3. Color

Reading

Suggested:

- Hearn and Baker, Chapter 15
- Foley et al., Sections 13.2–13.6
- Glassner, Sections 1.7, 2.1, 2.2, 3.6

Further reading:

- Gerald S. Wasserman. *Color Vision: An Historical Introduction.* John Wiley & Sons, New York, 1978.
- Michael Wilcox. *Blue and Yellow Don't Make Green.* North Light Books, Cincinnati, 1987.
- Brian Wandell, *Foundations of Vision.* Sinauer Associates, Sunderland, MA, 1995.
- John E. Kaufman, ed. *IES Lighting Handbook: Reference Volume.* Illuminating Engineering Society, New York, 1981.

Overview

1. Physics of light

2. Historical development of color theory

3. The CIE XYZ color system

4. Color spaces for computer graphics

Theories of light

Many theories have been advanced:

- Wave theory [Hooke, Huygens, 1600's]
  Light transmitted through the "aether" in waves.

- Corpuscular theory [Newton, 1600's]
  Light propagated as minute particles, ejected intermittently in straight lines.

- Wave theory, again [Young, 1801]
  Waves again, as demonstrated by interference fringes in the two slit experiment.

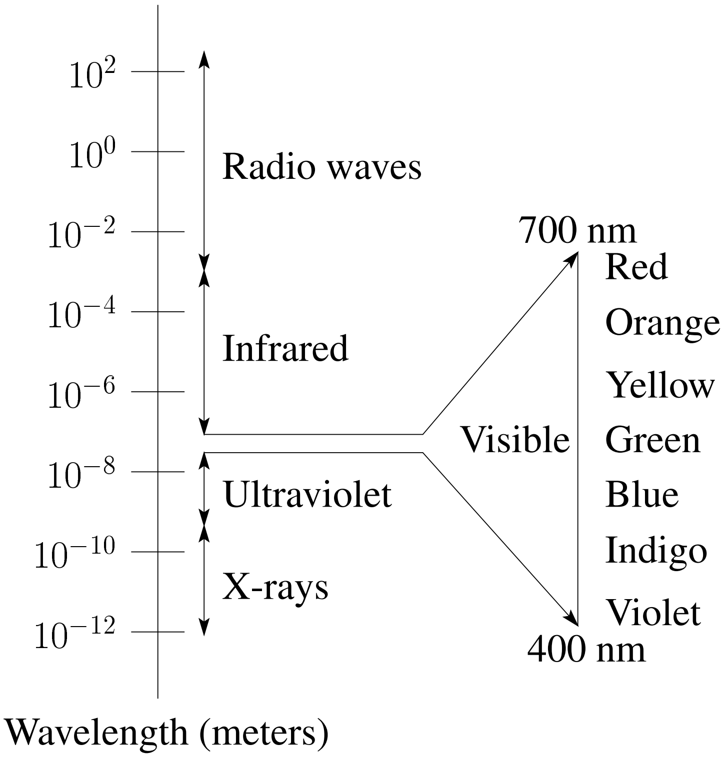
- Electromagnetic theory [Maxwell, 1888]
  Waves, propagated by coupled electric and magnetic fields: $\nu = c\lambda$

- Quantum theory [Planck, Einstein, 1900]
  Particles again: $Q = h\nu$

- Unified theory [De Broglie, Heisenberg, 1913]
  Both: Waves *and* particles!

The radiant energy spectrum

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



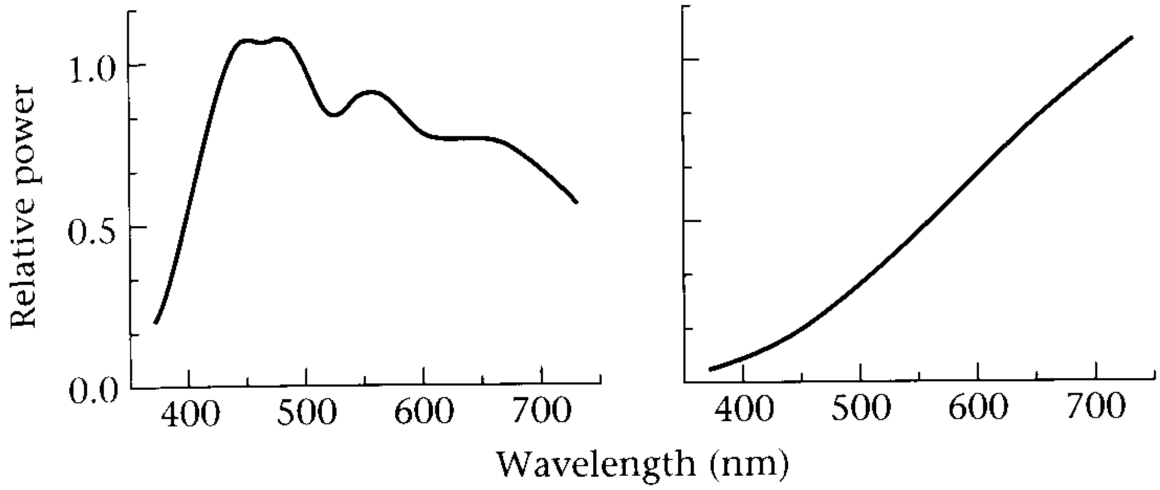
The EMR spectrum

Note:

- All EMR travels at same speed in a given medium.
- Energy proportional to frequency.

Emission spectra

A light source can be characterized by an <u>emission spectrum</u>:

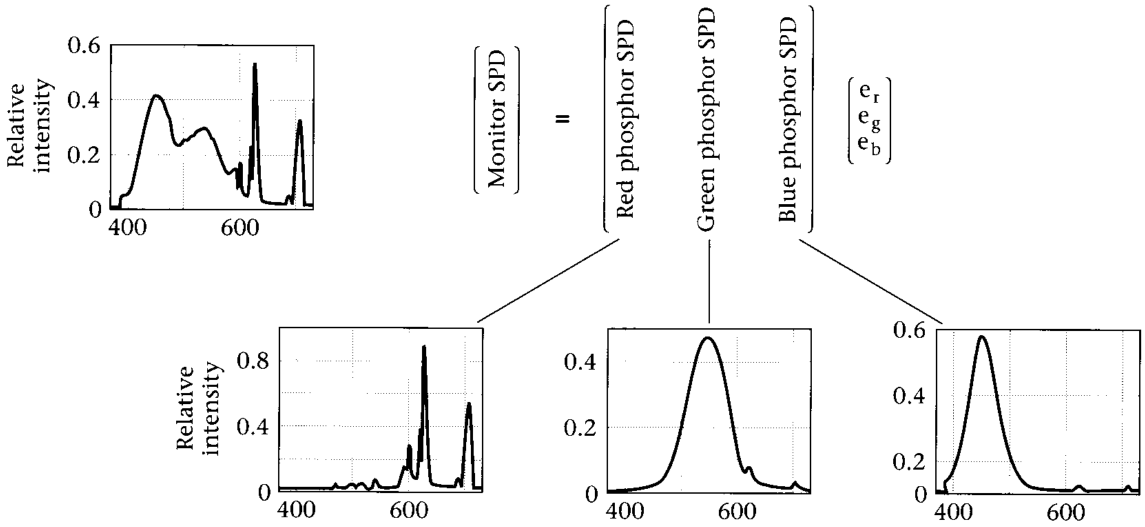


Emission spectra for daylight and a tungsten lightbulb (Wandell 4.4)

The spectrum describes the energy at each wavelength.

Emission spectra, cont'd

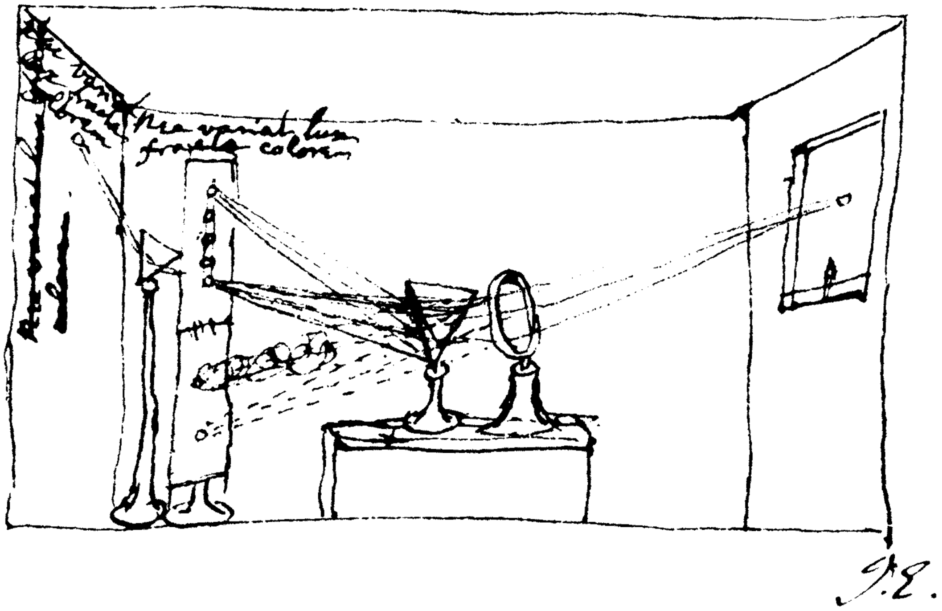
Here are the spectra for typical R,G,B phosphors in a color monitor:



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

Newton's experiments on color

Newton was the first to perform scientific experiments on color, in 1666.



Newton's sketch of his experiment (Wandell, 4.1)

Built a simple colorimeter:

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

Newton's experiments, cont.

Newton defined two types of light:

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

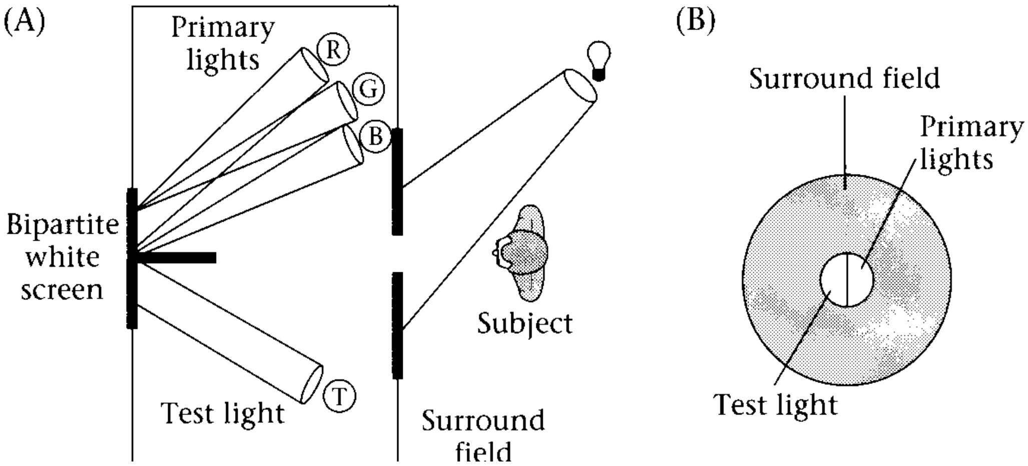
He called the colors of simple lights primaries.

[This term has many other meanings today.]

Newton's experiments, cont.

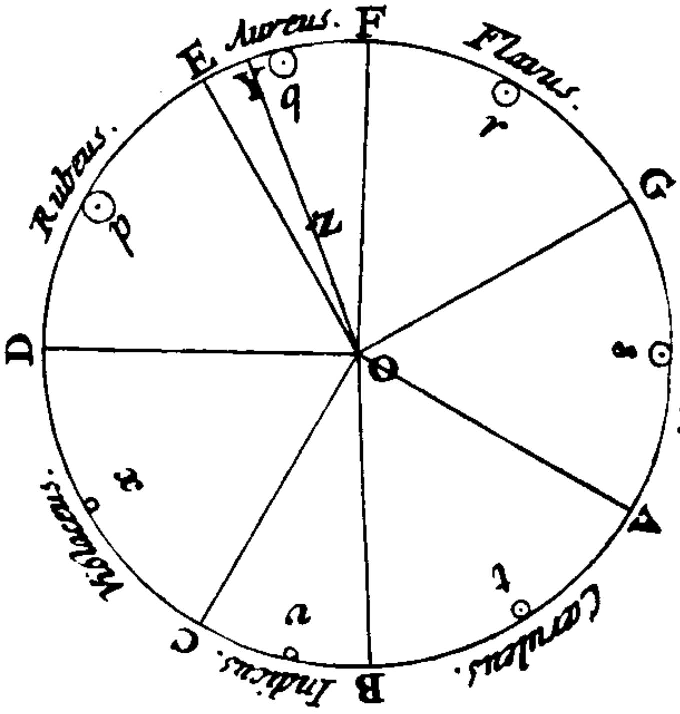
To study the appearance of colors, Newton recombined primaries to create new colors.

