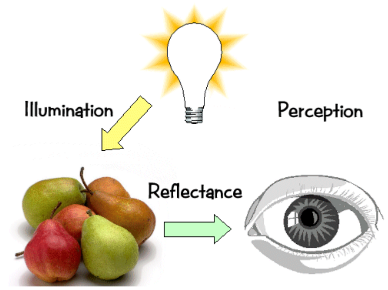
Color Topics in Computer Graphics

- Color Perception
- Color Spaces
- Gamma
- Alpha

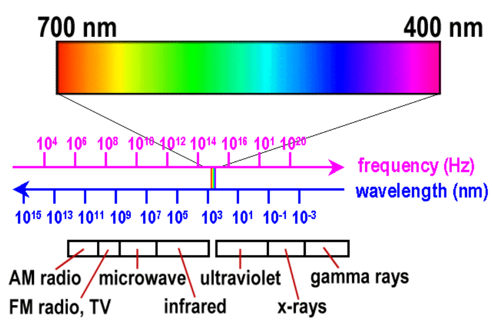
Hearn & Baker pp. 513-515, 565-581 (study)

Elements of Color



Visible Spectrum

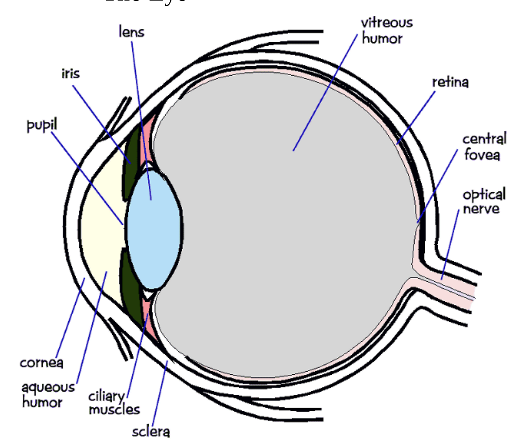
We percieve electromagnetic energy having wavelengths in the range 400-700 nm as *visible light*.



The Eye

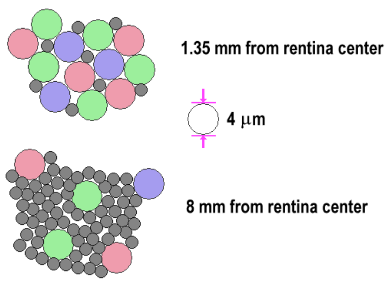
The photosensitive part of the eye is called the *retina*.

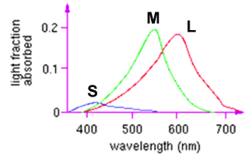
The retina is largely composed of two types of cells, called *rods* and *cones*. Only the cones are responsible for color perception.



The Fovea

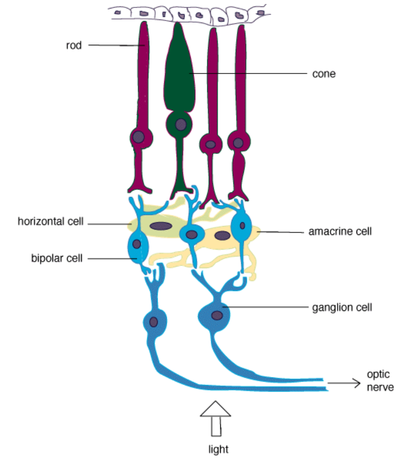
Cones are most densely packed within a region of the eye called the *fovea*.

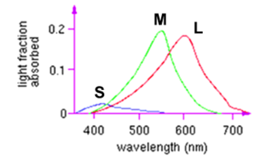




There are three types of cones, referred to as S, M, and L. They are roughly equivalent to blue, green, and red sensors, respectively. Their peak sensitivities are located at approximately 430nm, 560nm, and 610nm for the "average" observer.

