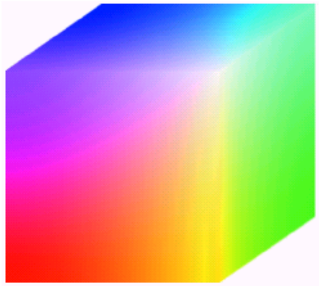
$p_1 = 645.2$ nm
$p_2 = 525.3$ nm
$p_3 = 444.4$ nm

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

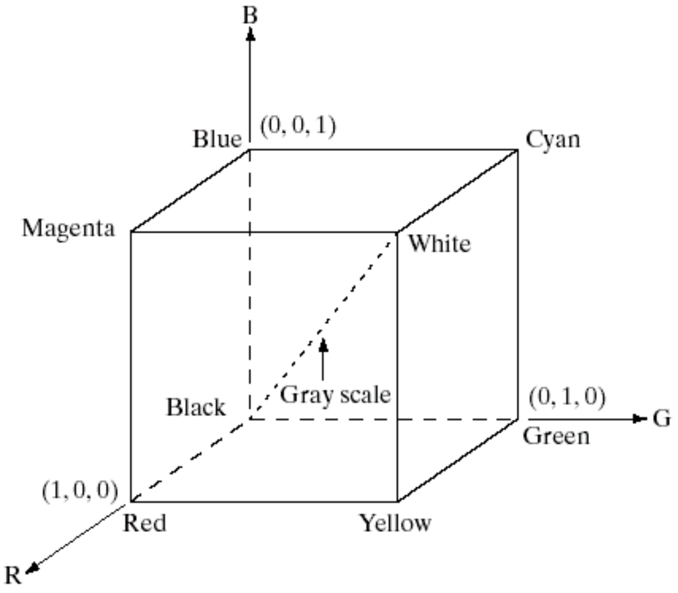



RGB matching functions

# RGB model



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



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

# CMY model

- 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.

