Basics of Colors in Graphics
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1. Visible Spectrum 2
2. Additive *vs*. subtractive color systems, RGB *vs.* CMY. 3
3. RGB and CMY Color Cubes 4
4. CMYK (Cyan-Magenta-Yellow-Black 6
5. Converting RGB ↔ CMY ↔ CMYK 7
6. Conversion Examples 8

1. Visible Spectrum

Light is visible to the human eye in the approximate range 400-700 nm, which ranges from red to violet. Below red there is infrared, above violet there is ultraviolet, both of which are invisible to the naked eye. The color spectrum is considered to have seven major bands, Red, Orange, Yellow, Green, Blue, Indigo, and Violet, and there are a number of acronym reminders that have been created to remember them; for some reason the name Roy G. Biv appears to be the most popular, but my favorite is "Richard Of York Goes Battling In Vain."

Later in the semester, when we consider color specification systems and the CIE Diagram, we'll look at the visible spectrum in more detail. The goal of this lecture is to get you comfortable with basic color systems, and in particular with RGB.

Colors intensities are usually either given as floats from 0→1, or as integers in one of the ranges 0→256, 0→32767, or 0→65535. Conversions between these are linear and so trivial. In these notes I'll use floats from 0→1.

2. Additive *vs.* Subtractive Color Systems RGB and CMY

There are two basic categories of output devices for images; monitors and printers. Unfortunately this means that we have to deal with two sets of primary colors, which are called additive primaries and subtractive primaries.

RGB

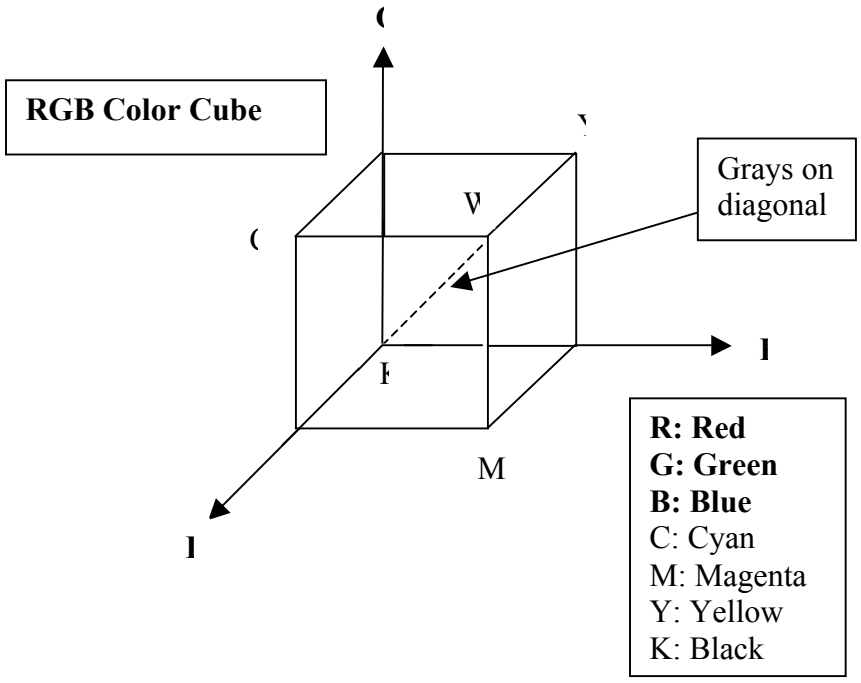
Additive primaries occur on computer monitors. Typically these will have small triangles consisting of red, green, and blue spots, which can be excited with a range of different intensities by an electron beam. The background is black. This system relies on the human visual system adding up the red, green, and blue colors to perceive the mixed color. So since the three colors are added together by the viewer to create the color, Red, Green, and Blue are the additive color primaries, and this additive color system is called RGB.

