Light, Color, Perception, and Color Space Theory

Professor Brian A. Barsky

barsky@cs.berkeley.edu
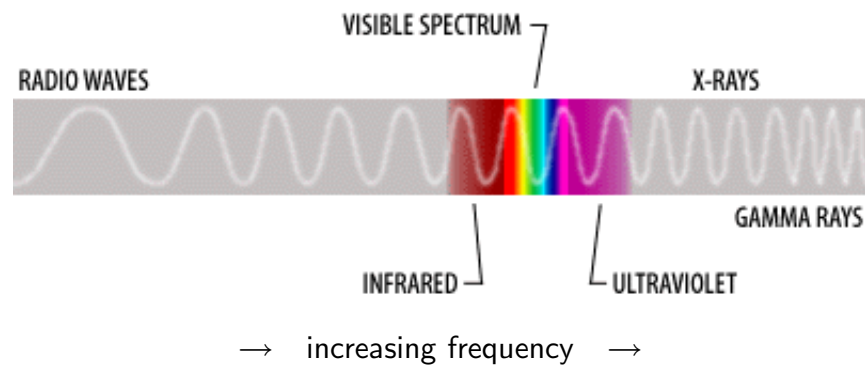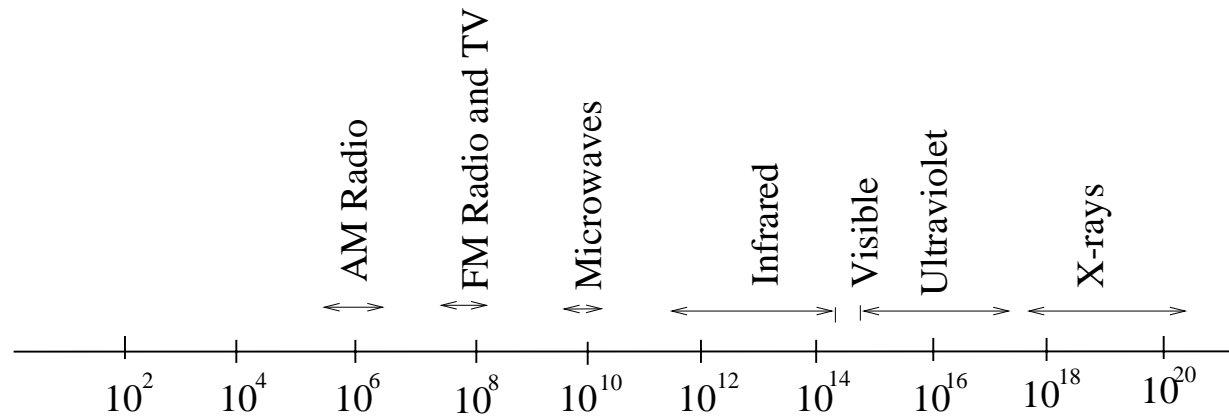
Computer Science Division
Department of Electrical Engineering and Computer Sciences
University of California, Berkeley

Why Color?

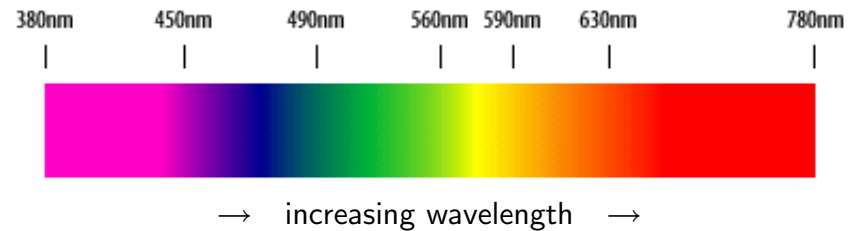- Realism (world is in color)

- Aesthetics (looks better)

LIGHT—FREQUENCY

- Part of the spectrum of electromagnetic radiation that can affect the human sense of sight

→ increasing frequency →

LIGHT—WAVELENGTH

- Visible part (for humans) is from 400 nm (violet) to 700 nm (red)

- Each frequency value within the visible band corresponds to a distinct color

LIGHT

- Parameters of light:

  - wavelength, λ
  - frequency, f

- Speed of light denoted by c

- Speed of light $=$ wavelength $\times$ frequency; $c = \lambda f$

- Speed (in a vacuum) is approximately 3×10^8 m/sec

- Speed is less in media

- *Index of refraction* of a material is the ratio of the speed of light in a vacuum to that in this material

Color

- *Color* is the *perceived* property by which we distinguish different lights

- Different wavelengths of light yield different sensations of color

- But different spectral distributions may produce the same color

- Metamers

- Perceptual factors

- Discussions of color perception usually involves three quantities:

  Hue colors (e.g., red, green, purple, yellow)
  Saturation vivid pure colors versus pastel colors (e.g., red is highly saturated, pink is relatively unsaturated)
 **Lightness or Brightness** is the perceived intensity. Lightness is used for reflecting objects whereas brightness is used for light-emitting objects (light bulb, sun, CRT).
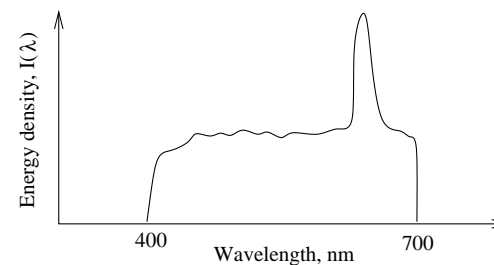
Spectral Energy Distribution

