Causes of color

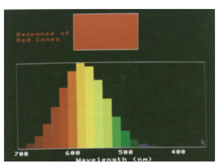
- The sensation of color is caused by the brain.
- One way to get it is through a **response** of the eye to the presence/absence of light at various wavelengths.
- Dreaming, hallucination, etc.
- Pressure on the eyelids

Trichromaticity

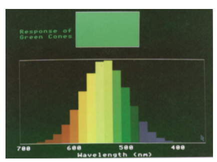
Empirical fact--colors can be approximately described/matched by three quantities (assuming normal color vision).

Need to reconcile this observation with the spectral characterization of light

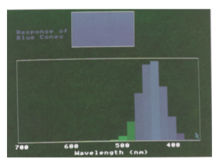
Color receptors



"Long" cone



"Medium" cone



"Short" cone

Some understanding results from an analogy with camera sensors

Directly determining the camera like sensitivity response is hard!

Colour Reproduction

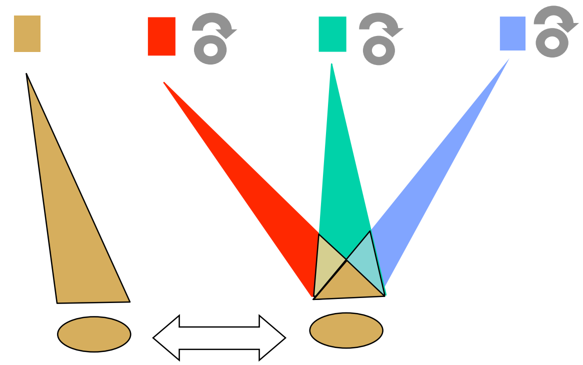
Motivates specifying color numerically (there are other reasons to do this also)

General (man in the street) observation--color reproduction *sort of* works.

Specifying Colour

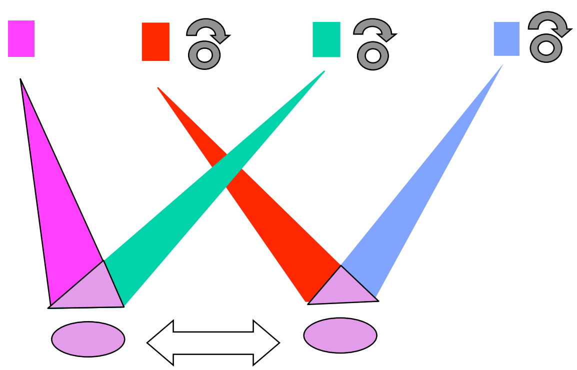
Test Light

Three standard lights



Test Light

Three standard lights



Trichromacy

Experimental fact about people (with “normal” colour vision)---matching works (for reasonable lights), provided that we are sometimes allowed negative values.

Our “knob” positions correspond to (X,Y,Z) in the standard colorimetry system.

Technical detail: (X,Y,Z) are actually arranged to be **positive** by a linear transformation, but these “knob” positions **cannot** correspond to any **physical** light.

Specifying Colour

(50,150,75)

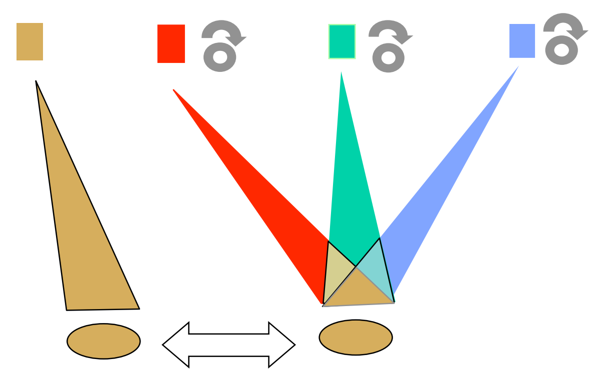
(50,150,75)

