Color fundamentals and processing

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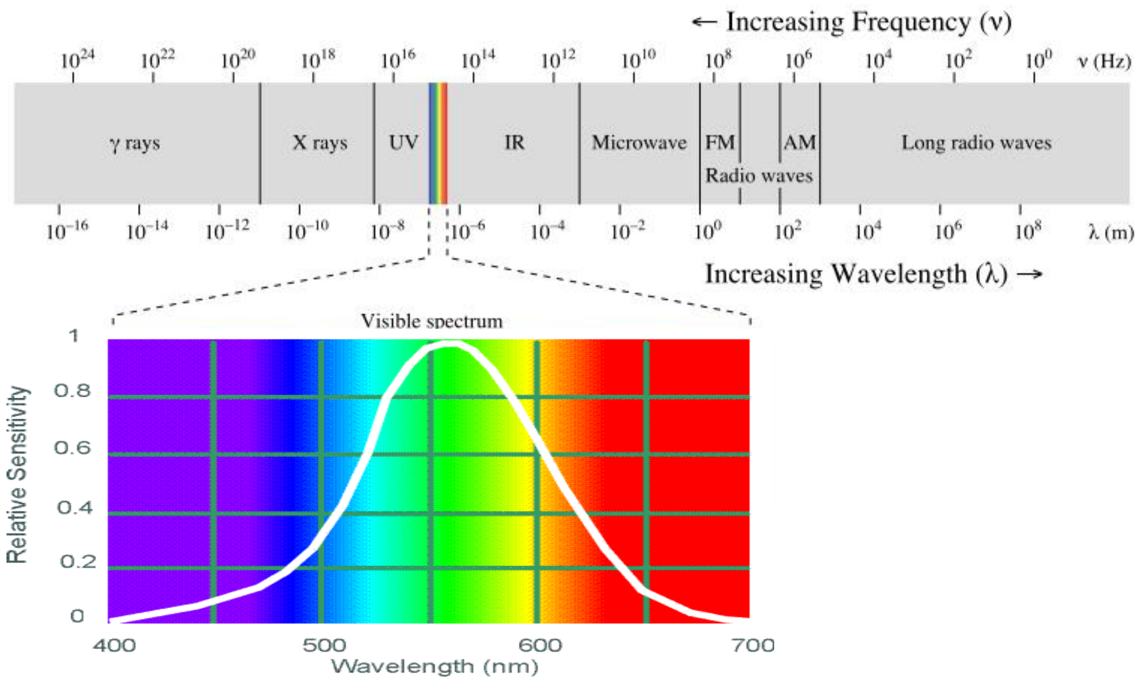
Wassily Kandinsky (1866-1944),
Murnau Street with Women, 1908

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



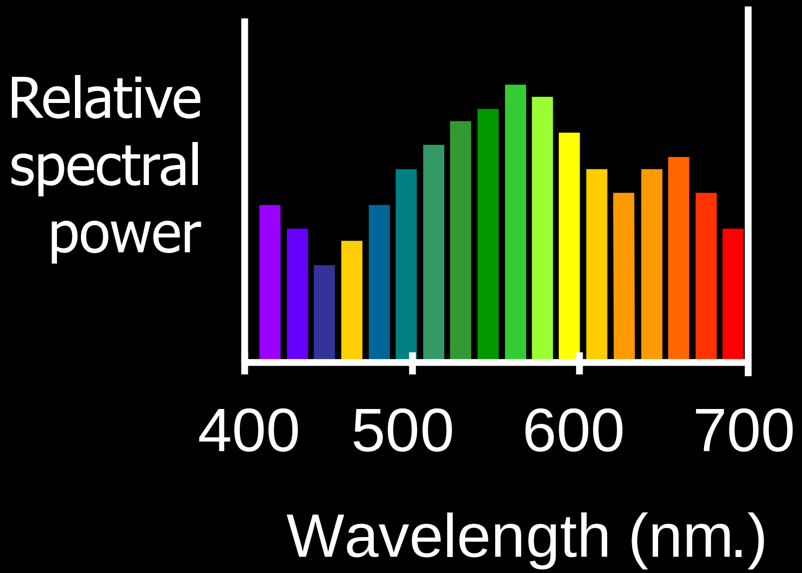
Human Luminance Sensitivity Function

Why do we see light at these wavelengths?

Because that's where the sun radiates electromagnetic energy.

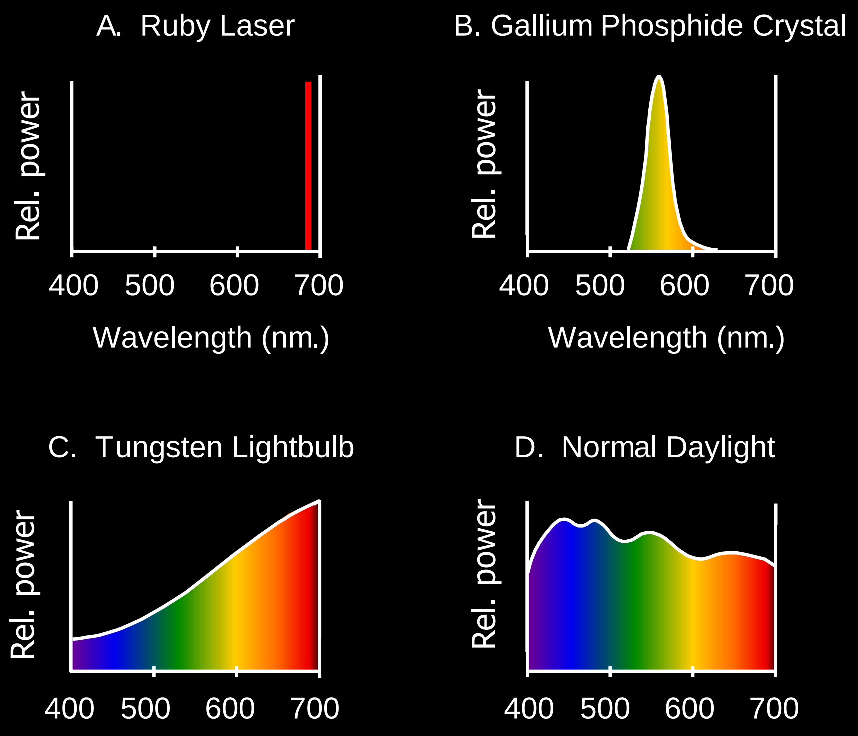
The Physics of Light

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

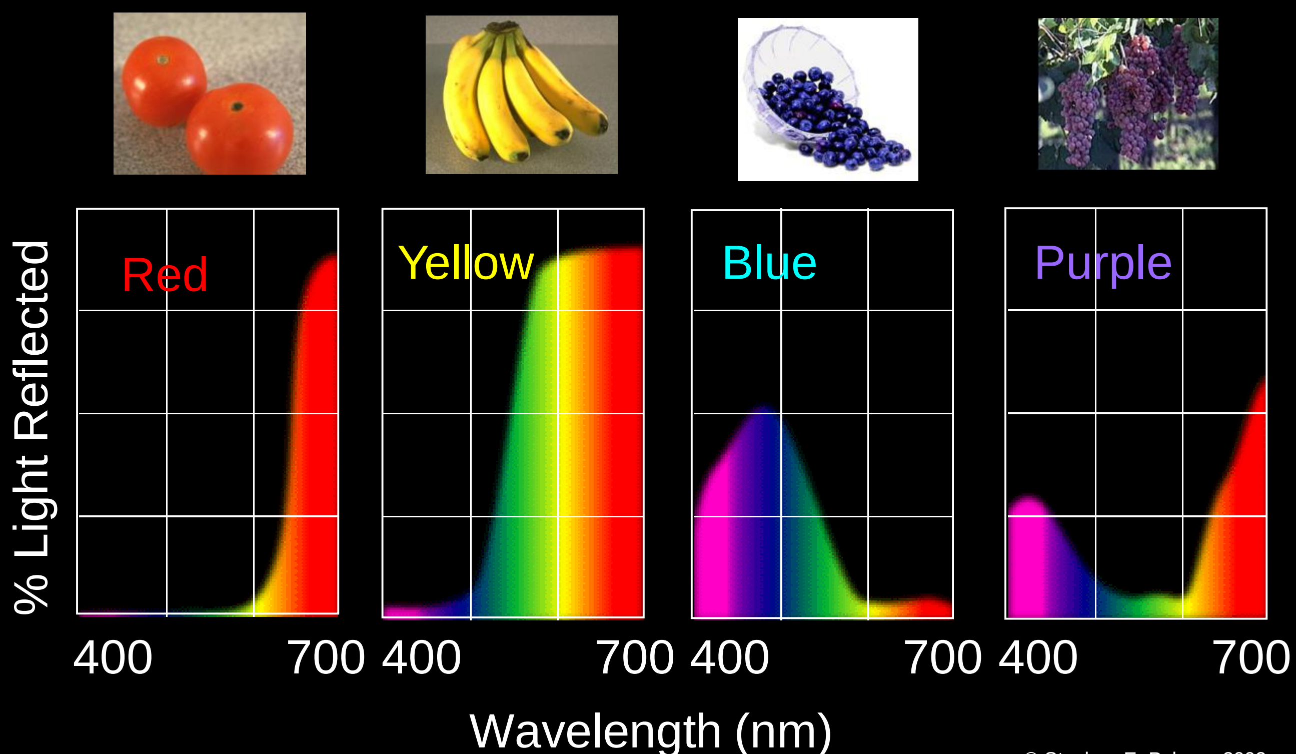
- Construct a hot body with near-zero albedo (black body)
  - Easiest way to do this is to build a hollow metal object with a tiny hole in it, and look at the hole.
- The spectral power distribution of light leaving this object is a simple function of temperature

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

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

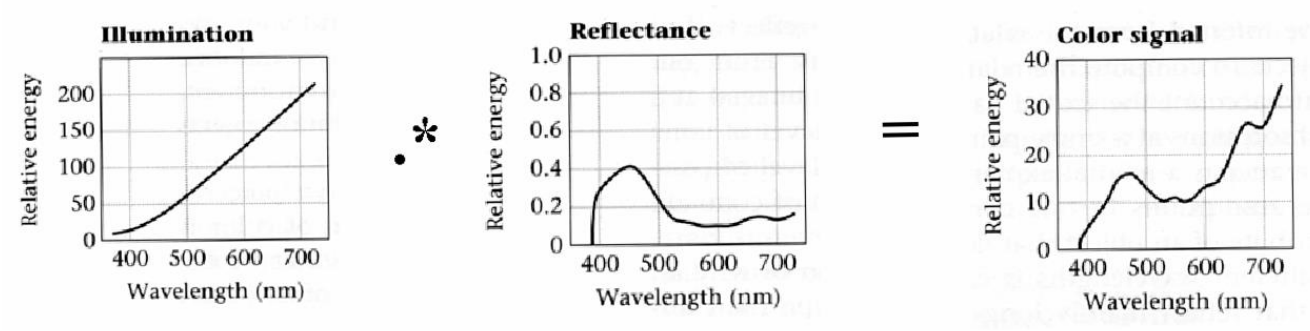
The Physics of Light

Some examples of the reflectance spectra of surfaces

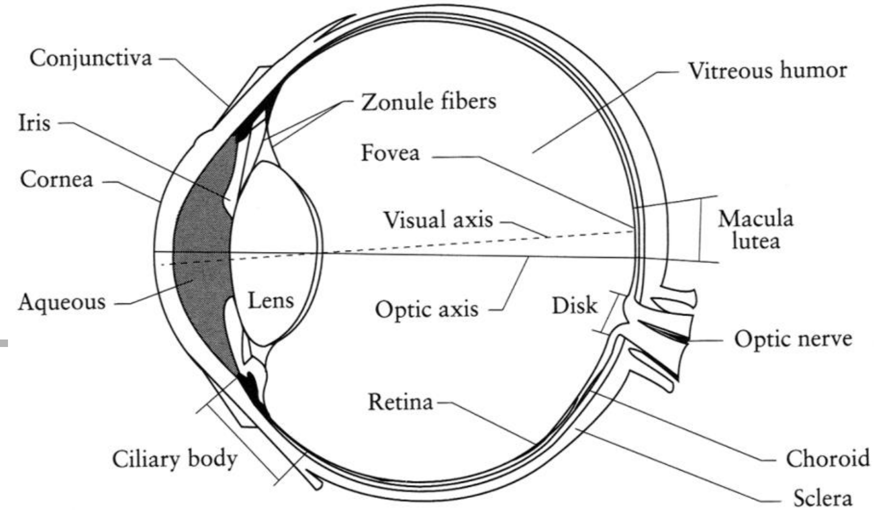


Interaction of light and surfaces

- 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



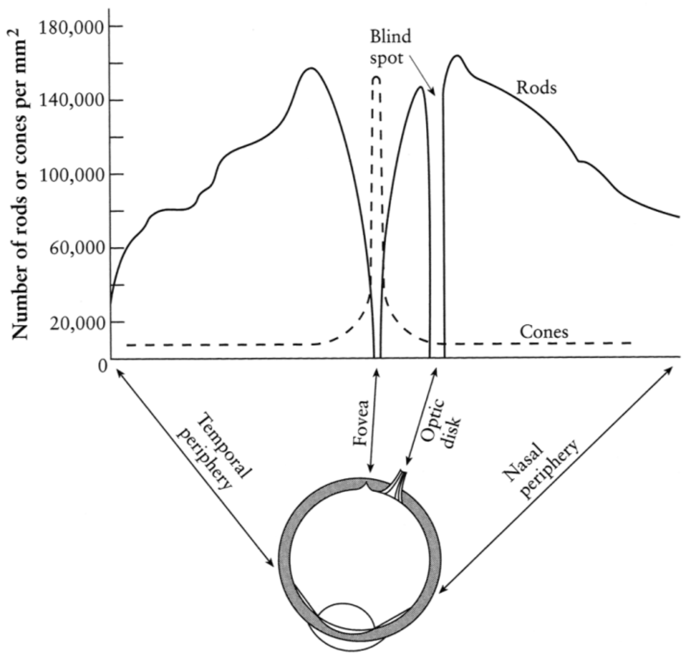
The human eye is a camera!

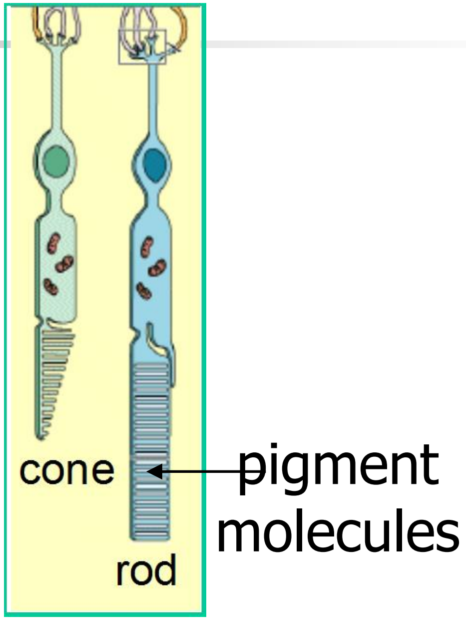
- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- What's the "film"?

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

Slide by Steve Seitz

Density of rods and cones





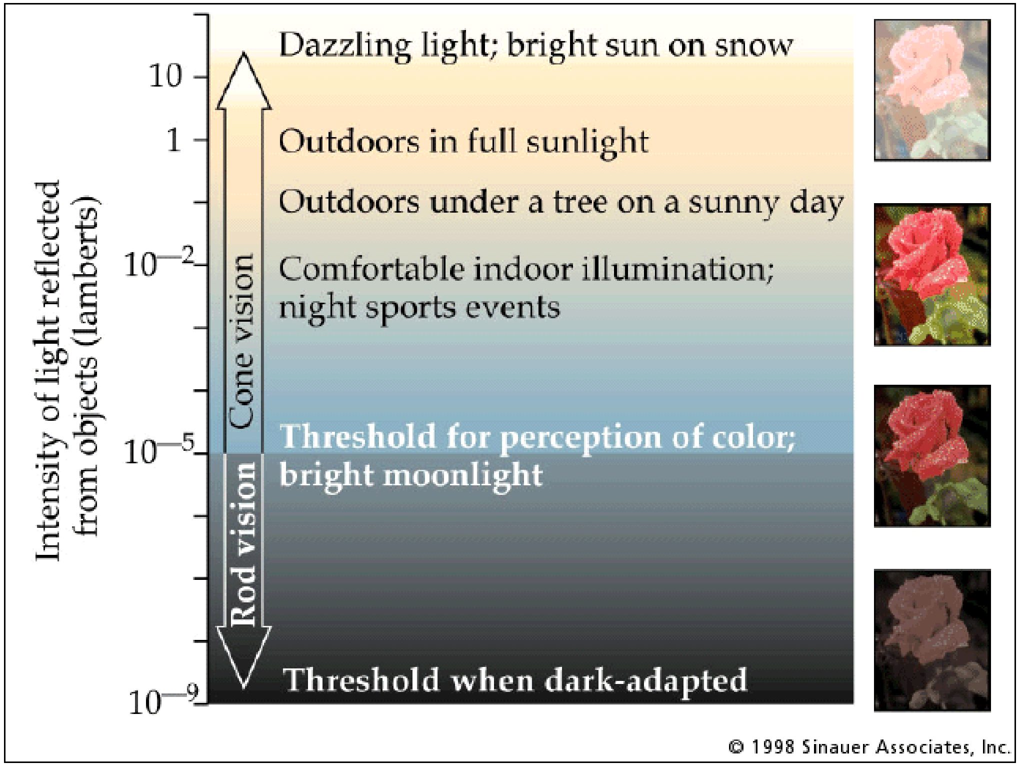
Rods and cones are *non-uniformly* distributed on the retina

- 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.



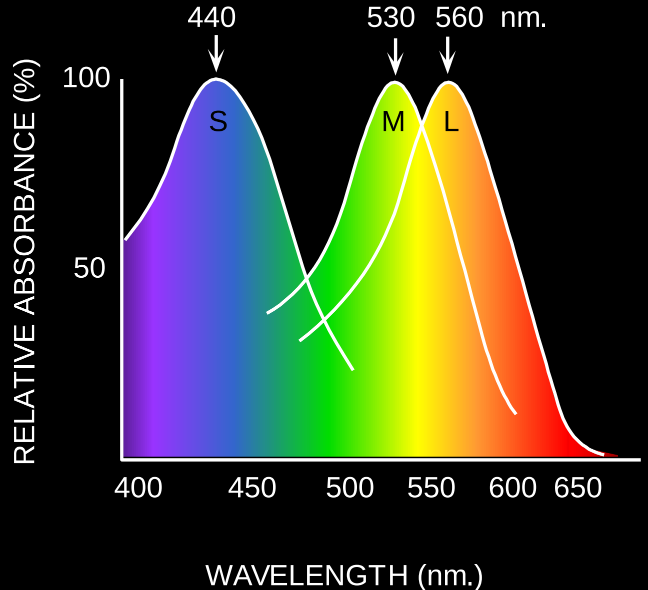
1 lambert (L) = $\frac{1}{\pi}$ candela per square centimetre (0.3183 cd/cm²) or $\frac{10^4}{\pi}$ cd m^{-2}

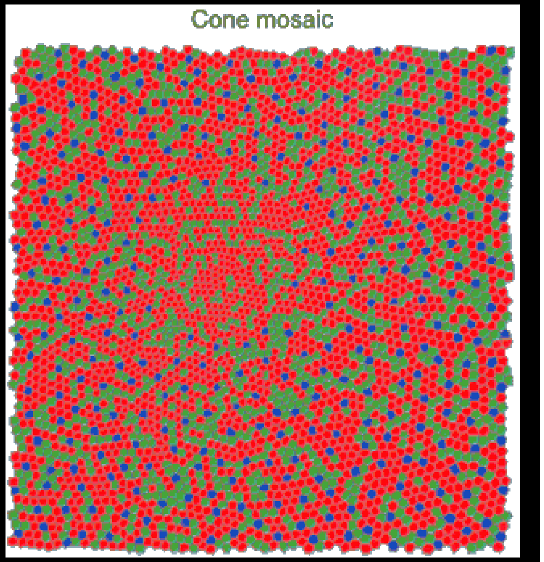
Why can't we read in the dark?