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

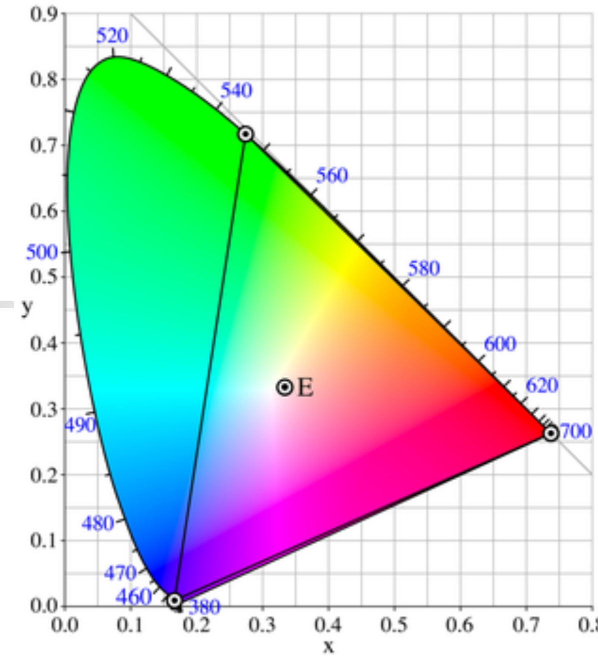
Adapted from Octavia Camps, Penn State

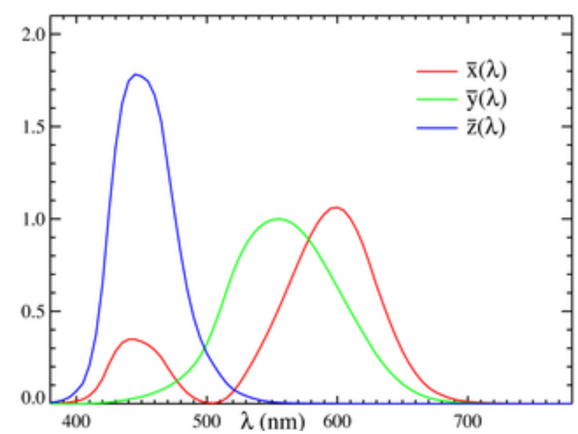
# CIE XYZ: Linear color space

- 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

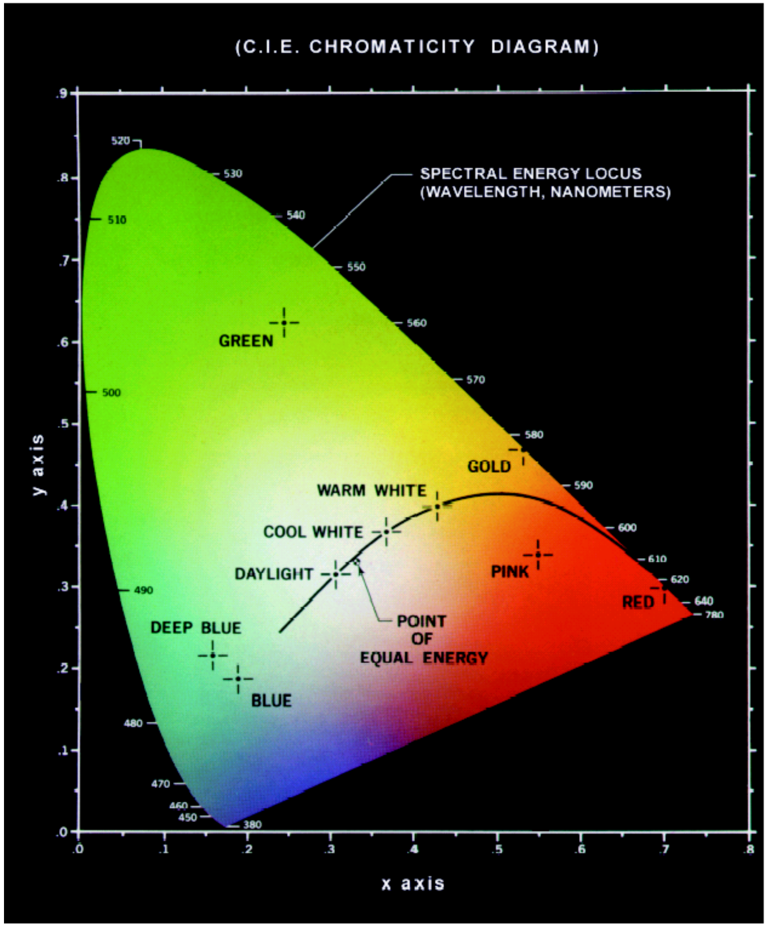
- x, y, z normalize X, Y, Z such that

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

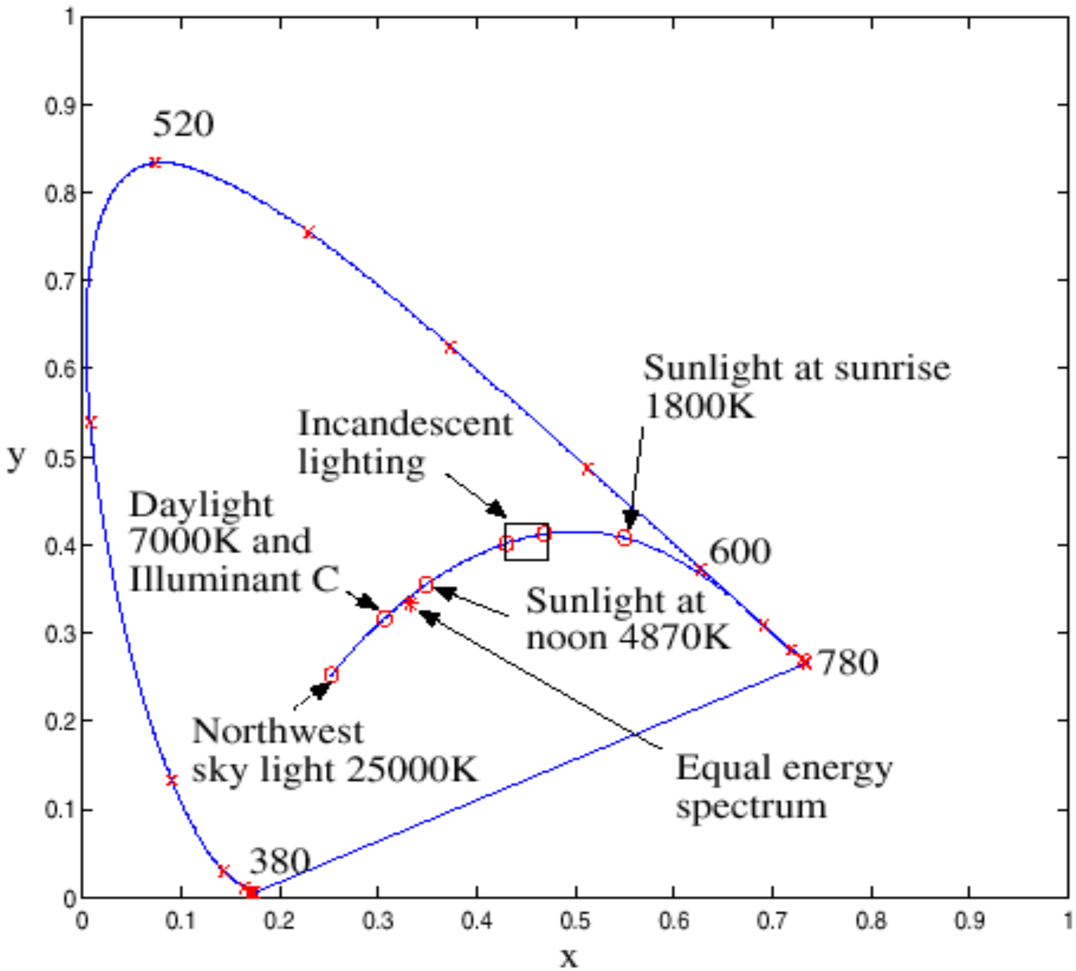
- Actually only x and y are needed because

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

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



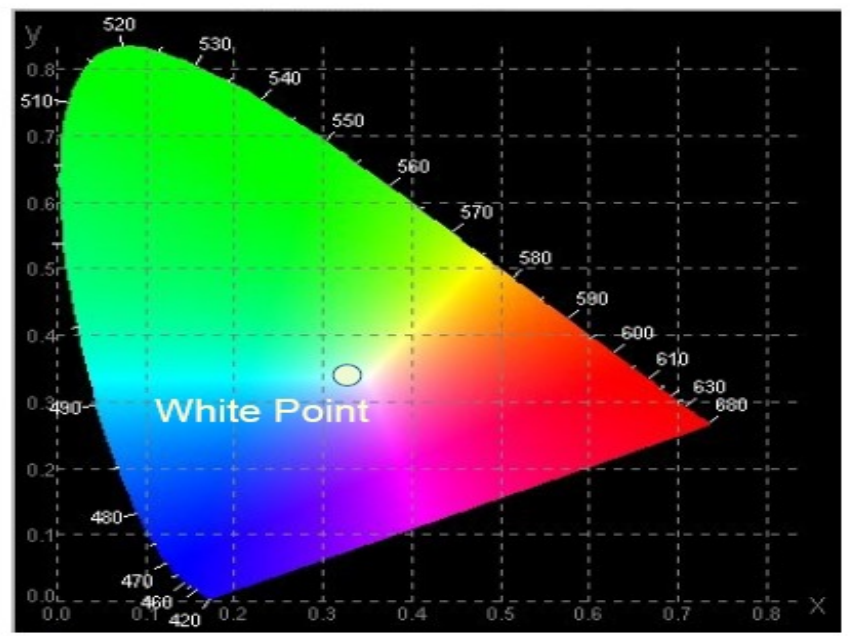
# Spectral locus of monochromatic lights and the heated black-bodies