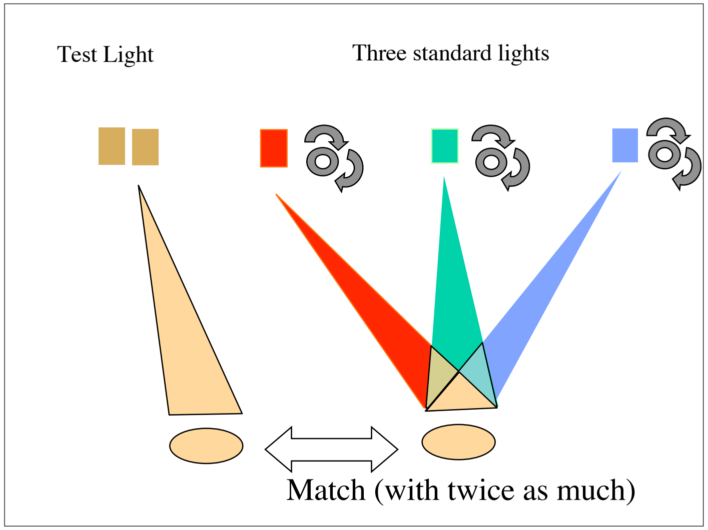
Specifying Colour

We don't want to do a matching experiment every time we want to use a new color!

Grassman's Contribution

Colour matching is linear



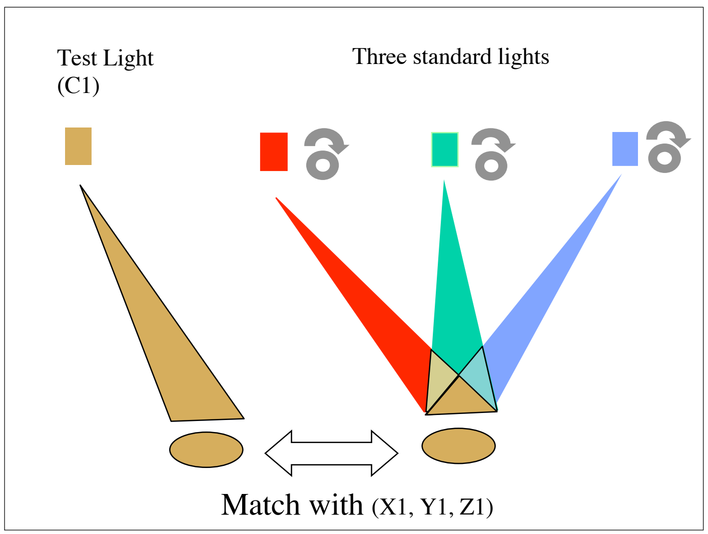


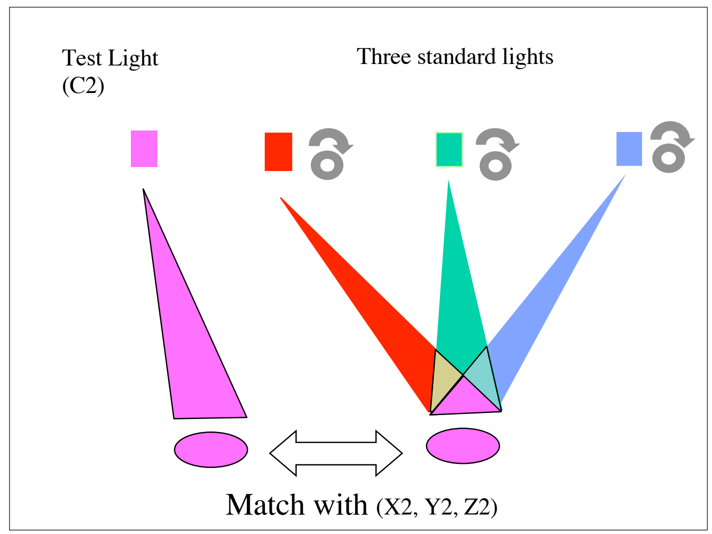
Matching is Linear (Part 1)

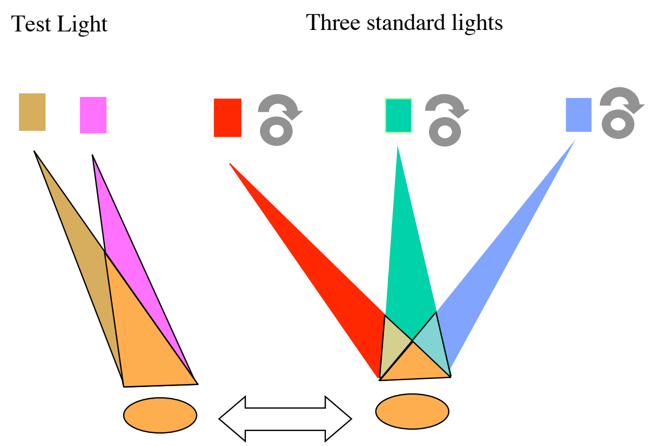
C1 is matched with (X1,Y1,Z1)

C = a*C1

C is matched with a * (X1, Y1, Z1)







