Color fundamentals and processing (Week-08: Lectures 34-40)

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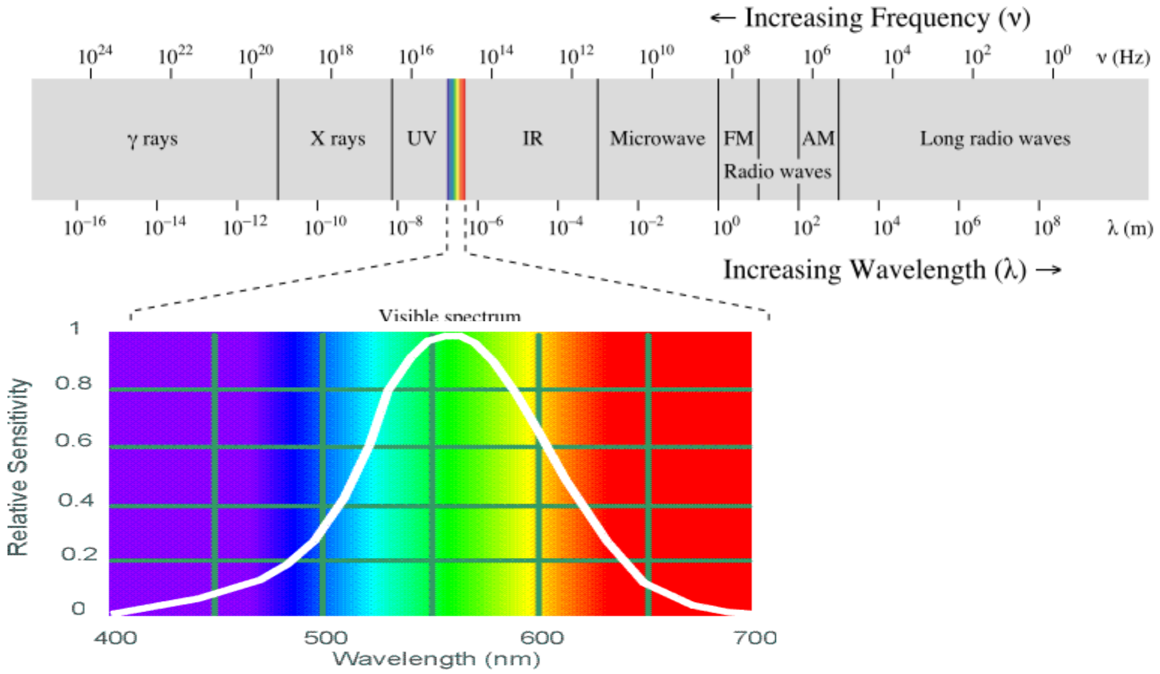
What is color?

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

S. Palmer, Vision Science: Photons to Phenomenology, The MIT Press, 1999.

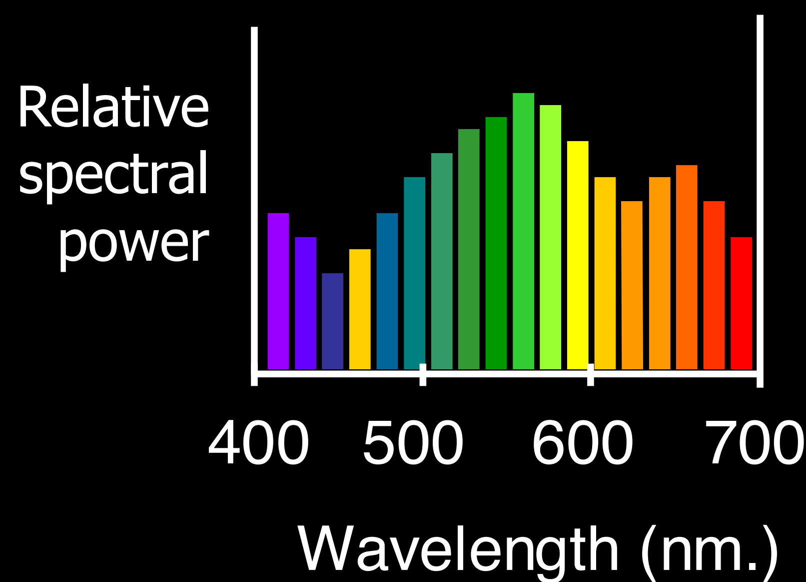
Electromagnetic spectrum



Human Luminance Sensitivity Function

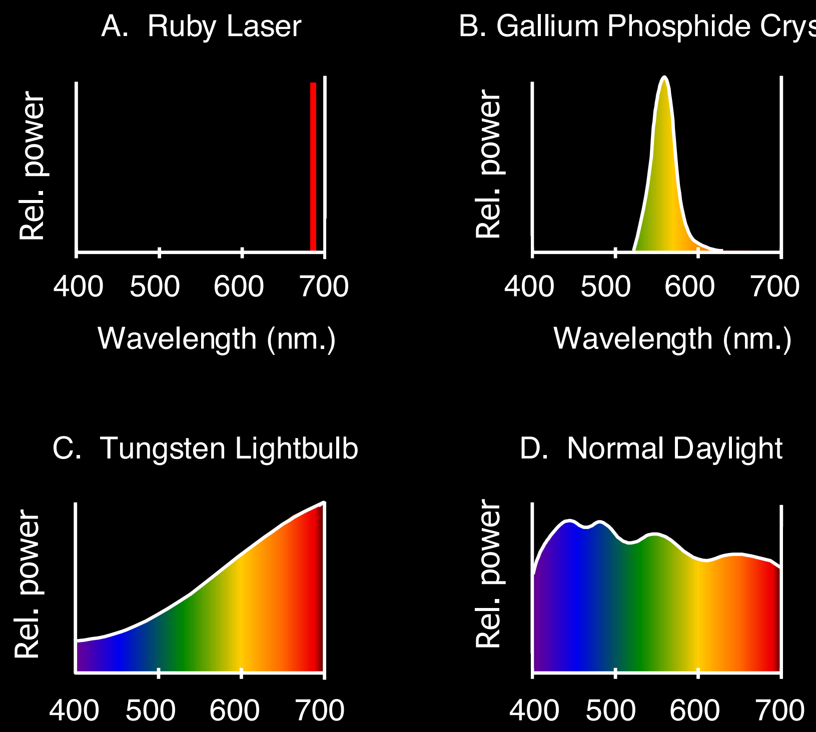
The Physics of Light

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

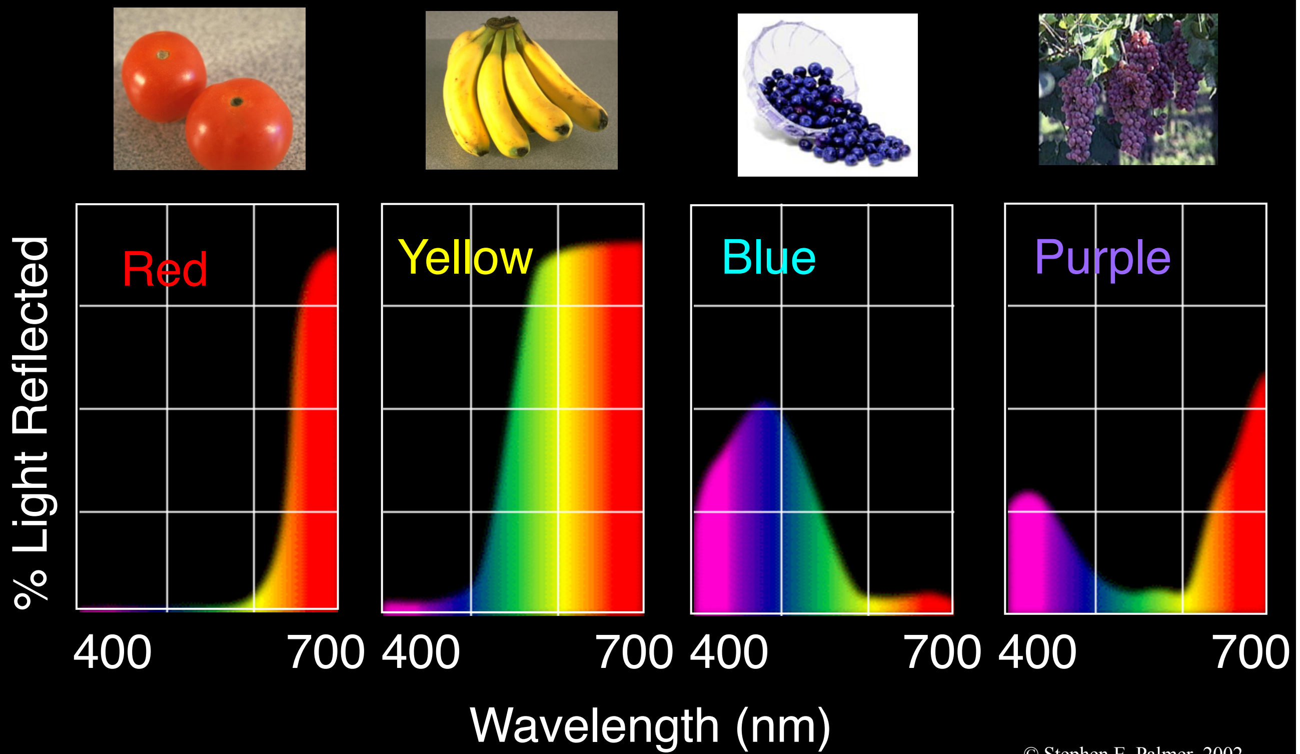
- Construct a hot body with near-zero albedo (black body).
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature.

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

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

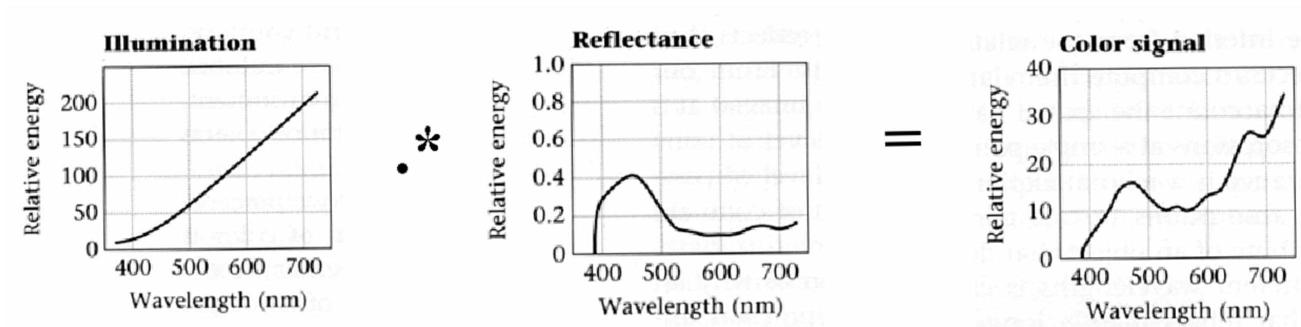
Reflection of Light

Some examples of the reflectance spectra of surfaces



Interaction of light and surfaces

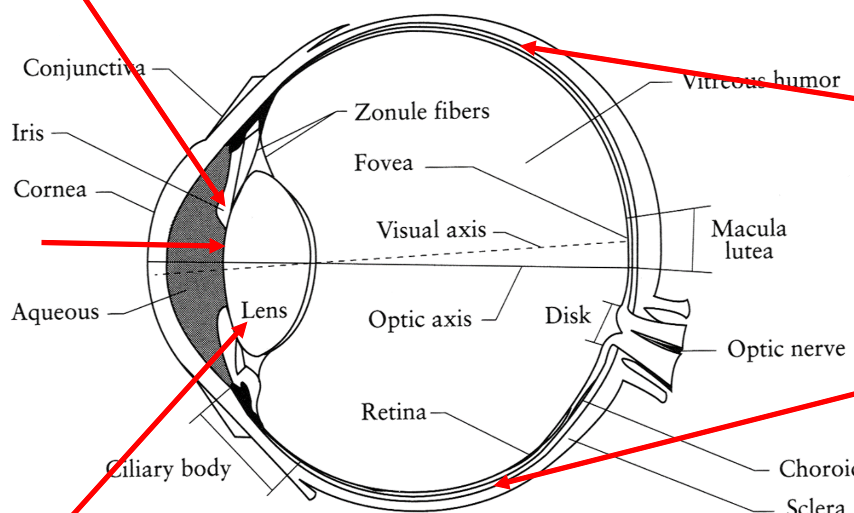
- Observed color is the result of interaction of light source spectrum with surface reflectance.



The Eye: A Camera!

Iris - colored annulus with radial muscles

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

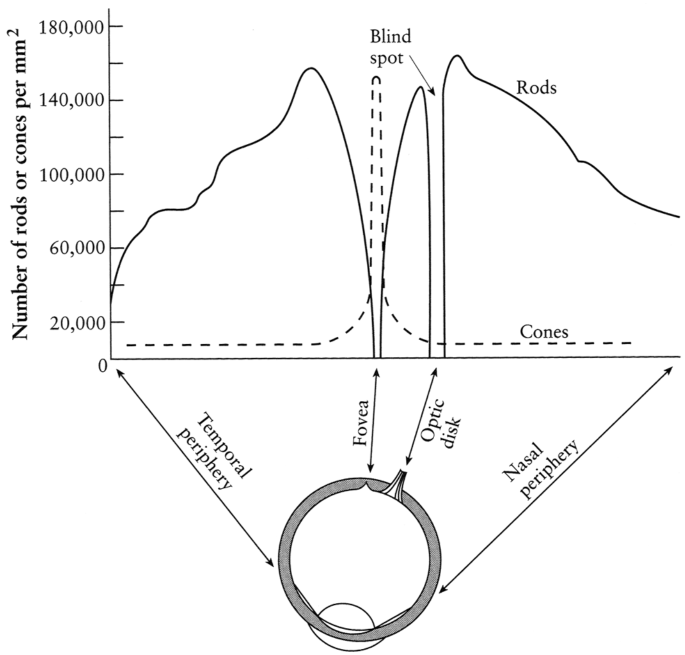


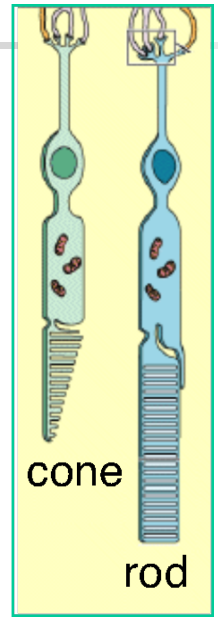
Retina -photoreceptor cells (rods and cones) acting like the film or array of sensors of a camera.

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

Adapted from slides by Steve Seitz.

Density of rods and cones





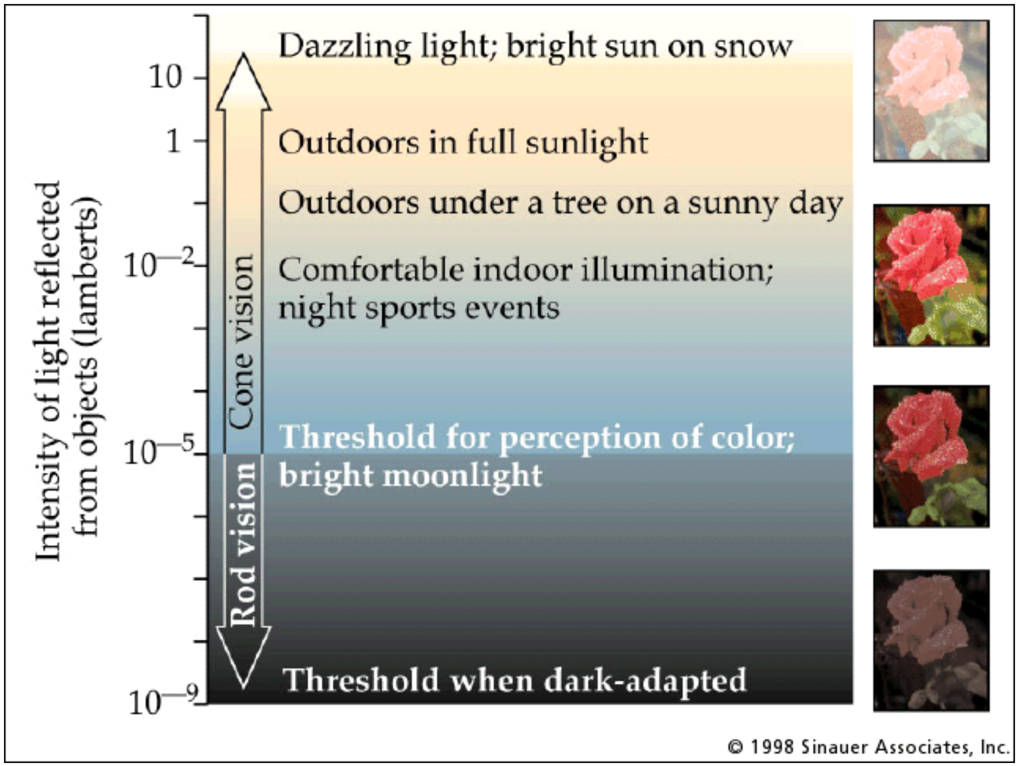
Rods and cones are *non-uniformly* distributed on the retina

- 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.



