Color

Reading

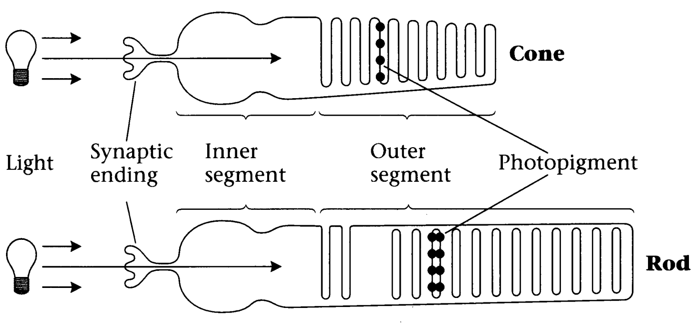
Foley, *Computer graphics*, Chapter 13.

Optional

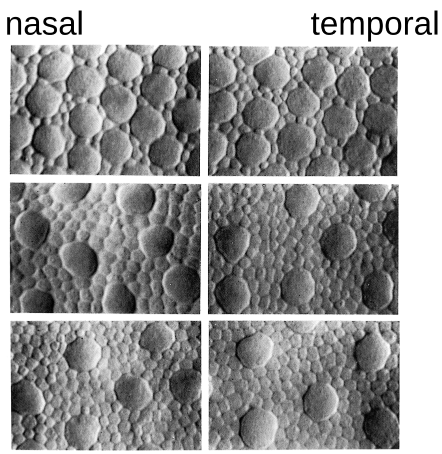
Brian Wandell. *Foundations of Vision*. Sinauer Associates, Sunderland, MA 1995.

Gerald S. Wasserman. *Color Vision: An Historical Introduction.* John Wiley & Sons, New York, 1978

Light Gathering



The human retina



Photomicrographs at increasing distances from the fovea.
The large cells are cones; the small ones are rods.

Perceptual light intensity

We perceive light intensity as we do sound: on a *relative* or *logarithmic* scale.

Example: The perceived difference between 0.20 and 0.22 is the same as between 0.80 and ______.

Ideally, to display *n+1* equally-spaced intensity levels

$$\frac{I_1}{I_0} = \frac{I_2}{I_1} = \cdots = \frac{I_n}{I_{n-1}}$$

Noise

Noise can be thought of as randomness added to the signal.

The eye is relatively insensitive to noise.

Lightness contrast

A related phenomenon is known as:

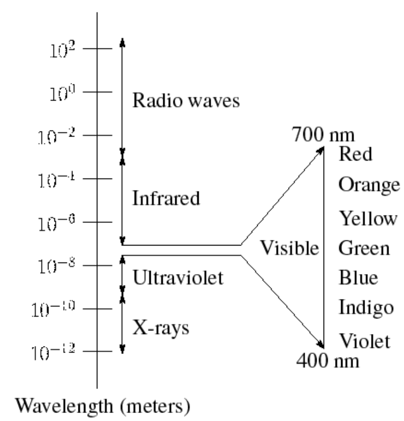
- **lightness contrast**
- **simultaneous contrast**
- **color contrast** (for colors)

This phenomenon helps us maintain a consistent mental image of the world, under dramatic changes in illumination.

Light as Waves

We can think of light as waves, instead of rays.

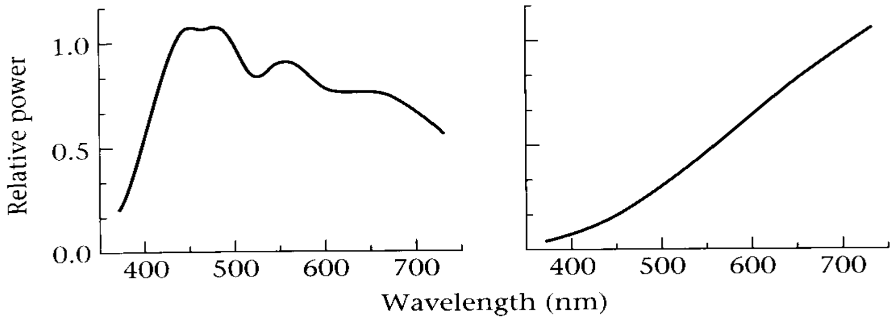
Wave theory allows a nice arrangement of electromagnetic radiation (EMR) according to wavelength:



Light as Particles

At any given moment, a light source emits some relative amount of photons at each frequency.

We can plot the *emission spectrum* of a light source as power vs. wavelength.



What is Color?

