Chapter 4

Color

4.1 What is Color?

There is probably nothing more important to the study of images than the notion of color, what it means exactly, how it can be encoded, and how it can be manipulated. In our attempt to answer the question "what is color?", we will examine several ways of looking at the phenomenon. We will first take the point of view of the physicist, later the physiologist, and finally the artist. Each point of view has its own validity within its own context, and knowledge of each will help us to develop a more complete understanding of this higly complex question.

4.1.1 Physical vs. physiological models

The physical model of color is directly related to the physical phenomenon of light, and is actually a way of describing distributions of light energy. Light is energy in the form of electromagnetic waves, with wavelengths in the visible range from 400 to 700 nanometers. The energy of an electromagnetic wave is generally not concentrated at a single wavelength but is distributed across a range of wavelengths. This distribution is known as the *spectrum* of the wave, and it is this spectrum that is interpreted by our eyes as the color of the light. Knowing only this distribution, we can make reasonable predictions about perception of color.

Graphs of two light energy spectra are shown in Figure 4.1. The area under each curve gives the total energy per unit illuminated surface area. This total energy relates directly to the luminance or percieved brightness of the color. Both spectra shown in Figure 4.1 have about the same luminance. The "dominant" wavelength of the curve determines the hue or color name of the color. Both of the spectra in Figure 4.1 have a maximum concentration of energy around 560 nm, and energy at this wavelength is perceived by humans to have a yellow hue. The peakedness of the spectrum, i.e. the percentage of the total energy concentrated in a narrow band around the dominant wavelength, determines the saturation or purity of the color. The spectrum in Figure 4.1 that is labeled "yellow" will look like a fairly pure yellow or orange, whereas the spectrum labeled "brown" will look muddy, like a yellow ochre.

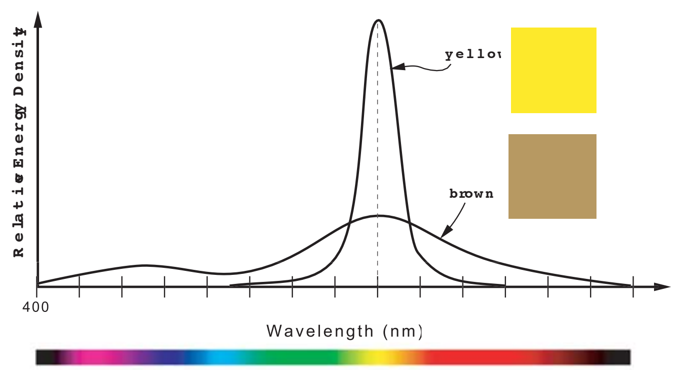
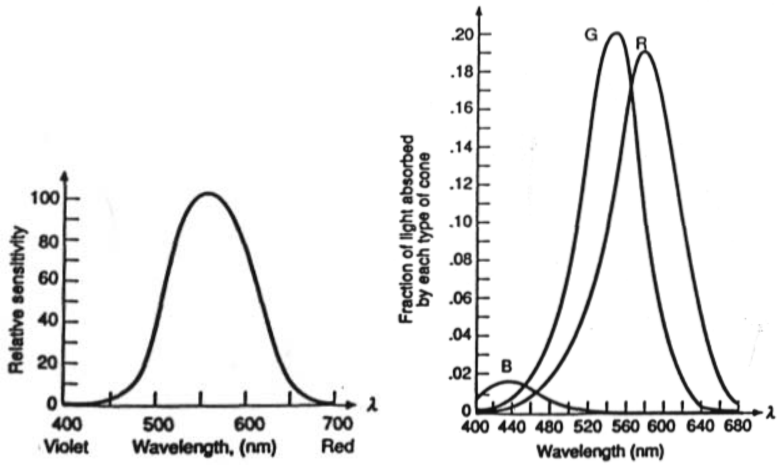


Figure 4.1: Physics of Color

However, from the point of view of the physiology of human vision, we can find no "machinery" in the eye that does anything like measure the shape of light spectra. Instead, perception of color is the result of various mental processes that receive their initial input from broadly-tuned photo sensors in the retina. These sensors are of two main types.

Retinal *rod* cells measure illumination level (grey level) and have a spectral sensitivity or *efficiency function* of the shape shown in Figure 4.1.1a. Even though the rod cells convey no color information, they are maximally sensitive to the greens and yellows. This means that under very low illumination, when there is no color perception, we still see yellow and green objects as being brighter than red or blue objects.

