Lecture 2:
Color

Reading

- Hearn & Baker, Chapter 15.

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

Outline

- Spectrum and color

- Measuring color

- The CIE XYZ color space

- Color spaces for computer graphics

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*.

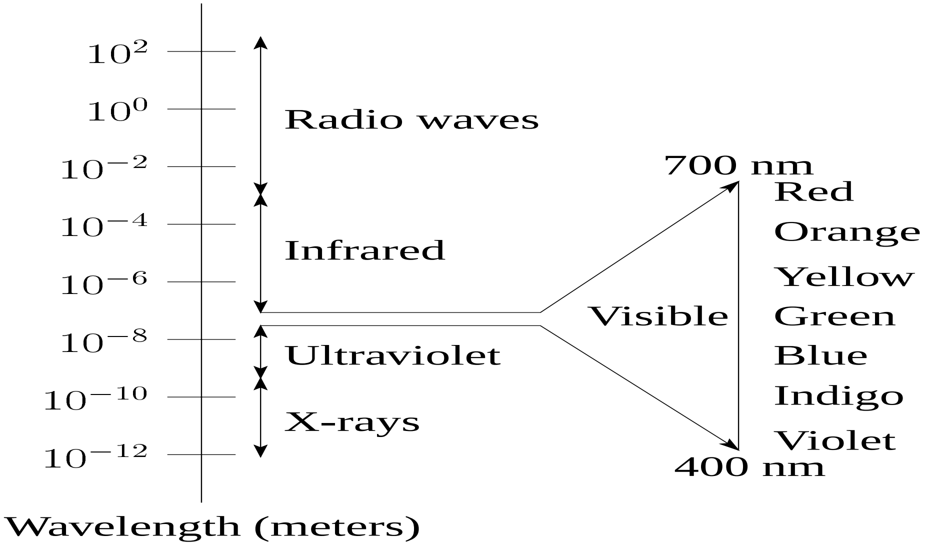
Color science asks some basic questions:

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

One more question: why should we care?

Light as Waves

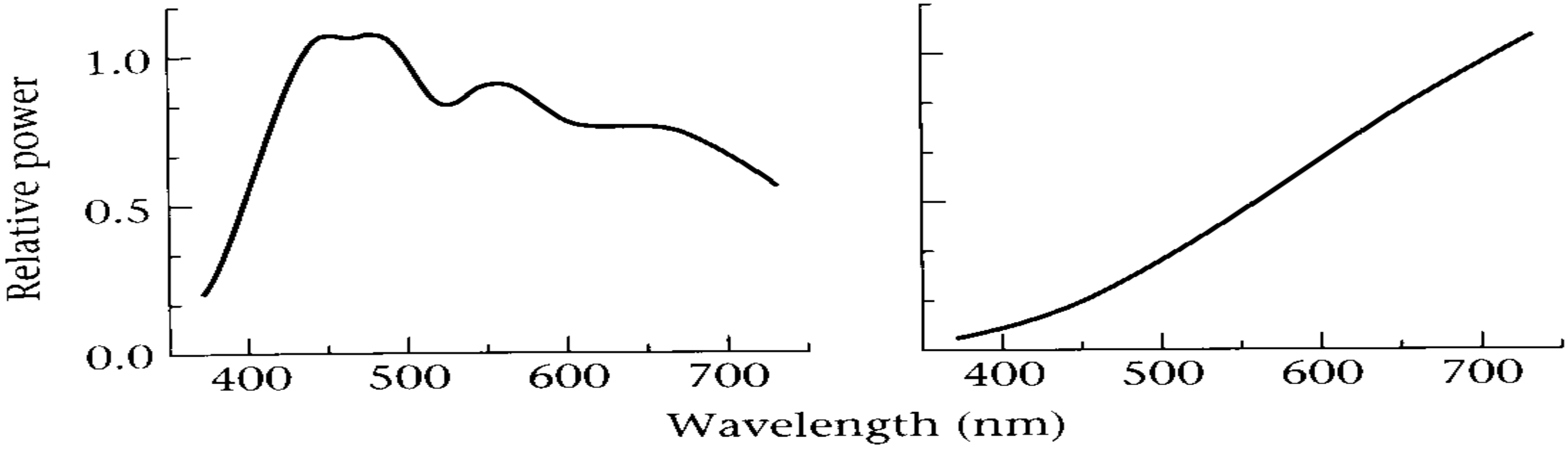
Maxwell described the *electromagnetic spectrum* and showed that visible light was just part of the spectrum.



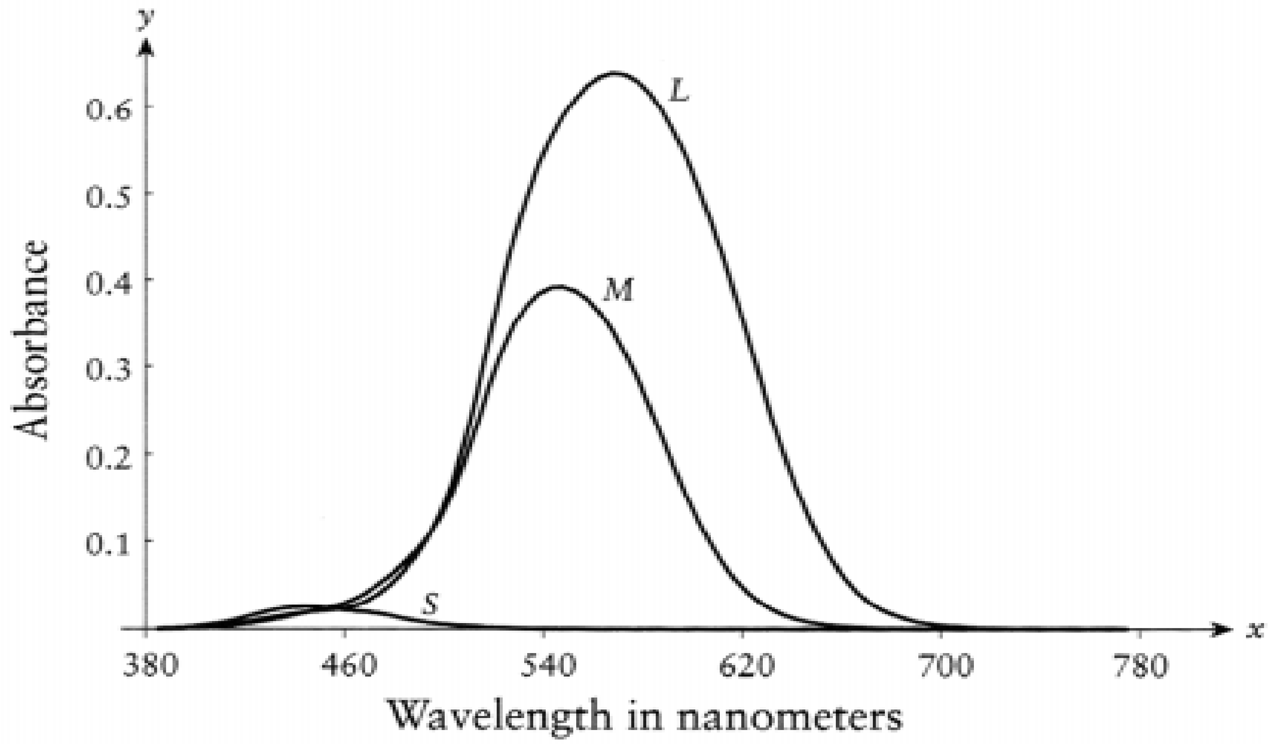
Light as Particles

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.



