11.1 NEWTON'S WORK

The scientific study of color in itself began with that great British genius of the seventeenth century, Sir Isaac Newton. Newton was the first to show that white light is composed of a mixture of all the colors of the rainbow by passing sunlight through a prism, as shown in Figure 10-5. More, however, was required than that simple demonstration to reach such a conclusion. Newton separated single colors from the rest and showed that further refraction in a prism did not alter them more, as may be seen from the experiment shown in Fig. 11-1. He showed further that recombining the colors with a second prism again produces white light, as illustrated by Fig. 11-2. Such experiments serve to show that the color is not being "added" to the light in any way by the prism (as in passing white light through a color filter), but rather is inherent in the white light from the start. Because they were not associated with any

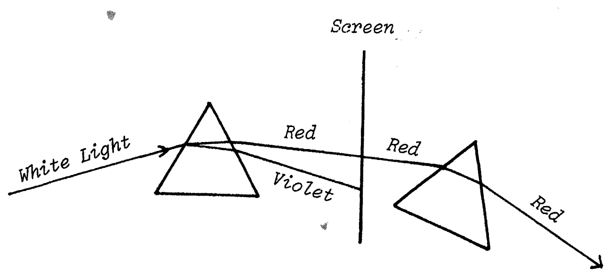

Figure 11-1 Second refraction of a single color

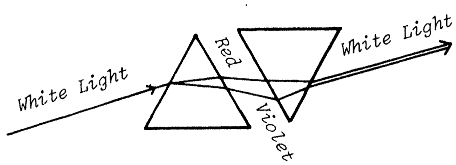

Figure 11-2 Recombination of the colors

physical object but seemed to be in the light itself, Newton called the colors **spectra** (specters or ghosts) and the collection of colors together a **spectrum**.[1]

Newton named seven colors in the spectrum: red, orange, yellow, green, blue, indigo, and violet. More commonly today we only speak of six major divisions, leaving out indigo. A careful reading of Newton's work indicates that the color he called indigo, we would normally call blue; his blue is then what we would name blue-green or cyan. Newton also noted that purples could be created by combining light from the two ends of the spectrum, red and violet. Since all the spectral colors merge rather imperceptibly one into the next and the purples can, in a similar manner, bridge the gap from red to violet, Newton introduced a color circle with no abrupt color changes, as shown in Fig. 11-3. White was represented at the center of the circle because it was a mixture of all colors; remember that we are still talking about mixing lights, not pigments. Now as colors become less "intense" or tended more toward white, they could be placed on a radius line to the correct hue but closer to the center. Rules for mixing colors could then be based on positions on or in the color circle. In particular, two colors on opposite sides of the circle could be mixed to produce white. This scheme was a good beginning and incorporates ideas we still use today, but much more work was required.

One reason that color science is a difficult field is that it combines the usually separate areas of physics and psychology. For example, in Newton's time the wave nature of light and its connection with color were not understood at all, and it took the general advance of physics to clear that up (see Chapter 2). But in the final analysis, when we speak of *color* we are speaking about human perceptions and sensations, clearly subjective and in the area of psychology.

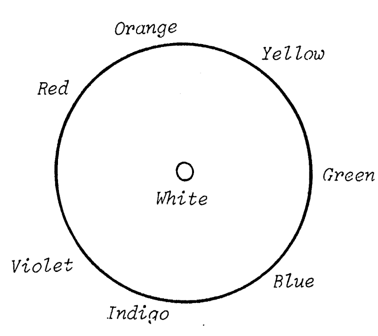

Figure 11-3 Newton's color circle

[1] David L. Mac Adam, *J. Opt. Soc. Am.* 65, (1975), 483.

11.2 PRIMARY COLORS

One very basic subjective aspect of color is that some seem to be **primary** or to come before the others. Those who have studied the development of language tell us that the names for black and white are invented first. From our point of view we can think of these two as the mixtures of no colors and all colors respectively; sometimes they are called **achromatic.** Next the color name for red appears, then yellow, green, and blue. Any other color names come much later in the evolution of the language. Notice that the colors that Newton chose to name in the spectrum include these four: red, yellow, green, blue. These four are almost always named also in any modern description of the spectrum or the rainbow. They seem to be subjectively distinct, whereas other colors of the spectrum seem to be mixtures. For example, cyan *subjectively appears* to be partly green and partly blue; orange has aspects of red and yellow, and so on.

A French contemporary of Newton, Edmé Mariotte (1620–1684) was one of the earliest to specifically state the basic premise upon which color science is now based: all colors can be produced by a mixture of just three primary colors. Mariotte chose as his primaries red, yellow, and blue. Thomas Young in his earliest descriptions of color vision also named red, yellow, and blue as primaries, but later substituted green for yellow. Actually there is a good deal of leeway as to which three colors are chosen as primary. The fundamental fact of color science is that almost all colors (and certainly all spectral colors) can be produced by a mixture of three primaries which satisfy the following conditions:[2] no one primary can be matched by a mixture of the other two, and all three in some proportion can produce white.

