Color fundamentals and processing

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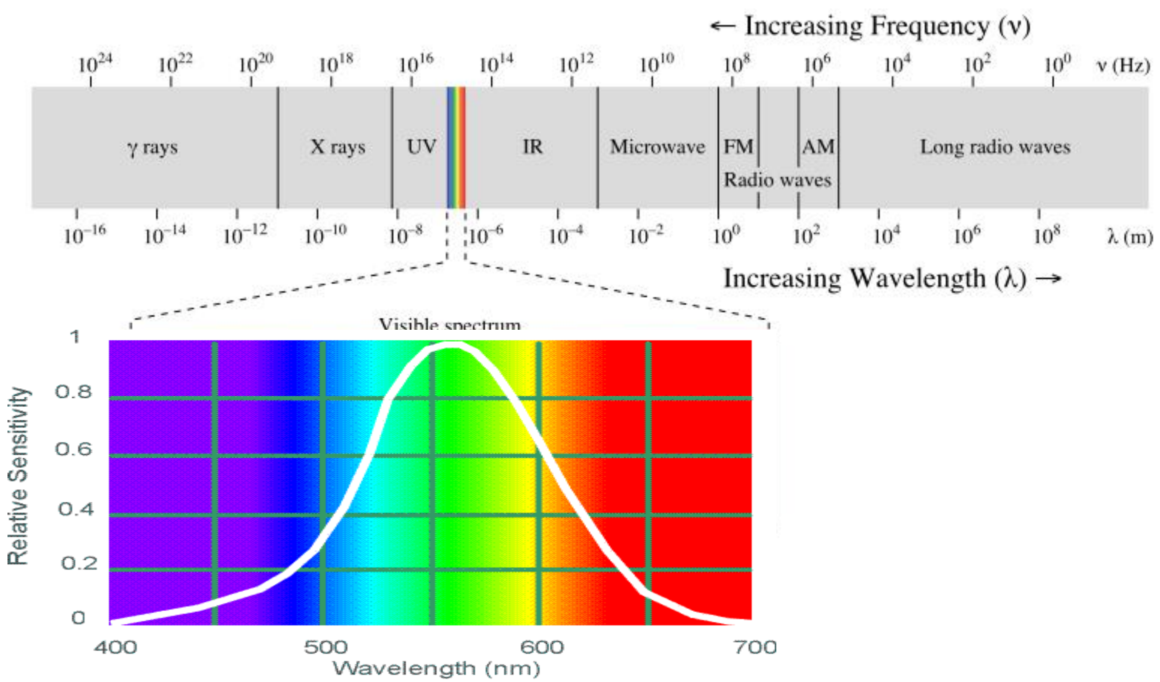
What is color?

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

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

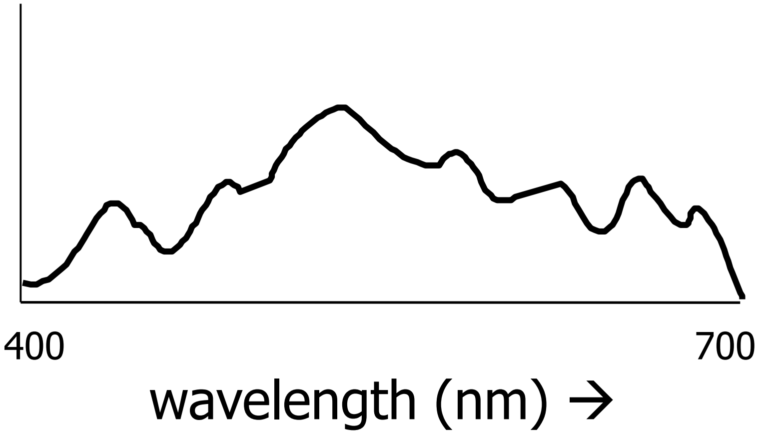
Electromagnetic spectrum



Human Luminance Sensitivity Function

Components of a light source

- Could be described physically by its spectrum: energy emitted per unit time at each wavelength
  - Relative spectral power



Black body radiators

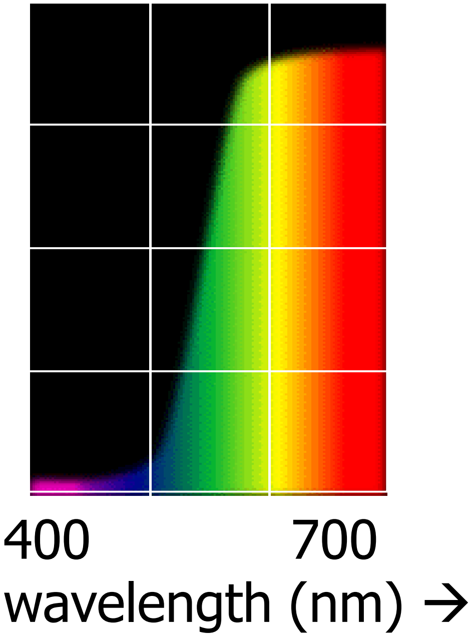
- Construct a hot body with near-zero albedo (black body).
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature.

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

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

Reflection of light

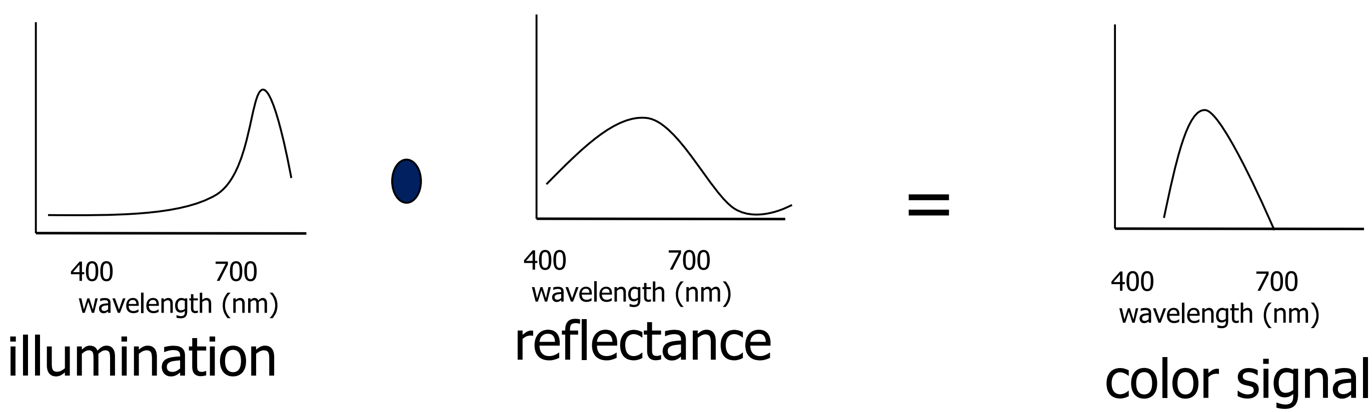
- Modulated by coefficient of reflection
  - Varies with wavelength of incident ray



Courtesy: Stephen A Palmer

Interaction of light and surfaces

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

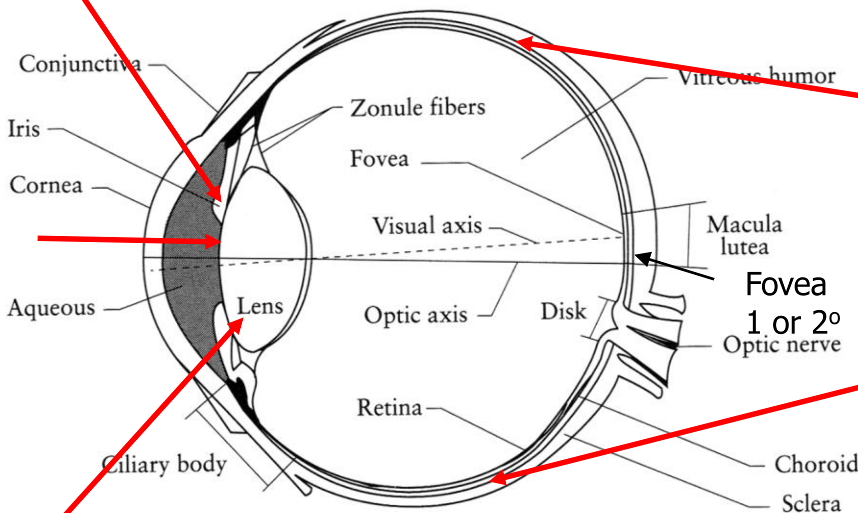


The Eye: A Camera!

Iris - colored annulus with radial muscles

Rods: low illumination vision
Cones: high illumination and color vision
Cones: red, green and blue 10:5:1

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



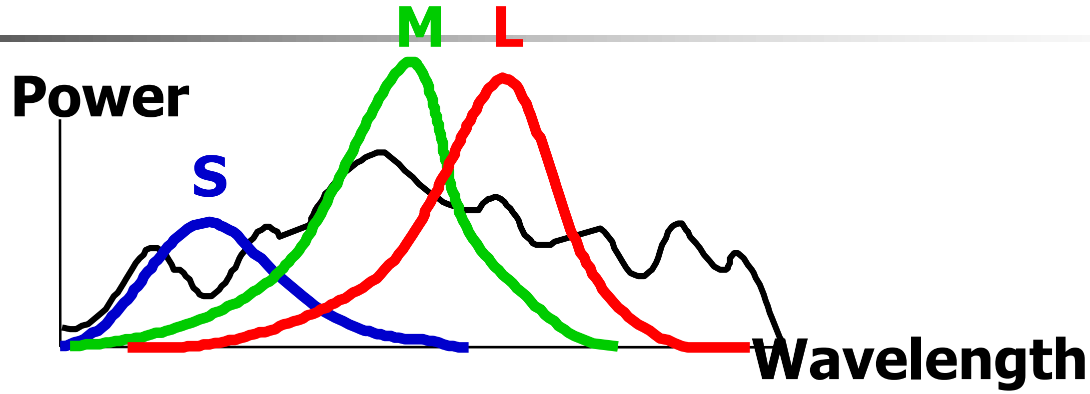
Retina -photoreceptor cells (rods and cones) acting like the film or array of sensors of a camera.