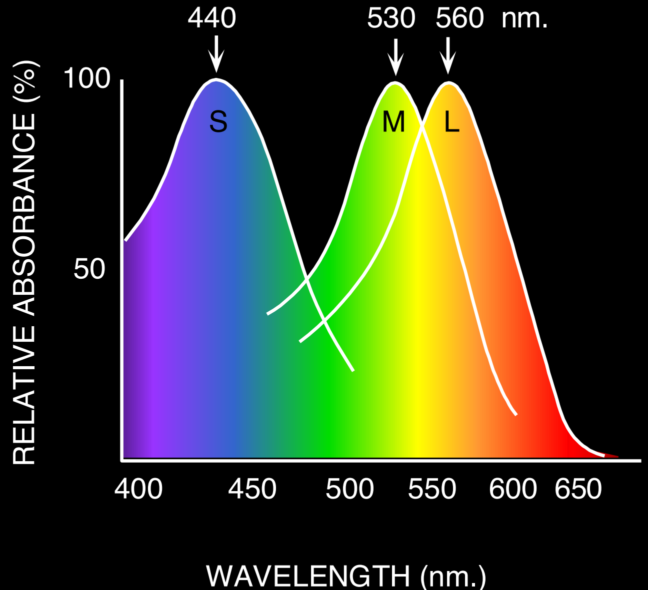
1 lambert (L) = $\frac{1}{\pi}$ candela per square centimetre (0.3183 cd/cm²) or $\frac{10^4}{\pi}$ cd m^{-2}

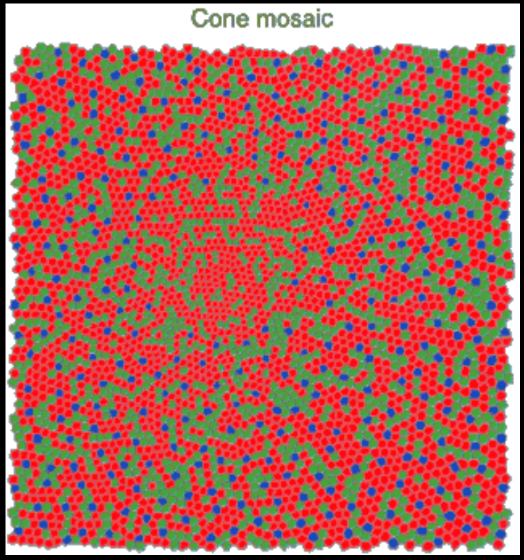
As cone vision is not activated in low illumination, we are unable to read.

Adapted from slides by A. Efros

Physiology of Color Vision

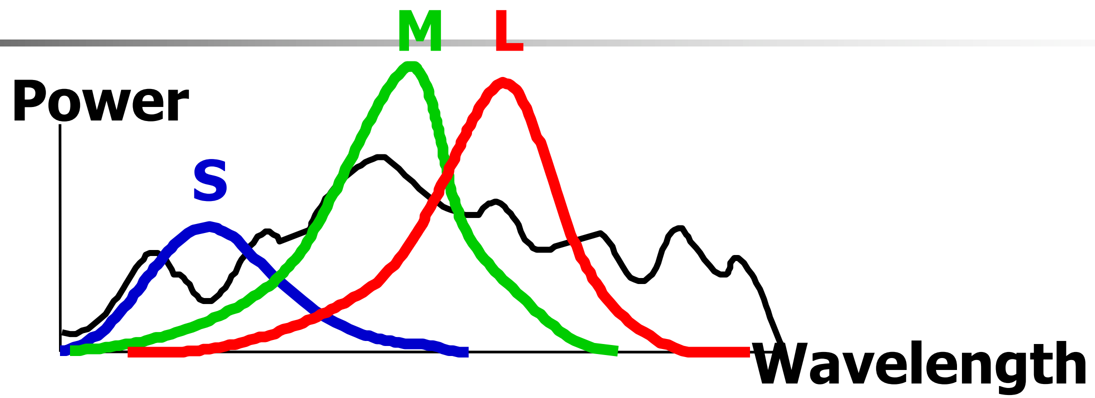
Three kinds of cones:





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

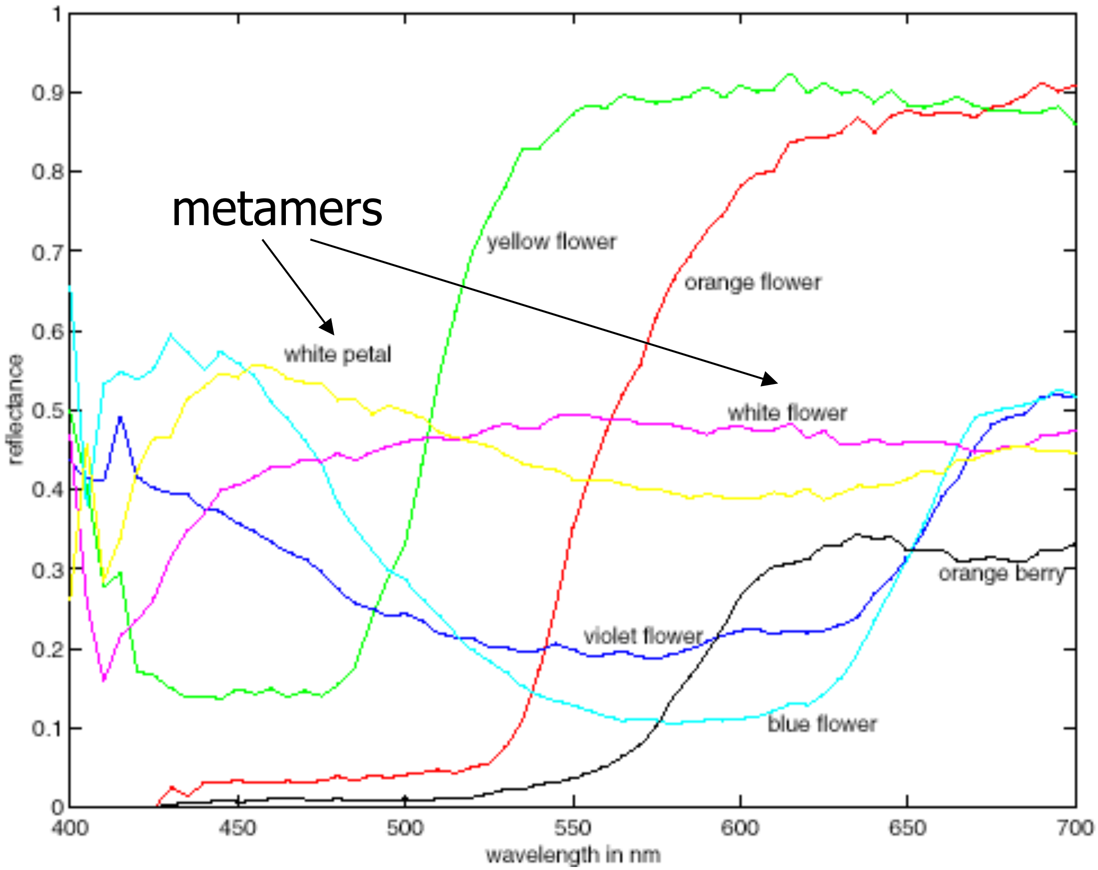
Color perception



- 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.**

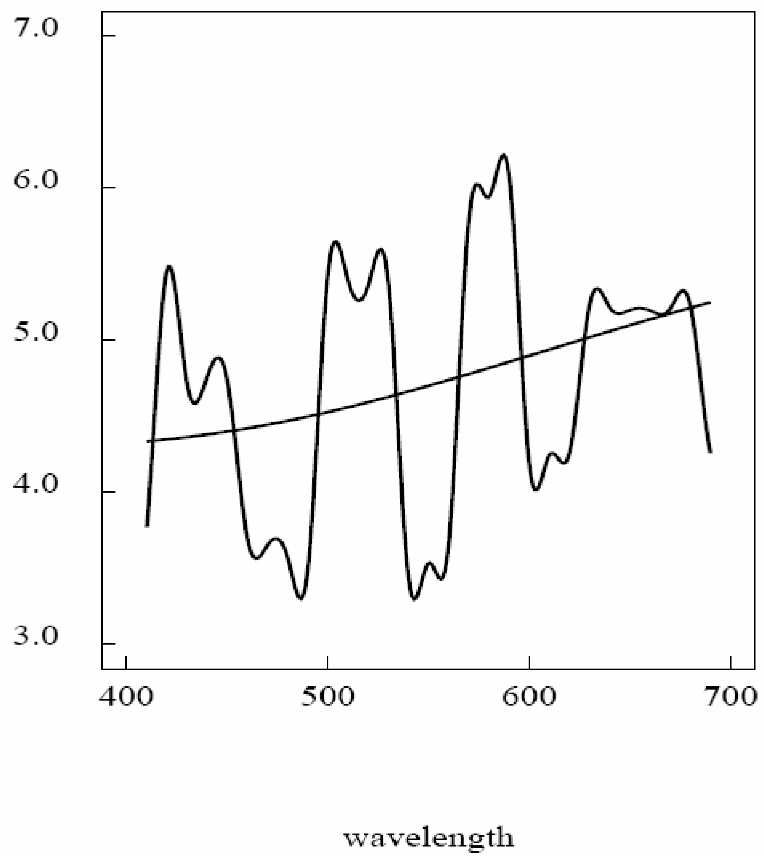
Adapted from slides by Steve Seitz.

Spectra of some real-world surfaces



Adapted from slides by Steve Seitz.

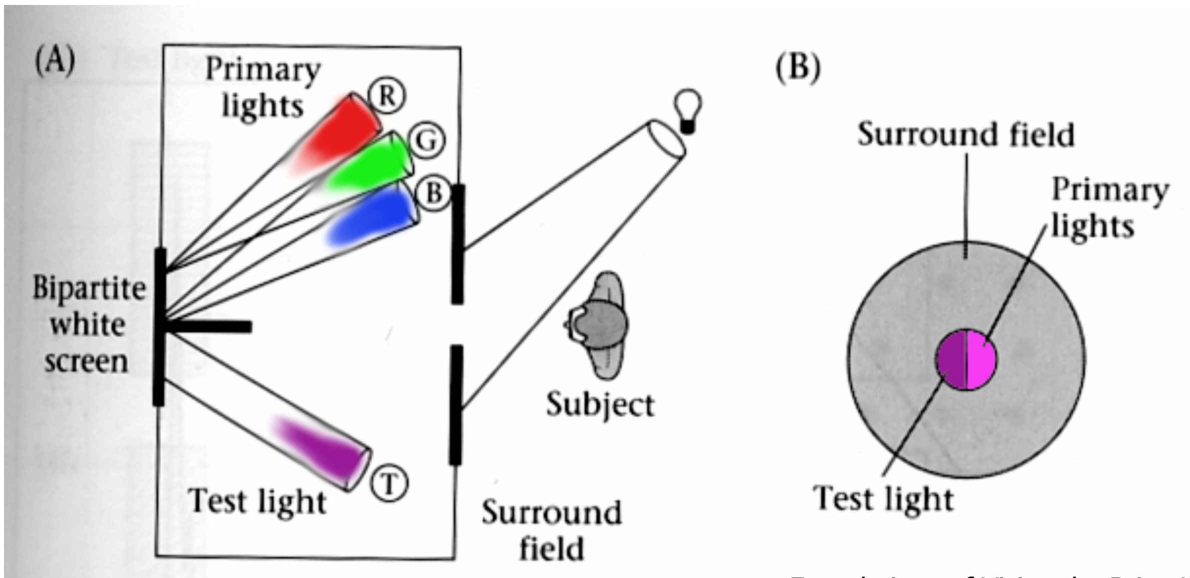
Metamers



Adapted from slides by Steve Seitz.

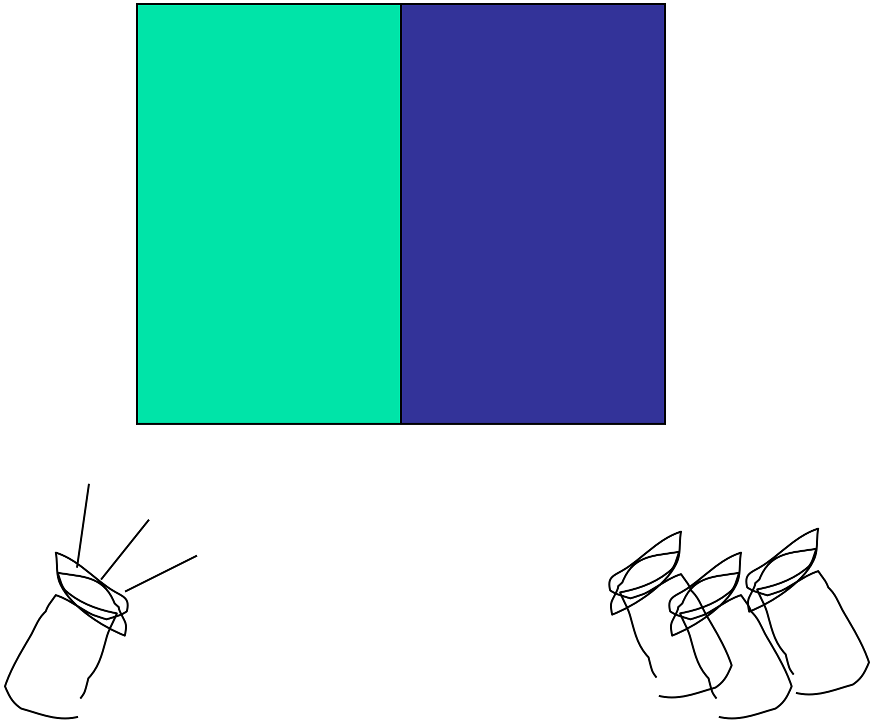
Standardizing color experience

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



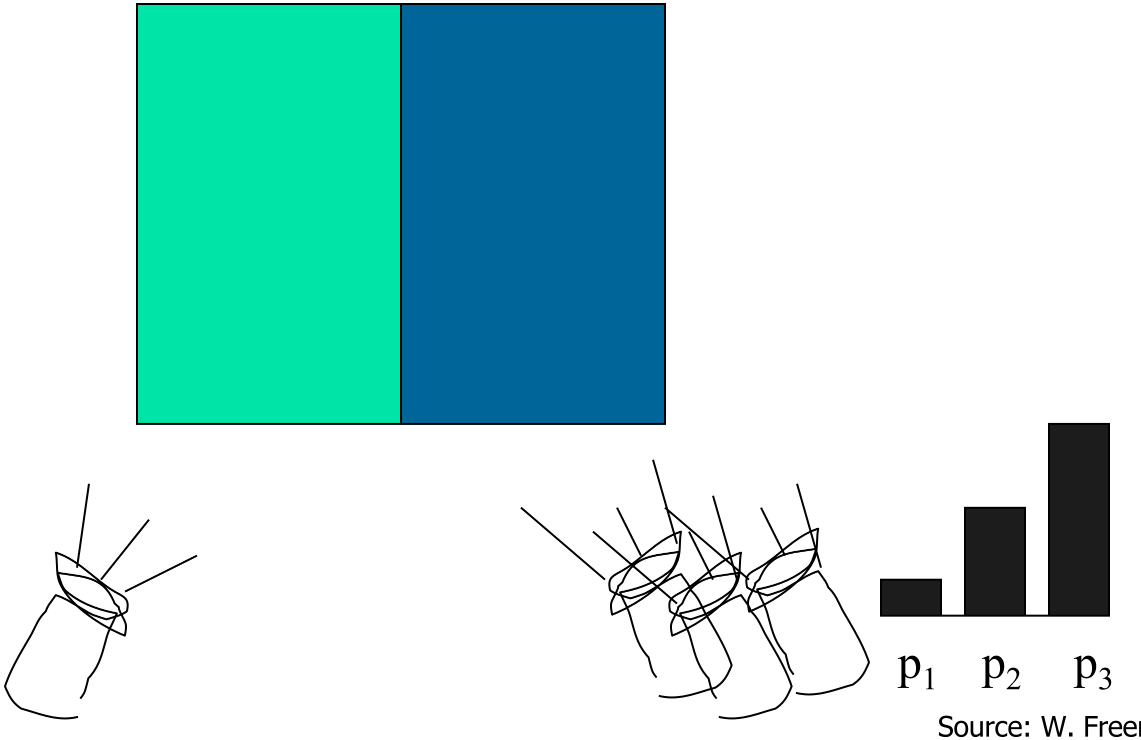
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Color matching experiment 1