- The amount of energy present at each wavelength is represented by a spectral energy distribution, $I(\lambda)$.
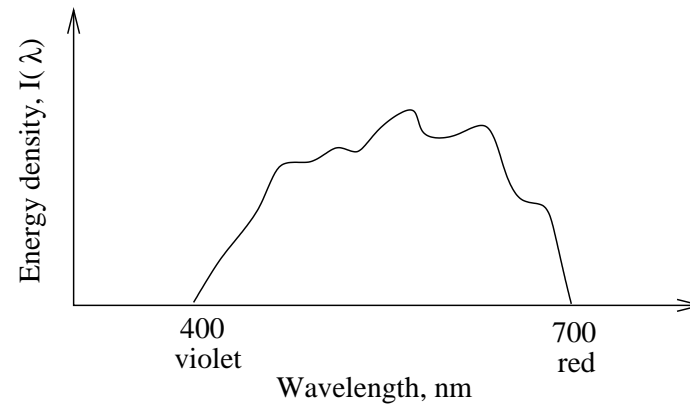
- Many different spectral energy distributions produce the same color (called *metamers*).
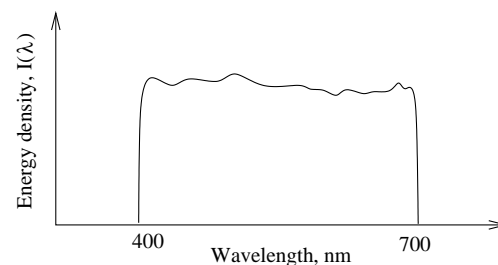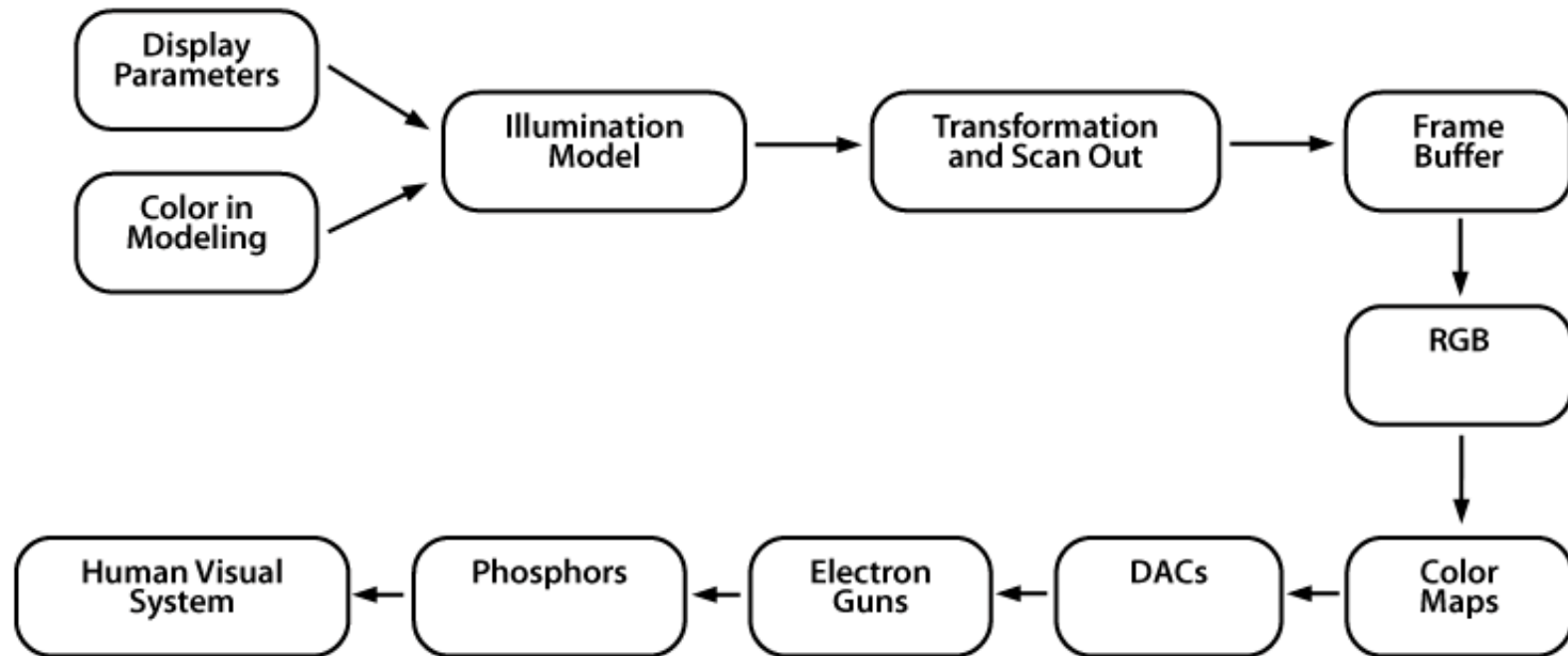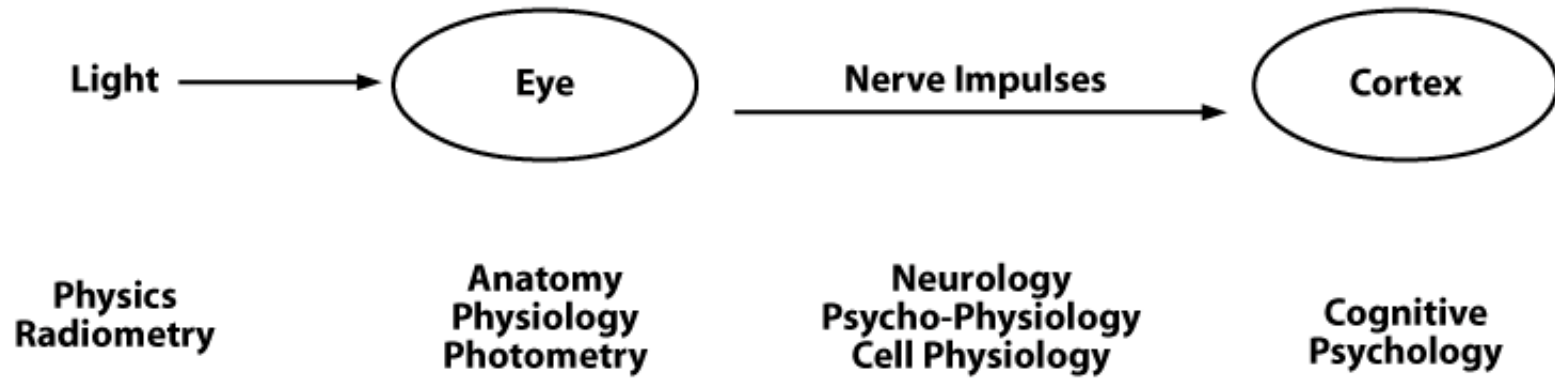

Energy distribution of a white light source

Energy distribution of a light source with a dominant wavelength near red

COLOR IN GRAPHICS SYSTEM

HUMAN VISUAL SYSTEM

RETINA

- Contains the light receptors

  - Rods
  - Cones

Rods

- *Scoptic* vision

- Response is function of wavelength

- Maximum response at 507 nm (cyan-green)

- Mechanism is chemical reaction which has to occur in the dark

- Thus sensitive under low illumination, but inactive under high illumination

- Cannot distinguish color since only one kind of rod

CONES

- *Photopic* vision

- Response is function of wavelength

- Maximum response at 555 nm (yellow-green)

- Insensitive to low illumination

- Three types of cones, having a maximum response at "red," "green," and "blue"

- But there is considerable overlap among the response curves

- "blue" sensitivity is less

- "red," "green," and "blue" cones are more aptly called high, medium, and low wavelength cones, respectively