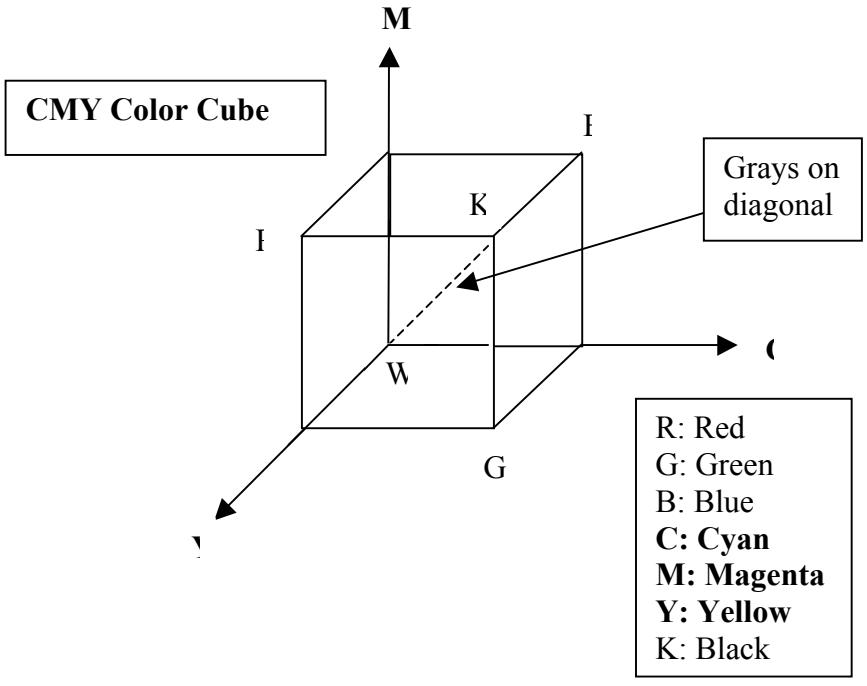
CMY

Subtractive primaries occur when we print an image. We start with a piece of white paper, and then add colored inks (or paints, etc.) which filter out light at specific frequencies. We can get the color we want by mixing different amounts of Cyan, Magenta, and Yellow inks. So our background is white, and the three colors which are mixed together to filter or subtract out light are called the subtractive color primaries, and this subtractive color system is called CMY.

3. RGB and CMY Color Cubes

We can see the relationships between RGB and CMY by looking at their color cubes:





First look at the RGB cube, where the axes show the intensities of red, green, and blue. Assume that the cube has sides with unit lengths, and that the intensity range of each color is 0→1. I.e., all color mixtures of red, green, and blue will lie inside the cube, and, for example, the vertex marked Y has RGB coordinates (1, 1, 0), which means that it is a mixture of full intensity red, full intensity green, and no blue.

A couple of things need emphasizing that we can find in the RGB cube:

- (0, 0, 0) represents black, and (1, 1, 1) represents white. I.e., if there is no color we get the background (black, which is represented by K since B has already been taken by blue), and full intensity of all three RGB colors gives white. Also, if R=G=B (all have equal intensity) then the color lies on the main diagonal from black to white (shown with a dotted line) and will be gray. E.g., (0.25, 0.25, 0.25) will be a dark gray and (0.5, 0.5, 0.5) will be a medium gray.
- All of the three subtractive primaries can be made by mixing two of the additive primaries at full intensity. C = (0, 1, 1), M = (1, 0, 1), and Y = (1, 1, 0), as is shown on the RGB cube.

The CMY color cube shows similar properties.

- (0, 0, 0) represents white, and (1, 1, 1) represents black. I.e., if there is no color we get the background (white), and full intensity of all three CMY colors gives black. Also, if C=M=Y (all have equal intensity) then the color lies on the main diagonal from white to black (shown with a dotted line) and will be gray. E.g., (0.25, 0.25, 0.25) will be a light gray and (0.5, 0.5, 0.5) will be a medium gray.
- All of the three additive primaries can be made by mixing two of the subtractive primaries at full intensity. R = (0, 1, 1), G = (1, 0, 1), and B = (1, 1, 0), as is shown on the CMY cube.