Match with (X1+X2, Y1+Y2, Z1+Z2)

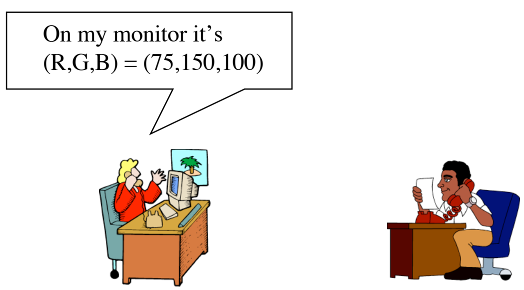
Matching is Linear (formal)

C = a*C1 + b*C2

C1 is matched with (X1,Y1,Z1)
C2 is matched with (X2,Y2,Z2)

C is matched by
a*(X1,Y1,Z1) + b*(X2,Y2,Z2)

Specifying Color



Specifying Colour

Specifying Colour

R matches (X_r, Y_r, Z_r)

G matches (X_g, Y_g, Z_g)

B matches (X_b, Y_b, Z_b)

Specifying Colour

Then by (R,G,B)=(75,150,100) you mean (X,Y,Z), where …..

$$X = 75^* X_r + 150^* X_g + 100^* X_b$$

$$Y = 75^* Y_r + 150^* Y_g + 100^* Y_b$$

$$Z = 75^* Z_r + 150^* Z_g + 100^* Z_b$$

(No need to match--just compute!)

Specifying Colour

… , now that we have specified the colour, I can print it!

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{vmatrix} \begin{vmatrix} 75 \\ 100 \\ 150 \end{vmatrix}$$

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = \begin{vmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{vmatrix} \begin{vmatrix} R \\ G \\ B \end{vmatrix}$$

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix} = M \begin{vmatrix} R \\ G \\ B \end{vmatrix}$$

Colour Reproduction
(Monitors & Projectors)

$$\rightarrow \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{apple}$$

Find (R,G,B)

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{apple} = M \begin{vmatrix} R \\ G \\ B \end{vmatrix}_{apple}$$

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix}_{apple} = M^{-1} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{apple}$$

$$\begin{vmatrix} R \\ G \\ B \end{vmatrix}_{apple} = M^{-1} \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{apple}$$

Possible problems?

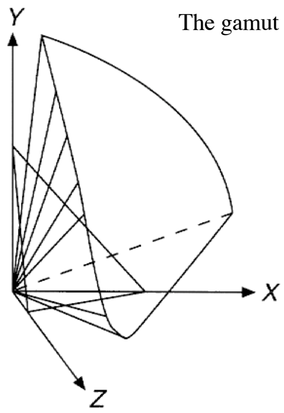
XYZ color space

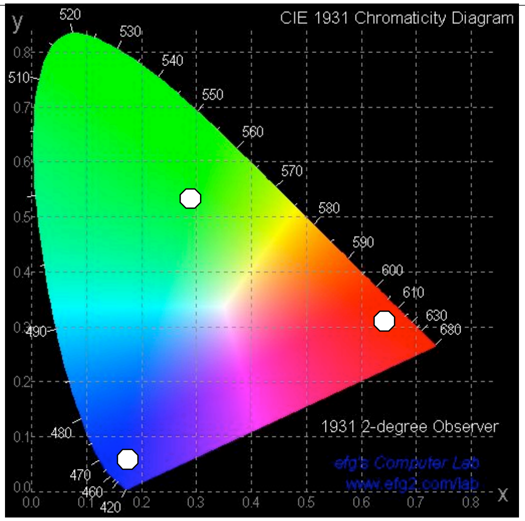
XYZ color space is a linear transformation of the matches to standard lights.

The transformation is used to ensure that all color co-ordinates are positive

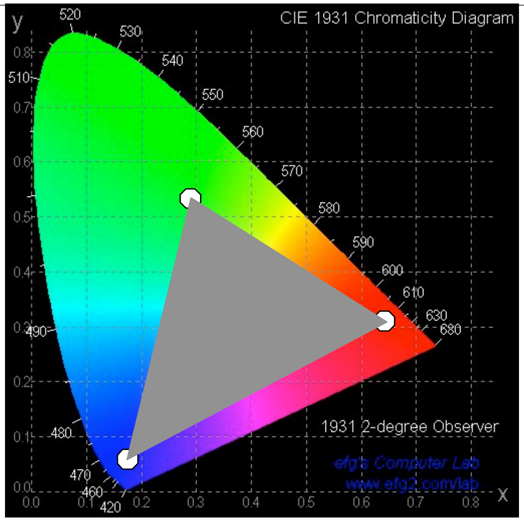
This means that XYZ corresponds to matches of fictitious (physically impossible) lights.