Cone Response Curves
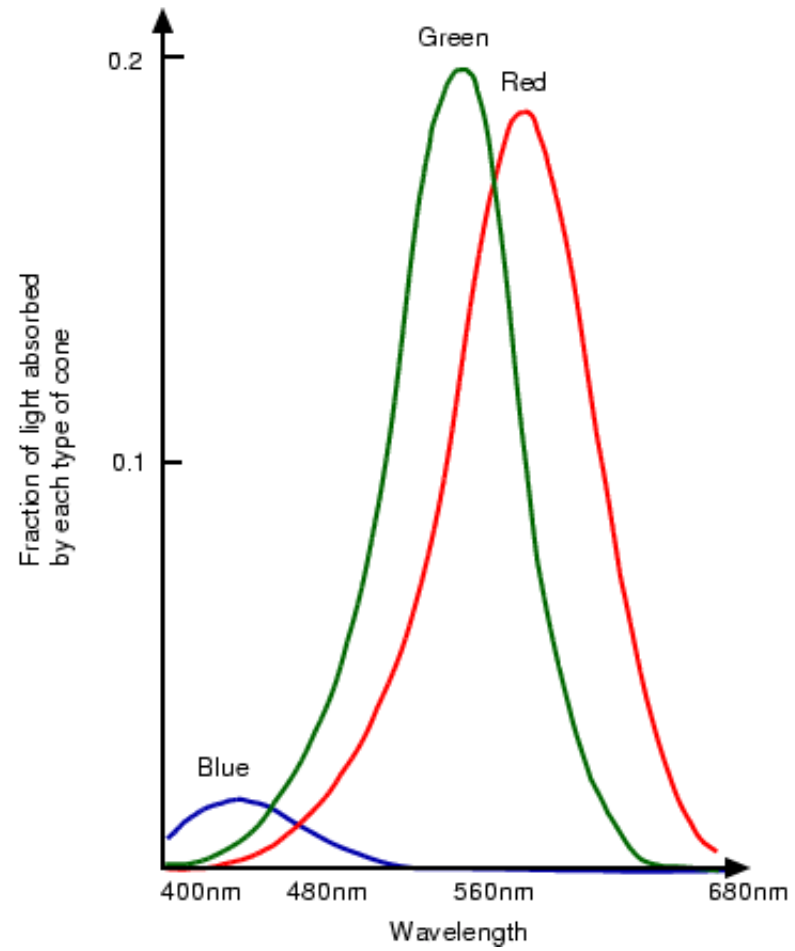
OPPONENT PROCESSING SCHEME

Three signals

- *Luminance:*

  - only the black and white information
  - also called the *achromatic* signal

- Red/Green opponent signal (R−G)

- Yellow/Blue opponent signal ((R+G)−B)

Color Specification

- Tristimulus theory

- Physiological evidence

- Experimentally, can match any color stimulus with appropriate amounts of three primary monochromatic colors

- Color is a three-dimensional space

- Many different coordinate systems

ALTERNATIVE COLOR SPACES

• CIE XYZ

• RGB

• CMY

• YIQ

• HSV

• HSL

• Ostwald

• Munsell

CIE XYZ System

- Commission Internationale de l'Eclairage

- Established the coordinate system in 1931

- Chromaticity diagram is two dimensional where R+G+B$= 1$

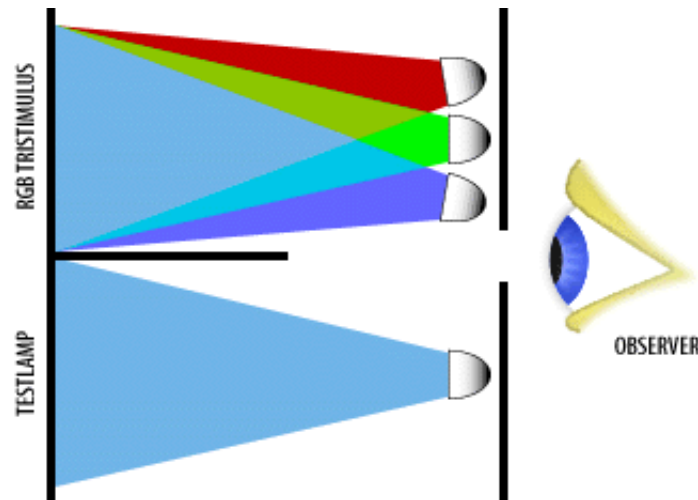- Color gamuts easily represented using Chromaticity diagram
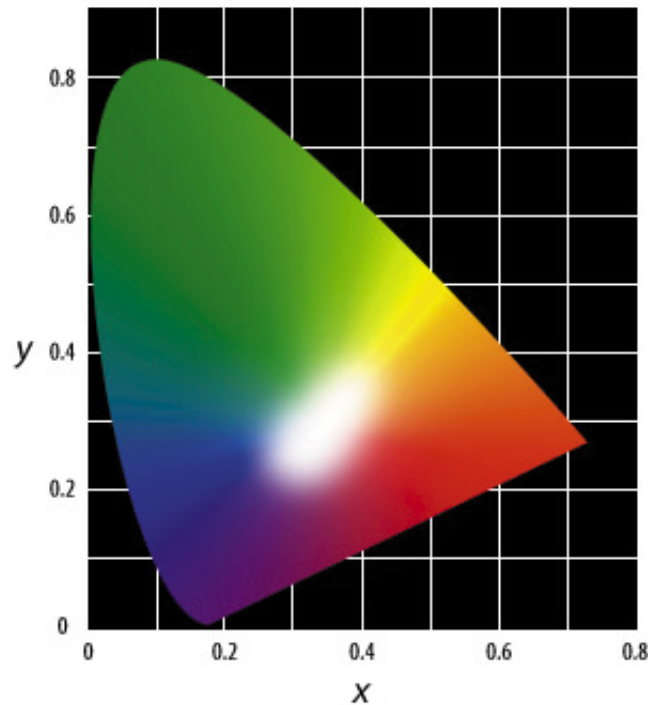
COLOR-MATCHING FUNCTIONS

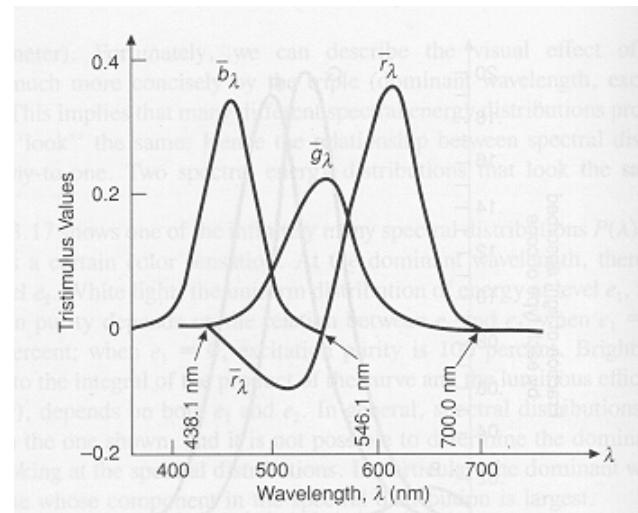- Colors can be specified by weighted sums of red, green, and blue

$$\mathbf{C} = r\mathbf{R} + g\mathbf{G} + b\mathbf{B}$$

where r, g, b are the amounts of $\mathbf{R}$, $\mathbf{G}$, $\mathbf{B}$ colors, respectively