11.2.1 Additive Mixing

Mixing colored lights, as opposed to pigments, is called **additive mixing.** Usually the three primaries for additive mixing are chosen as red, green, and blue. Three such colored spotlights shown overlapping on a screen produce an appearance like that shown in Fig. 11–4. Here *R, G,* and *B* stand for red, green, and blue, respectively, while the overlap regions are labeled *C* for cyan (blue-green), *M* and magenta (purple), *Y* for yellow, and *W* for white. By adjusting the amounts of the primaries in the various mixtures, we can change the overlap colors so that any spectral color is matched. For example, the yellow region can be adjusted from a greenish yellow to an orange yellow by increasing either the proportion of green or that of red. In addition, **desaturated colors** (those Newton called less intense) can be produced in the white or triple overlap portion of the pattern by adjustment of one or more of the primaries. So all the colors of Newton's circle can be produced in this manner.

Two colors that are opposite to each other on Newton's color circle can be

[2] Ralph M. Evans, *The Perception of Color* (New York: McGraw-Hill Book Company, 1974), p. 44.

mixed to produce white and are said to be **complementary.** Yellow and blue (Newton's indigo), red and cyan, and green and magenta form complementary pairs. Note that those colors which are complementary to the primaries show up as the overlap colors in Fig. 11-4. If we represent white by the addition of two complementary colors, then one of the complementary pair can, in the same sense, be said to be white minus the other. Thus

$$W = Y + B$$

and $$Y = W - B$$

Also $$C = W - R$$

$$M = W - G$$

Often the complementaries to the primaries are simply said to be minus the primaries, with the white being understood.

$$Y = -B$$
$$C = -R$$
$$M = -G$$

This designation also makes sense from the point of view of Fig. 11-4. The white region there is where all three primaries are present. If we move from white to a region where one of the primaries is absent, we find ourselves in a color complementary to the missing primary.

11.2.2 Subtractive Mixing

The negative primaries (cyan, magenta, yellow) are the colors used for mixing of pigments, called **subtractive mixing.** This name is used because pigments work by *absorption,* taking out certain wavelengths from the incident light. When pigments are mixed, what adds up is the light *removed.* Thus a cyan pigment absorbs red and a yellow pigment absorbs blue; when cyan and yellow pigments are mixed the resulting pigment removes both red and blue from incident white light, reflecting green. Figure 11-5 shows subtractive mixing results.

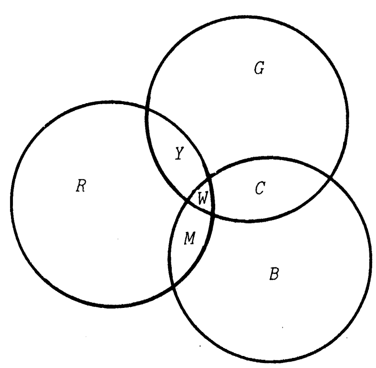

Figure 11-4 Additive primaries

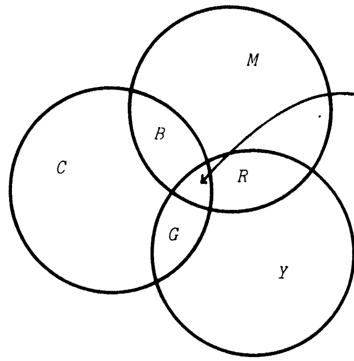

Figure 11-5 Subtractive primaries

The experimental facts of color science discussed above have very important implications. Consider the relationship of wavelengths to color. We can see that there is not a one-to-one correspondence: light with a wavelength of 580 nm always appears yellow, but yellow light (even the same shade of yellow) does not always consist of the one wavelength of 580 nm. A matching yellow might be produced by a combination of green and red light with *no* wavelengths of 580 nm. Such matching colors which differ in their spectrum (the amount of light at each wavelength) are called **metamers.** But the most practical result of the laws of color science is that they make color printing, color photography, and color television feasible. In each case we only need to work with three primaries instead of the vast array of colors which we wish to reproduce.

11.2.3 Examples of Primary Color Mixing

Color printing uses subtractive mixing of the negative primaries. Three separate printing plates (one for each negative primary) are used, which print the three inks in tiny dots of varying intensity. The eye integrates the dots to see different colors from different primary mixtures in different parts of the picture. Often a fourth plate in black ink is printed also to give shading and depth. Imagine trying to print in inks of all the different colors one wished to appear in the final picture!