Computer Vision - A Modern Approach :
Set: Color Slides by D.A. Forsyth

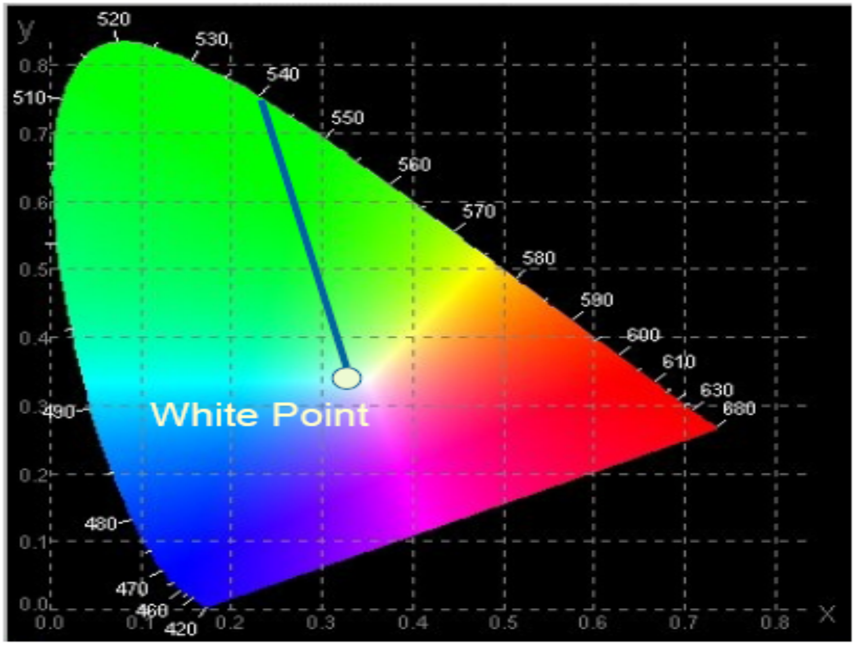
# CIE Chromaticity Chart

- Shows all the visible colors
- Achromatic Colors are at (0.33,0.33)
  - Called white point
- The saturated colors at the boundary
  - Spectral Colors



# Chromaticity Chart: Hue

- All colors on straight line from white point to a boundary has the same spectral hue
  - – Dominant wavelength



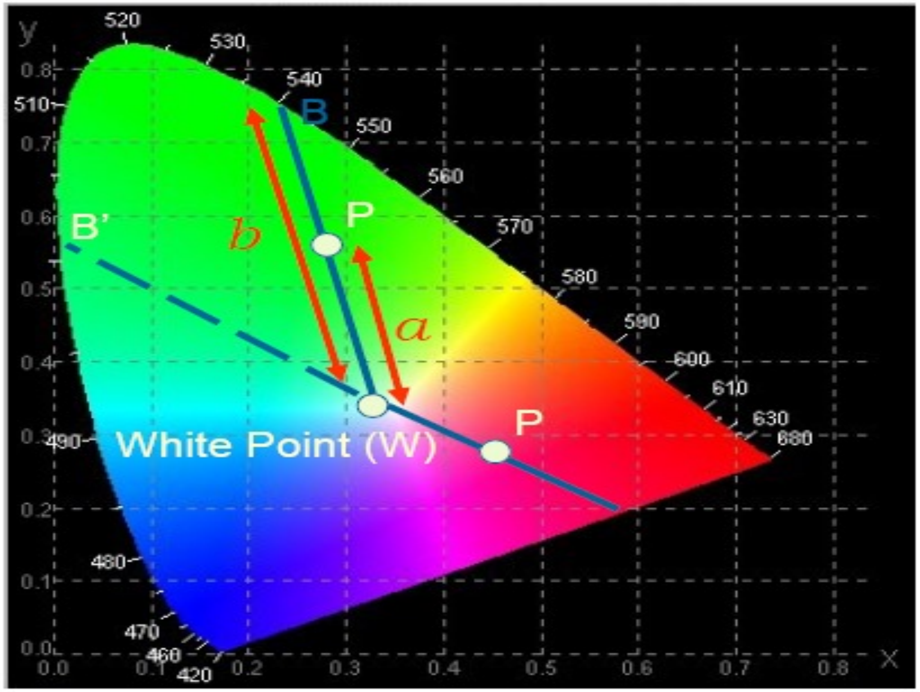
# Chromaticity Chart: Saturation

- Purity (Saturation)