- An experiment was carried out to find the *color-matching functions* for RGB primaries; they are obtained by averaging the judgements of a large number of observers
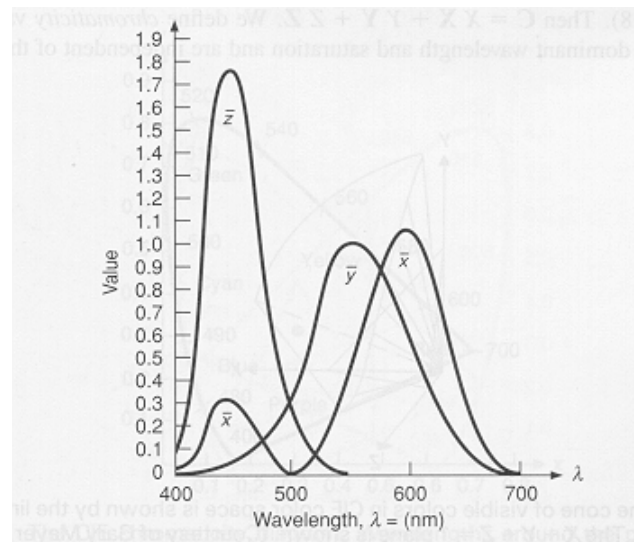
COLOR-MATCHING FUNCTIONS

- These curves yield the amounts of R, G, B light needed to match any visible color

- The negative value for the red primary in the vicinity of 500 nm means we cannot match the sample color by adding primaries

- However, the sample color can be matched if we add the red primary to the color being matched

CIE XYZ System

- Every color can be made with *positive* combinations of primaries called **X, Y, Z**

- The **X, Y, Z** primaries are non-realizable

- The color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ for CIE's **XYZ** primaries (transformed from RGB color-matching functions):

- By design, the $\bar{y}$ curve is just the *luminous efficiency curve* of our eyes

THE CIE COLOR-MATCHING FUNCTIONS

Given a color **C** with a spectral energy distribution $I(\lambda)$, find the amounts of **X, Y, Z** primaries to match it:

$$X = k \int I(\lambda)\, \bar{x}(\lambda)\, d\lambda$$

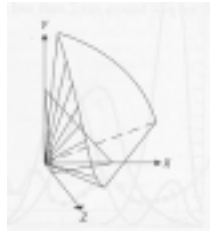$$Y = k \int I(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

$$Z = k \int I(\lambda)\, \bar{z}(\lambda)\, d\lambda$$

where k = 680 lumens/watt for CRT

$$\mathbf{C} = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$$

CIE XYZ COLOR SPACE
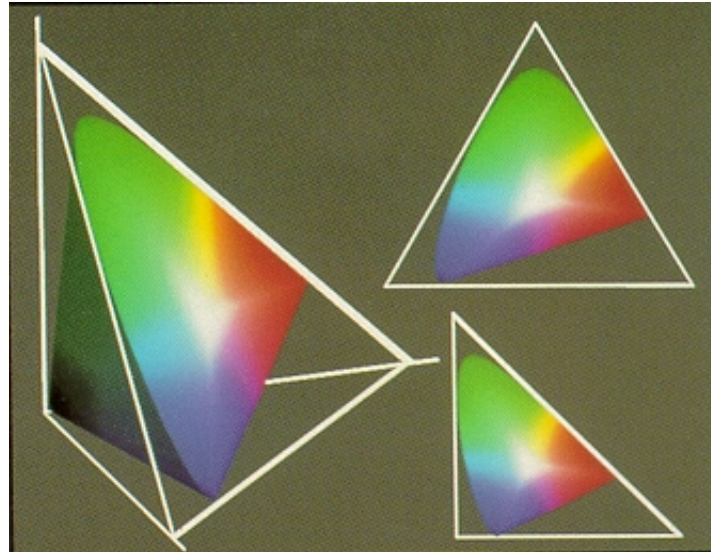
- The XYZ space of visible colors is cone shaped

- This is a 3D space, so it is hard to visualize. Hence, we normalize it by cutting with the plane $X + Y + Z = 1$

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

- As $x + y + z = 1$, we only need to keep (x, y). We can now represent all the colors on a 2D diagram

# Visualizations of the CIE Color Space

Several views of the $X + Y + Z = 1$ plane of CIE space:

- Left: the plane embedded in CIE space

- Top right: a view perpendicular to the plane

- Bottom right: the projection onto the (X, Y) plane, which is the chromaticity diagram
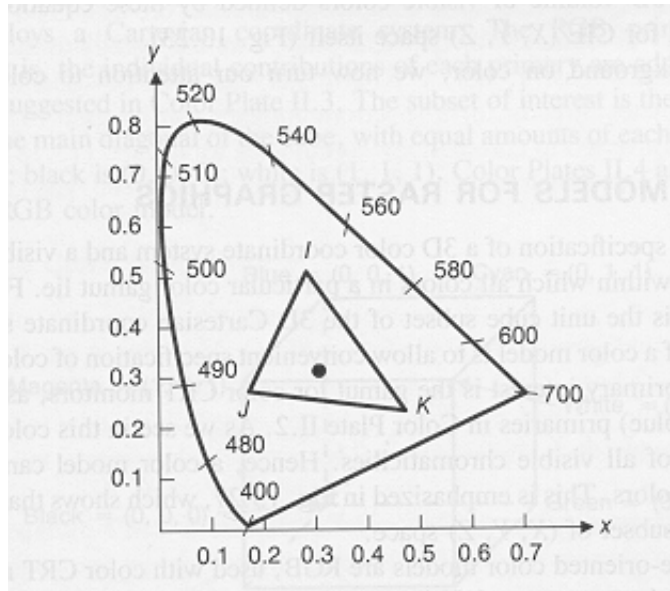
THE CIE CHROMATICITY DIAGRAM

- The *CIE chromaticity diagram* is the projection of the $X + Y + Z = 1$ plane onto the (X, Y) plane

