

Color

CSE 457, Autumn 2004
Computer Graphics

<http://www.cs.washington.edu/education/courses/457/04au/>

Readings and References

Readings

- Section 2.5, Color, *Interactive Computer Graphics*, Angel

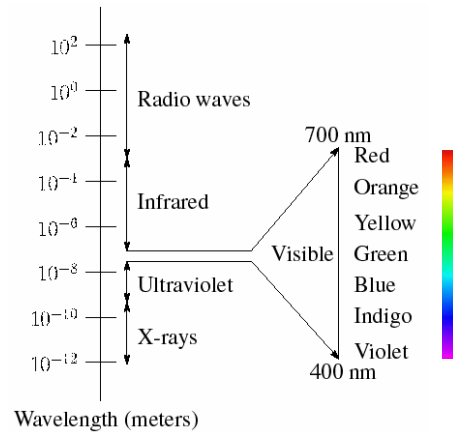
Other References

- Chapter 4, pp. 69-97, *Foundations of Vision*, Wandell

The radiant energy spectrum

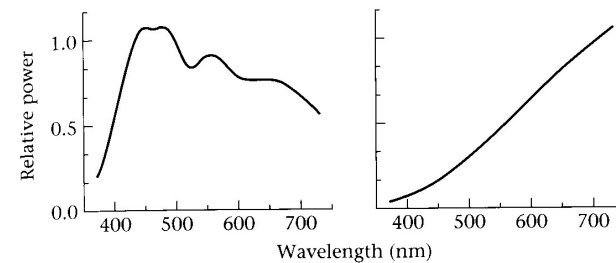
Wave theory allows a nice arrangement of electromagnetic radiation (EMR) according to wavelength.

Note: the "color" that we see is a point in 3D color space, it is not a point on this 1D spectral line. Details on following slides ...

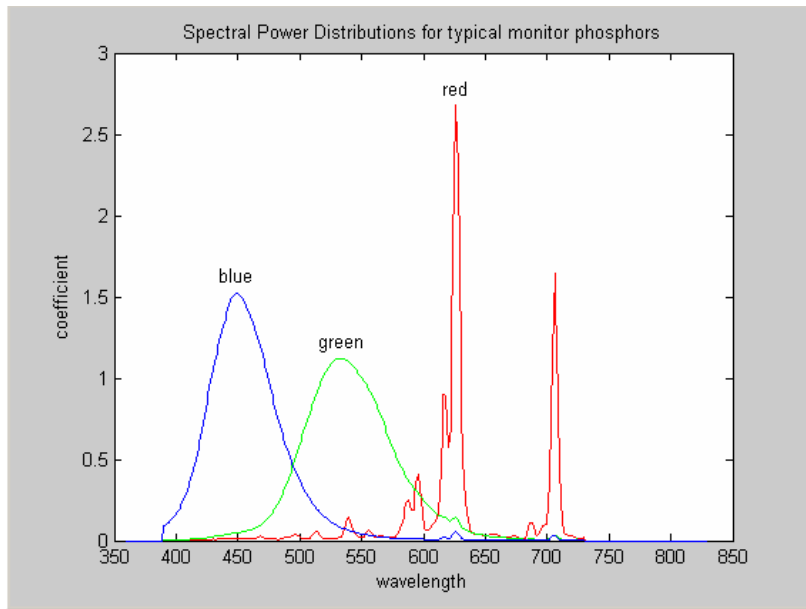


Emission spectra

- The basic nature of a light source can be described by its Spectral Power Distribution
 - » The SPD gives the energy at each wavelength



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



Data from Wandell, Applied Vision and Imaging Systems , <http://white.stanford.edu/~brian/>

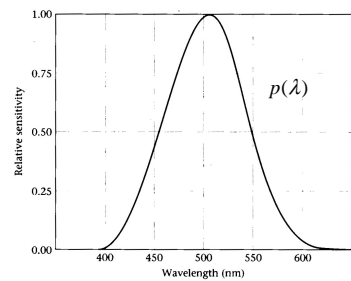
What is color?

- The eyes and brain turn an incoming emission spectrum into a discrete set of 3 values.
 - » These values are coordinates in a 3D color space
- The coordinates sent to our brain are *interpreted as color*.
 - » Color is not the same as Spectral Power Distribution
 - Color coordinates identify a point in 3-space
 - SPD is an infinite valued function of wavelength
- Color science asks some basic questions:
 - » When are two colors alike?
 - » How many pigments or primaries does it take to match another color?