– How far shifted towards the spectral color

– Ratio of *a/b*

– Purity =1 implies spectral color with maximum saturation



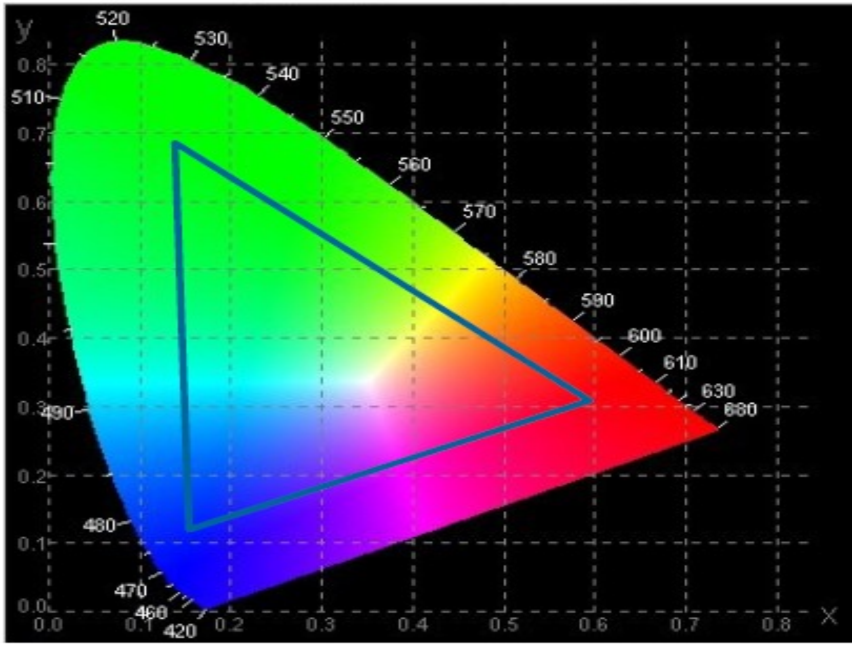
# Color Reproducibility

- Only a subset of the 3D CIE XYZ space called 3D color gamut
- Projection of the 3D color gamut