- (x, y) are known as the chromaticity values (or chromaticity coordinates)
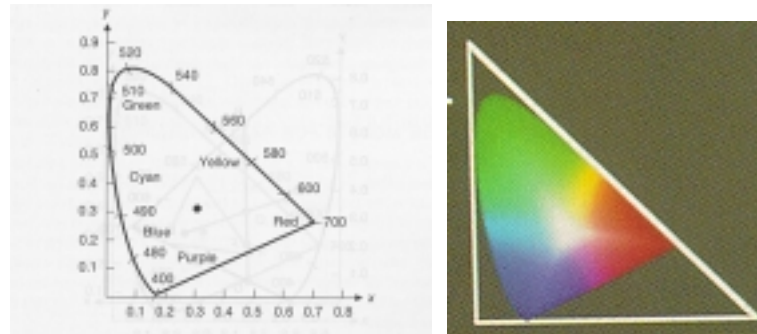
- White is roughly in the center

- Pure (saturated) colors are along the curved boundary (spectral colors)

- As we move towards the white point, the colors become less saturated

- Examples: red $= (0.735, 0.265)$, green $= (0.274, 0.717)$, blue $= (0.167, 0.009)$

THE CIE CHROMATICITY DIAGRAM

- We can predict the effect of additively combining various colors

- Any color in the triangle IJK can be created by some mixture of colors I, J, K

- Because the CIE chromaticity diagram is rounded like a shark fin, no matter which 3 visible colors we choose as primaries, we cannot span the entire fin

THE CIE CHROMATICITY DIAGRAM
COMPLEMENTARY COLORS

- Colors that can be mixed to produce white light (e.g red and cyan)

- If $a\mathbf{C_1} + (1 - a)\mathbf{C_2} =$ white, then $\mathbf{C_1}$ and $\mathbf{C_2}$ are complementary colors

- Lie on opposite sides of white
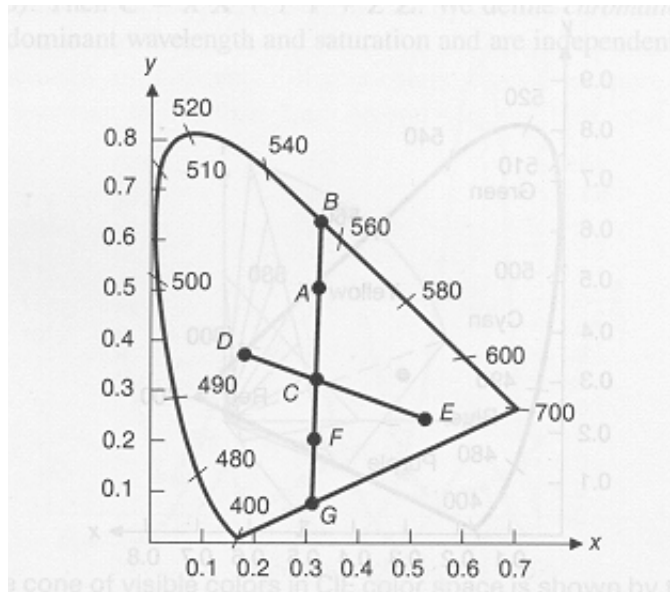
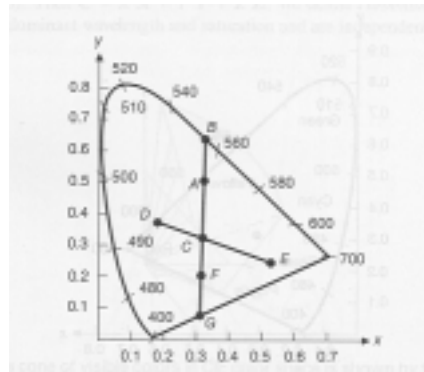- Example: colors D and E are complementary colors

THE CIE CHROMATICITY DIAGRAM
NONSPECTRAL COLORS

- Lie along the straight line on the lower part of the CIE diagram

- Examples: reds, magentas, purples, F and G

The CIE Chromaticity Diagram
Dominant Wavelength and Excitation Purity

- Dominant wavelengths go around the top of the fin

- The dominant wavelength of color A is at B

- The dominant wavelength of color F is the complement of the dominant wavelength of color A; deleting some light at frequency B from a flat spectral distribution will result in color F

- The ratio $\frac{AC}{BC}$ is the excitation purity of A

- The ratio $\frac{FC}{GC}$ is the excitation purity of F

RGB System

- R, G, B on orthogonal axes

- R, G, B each normalized to 0 to 1 (orthonormal)

- Gamut of all representable color inside the unit cube

- Corresponds to CRT color monitor technology

- Need to specify the coordinates of the primaries in the CIE XYZ system

- NTSC defined the CIE chromaticity values of the standard phosphors
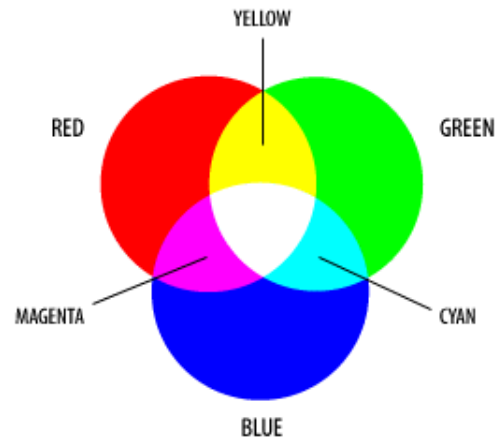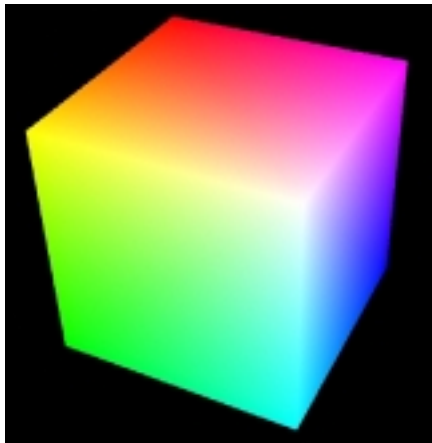
Gamuts

- A display device has a range of reproducible colors that depends on the spectra reproduced by the phosphors/pigments/etc. . .