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

Cones mostly concentrated in fovea
Rods in periphery

Adapted from slides by Steve Seitz.

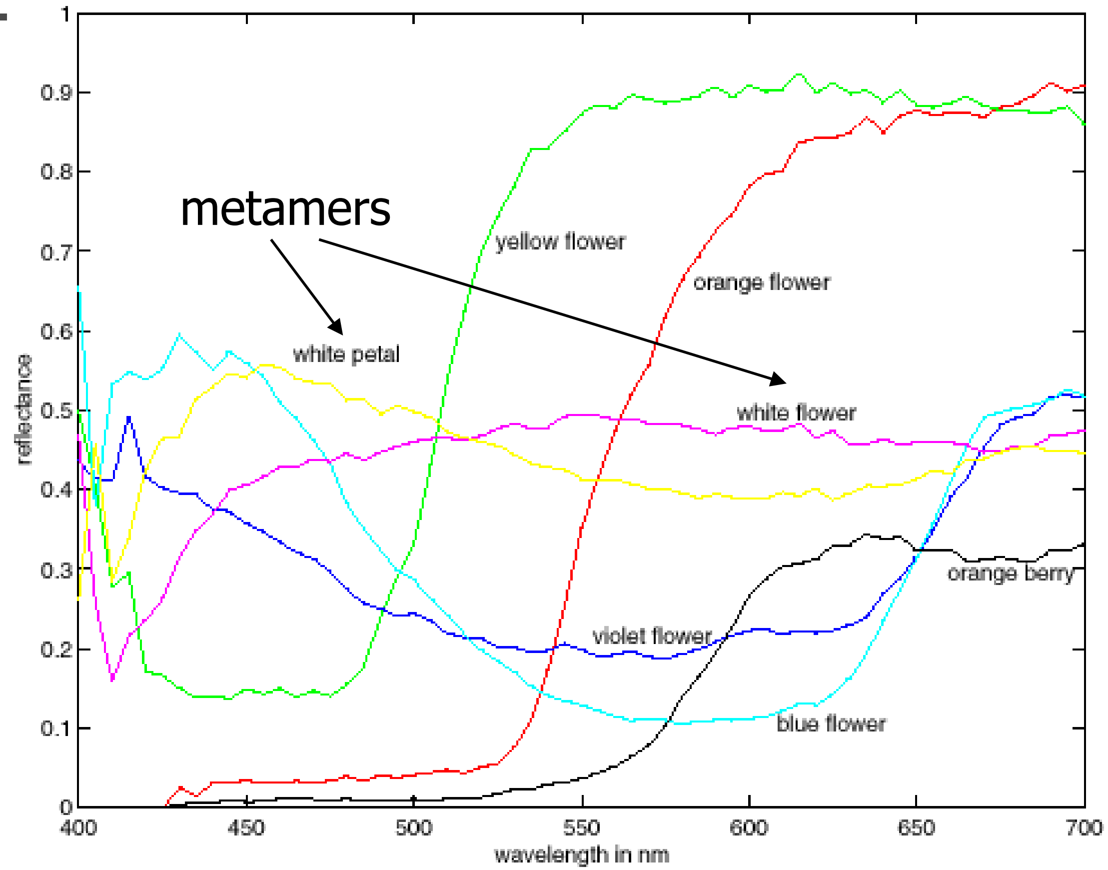
Color perception



- 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.**

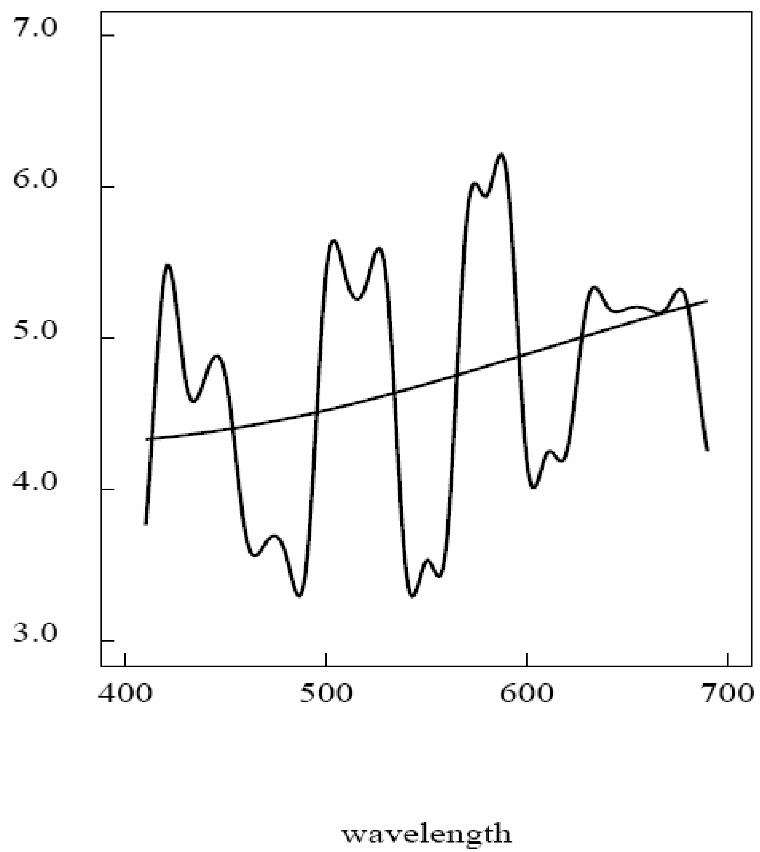
Adapted from slides by Steve Seitz.

Spectra of some real-world surfaces



Adapted from slides by Steve Seitz.

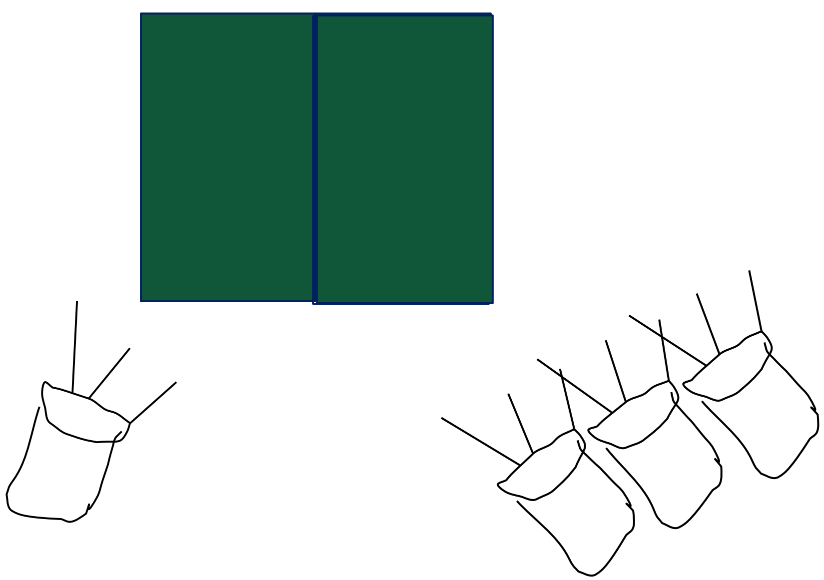
Metamers



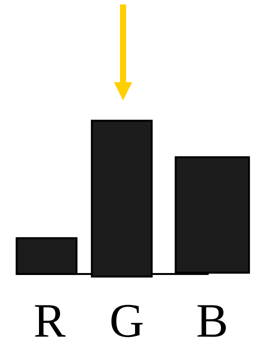
Adapted from slides by Steve Seitz.

Standardizing color experience

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



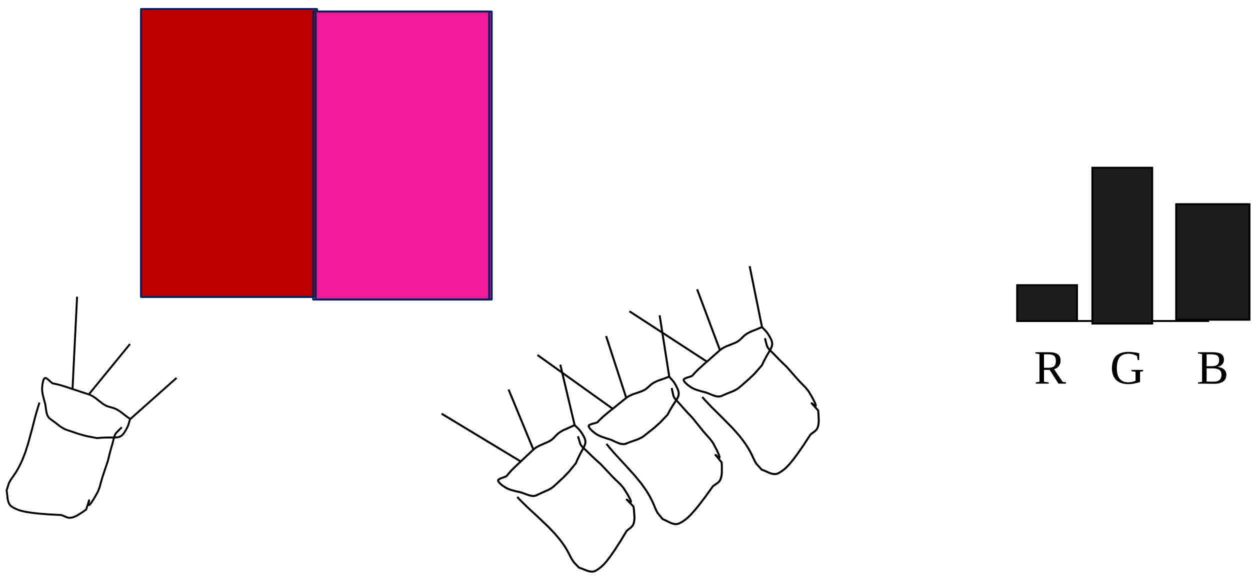
The primary color amounts needed for a match