Slide by A. Efros

Physiology of Color Vision

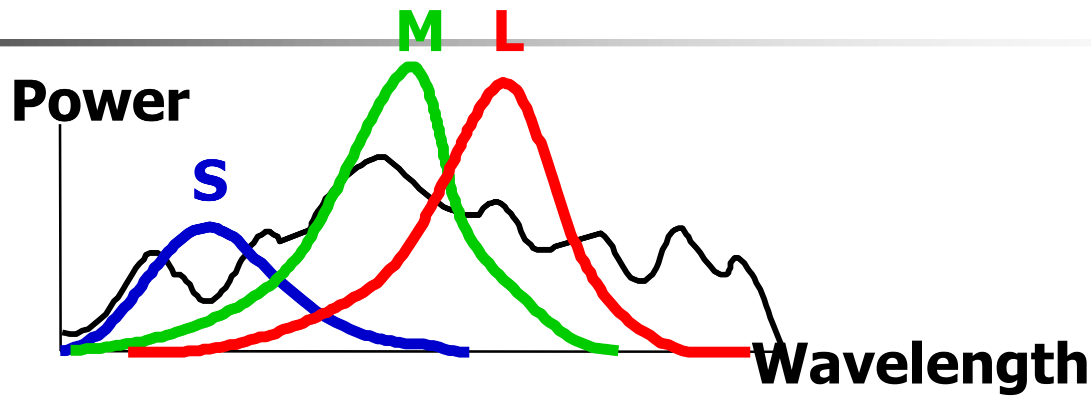
Three kinds of cones:





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

Color perception



Each cone yields one number

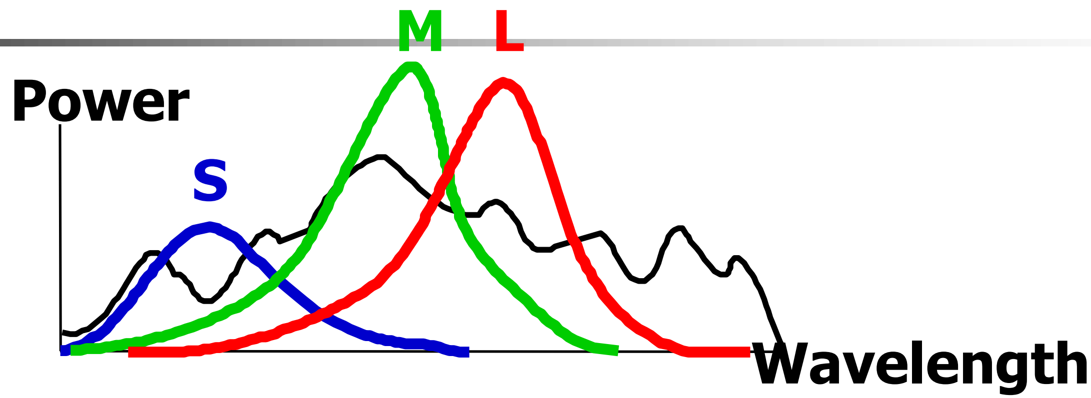
Rods and cones act as filters on the spectrum

- 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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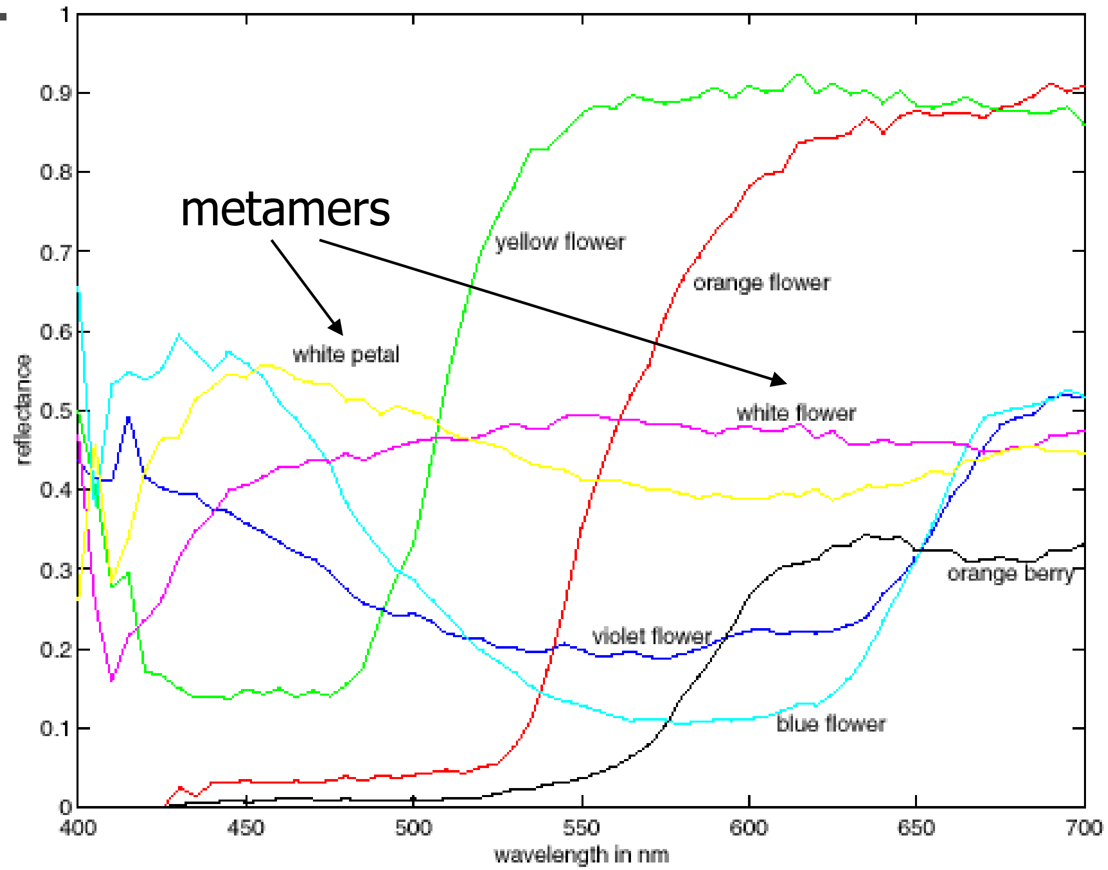
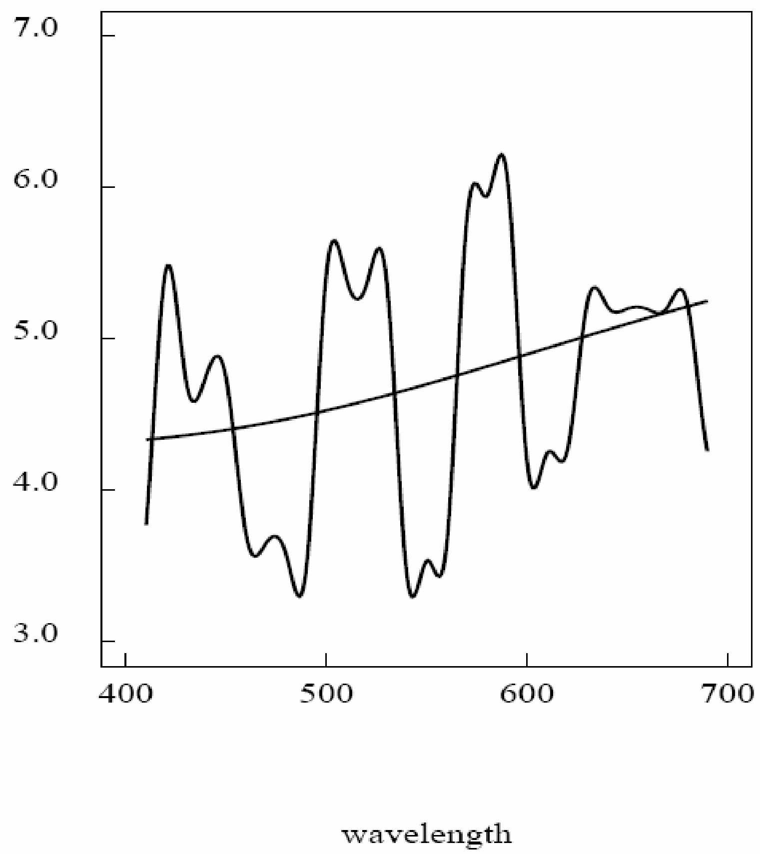
Slide by Steve Seitz

Spectra of some real-world surfaces

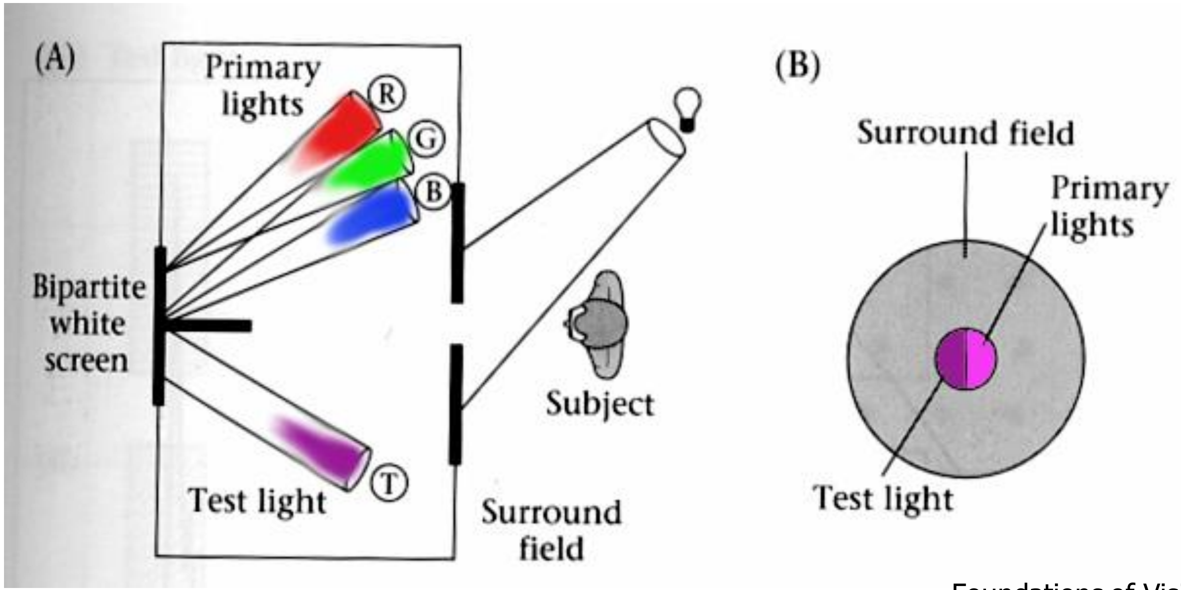


Metamers



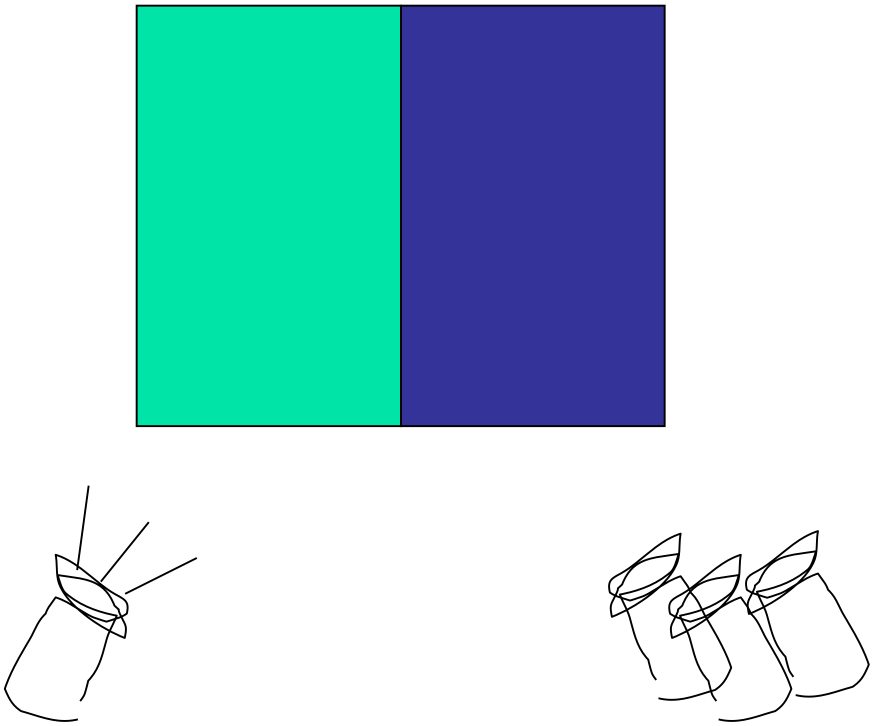
Standardizing color experience

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



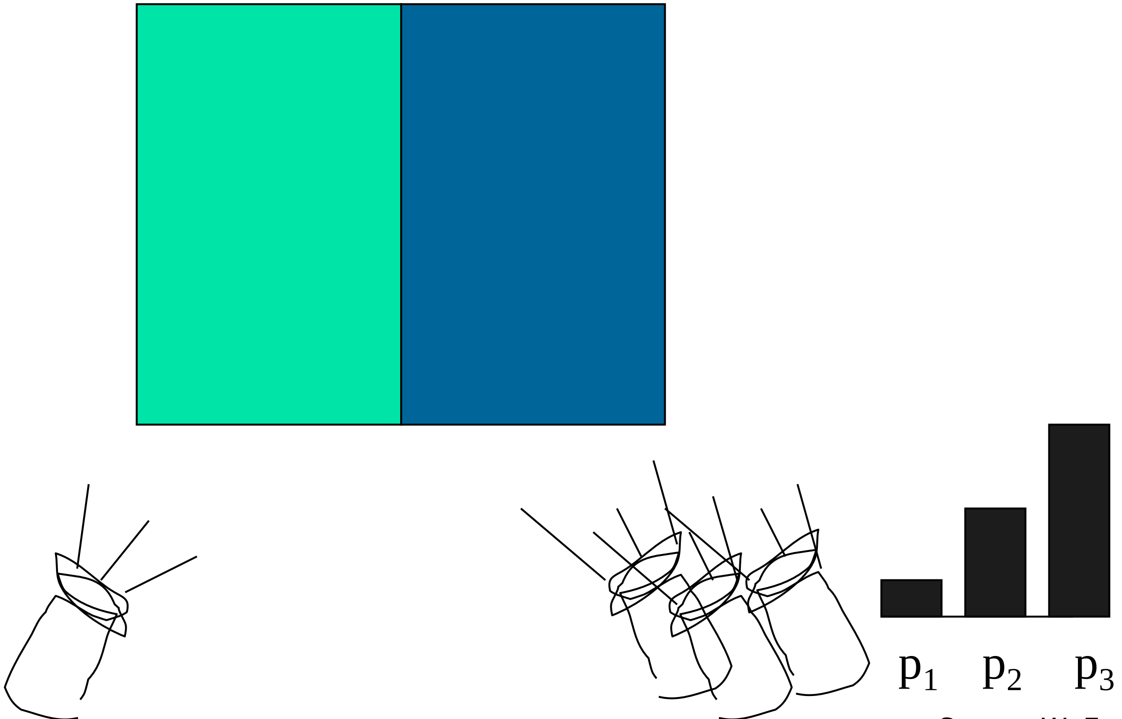
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 19