The eyes and brain turn an incoming emission spectrum into a discrete set of values.

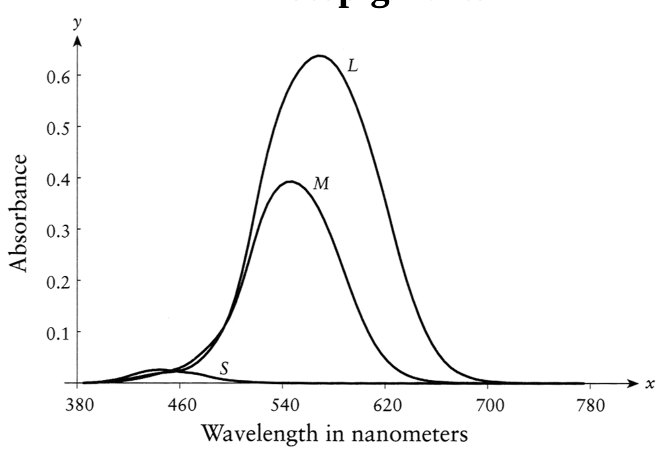
The signal sent to our brain is somehow interpreted as *color*.

Color science asks some basic questions:

- When are two colors alike?
- How many pigments or primaries does it take to match another color?

One more question: why should we care?

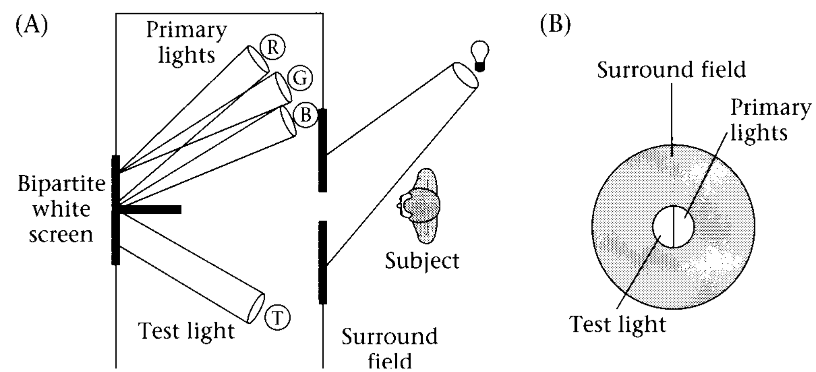
Photopigments



Photopigments are the chemicals in the rods and cones that react to light. Can respond to a single photon!

Cones come in three varieties: S, M, and L.

The Color Matching Experiment



Rods and “color matching”

A rod responds to a spectrum through its spectral sensitivity function, $p(\lambda)$. The response to a test light, $t(\lambda)$, is simply:

$$P_t = \int t(\lambda)\, p(\lambda)\, d\lambda$$

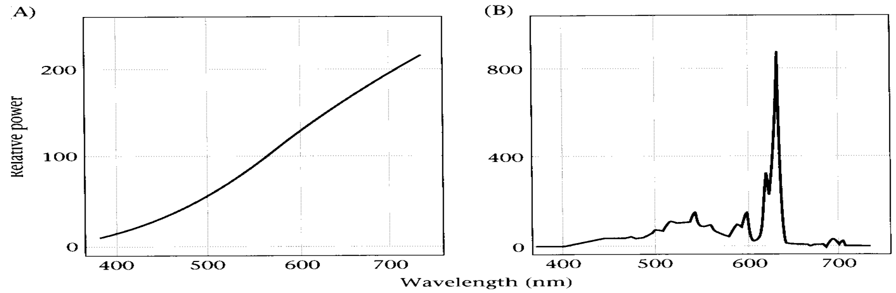
How many primaries are needed to match the test light?

What does this tell us about rod color discrimination?

Emission Spectrum is not Color

Recall how much averaging the eye does. Light is infinite dimensional!

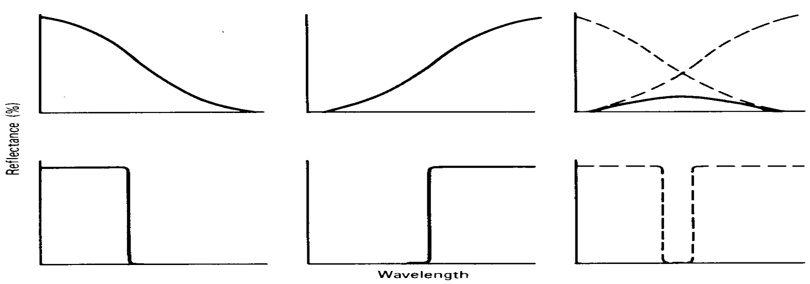
Different light sources can evoke exactly the same colors. Such lights are called **metamers**.



