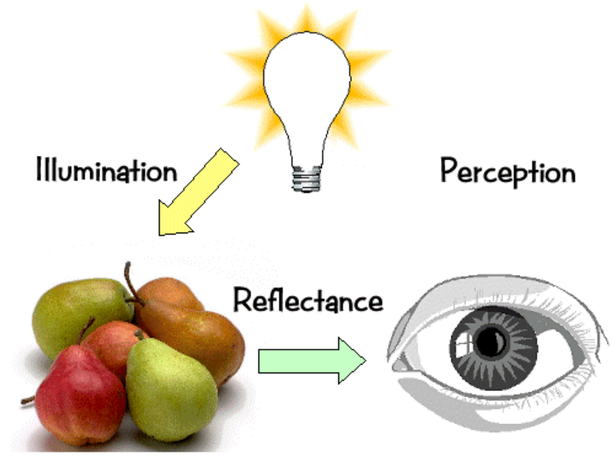
Color Topics in Computer Graphics

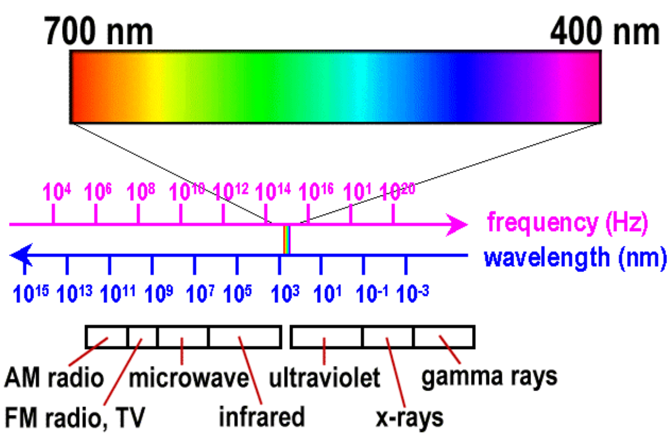
- Color Perception
- Color Spaces
- Gamma
- Tone Mapping

Elements of Color



Visible Spectrum

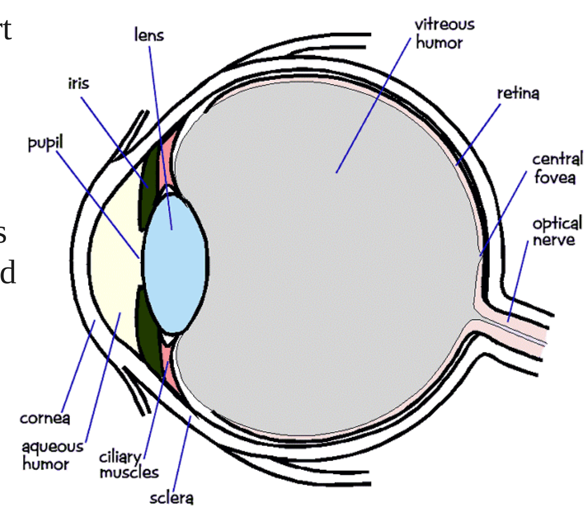
We perceive electromagnetic energy having wavelengths in the range 400-700 nm as *visible light*.



The Eye

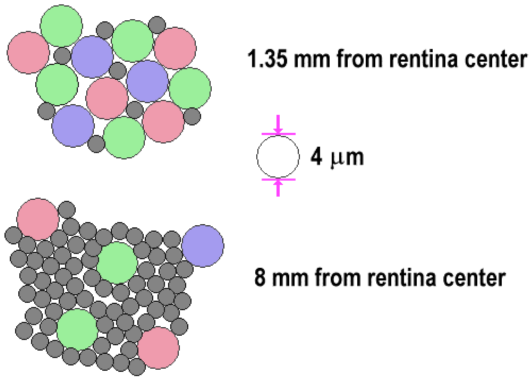
The photosensitive part of the eye is called the *retina*.

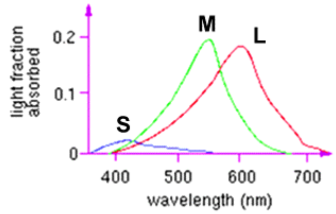
The retina is largely composed of two types of cells, called *rods* and *cones*. Only the cones are responsible for color perception.