–Triangle

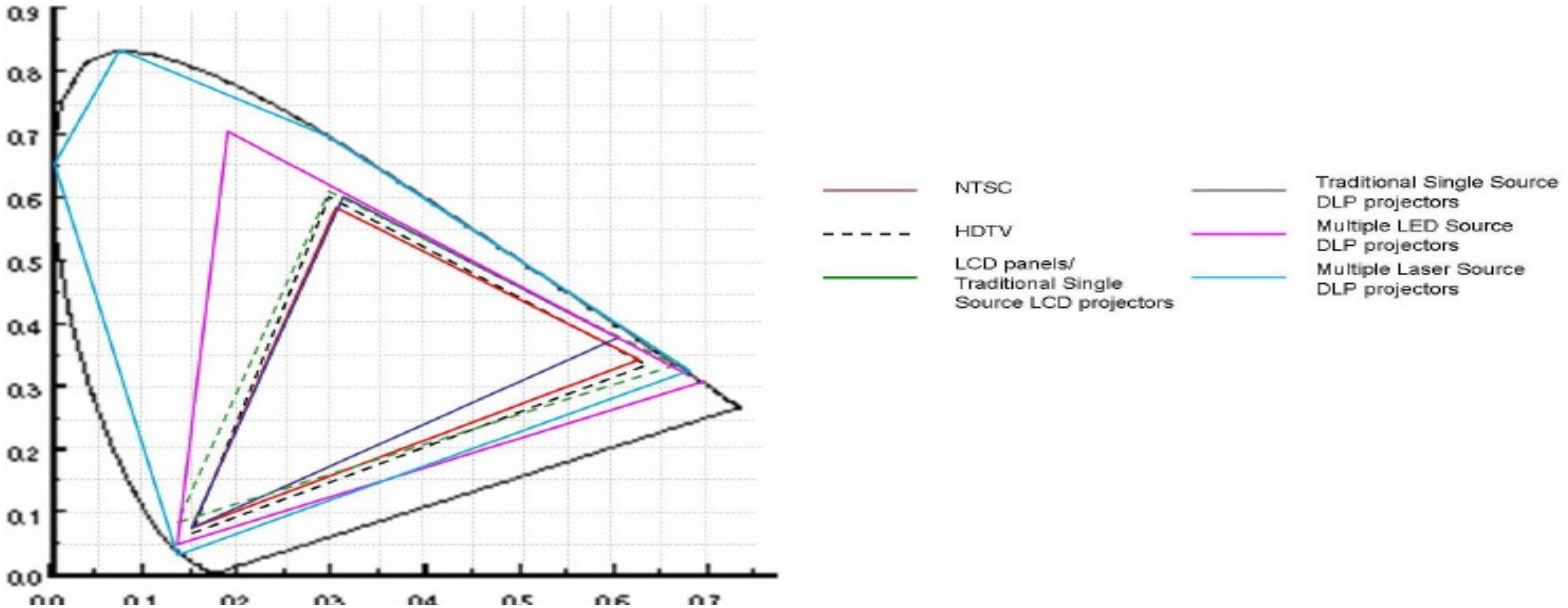
–2D color gamut

Large if using more saturated primaries



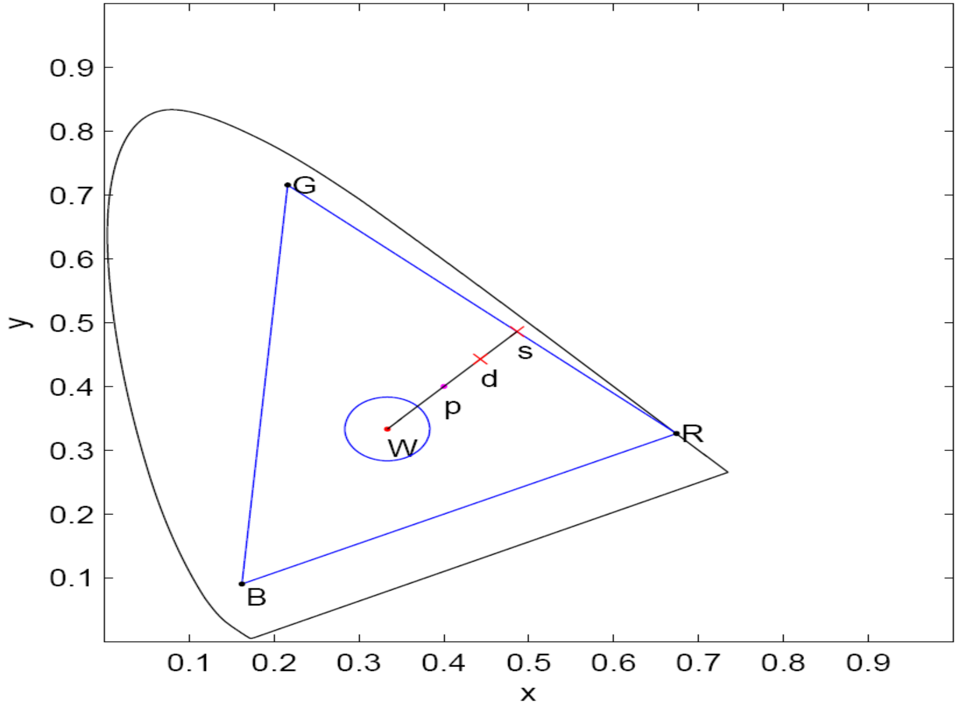

Cannot describe brightness range reproducibility

# Standard Color Gamut



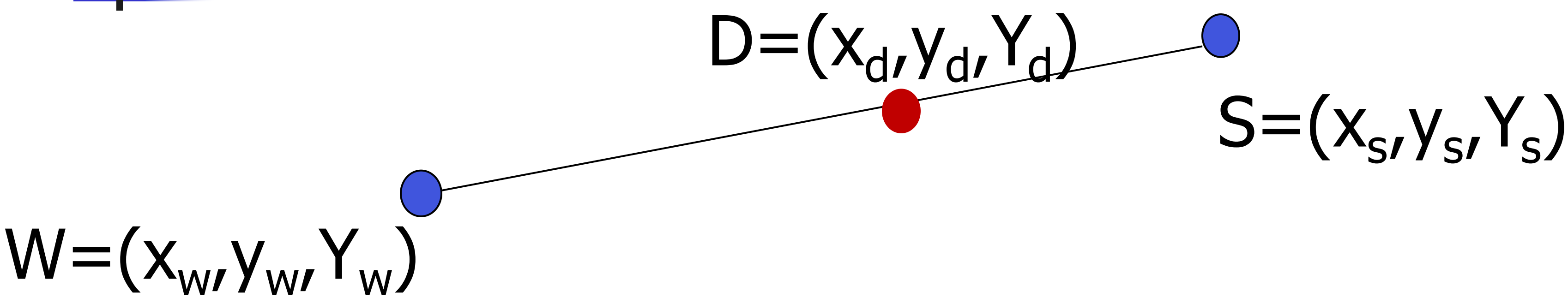
# Saturation and De-saturation Operation

- Move radially to the gamut edge → Maximum Saturation given a hue.
- Move inward using center of gravity law of color mixing.




*Luca Lucchese, SK Mitra, J Mukherjee, A new algorithm based on saturation and desaturation in the xy chromaticity diagram for enhancement and re-rendition of color images, ICIP 2001.*

# Desaturation using Center of Gravity Law




$$x_d = \frac{x_w \frac{|Y_w|}{y_w} + x_s \frac{|Y_s|}{y_s}}{\frac{|Y_w|}{y_w} + \frac{|Y_s|}{y_s}}$$

$$y_d = \frac{|Y_w| + Y_s}{\frac{|Y_w|}{y_w} + \frac{|Y_s|}{y_s}}$$

$$Y_d = |Y_w| + Y_s$$

$$Y_w = kY_{avg}$$

*Hunt, R.: Measuring Colour, 2nd Ed. Ellis Horwood Ltd. Publ., Chichester, UK (1987)*

# Desaturation using Center of Gravity Law

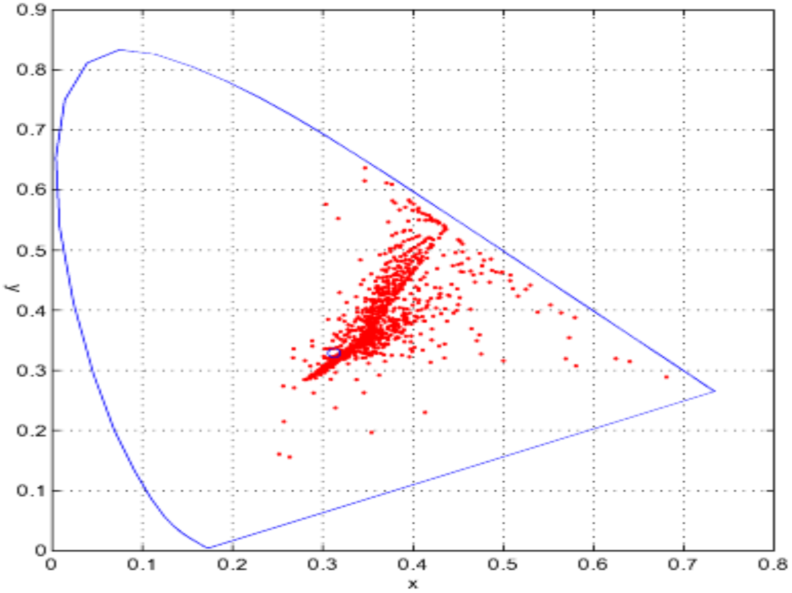
The *Center of Gravity Law* provides the resulting color $C_2 = (x_2, y_2, Y_2)$ of the mixture of the two colors $W = (x_W, y_W, |Y_W|)$ and $S = (x_S, y_S, Y_1)$ where

$$x_2 = \frac{x_W \frac{|Y_W|}{y_W} + x_S \frac{Y_1}{y_S}}{\frac{|Y_W|}{y_W} + \frac{Y_1}{y_S}}, \quad y_2 = \frac{|Y_W| + Y_1}{\frac{|Y_W|}{y_W} + \frac{Y_1}{y_S}}, \quad \text{and} \quad Y_2 = Y_W + Y_1. \qquad (3)$$