Retinal *cone* cells provide differential measurements of illumination, with spectral tuning that is much finer than that exhibited by rod cells. The cone cells give us the ability to discriminate hue. There are three distinct cone types, that can be thought of as corresponding very roughly to the color primaries red, green, and blue. Figure 4.1.1b shows the relative sensitivities of the three cone types to light across the visible spectrum of wavelengths.



a) rods b) cones

Figure 4.2: Spectral Sensitivity of Retinal Rod and Cone Cells copied from Foley, van Dam, Feiner and Hughes, *Computer Graphics Principles and Practice*, Addison-Wesley, 1990, pg. 577.

However, curves of rod and cone sensitivity are only measures at the eye. They say a lot about input to brain processes, but very little about the use to which the brain puts these inputs. Mental processing is complex and very ill understood. Judging from the amount of brain area devoted to it, visual processing is one of the most complex tasks undertaken by the brain. Thus, we would be making a gross oversimplification of the problem if we tried to relate eye physiology directly to color perception.

4.1.2 Color as a contextual phenomenon

The artist, Josef Albers, elevated the art of perceptual color manipulation to a very high level in his development of *color-field* painting. His working thesis was that color is a relative perceptual phenomenon, that transcends attempts to exactly quantify or measure individual colors. In other words, the color we will perceive cannot be predicted outside of the context within which the color will be presented. A memorable painting by Albers is simply a violet square immersed in a field of yellow. On close inspection, however, the violet square is seen to be slate grey. The presentation of the grey square in the context of a brilliant yellow surround, dramatically alters our perception. I will show two simple studies in class, that demonstrate some of the ideas that Albers worked with in his painting. For more on the contextual nature of color, see Joseph Albers, *Interaction of Color*, Yale Univ. Press, 1963.

The point is, that in the end, color perception transcends the physical and the physiological, involving the integration of context into the "reading" of a presentation.

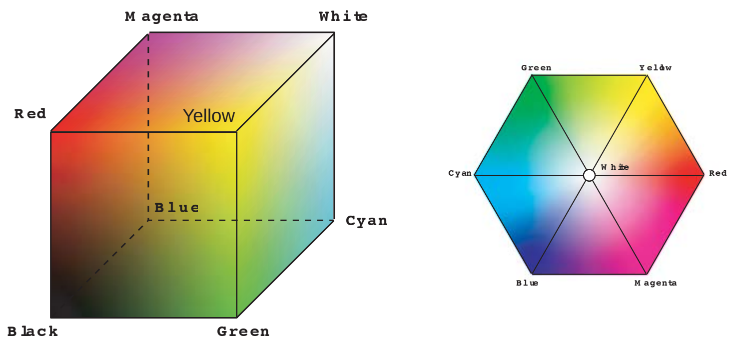
4.1.3 Tri-stimulus theory

Nevertheless, there is much evidence that a tri-stimulus theory of color (like the RGB system) provides a very useful color model, and if we ignore contextual issues, allows us to represent specific colors in a very compact form. This form is highly suitable for manipulation in a computer. In general, tri-stimulus theory says that color can be quantified by a 3-parameter system. There is much experimental and experiential evidence to back this theory, and it underlies most of current color technology in the print, broadcast, and film industries. The foundation principle of tri-stimulus theory is that most perceptual colors can be produced by presenting a mixture of three primary colors. A direct and important consequence of this theory is that many different light energy distributions will be read as the same perceptual color.

Some color systems extend the three color primary idea, and use a tri-stimulus system, where the three parameters are more abstract color measures.

4.2 HSV Color Space

One of the most widely used examples of an abstract tri-stimulus system is the HSV color space. The HSV system attempts to represent all perceptual colors using three measures that relate directly to how artists often think about color. It provides separate measures of *hue* (corresponding to dominant color name), *saturation* (purity of color), and *value* (brightness on grey scale). Its structure is derived directly from the RGB system, and in fact there is a simple translation from RGB to HSV and back. Figure 4.2 diagrams the relationship between the two systems. If the RGB color cube of Figure 4.2a is viewed along its white-black diagonal, it presents the hexagonal silhouette shown in Figure 4.2b. The complete HSV system is a cone-shaped space derived from this projection and shown in Figure 4.4.



a) RGB

b) HSV

Figure 4.3: Relationship Between RGB and HSV Color Systems

The HSV color space is parameterized by color coordinates (h, s, v), standing for hue, saturation and value. This parameterization is shown in the three diagrams of Figure 4.5. Hue h is measured by angular position around the face of the cone. As shown in Figure 4.5a, it goes from 0 to 360 degrees, starting with red at 0°, and proceeding counterclockwise around the color-wheel through yellow at 60°, green at 120°, cyan at 180°, blue at 240° and magenta at 300°. Saturation s is measured by distance from the central axis of the cone. As shown in Figure 4.5b, it is a fraction that goes from 0 for grey at the center to 1 for fully saturated at the boundary of the cone. Value is measured by v. As shown in Figure 4.5c, it is a fraction that goes from 0 for black at the apex or point of the cone to 1 for full intensity at the base of the cone, measured along the axis of cone. For example, a full intensity, fully saturated green would be $(120, 1, 1)$. A very dark but fully saturated green would be $(120, 1, 0.3)$, a pastel green would be $(120, 0.3, 1)$, and a neutral green brown would be $(120, 0.3, 0.3)$.

