Color

Reading

- Foley, Chapter 13.

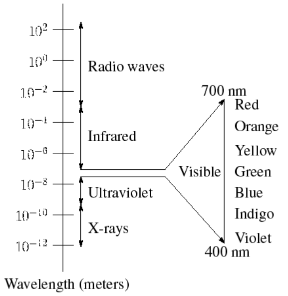
Further reading:

- Brian Wandell. *Foundations of Vision. Chapter 4.* Sinauer Associates, Sunderland, MA, 1995.
- Gerald S. Wasserman. *Color Vision: An Historical Introduction.* John Wiley & Sons, New York, 1978

The radiant energy spectrum

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

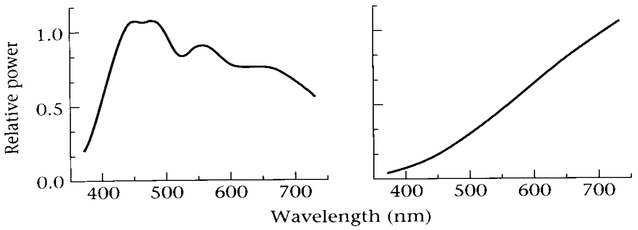
Wave theory allows a nice arrangement of electromagnetic radiation (EMR) according to wavelength:



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:

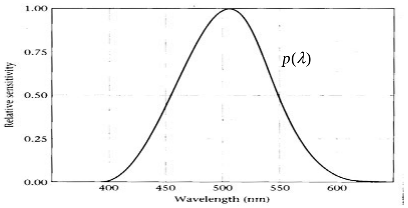
- When are two colors alike?
- How many pigments or primaries does it take to match another color?

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!

Rods contain **rhodopsin**, which has peak sensitivity at about 500nm.

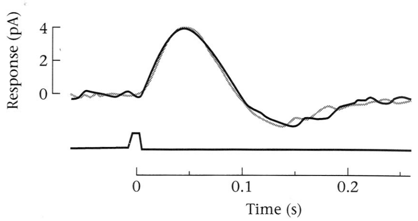


Rod sensitivity (Wandell ,4.6)

Rods are active under low light levels, i.e., they are responsible for **scotopic** vision.

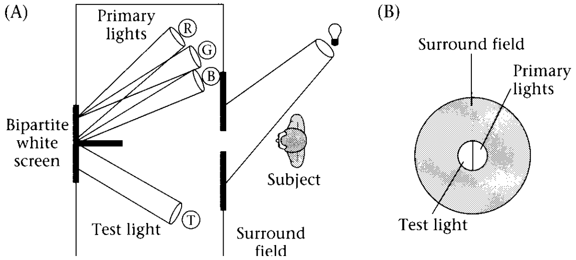
Univariance

Principle of univariance: For any single photoreceptor, no information is transmitted describing the wavelength of the photon.



Photocurrents measured for two light stimuli: 550nm (solid) and 659 nm (gray). The brightnesses of the stimuli are different, but the shape of the response is the same. (Wandell 4.17)

The Color Matching Experiment



Rods and "color matching"

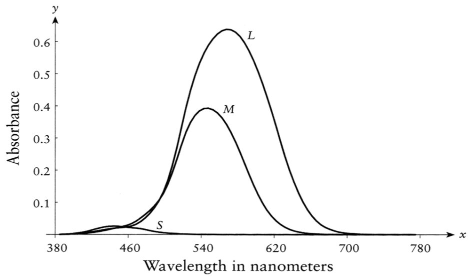
A rod responds to a spectrum through its spectral sensitivity function, $p(\lambda)$. The response to a test light, $t(\lambda)$, is simply:

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

How many primaries are needed to match the test light?

What does this tell us about rod color discrimination?

Cones



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

Cones and color matching

Color is perceived through the responses of the cones to light.

The response of each cone can be written simply as:

$$L_t = \int t(\lambda) l(\lambda) d\lambda$$
$$M_t = \int t(\lambda) m(\lambda) d\lambda$$
$$S_t = \int t(\lambda) s(\lambda) d\lambda$$

These are the only three numbers used to determine color.

Any pair of stimuli that result in the same three numbers will be indistinguishable.

How many primaries do you think we'll need to match t?

Color matching

Let's assume that we need 3 primaries to perform the color matching experiment.

$$e(\lambda) = Aa(\lambda) + Bb(\lambda) + Cc(\lambda)$$

Consider three primaries, $a(\lambda)$, $b(\lambda)$, $c(\lambda)$, with three emissive power knobs, A, B, C.