A dim tungsten bulb and an RGB monitor set up to emit a metameric spectrum

Colored Surfaces

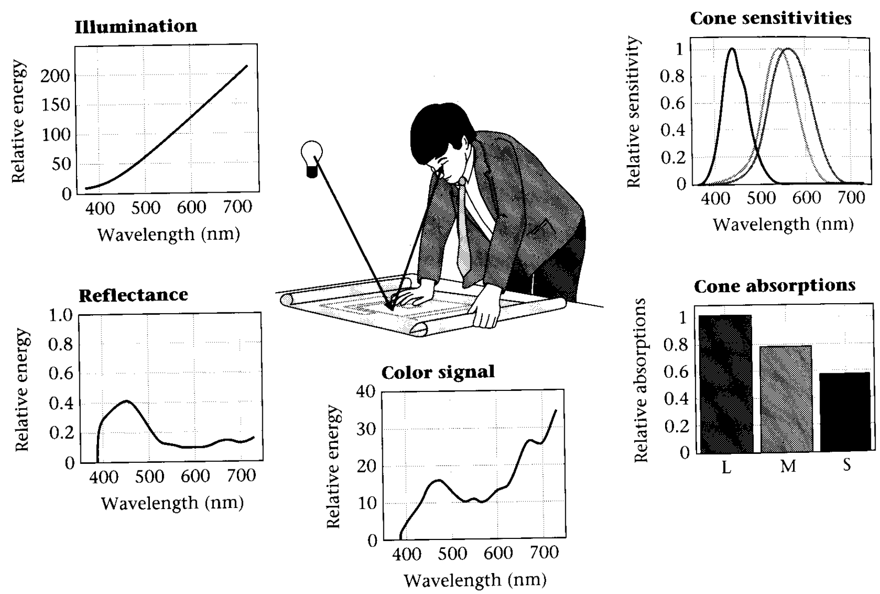
So far, we’ve discussed the colors of lights. How do *surfaces* acquire color?



A surface’s **reflectance** is its tendency to reflect incoming light across the spectrum.

Reflectance is combined **subtractively** with incoming light. (Actually, the process is multiplicative.)

Illustration of Color Appearance



Lighting design

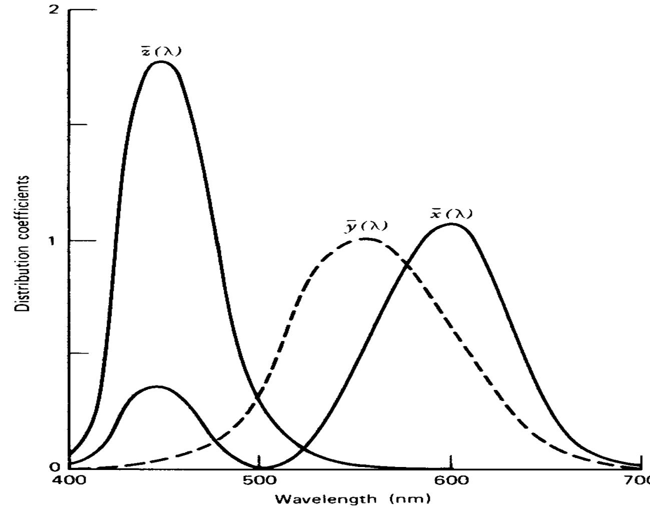
When deciding the kind of "feel" for an architectural space, the spectra of the light sources is critical.

Lighting design centers have displays with similar scenes under various lighting conditions.

We have one such center on Capitol Hill: The Northwest Lighting Design Lab. http://www.northwestlighting.com/

The CIE *XYZ* System

A standard created in 1931 by CIE, defined in terms of three color matching functions.