Rod Photopigments

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

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

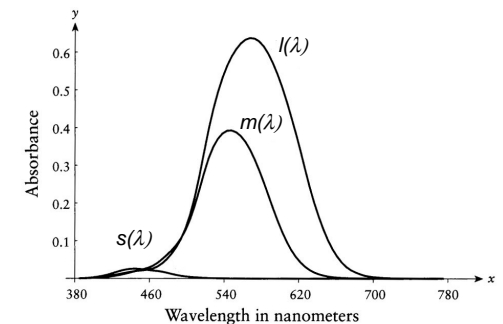


Spectral sensitivity function for rods (Wandell, 4.6)

Cone photopigments

Cones are active under higher light levels, i.e., they are responsible for **photopic** vision.

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



Cone photopigment absorption (Glassner, 1.1)

The color matching experiment

We can construct an experiment to see how to match a given test light using a set of lights called **primaries** with power control knobs.

The test light SPD function is

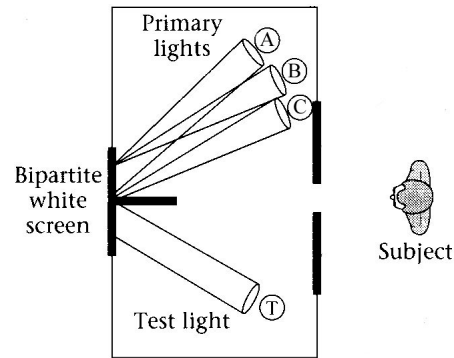
$$t(\lambda)$$

The primary light SPDs are

$$a(\lambda), b(\lambda), c(\lambda), \dots$$

The power knob settings are

$$A, B, C, \dots$$



The color matching experiment (Wandell, 4.10)

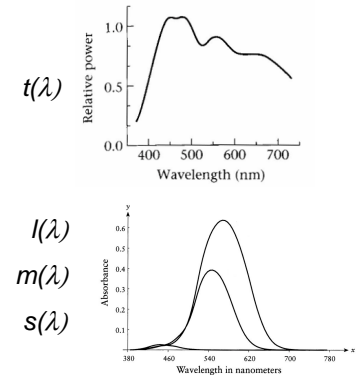
Cones and color matching

Cones respond to a spectrum according to their spectral sensitivity functions, $l(\lambda)$, $m(\lambda)$, and $s(\lambda)$. Thus, the cone responses to a test light with SPD $t(\lambda)$ are

$$L = \int t(\lambda)l(\lambda)d\lambda$$

$$M = \int t(\lambda)m(\lambda)d\lambda$$

$$S = \int t(\lambda)s(\lambda)d\lambda$$



This is a projection from ∞ -space to 3-space

Cone response to multiple primaries

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

The three knobs and three primaries create spectra of the form:

$$SPD_{abc} = A \cdot a(\lambda) + B \cdot b(\lambda) + C \cdot c(\lambda)$$

The m-cone response M to this combination of primary lights is

$$\begin{aligned} M_{abc} &= \int (Aa(\lambda) + Bb(\lambda) + Cc(\lambda))m(\lambda)d\lambda \\ &= \int Aa(\lambda)m(\lambda)d\lambda + \int Bb(\lambda)m(\lambda)d\lambda + \int Cc(\lambda)m(\lambda)d\lambda \\ &= A \int a(\lambda)m(\lambda)d\lambda + B \int b(\lambda)m(\lambda)d\lambda + C \int c(\lambda)m(\lambda)d\lambda \\ &= AM_a + BM_b + CM_c \end{aligned}$$

Color matching, cont'd

We end up with similar relations for all the cones:

$$L_{abc} = AL_a + BL_b + CL_c$$

$$M_{abc} = AM_a + BM_b + CM_c$$

$$S_{abc} = AS_a + BS_b + CS_c$$

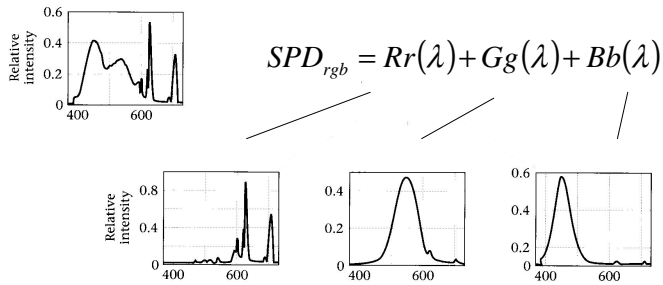
We can re-write this as a matrix and solve for the knob settings:

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

☞ We can find (A,B,C) to match any (L,M,S) and hence any color!
Negative values can be accommodated by adding the primary to the test light.