A modern day version of this kind of experiment looks like:



The color matching experiment (Wandell, 4.10)

Newton's barocentric model



Newton's barocentric model (Wasserman, 2-1)

Newton proposed a "barocentric model of color vision":

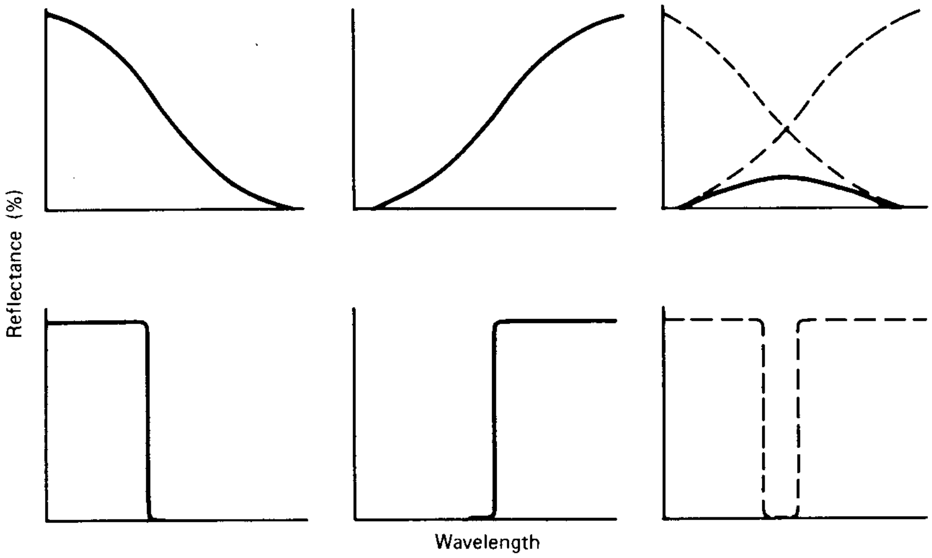
- Factored out brightness
- Identified the endpoints of the spectrum
- Placed white in the center
- Gave a qualitative model of light mixture

Q: Why did Newton choose seven divisions, or "tones"?

Newton's barocentric model, cont'd

Viewed as a "color wheel", Newton's barocentric model looked something like:

Subtractive mixtures



Two examples of subtractive color mixture (Wasserman, 2-2)

Newton also characterized the difference between additive and subtractive color mixtures.

Subtractive color mixtures:

- Due to selective absorption by pigments.
- Difficult to characterize in general.

How many primaries

Newton posed a fundamental question that took almost two centuries to answer:

Q: How many primaries does it take to produce a perfect white?

A: (Newton) Definitely more than 2; and 4 or 5 suffice.

In 1852, Helmholtz answered a generalized form of this question:

Q: How many primaries does it take to produce the *entire* spectrum?

A: (Newton) 7.

A: (Young, 1802) 3.

A: (Helmholtz) 5.