Color matching experiment 1



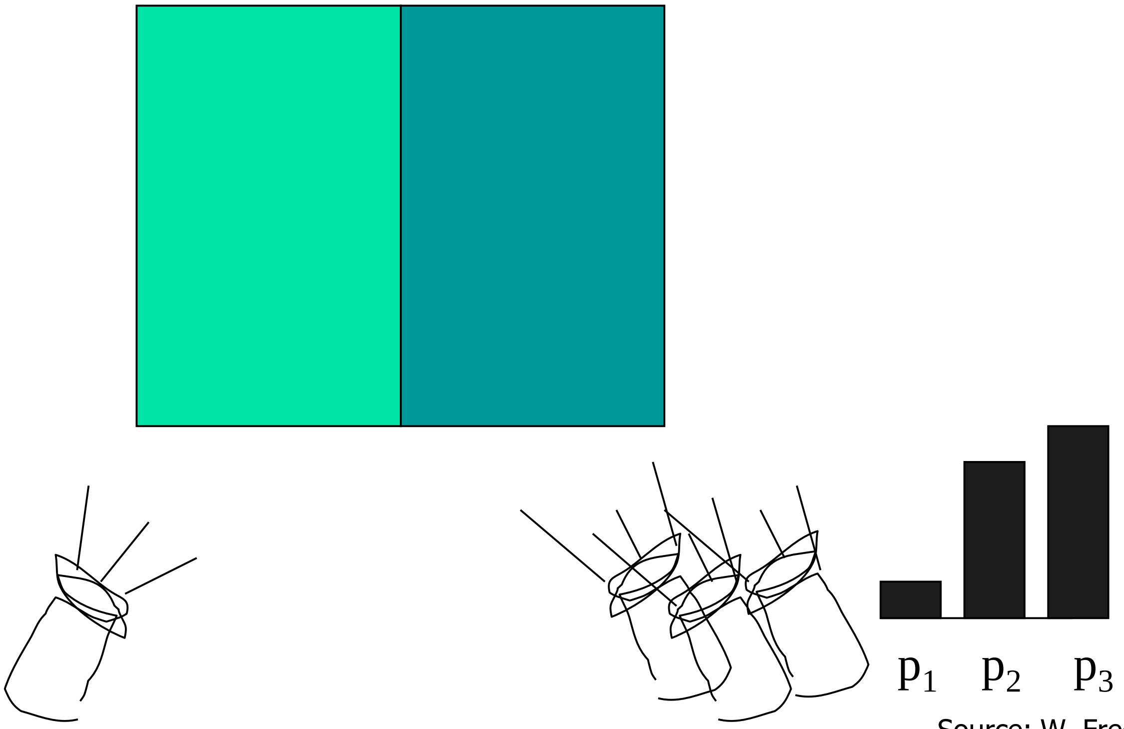
Source: W. Freeman

Color matching experiment 1



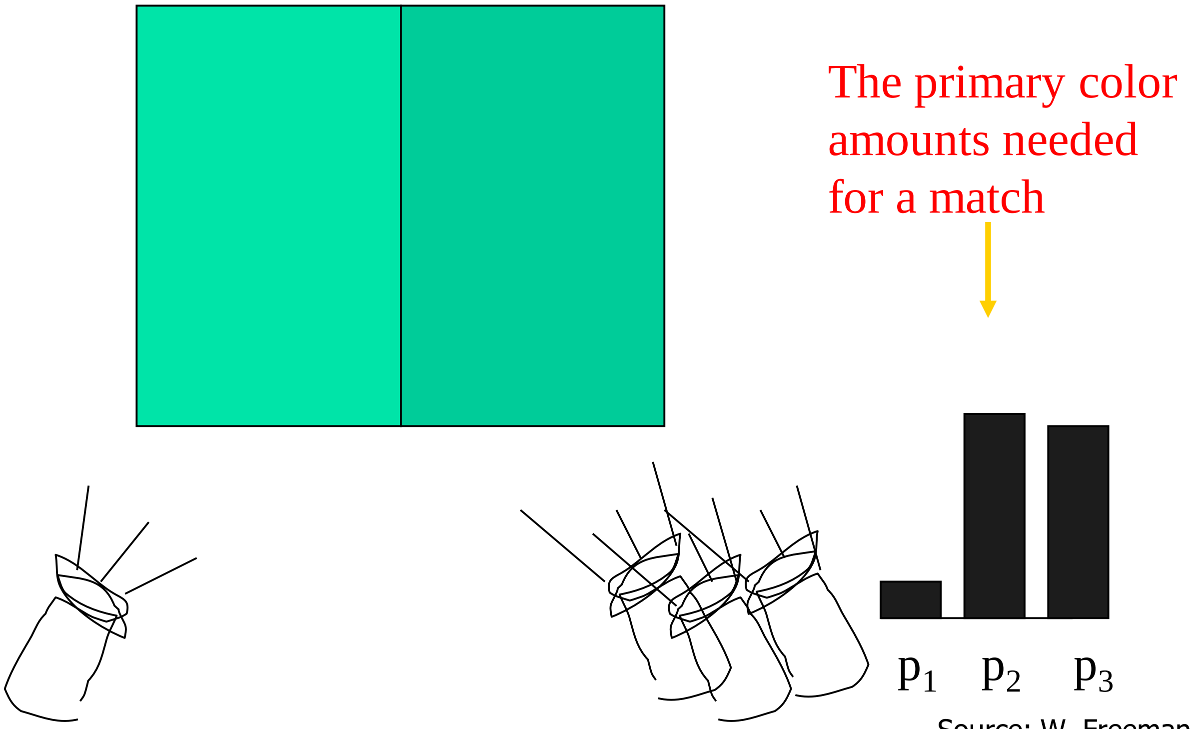
Source: W. Freeman

Color matching experiment 1



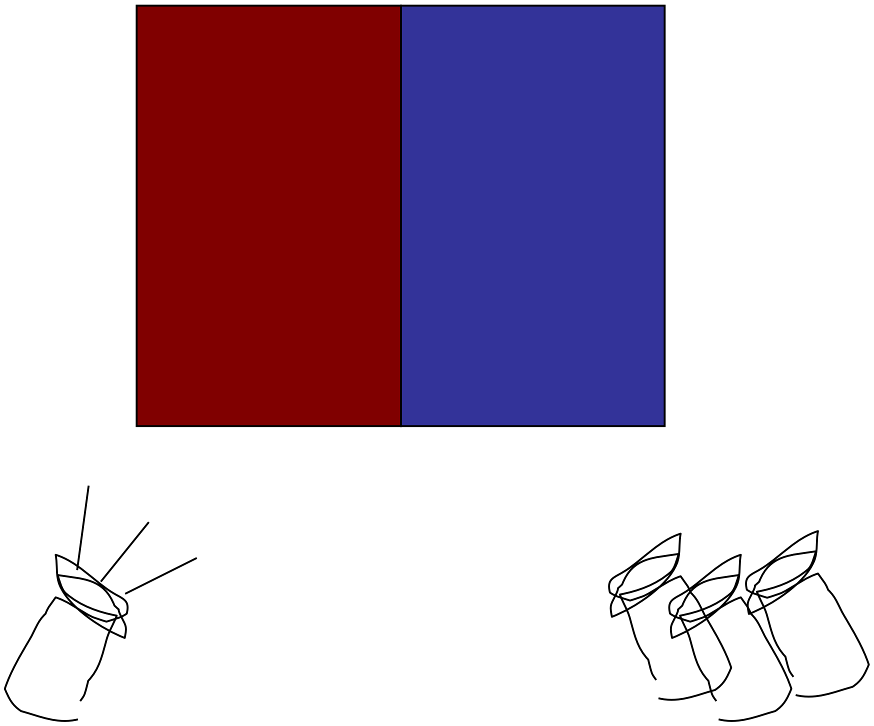
Source: W. Freeman

Color matching experiment 1



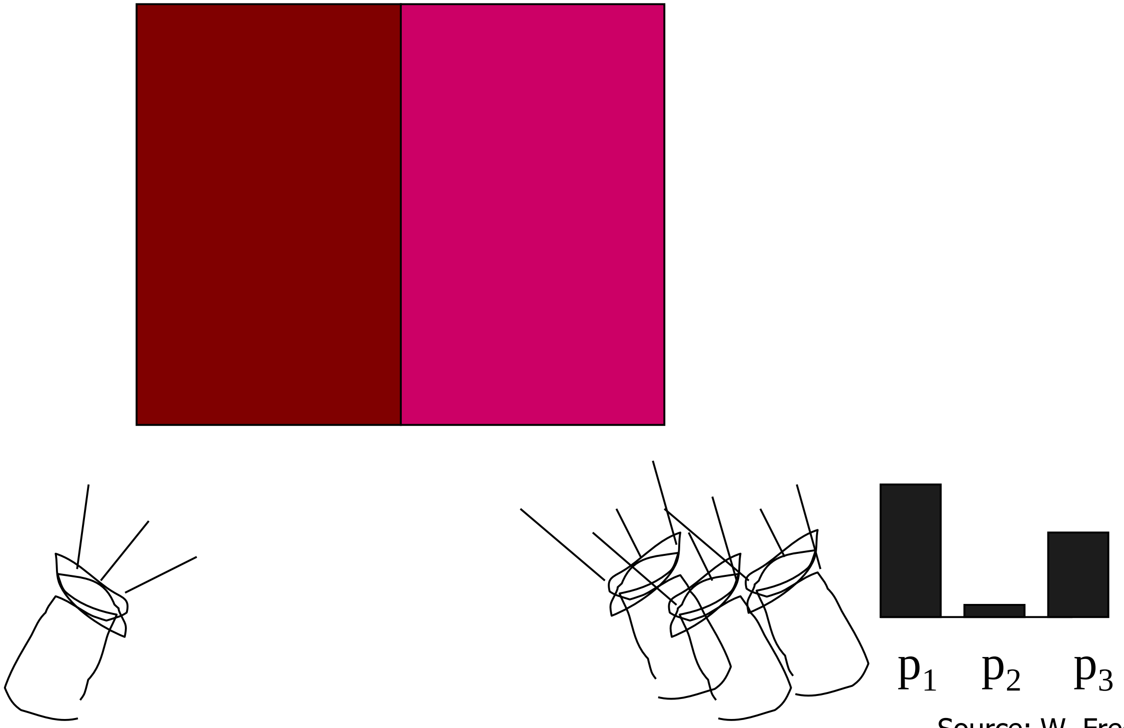
Source: W. Freeman

Color matching experiment 2



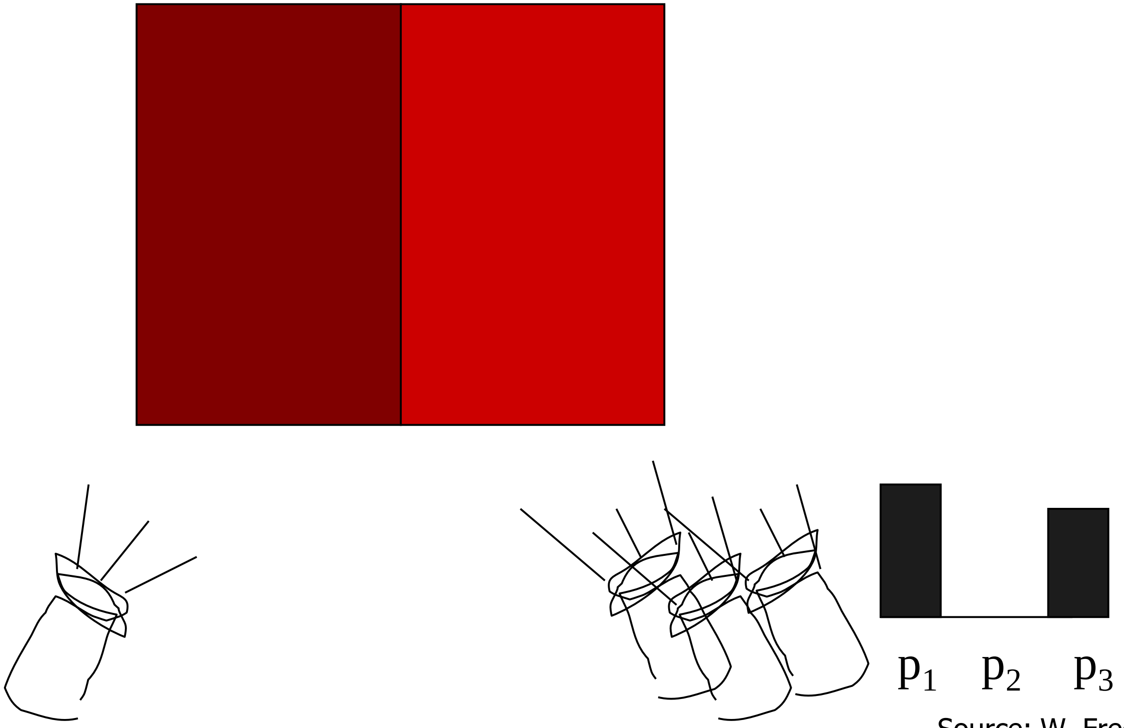
Source: W. Freeman

Color matching experiment 2



Source: W. Freeman

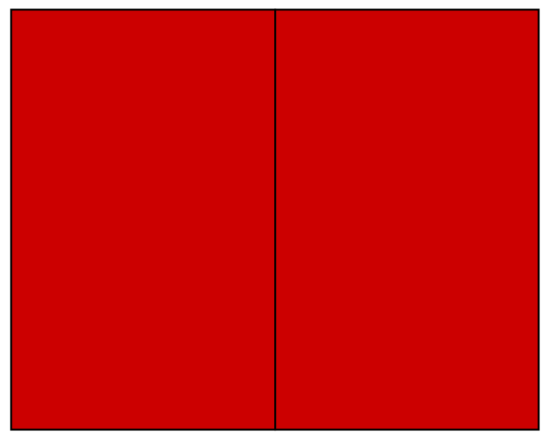
Color matching experiment 2



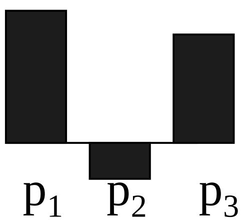
Source: W. Freeman

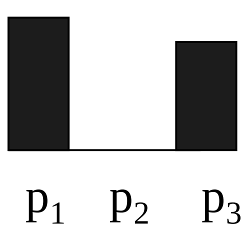
Color matching experiment 2

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



The primary color amounts needed for a match:





Source: W. Freeman

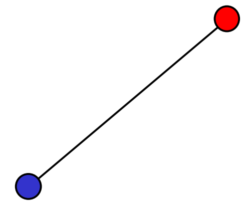
Trichromacy

- 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)

Grassman's Laws

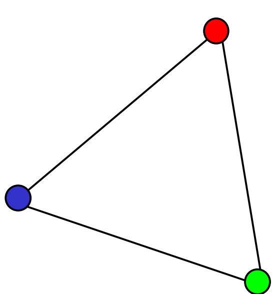
- Color matching appears to be linear.
- If two test lights can be matched with the same set of weights, then they match each other:
  - If $A = u_1P_1 + u_2P_2 + u_3P_3$ and $B = u_1P_1 + u_2P_2 + u_3P_3$. Then $A = B$.
- If we mix two test lights, then mixing the matches will match the result:
  - 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



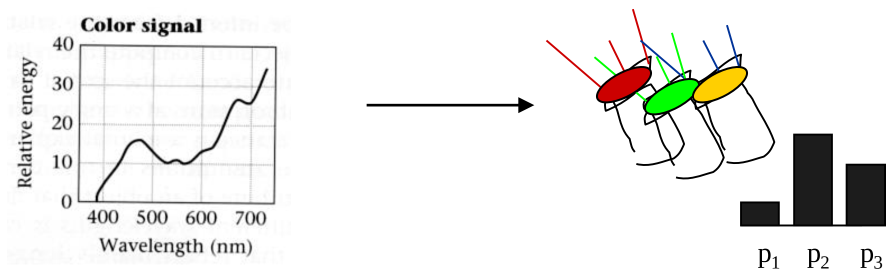
mixing two lights produces colors that lie along a straight line in color space

- 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

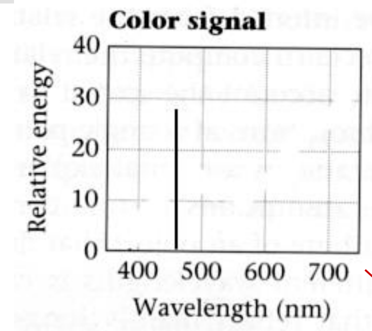


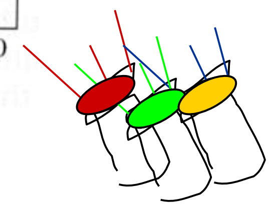
- Pick a set of primaries, $p_1(\lambda), p_2(\lambda), p_3(\lambda)$
- Measure the amount of each primary, $c_1(\lambda_0), c_2(\lambda_0), c_3(\lambda_0)$ needed to match a monochromatic light, $t(\lambda_0)$ at each spectral wavelength λ_0 (pick some spectral step size). These are the color matching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

Source: W. Freeman

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

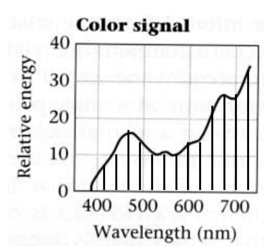
We know that a monochromatic light of wavelength λ_i will be matched by the amounts $c_1(\lambda_i), c_2(\lambda_i), c_3(\lambda_i)$ of each primary.





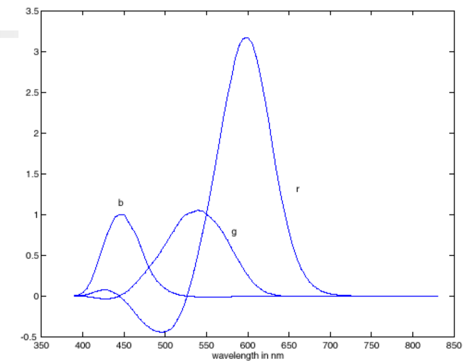
And any spectral signal can be thought of as a linear combination of very many monochromatic lights, with the linear coefficient given by the spectral power at each wavelength.

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



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*.

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

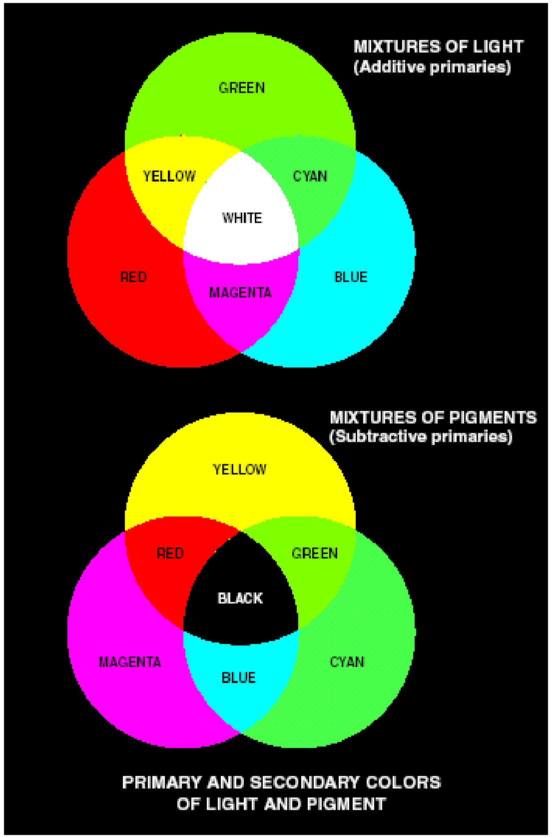
Then the amounts of each primary needed to match t are:

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

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

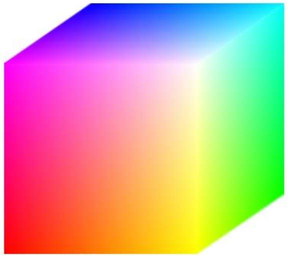


a
b

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

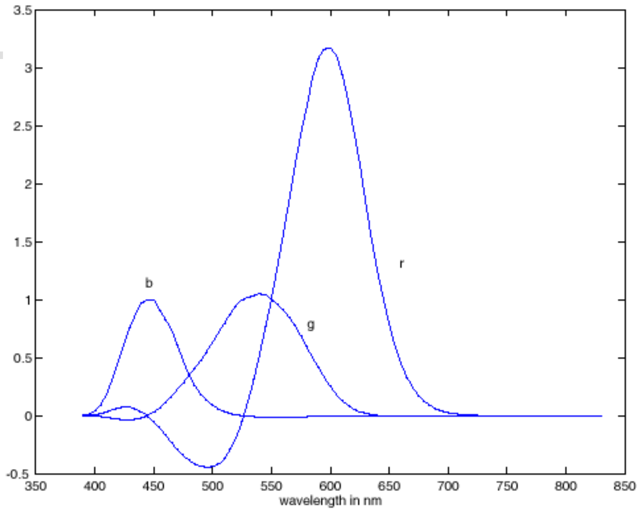


$p_1 = 645.2$ nm

$p_2 = 525.3$ nm

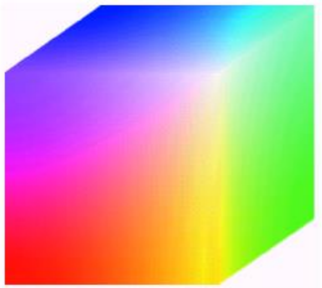
$p_3 = 444.4$ nm

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

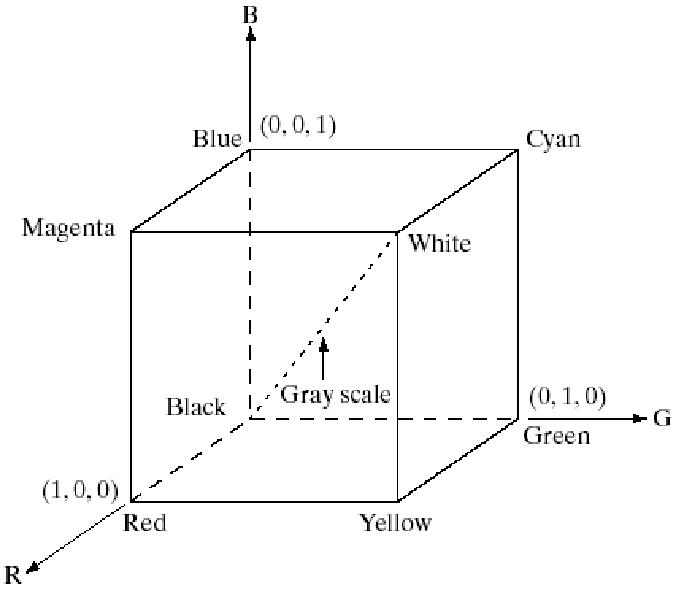


RGB matching functions

RGB model



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



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

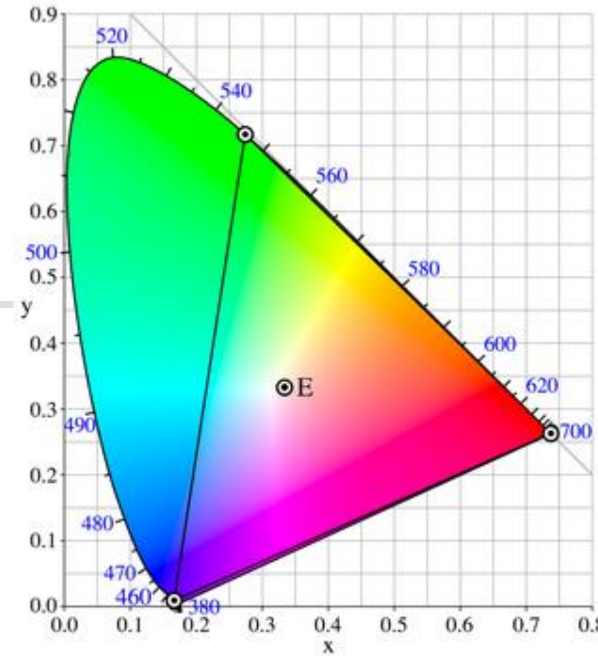
- The Commission Internationale de l'Eclairage (estd. 1931) defined 3 standard primaries: X, Y, Z that can be added to form all visible colors.
- Y was chosen so that its color matching function matches the sum of the 3 human cone responses.