The gamut of all colors





Available from efg2.com



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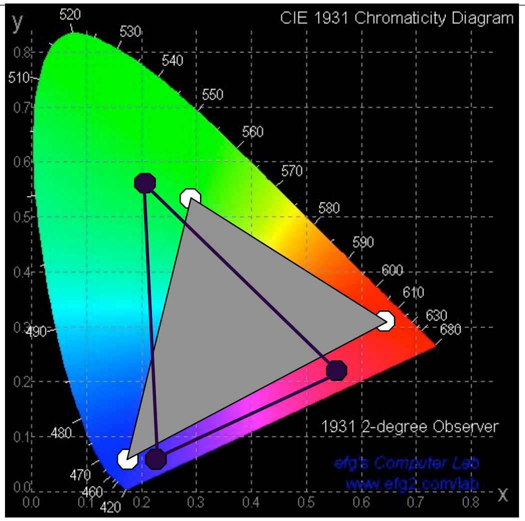
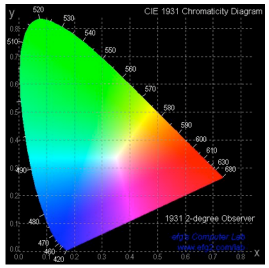


Available from efg2.com

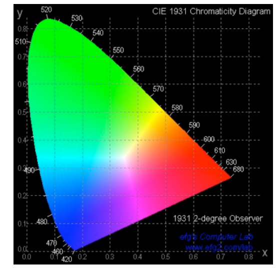
Qualitative features of CIE x, y

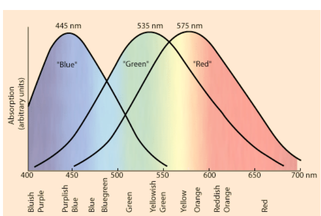
- Linearity implies that colors obtainable by mixing lights with colors A, B lie on line segment with endpoints at A and B
- Monochromatic colours (spectral colors) run along the “Spectral Locus”



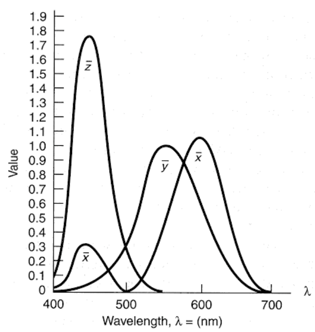
Qualitative features of CIE x, y

- Why the funny shape?





One measurement of human cone absorption



XYZ response curves

Matching is only for “aperture” color

- When color is viewed in the context of other colors numerous effects occur which complicate the characterization of color (simultaneous contrast, color constancy, etc)
- Other complications include chromatic aberration in the eye and different spatial resolution for different colors (these are linked)

Colour Reproduction

Key point--color reproduction is based on “metamerism”

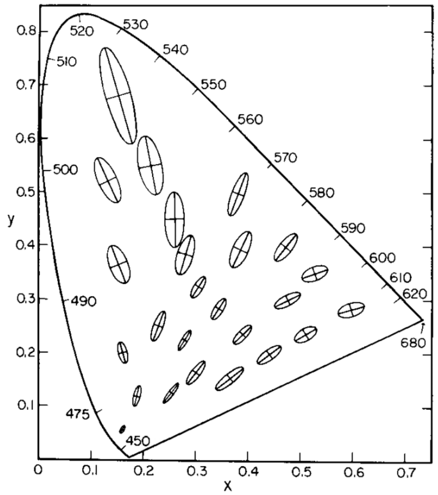
Metameric match--colors which match, despite different spectra.

Duplicating spectra would work, but for practical reasons, we duplicate the match.

For reflective surfaces, e.g prints, this means that the match can change if the illumination changes.

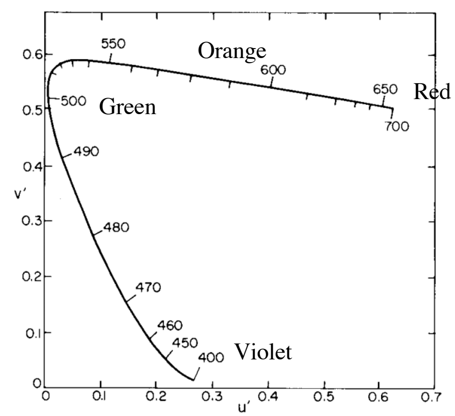
The quest for uniform colour spaces

- Definition of uniform: equal (small!) steps give the same perceived color changes.
- XYZ is not uniform!
- Uniformity only applies to small differences. There is no theory for numerically deciding if yellow is perceptually closer to green or red.