Cones



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

Transmitting color

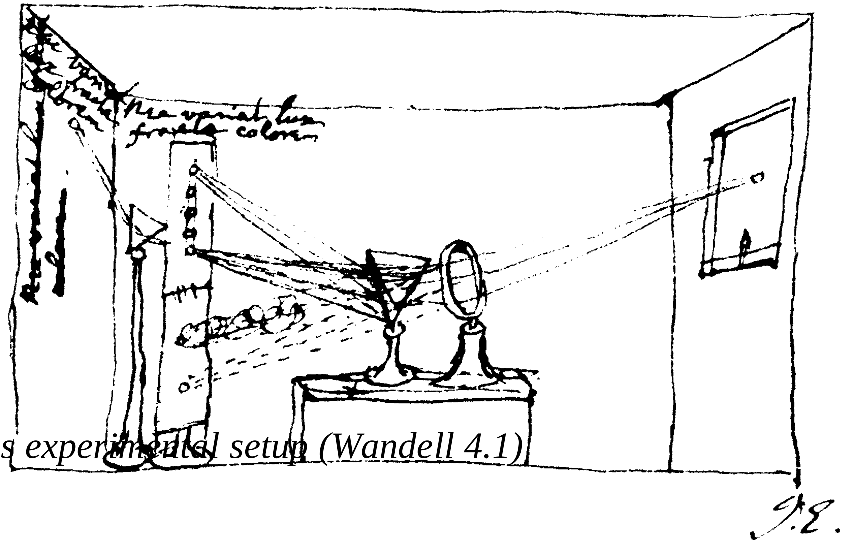
Color information is transmitted to the brain in three nerve bundles or **channels**:

- **Achromatic channel** A = M + L
- **Red-green chromatic channel** R/G = M - L
- **Blue-yellow chromatic channel** B/Y = S - A

Saturation is perceived as the ratio of chromatic to achromatic response.

Newton’s Experiments

Newton was the first to perform a scientific experiment on color in 1666.



Newton’s experimental setup (Wandell 4.1)

He built a simple colorimeter:

- Hole in a shutter
- Prism to disperse white light into a spectrum
- Comb-shaped aperture to manipulate the spectrum
- Converging lens to recombine the spectrum

Newton’s Experiments, cont’d

Newton defined two types of light:

- **Simple**: Light that cannot be furthered dispersed by a prism (now called **monochromatic**)
- **Compound**: Light that can be dispersed.

He called the colors of simple lights **primaries**.

[This term means many things today.]

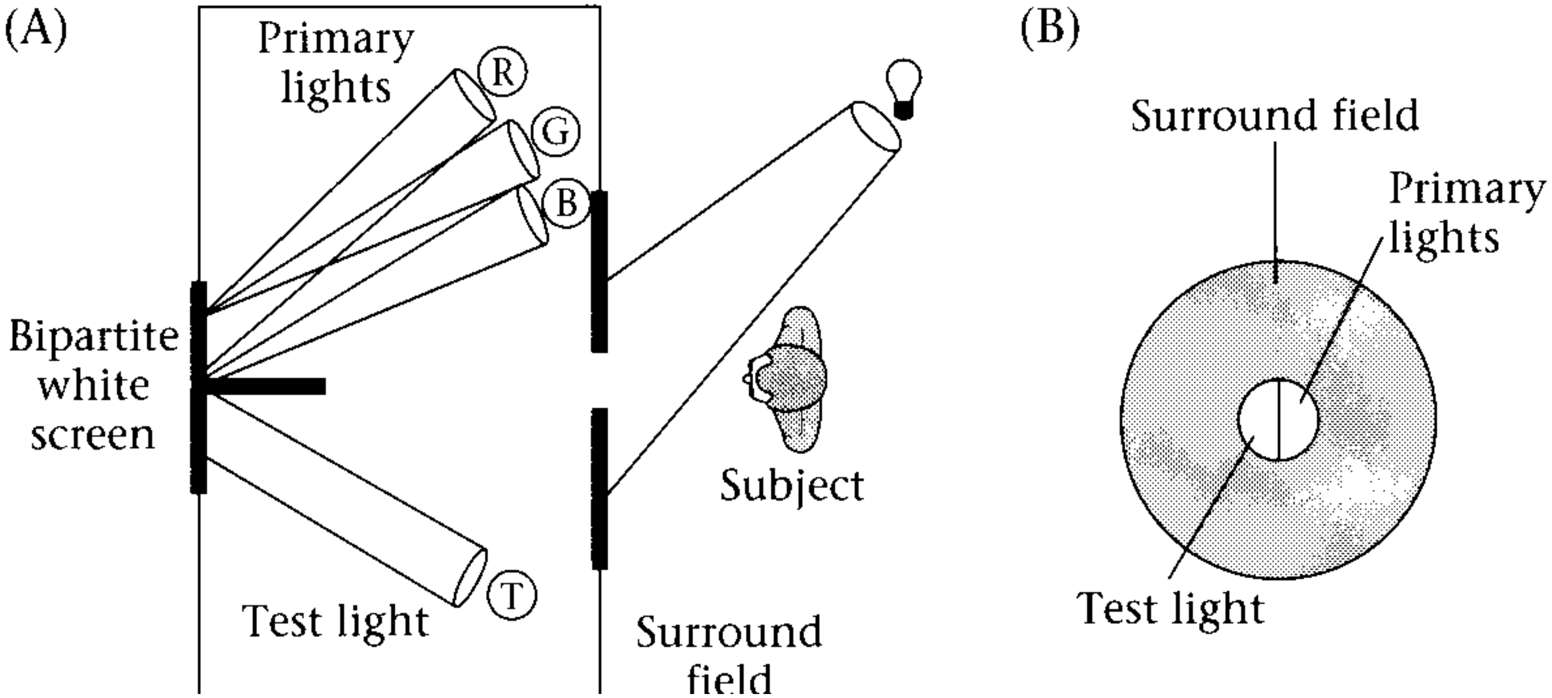
Color Matching

Conjecture: every color can be uniquely expressed as a mixing of a small number of *primaries*. (Why is this plausible?)