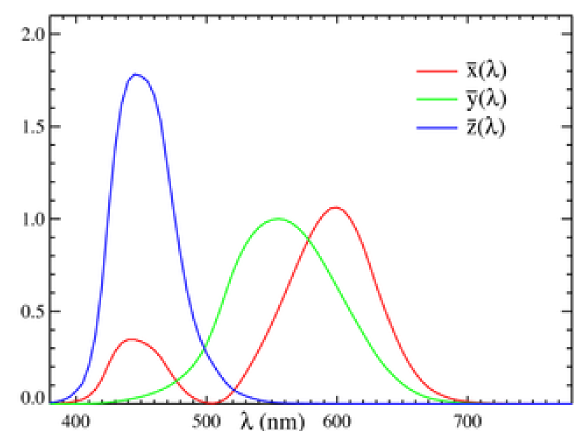
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.6067 & 0.1736 & 0.2001 \\ 0.2988 & 0.5868 & 0.1143 \\ 0.0000 & 0.0661 & 1.1149 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.9107 & -0.5326 & -0.2883 \\ -0.9843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

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
  $x = X/(X+Y+Z)$
  $y = Y/(X+Y+Z)$



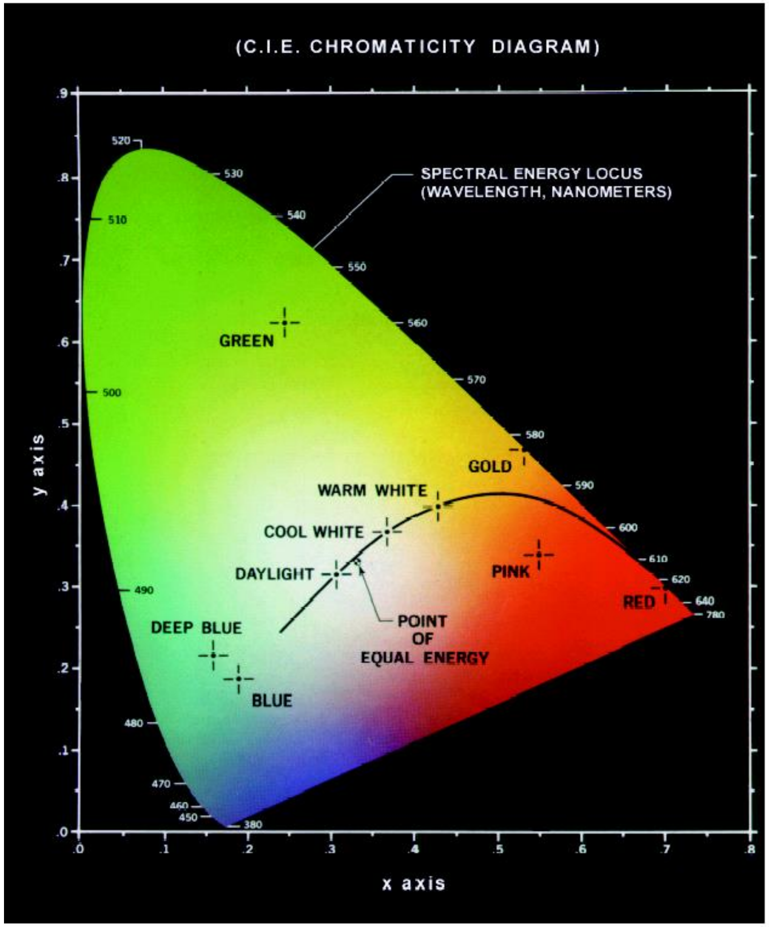


Matching functions

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

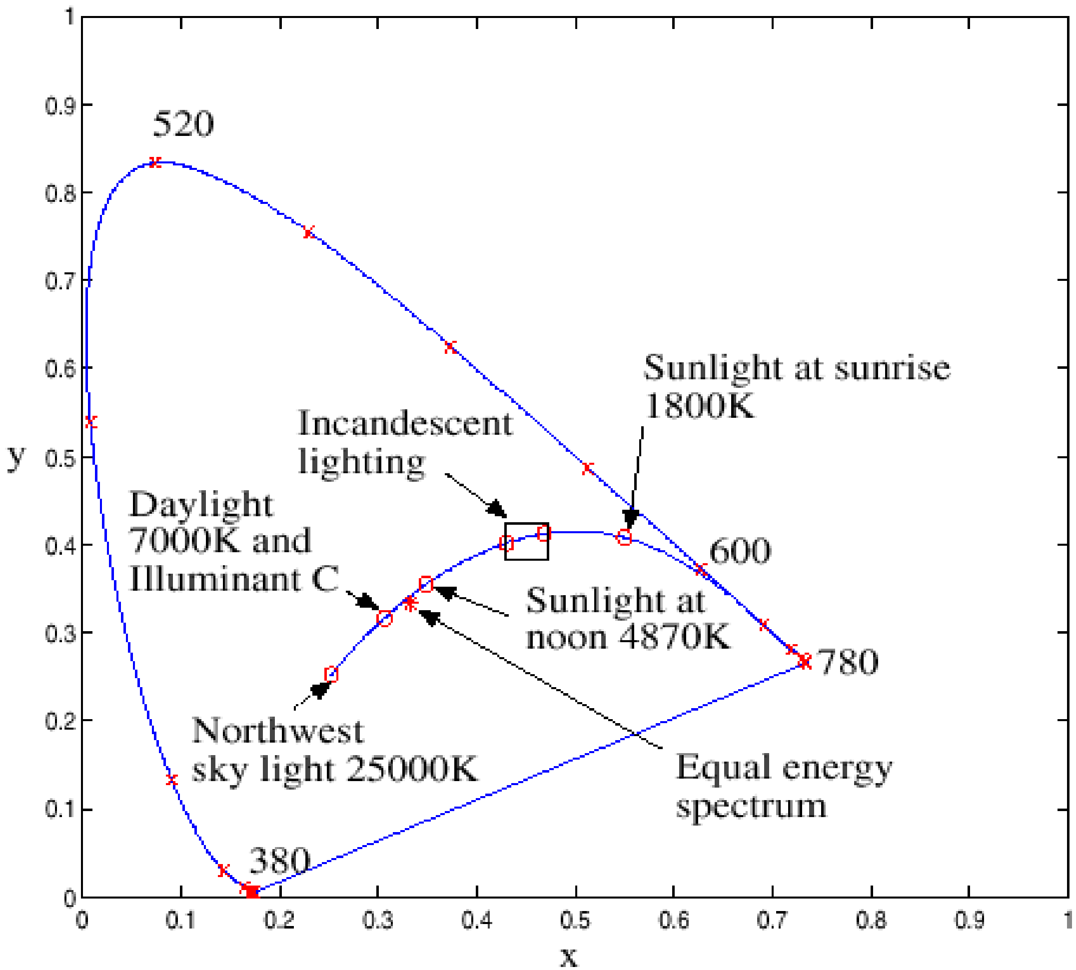
CIE chromaticity model

- 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

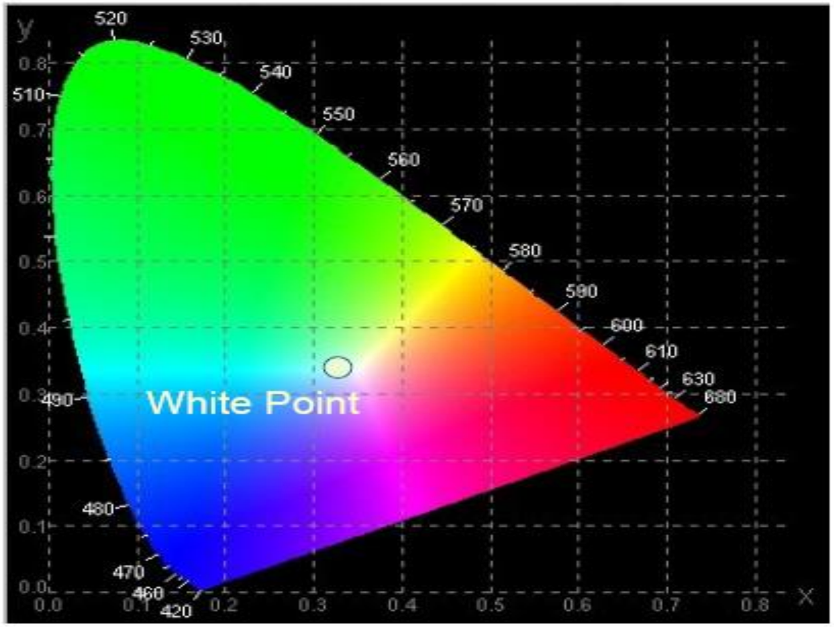
Spectral locus of monochromatic lights and the heated black-bodies



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

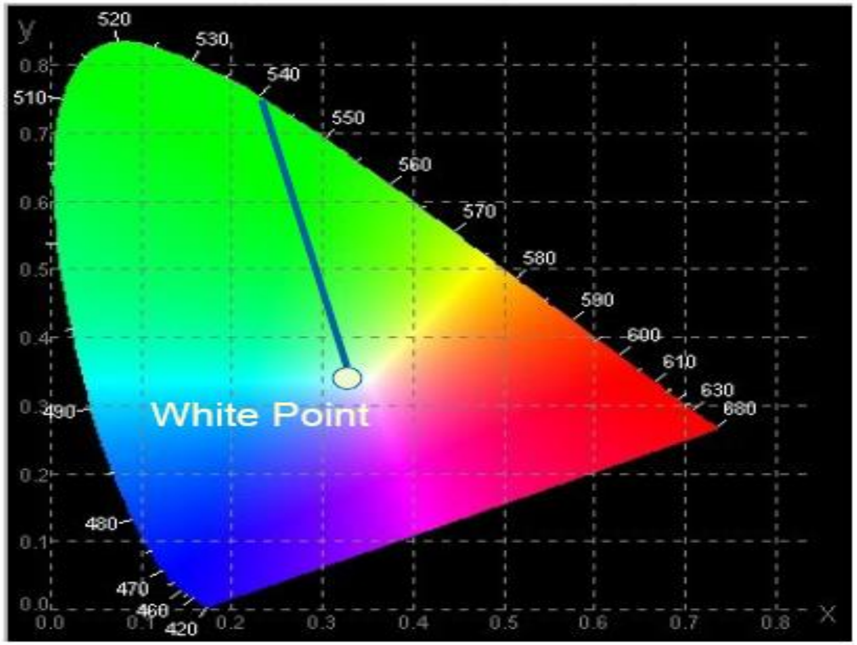
CIE Chromaticity Chart

- 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



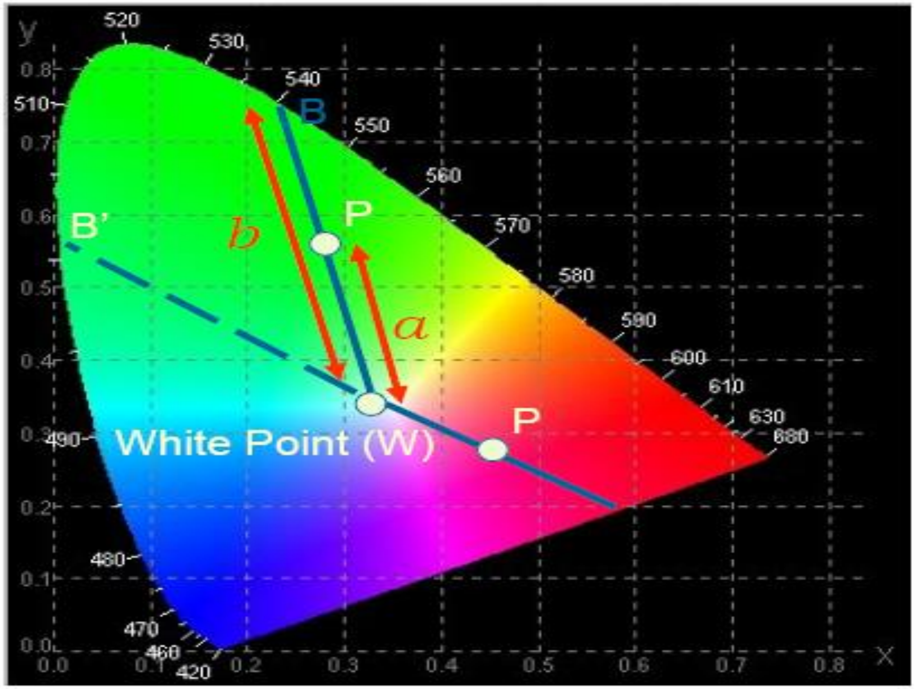
Chromaticity Chart: Saturation

- Purity (Saturation)

– How far shifted towards the spectral color

– Ratio of *a/b*

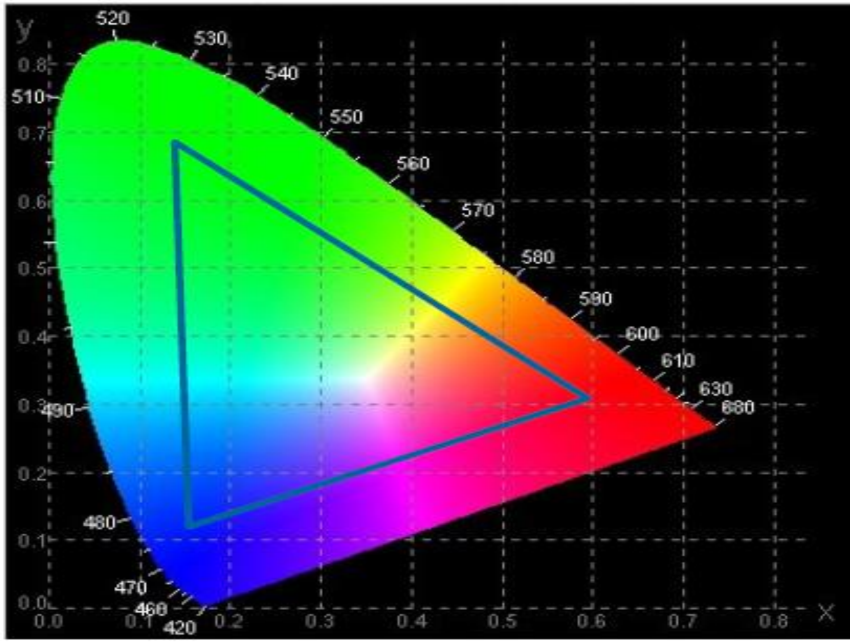
– Purity =1 implies spectral color with maximum saturation



Color Reproducibility

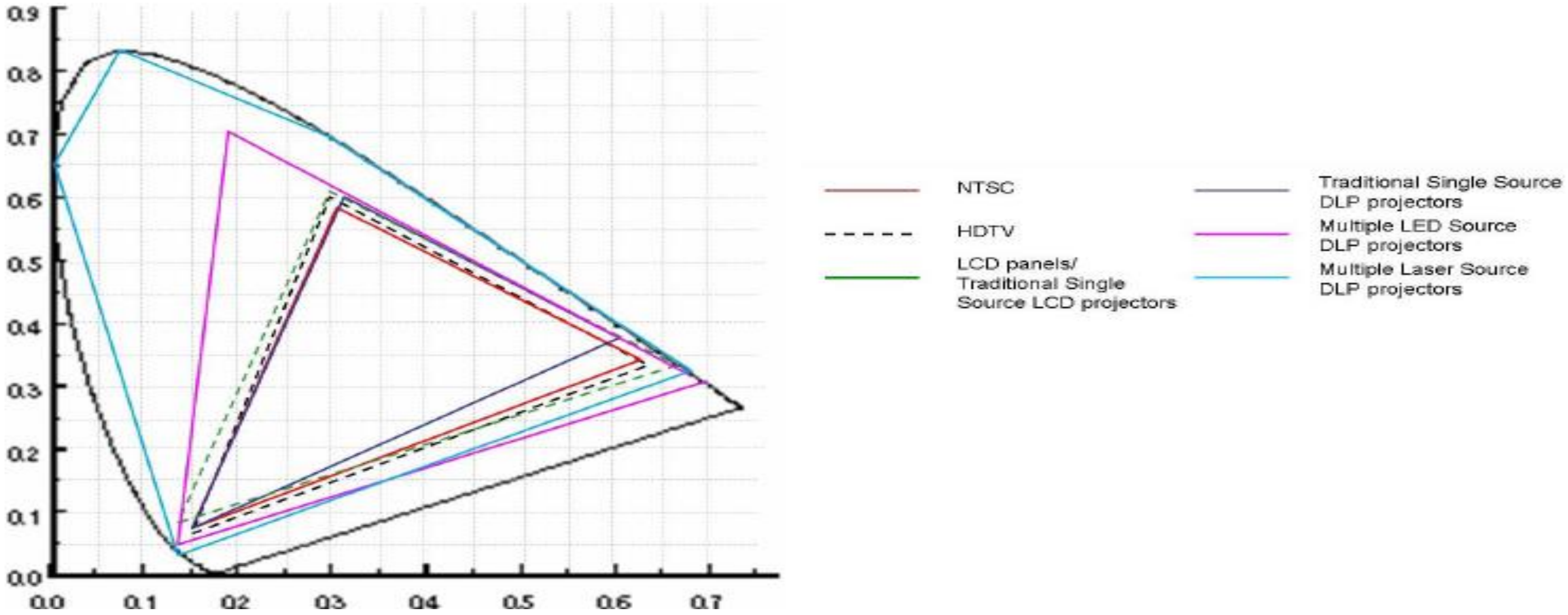
- Only a subset of the 3D CIE XYZ space called 3D color gamut
- Projection of the 3D color gamut
  - –Triangle
  - –2D color gamut

  Large if using more saturated primaries



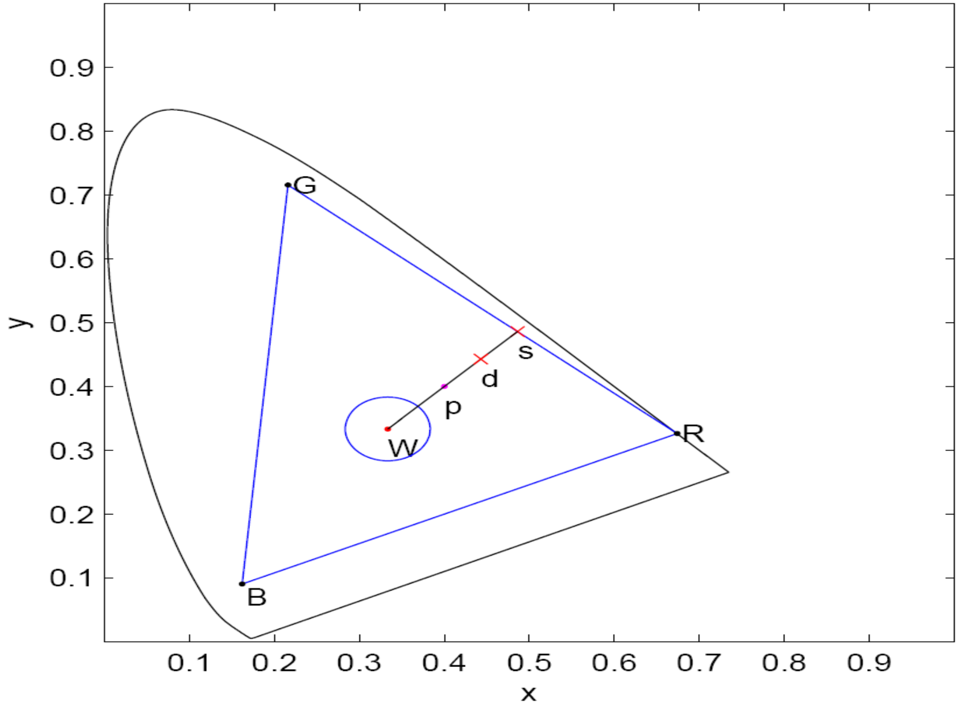
Cannot describe brightness range reproducibility