CIE Coordinates

Given an emission spectrum, we can use the CIE matching functions to obtain the *X, Y* and *Z* coordinates.

$$X = \int \bar{x}(\lambda)t(\lambda)d\lambda$$

$$Y = \int \bar{y}(\lambda)t(\lambda)d\lambda$$

$$Z = \int \bar{z}(\lambda)t(\lambda)d\lambda$$

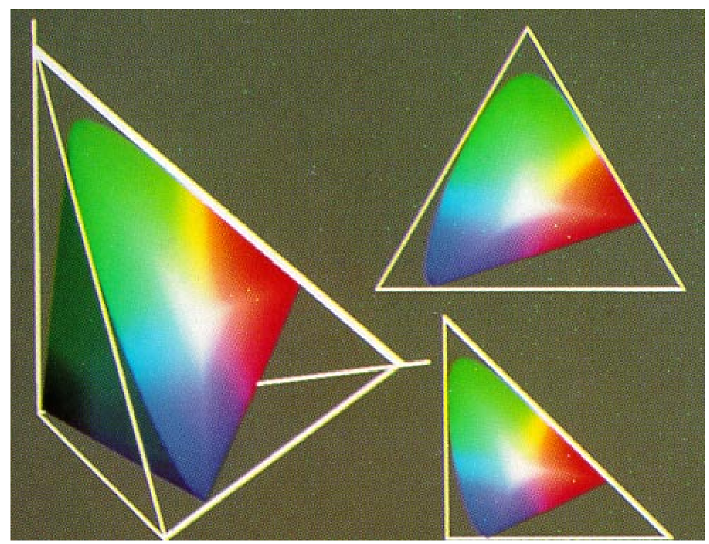
Then we can compute *chromaticity coordinates*. This gives a brightness independent notion of color.

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

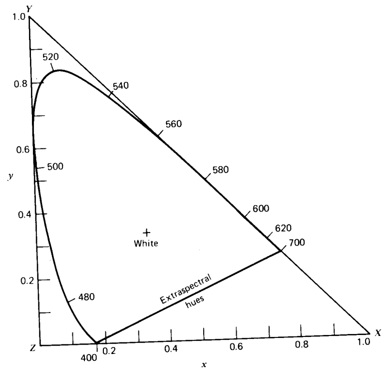
$$y = \frac{Y}{X+Y+Z}$$

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

The CIE Color Blob



The CIE Chromaticity Diagram



A projection of the plane $X+Y+Z=1$.

Each point is a chromaticity value, which depends on **dominant wavelength**, or **hue**, and **excitation purity**, or **saturation**.

More About Chromaticity

Dominant wavelengths go around the perimeter of the chromaticity blob.

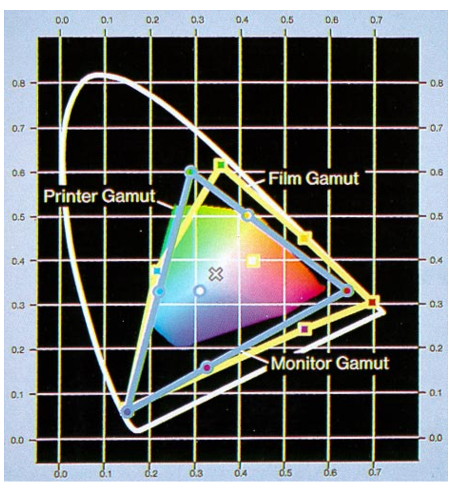
- A color's dominant wavelength is where a line from white through that color intersects the perimeter.
- Some colors, called *nonspectral* color's, don't have a dominant wavelength.

Excitation purity is measured in terms of a color's position on the line to its dominant wavelength.

Complementary colors lie on opposite sides of white, and can be mixed to get white.

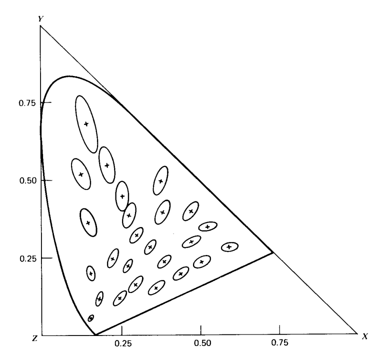
Gamuts

Not every output device can reproduce every color. A device's range of reproducible colors is called its **gamut**.



Perceptual (Non-)uniformity

The *XYZ* color space is not perceptually uniform!



Some modified spaces attempt to fix this:

- $L^*u^*v^*$
- $L^*a^*b^*$

Color Spaces for Computer Graphics

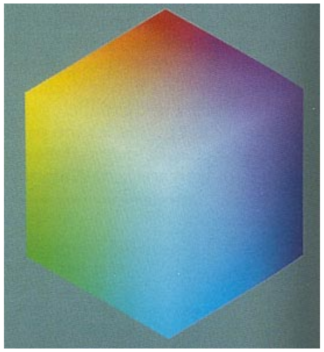
In practice, there's a set of more commonly-used color spaces in computer graphics:

- RGB for display
- CMY (or CMYK) for hardcopy
- HSV for user selection
- YIQ for television broadcast

RGB

Perhaps the most familiar color space, and the most convenient for display on a CRT.