Trivariant mixtures

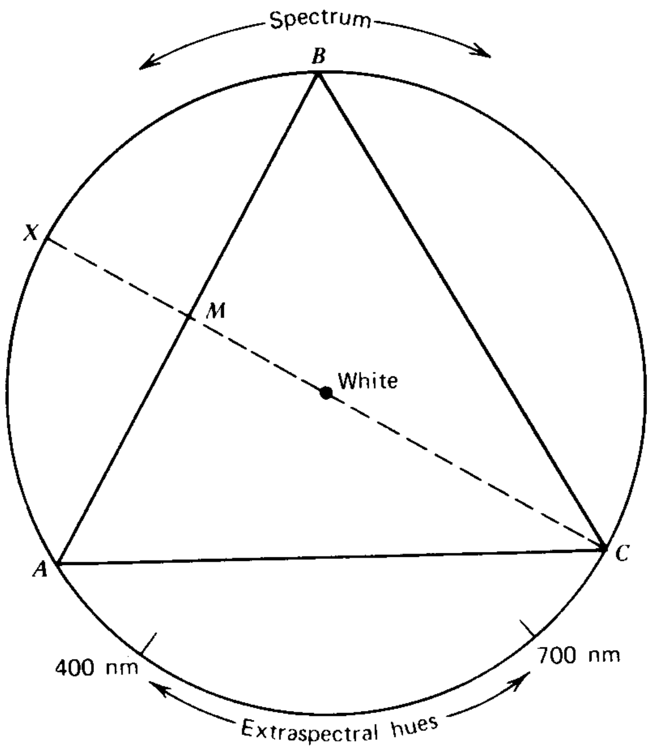


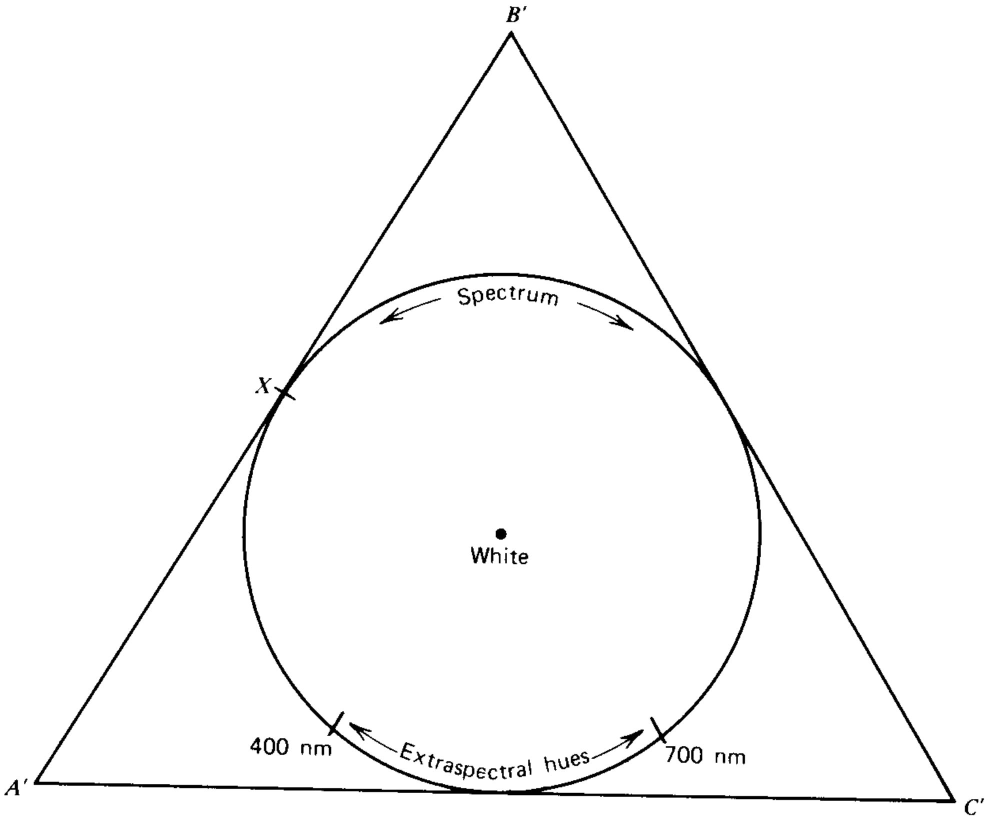
Illustration of trivariant color mixing (Wasserman, 2-3)

In 1856, Maxwell rescued the notion of trivariant color mixing by applying Newton's barocentric mixing more rigorously.

Q: How many primaries are required by Maxwell's model?

Q: In what sense can three primaries produce all colors?

Maxwell's imaginary primaries



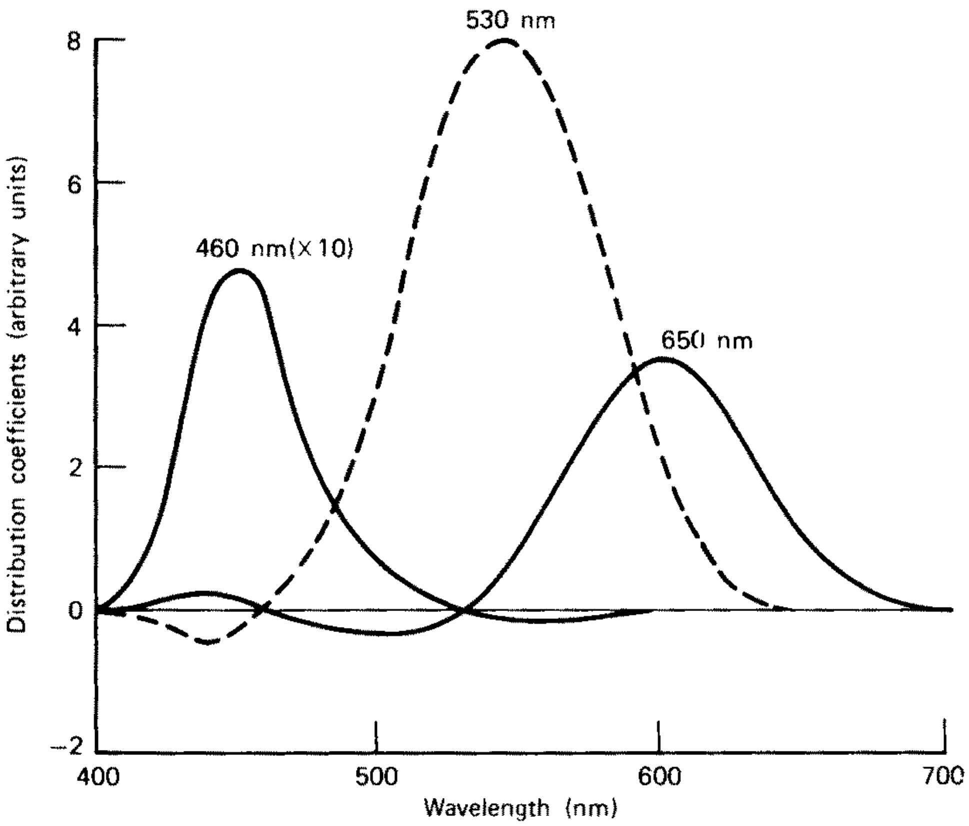
A color space associated with imaginary primaries (Wasserman, 2-5)

Maxwell observed that with three "imaginary" primaries, you no longer need to use one as a desaturant.

Q: But how do you select these imaginary primaries? (*Last* 100 years devoted to answering this.)

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:



Relative luminances for color matches (Wasserman, 3-3)

These functions are called color-matching functions.

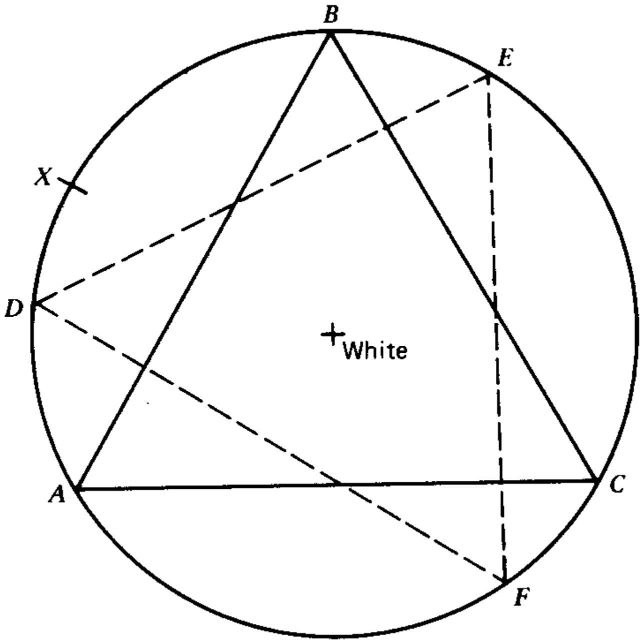
Color-matching functions

If we want to know how to set the primary knobs to match a monochromatic light, we just look up the values in the color-matching functions.

Q: How do we match a non-monochromatic light?

Q: Suppose you change the set of primaries. Is there a way to avoid repeating the experiment?

Transforming primaries



Transforming primaries (Wasserman, 3-6)

A transformation of primaries can be described as a simple change of basis. . . .