The Fovea

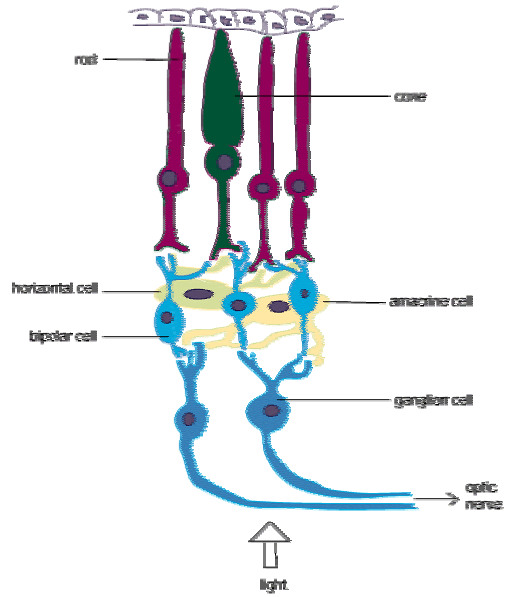
Cones are most densely packed within a region of the eye called the *fovea*.

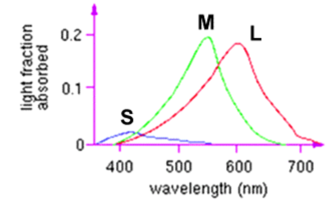




There are three types of cones, referred to as S, M, and L. They are roughly equivalent to blue, green, and red sensors, respectively. Their peak sensitivities are located at approximately 430nm, 560nm, and 610nm for the "average" observer.

The Fovea

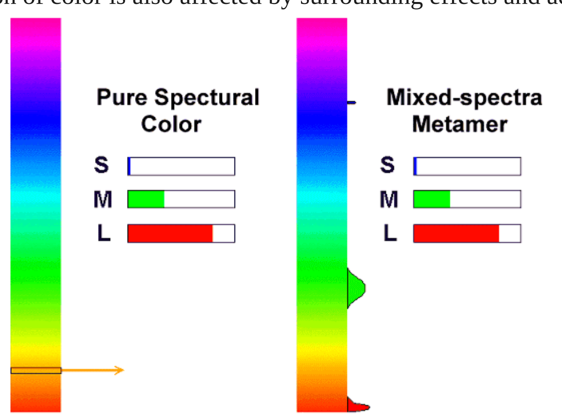




Colorblindness results from a deficiency of one cone type.

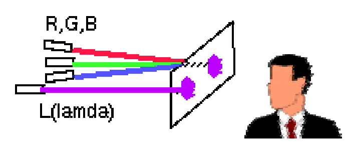
Color Perception

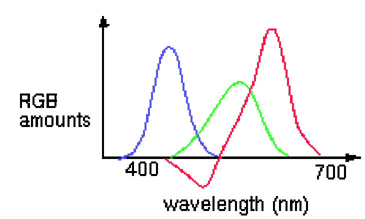
- Different spectra can result in perceptually identical sensations called *metamers*
- Color perception results from the simultaneous stimulation of 3 cone types (*trichromat*)
- Our perception of color is also affected by surrounding effects and adaptation



Color Matching

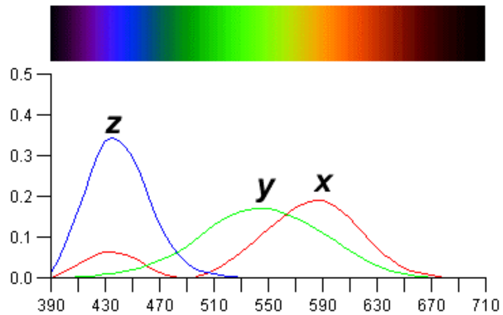
In order to define the perceptual 3D space in a "standard" way, a set of experiments can (and have been) carried out by having observers try to match color of a given wavelength, lambda, by mixing three other pure wavelengths, such as R=700nm, G=546nm, and B=436nm in the following example. Note that the phosphors 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.





CIE Color Space

In order to achieve a representation that uses only positive mixing coefficients, the 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.

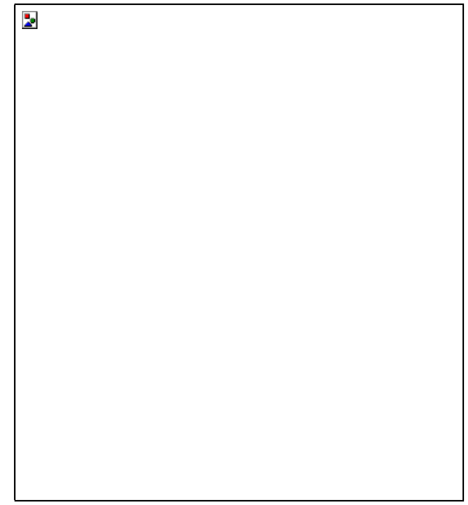
CIE Chromaticity Diagram

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:

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

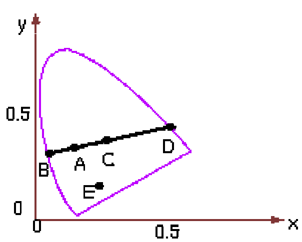
$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

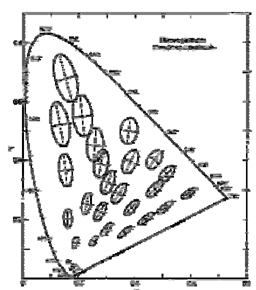
This gives the chromaticity diagram shown on the right.