The Fovea

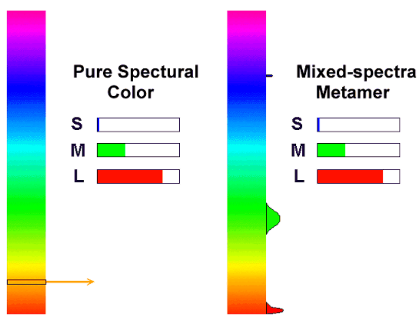




Colorblindness results from a deficiency of one cone type.

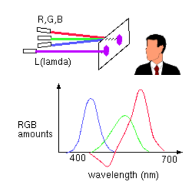
Color Perception

- Different spectra can result in a perceptually identical sensations called *metamers*
- Color perception results from the simultaneous stimulation of 3 cone types (*trichromat*)
- Our perception of color is also affected by surround effects and adaptation



Color Matching

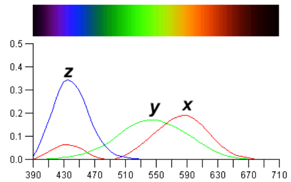
In order to define the perceptual 3D space in a "standard" way, a set of experiments can (and have been) carried by having observers try and match color of a given wavelength, lambda, by mixing three other pure wavelengths, such as R=700nm, G=546nm, and B=436nm in the following example. Note that the phosphours of color TVs and other CRTs do not emit pure red, green, or blue light of a single wavelength, as is the case for this experiment.



The scheme above can tell us what mix of R,G,Bis needed to reproduce the perceptual equivalent of any wavelength. A problem exists, however, because sometimes the red light needs to be added to the target before a match can be achieved. This is shown on the graph by having its intensity, R, take on a negative value.

CIE Color Space

In order to achieve a representation which uses only positive mixing coefficients, he CIE ("Commission Internationale d'Eclairage") defined three new hypothetical light sources, x, y, and z, which yield positive matching curves:



If we are given a spectrum and wish to find the corresponding X, Y, and Z quantities, we can do so by integrating the product of the spectral power and each of the three matching curves over all wavelengths. The weights X,Y,Z form the three-dimensional CIE XYZ space, as shown below.

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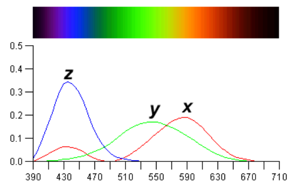

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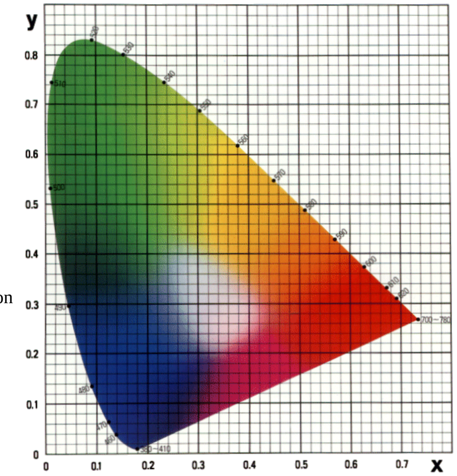
CIE Chromaticity Diagram



Often it is convenient to work in a 2D color space. This is commonly done by projecting the 3D color space onto the plane X+Y+Z=1, yielding a *CIE chromaticity diagram*. The projection is defined as:

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

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

Giving the chromaticity diagram shown on the right.

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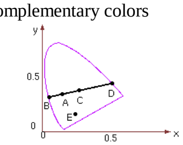
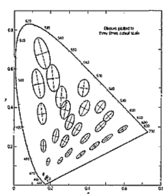
Giving the following chromaticity diagram.

Definitions:

- Spectrophotometer
- Illuminant C
- Complementary colors



- Dominant wavelength
-
- Non-spectral colors
- Perceptually uniform color space



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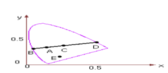
A few definitions:

spectrophotometer
: A device to measure the spectral energy distribution. It can therefore also provide the CIE xyz tristimulus values.

illuminant C
: A standard for white light that approximates sunlight. It is defined by a color temperature of 6774 K.