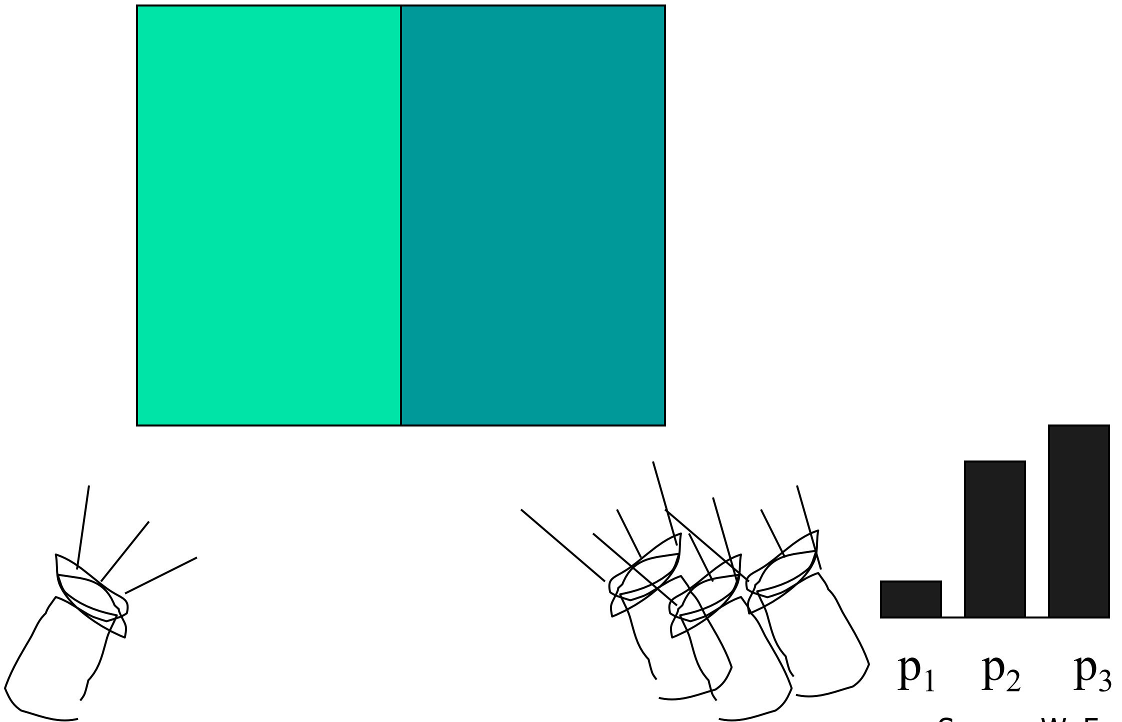
Source: W. Freeman

Color matching experiment 1



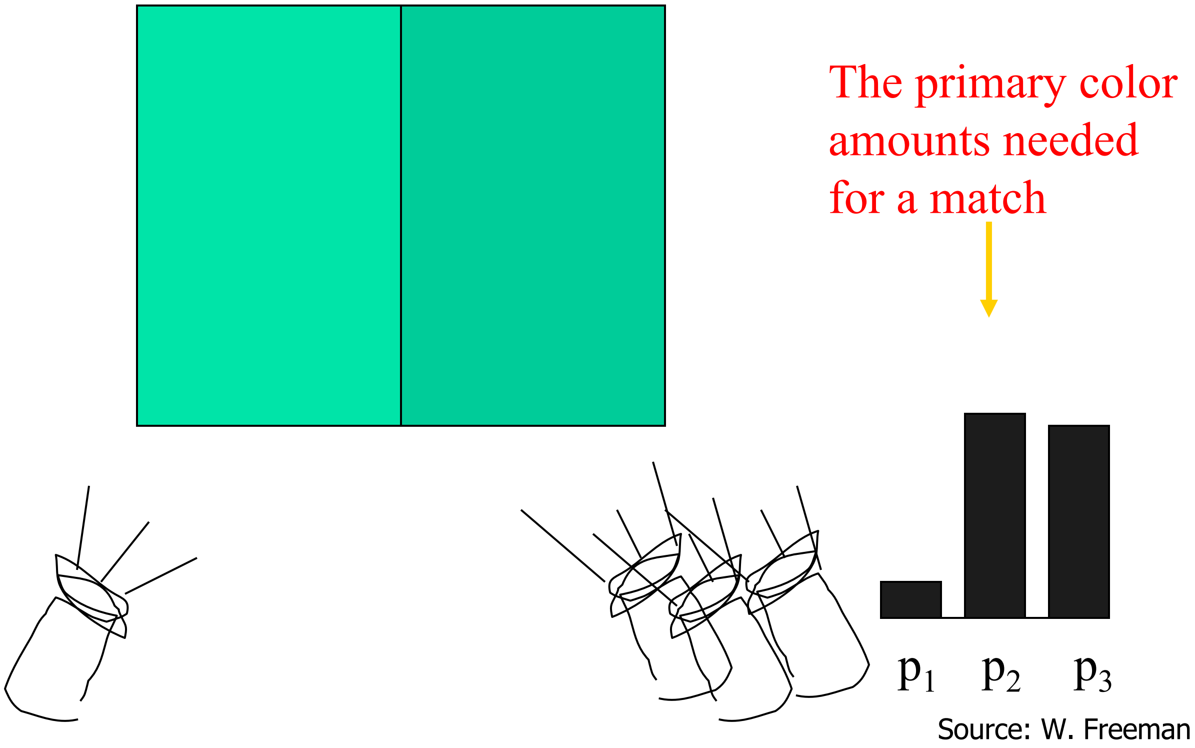
Source: W. Freeman

Color matching experiment 1

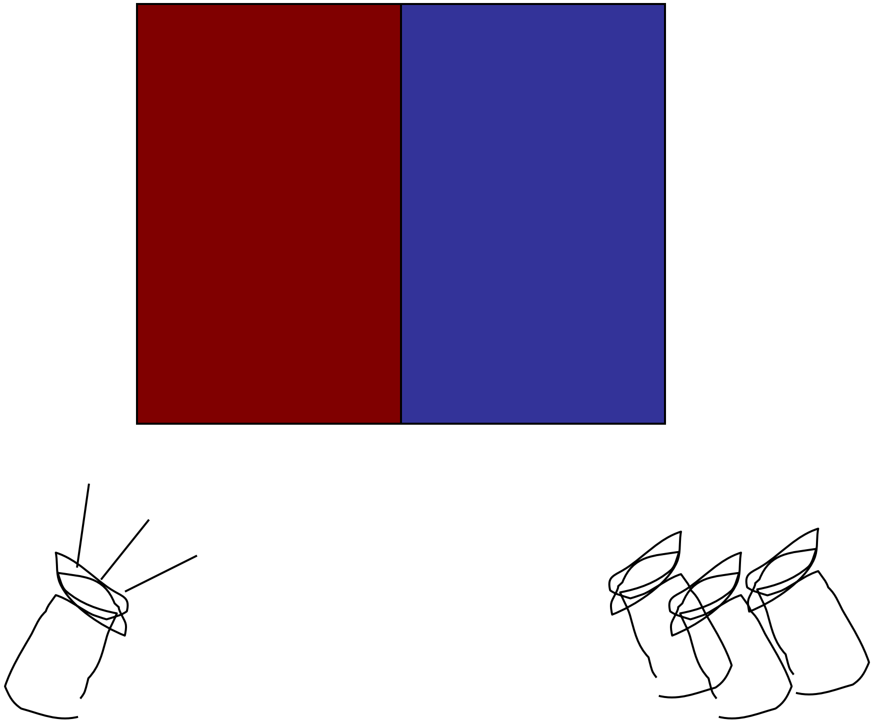


Source: W. Freeman

Color matching experiment 1

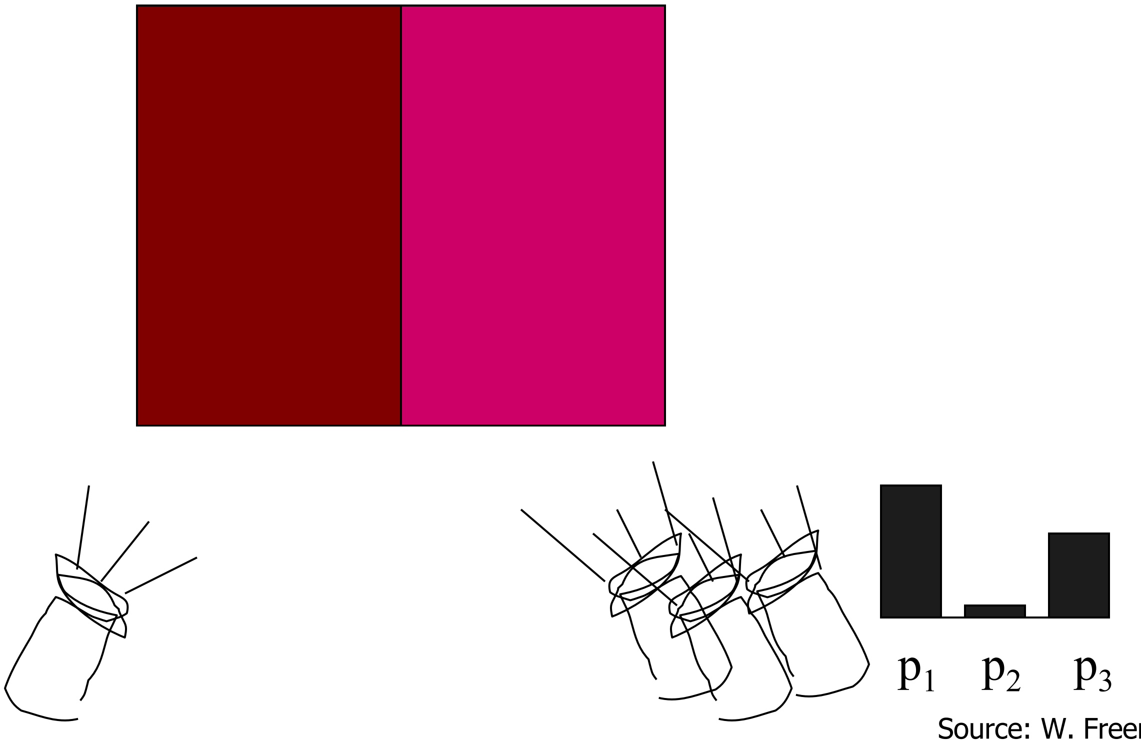


Color matching experiment 2



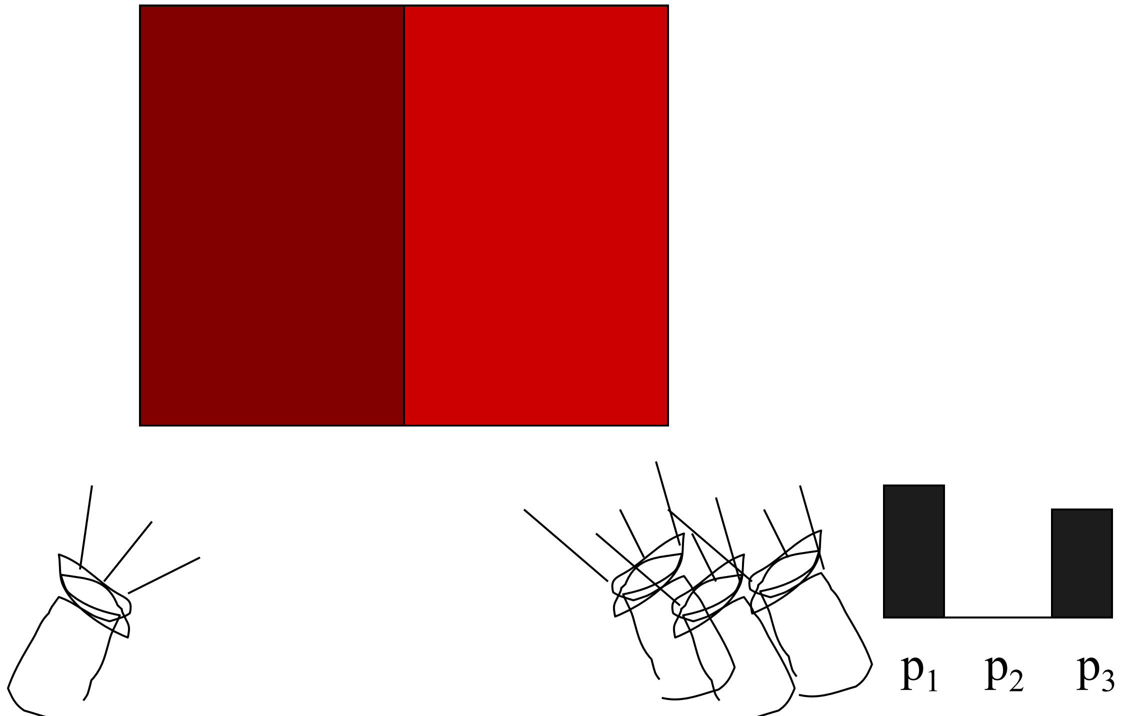
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

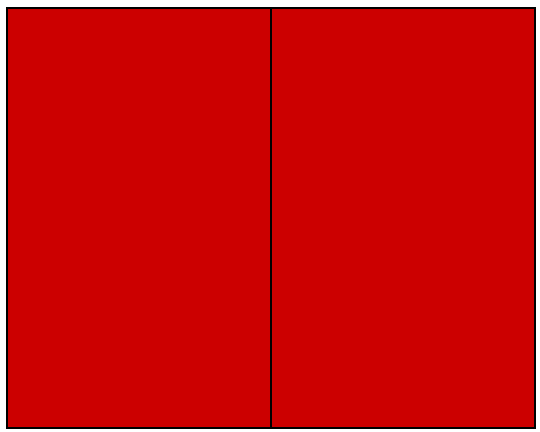
Color matching experiment 2

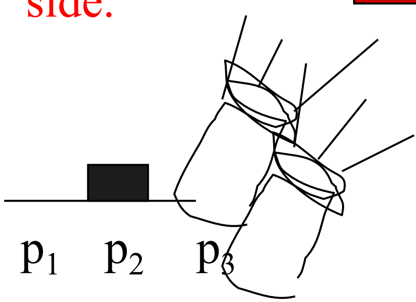


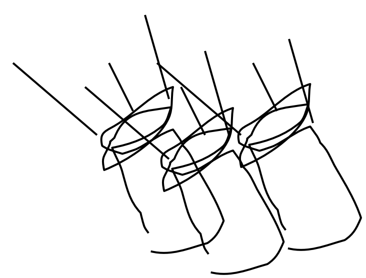
Source: W. Freeman

Color matching experiment 2

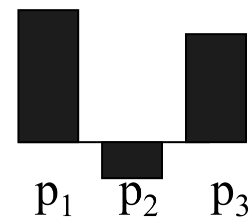
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.

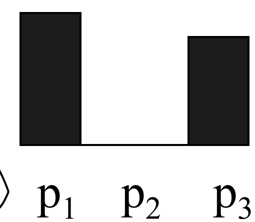






The primary color amounts needed for a match:





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 18th century (Thomas Young).

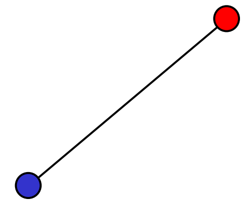
Adapted from W. Freeman

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 $kA = (ku_1)\, P_1 + (ku_2)\, P_2 + (ku_3)\, P_3$.

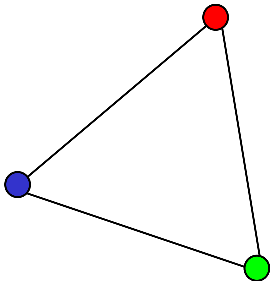
Adapted from W. Freeman

Linear color spaces



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

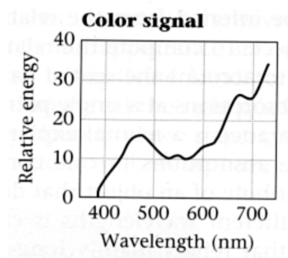
- Defined by a choice of three primaries
- The coordinates of a color are given by the weights of the primaries used to match it.
- *Matching functions*: weights required to match single-wavelength light sources.