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

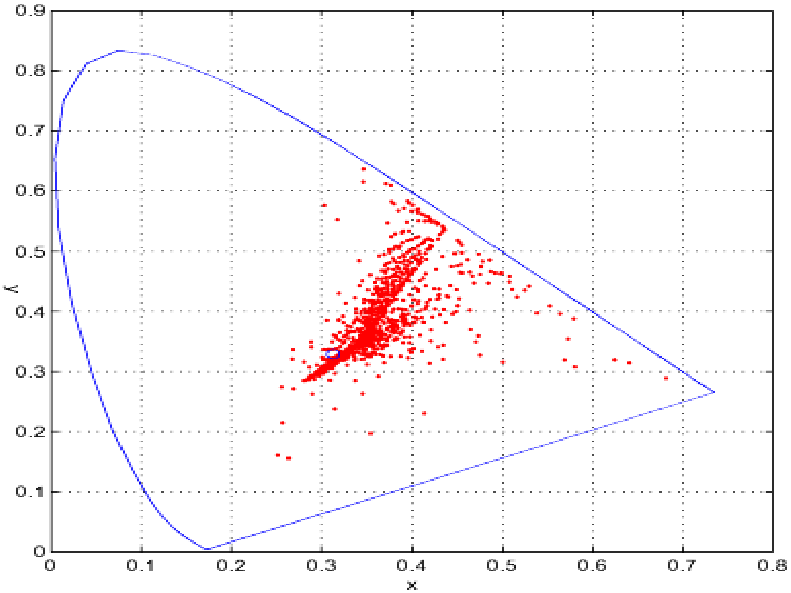
The *Center of Gravity Law* provides the resulting color $C_2 = (x_2, y_2, Y_2)$ of the mixture of the two colors $W = (x_W, y_W, |Y_W|)$ and $S = (x_S, y_S, Y_1)$ where

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

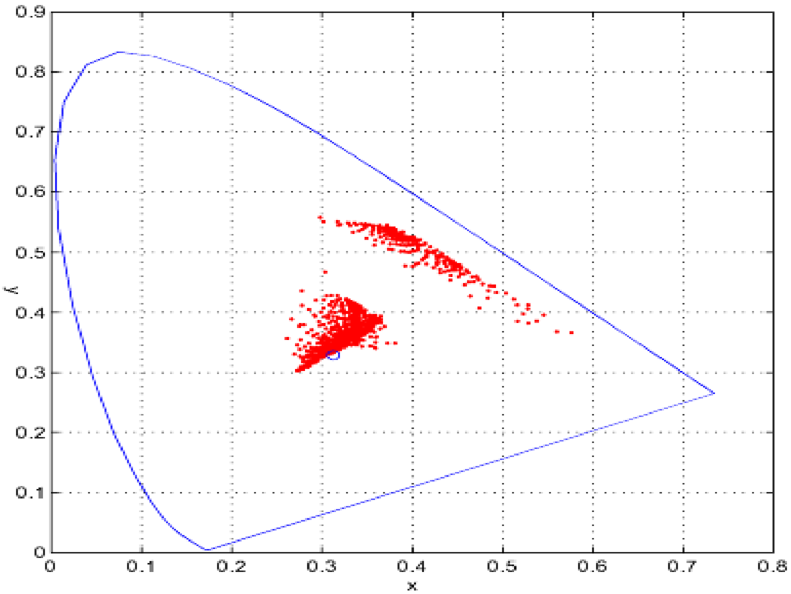
$$Y_W = \kappa Y_{avg}$$

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

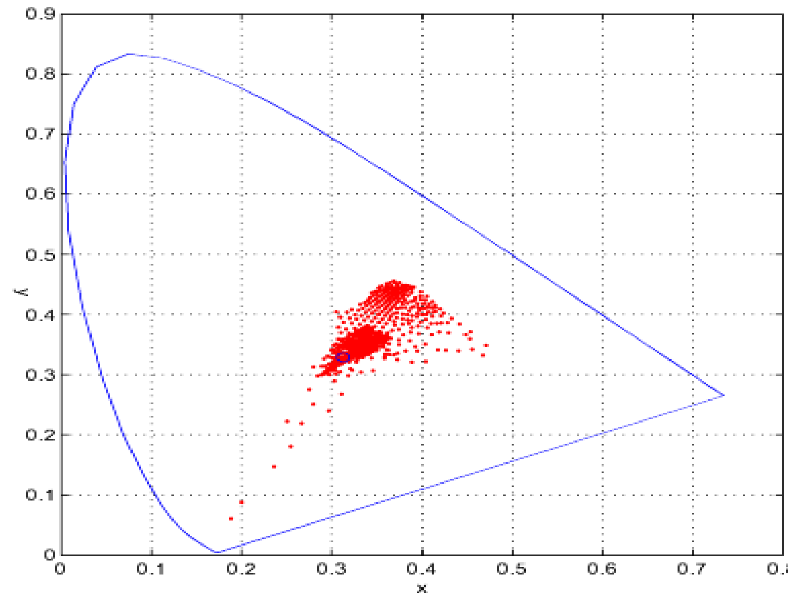
Alps - Original



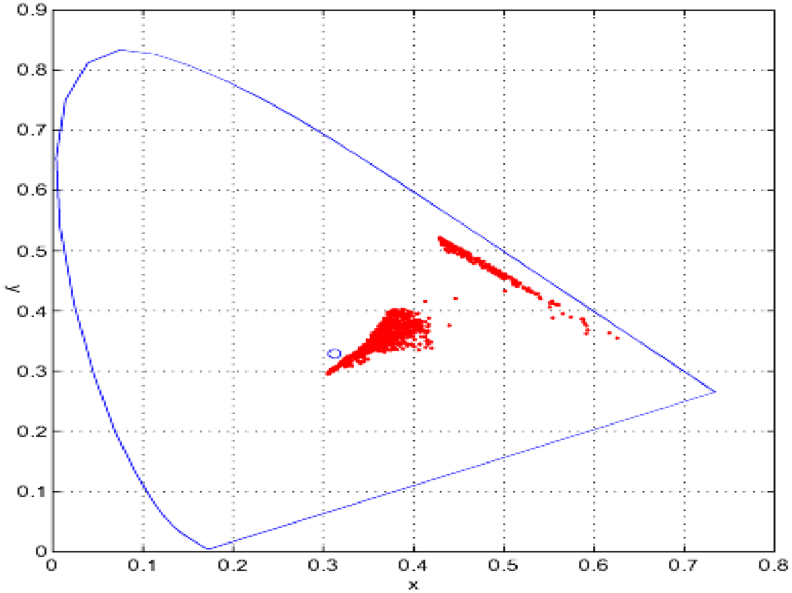
Saturated Image



De-saturated Image



Saturated – De-saturated



Desturated image with –ve k

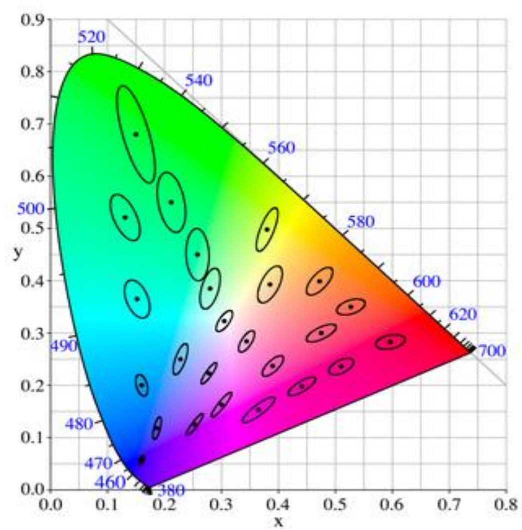
Desaturation by shifting white to (0.5,0.2)

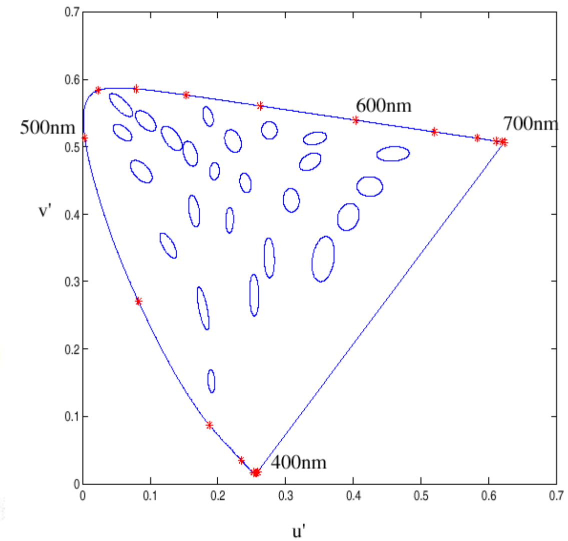
Shifting white to (0.5,0.4)

Shifting white to (0.2,0.5)

Uniform color spaces

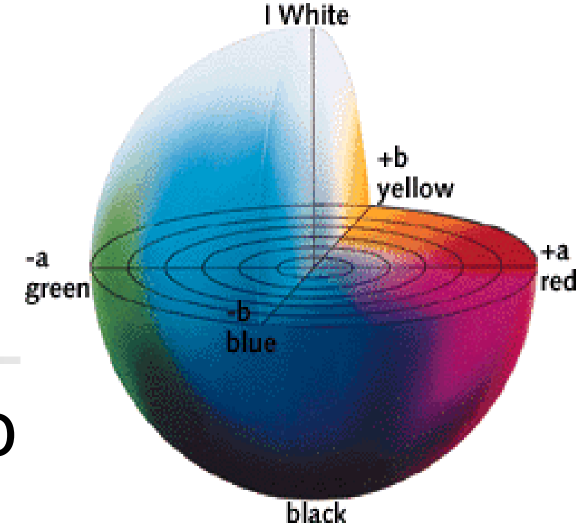
- Unfortunately, differences in x,y coordinates do not reflect perceptual color differences
- CIE u'v' is a projective transform of x,y to make the ellipses more uniform





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

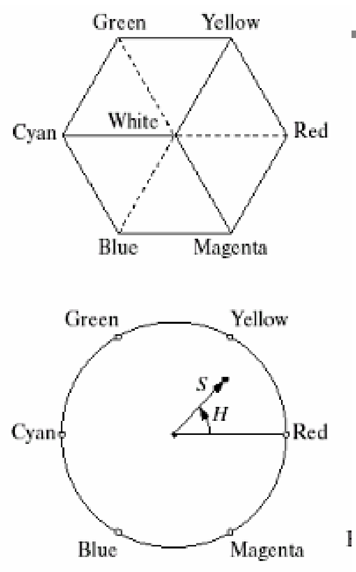
Adapted from Linda Shapiro, U of Washington

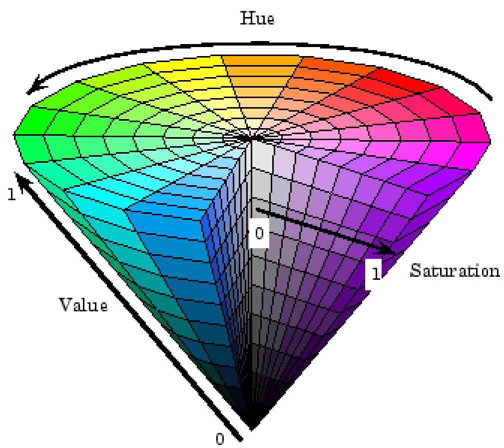
YIQ model

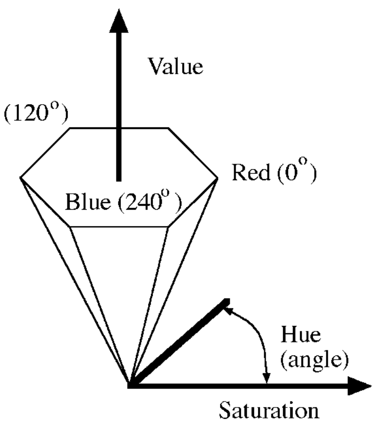
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.532 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- 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.

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

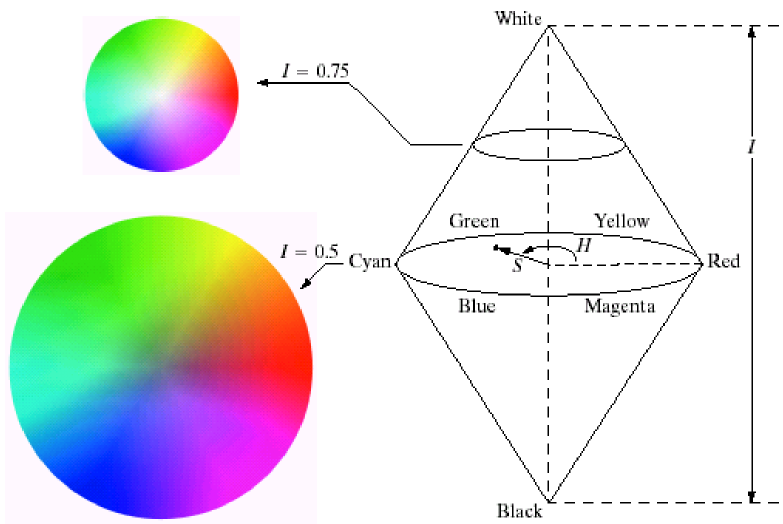
$$S = 1 - \frac{\min(R, G, B)}{I}$$

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

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

HSV model

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

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

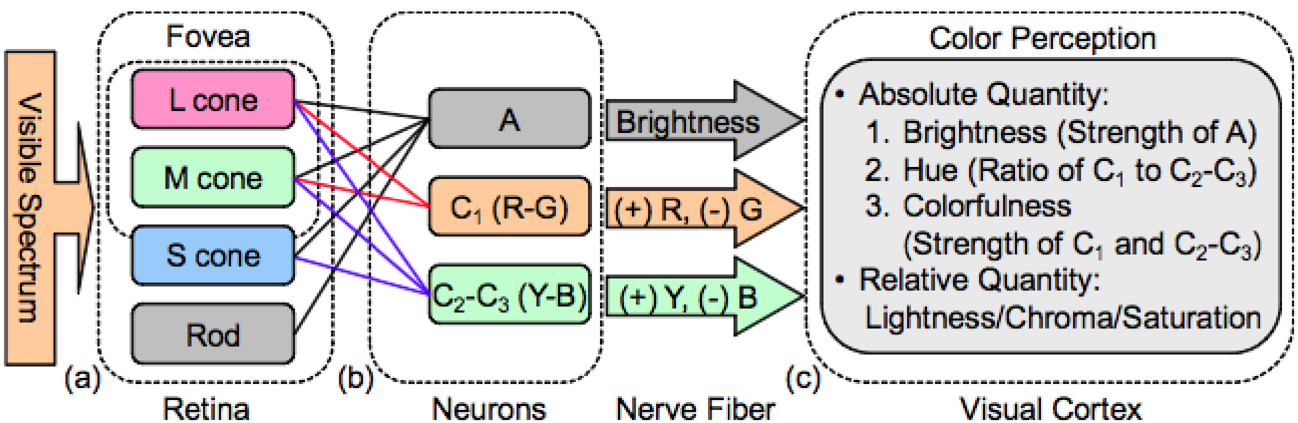
Adapted from Gonzales and Woods

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

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

Lighting conditions

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

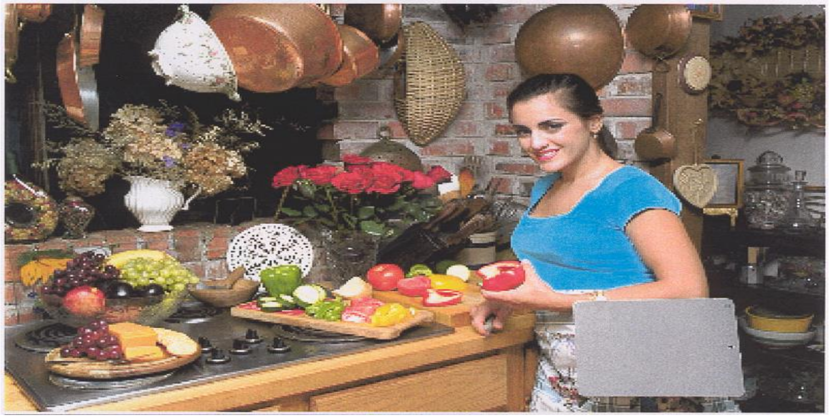


Image taken lit by a flash.

Image taken lit by a tungsten lamp.

The following four images of the same scene were acquired under different lighting conditions:

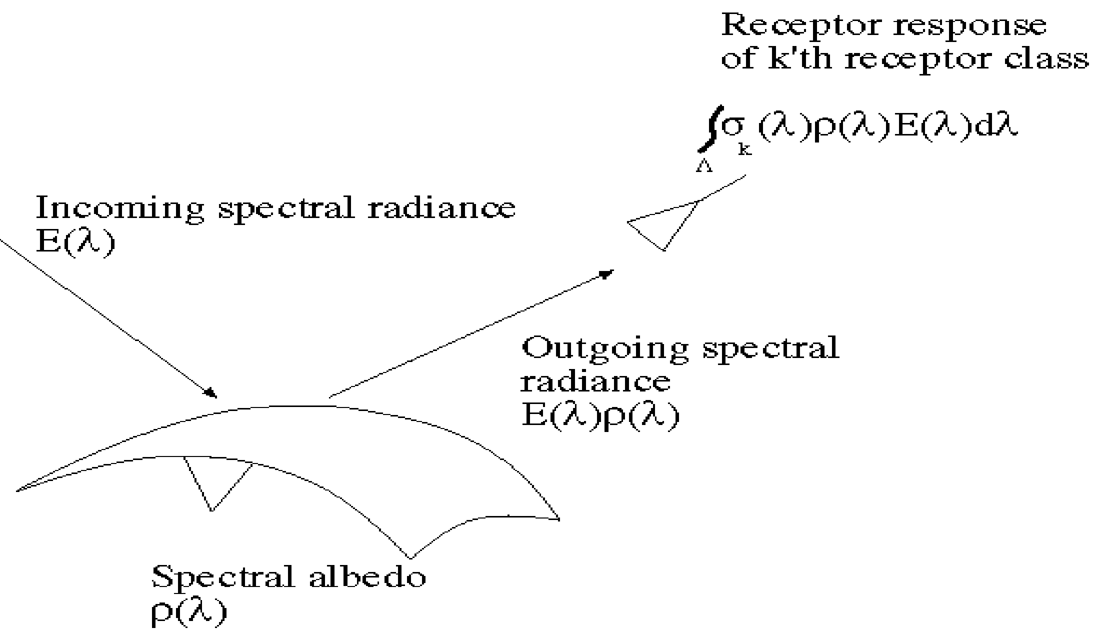



Dealing with Lighting Changes

- 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 lighting should be calibrated.
- For multimedia applications, this is more difficult to organise:
  - Algorithms exist for estimating the illumination colour.