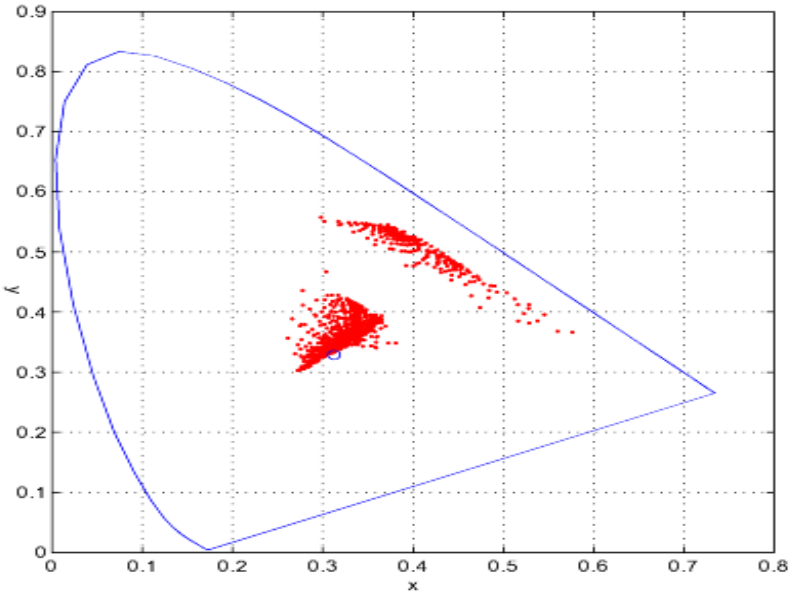
$$Y_W = \kappa Y_{avg}$$

Note apparent masses for chromatic mixture:
$Y_W/y_W$ and $Y_1/y_S$.

