

Chapter 12

Color

12.1 Introduction

Image-processing programs like Photoshop and Illustrator support a bewildering variety of color models. In place of the simplicity of the eight-color crayon box or the elementary school claim that there are only three primary colors, one has a blizzard of RGB, CMYK, HSB, PANTONE, Duotone, Bitmap, Grayscale, and a host of other characters. Where does all this come from, and what does it have to do with scientific graphics.

The short answer is that the human visual system, a computer monitor, and a printer all reproduce the color spectrum in different ways. In part, the multiplicity of color models and jargon reflects the different physics of different color-making and color-analysis hardware. However, the variety of models also reflects that artists approach the world differently from their hardware, and this introduces additional ways to look at color. Finally, other color schemes have been introduced because of the practical needs of the publishing industry. In this chapter, we will try to sort them out.

12.2 Spectroscopy: the Digital and Analog Eyes

A spectroscope splits light into many spectral bands and computes the intensity in each band. It is a sort of digital eye. It would be very difficult for a scientific visualization system to reproduce a spectroscopic analysis; each pixel would need to have thousands of elements, one for each band resolvable by the spectroscope.

Fortunately, the human visual system can only resolve three broad bands of color. This makes it possible for color televisions and monitors to produce very realistic color using just three different colors of phosphors (red, green, blue) for each pixel.

However, the input from these color-channels is processed in very sophisticated and complex ways by the human visual machinery. When the eye perceives a lot of light in both the red and blue channels, but little in green, it produces a distinct color “purple”.

12.3 Emission: Red-Green-Blue (RGB) or “Additive” Color Model

A computer monitor or television screen glows because phosphors on the screen are blasted with a controlled beam of electrons. Screen light is thus *emission* of light.

The three primary colors of emission are red, green and blue. These correspond to bands of wavelengths in visible light: red is the band of long wavelengths, blue is the band of short wavelengths, and green is intermediate.

Emission color is therefore described by the RGB (Red-Green-Blue) color model. Since there are three phosphors, each emitting in a different band, all monitor-displayable colors are described by specifying the intensity with which each of these phosphors is stimulated. Put another way, three numbers describe a color, and each number is the intensity of red, green, or blue.

12.3.1 The Purple Phosphor

The eye perceives purple as distinct from red and blue. Why then, couldn't one apply a different color model with purple as one of three primary colors?

The answer is that it is almost impossible to make a purple phosphor. Such a phosphor would have to emit strongly in both the red and blue parts of the spectrum, but not in the middle (green). It would have to emit with roughly equal strength in both red and blue, or the purple wouldn't be very purplish. It would have to have identical power-to-emission curves in both red and blue.

One complication with phosphors is that the intensity of the emitted light is not a linear function of the power applied to the phosphor. Monitor circuit corrects for the nonlinearity. A purple phosphor would likely have different nonlinear response curves for blue and red. The phosphor might shine as a reddish-purple at low intensity but a bluish-purple at high intensity, for example. This would make it very difficult to control the color. If the primary phosphors were red, green and purple, then it would be very difficult to make a pure blue at low intensity because the purple phosphor is the only phosphor capable of making blue, but at low intensity (by assumption) it generates even more red.

Thus, a useful emission model that replaces red or blue with purple would be very impractical. RGB is the fundamental emission model because it is fairly easy to create three different phosphors that emit in a single contiguous band of visible light, and these bands are red, green and blue.

12.3.2 Additive Color Model

To build up more complicated colors from the three primaries, we add the emission from different phosphors. The RGB model is therefore said to be an "additive" color model.

12.4 Reflection: The Cyan-Yellow-Magenta-Black "Subtractive" Model

Unlike a cathode ray tube monitor, a sheet of paper has no internal energy source. The light which allows us to read a sheet of paper is light which has come from an external source, such as the sun or a lamp. As a first approximation, we can pretend that the light source is white, that is, a blend of red, green and blue. The reason that we do not see white on a printed page is because the dyes in the ink *absorb* some of the white light.