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

The other situation

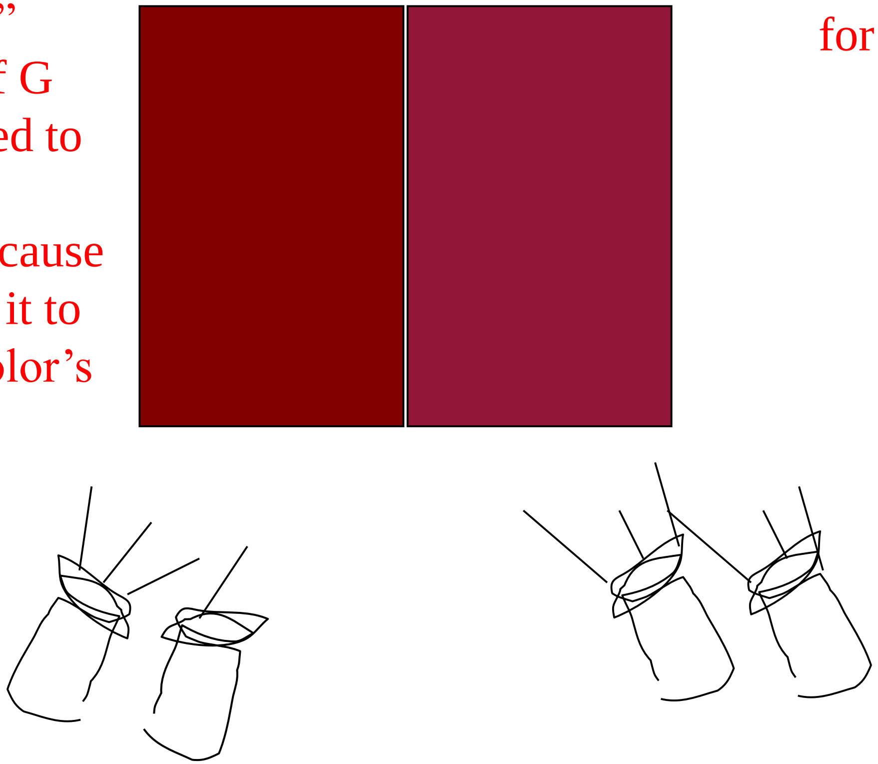
- Not every color could be produced through superposition.



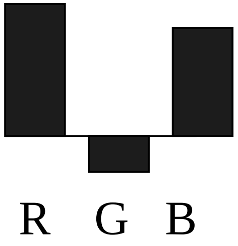
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

The other situation

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



The primary color amounts needed for a match:



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).

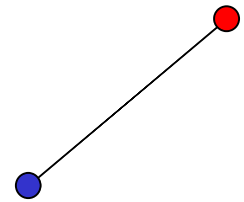
Adapted from W. Freeman

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

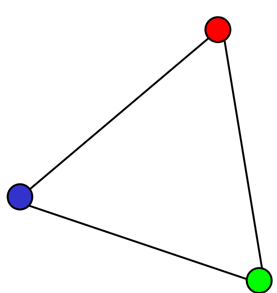
Adapted from W. Freeman

Linear color spaces



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

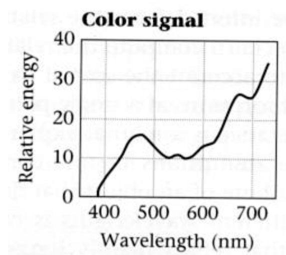
- Defined by a choice of three primaries
- The coordinates of a color are given by the weights of the primaries used to match it.
- *Matching functions*: weights required to match single-wavelength light sources.

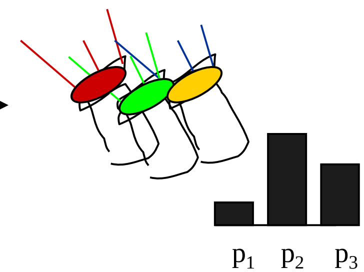


mixing three lights produces colors that lie within the triangle they define in color space.

Adapted from W. Freeman

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



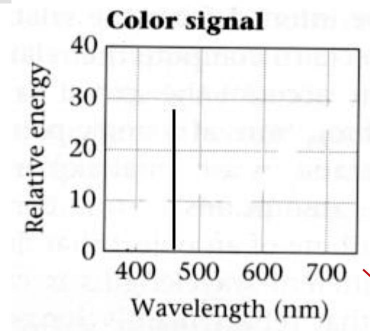


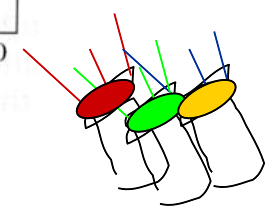
- Pick a set of primaries, $p_1(\lambda), p_2(\lambda), p_3(\lambda)$
- Measure the amount of each primary, $c_1(\lambda_0), c_2(\lambda_0), c_3(\lambda_0)$ needed to match a monochromatic light, $t(\lambda_0)$ at each spectral wavelength λ_0 (pick some spectral step size). These are the color matching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

Source: W. Freeman

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

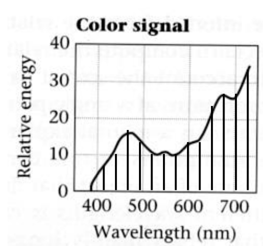
A monochromatic light of λ_i wavelength will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.





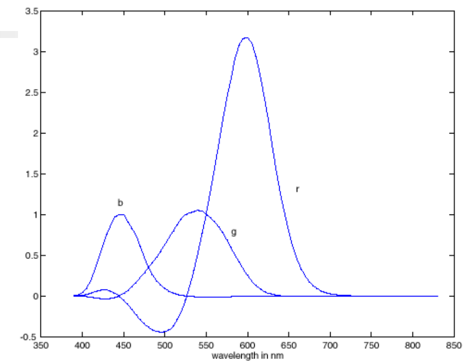
And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

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



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*.

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

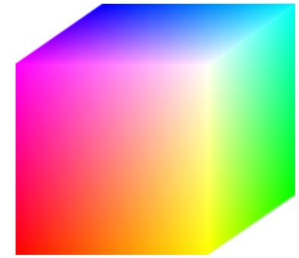
Then the amounts of each primary needed to match t are:

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

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

Linear color spaces: RGB

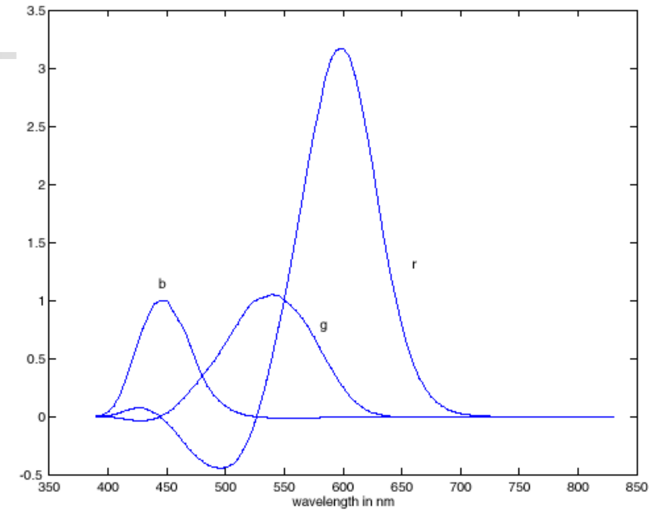


$p_1 = 645.2$ nm

$p_2 = 525.3$ nm

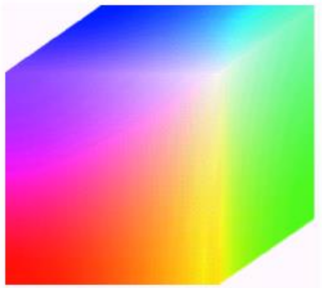
$p_3 = 444.4$ nm

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

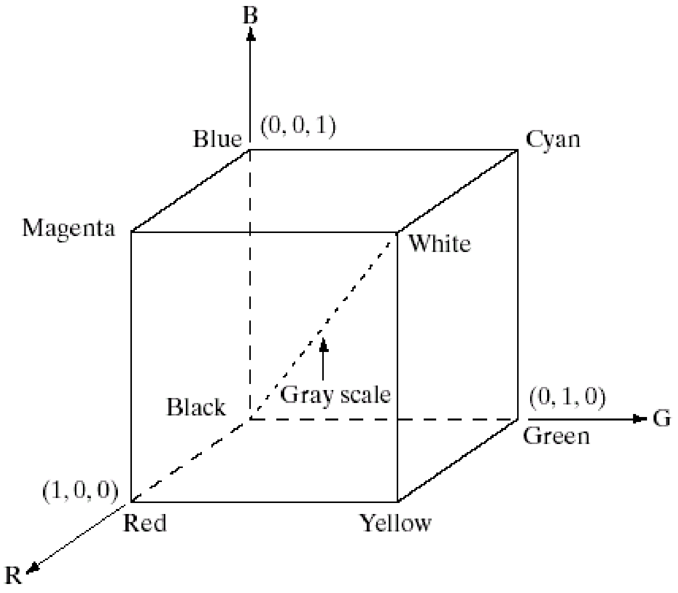


RGB matching functions

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

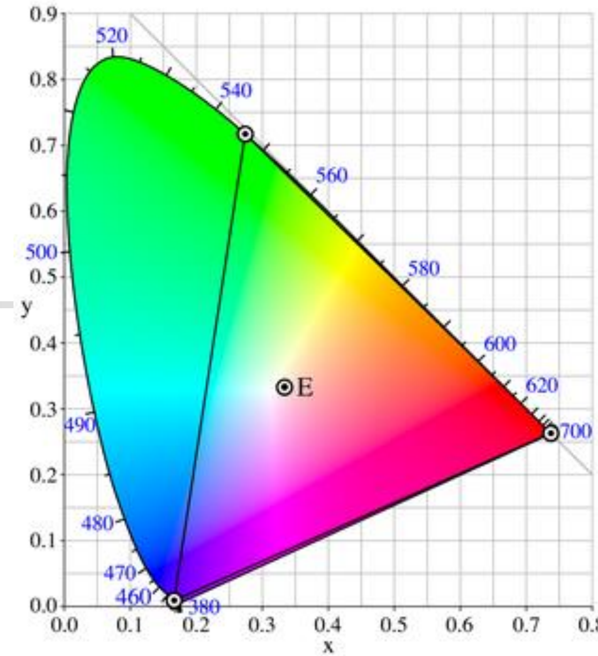
- The Commission Internationale de l'Eclairage (estd. 1931) defined 3 standard primaries: X, Y, Z that can be added to form all visible colors.
- Y was chosen so that its color matching function matches the sum of the 3 human cone responses.