The three knobs create spectra of the form:

$$\begin{aligned} L_{abc} &= \int e(\lambda) l(\lambda) d\lambda \\ &= \int \left[Aa(\lambda) + Bb(\lambda) + Cc(\lambda) \right] l(\lambda) d\lambda \\ &= A\int a(\lambda) l(\lambda) d\lambda + B\int b(\lambda) l(\lambda) d\lambda + C\int c(\lambda) l(\lambda) d\lambda \\ &= AL_a + BL_b + CL_c \end{aligned}$$

What is the response of the l-cone? How about the m- and s-cones?

Color matching, cont'd

We end up with similar relations for all the cones:

$$L_{abc} = AL_a + BL_b + CL_c$$
$$M_{abc} = AM_a + BM_b + CM_c$$
$$S_{abc} = AS_a + BS_b + CS_c$$

We can re-write this as a matrix:

$$\begin{bmatrix} L_{abc} \\ M_{abc} \\ S_{abc} \end{bmatrix} = \begin{bmatrix} L_a & L_b & L_c \\ M_a & M_b & M_c \\ S_a & S_b & S_c \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix}$$

and then solve for the knob settings:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} L_a & L_b & L_c \\ M_a & M_b & M_c \\ S_a & S_b & S_c \end{bmatrix}^{-1} \begin{bmatrix} L_{abc} \\ M_{abc} \\ S_{abc} \end{bmatrix}$$

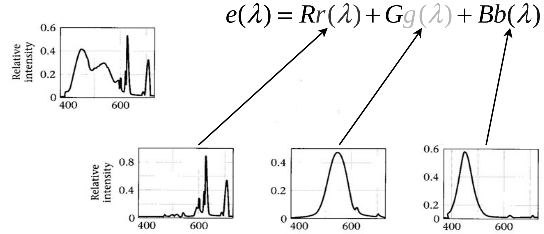
In other words, we can choose the knob settings to cause the cones to react as we please!

Choosing Primaries

The primaries could be three color (monochromatic) lasers.

But, they can also be non-monochromatic, e.g., monitor phosphors:

$$e(\lambda) = Rr(\lambda) + Gg(\lambda) + Bb(\lambda)$$

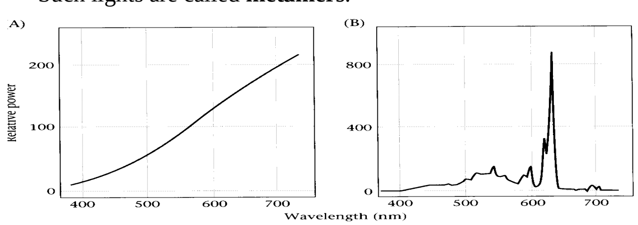


Emission spectra for RGB monitor phosphors (Wandell B.3)

Emission Spectrum is not Color

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

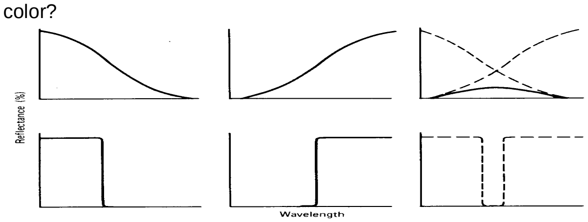
Different light sources can evoke exactly the same colors. Such lights are called **metamers**.



A dim tungsten bulb and an RGB monitor set up to emit a metameric spectrum (Wandell 4.11)

Colored Surfaces

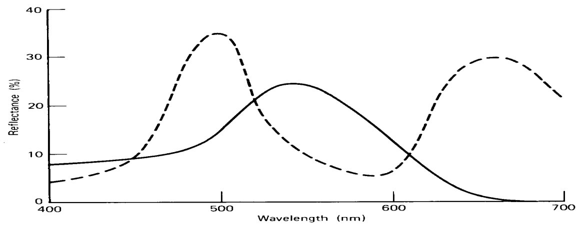
So far, we've discussed the colors of lights. How do *surfaces* acquire color?



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.)

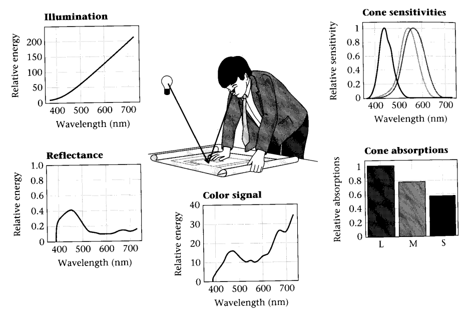
Subtractive Metamers



Reflectance adds a whole new dimension of complexity to color perception.