Viewing colored objects

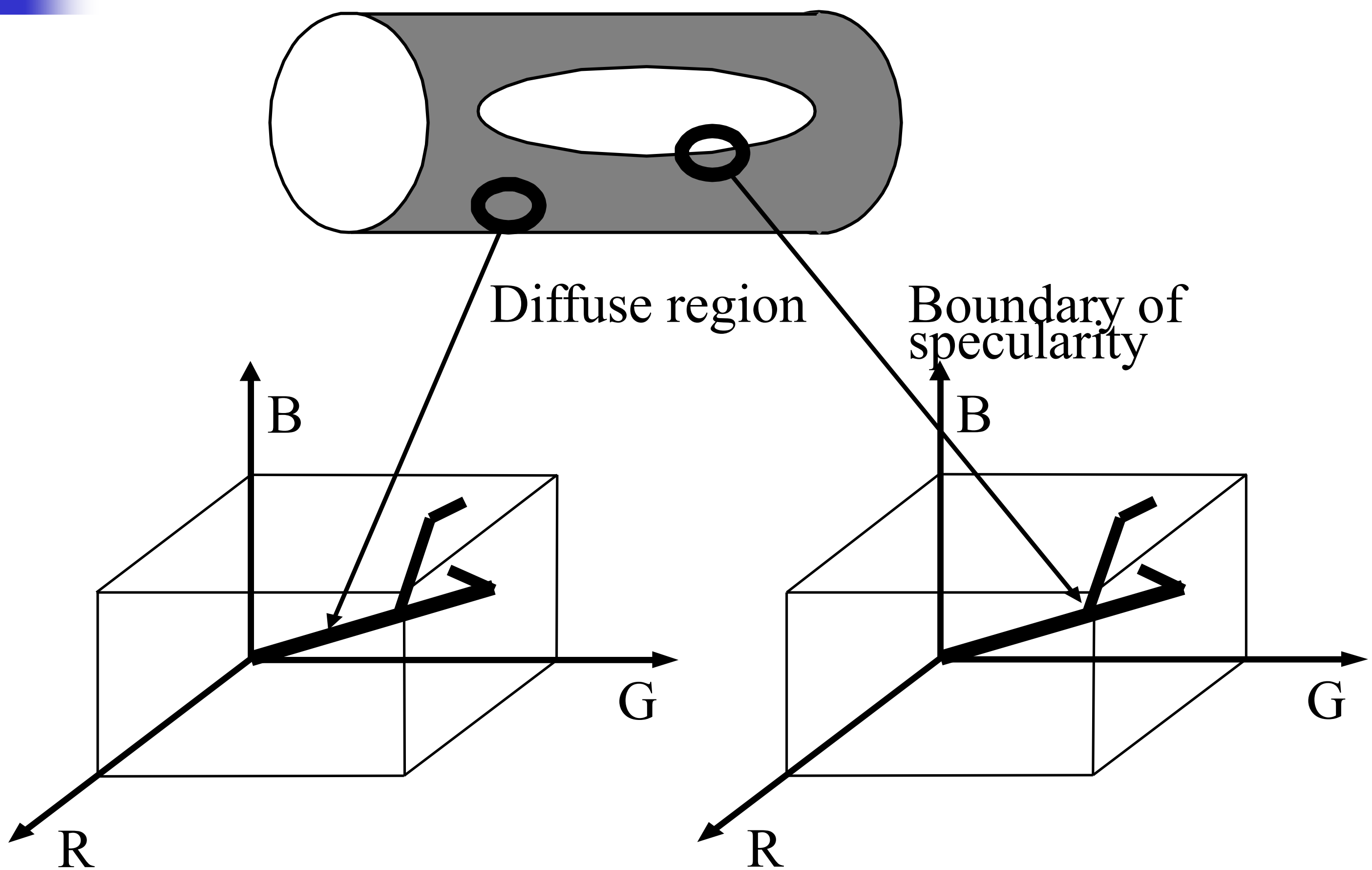
- Assume diffuse+specular model
- Specular
  - specularities on dielectric objects take the colour of the light
  - specularities on metals can be coloured
- Diffuse
  - colour of reflected light depends on both illuminant and surface
  - people are surprisingly good at disentangling these effects in practice (colour constancy)
  - this is probably where some of the spatial phenomena in colour perception come from



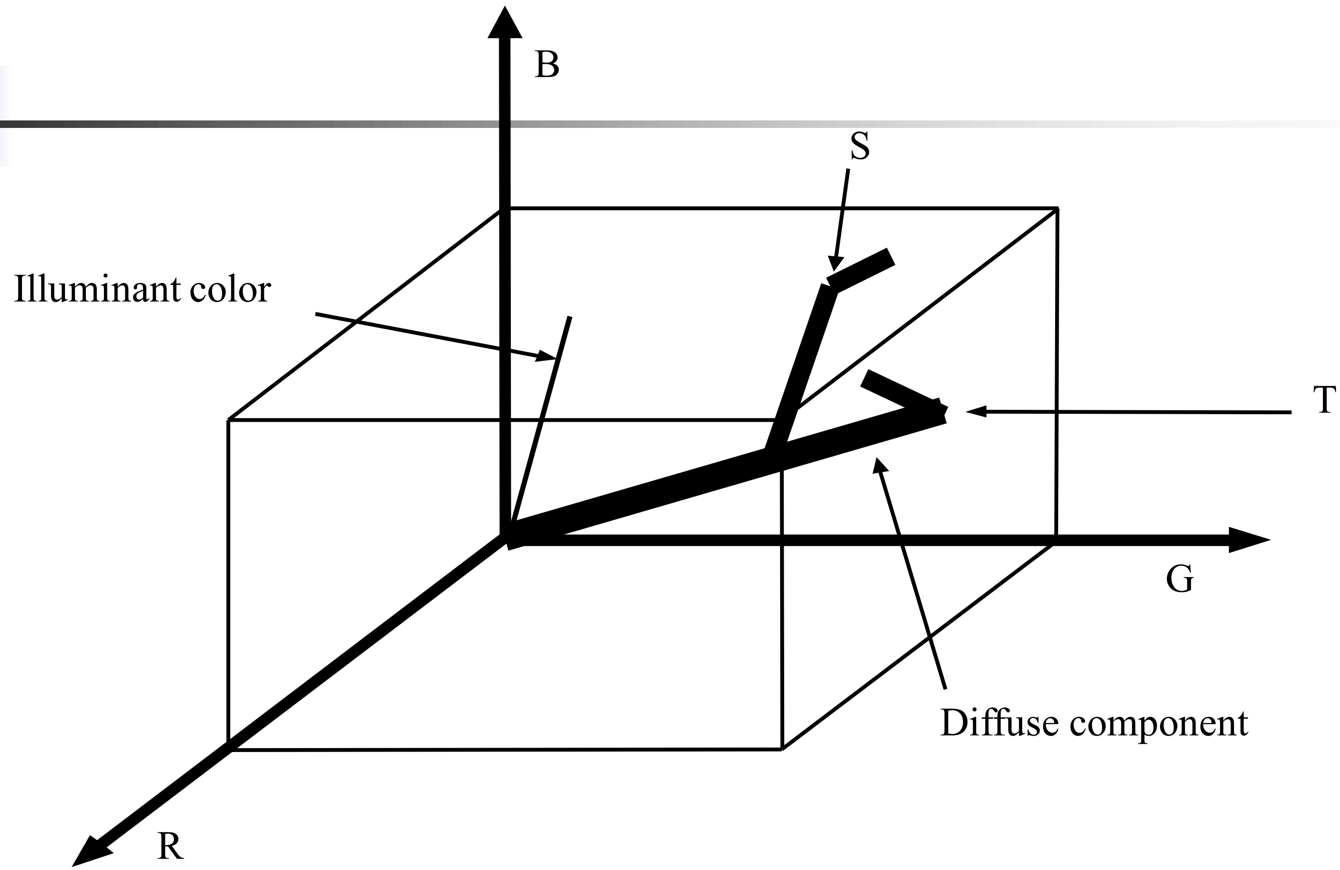
When one views a colored surface, the spectral radiance of the light reaching the eye depends on both the spectral radiance of the illuminant, and on the spectral albedo of the surface. We're assuming that camera receptors are linear, like the receptors in the eye. This is usually the case.

Finding Specularities

- Reflected light has two components
  - Diffuse: product of SPD and Reflectance curve
  - Specular: The same color as source
  - and we see a weighted sum of these two
- Specularities produce a characteristic dog leg in the histogram of receptor responses
  - in a patch of diffuse surface, we see a color multiplied by different scaling constants (surface orientation)
  - in the specular patch, a new color is added; a "dog-leg" results



Diffuse region
Boundary of specularity
B
G
R
B
G
R


B
S
Illuminant color
T
G
Diffuse component
R

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.

E(λ) → <R, G, B>

  - Estimation of SPD of Light Source.

$$
\begin{aligned}
k_r &= \frac{R_d}{R_s}; \quad & k_g &= \frac{G_d}{G_s}; \quad & k_b &= \frac{B_d}{B_s}; \\
& & f &= \frac{R+G+B}{k_r R + k_g G + k_b B}; & & \\
R_u &= f k_r R; \quad & G_u &= f k_g G; \quad & B_u &= f k_b B;
\end{aligned}
$$

- Color Correction
  - Diagonal Correction.

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)

$$\mathbf{e}^{n,p,\sigma} = \left(\int \left|\frac{\partial^n f_{c,\sigma}(\mathbf{x})}{\partial \mathbf{x}^n}\right|^p d\mathbf{x}\right)^{\frac{1}{p}} = k e_c$$

Minkowski's 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.

Color Demosaicing

- USE OF COLOR FILTER ARRAY IN SINGLE CHIP CCD CAMERA
- GENERATION OF DENSE PIXEL MAPS FROM SPARSE DATA BY INTERPOLATION
- HARDWARE COST AND COMPUTATION TIME 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.

$$B_7 = \frac{(B_6 + B_8)}{2} \qquad R_8 = \frac{(R_2 + R_4 + R_{12} + R_{14})}{4}$$

$$R_7 = \frac{(R_2 + R_{12})}{2} \qquad B_{12} = \frac{(B_6 + B_8 + B_{16} + B_{18})}{4}$$

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.

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

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

- 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

Laplacian corrected edge correlated interpolation (LCEC)

- Interpolate green pixels.

 Define horizontal and vertical gradients as:

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

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

- 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

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

End

		B_1		
		G_2		
B_3	G_4	B_5	G_6	B_7
		G_8		
		B_9		

BAYER'S

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

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:

$$R_4 = \frac{R_1 + R_7}{2} + \frac{G_4 - G_1 + G_4 - G_7}{4}$$

- Case 2:

$$R_2 = \frac{R_1 + R_3}{2} + \frac{G_2 - G_1 + G_2 - G_3}{4}$$

- Case 3: Define two diagonal directions (-ve and +ve)

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

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

If $\Delta N < \Delta P$

$$R_5 = \frac{R)1+R_9}{2} + \frac{G_5 - G_1 + G_5 - G_9}{2}$$

Else if $\Delta N > \Delta P$

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

Else

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

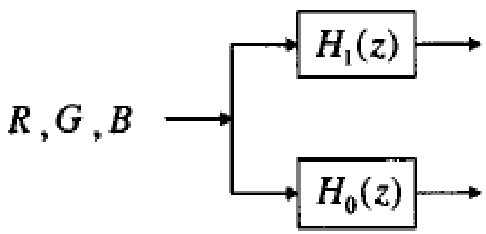
End

Alternative Projection Method

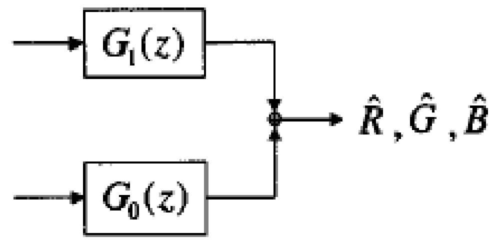
	R_1	G_2	R_3	
	G_4	B_5	G_6	
	R_7	G_8	R_9	

BAYER'S

Wavelet decomposition and synthesis



(a) Analysis filterbank



(b) Synthesis filterbank

Perfect Reconstruction Condition

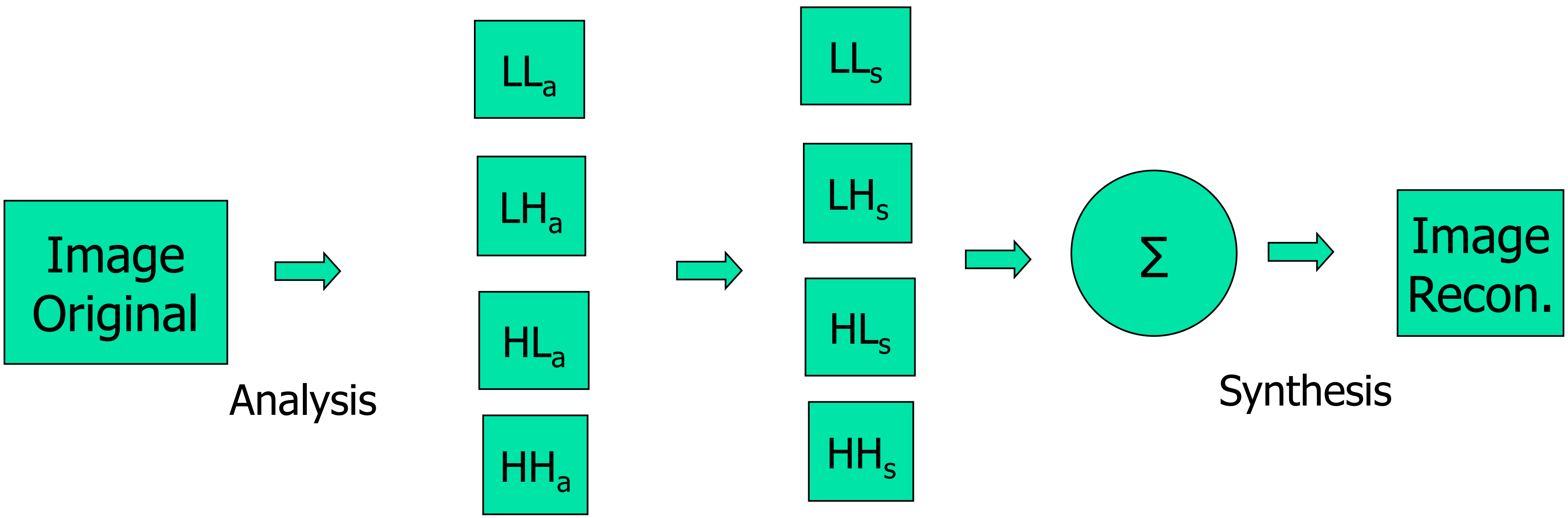
$$H_0(z)G_0(z) + H_1(z)G_1(z) = 1.$$

h_0= [1 2 1]/4
h_1=[1 -2 1]/4

g_0= [-1 2 6 2 -1]/8
g_1= [1   2 -6 2 1]/8

Alternative Projection Method

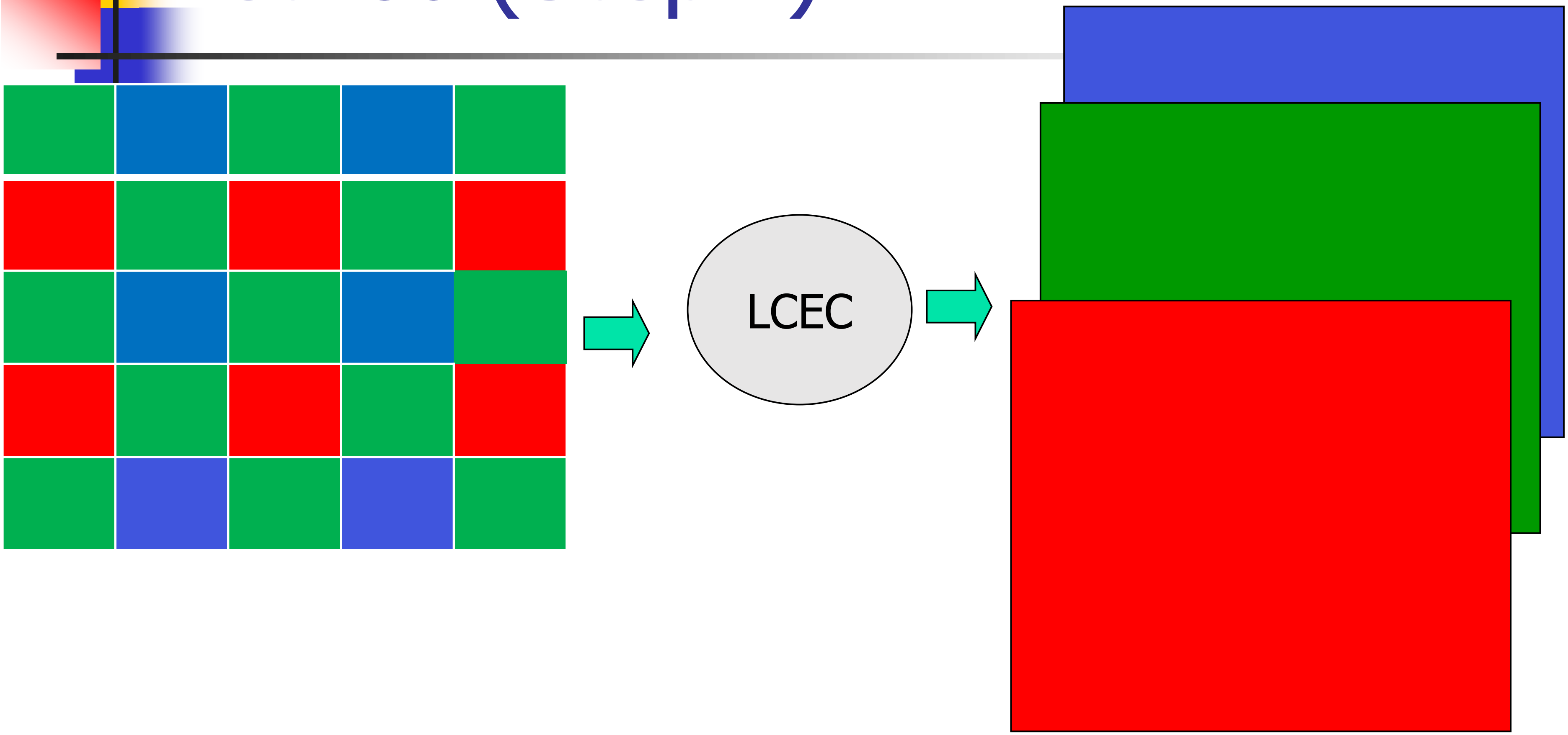
Wavelet decomposition and synthesis of an image



Apply $H_0(z)$ and $H_1(z)$ in rows and columns in cascade in all combinations.

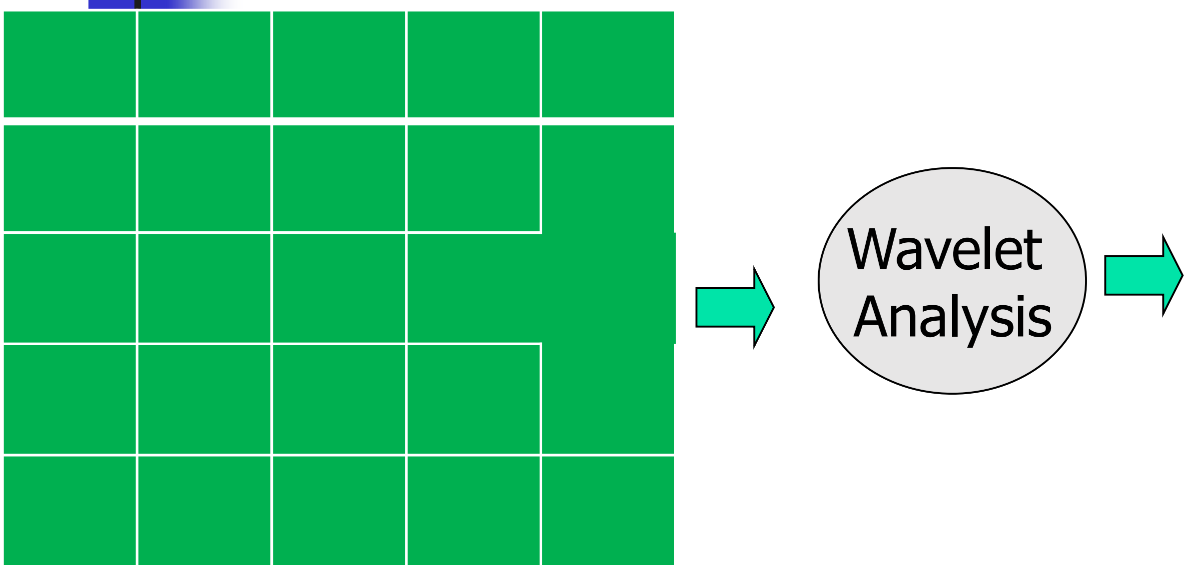
Apply $G_0(z)$ and $G_1(z)$ in rows and columns in cascade in respective combinations and add them.