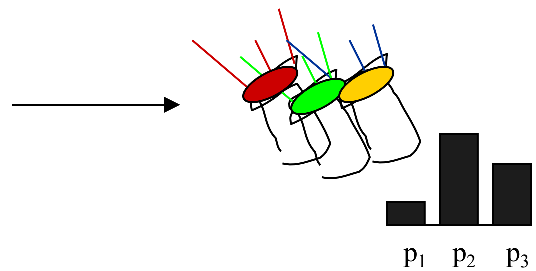


mixing three lights produces colors that lie within the triangle they define in color space.

Adapted from W. Freeman

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



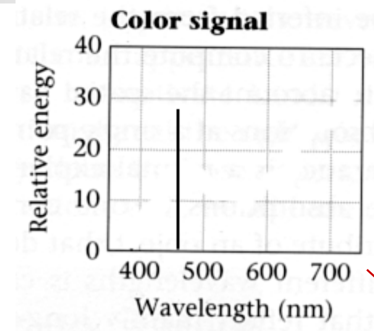


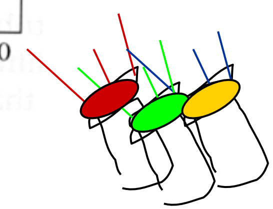
- Pick a set of primaries, $p_1(\lambda), p_2(\lambda), p_3(\lambda)$
- Measure the amount of each primary, $c_1(\lambda_0), c_2(\lambda_0), c_3(\lambda_0)$ needed to match a monochromatic light, $t(\lambda_0)$ at each spectral wavelength λ_0 (pick some spectral step size). These are the color matching functions.

Source: W. Freeman

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

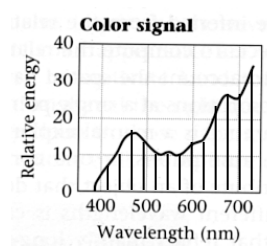
A monochromatic light of λ_i wavelength will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.





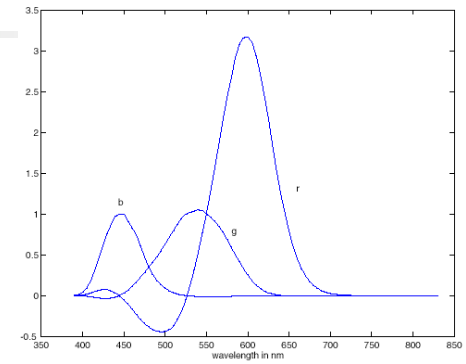
And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

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



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*.

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

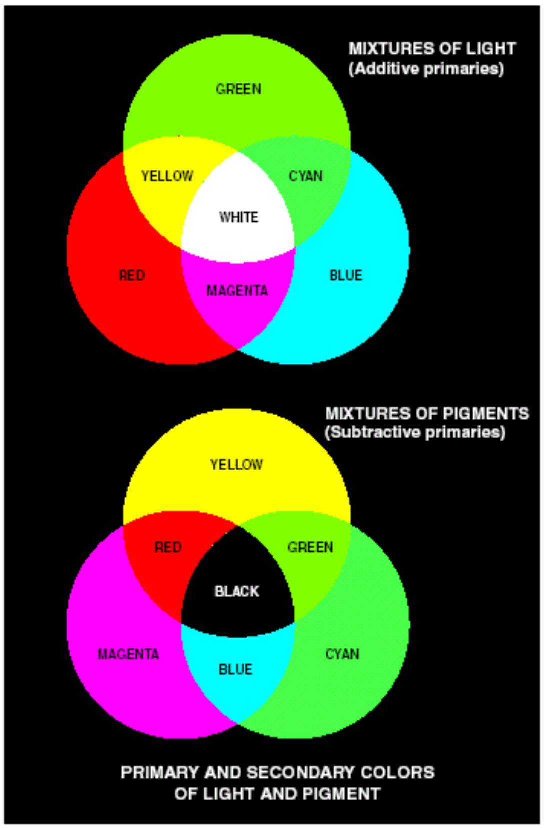
Then the amounts of each primary needed to match t are:

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

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

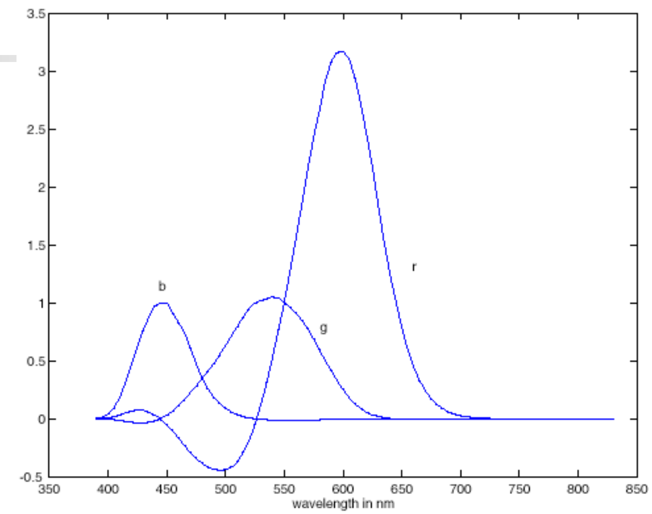
FIGURE 6.4 Primary and secondary colors of light and pigments. (Courtesy of the General Electric Co., Lamp Business Division.)

Adapted from Gonzales and Woods

Linear color spaces: RGB

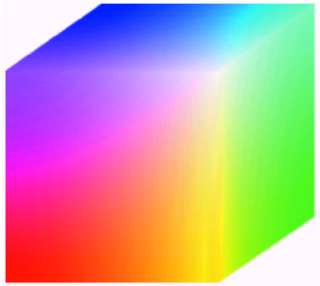
$p_1 = 645.2$ nm
$p_2 = 525.3$ nm
$p_3 = 444.4$ nm

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

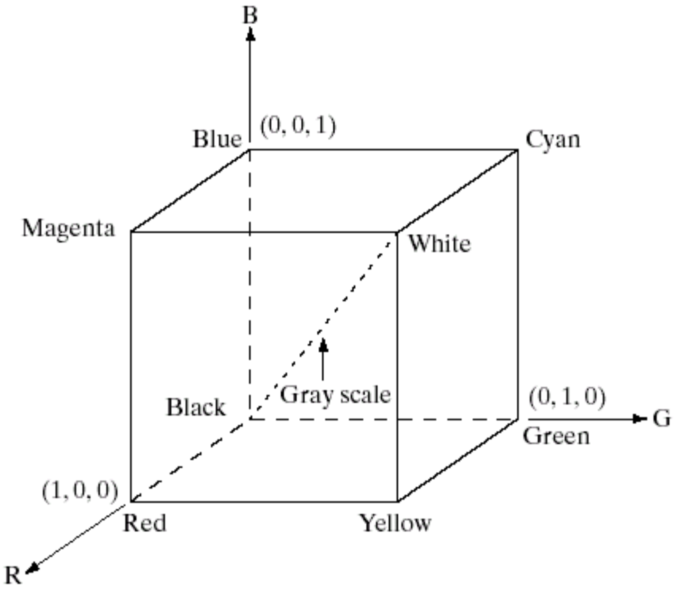


RGB matching functions

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.

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

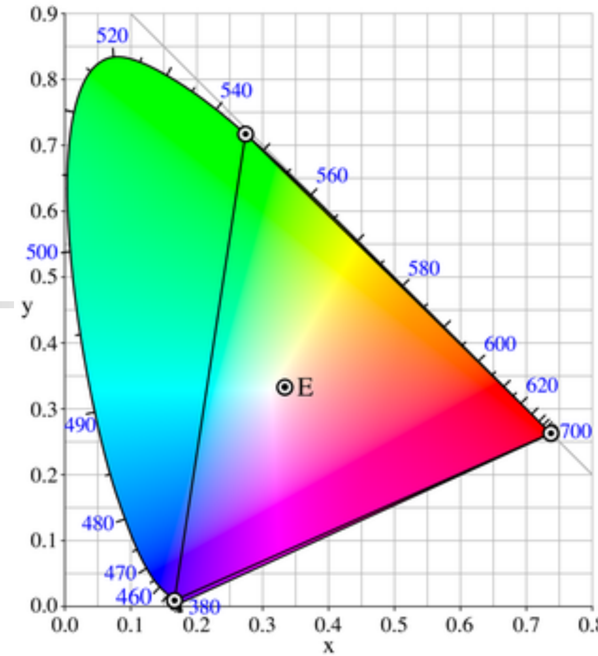
CIE chromaticity model

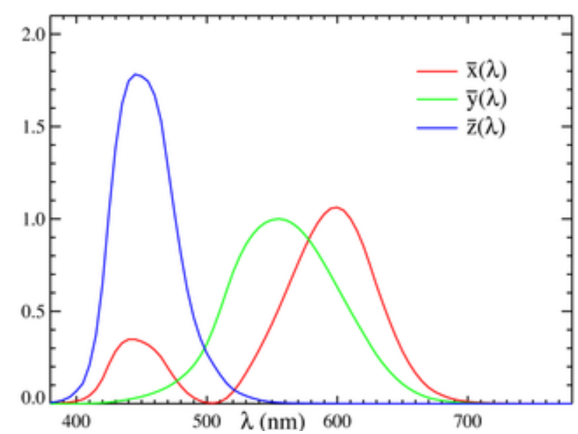
- The Commission Internationale de l'Eclairage (estd. 1931) defined 3 standard primaries: X, Y, Z that can be added to form all visible colors.
- Y was chosen so that its color matching function matches the sum of the 3 human cone responses.

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

CIE XYZ: Linear color space

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



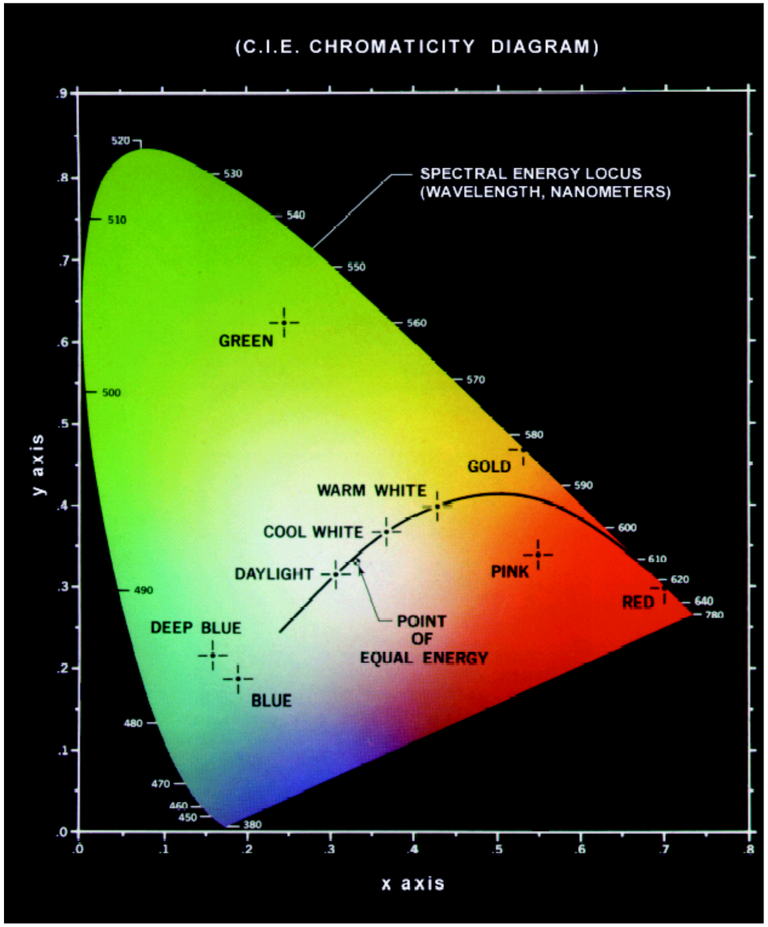


Matching functions

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

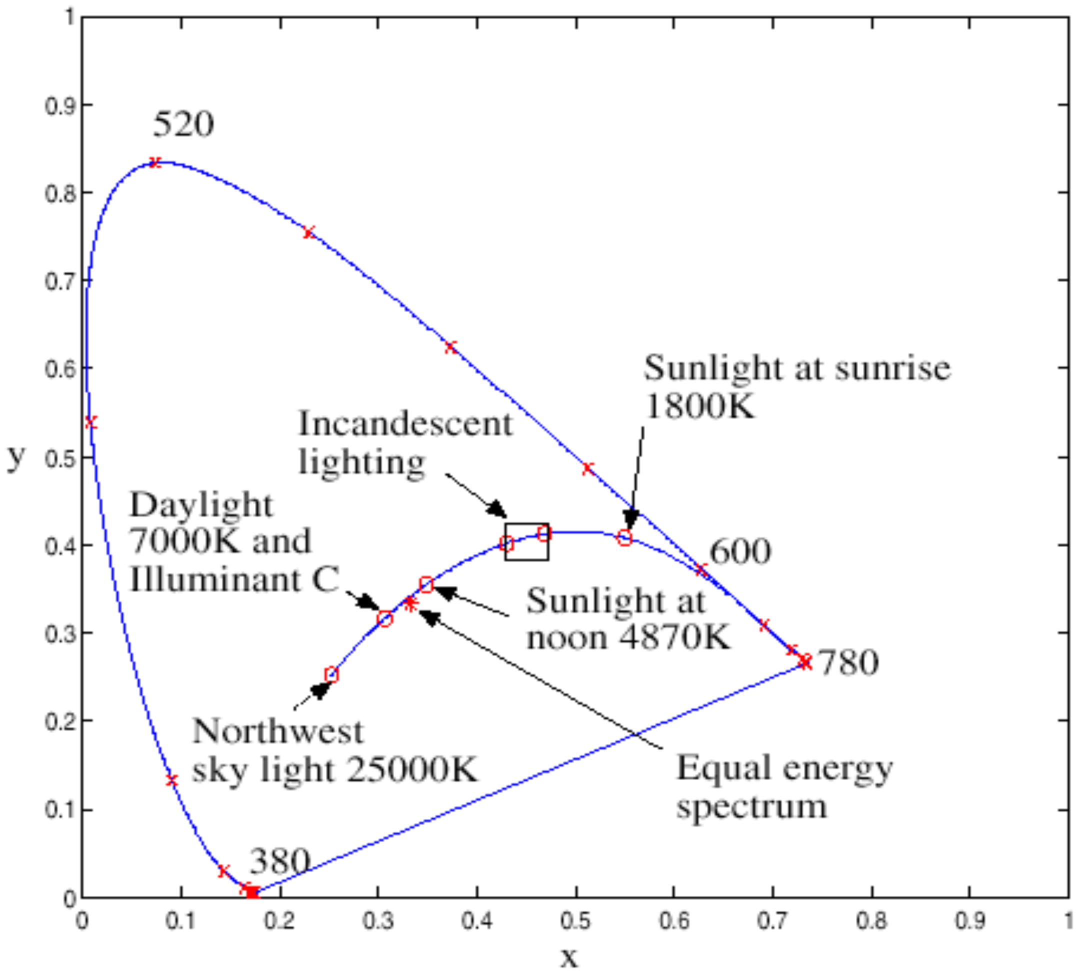
CIE chromaticity model

- 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).