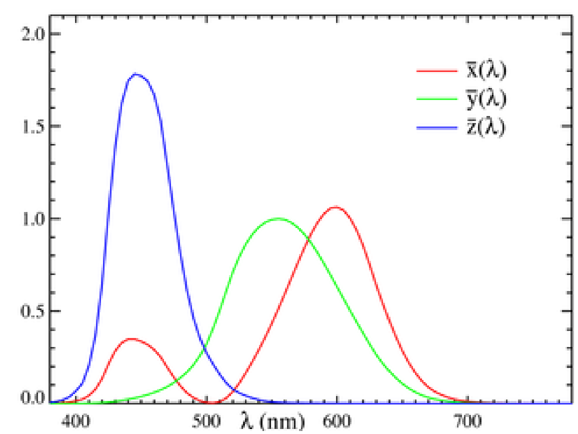
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.6067 & 0.1736 & 0.2001 \\ 0.2988 & 0.5868 & 0.1143 \\ 0.0000 & 0.0661 & 1.1149 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.9107 & -0.5326 & -0.2883 \\ -0.9843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

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

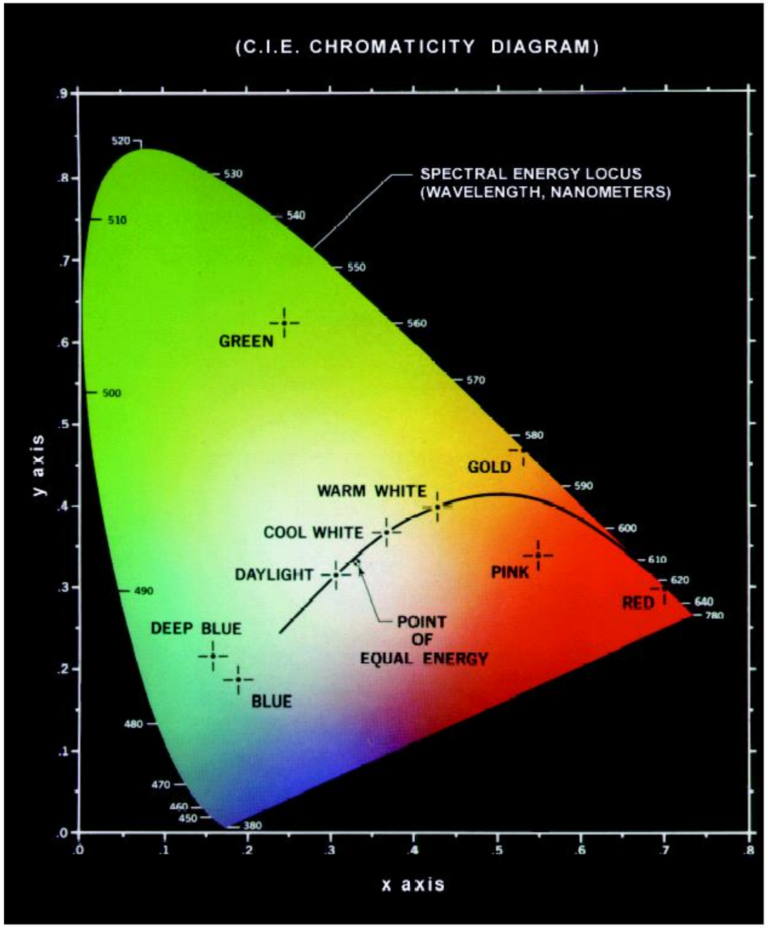
- x, y, z normalize X, Y, Z such that

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

- Actually only x and y are needed because

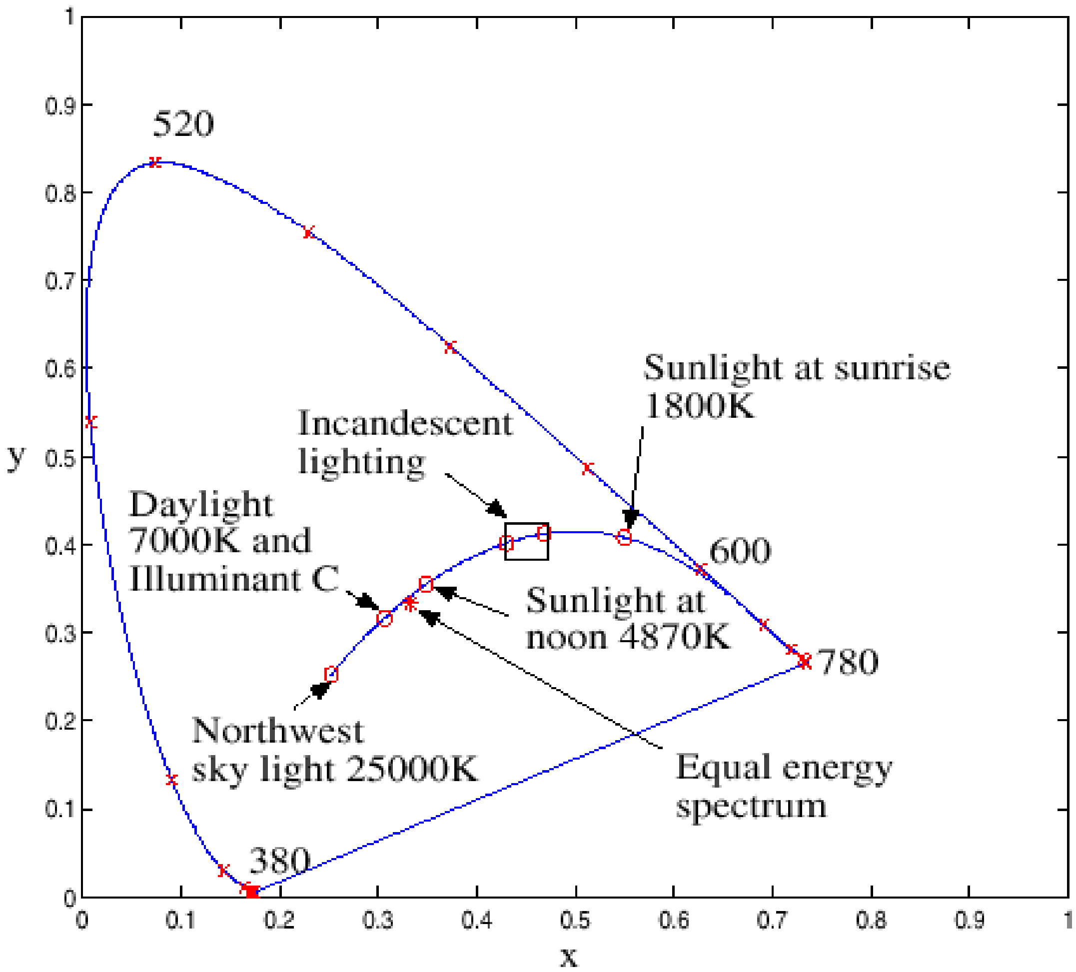
  $$z = 1 - x - y.$$

- 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



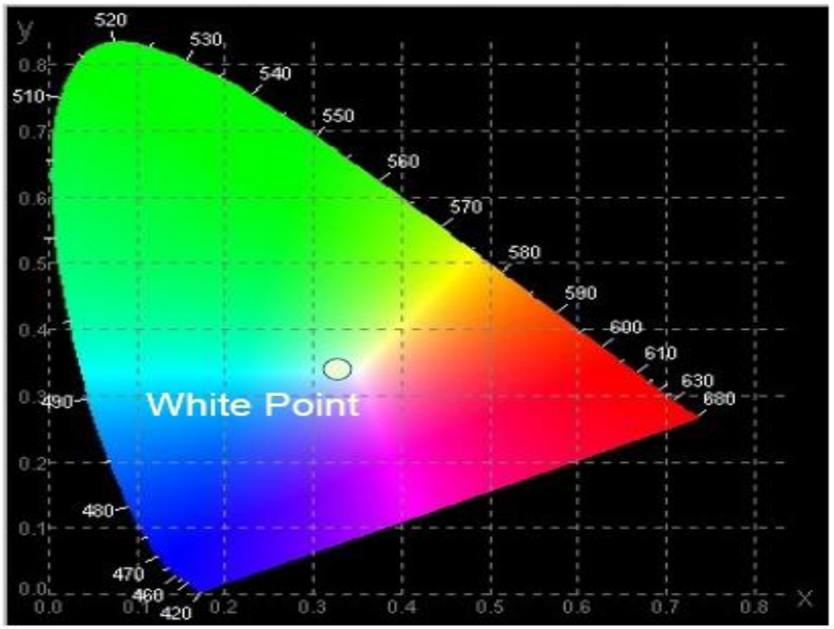
CIE Chromaticity Chart

- Shows all the visible colors
- Achromatic Colors are at (0.33,0.33).

– Called white point.

- The saturated colors at the boundary.