Choosing Primaries

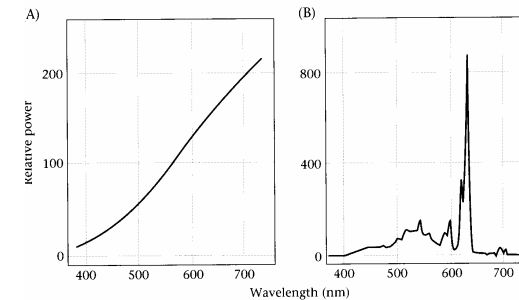
The primaries could be three color (monochromatic) lasers, but there is no reason why they have to be. They are just a way to form basis vectors in LMS space. They can be non-monochromatic, e.g., monitor phosphors:



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

Emission Spectrum *is not* Color

- The light spectrum is infinite dimensional!
- Different light sources can evoke exactly the same perceived colors. Such lights are called **metamers**.



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

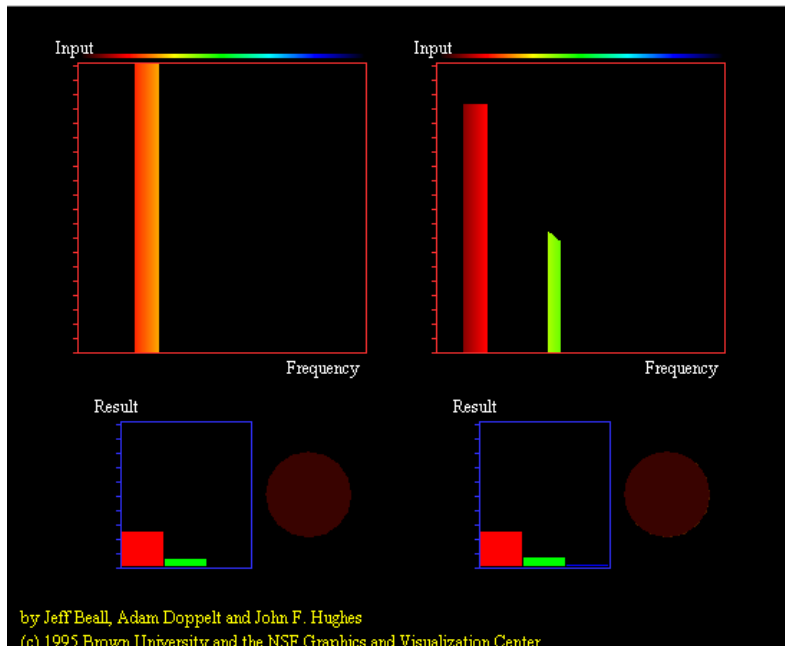
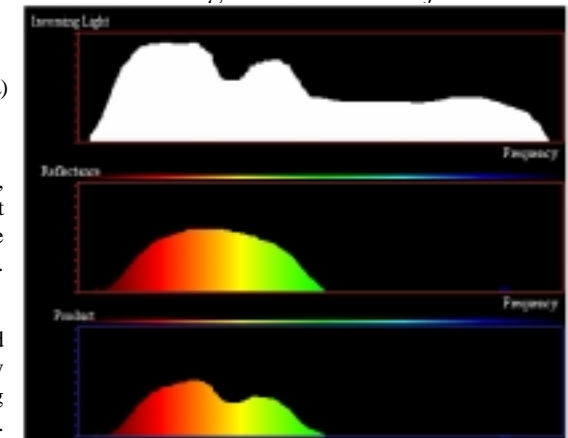
Colored Surfaces

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

SPD of the incoming light $t(\lambda)$

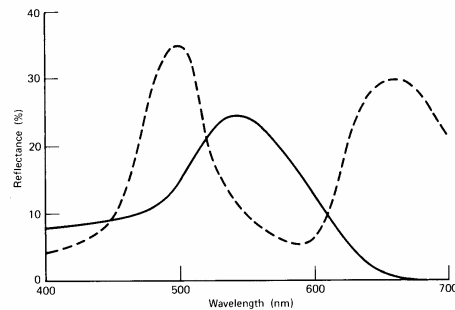
A surface's **reflectance**, $\rho(\lambda)$, is its tendency to reflect incoming light across the spectrum.