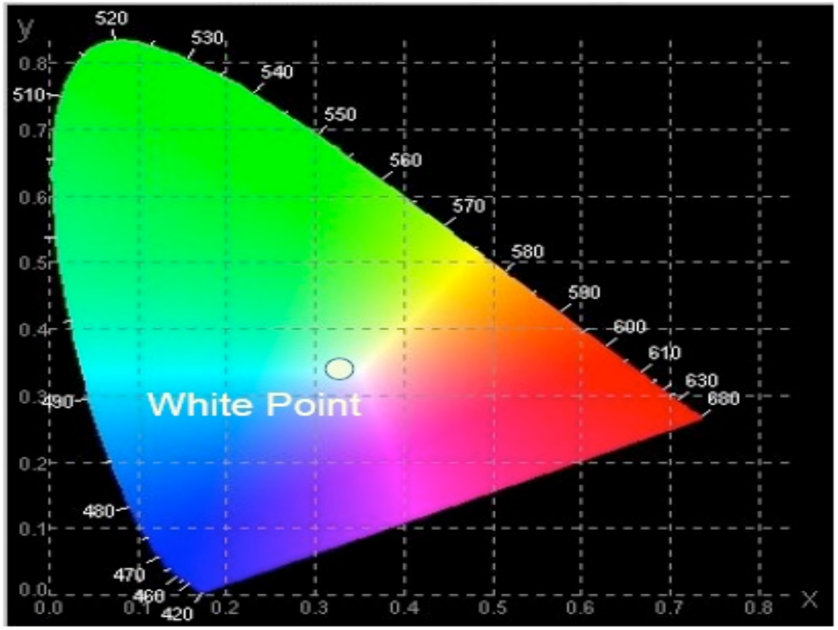
Adapted from Octavia Camps, Penn State

Spectral locus of monochromatic lights and the heated black-bodies



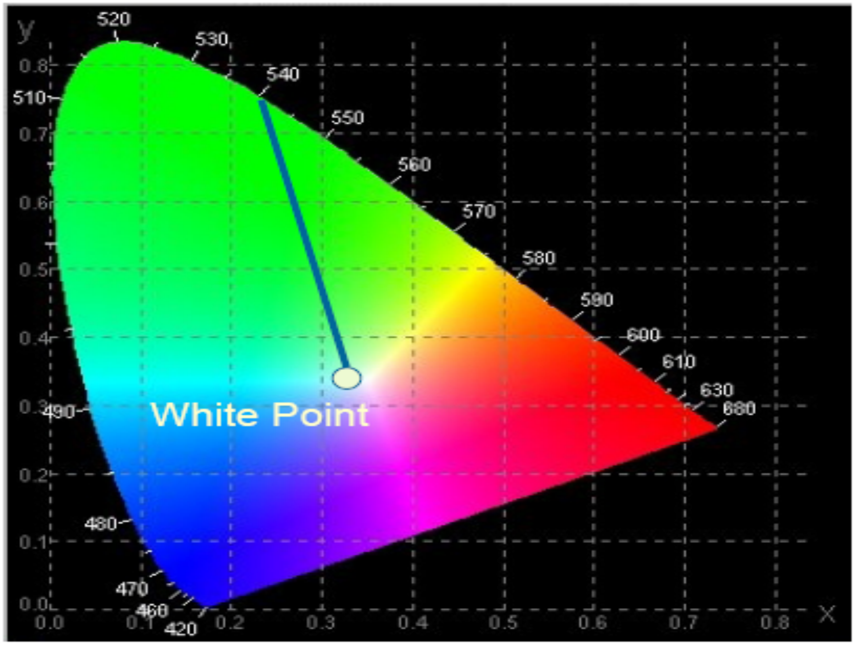
CIE Chromaticity Chart

- 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



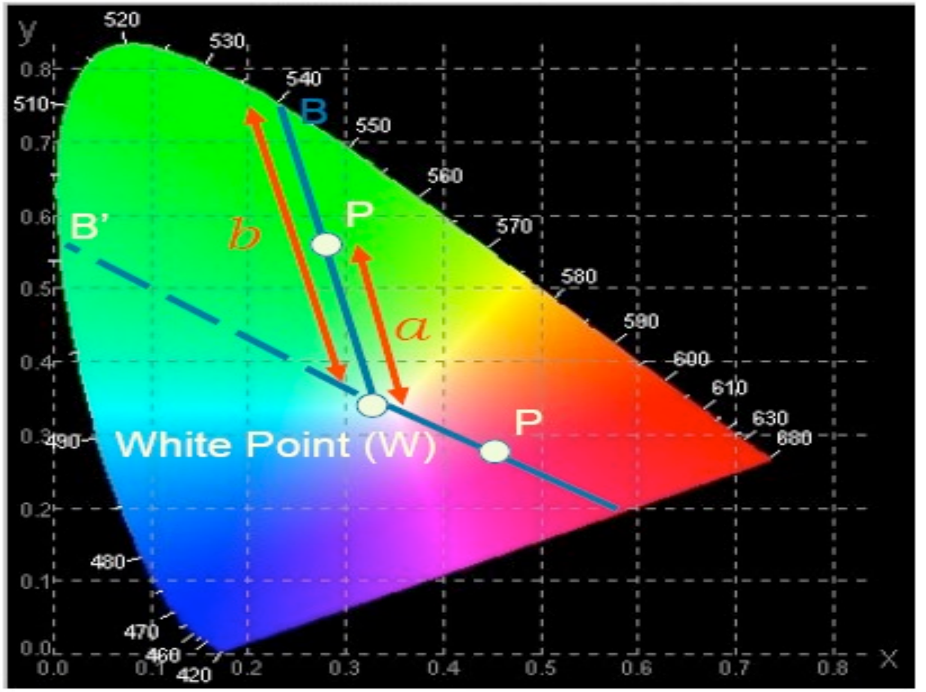
Chromaticity Chart: Saturation

- Purity (Saturation)

– How far shifted towards the spectral color?

– Ratio of *a/b*

– Purity =1 implies spectral color with maximum saturation.



Adapted from Octavia Camps, Penn State

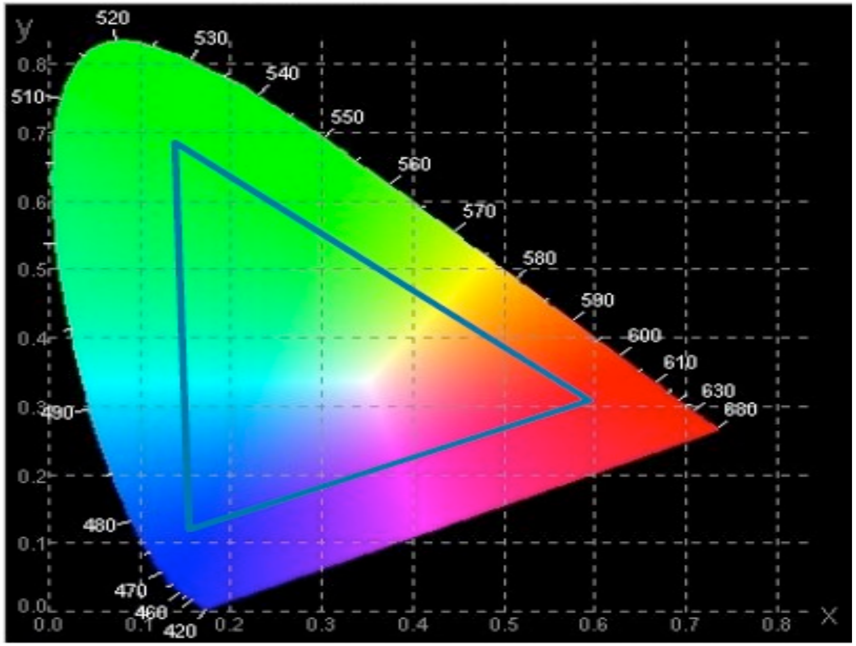
Color Reproducibility

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

–Triangle

–2D color gamut

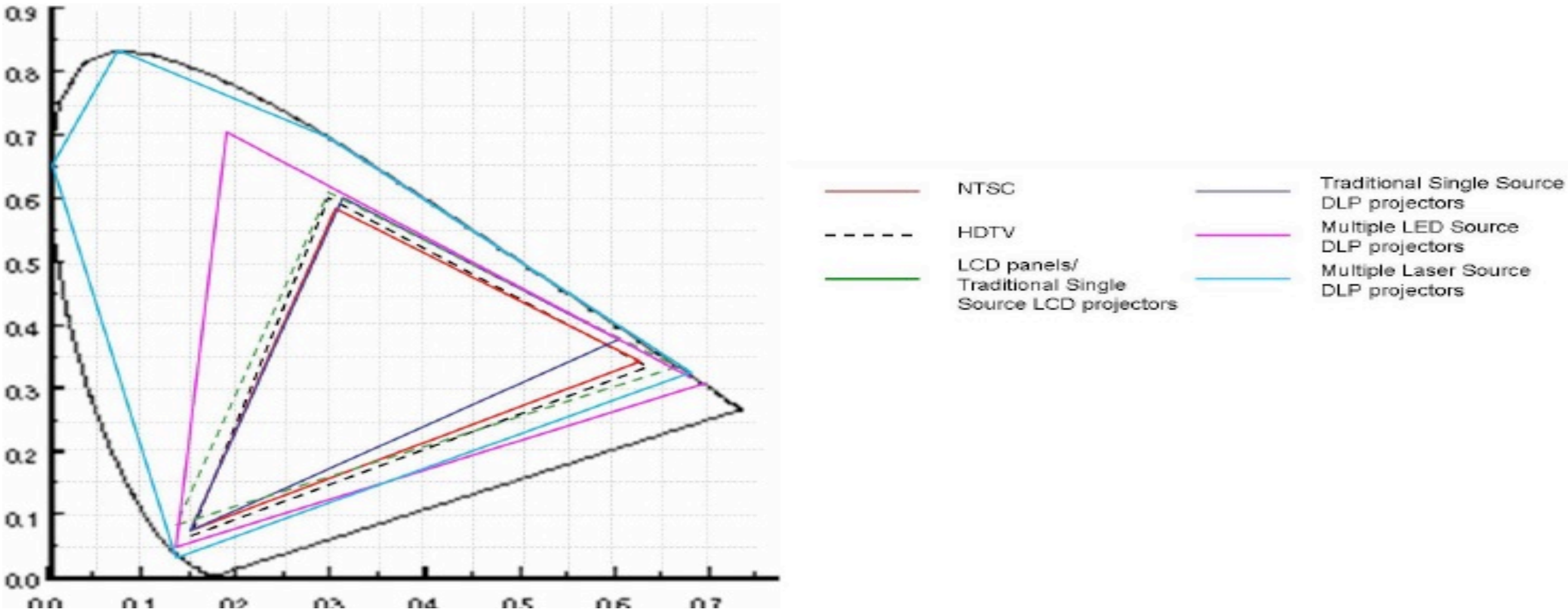
Large if using more saturated primaries.



Cannot describe brightness range reproducibility.

Adapted from Octavia Camps, Penn State

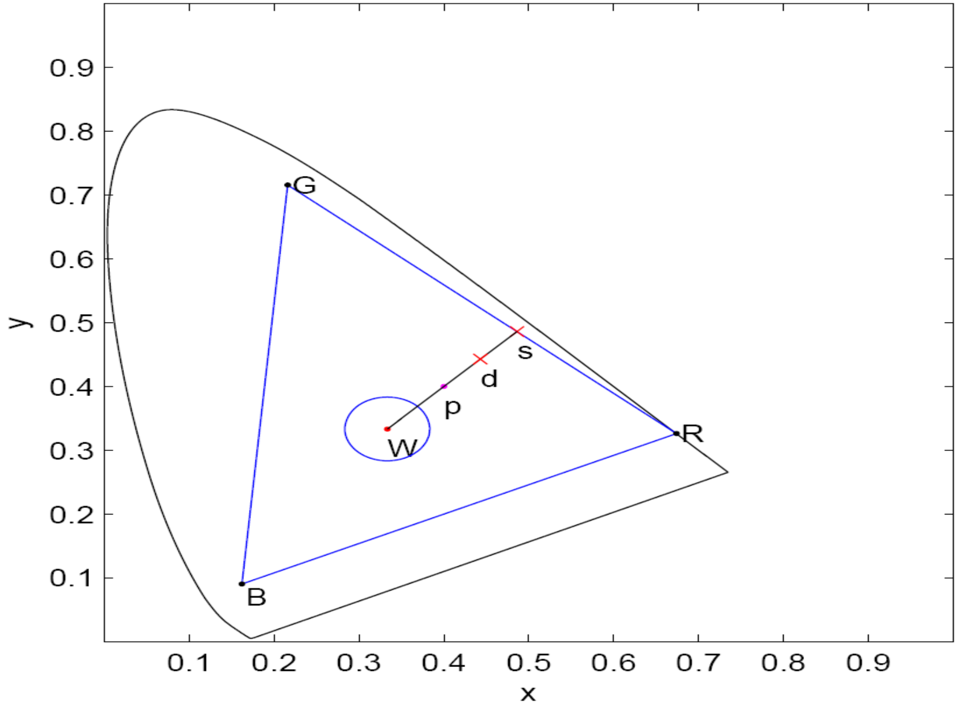
Standard Color Gamut



Adapted from Octavia Camps, Penn State

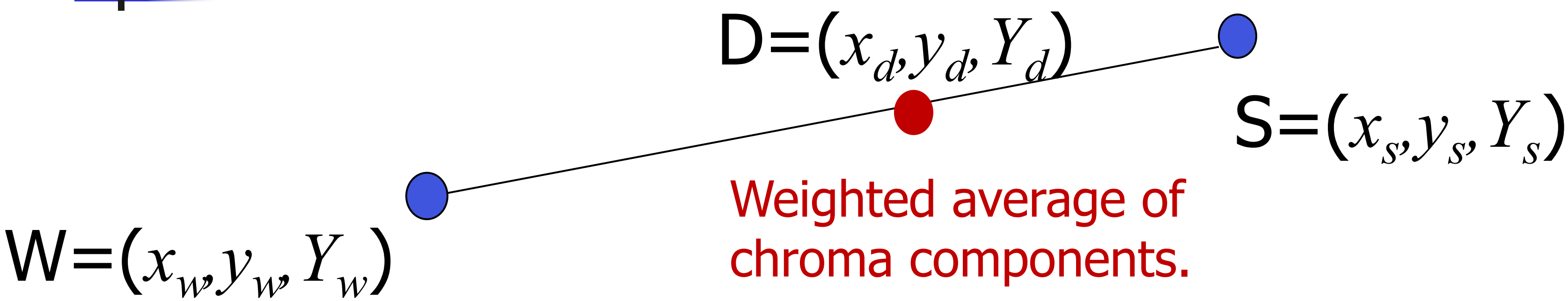
Saturation and De-saturation Operation

- 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



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

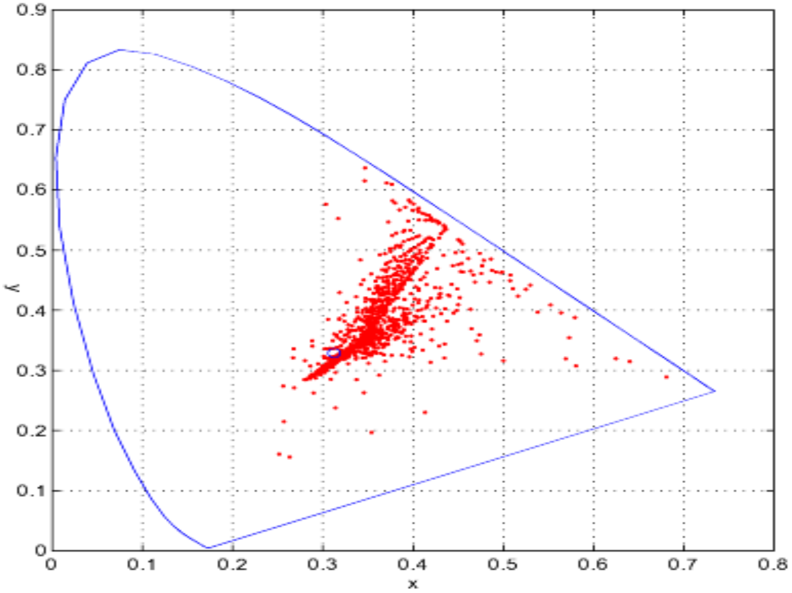
$$y_d = \frac{|Y_w| + Y_s}{\frac{|Y_w|}{y_w} + \frac{|Y_s|}{y_s}}$$