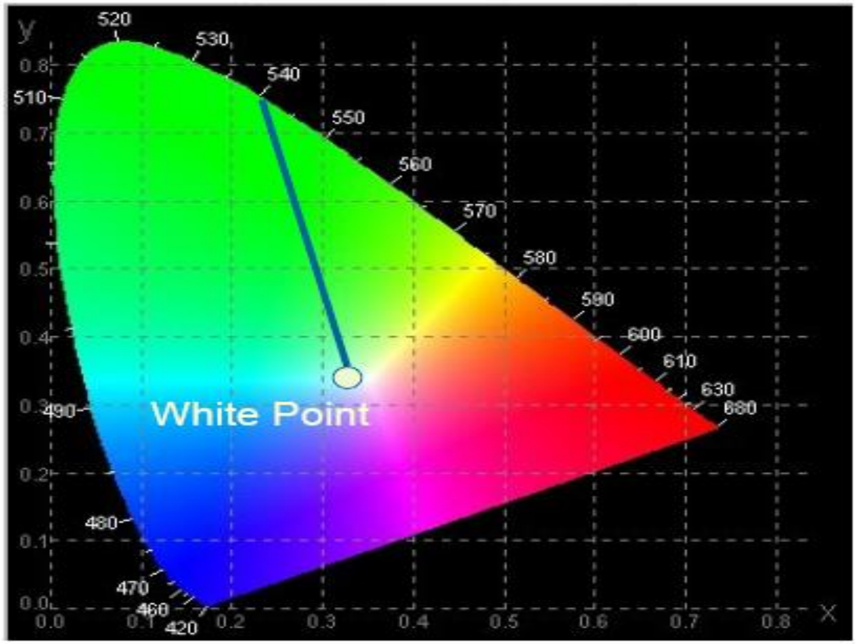
– Spectral Colors



Adapted from Octavia Camps, Penn State

Chromaticity Chart: Hue

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



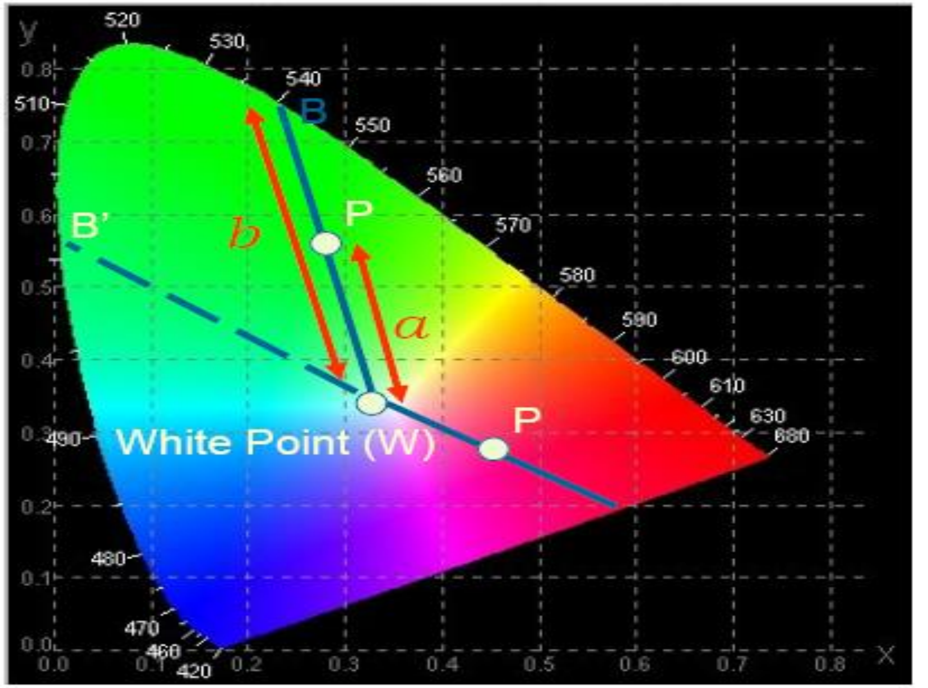
Chromaticity Chart: Saturation

- 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

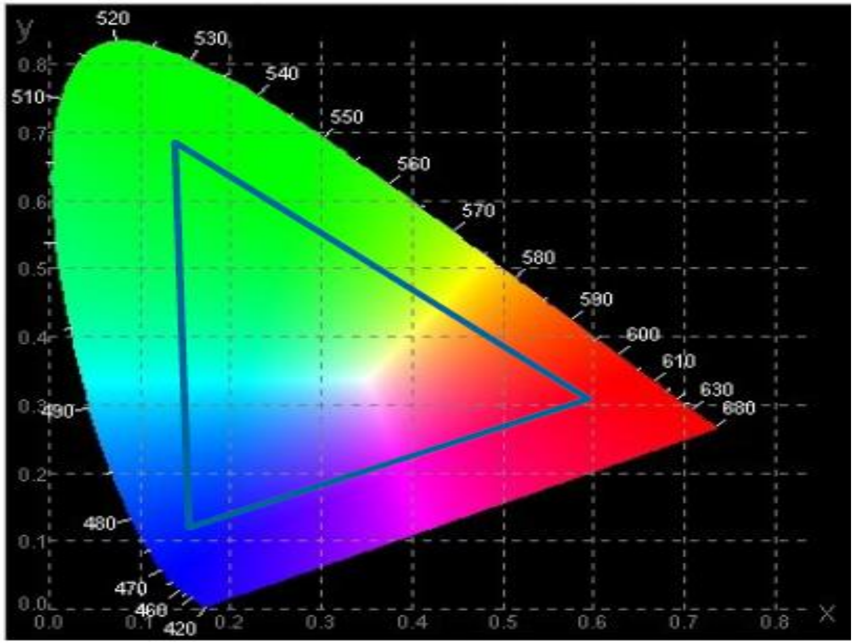
Color Reproducibility

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

–Triangle

–2D color gamut

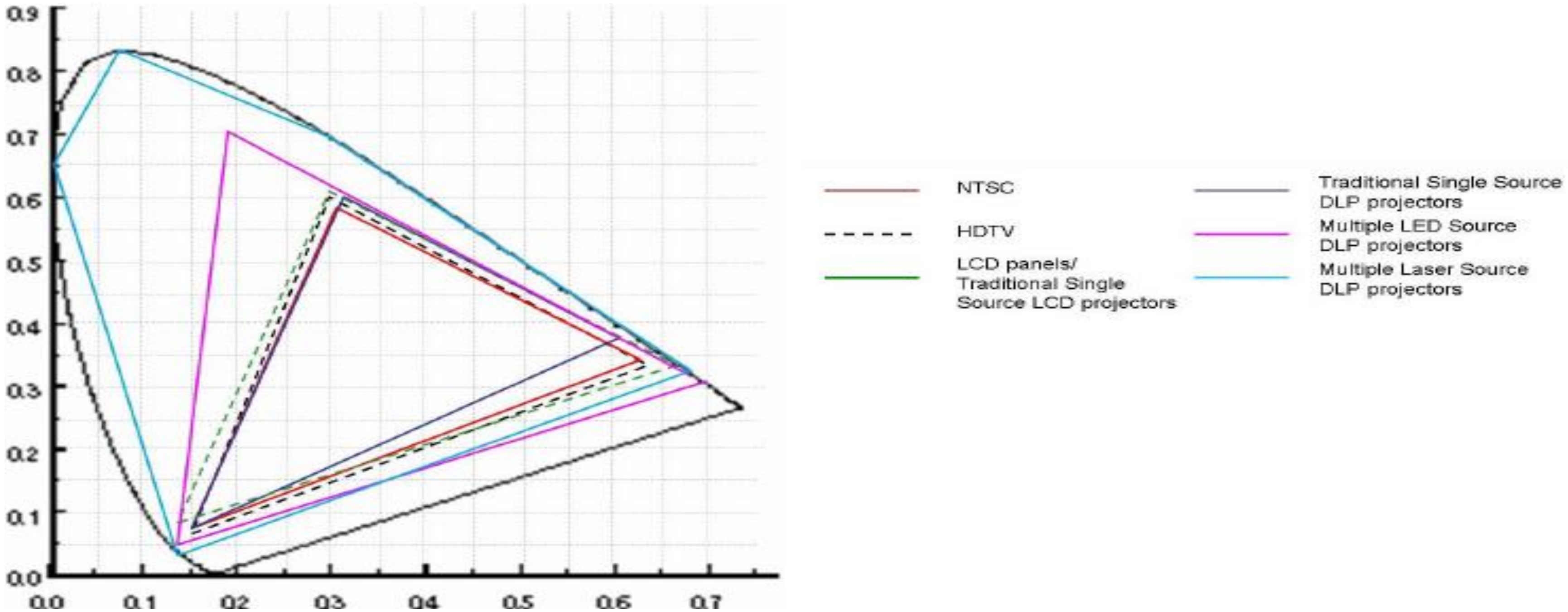
Large if using more saturated primaries.



Cannot describe brightness range reproducibility.