If true, this gives us a meaningful definition of color as a set of primaries and the range of possible combinations between them.

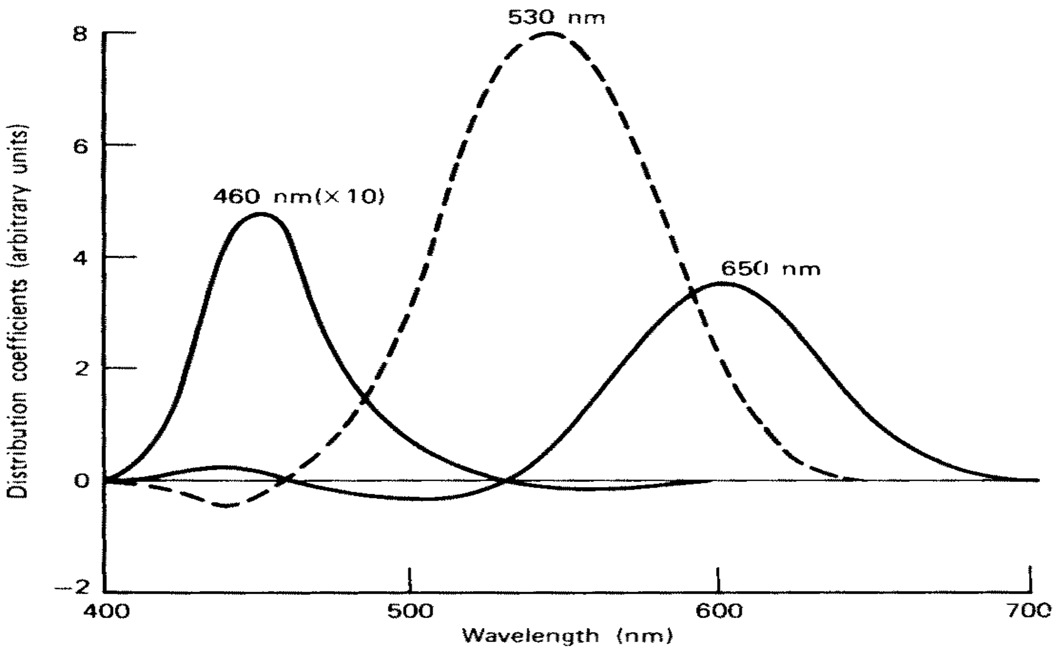
Given a choice of primaries, how can we verify the conjecture?

The Color Matching Experiment



Example: Wright's experiments

In the late 20's, Wright found that the colors of all wavelengths could be reproduced with combinations of 3 primaries at 460, 530, and 650nm:



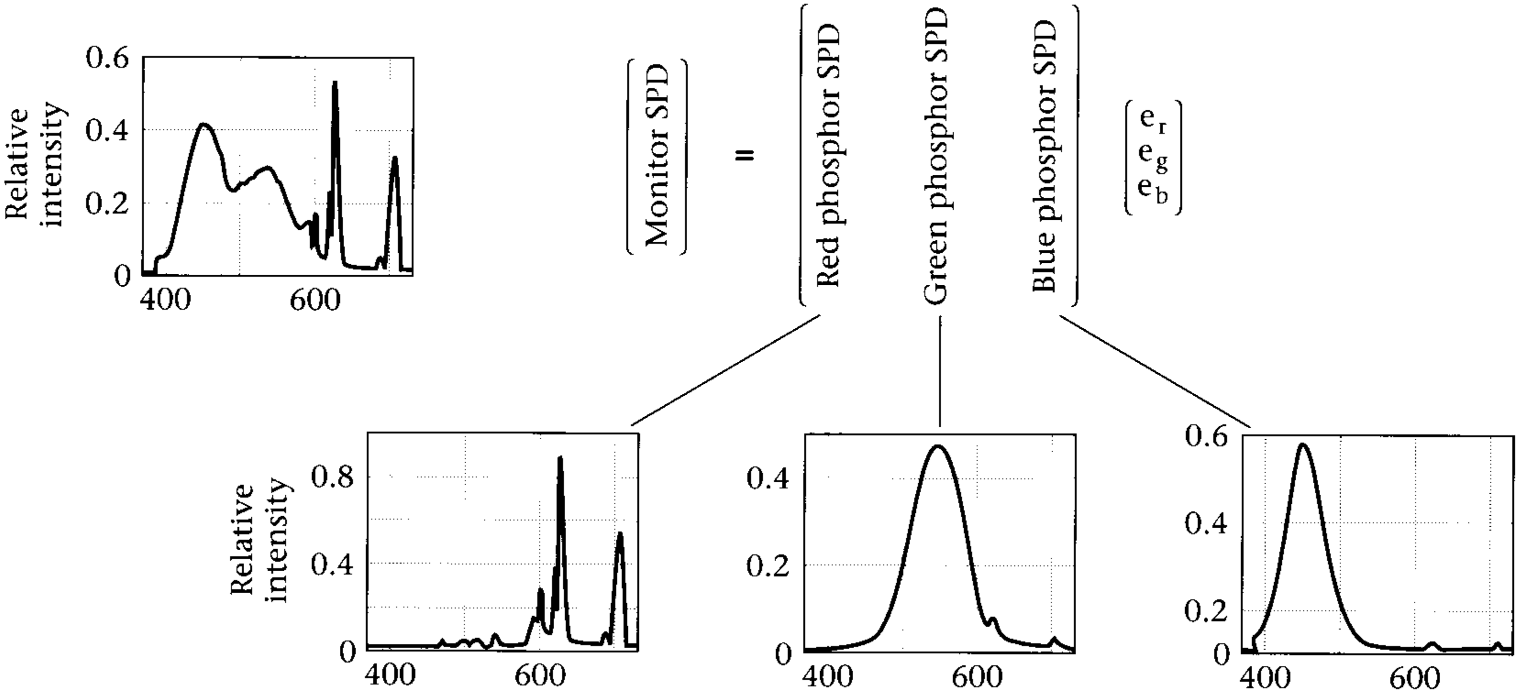
These functions are color-matching functions for the given primaries.

Color matching, cont’d

Key observations:

1. Three primaries are “sufficient” for color matching.
2. We can compute the knob settings using three functions. These are called the **color matching functions**.
3. Color matching functions are linear transforms of the cone responses.
4. All sets of color matching functions are linear transforms of each other.
5. The resulting knob settings can take on negative values.