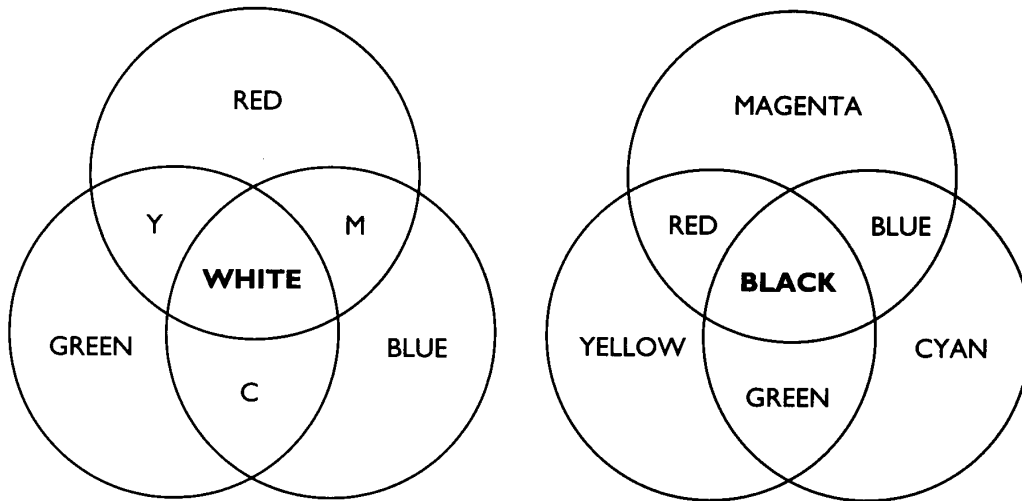


Figure 12.1: A comparison of the primary additive and subtractive colors, showing how other colors are constructed from the primaries.

Because paper is an absorber of colors rather than an emitter, printing is forced to use a different color model than screen display. The standard print employs cyan, magenta and yellow as the primary colors.

Why not use red, green and blue as the primary colors? To make a printed image appear red, one must use a mixture of dyes which absorb in both the green and blue bands of the spectrum. This is not a difficult technical problem, and indeed every printing shop has red inks.

However, red is not a primary “reflective” color because the red ink is absorbing in *two* of the three bands of wavelength, not one. A dye which absorbs in only the green band will reflect both red and blue, creating a reddish hue which printers usually call “magenta”.

When printing a photograph or other image with a wide range of colors, it is not feasible to use a bright, emission-type red as a primary color. By eliminating two of the three bands of color, a red-appearing dye leaves too little control for the other primary dyes.

Instead, we have the relationships

$$\text{blue-absorbing} = \text{yellow} \quad (12.1)$$

$$\text{green-absorbing} = \text{magenta} \quad (12.2)$$

$$\text{red-absorbing} = \text{cyan} \quad (12.3)$$

In theory, the mixing of all three subtractive colors will give black. In practice, mixing the cyan, magenta and yellow inks gives only a muddy-black, a dark brown. This looks very bad when used for figure labels and the main text, which should be black-on-white. For this reason, a fourth ink which is *very* absorbing is added to give black. In the usual acronym, black is denoted by “K” to avoid confusion with blue.

The usual subtractive color scheme requires four inks. It is abbreviated CMYK for Cyan-Magenta-Yellow-Black.

Fig. 12.2 shows how different colors are constructed from the primaries in the two color systems. Fig. ?? is another popular aid to understanding the models, the so-called “color cube”.