The incoming light is multiplied by the reflectance (thereby "subtracting" or removing $I(\lambda) = \rho(\lambda)t(\lambda)$).



by Jeff Beall, Adam Doppelt and John F. Hughes
(c) 1995 Brown University and the NSF Graphics and Visualization Center

Subtractive Metamers



Surfaces that are metamers under only some lighting conditions (Wasserman 3.9)

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.

Lighting design

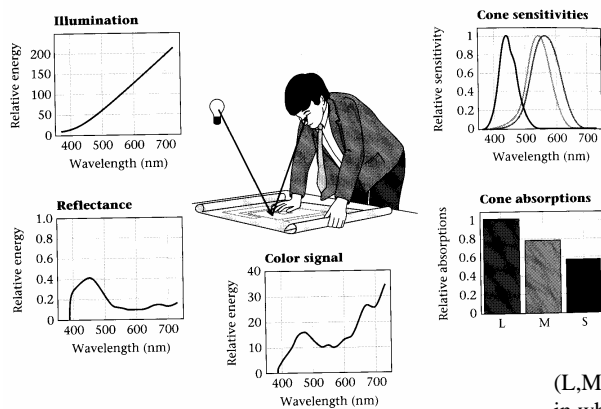
When deciding the kind of “feel” for an architectural space, the spectra of the light sources is critical.

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



Lighting Design Lab in Seattle: <http://lightingdesignlab.com/>

Illustration of Color Appearance



(L,M,S) is the 3-D space in which we perceive colors

How light and reflectance become cone responses (Wandell, 9.2)

The CIE XYZ System

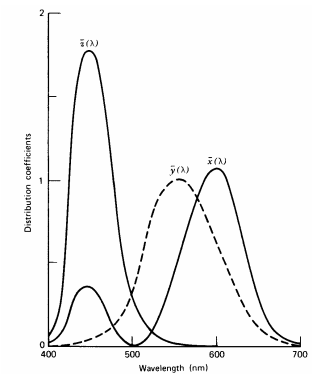
A standard created in 1931 by CIE, defined in terms of three color matching functions.

These functions are related to the cone responses as roughly:

$$\bar{x}(\lambda) \approx k_1 s(\lambda) + k_2 l(\lambda)$$

$$\bar{y}(\lambda) \approx k_3 m(\lambda)$$

$$\bar{z}(\lambda) \approx k_4 s(\lambda)$$



The XYZ color matching functions (Wasserman 3.8)

CIE Coordinates

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

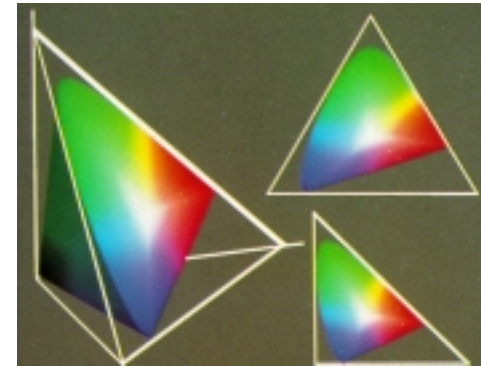
$$X = \int \bar{x}(\lambda)t(\lambda)d\lambda \quad Y = \int \bar{y}(\lambda)t(\lambda)d\lambda \quad Z = \int \bar{z}(\lambda)t(\lambda)d\lambda$$

Given the equations on the preceding page, the XYZ coordinates are closely related to LMS responses.

The XYZ space is a linear transformation of LMS space and we can think of it exactly the same way. The CIE primaries are the basis vectors for a 3-D space, and (X,Y,Z) are the coordinates of a particular color in this space.

Using the color matching functions, we can map any SPD to a particular point in this space and that point represents the perceived color for that SPD.

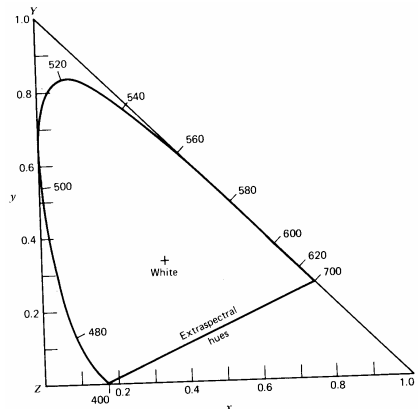
The CIE Colour Blob



Different views of the CIE color space (Foley II.1)

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**.