$$Y_d = |Y_w| + Y_s$$

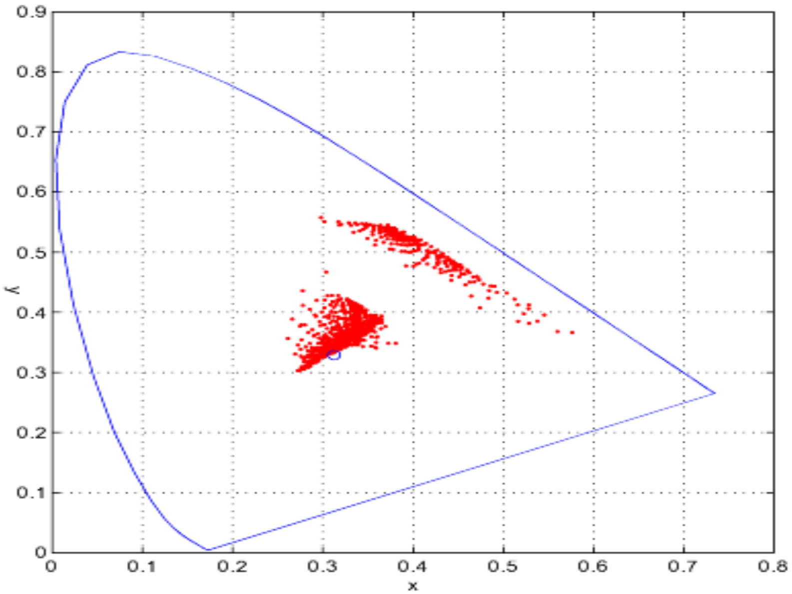
$$Y_w = kY_{avg}$$

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

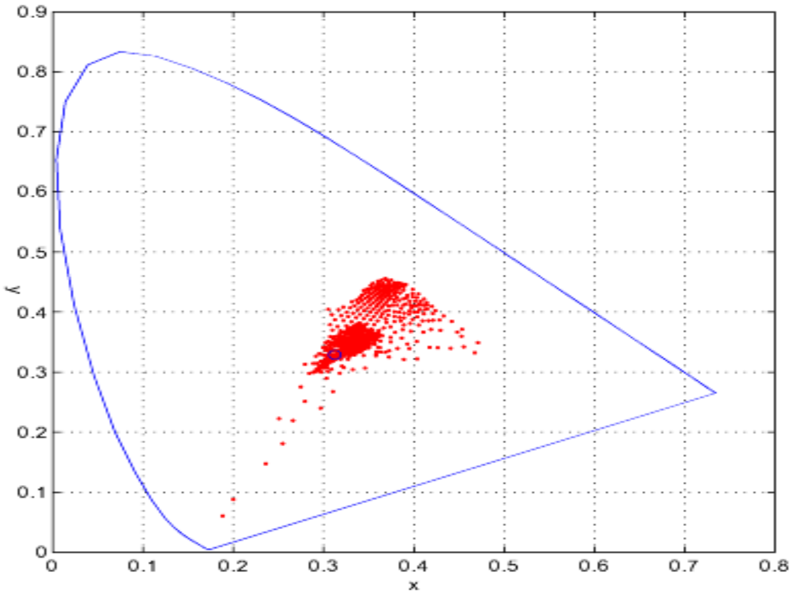
Alps - Original



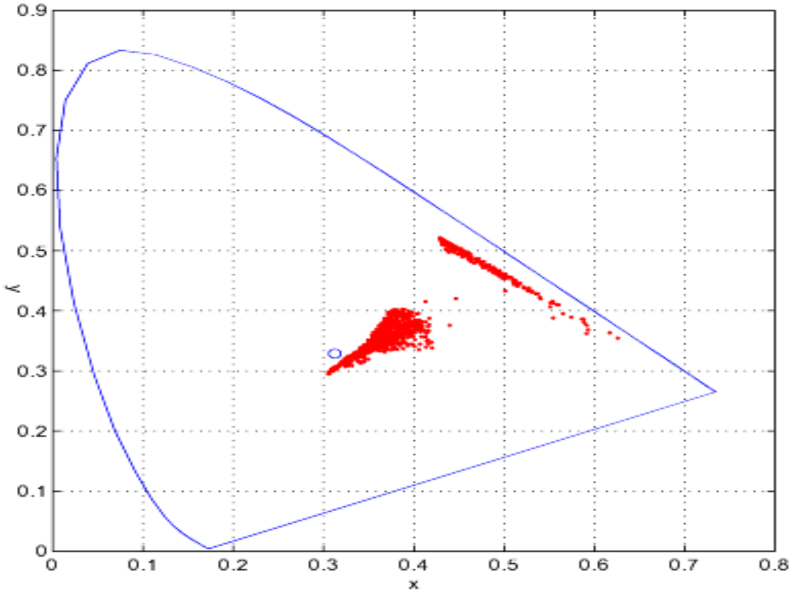
Saturated Image



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)

Ex 1

Consider the following transformation matrix of color spaces (from RGB to XYZ).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} .49 & .31 & .2 \\ .18 & .81 & .01 \\ 0 & .01 & .99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

(a) Given a color value in RGB space as (100, 80, 200) compute its corresponding point in the normalized x-y chromaticity space.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} .49 & .31 & .2 \\ .18 & .81 & .01 \\ 0 & .01 & .99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Ans. 1 (a)

(X, Y, Z)

$$\begin{bmatrix} 113.8 \\ 84.8 \\ 198.8 \end{bmatrix} = \begin{bmatrix} .49 & .31 & .2 \\ .18 & .81 & .01 \\ 0 & .01 & .99 \end{bmatrix} \begin{bmatrix} 100 \\ 80 \\ 200 \end{bmatrix}$$

x= X / (X+Y+Z)=113.8/397.4=0.2864

y= Y / (X+Y+Z)=84.8/397.4=0.2134

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} .49 & .31 & .2 \\ .18 & .81 & .01 \\ 0 & .01 & .99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

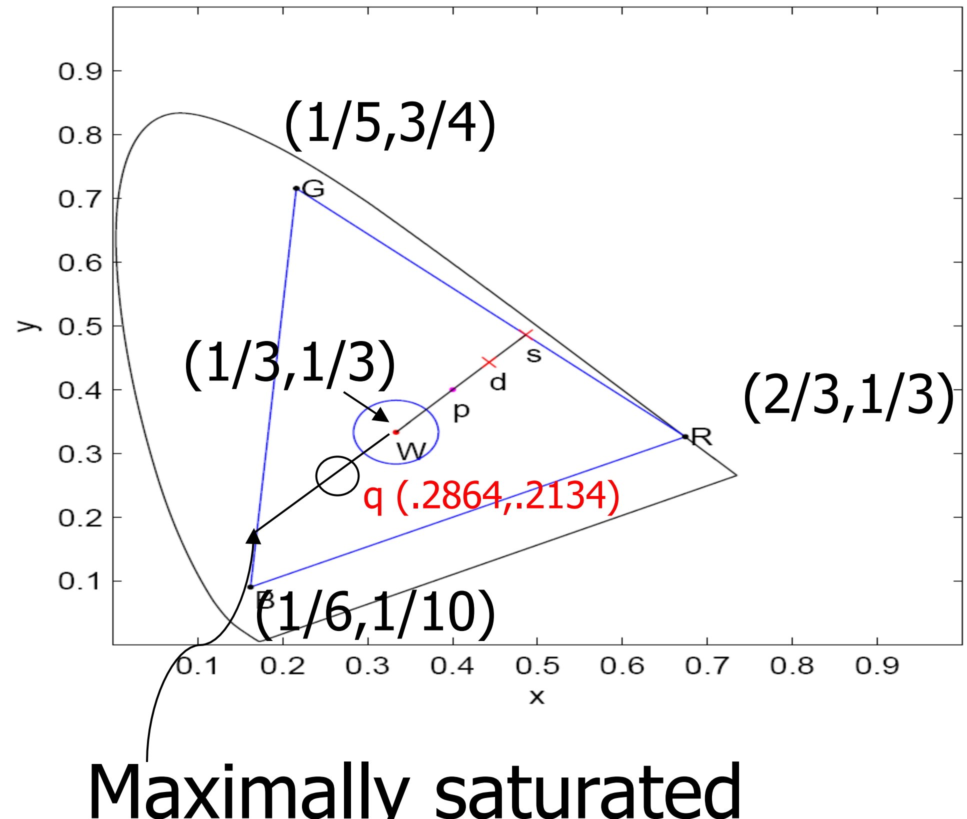
Ex. 1 (b)

Given the coordinates in the normalized x-y chromaticity space of three primary colors as (2/3, 1/ 3), (1/5, 3/4), and (1/6, 1/10), compute the corresponding maximally saturated color in the RGB space preserving the same hue and intensity for the above point.

Ans. 1(b)

- Move radially to the gamut edge → Maximum Saturation given a hue.

Intersection of point between the line formed by an edge of the triangle and wq.



Ans. 1(b)

Use projective space concepts.

First check for BG and wq

BG=(1/6 1/10 1) x (1/5 3/4 1)

= (-0.6500   0.0333   0.1050)

wq = (1/3 1/3 1) x (.2864 .2134 1)

=(0.1199   -0.0469   -0.0243)

Intersection point

= BG x wq

=(-0.0041   0.0032   -0.0265)

Not a point within the x-y space.

In non-homogeneous coordinates: (.1553, -.1216)

Ans. 1(b)

Use projective space concepts.

Next check for BR and wq (= (.1100 -.0469 -.0243))

BR=(1/6 1/10 1) x (2/3 1/3 1)

= (-0.2333   0.5000   -0.0111)

Intersection point = BR x wq

=(0.0127   0.0070   0.0490)

Maximally saturated point in x-y.

In non-homogeneous coordinates: (.2592, .1429)

$$\begin{bmatrix}113.8\\84.8\\198.8\end{bmatrix}=\begin{bmatrix}.49 & .31 & .2\\.18 & .81 & .01\\0 & .01 & .99\end{bmatrix}\begin{bmatrix}100\\80\\200\end{bmatrix}$$

Ans. 1(b)

Inverse

Maximally saturated point in x-y. (.2592, .1429)

Convert x-y to XYZ (keeping the intensity same)

X=(397.4) x .2529=103.0061

Y=(397.4) x .1429 = 56.7885

Z=397.4 – (103.0061+56.7885)=237.6054

XYZ to RGB transformation matrix: $\begin{bmatrix}2.37 & -.90 & -.47\\-.52 & 1.44 & .09\\.01 & -.01 & 1.01\end{bmatrix}$

Convert from XYZ to RGB: (81.42 49.06 239.51)

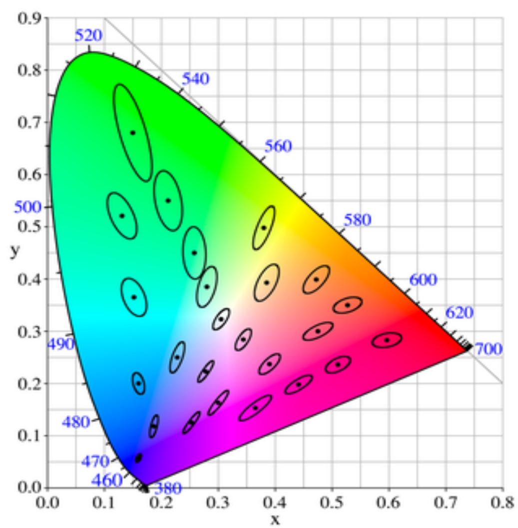
⇩

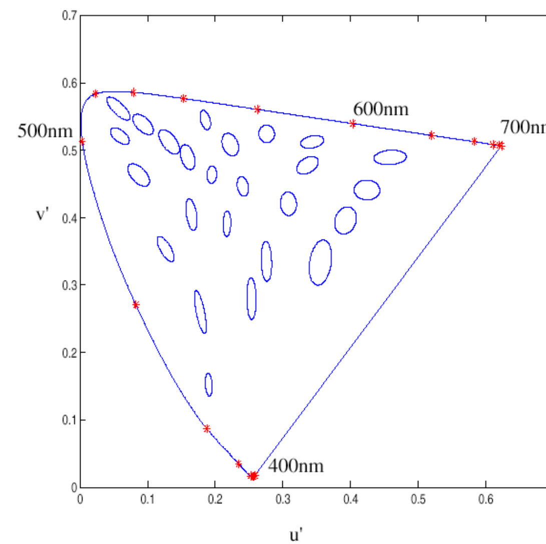
(81, 49, 240)

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.

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

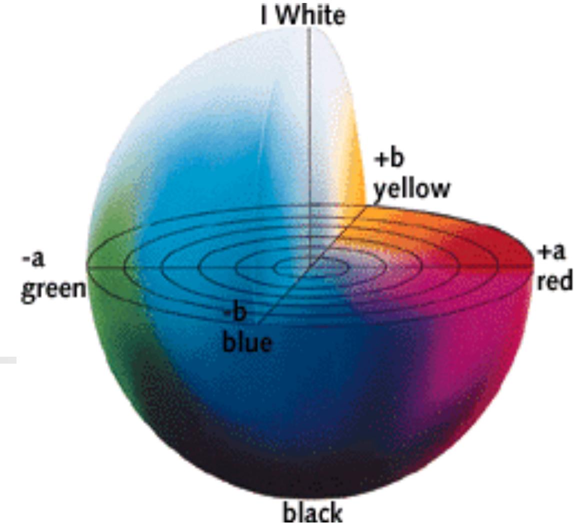




McAdam ellipses:
Just noticeable differences in color

Adapted from Linda Shapiro, U of Washington

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

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

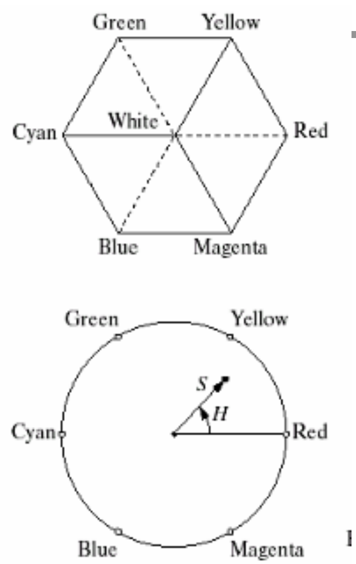
- Have better compression properties.
- Luminance Y is encoded using more bits than chrominance values I and Q (humans are more sensitive to Y than I and Q).
- Luminance used by black/white TVs.
- All 3 values used by color TVs.

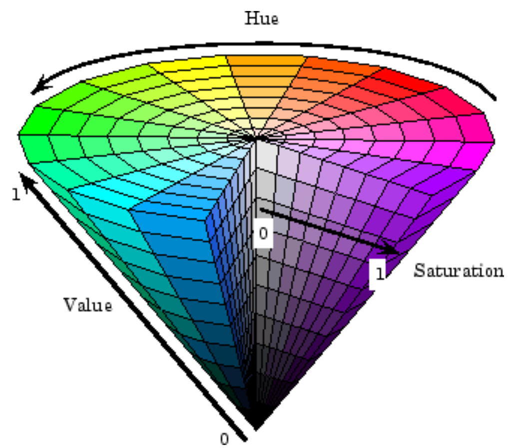
YCbCr space

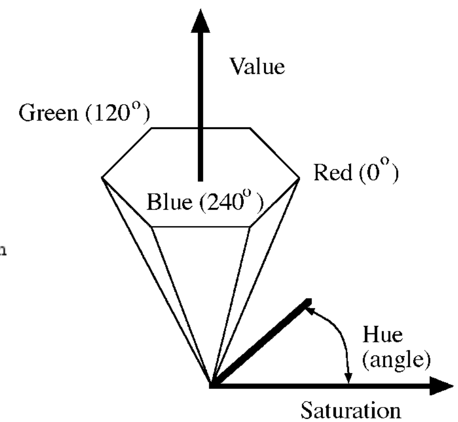
$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.256 & 0.502 & 0.098 \\ -0.148 & -0.290 & 0.438 \\ 0.438 & -0.366 & -0.071 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 0 \\ 128 \\ 128 \end{bmatrix}$$

- 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.

Nonlinear color spaces: HSV







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

HSV model

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

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

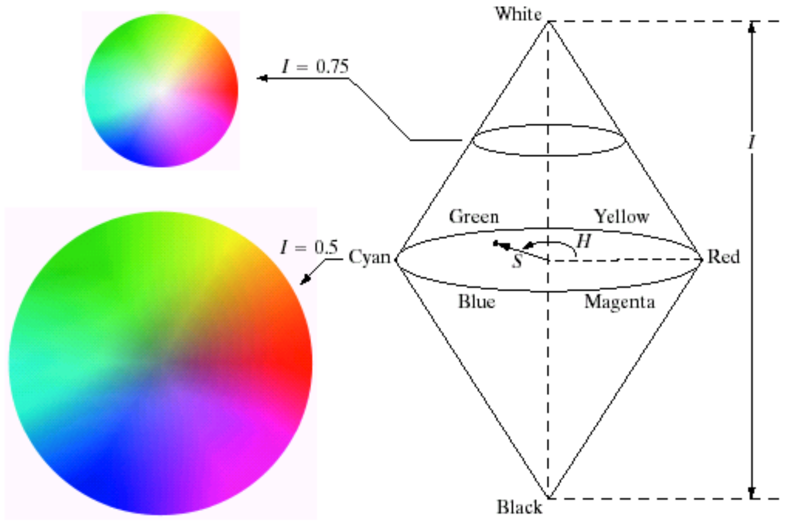
$$S = 1 - \frac{\min(R, G, B)}{I}$$

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

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

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).