The solid curve appears green indoors and out. The dashed curve looks green outdoors, but brown under incandescent light.

Illustration of Color Appearance Demo



Lighting design

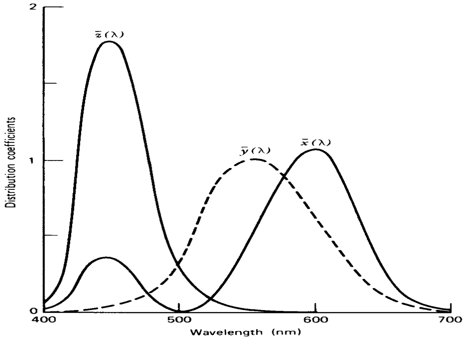
When deciding the kind of "feel" for an architectural space, the spectra of the light sources is critical.

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.

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

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

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

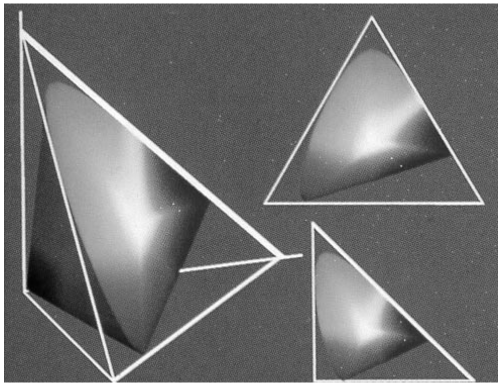
Then we can compute *chromaticity coordinates*. This gives a brightness independent notion of color.

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

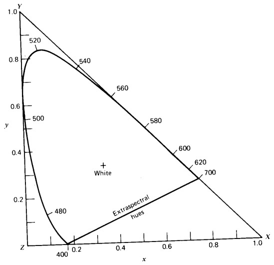
$$y = \frac{Y}{X+Y+Z}$$

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

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.

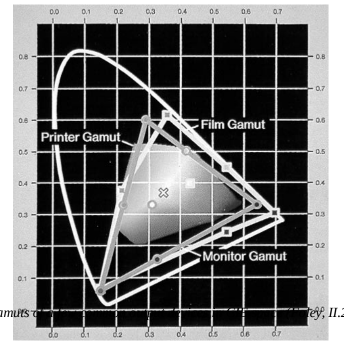
- A color's dominant wavelength is where a line from white through that color intersects the perimeter.
- Some colors, called *nonspectral* color's, don't have a dominant wavelength.

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

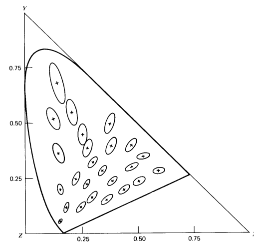
Not every output device can reproduce every color. A device's range of reproducible colors is called its **gamut**.



Gamuts of a few common output devices in CIE space (Foley, II.2)

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

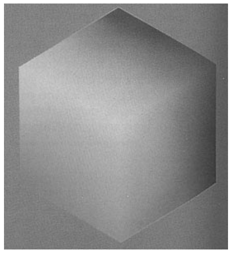
In practice, there's a set of more commonly-used color spaces in computer graphics:

- 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.

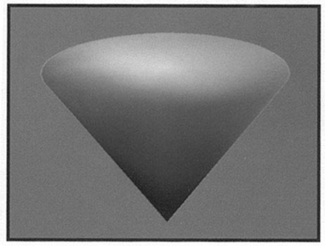
What does the RGB color space look like?



HSV

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

The HSV space looks like a cone:



CMY

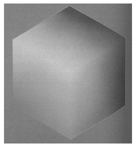
A subtractive color space used for printing.

Involves three subtractive primaries:

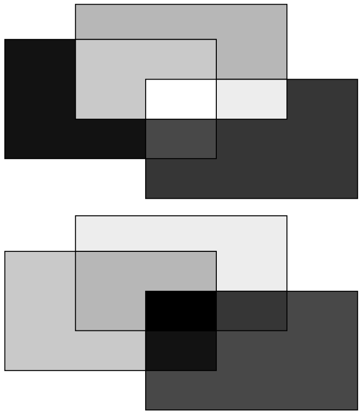
- Cyan - subtracts red
- Magenta - subtracts green
- Yellow - subtracts blue

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 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