4.3 CIE Color Space

The final space we will look at is the CIE system. This system was developed in the 1930's to place the determination of color and illumination

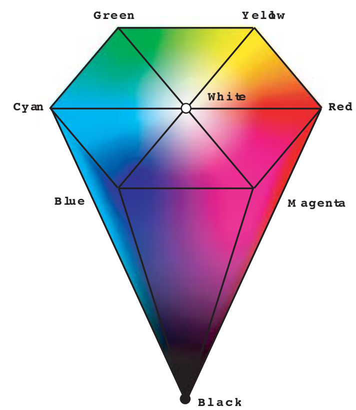
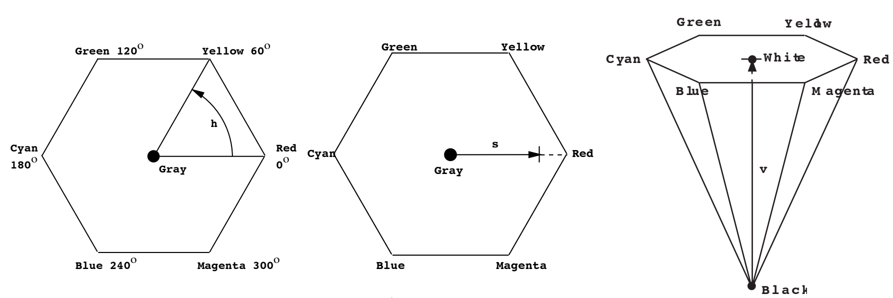


Figure 4.4: HSV Color Cone

on a more scientific basis with respect to human perception. One problem with both the RGB and HSV systems, is that they do not allow for precise color specification because they have no set basis for the colors that can be formed. In other words, the pure red color on one display or printer may look quite different from pure red on another device, although they both have the same RGB specification $(1, 0, 0)$ or HSV specification $(0, 1, 1)$. The CIE system, on the other hand, makes it possible to specify exactly reproducible colors. Thus, CIE colors can be catalogued and then displayed on CRT's, printed in ink, mixed as paint - always giving the same result.



a) hue b) saturation c) value

Figure 4.5: Parameterization of HSV Color Space

The CIE system was developed using the experimental configuration shown in Figure 4.6. Observers were presented with a split screen. A colored test light illuminated one side of the screen, and a set of three pure primary lights illuminated the other side. The observer could adjust the intensity of each primary with a dial. The task was to adjust the screen color produced by the three primaries, to match the color projected by the test light.

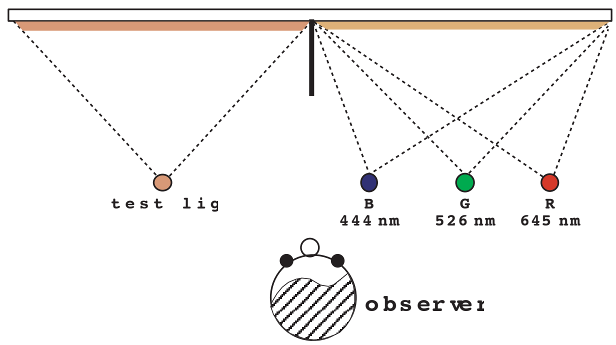


Figure 4.6: CIE Test Apparatus

Using a range of pure single-wavelength test lights, the curves of primary intensities shown in Figure 4.3 were obtained. For each wavelength of test light, the exact setting of each primary necessary to reproduce the perceived color of that test light was determined. A complication was that for some colors the primary settings needed to be negative – in other words it was not possible to reproduce all test colors with the three additive primaries. To deal with this complication, the nonreproducable colors were matched by adding primary colors to the test light. This was considered to be equivalent to subtraction of the corresponding primary from the additive mixture and shows up as negative values on the curves.