Given: Color X in the ABC system:

$$X = aA + bB + cC$$

Find: Color X in the DEF system:

$$X = dD + eE + fF$$

Transforming primaries, cont.

Solution: Write A, B, C in terms of D, E, F:

Transforming matching functions

Q: What happens to the color matching functions when we transform the primaries?

The LMS color-matching functions

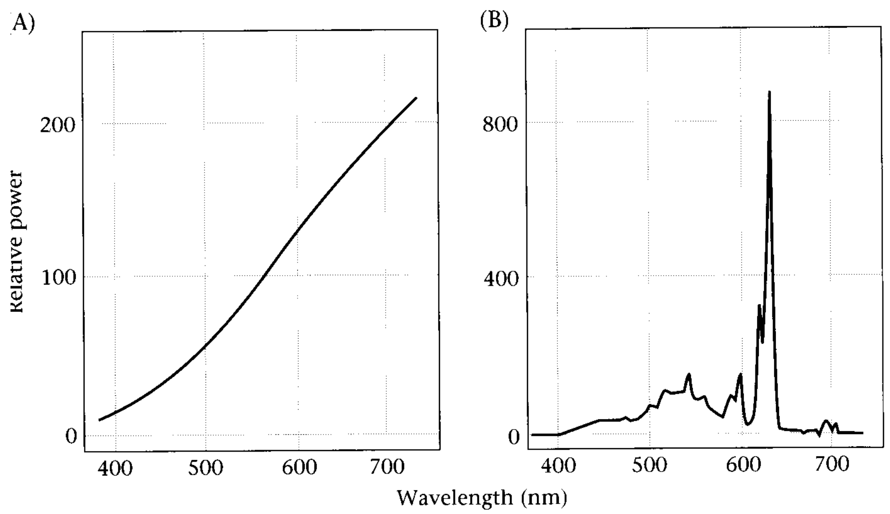
Q: What is the biological basis for needing three matching functions?

[Note: Hearn and Baker has an error in the LMS positions. They peak at 570 nm, 540 nm, and 450 nm.]

<u>Metamers</u>

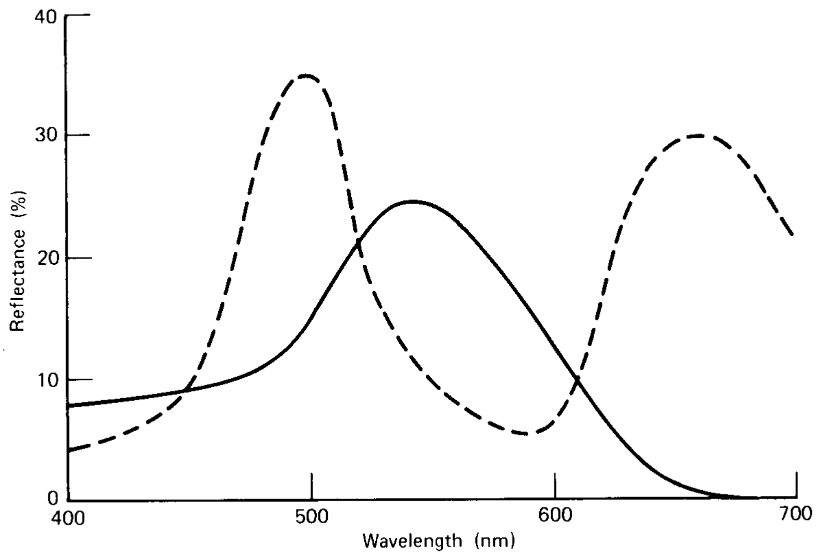
After integrating a spectrum against a set of color matching functions, you are left with 3 numbers known as the <u>color coordinates</u>.

Spectra that share the same color coordinates will be *indistinguishable*. Such spectra are called <u>metamers</u>.



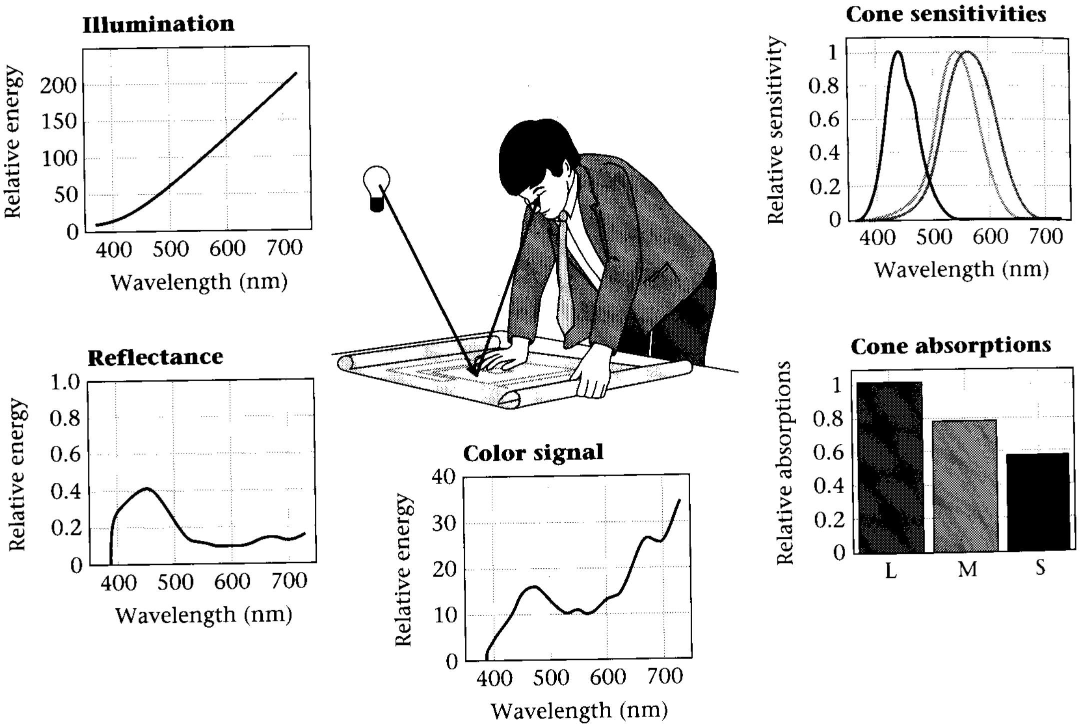
Metamers: dim tungsten bulb and RGB monitor with suitably chosen R,G,B (Wandell, 4.11)