Color photography was first demonstrated in 1861 by James Clerk Maxwell (see Chapter 2). Photography itself was only about 20 years old then. Maxwell took three different black and white photographs, each through a separate primary filter. When these were made into positive transparencies and projected, each through its own filter so the images overlapped on a screen, a full-color reproduction appeared. In this demonstration additive mixing from three different projectors was used to form the color image. Any area in the original scene that had a large proportion of red, say, would have sent a relatively large amount of light through the red filter and appeared light on that transparency. But that transparency was later projected through a red filter so that the corresponding area in the final image would receive a large amount of red light, as it should. Maxwell was limited by the fact that the black and white films then were far from equally sensitive to all colors, and this scheme was far too cumbersome for practical application anyway. However it did establish the possibility of color photography.

In modern **color photography** the filtering is all done within the film itself. There are three layers within the color film, sensitive to the three primary colors. Upon development, three dyes in the three negative primary colors are activated at the appropriate positions. The final color print is a subtractive mixture of these dyes.

Color television depends on additive mixing, the mixing of colored lights. There are actually three different phosphors in the television screen, arranged in tiny dots. These three phosphers produce red, green, or blue light when struck by the electron beam of the picture tube. As with the color print, the eye integrates the tiny dots of colored light to produce a mixture of primaries, so any color can be reproduced by stimulating the phosphors in proper proportion. Again, without the simplicity of only three primary colors color television would be next to impossible.

11.3 ATTRIBUTES OF COLOR

Before considering color mixing in a quantitative manner, it will be worth while to take a closer look at the naming and classification of colors. We have already seen how colors can be placed around and in a circle in a continuous manner, with white at the center. In that discussion we used the words **hue** and **saturation** without any careful definitions. In everyday language *hue* is often used as a synonym for *color,* but in color science we shall used *color* in a more general way. We may think of hue as the color variable to which we assign names, such as red, blue, yellow, and magenta. In other words, hue is what changes as you move around the color circle of Fig. 11–3 either on its outer circumference or on a smaller circle inside. All colors along one radius line of the color circle have the same hue. On the other hand, the colors along one radius line are perceptibly different, being closer to white, or less saturated, near the center, and further from white, or more saturated, at the circumference. Saturation is what varies as you move from the center of the circle outward. If either the hue or the saturation of two colors is different, we say the colors are different. With these definitions one can see that *hue* and *color* do not mean the same thing; all the colors along one radius of the color circle have the same hue but they are different colors because they have different saturations.

Hue and saturation are said to be **attributes** of color. But there is still (at least) one more attribute of color. That is, we can perceive two samples that seem to have the same hue and saturation but are still perceptibly different in color because they are different in another attribute. This third attribute of color is called **brightness** for colored lights or **lightness** for colored pigments reflecting light. The identification of brightness in the one case with lightness in the other is somewhat questionable,[3] but it will serve for our purposes as a first approximation.

The attribute of lightness might best be approached by considering a number of achromatic samples (perhaps paint chips) ranging from white to black through various shades of gray. Physically, each of these samples reflects all visible wavelengths equally, but different samples reflect different amounts: white reflects all wavelengths 100 percent, black 0 percent, and some gray 50 percent. These samples have zero saturation and no hue (hence the name achromatic). For example we have already placed white in our color circle at the center. Since saturation increases outward from the center in any direction, white at the center has zero saturation. Also, the center of a circle has no definable position around the circle, so we cannot assign any hue name to white.[4] In fact, the only attribute which distinguishes the samples is lightness. We could arrange them in order of increasing lightness from black to white.

11.4 COLOR SOLID AND COLOR ATLASES

These facts imply that the color circle is inadequate to represent all colors. Colors should be arranged in a three-dimensional space, corresponding to three attributes, instead of a two-dimensional space corresponding to two attributes. So we are led to a color solid to replace the color circle. The simplest way to obtain such a color solid is to imagine a number of color circles, similar to Fig. 11-3 and each corresponding to a different lightness, piled on top of one another. Now each color circle has, rather than white at its center, the achromatic color appropriate to the lightness of all colors in that circle. We still have hue varying around each circle and saturation varying outward from the center. Figure 11-6 shows such a color solid.

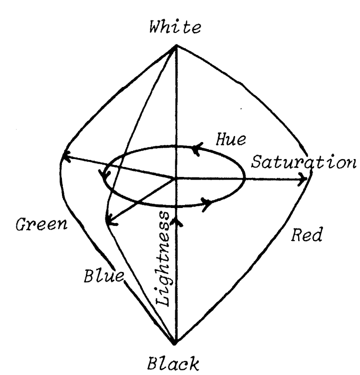

Figure 11-6 Color solid

[3] Ibid., p. 7.

[4] *The Science of Color* (Washington, D.C.: Optical Society of America, 1963), p. 66.