Adapted from Octavia Camps, Penn State

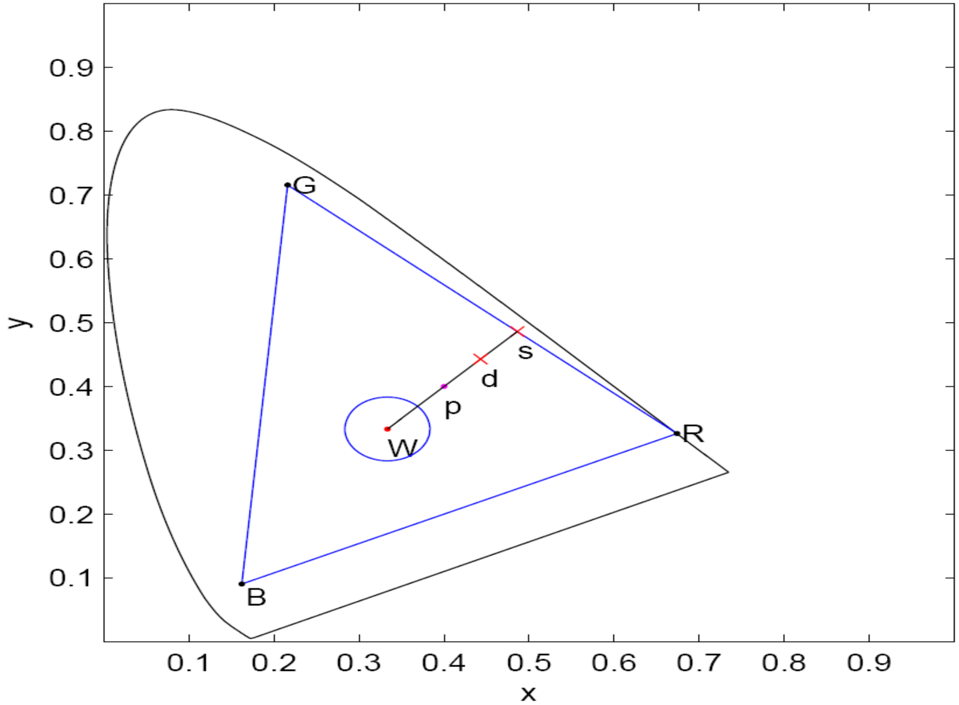
Standard Color Gamut



Adapted from Octavia Camps, Penn State

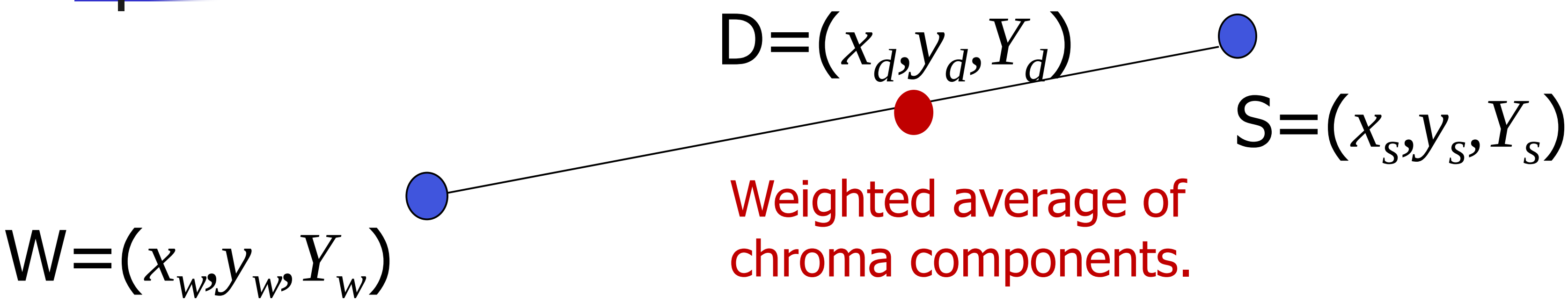
Saturation and De-saturation Operation

- 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



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

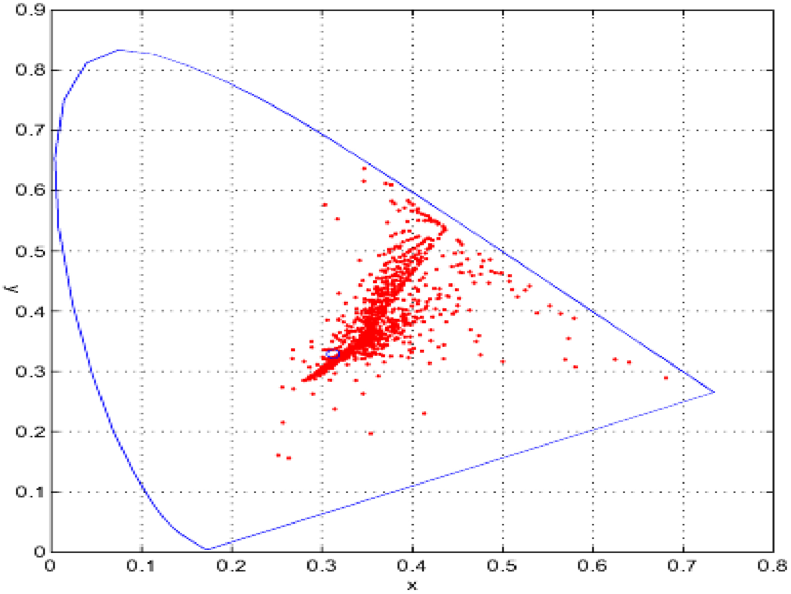
$$y_d = \frac{|Y_w| + Y_s}{\frac{|Y_w|}{y_w} + \frac{|Y_s|}{y_s}}$$