- This range or reproducible colors is called the *gamut* of the device
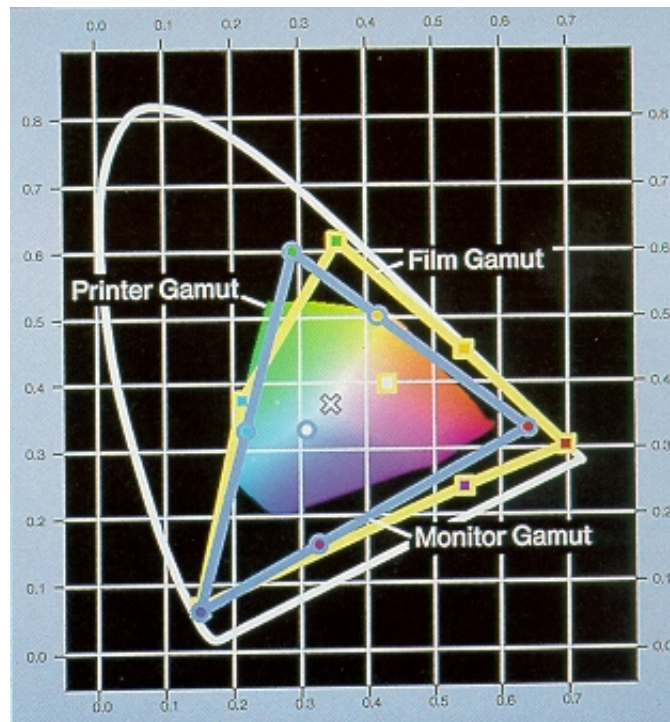
CMY System

- A subtractive system, used in most printing devices

- Consider media where color is achieved by reflectance or transmittance

- Ink absorbs some color, what we see is that which is reflected (not absorbed)

- Final color results from removal of light from the source used for illumination

- More convenient to use system where colors are obtained by subtraction

- Subtractive primaries:

  - cyan = white−red
  - magenta = white−green
  - yellow = white−blue

CMY System

- Mixing two pigments subtracts their opposites from white

- Although in theory black is the sum of the three primaries, in practice a black pigment is added to form the *four color printing process*
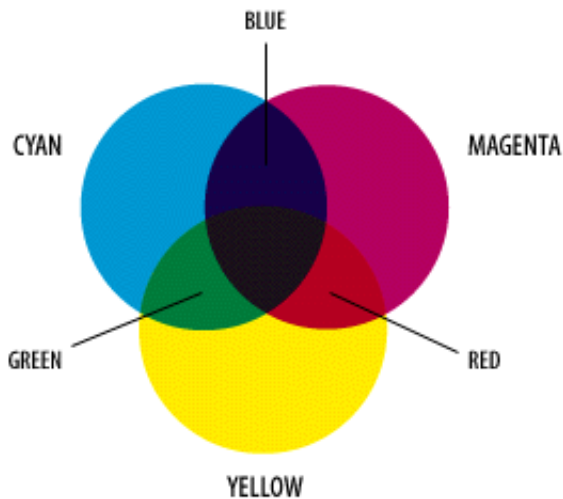
YIQ System

- Used in the US for color television broadcasting

- NTSC standard

- It is a recoding of RGB with some tricks for broadcasting efficiency and compatibility with black-and-white

- Y is the Y of the CIE XYZ system

- Y is the luminance

- I is Caucasian "flesh tones" axis (orange–cyan)

- Q is green–purple

- Relation between YIQ and RGB depends on particular RGB phosphors

HSV System

- RGB, CMY, YIQ are tailored for particular devices (CRT's, printers, video), but users find these systems difficult to work with

- HSV is more intuitive to users

- *Hue:* what distinguishes "red" quality from "blue" quality

- *Saturation:* vividness or proportion of "pure" color mixed with white

- *Value:* related to intensity

- Normally represented as a cone or *hexcone*

- Hue is the angle around the circle or the regular hexagon; $0 \leq H \leq 360$

- Saturation is the distance from the center; $0 \leq S \leq 1$

- Value is the position along the axis of the cone or hexcone; $0 \leq V \leq 1$

HSV System

- Value is not perceptually-based, so colors of the same value may have slightly different brightnesses
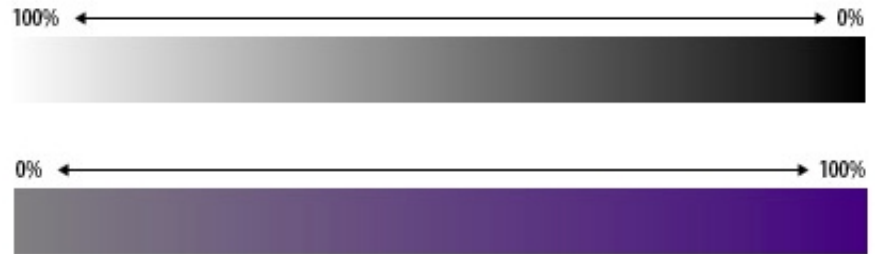
- Main axis is grey scale
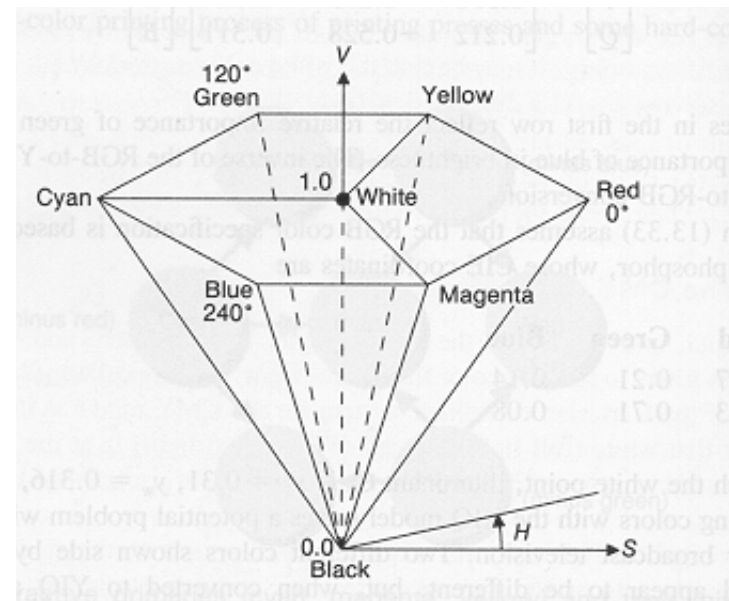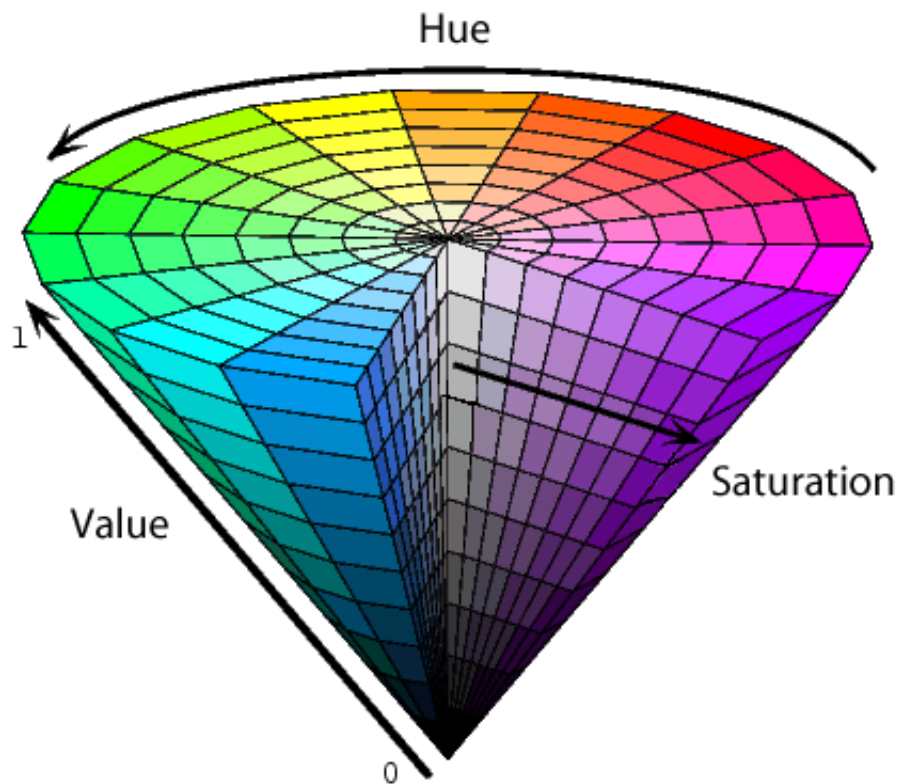
HSV System