Choosing Primaries



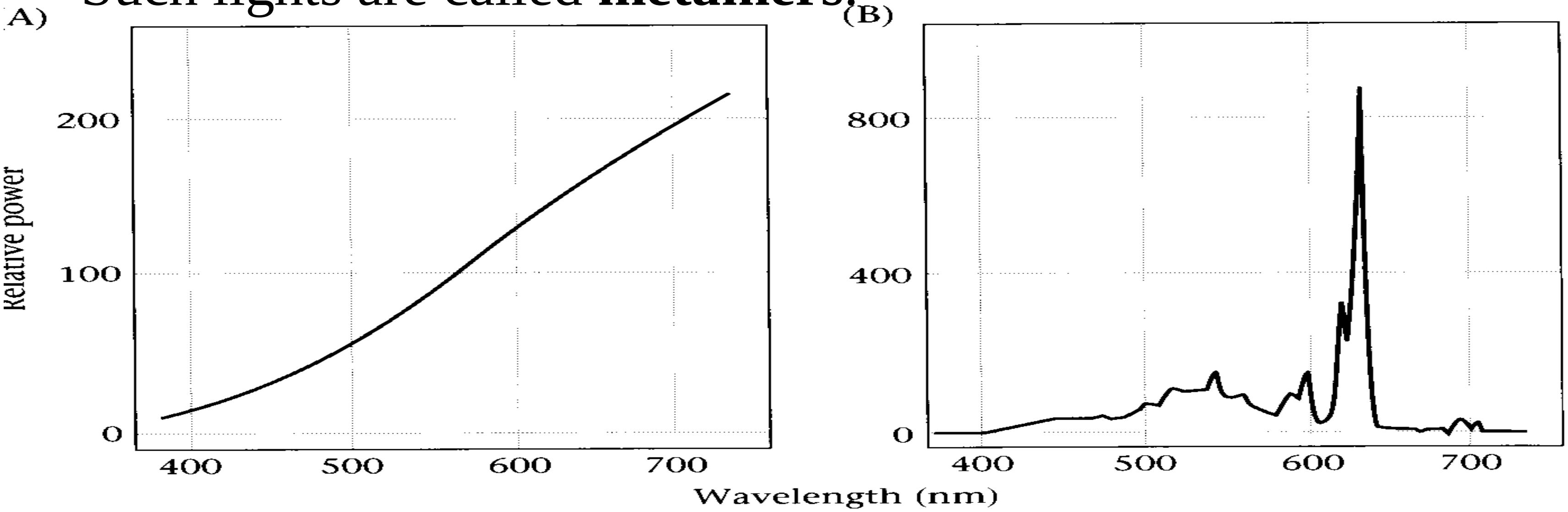
Emission spectra for RGB monitor phosphors (Wandell B.3)

Primaries don’t have to be monochromatic. You can still derive color matching functions.

Emission Spectrum is not Color

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

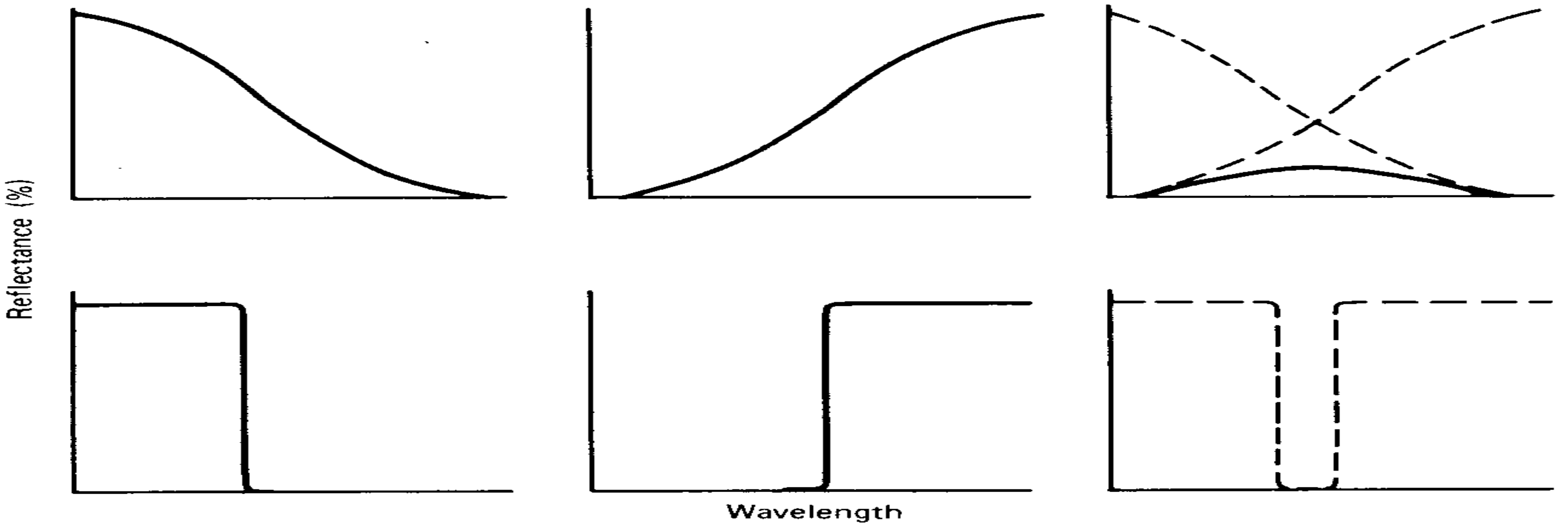
Different light sources can evoke exactly the same colors. Such lights are called **metamers**.