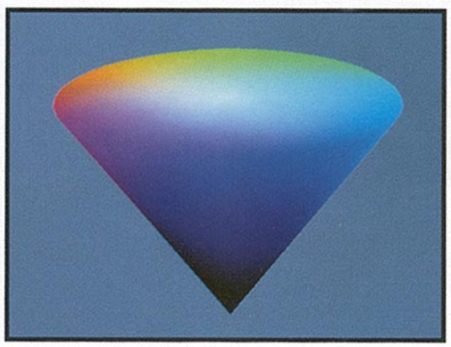
What does the RGB color space look like?



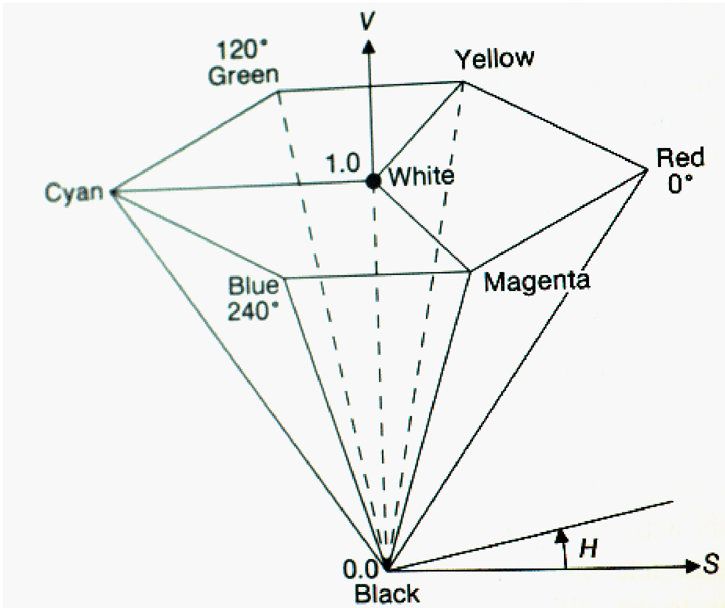
HSV

More natural for user interaction, corresponds to the artistic concepts of tint, shade and tone.

The HSV space looks like a cone:



HSV



CMY

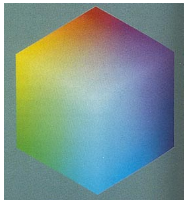
A subtractive color space used for printing.

Involves three subtractive primaries:

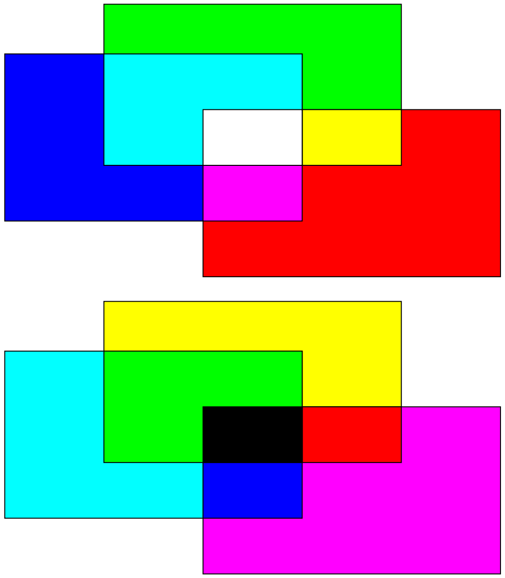
- Cyan - subtracts red
- Magenta - subtracts green
- Yellow - subtracts blue

Mixing two pigments subtracts their opposites from white.

CMYK adds blacK ink rather than using equal amounts of all three.



RGB vs. CMY



YIQ

Used in TV broadcasting, YIQ exploits useful properties of the visual system.

- Y - luminance (taken from CIE)
- I - major axis of remaining color space
- Q - remaining axis

YIQ is broadcast with relative bandwidth ratios 8:3:1

- We're best as distinguishing changes in luminance.
- Small objects can be compressed into a single color dimension.

Why do we devote a channel to luminance?

Summary

- How light is a form of EMR.
- The eye's relative sensitivity to intensity discontinuities, but insensitivity to noise.
- How the color matching experiment works
- The relationship between color matching and functions cone responses
- The difference between emissive and reflective color
- The CIE XYZ color standard and how to interpret the chromaticity diagram
- The color spaces used in computer graphics