$$Y_d = |Y_w| + Y_s$$

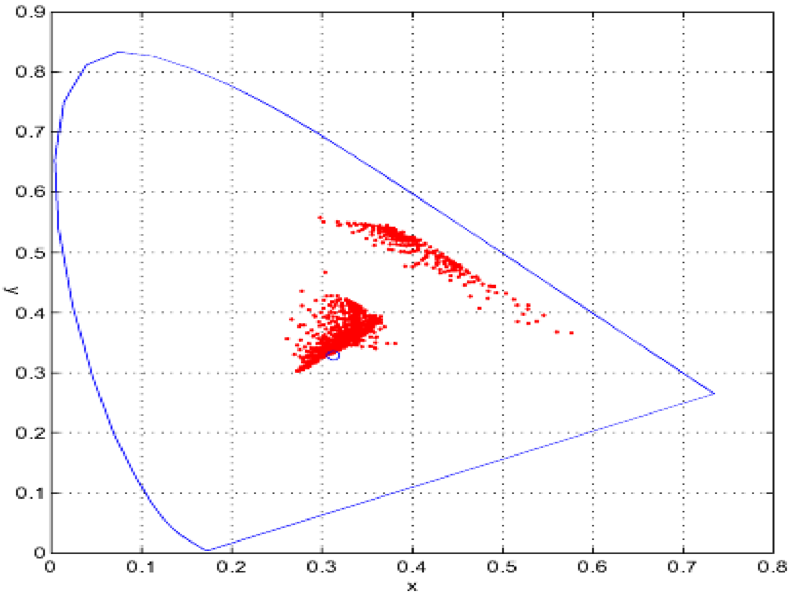
$$Y_w = kY_{avg}$$

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

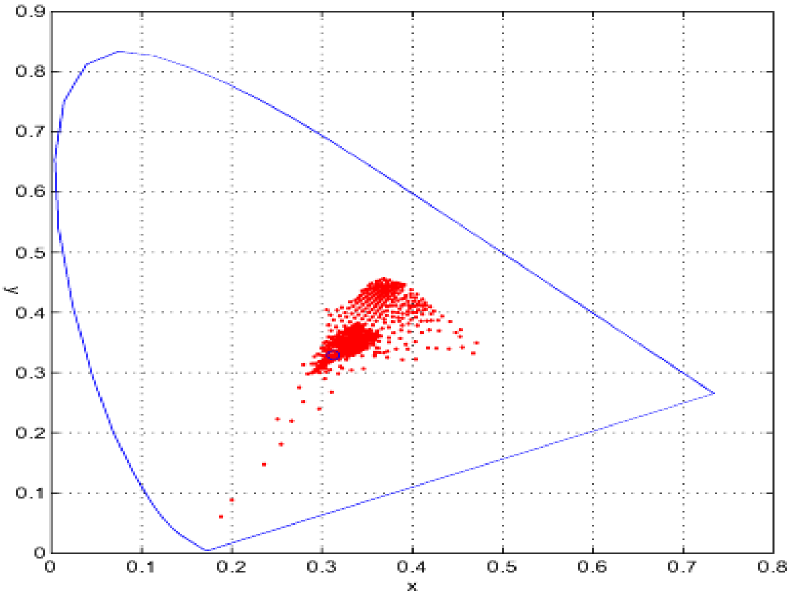
Alps - Original



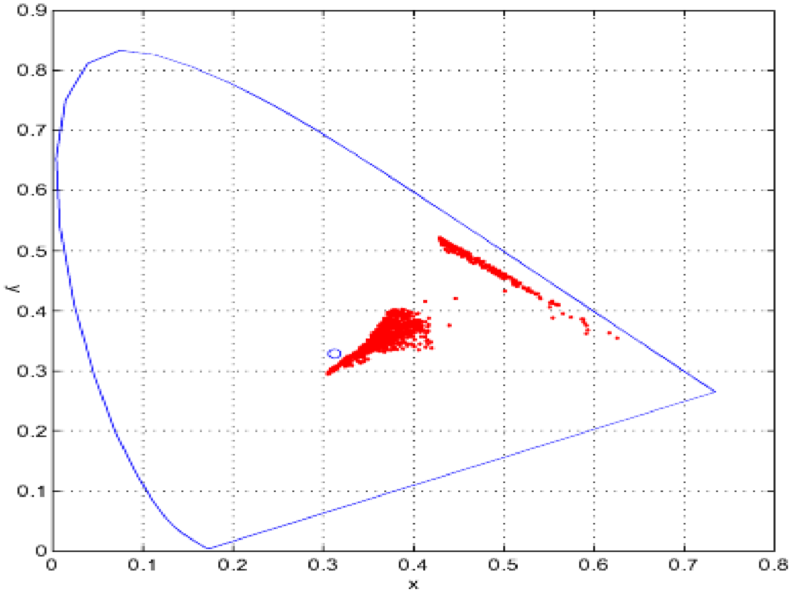
Saturated Image



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

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

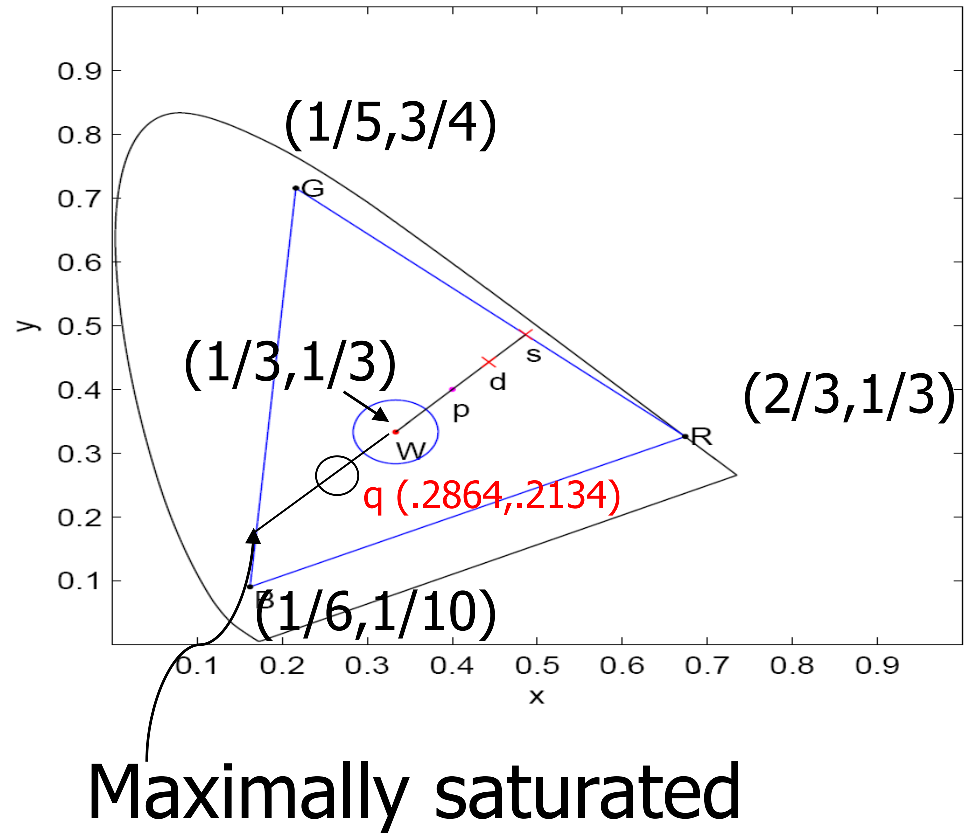
Ex. 1 (b)

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)

Ans. 1(b)

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

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)

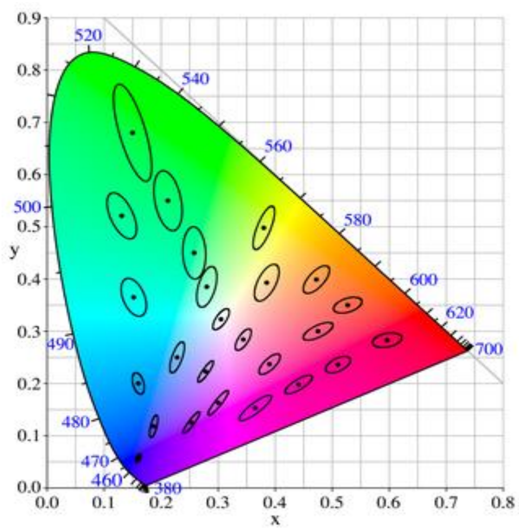
⇩

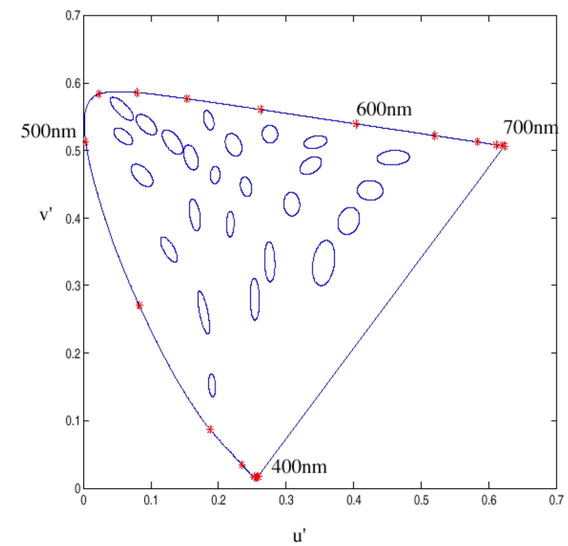
(81, 49, 240)

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.

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

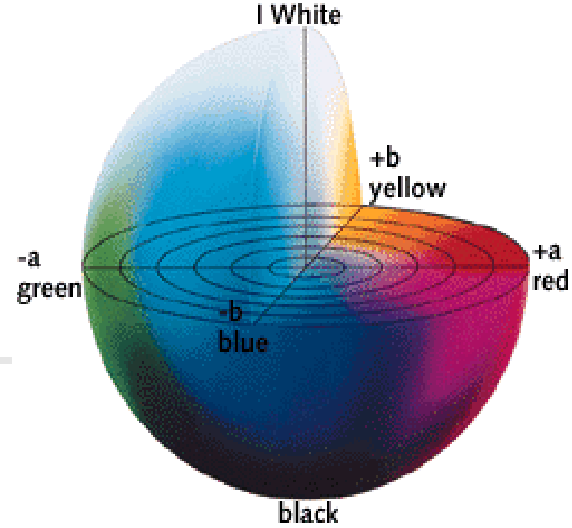




McAdam ellipses:
Just noticeable differences in color

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

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

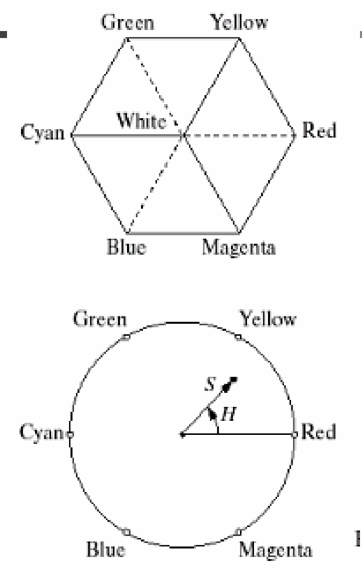
- Have better compression properties.
- Luminance Y is encoded using more bits than chrominance values I and Q (humans are more sensitive to Y than I and Q).
- Luminance used by black/white TVs.
- All 3 values used by color TVs.

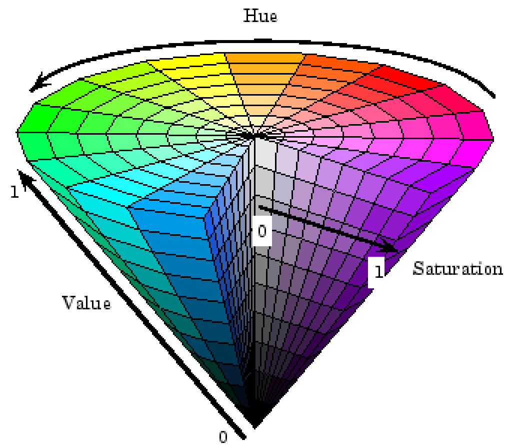
YCbCr space

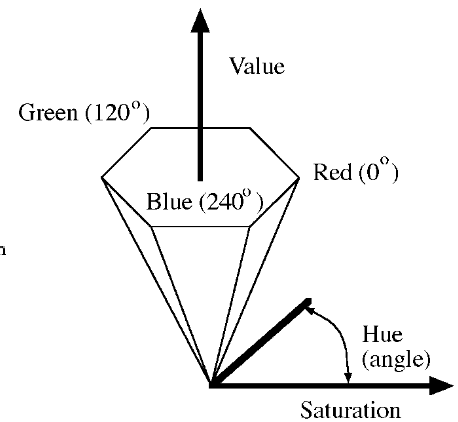
$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.256 & 0.502 & 0.098 \\ -0.148 & -0.290 & 0.438 \\ 0.438 & -0.366 & -0.071 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 0 \\ 128 \\ 128 \end{bmatrix}$$

- 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.

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

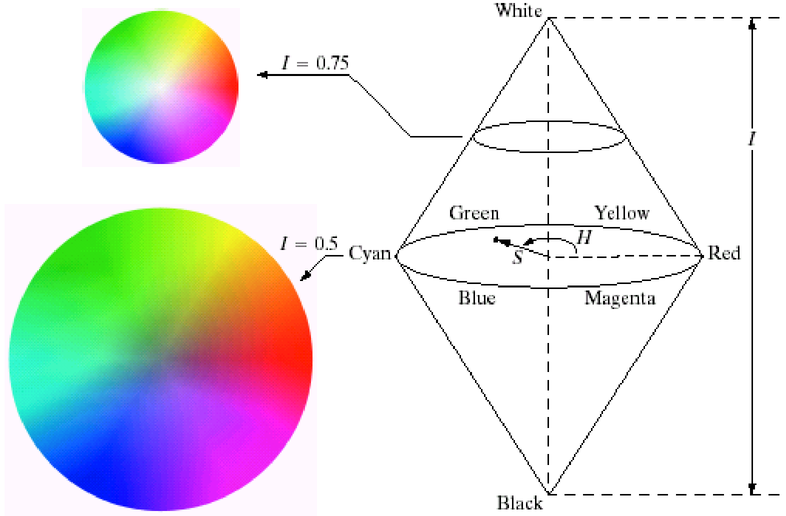
$$S = 1 - \frac{\min(R, G, B)}{I}$$

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

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

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).



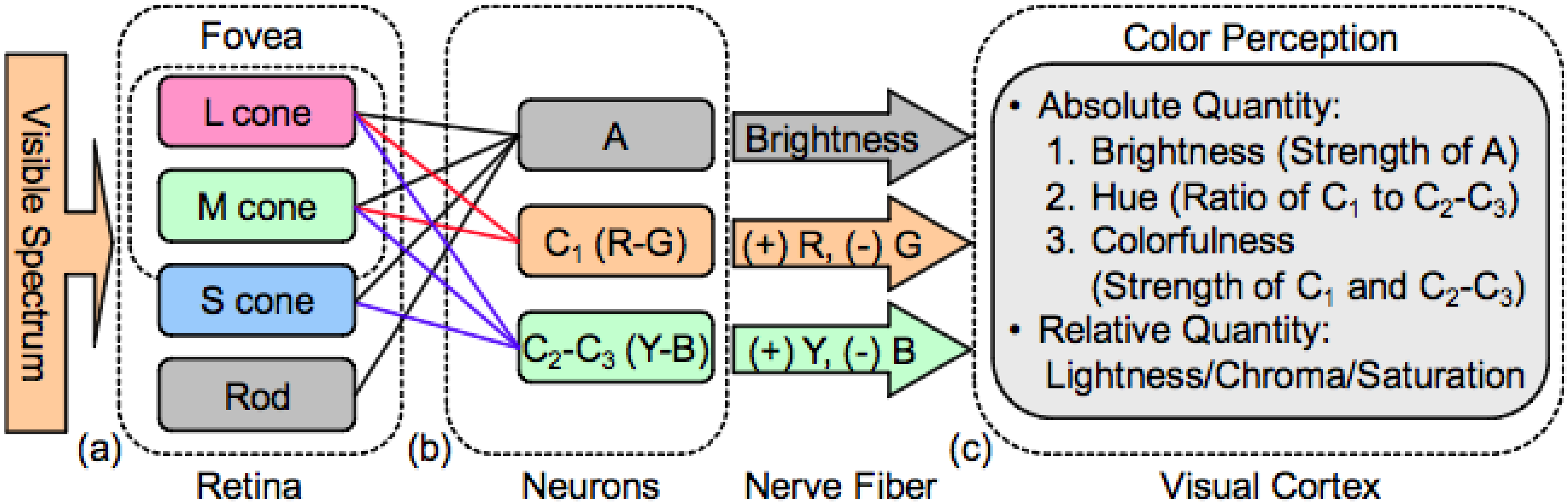
Adapted from Gonzales and Woods

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.