Metamers, cont'd



Reflectances of two surfaces that are metamers in daylight, but appear to have different colors under tungsten light (Wasserman, 3.9)

Illustration of color appearance



From illumination to cone responses (Wandell, 9.2)

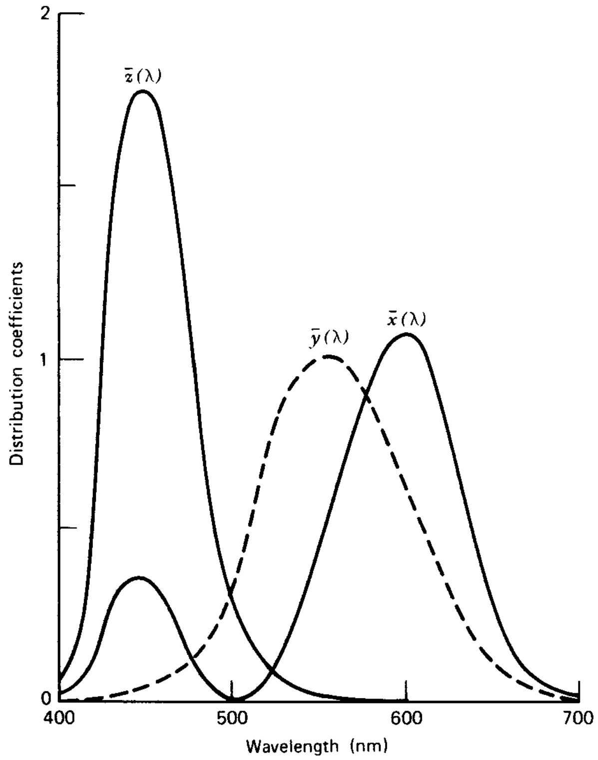
The XYZ system

In 1931, the CIE (Commission Internationale de l'Eclairage) adopted the XYZ system, which has the following properties:

- Every color can be made with *positive* combinations of primaries called $\mathbf{X}$, $\mathbf{Y}$, $\mathbf{Z}$.
- The $\mathbf{X}, \mathbf{Y}, \mathbf{Z}$ primaries are imaginary.

The CIE color-matching functions

Here are the color-matching functions $\overline{x}, \overline{y}, \overline{z}$:



The XYZ color-matching functions (Wasserman 3-8)

Note: By design, the $\overline{y}$ curve is just the "luminous efficiency curve."

Computing CIE coordinates

The X, Y, Z coordinates are computed by:

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

$$\vdots$$

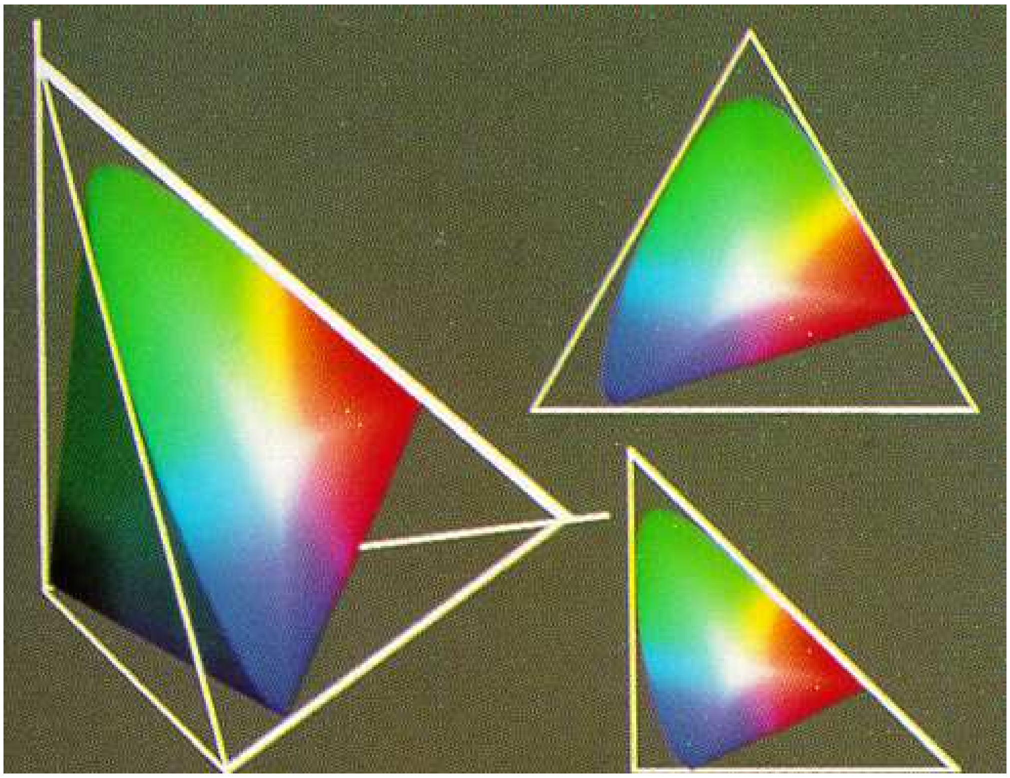
From these, the chromaticity coordinates x, y, z are computed by:

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

$$\vdots$$

Note: x, y, z are all on the $X + Y + Z = 1$ plane.

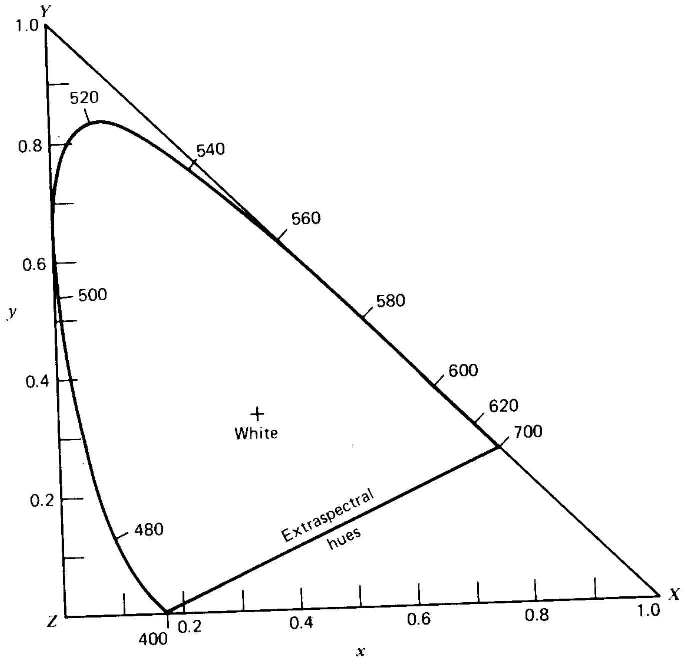
Visualizations of the CIE color space



Visualizations fo the CIE color space (Foley, II-1)