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

Colored Surfaces

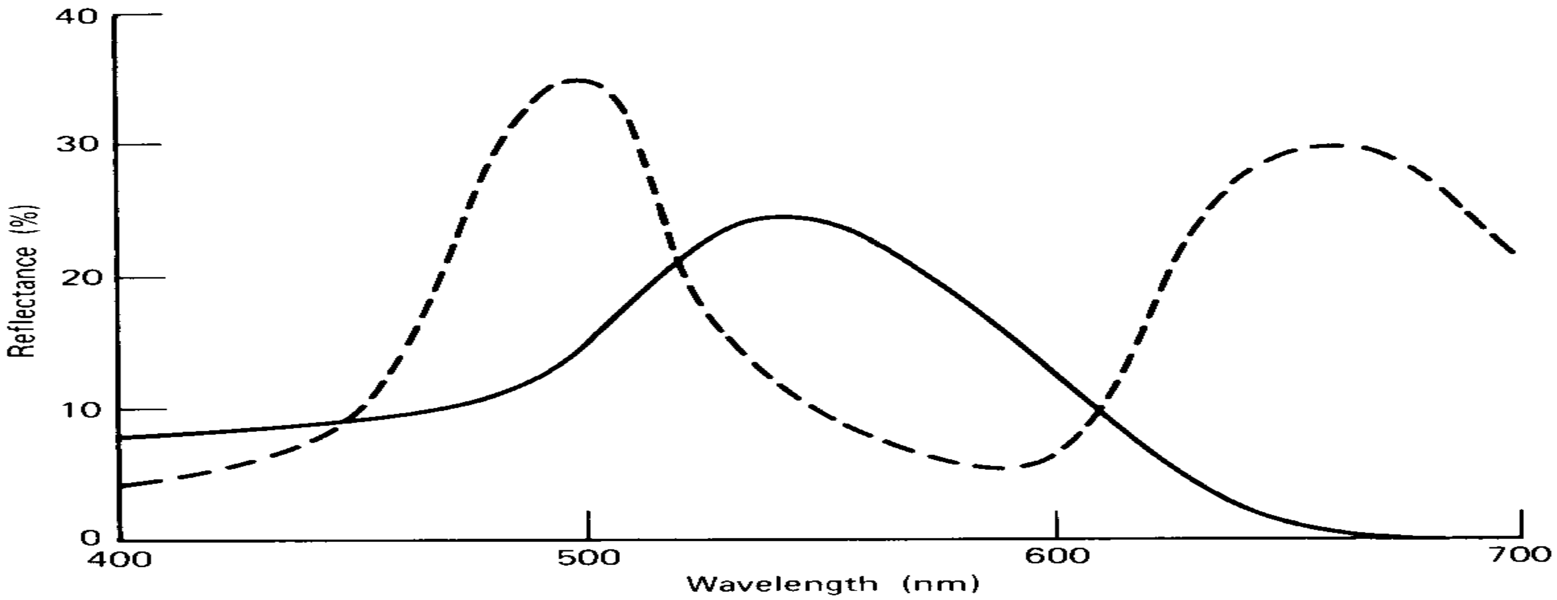
So far, we've discussed the colors of lights. How do *surfaces* acquire color?



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.)