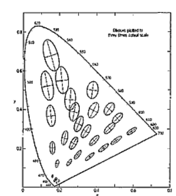
complementary colors
: colors which can be mixed together to yield white light. For example, colors on segment CD are complementary to the colors on segment CB.



dominant wavelength
: The spectral color which can be mixed with white light in order to reproduce the desired color. color B in the above figure is the dominant wavelength for color A.

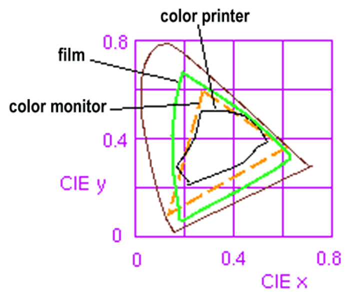
non-spectral colors
: colors not having a dominant wavelength. For example, color E in the above figure.

perceptually uniform color space
: A color space in which the distance between two colors is always proportional to the perceived distance. The CIE XYZ color space and the CIE chromaticity diagram are *not* perceptually uniform, as the following figure illustrates. The CIE LUV color space is designed with perceptual uniformity in mind.



Color Gamuts

The chromaticity diagram can be used to compare the "gamuts" of various possible output devices (i.e., monitors and printers). Note that a color printer cannot reproduce all the colors visible on a color monitor.



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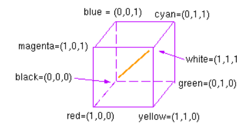
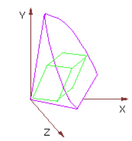
The RGB Color Cube

The additive color model used for computer graphics is represented by the RGB color cube, where R, G, and B represent the colors produced by red, green and blue phosphours, respectively.



The color cube sits within the CIE XYZ color space as follows.



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Color Printing

Green paper is green because it reflects green and absorbs other wavelengths. The following table summarizes the properties of the four primary types of printing ink.

dye color	*absorbs*	*reflects*
cyan	red	blue and green
magenta	green	blue and red
yellow	blue	red and green
black	all	none

To produce blue, one would mix cyan and magenta inks, as they both reflect blue while each absorbing one of green and red. Unfortunately, inks also interact in non-linear ways. This makes the process of converting a given monitor color to an equivalent printer color a challenging problem.

Black ink is used to ensure that a high quality black can always be printed, and is often referred to as to K. Printers thus use a CMYK color model.

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Color Conversion

To convert from one color gamut to another is a simple procedure. Each phosphour color can be represented by a combination of the CIE XYZ primaries, yielding the following transformation from RGB to CIE XYZ:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} X_R & X_G & X_B \\ Y_G & Y_G & Y_B \\ Z_B & Z_G & Z_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

The transformation $\mathbf{C}_2 = \mathbf{M}_2^{-1}\mathbf{M}_1\mathbf{C}_1$ yields the color on monitor 2 which is equivalent to a given color on monitor 1. Conversion to-and-from printer gamuts is difficult. A first approximation is as follows:

```
C = 1 - R
M = 1 - G
Y = 1 - B
```

The fourth color, K, can be used to replace equal amounts of CMY:

```
K = min(C,M,Y) C' = C - K
M' = M - K
Y' = Y - K
```

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Other Color Systems

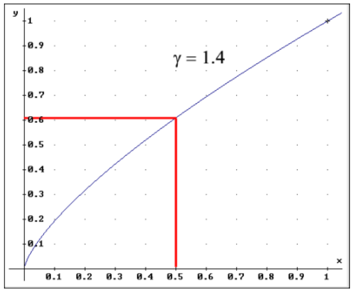
Several other color models also exist. Models such as HSV (hue, saturation, value) and HLS (hue, luminosity, saturation) are designed for intuitive understanding. Using these color models, the user of a paint program would quickly be able to select a desired color.