Alternative Projection Method (Step-I)



Reconstruction of full interpolated color components

Alternative Projection Method (Step-II)



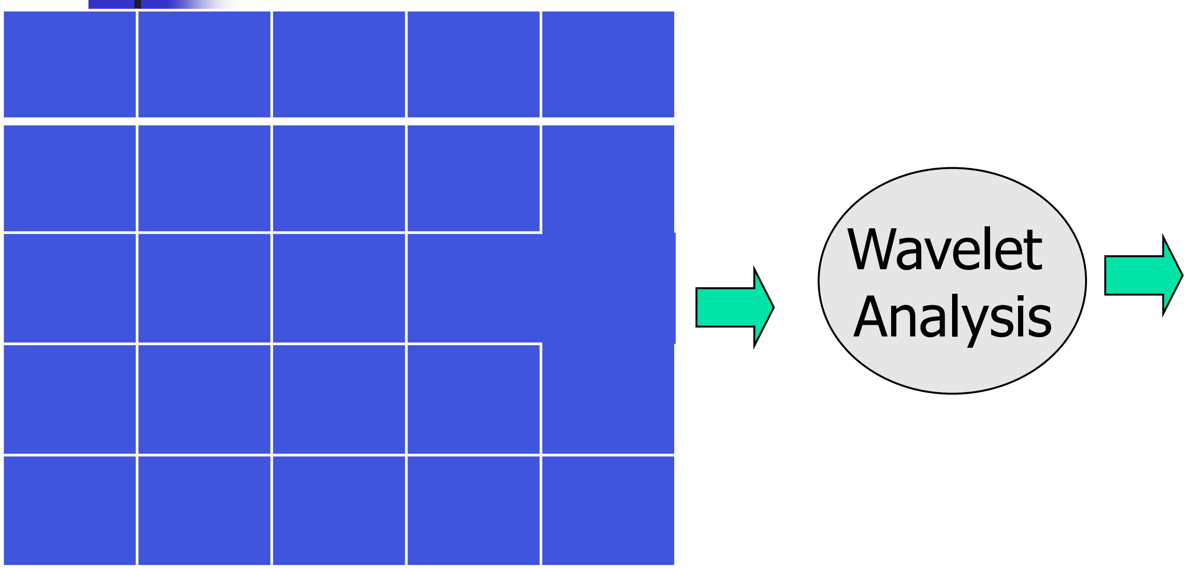
$G^{(F)}_{LL}$,
$G^{(F)}_{LH}$,
$G^{(F)}_{HL}$,
$G^{(F)}_{HH}$

(Full interpolated)

LCEC interpolated green

Wavelet analysis of full interpolated green component

Alternative Projection Method (Step-II)



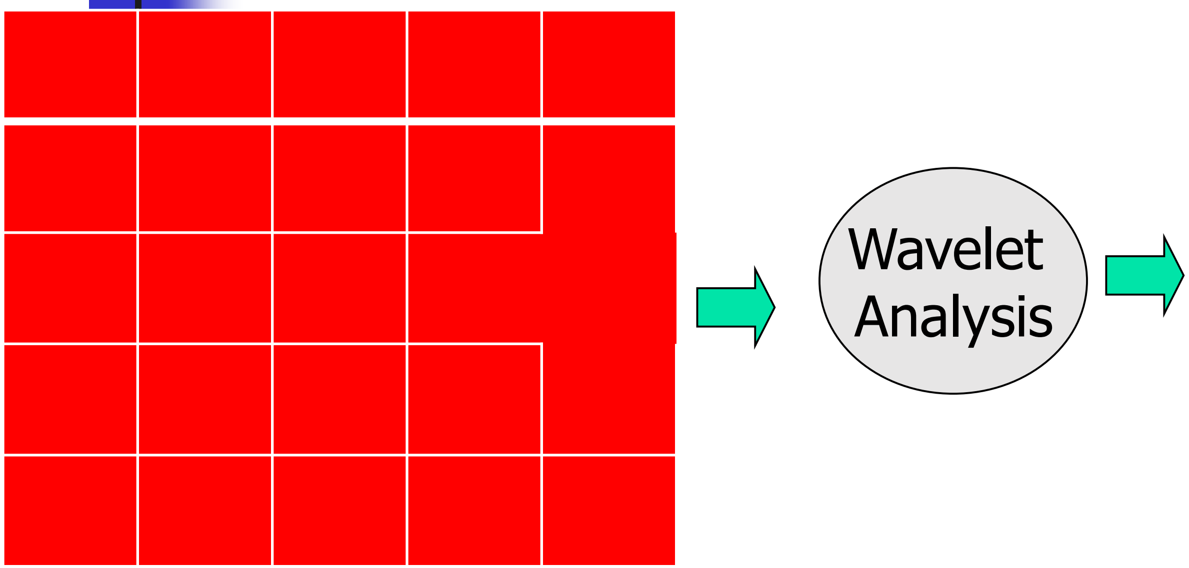
$B^{(F)}_{LL}$, $B^{(F)}_{LH}$, $B^{(F)}_{HL}$, $B^{(F)}_{HH}$

(Full interpolated)

LCEC interpolated blue

Wavelet analysis of full interpolated blue component

Alternative Projection Method (Step-II)



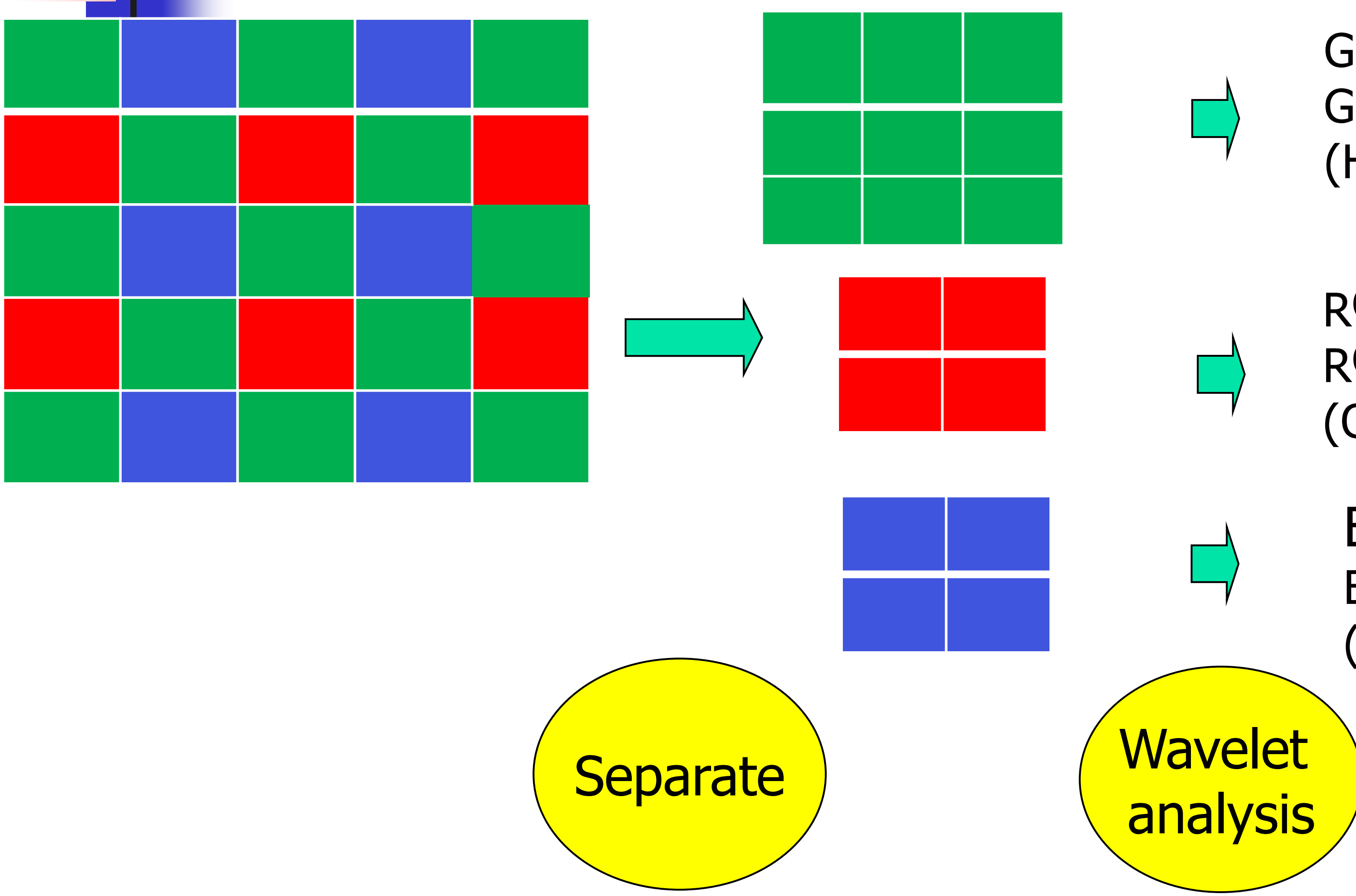
$R^{(F)}_{LL}$,
$R^{(F)}_{LH}$,
$R^{(F)}_{HL}$,
$R^{(F)}_{HH}$

(Full interpolated)

LCEC interpolated red

Wavelet analysis of full interpolated red component

Alternative Projection Method (Step III)



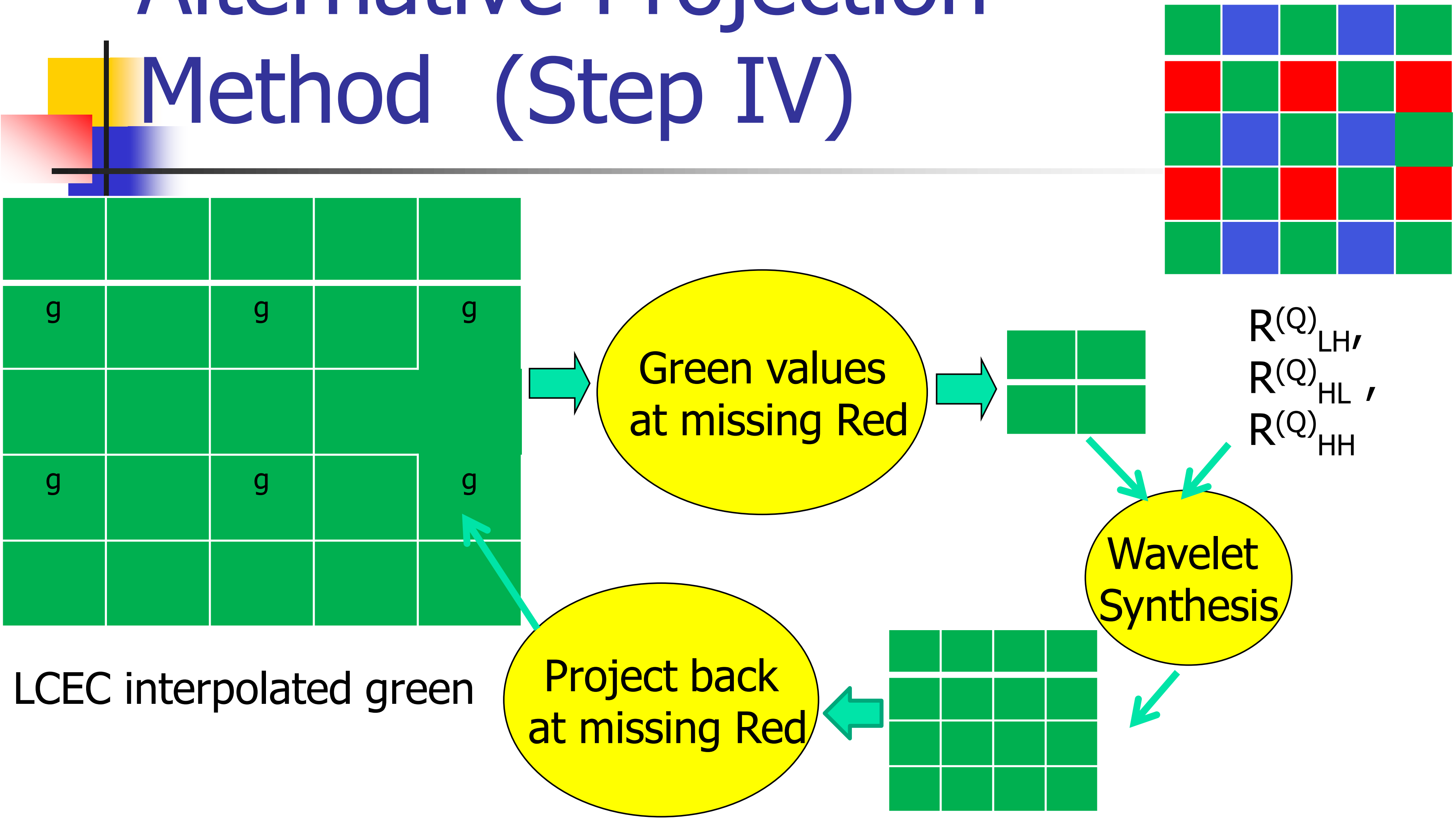
$G^{(H)}_{LL}$, $G^{(H)}_{LH}$,
$G^{(H)}_{HL}$, $G^{(H)}_{HH}$
(Half sampled)

$R^{(Q)}_{LL}$, $R^{(Q)}_{LH}$,
$R^{(Q)}_{HL}$, $R^{(Q)}_{HH}$
(Quarter sampled)

$B^{(Q)}_{LL}$, $B^{(Q)}_{LH}$,
$B^{(Q)}_{HL}$, $B^{(Q)}_{HH}$
(Quarter sampled)

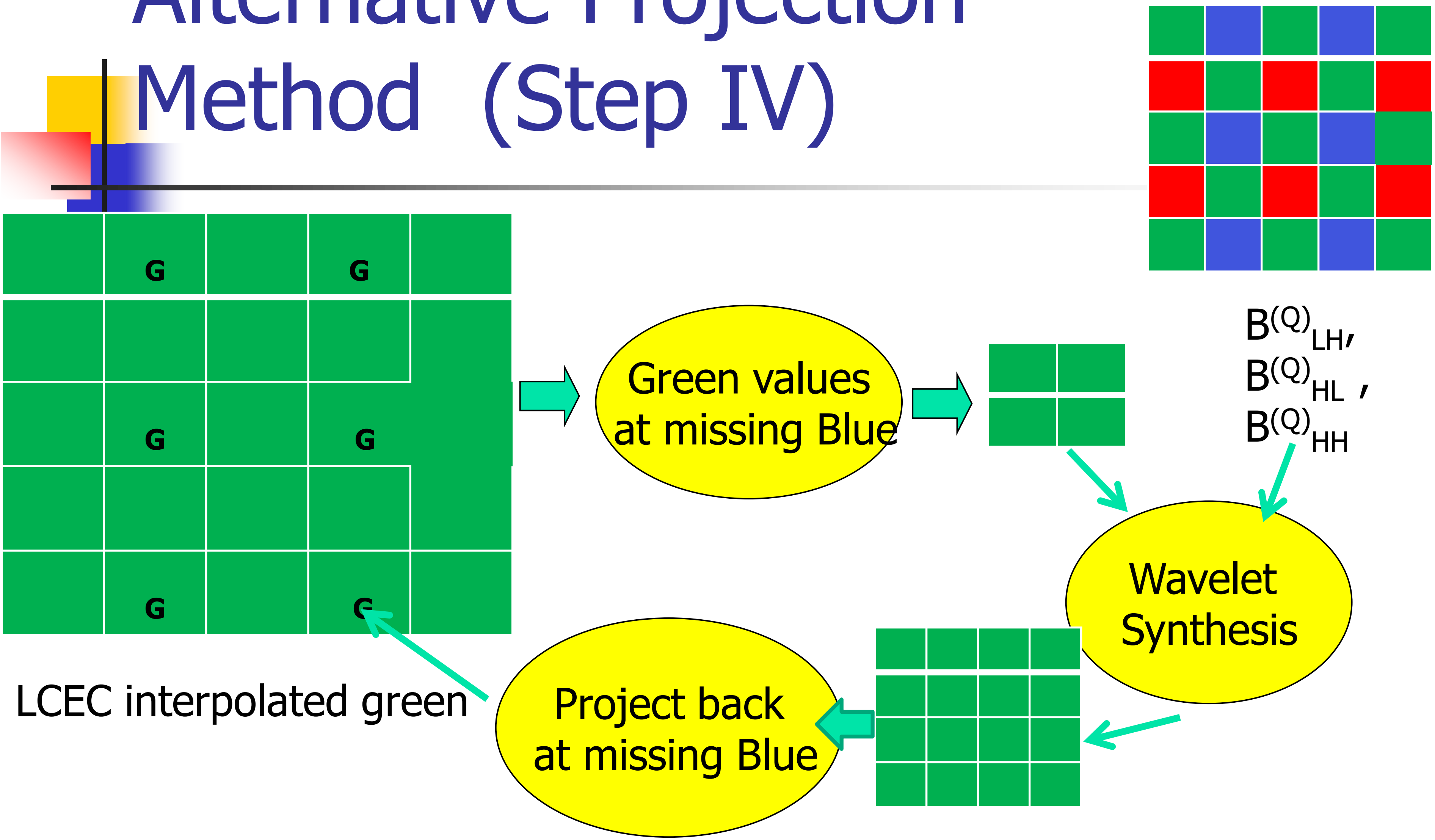
Wavelet analysis of true pixels accumulated at diff. res.

Alternative Projection Method (Step IV)



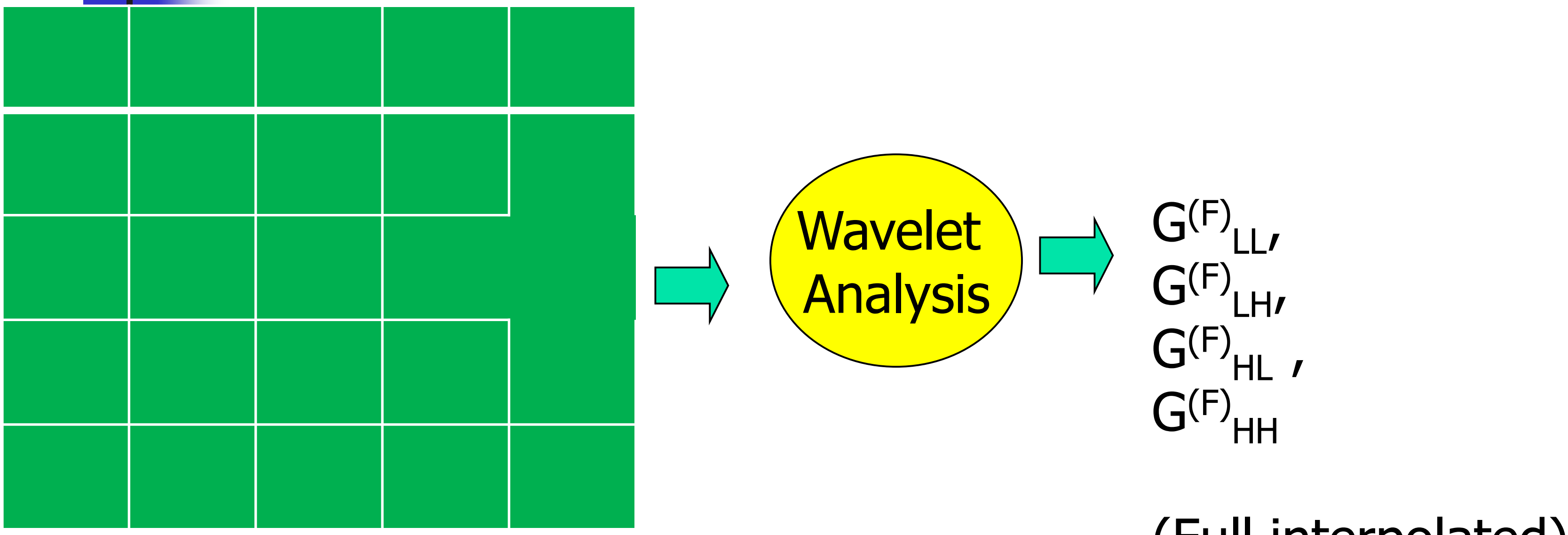
Compute green values at missing red masks

Alternative Projection Method (Step IV)



Compute green values at missing blue masks

Alternative Projection Method (Step-V)