4. CMYK (Cyan-Magenta-Yellow-Black)

As the CMY cube shows, full intensities of Cyan, Magenta, and Yellow should generate black, but unfortunately most inks and paints produce a rather ugly dark brown color. Another factor is that black ink is usually cheaper than the colored inks. As a result most printers have black cartridges in addition to their three CMY cartridges, so that (a) it can be used when grays are wanted, and (b) it can be used as much as possible as part of all colors. By convention we use K for black since B is already in use for blue, and so the modified color system will be called CMYK.

Consider the CMY color (0,5, 0.2, 0.7). It can be considered as the sum of a gray component with CMY intensity (0.2, 0.2, 0.2) with 0.3 intensity cyan and 0.5 intensity yellow because

$$(0.5, 0.2, 0.7) = (0.2, 0.2, 0.2) + (0.3, 0.0, 0.5).$$

So instead of using the CMY colors at (0.5, 0.2, 0.7) we can use black at 0.2 intensity and CMY at (0.3, 0.0, 0.5). Note that we've saved on the amount of ink used (1.0 instead of 1.4 total) and have also used cheaper black ink instead of more expensive colored ink.

So the technique when using CMYK to print a CMY specified color is to subtract the smallest CMY value from all three and assign to black. In the example above, the CMY color (0.5, 0.2, 0.7) is printed as (0.3, 0.0, 0.5, 0.2) on a CMYK system. If, as another example, we have the medium gray CMY color (0.5, 0.5, 0.5) then in CMYK it will become (0.0, 0.0, 0.0, 0.5) which will also be optimal in terms of image quality.

5. Converting RGB↔CMY↔CMYK

Conversions between color systems occur all of the time in computer graphics systems, although they are usually concealed from the user by the hardware. E.g., if you have an image on your screen and you print it, then a conversion will happen from RGB to CMYK, *via* CMY. Or if you take a color separation picture, which will be CMY or CMYK, and display it on your screen, then you convert it to RGB. So given any of the three models we need to be able to convert to any of the others. The approach that will be taken is to do conversions of the form RGB↔CMY↔CMYK. E.g., to convert from CMYK to RGB we'll go through CMY.

RGB↔CMY

Based on either of the color cubes, cyan, (0, 1, 1) RGB, can be referred to as not red, and similarly for the other three. This is usually formalized in the two equivalent matrix equations:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}.$$

So conversions between RGB and CMY are trivial; you just subtract the value from (1, 1, 1) to get the new value. E.g., (0.2, 0.7, 0,3) in one system is (0.8, 0.3, 0.7) in the other system.

CMY↔CMYK

The description of CMYK, in the last section, informally covered the conversion to and from CMY. To convert from CMYK to CMY we just add in the K value to all three of the CMY values, and we are done. (If one of the values becomes > 1 then the CMYK wasn't a legal color. Most systems would just consider a value like that as a saturation, and set it to 1.) To covert from CMY to CMYK find the smallest of the three CMY values, subtract it from all three, and set K to that value. E.g.,

(0.8, 0.6, 0.7) CMY = (0.2, 0.0, 0.1, 0.6) CMYK
(0.3, 0.4, 0.0) CMY = (0.3, 0.4, 0.0, 0.0) CMYK

6. Conversion Examples

Convert (0.3, 0.2, 0.4) RGB to CMYK:

(0.3, 0.2, 0.4) RGB = (0.7, 0.8, 0.6) CMY = (0.1, 0.2, 0.0, 0.6) CMYK

Convert (0.3, 0.2, 0.4, 0.3) CMYK to RGB:

(0.3, 0.2, 0.4, 0.3) CMYK = (0.6, 0.5, 0.7) CMY = (0.4, 0.5, 0.3) RGB