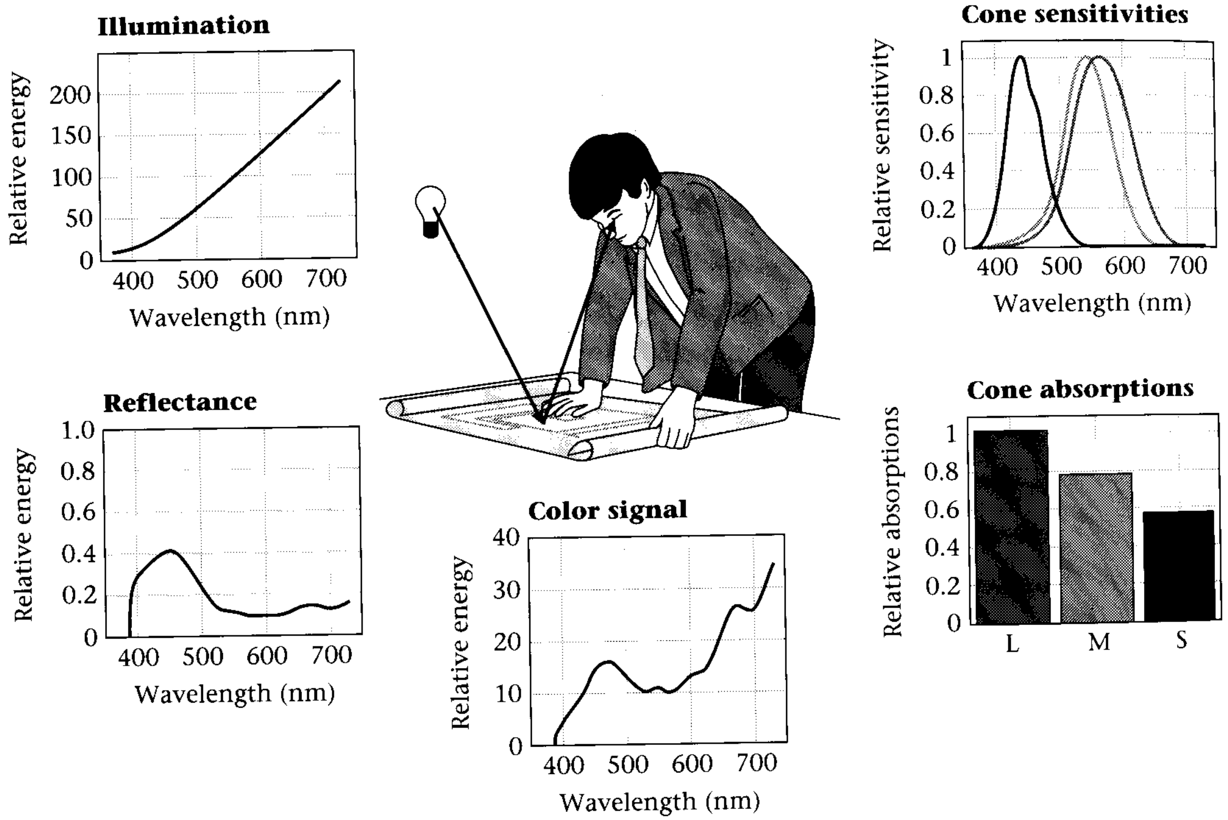
Subtractive Metamers



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

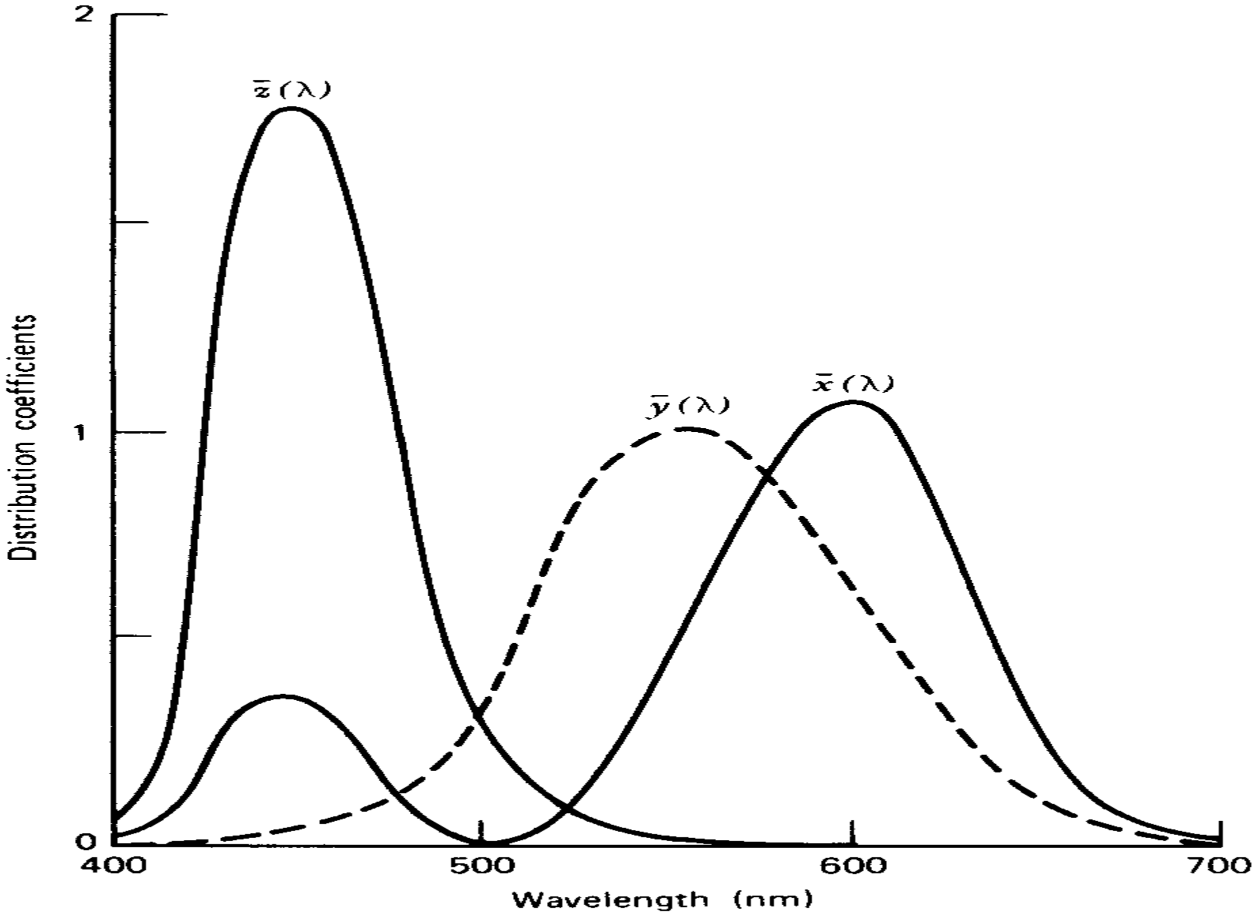
The solid curve appears green indoors and out. The dashed curve looks green outdoors, but brown under incandescent light.

Illustration of Color Appearance



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.

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

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

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

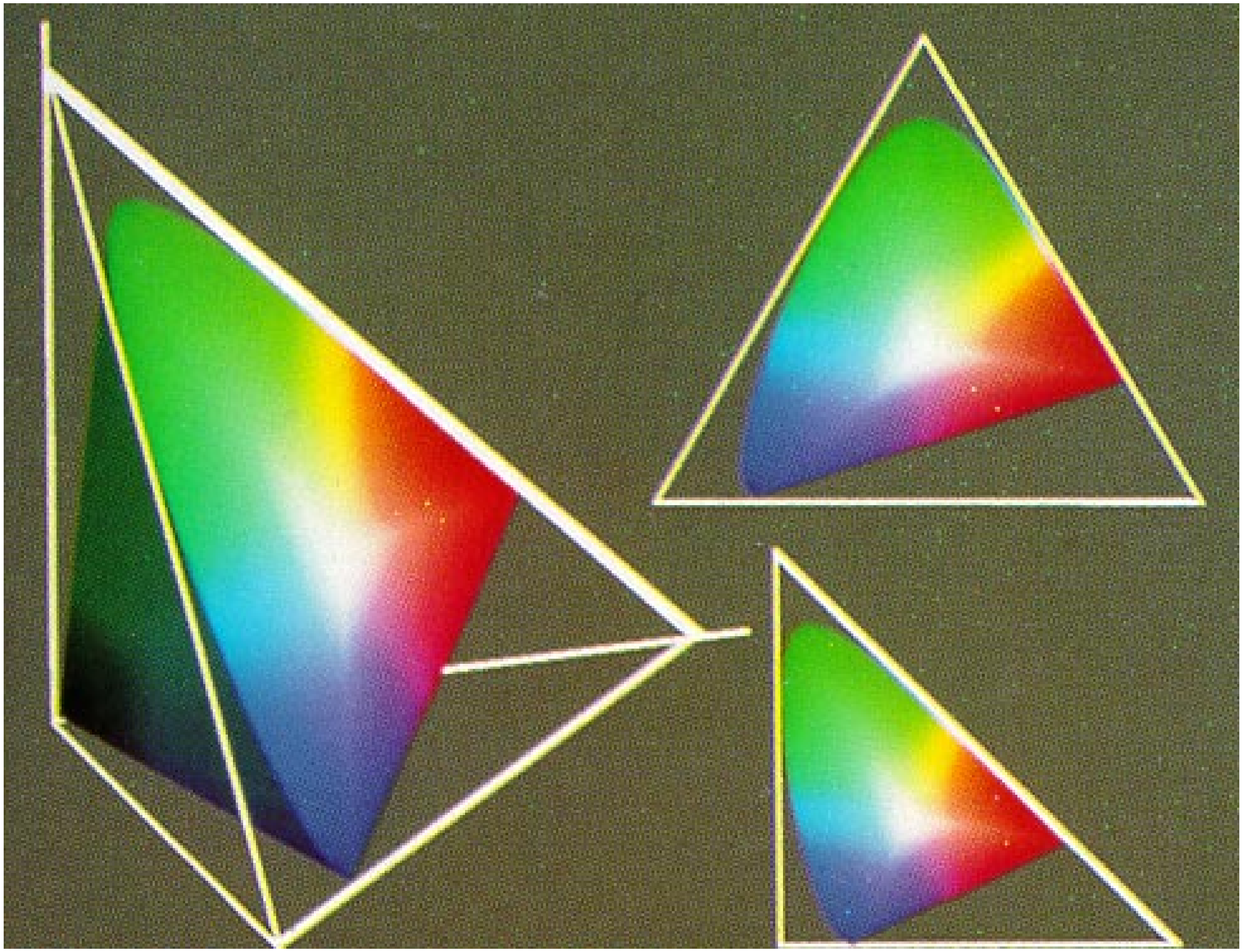
Then we can compute *chromaticity coordinates*. This gives a brightness independent notion of color.