From the test data, three functions of wavelength, known as the CIE **x**, **y** and **z** color matching functions were developed. These functions are graphed in Figure 4.3. They do not correspond to realizable light sources, but can be thought of mathematically as if each were a primary light source. The corresponding three light levels of the matching functions necessary to match a given color are called the color's CIE XYZ coordinates. Thus, any color C can be represented by a weighted sum of these 3 primaries

$$C = X\mathbf{x} + Y\mathbf{y} + Z\mathbf{z}. \tag{4.1}$$

Usually, however, the CIE coordinate system is given in modified form,

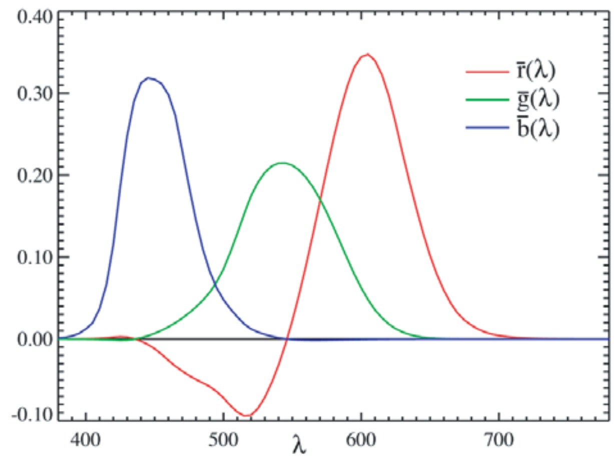


Figure 4.7: CIE Color Matching Experiment Data copied from Wikpedia, *CIE 1931 Color Space*, http://en.wikipedia.org/wiki/CIE_1931_color_space.

by defining the color's chromaticity coordinates (x, y, z). These coordinates measure the color's chromatic content, and are given by

$$x = X/(X + Y + Z), \tag{4.2}$$

$$y = Y/(X + Y + Z), \tag{4.3}$$

$$z = Z/(X + Y + Z) = 1 - (x + y). \tag{4.4}$$

The CIE matching function **y** was chosen to be identical to the human response to luminance (compare Figures 4.1.1a and 4.3). Thus, the CIE Y coordinate does not contribute to the chromatic content of a color and can be thought of as the luminance or brightness of the color. Since the z component of chromaticity can be calculated directly from the x and y components, a unique color specification is given by (x, y, Y). This is known as the CIE xyY color specification. It has the advantage that all of the chromatic information is contained in the coordinate pair (x,y) and all of the luminance information is given by one coordinate Y. A cross section through the CIE xyY space for a fixed luminance (i.e. a fixed value of Y) looks like that shown in Figure 4.3.

There are methods of going from a catalogued CIE color to an RGB triple, that require knowing some characteristics of the display device (e.g. the CIE coordinates of the phosphors of a CRT). The science of using CIE

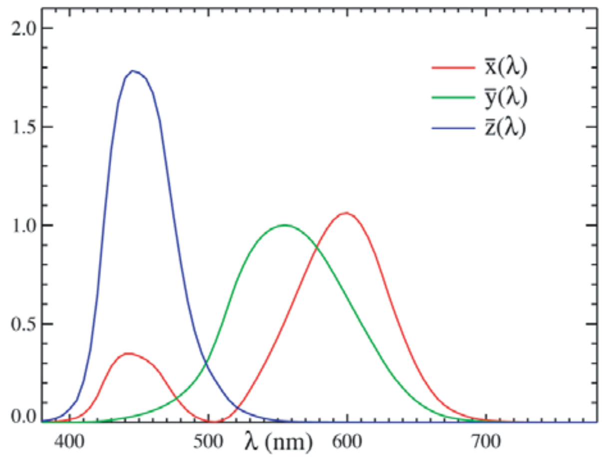


Figure 4.8: The CIE XYZ Color Matching Functions copied from Wikpedia, *CIE 1931 Color Space*, http://en.wikipedia.org/wiki/CIE_1931_color_space.

information fits into the broad area of colorimetry, and is something that you may want to study further if you have a deep interest in color.

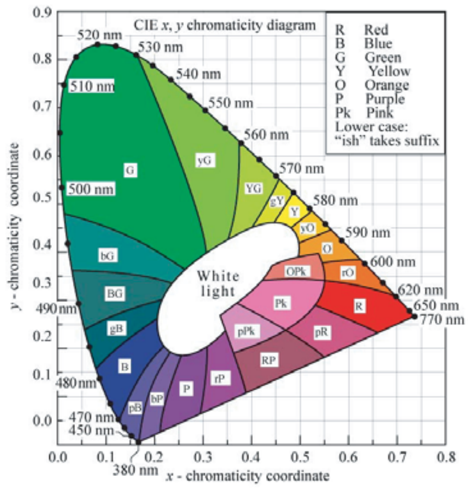


Figure 4.9: Cross Section of the CIE Space for Fixed Luminance Y from Schubert, E.F., *Light Emitting Diodes*, Colorimetry, 2003. ¡http://www.ecse.rpi.edu/ schubert/Light-Emitting-Diodes-dot-org/¿