The CIE chromaticity diagram

The CIE chromaticity diagram is the projection of the $X + Y + Z = 1$ plane onto the (X, Y) plane:

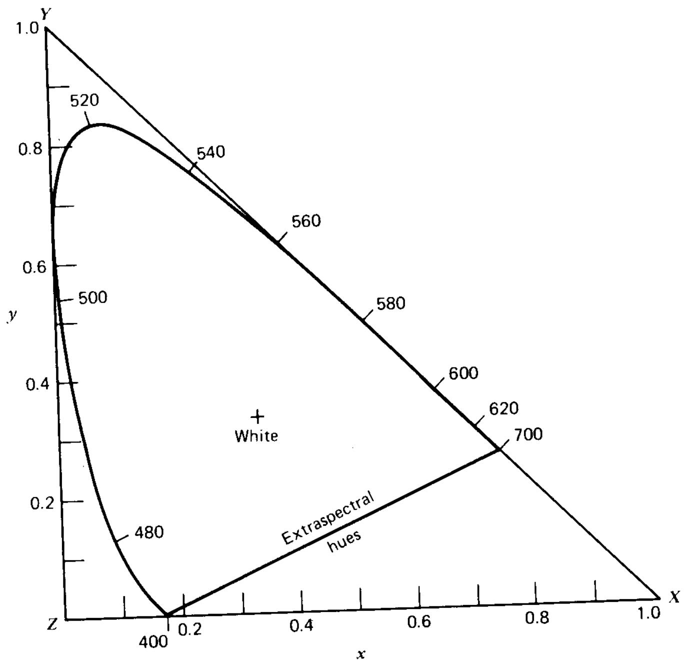


The chromaticity diagram (Wasserman 3-7)

Each point of the diagram gives a chromaticity value, which depends on:

- the "dominant wavelength" or "hue" — red, yellow, etc.;
- the "excitation purity" or "saturation" — closeness to grey.

The CIE diagram, cont.

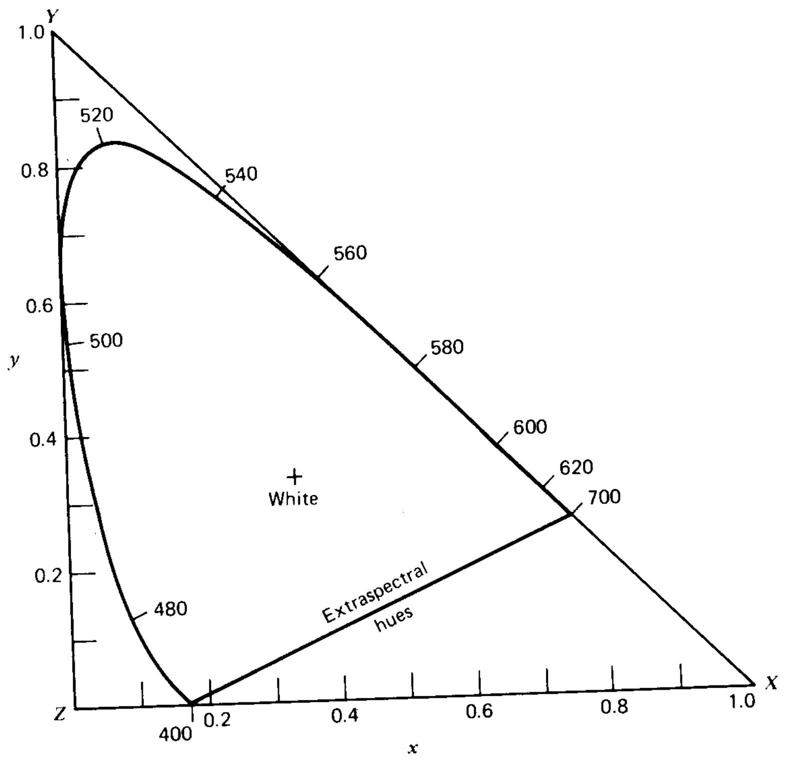


The chromaticity diagram (Wasserman 3-7)

- *Dominant wavelengths* go around the outside of the diagram.

- *Excitation purity* is given by the ratio AC/BC, where
  - C is white light;
  - A is color being tested;
  - B is extrapolation of CA to curve — i.e., the dominant wavelength.

The CIE diagram, cont.



The chromaticity diagram (Wasserman 3-7)

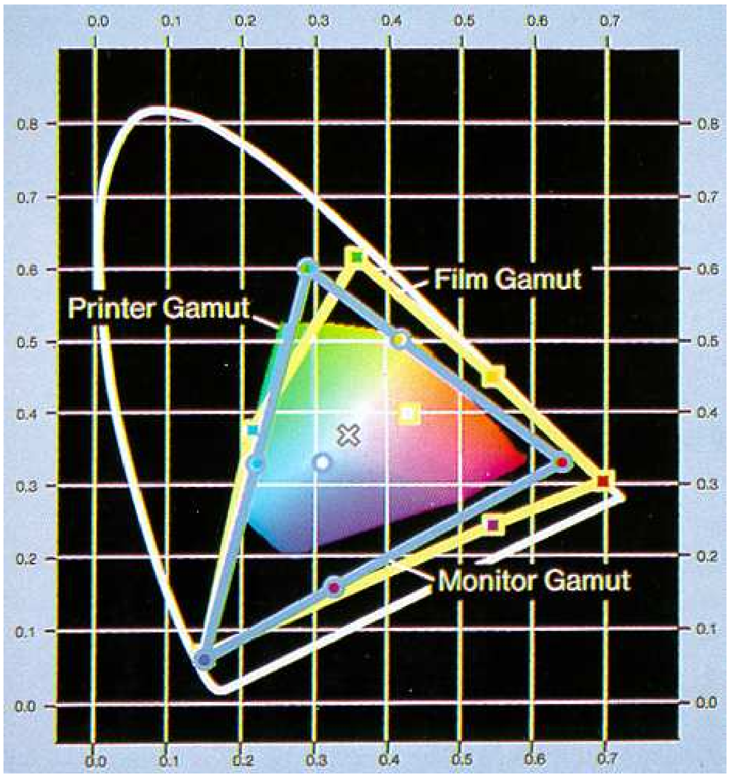
- "Complementary colors"
  - · Colors that can be mixed to produce white light.
  - · Lie on opposite sides of C.