- Hexcone can be formed by standing the RGB cube on its main diagonal with the black vertex at the bottom and the white vertex at the top, and then flattening it until the top half is reduced to a plane

- No linear transformation between RGB and HSV

- Arbitrary transformation exists
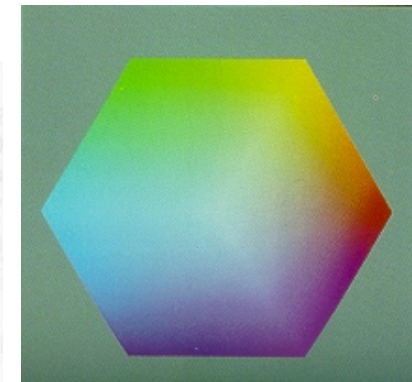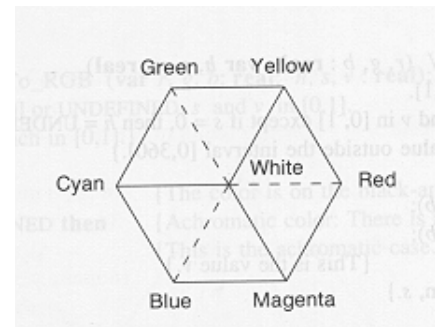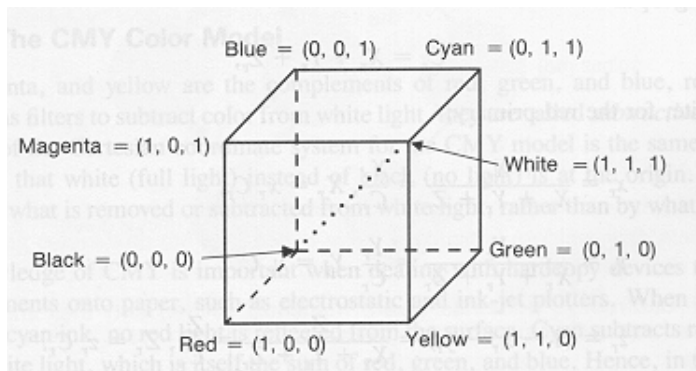
HLS System

- Recall that the HSV system flattened the "bright" half of the RGB cube

- HLS is symmetric with respect to black and white

- Represented as a double cone or double hexcone

- Double hexcone can be formed by standing the RGB cube on its main diagonal and imagining that the remaining six vertices (representing R, Y, G, C, B, M) are somehow made coplanar.

- No linear transformation between RGB and HLS

- Arbitrary transformation exists

HLS System

LIGHTNESS 0% - 100%

SATURATION
0% - 100%

HUE
0° - 360°

0°/360°

315°

45°

270°

90°

225°

135°

180°

100%

0%

0%

100%
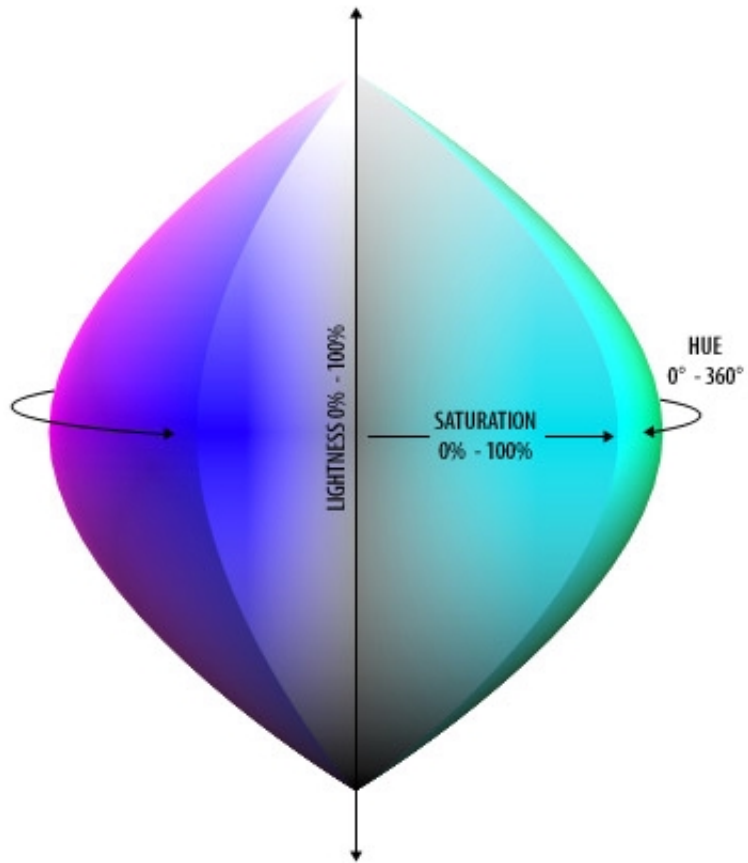
Ostwald System

- Color samples gathered in book

- Color solid

- Geared toward the mixing of a discrete number of "pure" color pigments, the pure hues, with black and white paint