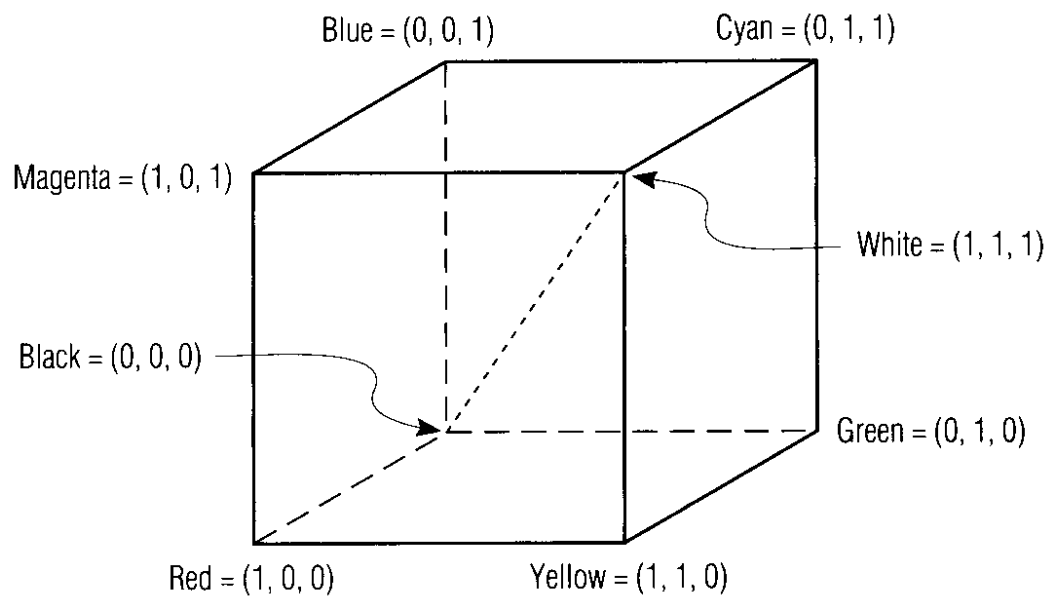


Figure 12.2: “Color cube”. The numbers next to each color indicate its representation in the RGB color scheme. Thus, red is (1,0,0), green is (0,1,0) and blue is (0,0,1). The subtractive colors are each a mixture of two of the RGB colors; the color which is zero in the numerical label of a subtractive color indicates which RGB color that subtractive color *absorbs*.

The Visualization of Natural Phenomena by Robert S. Wolff

12.5 Gamut

The range of colors that can be represented by a color model is called the “gamut”. A crucial point is that the gamut of CMYK inks is *smaller* than the gamut of RGB screen phosphors. This means that many bright hues which look fine on a computer monitor cannot be effectively printed. Naive users are often very surprised that bright colors print rather dully.

Illustrator and Photoshop provide some help. When moving the colored sliders in the RGB model, a little yellow triangle with an explanation point sometimes appeared. This is a warning that the RGB color, as chosen by the instantaneous position of the red, green and blue color sliders, is outside the gamut of CMYK. Such a color will display well, but print badly.

12.6 Hue-Saturation-Brightness (HSB or HSV) Color Model

Drawing and image-processing programs provide ways to adjust a color by moving sliders that control the intensity in each of the primary colors — one slider for red, one for green, one for blue in the RGB model. Although the RGB and CMYK models are closely connected to the physics of emission and reflection, respectively, manipulating color sliders is not an *artist’s* or a photographer’s way of manipulating color.

For this reason, many image-processing programs offer a third model, which is called the HSB or HSV model. (The third letter is for a property which is variously called the “brightness” or “value”; the “brightness” label seems to be growing in popularity.

“Hue” is a synonym for “wavelength”. A “red hue” means that the color is centered in the long wavelength region of visible light.

The “saturation” is a little more subtle. In graphics, “color” and “wavelength” never denote precise quantities as in spectroscopy. Rather, a “red” is always a *broad band* centered on the red part of the spectrum. A smooth Gaussian shape for the distribution of intensity versus wavelength implies that “red” usually has a little intensity in the green and a tiny bit in the blue parts of the spectrum, too. The “saturation” is the inverse width of this distribution of intensity versus wavelength. A “fully saturated” color has a narrow distribution with near-zero amplitude in green and blue. A weakly saturated red has some green and blue, too.

However, the Gaussian shape of a spectroscopic band is misleading. In the graphics world, a better model is a peak about some wavelength plus a background of white light. The saturation is the amount of this white background. An unsaturated image is pure white. A fully saturated image has no white and is narrowly peaked in wavelength as already asserted.

The “brightness” is the intensity of a color, the amount of energy being pumped toward the eye by the pixel. Some purists reserve “brightness” for self-luminous or emitting objects (like computer monitor phosphors) while reserving “lightness” to describe intensity-in-reflection. However, this distinction is usually ignored.

The reason that HSB model is helpful is that a child picking crayons out of 64-color Crayola box does not think “20 % green, 40 % blue, 70 % red”, which is the RGB way of describing a color. Instead, a child first thinks “Trees — I need some green.” This is a choice of hue. The second question is the choice of saturation, “dark red” versus “red” versus “pink”. The third question is: “How hard do I rub the color on”, which is a choice of intensity.