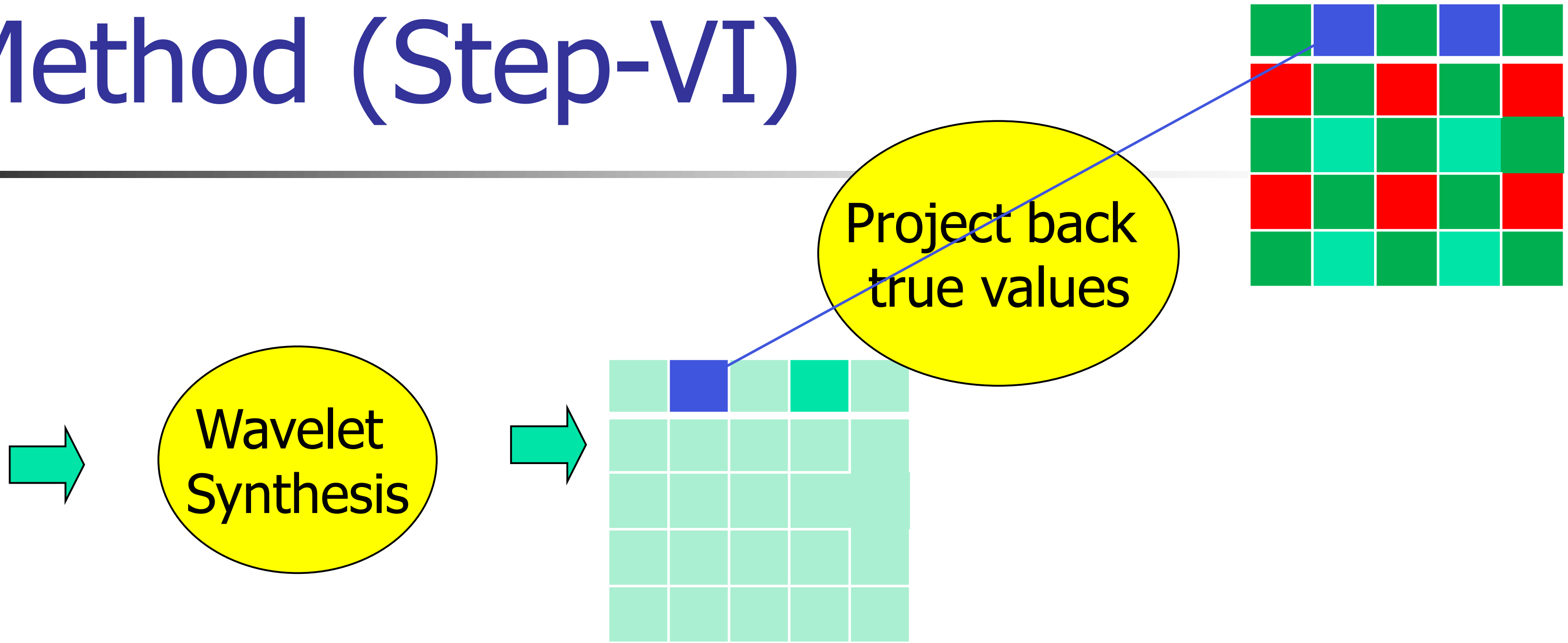
Updated green

Recompute wavelet bands for G

Alternative Projection Method (Step-VI)

$B^{(F)}_{LL}$, $G^{(F)}_{LH}$, $G^{(F)}_{HL}$, $G^{(F)}_{HH}$

(Full interpolated)

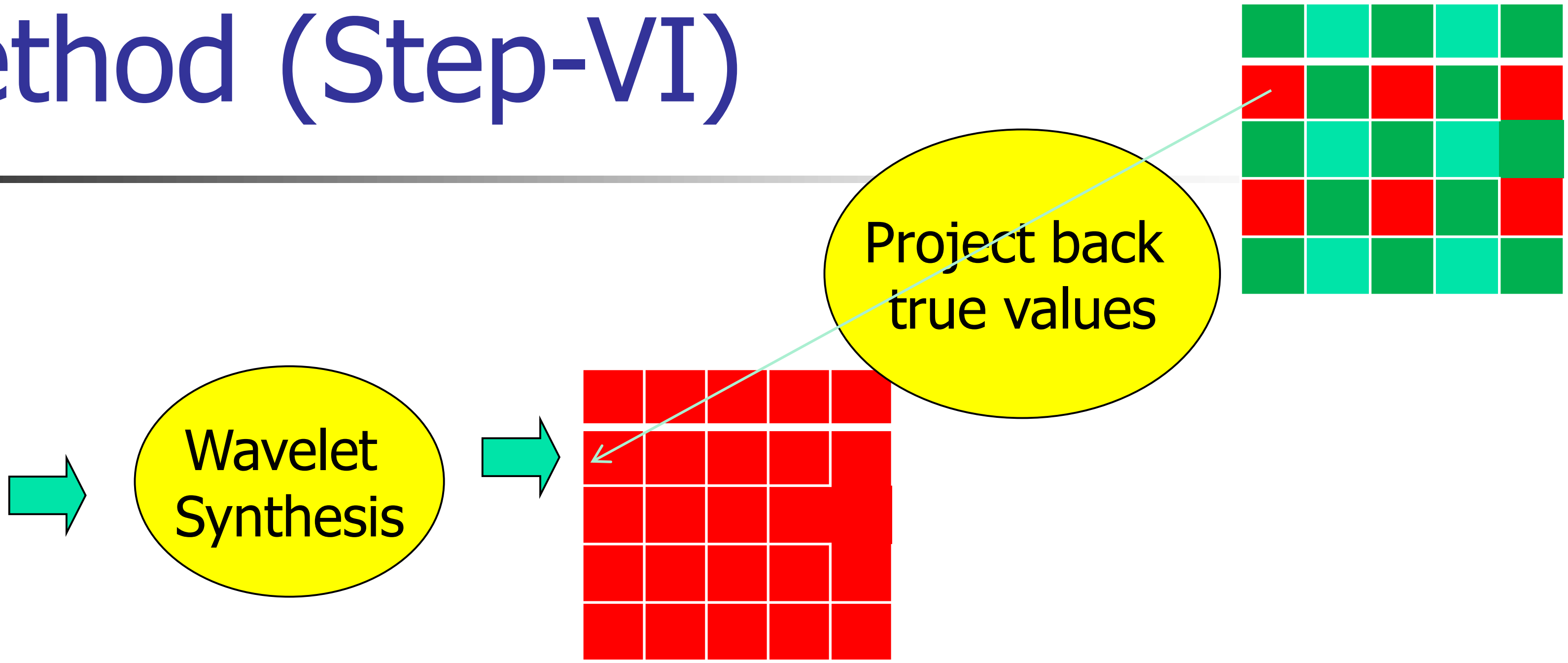


Reconstruct full interpolated blue

Alternative Projection Method (Step-VI)

$R^{(F)}_{LL}$,
$G^{(F)}_{LH}$,
$G^{(F)}_{HL}$,
$G^{(F)}_{HH}$

(Full interpolated)



Reconstruct full interpolated red

Alternative Projection Method (Step-VII ….)

Iterate till no significant difference between true and updated values at known pixels.

Color Demosaicing: An example.

LCEC

ORIGINAL

AP

BI

ARBH

Color Demosaicing: An example.

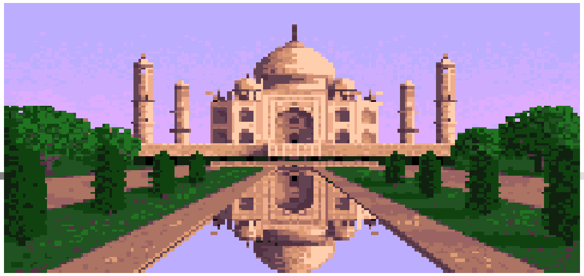
BI

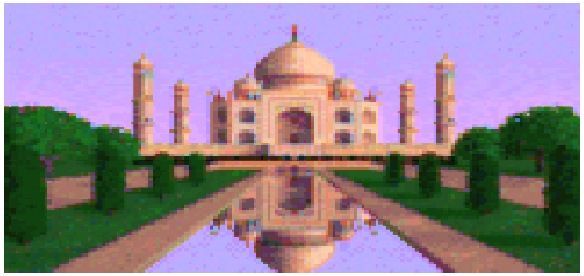
LCEC

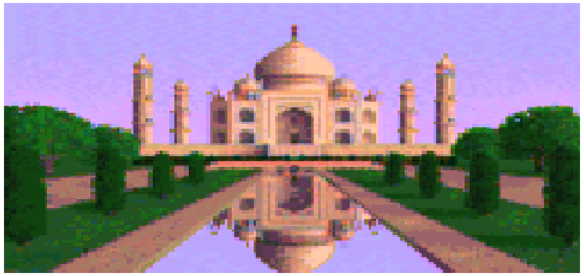
ORIGINAL

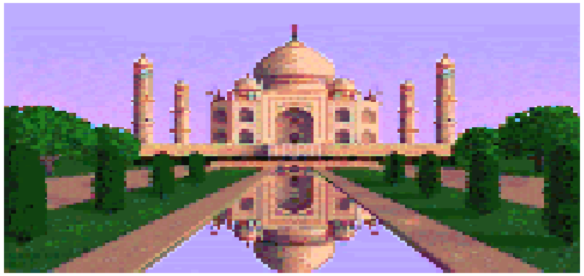
AP

ARBH


ORIGINAL


BI


ARBH


LCEC

Two major problems in the reconstruction

- Blurred Edges.

- Appearance of false colors

False Colors: An Example

Original

Reconstructed

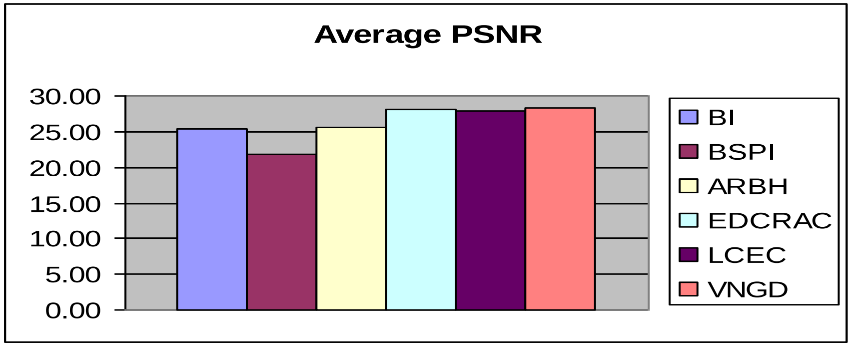
PERFORMANCE MEASURE

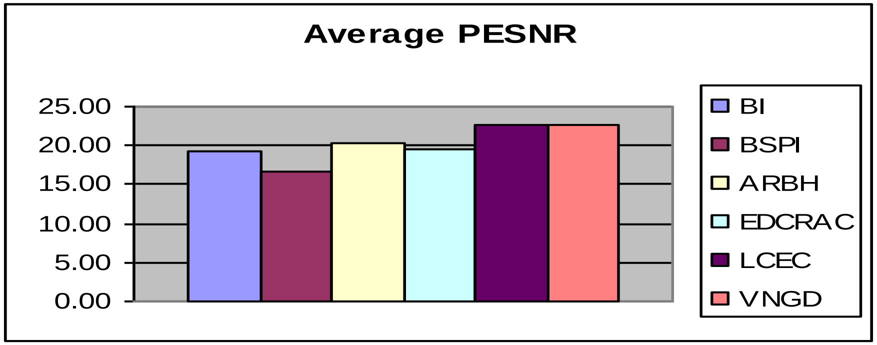
Peak Signal to Noise Ratio (PSNR)

$$PSNR = 20 \times \log_{10}\left(\frac{255}{\sqrt{\dfrac{\sum_{\forall s}\sum_{\forall x}\sum_{\forall y}(I_s(x,y) - I_s^{'}(x,y))^2}{3 \times N \times M}}}\right)$$

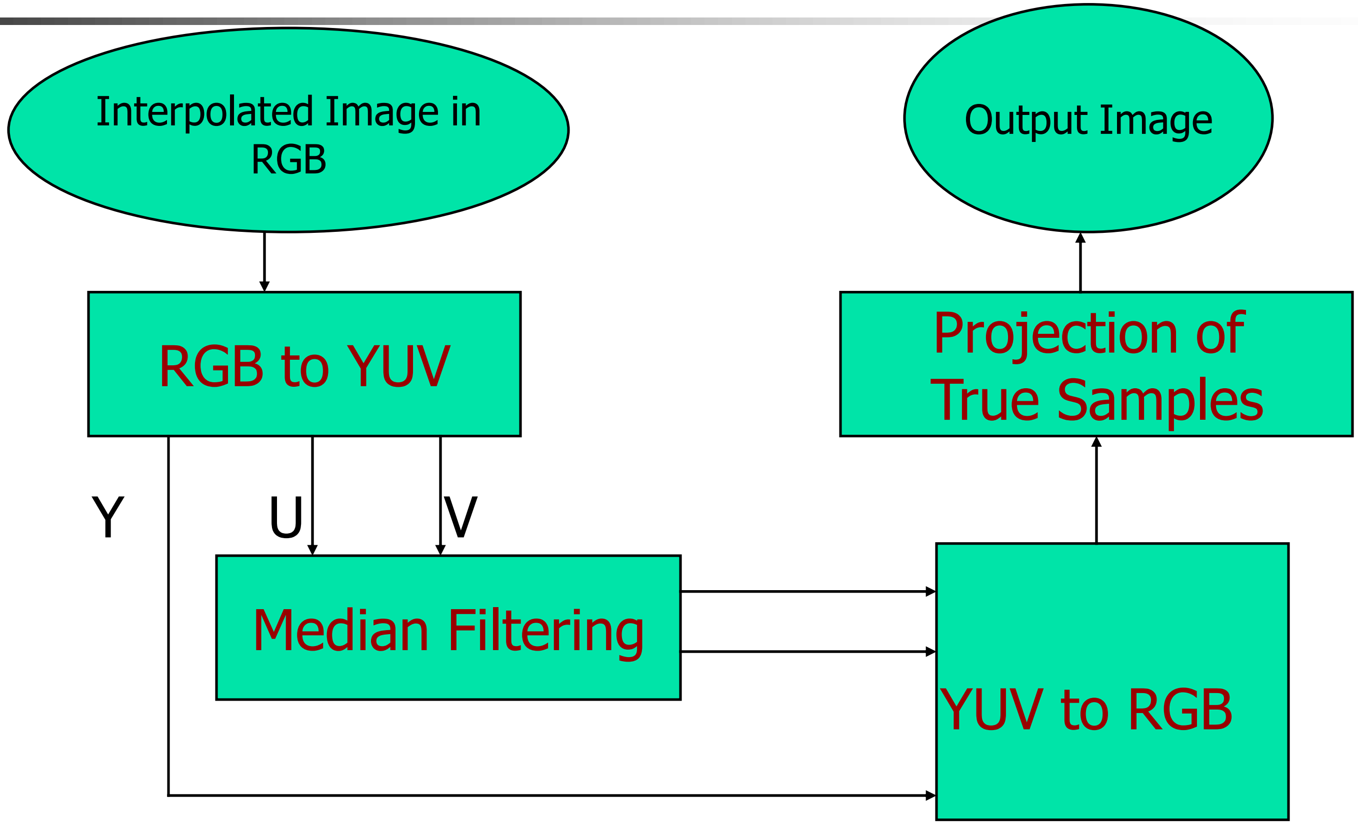
Peak Edge Signal to Noise Ratio (PESNR)

$$PESNR = 20 \times \log_{10}\left(\frac{255}{\sqrt{\dfrac{\sum_{\forall s}\sum_{\forall x}\sum_{\forall y} e(x,y) \times (I_s(x,y) - I_s^{'}(x,y))^2}{3 \times \sum_{\forall x}\sum_{\forall y} e(x,y)}}}\right)$$


Average PSNR
30.00
25.00
20.00
15.00
10.00
5.00
0.00
BI
BSPI
ARBH
EDCRAC
LCEC
VNGD


Average PESNR
25.00
20.00
15.00
10.00
5.00
0.00
BI
BSPI
ARBH
EDCRAC
LCEC
VNGD

False Color Suppression



Examples

LCEC

LCEC with Median
(3 x 3 Mask)

LCEC with Median
(5 x 5 Mask)

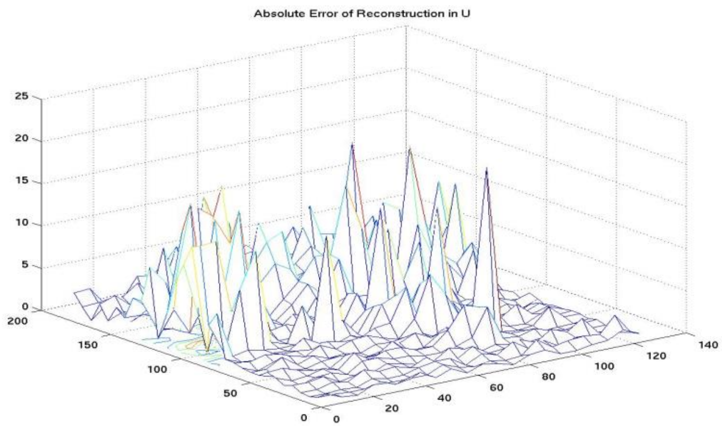
Gains in CPSNR (dB) with 3x3 Median Filtering

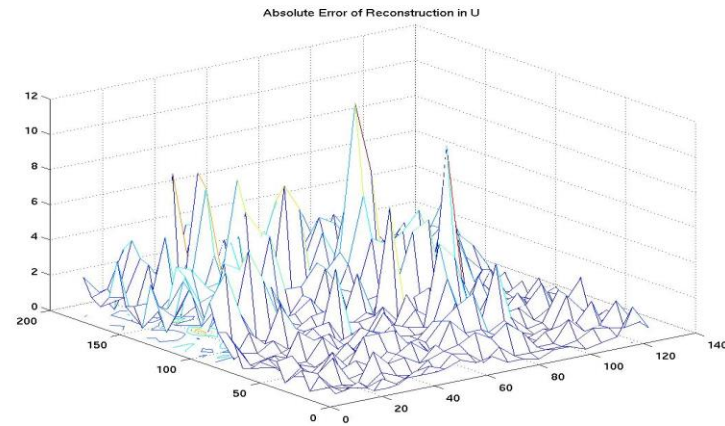
Images	BI	LCEC	AP
Statue	2.96	3.07	1.26
Window	2.79	2.48	0.48
Pepper	1.80	1.34	0.11
L'House	2.54	2.86	0.79
Sail	2.33	1.50	0.30

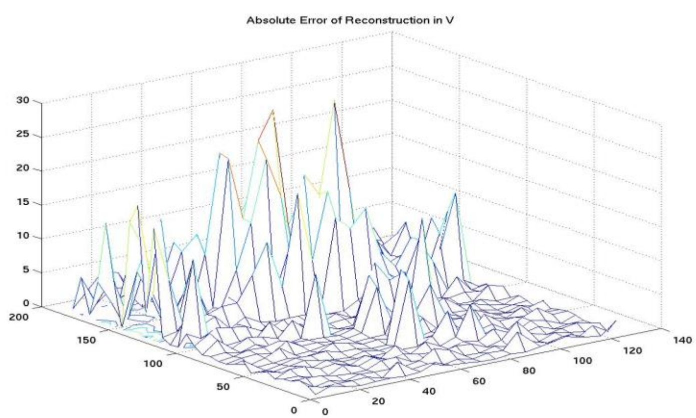
Gains in PEINR (dB) with 3x3 Median Filtering

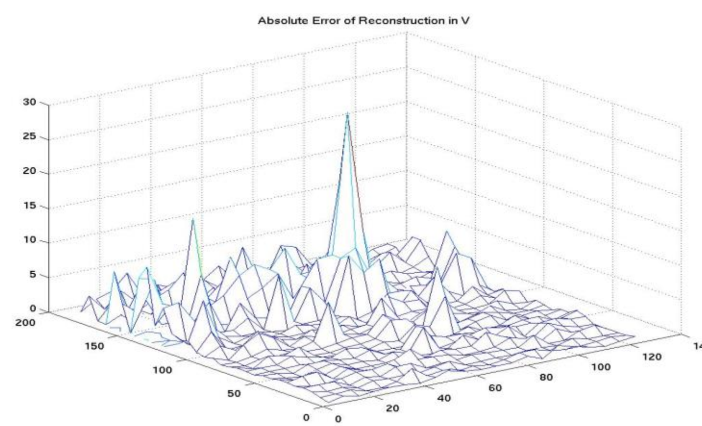
Images	BI	LCEC	AP
Statue	4.36	5.7	0.65
Window	2.58	2.16	-0.12
Pepper	3.13	3.72	0.48
L'House	2.15	2.55	0.92
Sail	1.51	2.26	0.14

Suppression of Impulsive Noise









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.
- In digital cameras color images are mostly captured using a CFA, which need to be interpolated to provide full color information.

Thank you!