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

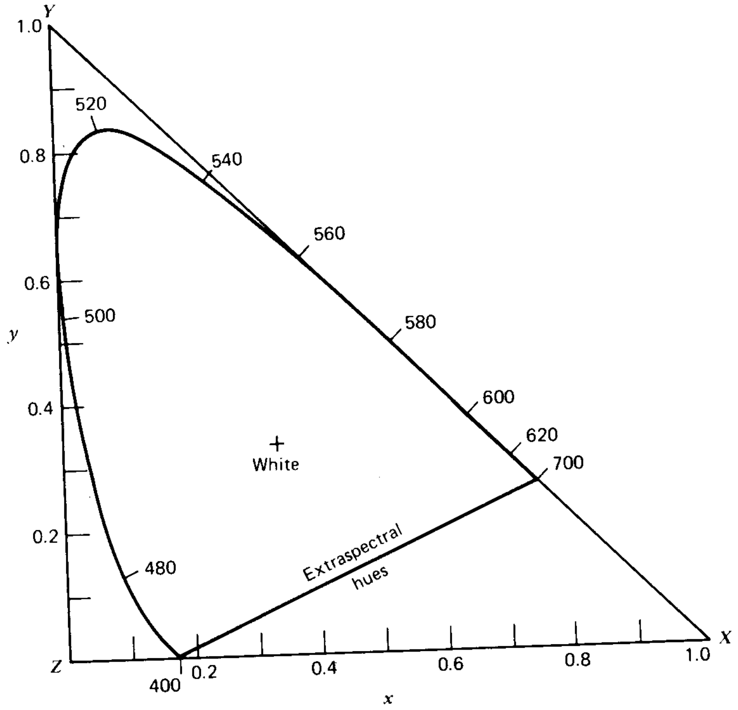
$$y = \frac{Y}{X + Y + Z}$$

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

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.

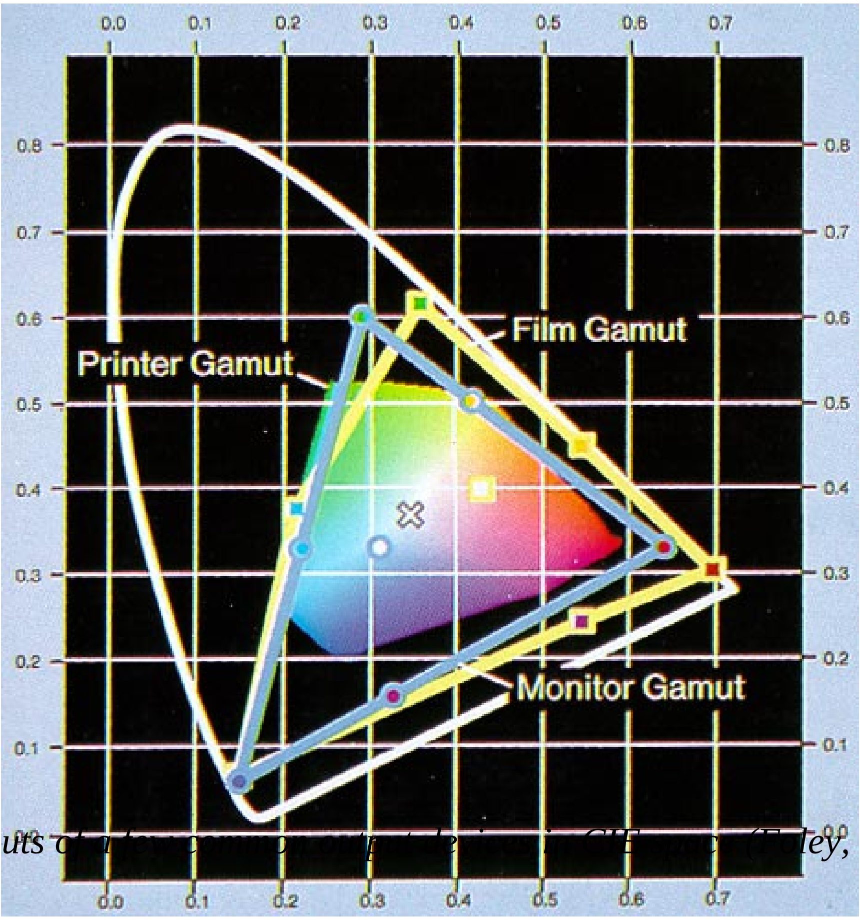
- A color’s dominant wavelength is where a line from white through that color intersects the perimeter.
- Some colors, called *nonspectral* color’s, don’t have a dominant wavelength.

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

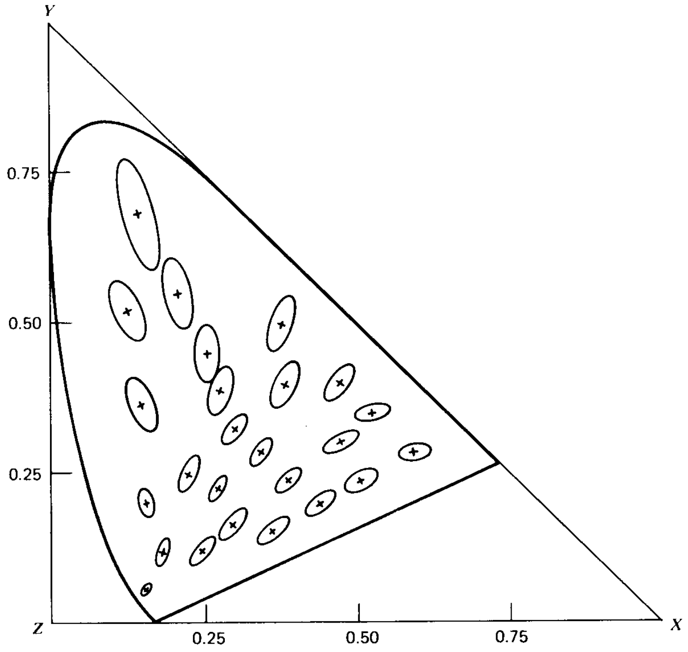
Not every output device can reproduce every color. A device's range of reproducible colors is called its **gamut**.



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

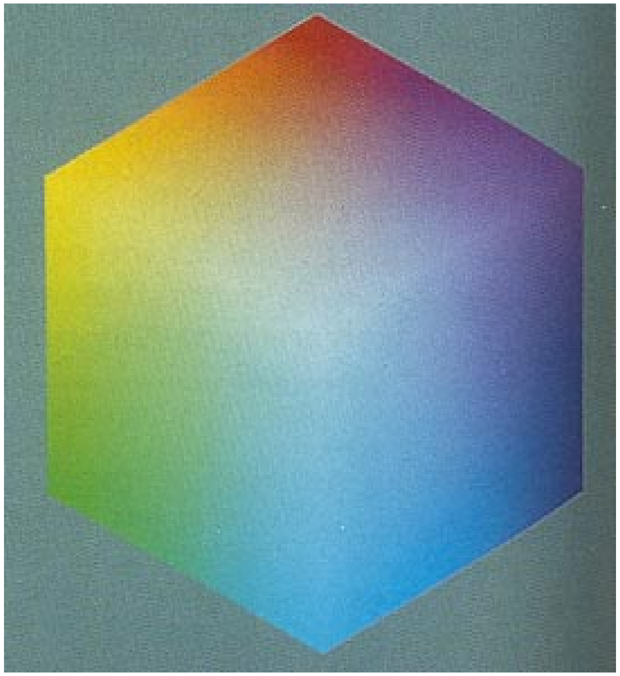
In practice, there's a set of more commonly-used color spaces in computer graphics:

- 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.