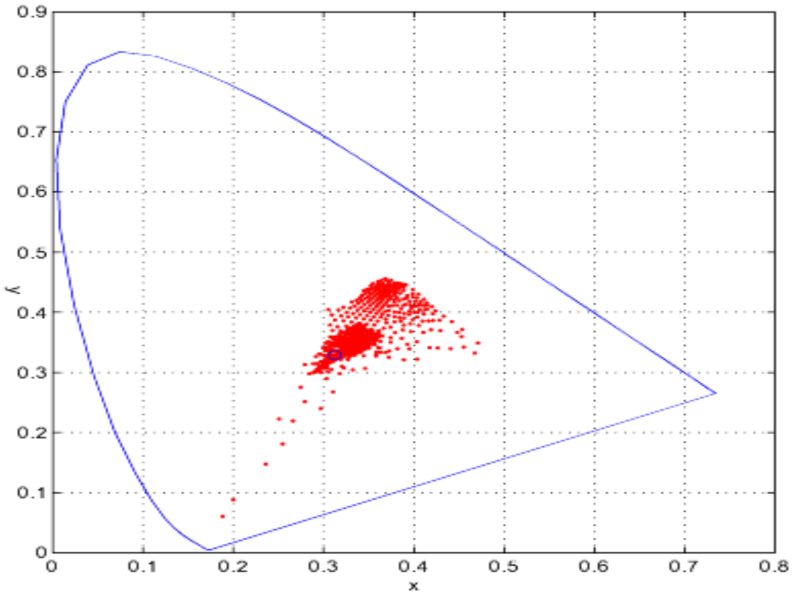
# Alps - Original



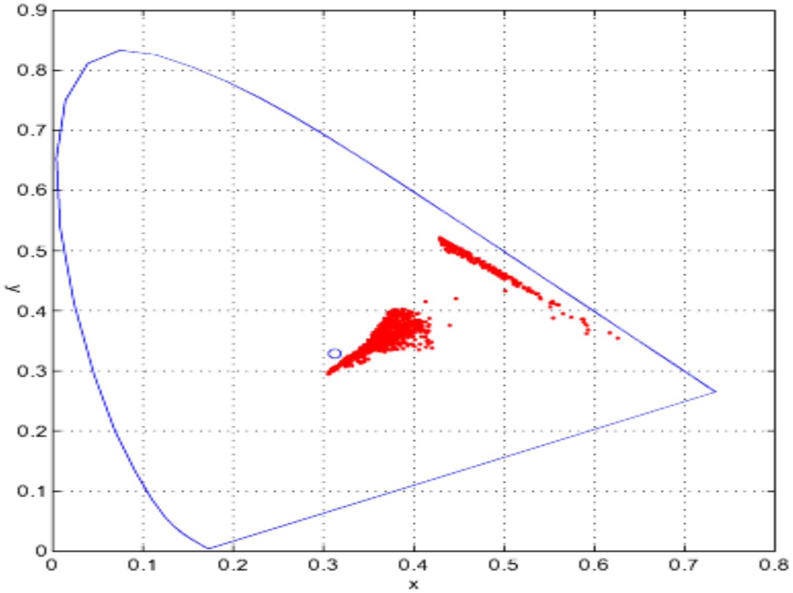
# Saturated Image



# De-saturated Image



# Saturated – De-saturated



# Desturated image with –ve k

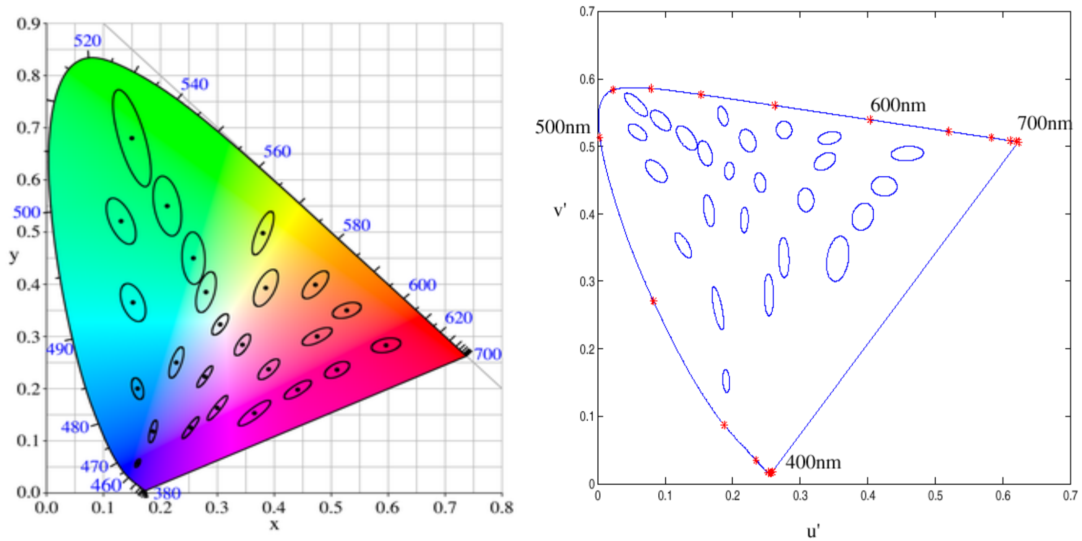
# Desaturation by shifting white to (0.5,0.2)

# Shifting white to (0.5,0.4)

# Shifting white to (0.2,0.5)

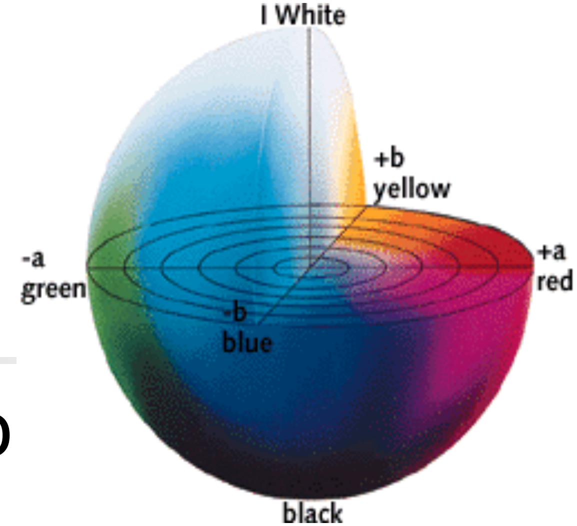
# Uniform color spaces

- Unfortunately, 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




**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 you 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.

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



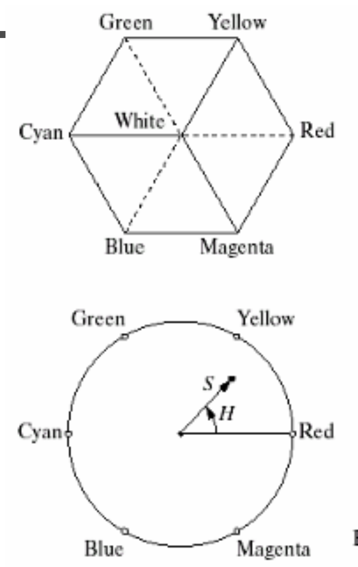
Adapted from Linda Shapiro, U of Washington

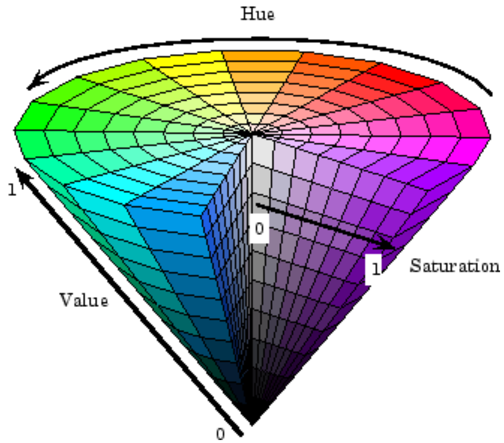
# YIQ model

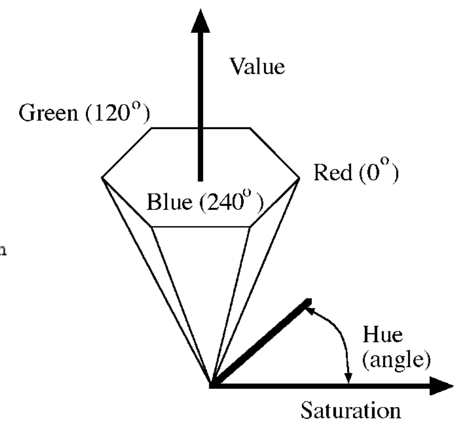
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.532 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- 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.

# Nonlinear color spaces: HSV




- Perceptually meaningful dimensions: Hue, Saturation, Value (Intensity)
- RGB cube on its vertex

# HSV model

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

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

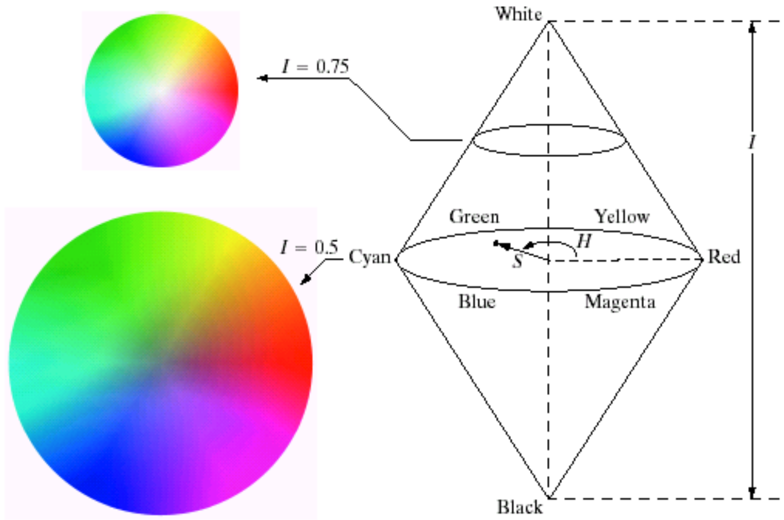
$$S = 1 - \frac{\min(R, G, B)}{I}$$

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

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

# HSV model

- Uniform: equal (small) steps give the same perceived color changes.
- Hue is encoded as an angle (0 to $2\pi$).
- 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

# HSV model

(Left) Image of food originating from a digital camera.