MacAdam Ellipses (scaled by a factor of 10) on CIE x, y

Omitted Fall 2005



CIE u’v’ is a linear colour space where colour differences are more uniform

$(u', v') = (4X/(X+15Y+3Z), 9Y/(X+15Y+3Z))$

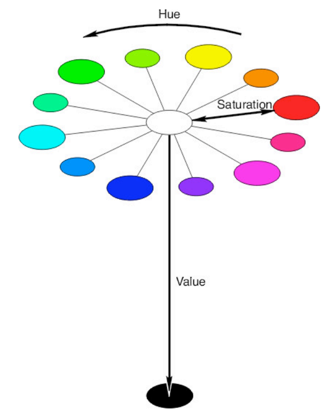
Omitted Fall 2005

Non-linear colour spaces

- HSV: Hue, Saturation, Value are non-linear functions of XYZ.
  - hue relations are naturally expressed in a circle
  - popular in graphics
  - a variety of similar but different formulas are available for converting between RGB and HSV
- Munsell: describes surfaces, rather than lights - less relevant for graphics. Surfaces must be viewed under fixed comparison light
- L*a*b: Another attempt to approximate uniformity
  - popular in colour science

Omitted Fall 2005

HSV (cont)



From http://www2.ncsu.edu:8010/scivis/lessons/colormodels/

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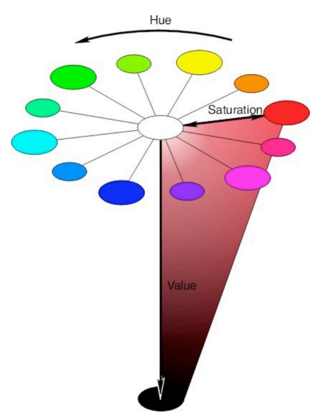
HSV (cont)



From http://www2.ncsu.edu:8010/scivis/lessons/colormodels/

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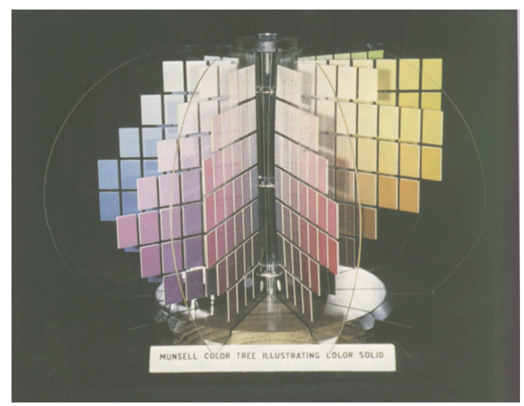
Munsell color space



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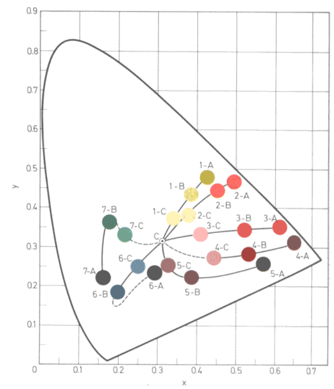
Subtractive mixing

- Treatment so far has been for additive mixing
- Inks subtract light from white.
- Linearity depends on pigment properties - often non-linear!
- Typical system (printers)
  - Cyan = White – Red
  - Magenta = White – Green
  - Yellow = White – Blue.
- Usually have black also, because colored inks are more expensive, black is very common, and registration is hard
- For a good choice of inks, matching is not too from linear
- Printers can have both additive and subtractive qualities

Mixing pigments in CIE



Color matching is linear, but combining pigments is not necessarily linear like mixing light .

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Device independent colour imaging

- Problem: ensure that colours on a display, printer, etc. give the same experience that a viewer would have seeing relevant light spectra
- Difficulty: limited gamuts of most output devices
- Strategy: exploit a model of human experience
  - Simple model: The CIE XYZ matching paradigm
    - Being implemented in "Color Management Systems"
  - These try to relieve the user of the different color capabilities of devices
  - Complicated because every device needs to register properly with the CMS
- Deficiencies--as we have seen, the CIE systems does not count for spatial effects, illumination environments, etc., and these are important
- Some progress is being made but the models tend to be complicated