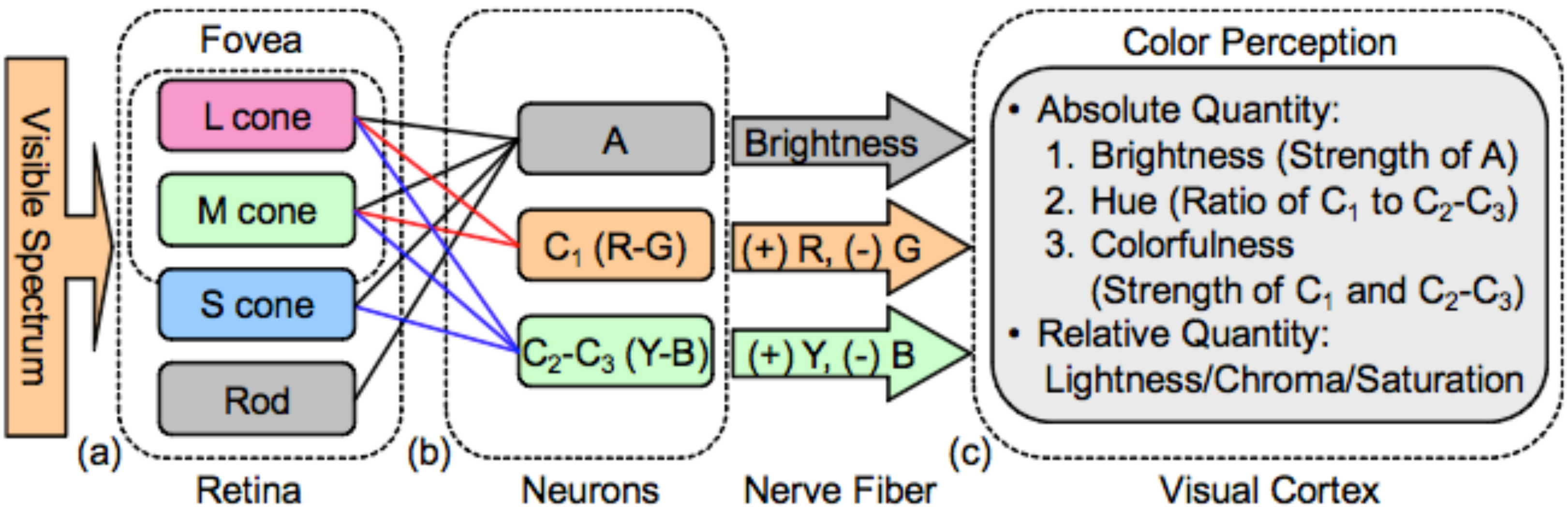
Adapted from Gonzales and Woods

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.

Lighting conditions

- The lighting conditions of the scene have a large effect on the colours recorded.

Image taken lit by a flash.

Image taken lit by a tungsten lamp.

Adapted from Gonzales and Woods

Example images of the same scene acquired under different lighting conditions

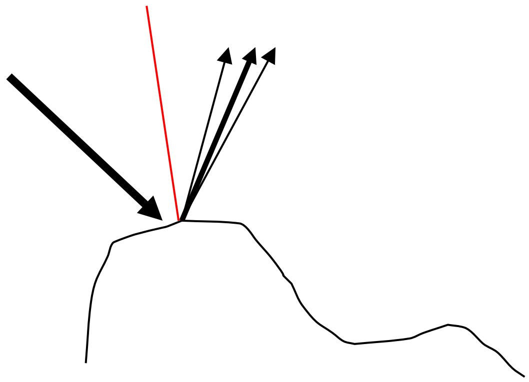
Adapted from Gonzales and Woods

Dealing with Lighting Changes

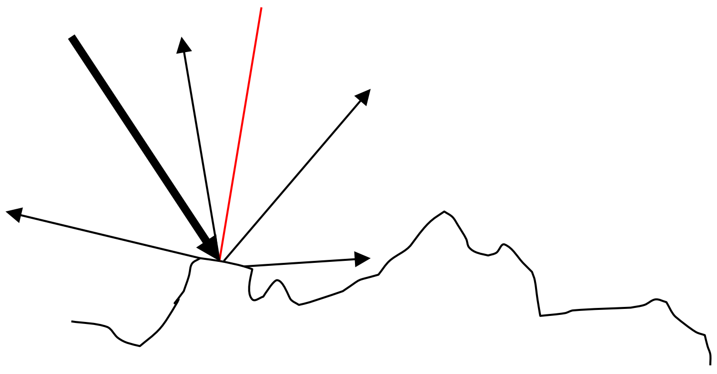
- Knowing just the RGB values is not enough to know everything about the image.
  - The R, G and B primaries used by different devices are usually different.
- For scientific work, the camera and light source should be calibrated.
- For multimedia applications, this is more difficult to organise:
  - Algorithms exist for estimating the illumination colour.

Two types of reflection

- Two components of reflected light
  - Diffuse: product of spectral power density and the reflectance curve.
  - Specular: The same color as source.
  - A weighted sum of these two.



Specular



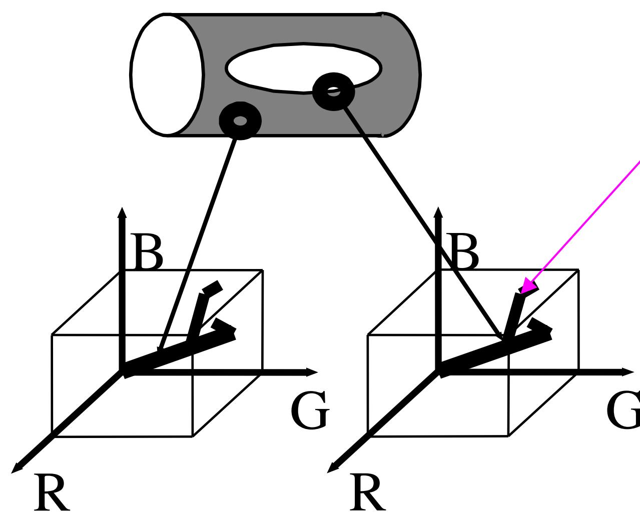
Diffused

Viewing colored objects

- Assume diffuse+specular model
- Specular
  - Colour of the light
    - on dielectric objects.
    - on metals.
- Diffuse
  - depends on both illuminant and surface.
  - Human vision capable of disentangling effects of varying illumination (colour constancy).

Finding Specularities

- a characteristic dog leg in the histogram of receptor responses
  - in a patch of diffuse surface: a color multiplied by different scaling constants (surface orientation)
  - in the specular patch: a new color → a "dog-leg" results.



Color Constancy

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

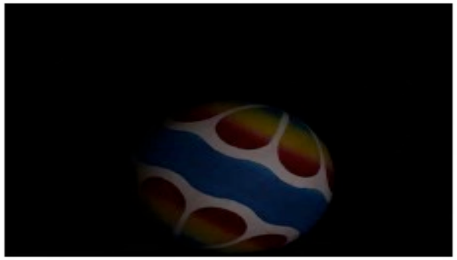
Surface Reflectance Spectrum

Objects present in the scene.

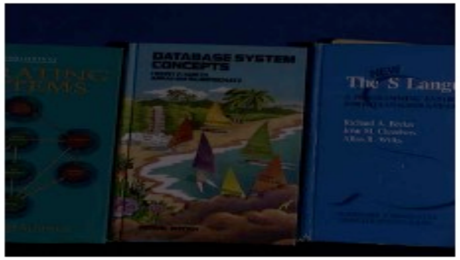
Spectral Energy of Light Sources.

Spectral Sensitivity of sensors.

Same Scene Captured under Different Illumination



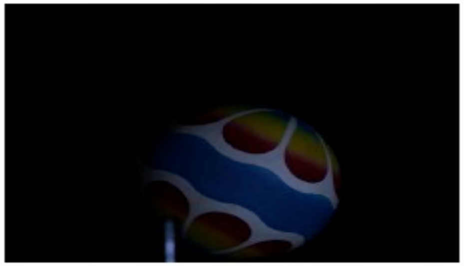
ball



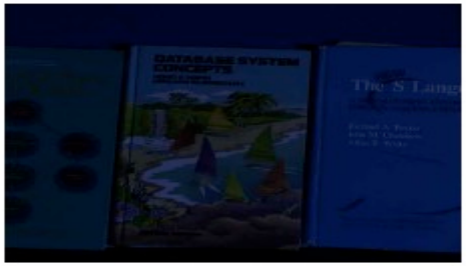
books

macbeth

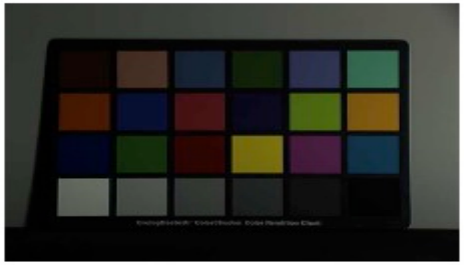
Can we transfer colors from one illumination to another one?



ball (solux-4100)



books (syl-50mr16q+3202)



macbeth (ph-ulm)

Computation of Color Constancy

- Deriving an illumination independent representation.
  - Estimation of SPD of Light Source.

E(λ) → <R, G, B>

  - Color Correction

    - Diagonal Correction.

$$k_r = \frac{R_d}{R_s} \qquad k_g = \frac{G_d}{G_s} \qquad k_b = \frac{B_d}{B_s} \qquad f = \frac{R + G + B}{k_r R + k_g G + k_b B}$$

$$R = f k_r R \qquad G = f k_g G \qquad B = f k_b B$$

Different Approaches

- Gray World Assumption (Buchsbaum (1980), Gershon et al. (1988))

$$\langle R, G, B \rangle \equiv \langle R_{avg}, G_{avg}, B_{avg} \rangle$$

- White World Assumption (Land (1977))

$$\langle R, G, B \rangle \equiv \langle R_{max}, G_{max}, B_{max} \rangle$$

Edge based color constancy computation

- Extending pixel-based methods to incorporate derivative information

Color image component (channel c)

Order of derivative

Scale

$$\mathbf{e}^{n,p,\sigma} = \left(\int \left| \underbrace{\frac{\partial^n f_{c,\sigma}(\mathbf{x})}{\partial \mathbf{x}^n}}_{\text{Minkowski's norm}} \right|^p d\mathbf{x} \right)^{\frac{1}{p}} = k e_c$$

Type of norm

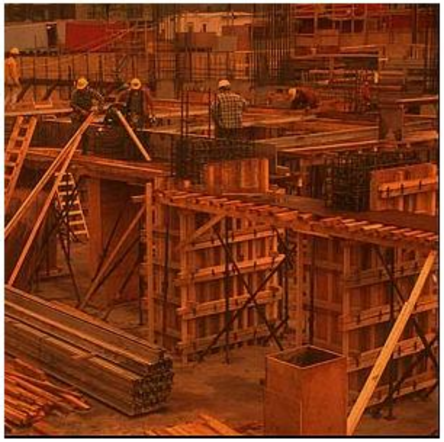
Select from a set of Canonical Illuminants

- Observe distribution of points in 2-D Chromatic Space.
- Assign SPD of the nearest illuminant.

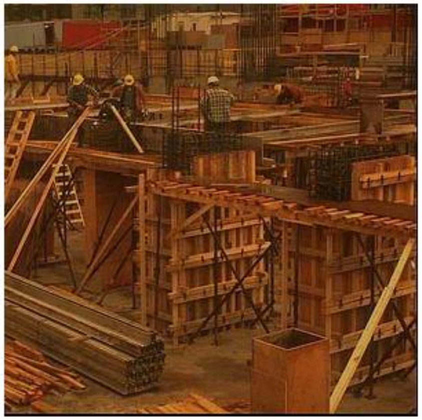
- Gamut Mapping Approach (Forsyth (1990), Finlayson (1996))
  - Existence of chromatic points.
- Color by Correlation (Finlayson et. al. (2001))
  - Relative strength over the distribution.
- Nearest Neighbor Approach
  - Mean and Covariance Matrix.
  - Use of Mahalanobis Distance.

Examples:

Target Image



Color corrected

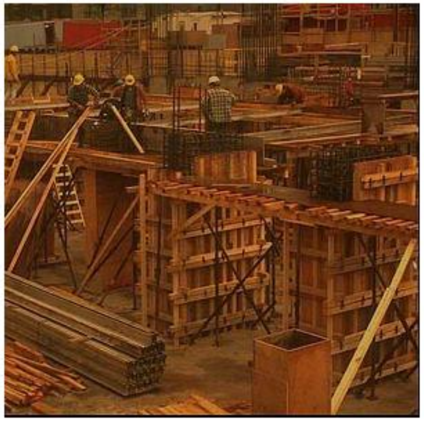


Max-World

Grey-World

Gamut-Mapping

Color corrected



Color corrected

Ex. 2

- Consider that the color of a source illuminant is represented by an RGB vector (200, 240, 180), whereas the target color is given by (240,240,240). Given a color vector (100, 150, 200) in the source image, compute the color corrected vector using diagonal correction rule.

Sum of the original vector and the corrected vector remains the same.

Ans. 2

- Diagonal Color Correction

$$k_r = \frac{R_d}{R_s} \qquad k_g = \frac{G_d}{G_s} \qquad k_b = \frac{B_d}{B_s} \qquad f = \frac{R+G+B}{k_r R + k_g G + k_b B}$$

$$R = f k_r R \qquad G = f k_g G \qquad B = f k_b B$$

(R_d, G_d, B_d)=(240, 240, 240) (R_s, G_s, B_s)= (200, 240, 180)

k_r=1.2 k_g=1 k_b=1.33

Color: (R, G, B)= (100, 150, 200)

f=(450)/(120+150+266) = 450/536=0.8396

Color corrected vector:

R=.8396 x 1.2 x 100=100.75=101

G=.8396 x 1 x 150=125.94=126

B=.8396 x 1.33 x 200 =223.33= 223

(101,126,223)

Color Transfer

- A more general form of color correction that borrows one image's color characteristics from another.

Target illumination

Source

Erik Reinhard, Michael Ashikhmin, Bruce Gooch, and Peter Shirley, Color Transfer between Images, IEEE Computer Graphics and Applications, Sept./Oct. 2001, 34-41.

Algorithm

Convert RGB to an opponent color space.

LMS-cone space

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.3811 & 0.5783 & 0.0402 \\ 0.1967 & 0.7244 & 0.0782 \\ 0.0241 & 0.1288 & 0.8444 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\mathbf{L} = \log L$$
$$\mathbf{M} = \log M$$
$$\mathbf{S} = \log S$$

$$\begin{bmatrix} l \\ \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{6}} & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & -2 \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{L} \\ \mathbf{M} \\ \mathbf{S} \end{bmatrix}$$

Opponent color space
(A variant)

- Modify $l-\alpha-\beta$

$$l^* = l - \underbrace{\langle l_s \rangle}$$
$$\alpha^* = \alpha - \langle \alpha_s \rangle$$
$$\beta^* = \beta - \langle \beta_s \rangle$$

Means of source distribution

$$l' = \frac{\sigma_t^l}{\sigma_s^l} l^*$$

s.d.'s of source and target distributions.

$$\alpha' = \frac{\sigma_t^\alpha}{\sigma_s^\alpha} \alpha^*$$

$$\beta' = \frac{\sigma_t^\beta}{\sigma_s^\beta} \beta^*$$

$$\left.\begin{aligned} l_m &= l' + < l_t > \\ \alpha_m &= \alpha' + < \alpha_t > \\ \beta_m &= \beta' + < \beta_t > \end{aligned}\right\}$$

Means of target distribution

Convert back to RGB

$$\begin{bmatrix}\mathbf{L}\\ \mathbf{M}\\ \mathbf{S}\end{bmatrix} = \begin{bmatrix}1 & 1 & 1\\ 1 & 1 & -1\\ 1 & -2 & 0\end{bmatrix}\begin{bmatrix}\frac{1}{\sqrt{3}} & 0 & 0\\ 0 & \frac{1}{\sqrt{6}} & 0\\ 0 & 0 & \frac{1}{\sqrt{2}}\end{bmatrix}\begin{bmatrix}l_m\\ \alpha_m\\ \beta_m\end{bmatrix}$$

$L = e^{\mathbf{L}}$

$M = e^{\mathbf{M}}$

$S = e^{\mathbf{S}}$

$$\begin{bmatrix}R\\ G\\ B\end{bmatrix} = \begin{bmatrix}4.4679 & -3.5873 & 0.1193\\ -1.2186 & 2.3809 & -0.1624\\ 0.0497 & -0.2439 & 1.2045\end{bmatrix}\begin{bmatrix}L\\ M\\ S\end{bmatrix}$$

The other example:

Target illumination

Color Demosaicing

- Use of color filter array (CFA) in a single chip CCD camera.
- Generation of dense pixel maps from sparse data by interpolation.
- Hardware cost and computation time to be kept low.

G	R	G	R
B	G	B	G
G	R	G	R
B	G	B	G

BAYER'S

G	B	G	R
R	G	B	G
G	B	G	R
R	G	B	G

KODAK

Two observations

- A high correlation between the red, green, and blue channels→ very likely to have the same texture and edge locations.