Definitions:

Spectrophotometer
Illuminant C
Complementary colors





Dominant wavelength
Non-spectral colors
Perceptually uniform color space

Definitions (continued)

Spectrophotometer: A device to measure the spectral energy distribution

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

Complementary colors: colors that can be mixed together to yield white light, e.g., colors on segment CD are complementary to the colors on segment CB (see previous slide)

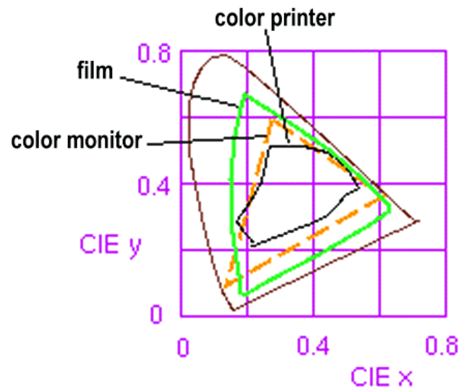
Dominant wavelength: The spectral color that can be mixed with white light in order to reproduce the desired color. Color B in the figure is the dominant wavelength for color A.

Non-spectral colors: Colors not having a dominant wavelength. For example, color E in the 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 right figure in the previous slide illustrates. The CIE LUV color space is designed with perceptual uniformity in mind.

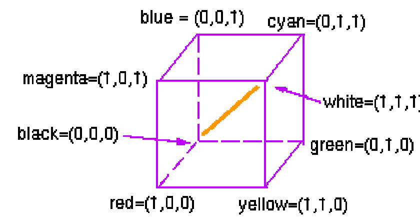
Color Gamuts

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.

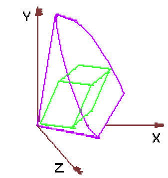


The RGB Color Cube

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 phosphors, respectively.



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



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 therefore use a CMYK color model.

Color Conversion

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

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

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:

$$C = 1 - R \qquad M = 1 - G \qquad Y = 1 - B$$

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

$$K = \min(C,M,Y) \quad C' = C - K \qquad M' = M - K \qquad Y' = Y - K$$

Other Color Systems

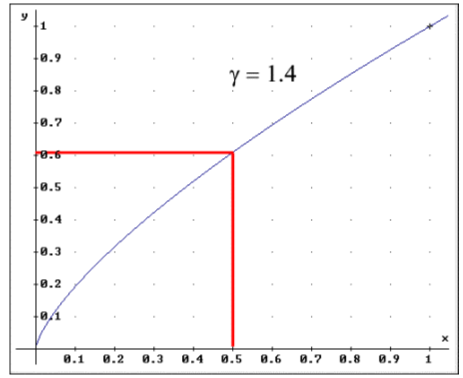
Several other color models also exist. Models such as HSV (hue, saturation, value) and HLS (hue, luminosity, saturation) are designed for intuitive understanding. Using these color models, the user of a paint program would quickly be able to select a desired color.

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 quantities.



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

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

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

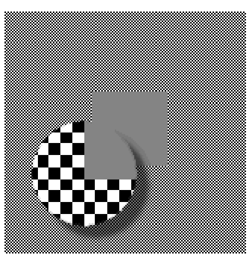
$$y = 255 \left(\frac{x}{255} \right)^{\frac{1}{\gamma}} \quad \textit{if} \quad 0 \le x \le 255$$

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

How to Gamma Correct

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

Start with a simple test pattern.

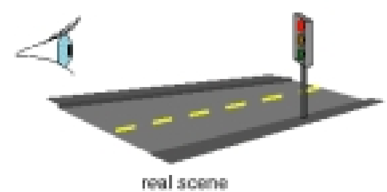


We only have one parameter γ so we match the function at one point.

