

# Color

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## 1 Digital Images

*Digital images* represent an image as a set of discrete numbers on a grid. When drawing, this grid is stored in a part of memory called the *frame buffer*. These numbers can represent only *greyscale* (also called *achromatic*), or the numbers can represent colors (*chromatic*).

The only characteristics of achromatic light is the amount of light. This is called *intensity* or *luminance* (in the physics sense) or *brightness* (in the perceived psychological sense).

We can think of real numbers in the range of 0 to 1 as representing all possible intensities of light from black to white (0 is black and 1 is brightest white). The greys are all the numbers between 0 and 1. However, because the intensities that can be stored depends on the number of bits in your frame buffer, sometimes the intensities are stored as integers (whole numbers) between 0 and some maximum dependent on the frame buffer. The minimum value of intensity (black) is always 0.

If your frame buffer has only 1 bit per pixel, the maximum value (brightest white) will be stored as  $2^1 - 1$ , or 1. Because the frame buffer only stores integers, the only choices are then 0 and 1. (There aren't other integers between 0 and 1.)

If there is more than 1 bit per pixel in the frame buffer, the number of intensities that can be stored is always  $2^n$  where  $n$  is the number of bits per pixel in your frame buffer. That is, if your frame buffer has 2 bits per pixel,  $2^2$  different intensities can be stored (0,1,2,3). If your frame buffer has 4 bits per pixel,  $2^4$  different intensities can be stored. The maximum intensity value is  $2^4 - 1$  or 15. This represents brightest white. The integers 1 to 14 are the different choices of greys.

If you have 8 bits per pixel in the frame buffer, each pixel can store 256 ( $2^8$ ) intensities. Then 0 is (black) and 255 (white). Now there are 254 grey values between 0 and 255, and 256 intensity values in total. This is about how many grey values the eye can distinguish, and is a sufficient number for smooth greyscale images. If there are fewer, you will see sharp transitions between grey scales that will appear as bands. This is referred to as *banding* (*contouring*).

## 2 Color

Color is complicated. It can be studied as a physical phenomena in terms of wavelengths of light, or it can be studied as a psychological phenomena in terms of how we see color. Also, there are many *color models*, which are ways to specify color.

### 2.1 Color Models

A quite natural way to specify color perception is as *hue* (the basic color, like red, blue, yellow), *saturation* (the vividness of the color), and *value* (the intensity of the color, or the brightness). *Hue* distinguishes the

basic colors of the rainbow (plus a few more). *Saturation* is how little the color is diluted with white. That is, vivid red is totally saturated, but pink is less saturated. You can get pink from red just by adding white. *Value* is a measure of the amount of light. As the light in a room becomes dimmer, colors become darker, and they have lower value. Often color selectors in graphics programs allow you to specify colors by this system, called the *HSV* model.

New colors can be created by mixing some standard colors, which are called *primaries*. In a CRT (cathode ray tube), the three primaries are red, green, and blue. Because the eye perceives new colors from mixtures of these (such as we see yellow by mixing red and green), combining these three primaries creates a wide variety of colors. For example, you will see yellow when red light and green light are mixed together, just as you would if you saw a pure yellow light. All the colors that can be created from the given primaries is called their *gamut*. Remember, a CRT creates colors by emitting light, and is an *additive* color scheme. However, not all the colors in nature can be represented from three primaries. This is called the red-green-blue or *RGB* model. Graphics programs generally allow you to specify color using this model.

Paint and printing create color by subtracting color from incoming light. If you shine a white light on a blue surface, all the colors but blue are absorbed by the surface, and only the blue is reflected. For this reason, the surface looks blue. This is a *subtractive* color scheme. Three primaries often used in printing are yellow, cyan, and magenta. This is referred to as the *CMY* model. Again, these three primaries can be mixed to make many colors but not all colors. Also, the colors you can make with these primaries are not all the same colors you can make with the RGB system. Because of this, it is hard to create exactly the same image by printing that you see on the screen.

Another color model often used with pigments is *tints*, *shades*, and *tones*. A tint is created by adding white to a pure pigment, so it acts similar to saturation. A shade is created by adding black to a pure pigment, so it is similar to value. Tone changes both. This model assumes these changes are made to some pure color, or hue.

Color TV's use a model called YIQ, which is a recoding of RGB for transmission efficiency. This was created in the 1950's to be compatible with black and white televisions. That is about the best that can be said about it. Hopefully, in the not too distant future, the digital televisions will become widespread, and television images will become as sharp and clear as those visible on graphics monitors.

## 2.2 The Physics of Color

If we consider color as a physical phenomena, it is electromagnetic radiation of a certain range of frequencies to which the eye responds. The shortest visible wavelength is about 400 nanometers and looks violet. The longest visible wavelength is about 700 nanometers and looks red. Wavelengths below 400 are called ultraviolet, x-rays, gamma radiation, etc. We can't see them. Wavelengths above 700 are called infrared and we can't see them either. A nanometer is  $10^{-9}$  meters, or 1/10 multiplied by itself nine times.

If you look at light of a single frequency it has a distinct hue, and is one of the colors of the rainbow. The rainbow splits white light, which is made of all visible frequencies, into its component frequencies. Usually, however, light you see is a mixture of various frequencies, called a *spectrum*. You can draw this as a graph. If there is mostly just one frequency in the light, that is called the dominant frequency, which is very much like hue. The amount of white light in the frequency indicates how saturated it is. The total amount of light is the intensity.

Remember that because of the way the eye and brain work, different spectra may look the same. For example, pure yellow light (a single frequency) may look just like a mixture of red light and green light. Different spectra that look alike are called *metamers*.

## 2.3 Color Vision

The eye sees color because it contains three kinds of light receptors called *cones* that are sensitive to different ranges of light. They are called red, green, and blue cones, though their sensitivities are actually quite spread out and overlap. When light hits the eye, it affects the cones to a greater or lesser degree, and the cones send nerve impulses to the brain depending on how much they are stimulated. The brain interprets these impulses as color.

When colors are put side by side, people can differentiate hundreds of thousands of them. However, people can distinguish only about 128 fully saturated hues.

## 2.4 Color in Digital Images

When color images are stored and shown, the same rules apply as described for grey-scale above, except that red, green, and blue are each independently given a certain number of bits to store a range of values. Color at a pixel is then generally given as a triplet of numbers (R,G,B). Modern graphics computers usually provide 8 bits each of red, green, and blue values. We will discuss in class what RGB values for different hues, saturations, and values are, and how to convert from a real number range of 0 to 1 to an integer range dependent on bits in the frame buffer.