By Googolplexbyte - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=25539422

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.

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)

		B_1		
		G_2		
B_3	G_4	B_5	G_6	B_7
		G_8		
		B_9		

BAYER'S

- Interpolate green pixels.

Define horizontal and vertical gradients as:

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

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

- 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

Two major problems in the reconstruction

- Blurred Edges.

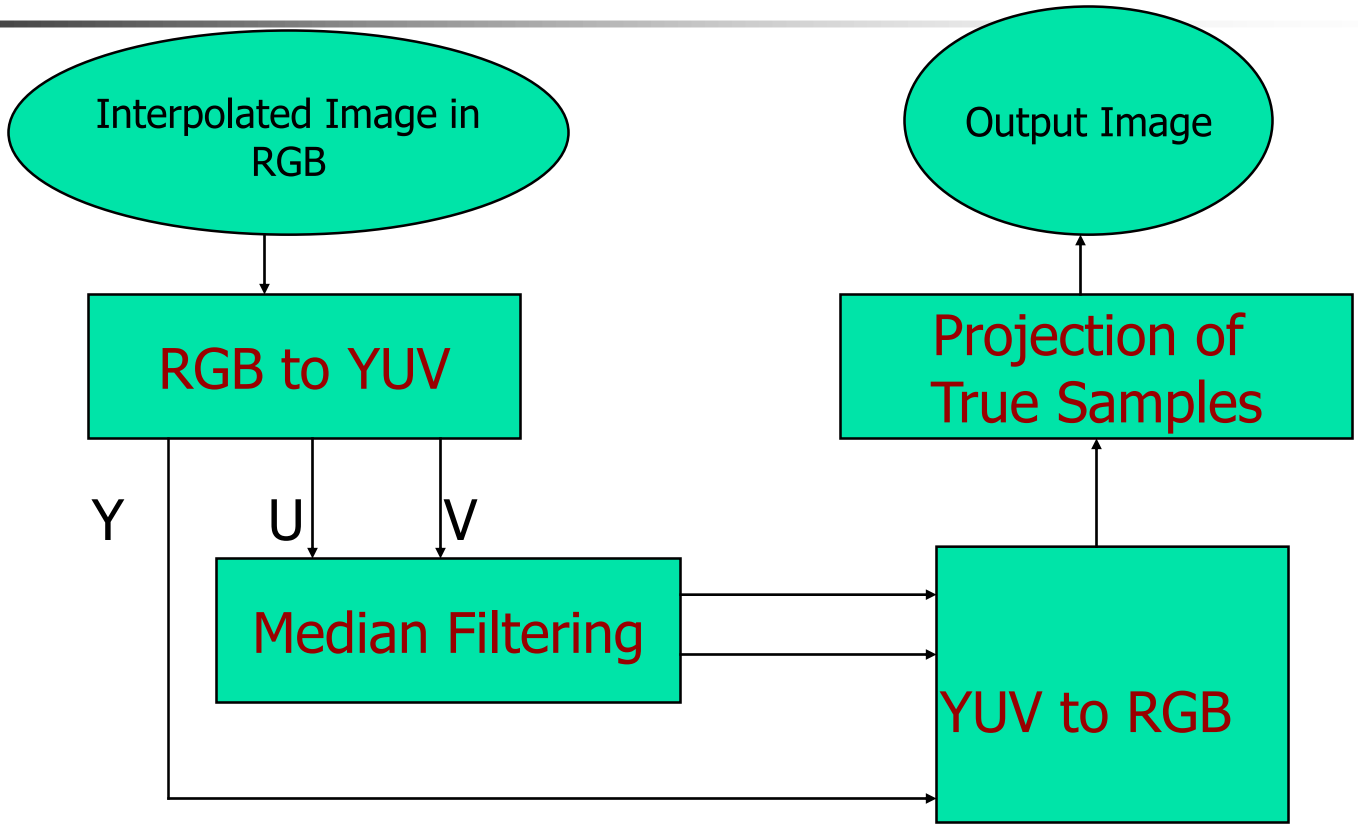
- Appearance of false colors

False Colors: An Example

Original

Reconstructed

False Color Suppression



Examples

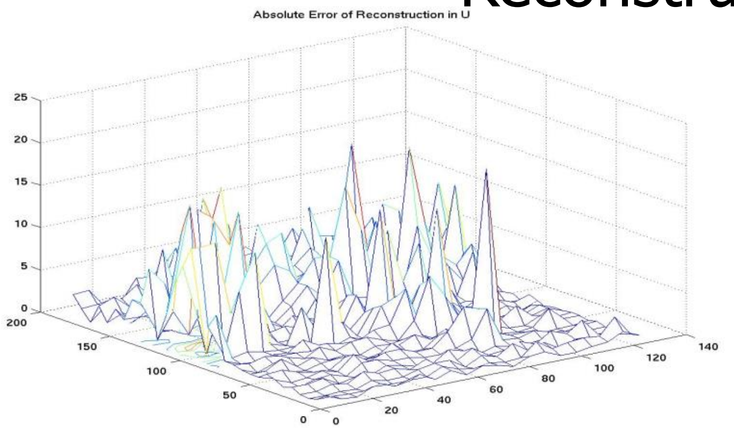
LCEC

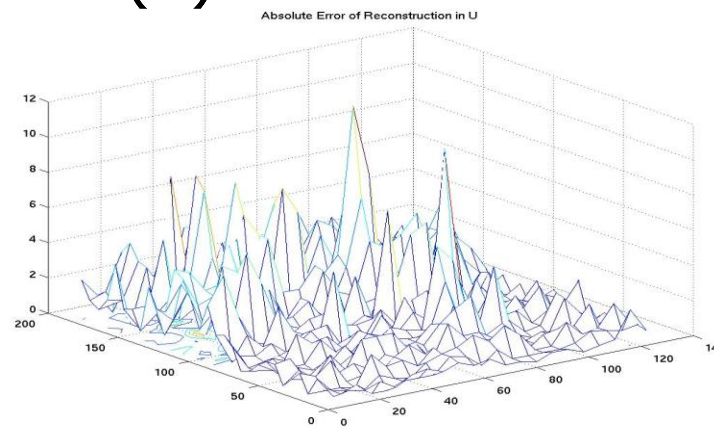
LCEC with Median (3 x 3 Mask)

LCEC with Median (5 x 5 Mask)

Suppression of Impulsive Noise

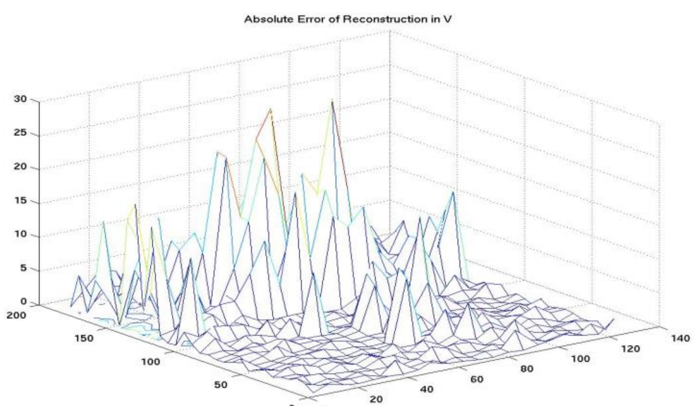
Reconstruction Error (U):

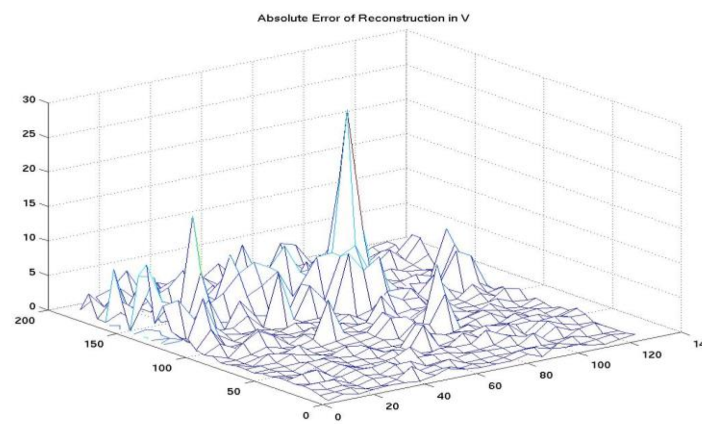




After median filtering.

Reconstruction Error (V):





Summary

- An important information for interpreting images
- Captured in the RGB color space
  - Not suitable for direct interpretation of color components such as Hue and Saturation.
- CIE Chromaticity Chart: colors in a 2-D space
  - according to tri-stimulus model of color representation
  - provides the gamut triangle for reproducing colors.
- Various other color spaces used for processing.
- In digital cameras color images mostly captured using a CFA
  - need to be interpolated to provide full color information.

Thank you!