Advanced Topic: Tone Mapping

Real scene: large range of luminances

- (from 10^{-6} to 10^{6} cd/m^2)



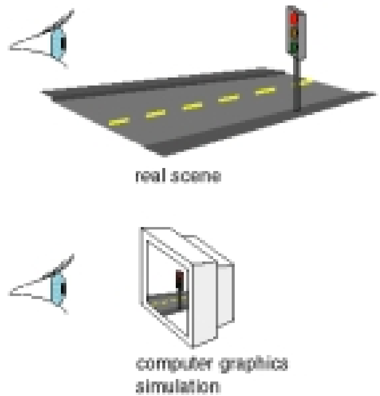
Tone Mapping

Real scene: large range of luminance

- (from 10^{-6} to 10^{6} cd/m^2)

Limitation of the display

- 1-100 cd/m^2



Tone Mapping

Real scene: large range of luminance

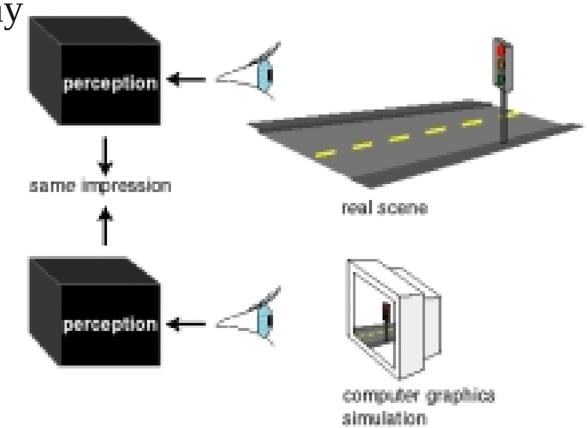
- (from 10^{-6} to 10^{6} cd/m^2)

Limitation of the display

- 1-100 cd/m^2

Goal:

Reproduce a faithful impression



Visual Adaptation

At a given time, our sensitivity is limited

The visual system adjusts its sensitivity

Neither perfect

- No color vision at night
- Acuity decreases

Nor instantaneous

Adaptation is crucial for tone mapping

Dynamic Visual Adaptation

Dazzling

- e.g., leaving a tunnel

Slow dark adaptation

- e.g., entering a dark theater

More subtle variations

Chromatic adaptation

  - Discount the color of the illuminant
  - White balance

Motivation

Architectural walkthroughs

- Better lighting immersion
- Differences in lighting ambiance

Games

- Feeling of going from dark to light and vice-versa

Simulators

- Adaptation is critical to reproduce the actual visibility conditions

Our Tone Mapping Operator

Threshold mapping

- Linear mapping
- Smallest perceptible intensities are matched

Transition from night to day vision

- Chromatic cone signal
- Achromatic rod signal
- Summed with blue shift for rods

Chromatic adaptation

- Similar to white balance
- Not always complete (depends on luminance)

Acuity decreases in the dark

- Blur

Time-Dependent Tone Mapping

Light adaptation

- Reasonably fast
- Different for decrement and increment
- Subtractive and multiplicative mechanisms

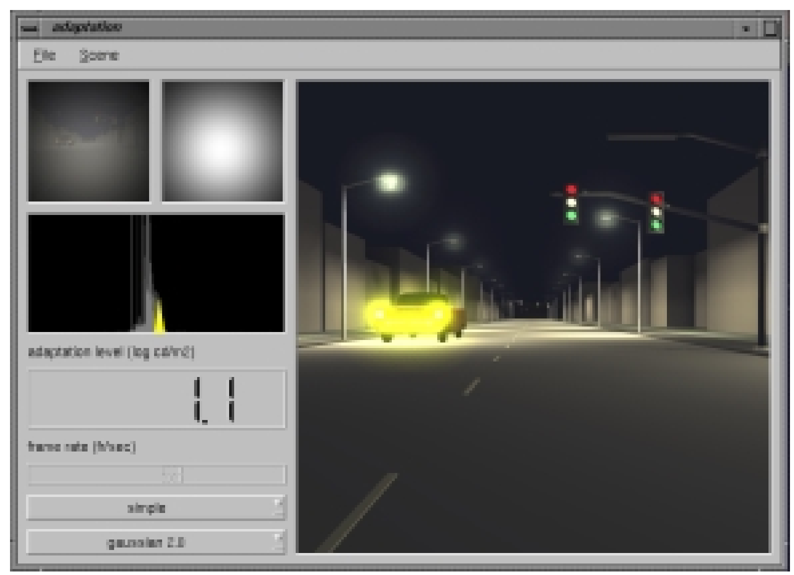
Dark adaptation

- For large decrement of luminance
- Slow (up to 40 minutes)
- Chemical regeneration of photopigments

Chromatic adaptation

- Sum of two exponentials

Results : Interactive Rendering



Future Work

Local model
- Challenge: interaction local adaptation / gaze movement

Tone mapping for night scenes
- Interaction rod/cone system

Display calibration
- Surrounding, brightness/contrast settings, gamut mapping

Next Time