(Center) Saturation value of each pixel decreased 20%.

(Right) Saturation value of each pixel increased 40%.

Adapted from Linda Shapiro, U of Washington

# Color models

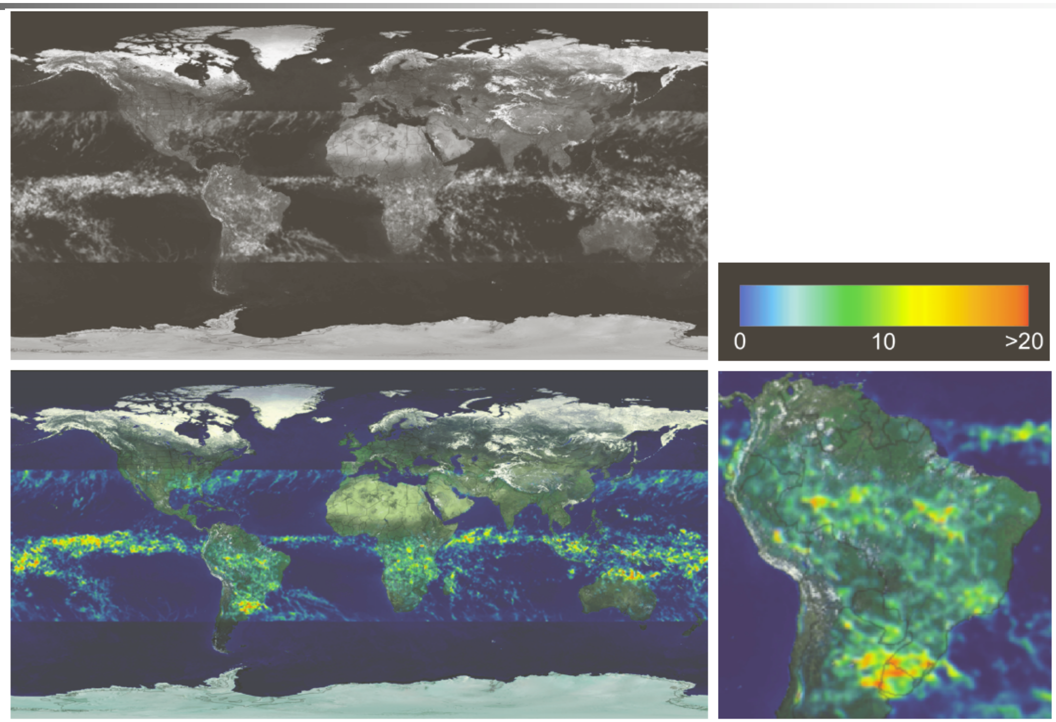

CMYK

RGB

HSV

Adapted from Gonzales and Woods

# Examples: pseudocolor

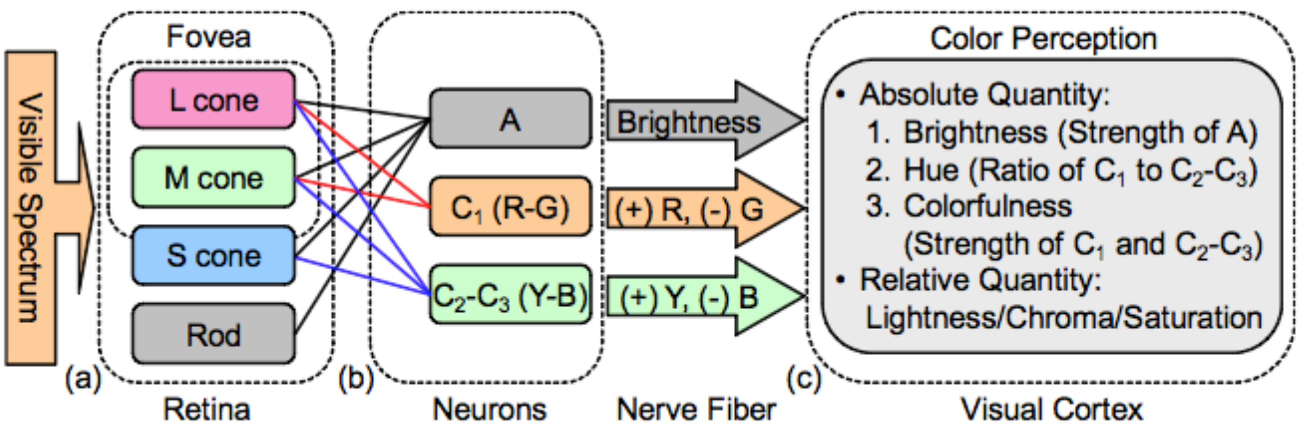


# Opponent Color Processing

- 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

- Trichromatic theory: Color perception with three types of cones,
- 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).

# Opponent Color Space of Wandell (1993)

- LMS color system

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.3910 & 1.1650 & 0.0870 \\ 0.0100 & -0.0080 & 0.5630 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- Opponent color space transform

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -0.59 & 0.80 & -0.12 \\ -0.34 & -0.11 & 0.93 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

# Summary

- Color is an important information for interpreting images and videos.
- Color is captured in the RGB color space: Not suitable for direct interpretation of color components such as Hue and Saturation.
- CIE Chromaticity Chart represents colors in a 2-D space according to tri-stimulus model of color representation and capable of providing the gamut triangle for reproducing colors.
- Various other color spaces used for processing.

Thank you!