- "Nonspectral colors"
  - · Lie on wedge that does not project to any dominant wavelength.
  - · Reds, magentas, purples

Gamuts

A display device has a range of reproducible colors that depend on the spectra reproduced by the phosphors/pigments/etc.

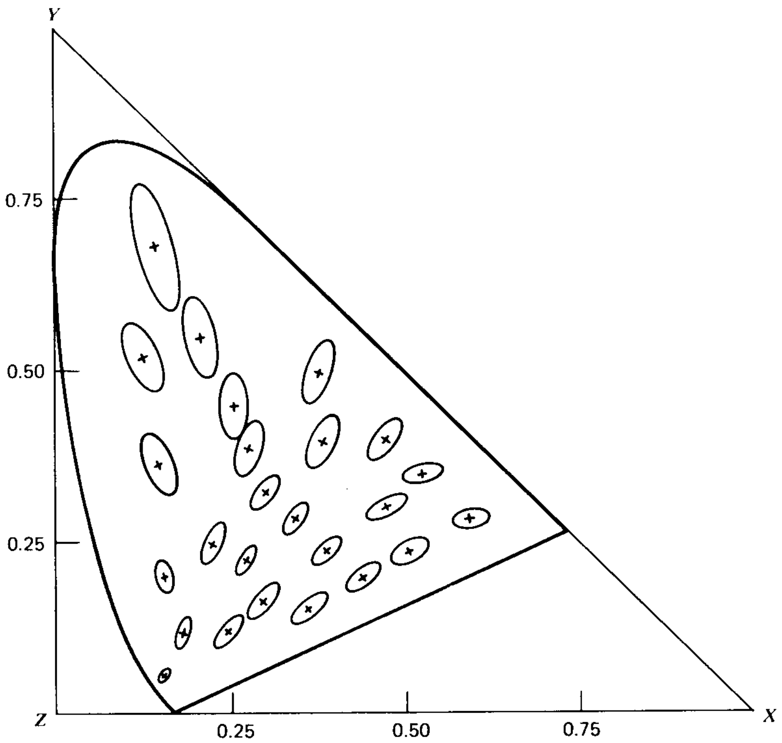
This range or reproducible colors is called the gamut of the device.



Gamuts of a monitor and a printer illustrated in CIE coordinates (Foley, II-2)

Perceptual uniformity

The XYZ space is not perceptually uniform:



Areas of constant color (enlarged) (Wasserman 3-10)

Perceptually-uniform color spaces

Some perceptually-uniform spaces include:

- $L^*u^*v^*$
- $L^*a^*b^*$
- "Farnsworth's non-linear transformation"

The first two of these involve taking cube roots, etc.

Formulas for $L^*u^*v^*$ and $L^*a^*b^*$ in terms of XYZ are given in [Glassner].

Main point is that Euclidean distance is supposed to work better in these spaces.

Other color spaces

Other color spaces commonly used in computer graphics include:

- RGB — most natural for CRTs
- HSV — more intuitive for users
- CMY — used for hardcopy
- YIQ — used for TV broadcasting

RGB

You're already familiar with this one:

Q: Where are the greys?

HSV

A more intuitive color space.

Most naturally represented by a cone:

- "Hue" — red, yellow, etc.
- "Saturation" — Distance from grey
- "Value" — Distance from black

Note: Value is not perceptually-based, so colors of the same value may have slightly different brightnesses.

CMY

A subtractive color space, used for printing.

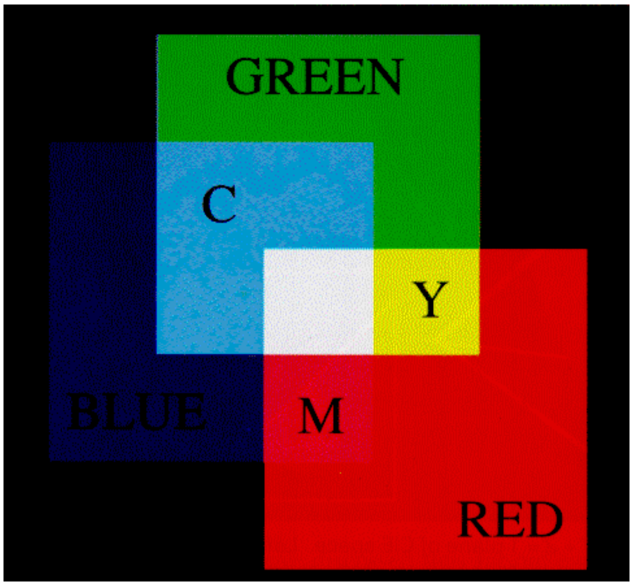
Involves three subtractive primaries:

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

Mixing two pigments subtracts their opposites from white.

Printers often use *black* ink rather than equal amounts of all three.

RGB vs. CMY



Additive combination of RGB colors (Foley, ii.3)

Subtractive combination of CMY colors (Foley, ii.6)

YIQ

Used in TV broadcasting. Exploits useful properties of the visual system:

- Uses most bandwidth for Y, the luminance
  - · Exploits ability to judge relative luminance better than hue and saturation changes
  - · Allows b&w TVs to just look at Y channel

- I chosen as major axis of remaining visual color space

- Q is the remaining axis

- Relative bandwidth ratios are 8:3:1

Summary

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

1. All the underlined names and names in quotations.
2. How light is characterized by an emission spectrum.
3. The difference between subtractive and additive color mixtures.
4. The notion of trivariant color mixing, using either a desaturant or imaginary primaries.
5. How color-matching functions work.
6. How to perform a transformation of primaries and color-matching functions.
7. The XYZ color system, and how a color's XYZ coordinates are computed.
8. How the CIE chromaticity diagram works.
9. A qualitative sense of what the various color spaces used in computer graphics are like.