The chromaticity diagram (a slice through CIE space, Wasserman 3.7)

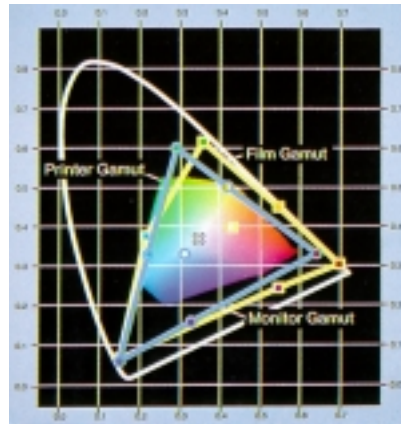
More About Chromaticity

- Narrow-band SPDs (single frequency lights) map to points 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 because their perimeter color cannot be obtained with a single narrow-band input.
- 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**.

The technology of the device determines the basis vectors of the subspace it can address.



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

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 broadcast

These are all linear transformations of each other. They describe the same colors, they just use different coordinates to do it.

RGB

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

What does the RGB color space look like?

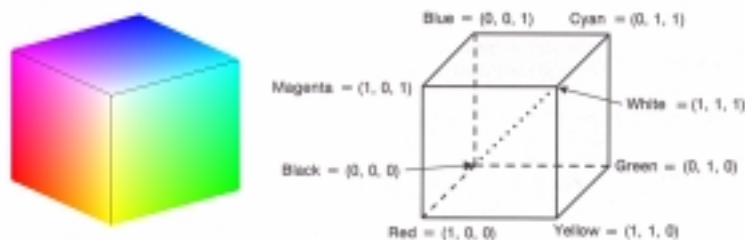


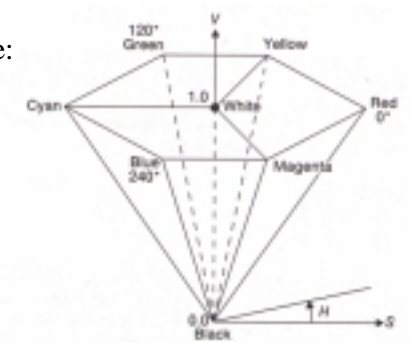
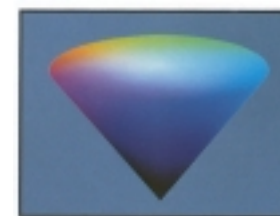
Fig. 13.28 The RGB cube. Grays are on the dotted main diagonal.

Foley

HSV

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

The HSV space looks like a cone:



Foley Fig 13.30

CMY

A subtractive color space used for printing.

Involves three subtractive primaries:

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

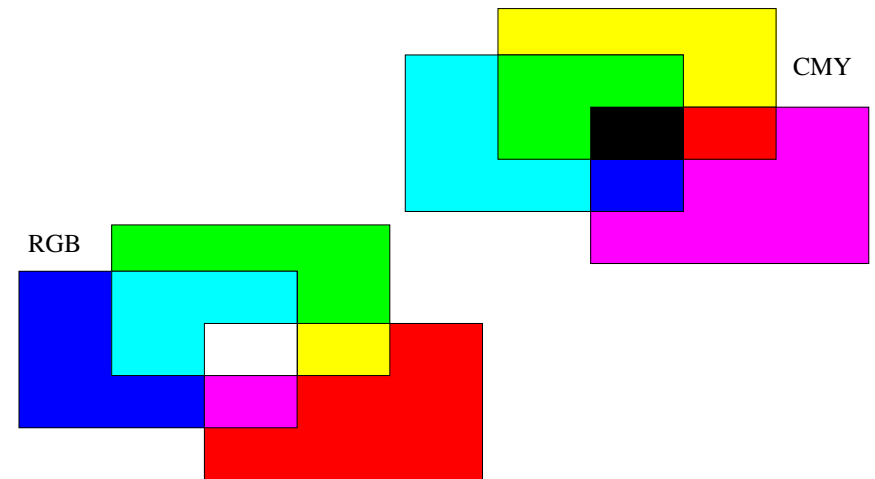


Mixing two pigments subtracts their opposites from white.

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

Canon i960 printer adds Photo Cyan, Photo Magenta.

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

Why do we devote a channel to luminance?

Summary

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

- All the **boldfaced terms**.
- How to compute cone responses
- The difference between emissive and reflective color
- What the CIE XYZ color standard and chromaticity diagram are
- The color spaces used in computer graphics