- In CFA the luminance (green) channel sampled at a higher rate than the chrominance (red and blue) channels.

The green channel less likely to be aliased, and details are preserved better in the green channel than in the red and blue channels.

Color Plane Interpolation Using Alternating Projections, Bahadir K. Gunturk, *Yucel Altunbasak,* Russell M. Mersereau, IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 11, NO. 9, SEPTEMBER 2002, 997-1013

Bilinear Interpolation

- Interpolate green pixels.

$$G_8 = \frac{G_3 + G_7 + G_9 + G_{13}}{4}$$

- Interpolate red and blue pixels.

$$R_7 = \frac{R_2 + R_{12}}{2} \qquad R_8 = \frac{R_2 + R_4 + R_{12} + R_{14}}{4}$$

$$B_7 = \frac{B_6 + B_8}{2} \qquad B_{12} = \frac{B_6 + B_8 + B_{16} + B_{18}}{4}$$

G_1	R_2	G_3	R_4	G_5
B_6	G_7	B_8	G_9	B_{10}
G_{11}	R_{12}	G_{13}	R_{14}	G_{15}
B_{16}	G_{17}	B_{18}	G_{19}	B_{20}
G_{21}	R_{22}	G_{23}	R_{24}	G_{25}

BAYER'S

Interpolation by averaging red and blue hues

- Interpolate green pixels.

$$G_8 = \frac{G_3 + G_7 + G_9 + G_{13}}{4}$$

- Interpolate red and blue pixels from average hues.

$$B_7 = \frac{G_7}{2}\left(\frac{B_6}{G_6} + \frac{B_8}{G_8}\right) \qquad B_{13} = \frac{G_{13}}{2}\left(\frac{B_8}{G_8} + \frac{B_{18}}{G_{18}}\right)$$

$$B_{12} = \frac{G_{12}}{4}\left(\frac{B_6}{G_6} + \frac{B_8}{G_8} + \frac{B_{16}}{G_{16}} + \frac{B_{18}}{G_{18}}\right)$$

- Similarly red pixels are also interpolated.

G_1	R_2	G_3	R_4	G_5
B_6	G_7	B_8	G_9	B_{10}
G_{11}	R_{12}	G_{13}	R_{14}	G_{15}
B_{16}	G_{17}	B_{18}	G_{19}	B_{20}
G_{21}	R_{22}	G_{23}	R_{24}	G_{25}

BAYER'S

Blue hue: B/G
Red hue: R/G

Hamilton, Jr. et.al., "Adaptive color plane interpolation in single sensor color electronic camera" U.S.Patent 5,629,734

Laplacian corrected edge correlated interpolation (LCEC)

- Interpolate green pixels.

Define horizontal and vertical gradients as:

$$\Delta H = |G_4 - G_6| + |B_5 - B_3 + B_5 - B_7|$$

$$\Delta V = |G_2 - G_8| + |B_5 - B_1 + B_5 - B_9|$$

		B_1		
		G_2		
B_3	G_4	B_5	G_6	B_7
		G_8		
		B_9		

BAYER'S

- Then compute G_5 as:

$if\ \Delta H < \Delta V$

$$G_5 = \frac{G_4 + G_6}{2} + \frac{B_5 - B_3 + B_5 - B_7}{4}$$

$else\ if\ \Delta H > \Delta V$

$$G_5 = \frac{G_2 + G_8}{2} + \frac{B_5 - B_1 + B_5 - B_9}{4}$$

$else$

$$G_5 = \frac{G_2 + G_4 + G_6 + G_8}{4} + \frac{B_5 - B_1 + B_5 - B_3 + B_5 - B_7 + B_5 - B_9}{8}$$

Second order derivative of a function:
(f(x+1)-f(x))-(f(x)-f(x-1))= f(x+1)+f(x-1)-2f(x)

Estimated from the other channel and subtracted for correction.

Laplacian corrected edge correlated interpolation –contd.

	R_1	G_2	R_3	
	G_4	B_5	G_6	
	R_7	G_8	R_9	

BAYER'S

- Interpolate Red and Blue pixels. For red pixels, the computation is shown.
- Case 1: $R_4 = \dfrac{R_1 + R_7}{2} + \dfrac{G_4 - G_1 + G_4 - G_7}{4}$
- Case 2: $R_2 = \dfrac{R_1 + R_3}{2} + \dfrac{G_2 - G_1 + G_2 - G_3}{4}$
- Case 3: Define two diagonal directions (-ve and +ve)

Cross-channel laplacian values.

$$\Delta N = |R_1 - R_9| + |G_5 - G_1 + G_5 - G_9|$$

$$\Delta P = |R_3 - R_7| + |G_5 - G_3 + G_5 - G_7|$$

if $\Delta N < \Delta P$

$$R_5 = \frac{R_1 + R_9}{2} + \frac{G_5 - G_1 + G_5 - G_9}{4}$$

else if $\Delta N > \Delta P$

$$R_5 = \frac{R_3 + R_7}{2} + \frac{G_5 - G_3 + G_5 - G_7}{4}$$

else

$$R_5 = \frac{R_1 + R_9 + R_3 + R_7}{4} + \frac{G_5 - G_1 + G_5 - G_9 + G_5 - G_3 + G_5 - G_7}{8}$$

Color Demosaicing: An example.

ORIGINAL

BI

ARBH

LCEC

ORIGINAL

BI

ARBH

LCEC

Ex. 3

Consider the following CFA whose first row corresponds to the red (R) row and first column of that row corresponds to a green (G) pixel of the Bayer pattern.

30	40	37	43	40
20	35	25	60	30
32	45	**45**	48	55
30	38	27	55	33
45	48	47	50	46

Central pixel.

Answer the following:

(a) What are the missing components of the central pixel?

(b) Compute them using Bilinear interpolation, and ARBH techniques.

Ans. 3 (a)

(a) What are the missing components of the central pixel?

30 G	40 R	37 G	43 R	40 G
20 B	35 G	25 B	60 G	30 B
32 G	45 R	**45 G**	48 R	55 G
30 B	38 G	27 B	55 G	33 B
45 G	48 R	47 G	50 R	46 G

Central pixel.

Missing components are: (i) red (R) and (ii) blue (B).

Ans. 3 (b)

(b) Compute them using Bilinear interpolation technique.

Only values required to apply BI shown.

30 G	40 R	37 G	43 R	40 G
20 B	35 G	25 B	60 G	30 B
32 G	45 R	**45 G**	48 R	55 G
30 B	38 G	27 B	55 G	33 B
45 G	48 R	47 G	50 R	46 G

		25 B		
	45 R	**45 G**	**48 R**	
		27 B		

BI: Missing components are: (i) red (R) = (45+48)/2=46.5

and (ii) blue (B)= (25+27)/2=26.

Ans. 3 (b)

(b) Compute them using ARBH technique.

30 G	40 R	37 G	43 R	40 G
20 B	35 G	25 B	60 G	30 B
32 G	45 R	**45 G**	48 R	55 G
30 B	38 G	27 B	55 G	33 B
45 G	48 R	47 G	50 R	46 G

30 G	40 R	37 G	43 R	40 G
20 B	35 G	**25 B**	60 G	30 B
32 G	**45 R**	**45 G**	**48 R**	55 G
30 B	38 G	**27 B**	55 G	33 B
45 G	48 R	47 G	50 R	46 G

ARBH: (i) Compute missing G values in respective B and R pixels.

For B pixels: top neighbor: G= (37+60+35+45)/4=44.25

bottom neighbor: G=(45+55+47+38)/4=46.25

For R pixels: left neighbor: G= (35+45+38+32)/4=37.5

right neighbor: G=(60+55+55+45)/4=53.75

Ans. 3 (b)

(b) Compute them using ARBH technique.

Only values required to apply ARBH shown.

30 G	40 R	37 G	43 R	40 G
20 B	35 G	25 B	60 G	30 B
32 G	45 R	**45 G**	48 R	55 G
30 B	38 G	27 B	55 G	33 B
45 G	48 R	47 G	50 R	46 G

		37 G		
	35 G	**25 B** **44.25**	60 G	
32 G	**45 R** **37.5**	**45 G**	**48 R** **53.75**	55 G
	38 G	**27 B** **46.25**	55 G	
		47 G		

ARBH: (ii) Compute average of hues and multiply with green value

Missing Blue: 45 x ((25/44.25 + 27/46.25)/2)= 25.847
Missing Red: 45 x ((45/37.5+48/53.75)/2)= 47.093

Two major problems in the reconstruction

- Blurred Edges.

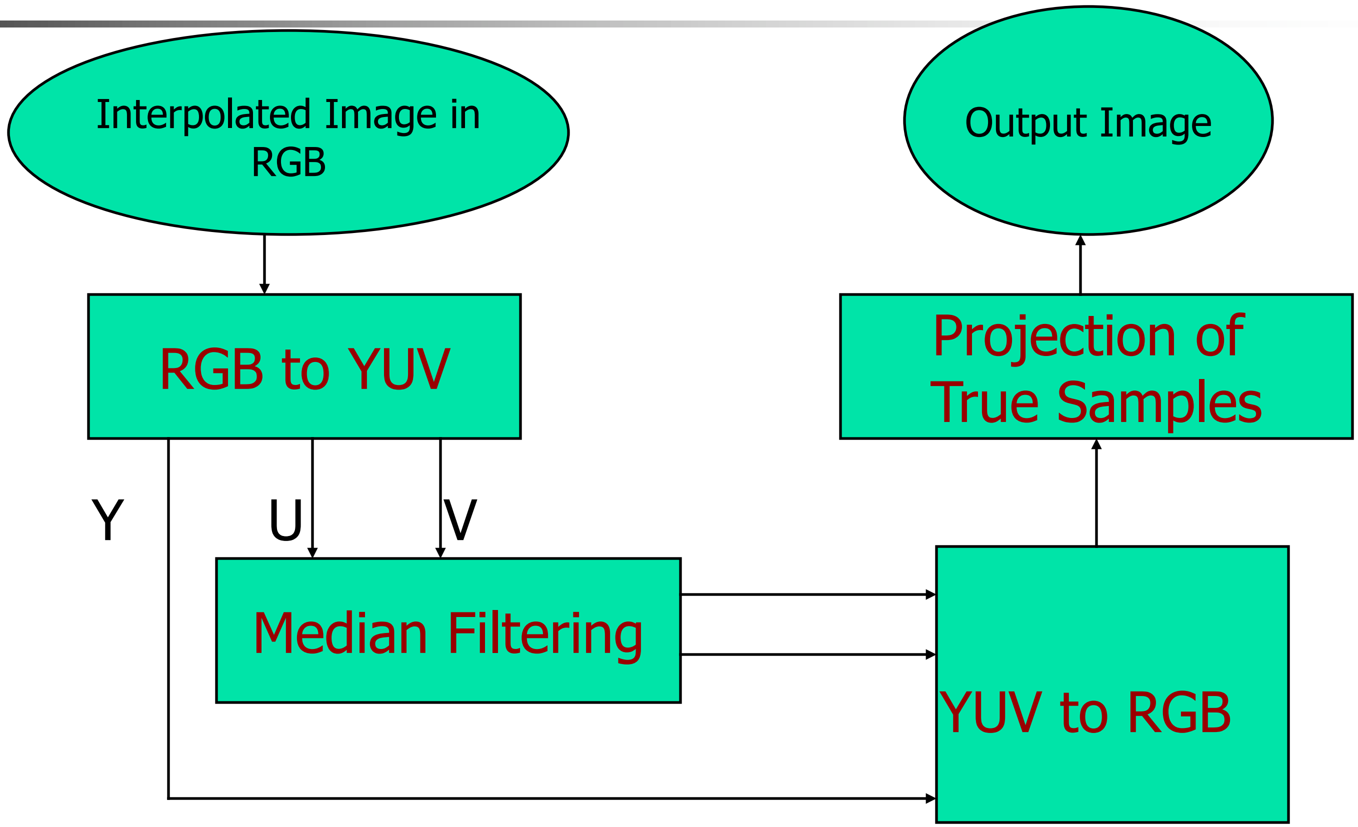
- Appearance of false colors

False Colors: An Example

Original

Reconstructed

False Color Suppression



Examples

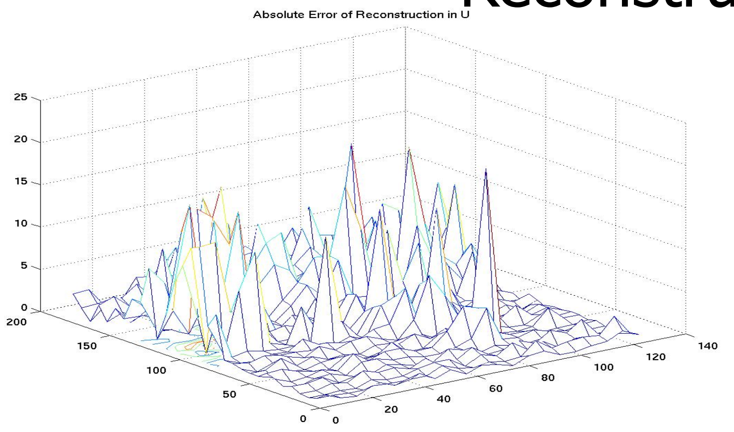
LCEC

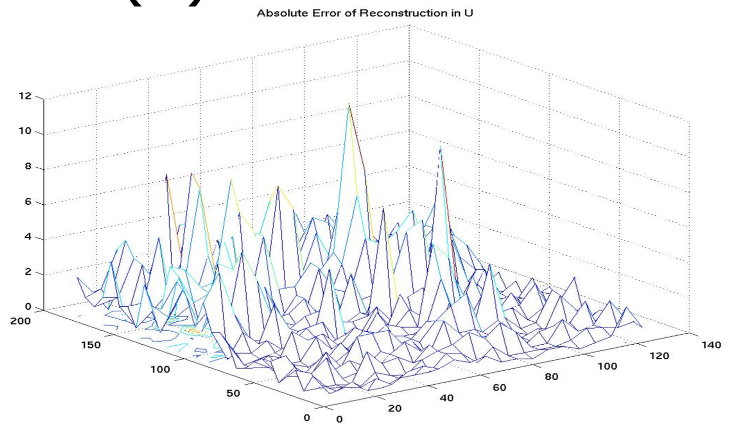
LCEC with Median
(3 x 3 Mask)

LCEC with Median
(5 x 5 Mask)

Suppression of Impulsive Noise

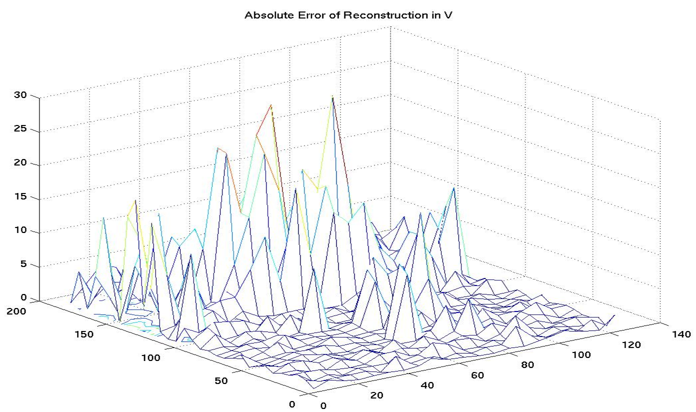
Reconstruction Error (U):

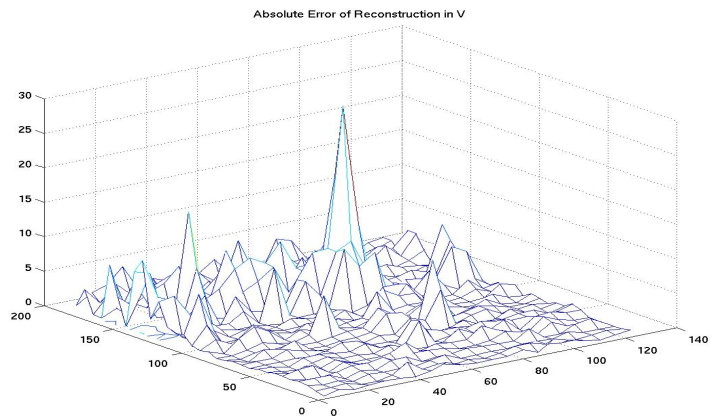




After median filtering.

Reconstruction Error (V):





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.

Summary (contd.)

- In digital cameras color images are mostly captured using a CFA, which need to be interpolated to provide full color information.
- A few problems on color processing discussed.
  - Color enhancement through saturation-desaturation.
  - Computing color constancy.
  - Color transfer
  - Color interpolation.