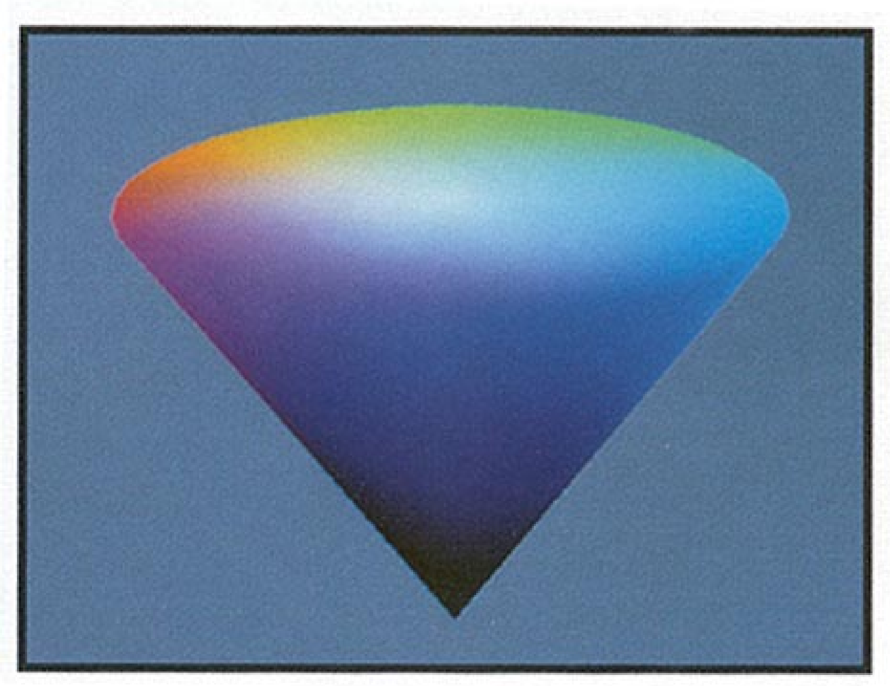
What does the RGB color space look like?



HSV

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

The HSV space looks like a cone:



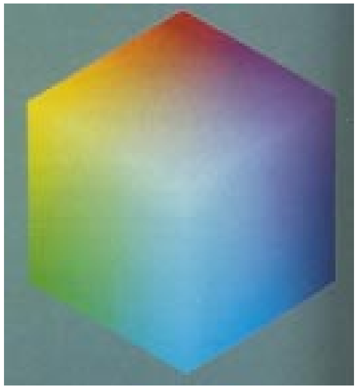
CMY

A subtractive color space used for printing.

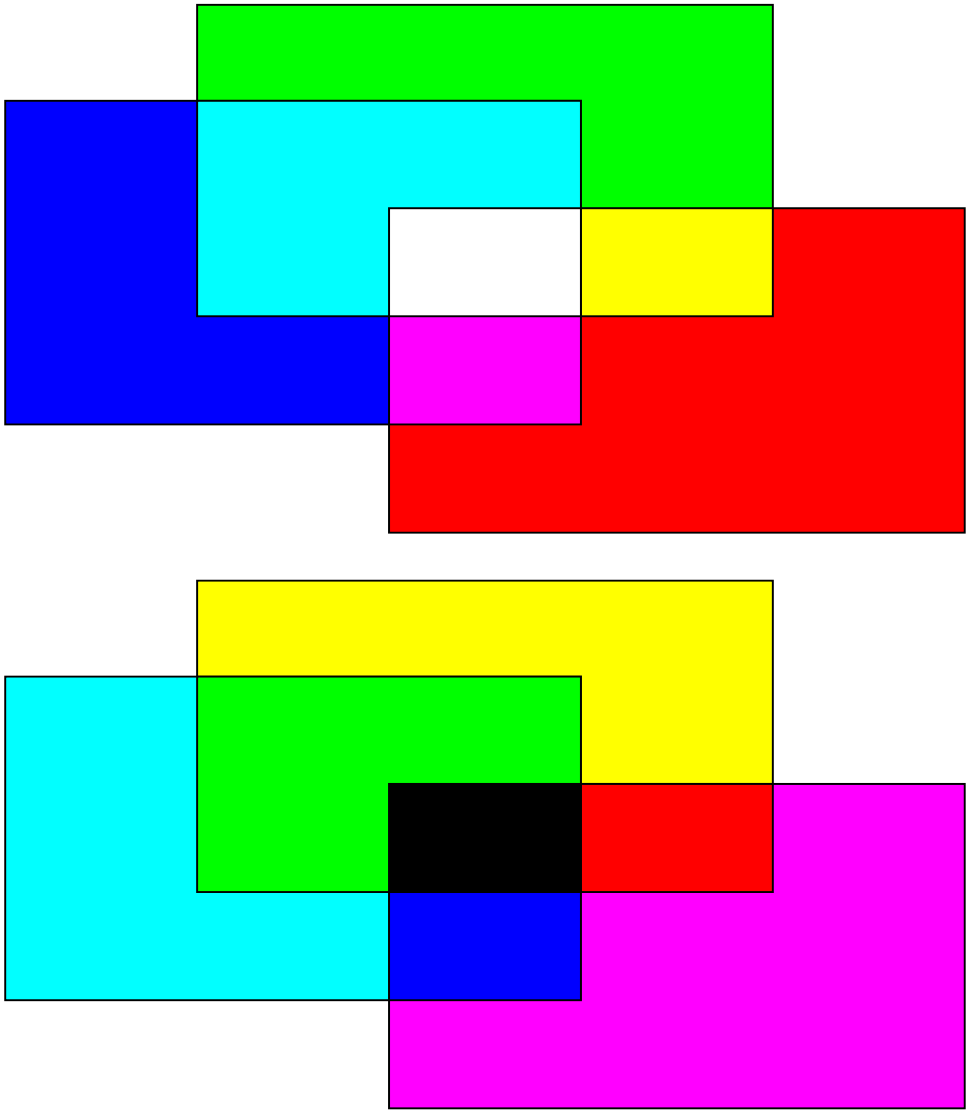
Involves three subtractive primaries:
- Cyan - subtracts red
- Magenta - subtracts green
- Yellow - subtracts blue

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

Here’s what you should take home from this lecture:

- All the **boldfaced terms**.
- 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