Munsell System

- Based on psychological perception of *hue, chroma*, and *value*

- Comprises actual color samples in a book

- Each page of the book contains a constant hue plane

- Within this plane, the samples are arranged in rows and columns

- Samples in the same row are perceived to have same "lightness"

- Samples in the same column are perceived to have the chroma
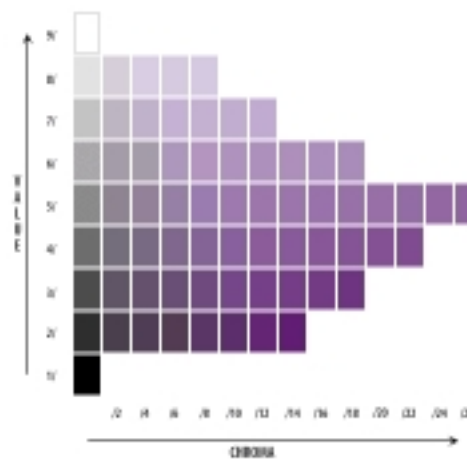
CONVERSION BETWEEN SYSTEMS

- XYZ, RGB, CMY, and YIQ are linearly related

- HLS and HSV are not linearly related to each other or to the other standard systems

RGB to YIQ & YIQ to RGB

- RGB to YIQ conversion:

$$
\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} mR \\ mG \\ mB \end{bmatrix}
$$

- YIQ to RGB conversion:

$$
\begin{bmatrix} mR \\ mG \\ mB \end{bmatrix} = \begin{bmatrix} 1 & 0.956 & 0.621 \\ 1 & -0.272 & -0.647 \\ 1 & -1.105 & 1.702 \end{bmatrix} \begin{bmatrix} Y \\ I \\ Q \end{bmatrix}
$$

- where mR, mG, and mB are based on the NTSC RGB monitor phosphors

- note that these specify different primaries from those defined by CIE, which are R $= 700$ nm, G $= 546.1$ nm, B $= 435.8$ nm

- using the CIE primaries, Y is expressed as follows:

$$
Y = .17R + .81G + .01B
$$

XYZ to RGB

- Using RGB (with CIE Standard D65 Illuminants white point)

- To transform from XYZ to RGB, the matrix transform used is:

$$
\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.240479 & -1.537150 & -0.498535 \\ -0.969256 & 1.875992 & 0.041556 \\ 0.055648 & -0.204043 & 1.057311 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
$$

- This matrix has negative coefficients.

- Some XYZ color may be transformed to RGB values that are negative or greater than one.

- This means that not all visible colors can be produced using the RGB system.

RGB to XYZ

- To transform from RGB to XYZ, the matrix transform used is:

$$
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}
$$

Interpolation in Color Space

- Mixing two colors according to two weights arises in shading algorithms, color filtering, and color mixing in paint systems

- Linear interpolation between two colors can give different results in different color spaces

- Result is the same in the linearly related spaces

PERCEPTUAL DISTANCES

- When we perceive the distance between two colors to be the same as that between another pair of colors, the corresponding distances in the color space may differ.

- Would like a more perceptually homogeneous system

- The L*u*v* system is an approximate solution

Perceptual Distances
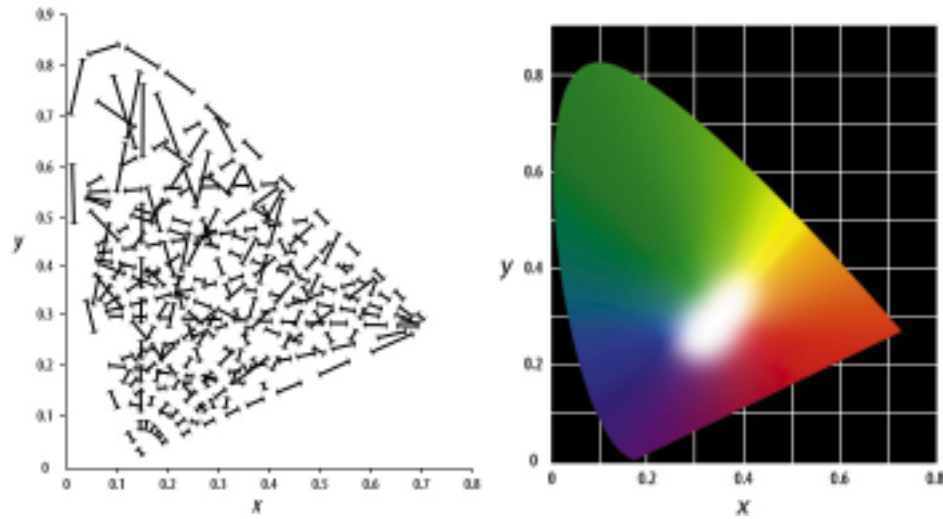
perceptual distances in CIE XYZ space
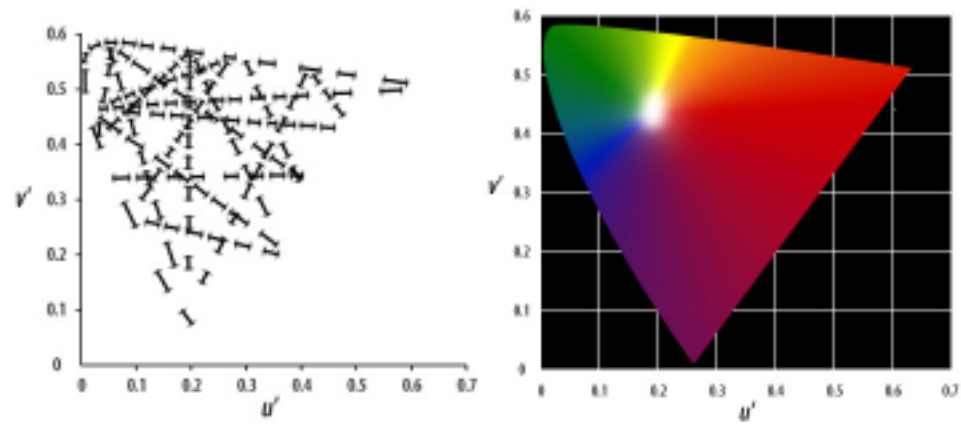
perceptual distances in CIE LUV space

How Many Colors?

- *jnd:* just noticeable difference

- 8 bits per primary $\rightarrow 256$ values per primary $\rightarrow 2^{24}$ colors $\rightarrow 16$ million colors

- But the values should be distributed logarithmically, so that the ratio between adjacent values is constant

- If linear scales are used, then more bits per primary are needed

- 10 bits per primary $\rightarrow 1024$ values per primary $\rightarrow 2^{30}$ colors $\rightarrow 1$ billion colors

- Note that a 1000 by 1000 image cannot show more than 1 million colors