Example: **NTSC YIQ color space**

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Gamma Correction

When we "compute" colors we generally assume that they are linear quanities.



Unfortunately, most display devices are nonlinear.
The most common correction method is called *gamma* correction.

$$y = x_{\min} + (x_{\max} - x_{\min})\left(\frac{x - x_{\min}}{x_{\max} - x_{\min}}\right)^{\frac{1}{\gamma}}$$

$$y = x^{\frac{1}{\gamma}} \quad \text{if} \quad 0 \le x \le 1$$

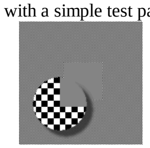
$$y = 255\left(\frac{x}{255}\right)^{\frac{1}{\gamma}} \quad \text{if} \quad 0 \le x \le 255$$

$$\text{Intensity}(\text{voltage}) \ne 2 \times \text{Intensity}(\text{voltage}/2)$$

How to Gamma Correct

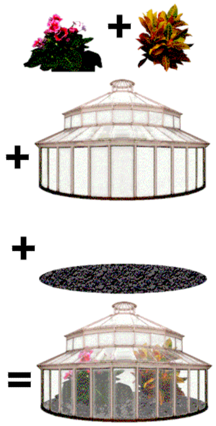
Most people consider gamma correction a black art, it is, in fact, quite simple.

Start with a simple test pattern.



We only have one parameter γ so we match the function at one point.

Alpha Blending



Alpha blending simulates the *opacity* of *cellophane-like* layers

General rules:

- Adds one channel per pixel
- Usually process layers back-to-front (using the *over* operator)
- 255 or 1.0 indicates an opaque pixel
- 0 indicates a transparent pixel
- Result is a function of foregrond and background pixel colors
- Simulate partial-pixel coverage
- Much ore capable than simple tranparency

See Microsoft's Image Composer for more info on these images

Alpha Compositing Details

Over compositing operation:

$$c_{result} = \alpha c_{fg} + (1-\alpha)c_{bg}$$

Issues with alpha:

Premultiplied (integral) alphas:

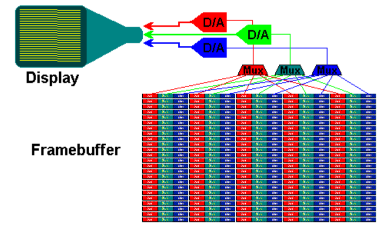
- pixel contains (α, αr, αg, αb)
- what Image Composer
- alpha value constrains color magnitude
- alpha modulates image shape

non-Premultiplied (independent) alphas:

- pixel contains (α, r, g, b)
- what Photoshop does (via layers)
- color values independent of alpha
- what does 100% tranparency mean?

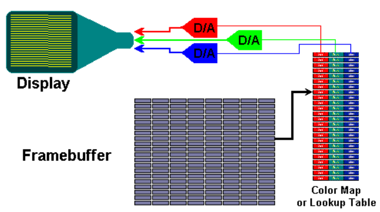
(An excellent reference on the subject)

True-Color Frame Buffers



- Each pixel requires at least 3 bytes. One byte for each primary color.
- Sometimes combined with a look-up table per primary
- Each pixel can be one of 2^24 colors
- Worry about your *Endians*

Indexed-Color Frame Buffers



- Each pixel uses one byte
- Each byte is an index into a color map
- If the color map is not updated synchronously then *Color-map flashing* may occcur.
- Color-map Animations
- Each pixel may be one of 2^24 colors, but only 256 color be displayed at a time

High-Color Frame Buffers

Pixels are packed in a short
Each primary uses 5 bits

- Popular *PC/(SVGA)* standard
- Each pixel can be one of 2^15 colors
- Can exhibit worse quantization effects than Indexed-color

Specialty Frame Buffers

- Non-RGB color models (YUV) or 4-2-2
- True color plus an *Overlay*
- Older 4-bit per pixel models [I,R,G,B]
- True-color with a lookup-per-color component

Next Time