Professional artists pose the same questions often without conscious thought. But the simple choice of “red” versus “pink”, which is easy in the HSV system and hard in

either RGB or HSV, explains why this third color system is used.

12.7 Uncolor Models: Bitmap/Line Art and Grayscale

Most image-processing programs support a mode which stores only 1 bit per pixel. This is sometimes called “Bitmap” mode, as in Photoshop, and sometimes “Line Art” mode, because it is appropriate for many species of scientific graphs where the curves are drawn in black-on-white.

All colored modes support black-and-white images, too. However, the file size of an image is enormously reduced when only 1 bit is stored per pixel than when 8-bit color intensity numbers are stored for each of three or four primary colors.

The other major uncolor mode is grayscale. This is always one byte or eight bits per pixel, which is sufficient to specify 256 levels of grayscale.

In practical terms, this is far more levels than the eye can readily perceive. There is little pressure to increase the number of levels because of this human visual limit; there is little pressure to reduce the number of levels below 256 because computers can handle information efficiently only in 8 bit or one bit groups.

12.8 Duotone

Because four-color printing is so expensive, a lot of children’s book are printed using just two colors. “Duotone” is the technical term for a mode that supports just two colors. Duotone is rarely used in science.

12.9 Indexed Color

To reduce image size, many graphic systems do not store bytes for the red, green and blue separately at each pixel, but instead store only a 1-byte index into a palette of 256 colors. This greatly reduces file size at the cost of a little photo-realism.

Because computers and storage devices have improved enormously, indexed color has diminished in importance relative to 24-bit or 32-bit RGB and CMYK color. However, indexed color is unlikely to go away any time soon.

One reason is historical. Matlab’s ubiquitous colormaps are indexed color. Because 256 colors are quite adequate for most scientific visualization, a domain where photo-realism is a low priority, there is little pressure for Matlab’s coders to undertake the enormous chore of rewriting codes to allow a wider range of color. Many other software systems have a similar historical legacy.

Another reason is that Web bandwidths are still mediocre. An indexed image can be transmitted three times as fast as a 24-bit RGB image. For this reason, Web images are almost always stored in a file format such as GIF which employs indexed color.

12.10 Spot Color

Professional-grade drawing and image-handling programs support “spot color”. The usual CMYK inks, also known as “process colors”, can never exactly represent the full range of colors that a graphic designer might wish for. In particular, the CMYK inks are relatively poor at representing very bright colors. For that reason, some high-end

printing jobs supplement the usual four inks with additional inks whose sole purpose is to cover parts of the page with a pure, bright color. These additional inks are called “spot colors”.

Logically speaking, “black” is a spot color. However, black is so important, and the use of a black ink to supplement cyan, magenta and yellow, is so common that by convention black is classified as a process color. However, the motive for including black as a separate ink is the same motive as for other spot colors.

Scientific graphics almost *never* employs spot colors. However, they are fairly common in high-end publishing. The program for a University of Michigan football game might use Wolverine blue as a spot color for the cover, while printing the interior in only the usual CMYK inks.

12.11 PANTONE Colors and All That

Different ink manufacturers use slightly different ratios of pigments and slightly different solvent and binder mixtures. This creates small but sometimes noticeable discrepancies when an image that was proofed on an office computer printer is printed on a huge offset press for a mass-market magazine. The computer printer and web press use different inks; why should the colors look the same?

To reduce this difficulty, the publishing and graphics industry have introduced a number of color-matching schemes. A professional designer, for example, can buy a PANTONE swatch book that shows the exact printed appearance of PANTONE #32, for example. By specifying PANTONE # 32 in Photoshop software, and then informing the publisher that PANTONE inks are to be used, the designer can ensure that what she has chosen is the exact shade that will appear in the final printed product.

12.12 Summary

It is important that scientists and engineers understand the RGB and CMYK models because these reflect the basic properties of computer monitors and printers, respectively. It is also important to understand the 1-bit-per-pixel bitmap/line art and grayscale modes since these uncolored formats are widely used in scientific graphics, too.

Scientific graphics rarely use spot colors, duotones, or commercial color-matching schemes like PANTONE, PANTONE Coated, TOTYO or TRUMATCH. These can largely be ignored, at least for the present.