

Experiment 10

Color

10.1 Objectives

- Observe the transmission properties of the three additive primary color filters and the three subtractive primary color filters.
- Observe and interpret the color sensations resulting from mixing additive primary colors and mixing subtractive primary colors.
- Be able to explain qualitatively the difference between additive and subtractive color mixing.

10.2 Introduction

Color is something we often take for granted (unless we are artists). Grass is green, the sky is blue (well, maybe not in the winter). But how are these colors formed? How can I mix two colors of paint and end up with a third color? I can hear two different sounds at the same time, but why does nothing look like two different colors at the same time?

Color is a complicated subject because it's a combination of physics (wavelengths, frequencies, atomic spectra, light, etc.), the physiology of color as perceived by humans, and history. It's somewhat muddled because through the history of painting and early attempts by Goethe and Newton to craft theories of color, some of their language has stuck.

10.3 Key Concepts

As always, you can find a summary online at Hyperphysics¹. Look for keywords: light and vision, color, color vision, additive color mixing.

10.4 Theory

How do we see color?

As you experienced in last week's lab, white light is composed of light from all wavelengths in the visible range (400–700 nm) but why do we “see” different wavelengths as different colors? A picture (made using a beam of electrons) of a human retina is shown in Fig. 10.1. There are two types of cells in the retina: rods (shown in green) and cones (shown in blue). The rod cells are sensitive to light and dark while our color vision is due to the cones. There are 3 types of cones and the relative response to the different cones is interpreted by your brain as light of a particular color. One kind of cone is most sensitive to red; another is most sensitive to green; and the third to blue. These three colors (red, green and blue) are called the **additive primaries**, as they are typically combined together (positively) to create other colors.

Each type of cone (or color receptor) is actually sensitive to a range of wavelengths and therefore colors. For example the “blue” cone responds to light with wavelengths between 400 to 550 nm, or colors ranging from violet to indigo to blue. Fig. 10.2 shows which wavelengths of light each type of cone is sensitive to and how sensitive they are. Notice that the human eye has less sensitivity to “blue” than “red”. This is one reason that stop signs are red and not blue. The exact color we see is dependent on how much each type of cone is stimulated with respect to the others. For example, when green and red cones are simultaneously stimulated, we can see orange or yellow, depending on how much more intense the red is with respect to the green. By mixing the three additive primary colors (R, G and B) with different intensities, we can generate all possible colors. For example, you can convince yourself that red and green make yellow by squinting at Fig. 10.3.

In order for us to see anything at all, the light has to enter our eyes. The light can come directly from the light source, or it can be reflected from an

¹<http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html>

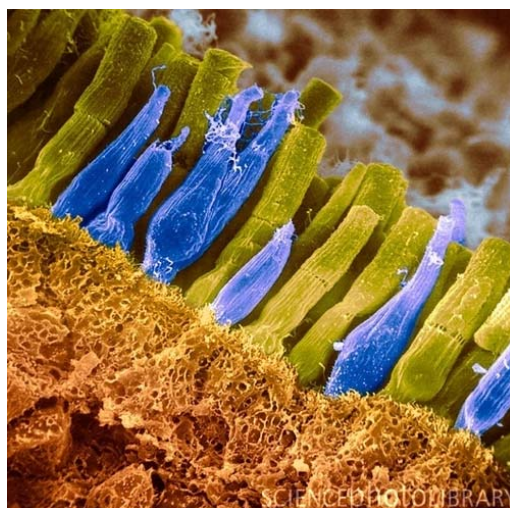


Figure 10.1: A picture of the human retina showing the rods (in green) and cones (in blue).

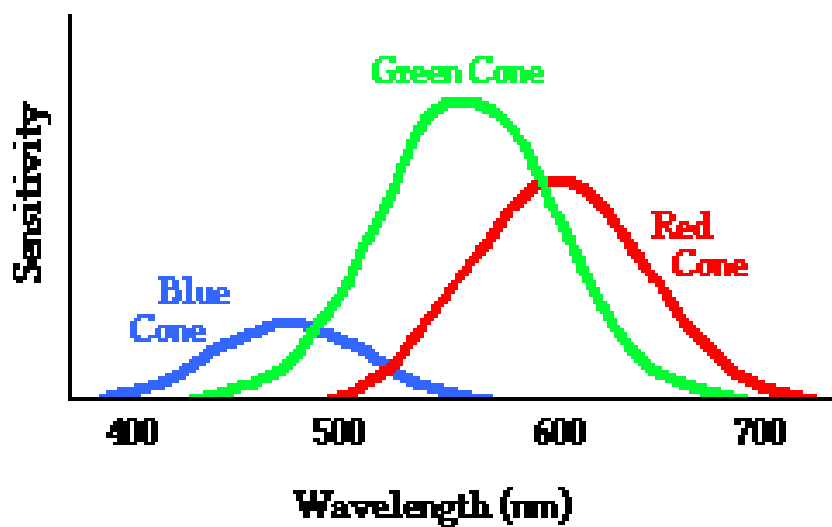


Figure 10.2: A plot showing the sensitivity of the 3 types of cones (red, green and blue) in a human eye.

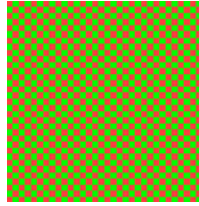


Figure 10.3: Squint at this and you'll see yellow, yet no actual yellow color is in the picture. This is Ferris Bueller's moment with M. Seurat...and how comic books work.

object. The red light at the top of a traffic signal is red because the light source is red. On the other hand, the red stop sign is red because it reflects red light, and absorbs all other colors. These examples represent two kinds of color mixing, additive and subtractive, respectively.

Additive color mixing

In the case of **additive** color mixing, we are adding colors from more than one light emitter. For example, mixing a red light and a green light with equal intensities will result in yellow light. Additive color mixing is used to form color images on the screen of older television and computer screens, called CRTs ("cathode ray tube"). The primaries used are red, green, and blue (from this point on, we'll call them R, G, and B). You start from black and add in the R, G and B colors to make the others. You cannot create black with the additive primaries, rather you can create white. Fig. 10.4 shows the additive color primaries at work. (You will mix these colors in the lab.)

The color wheel that you see on your computer, as in Fig. 10.5, shows the whole color spectrum. Notice that red, green, and blue are equidistant around the edges. You will play with additive colors by creating mixtures of them in a light projection box.

Subtractive color mixing

The earliest thinking about color came from trying to understand painting. Rather than the adding light colors like in our (older) TVs, they had to contend with how to make particular colors on a canvas. This is a **subtractive**

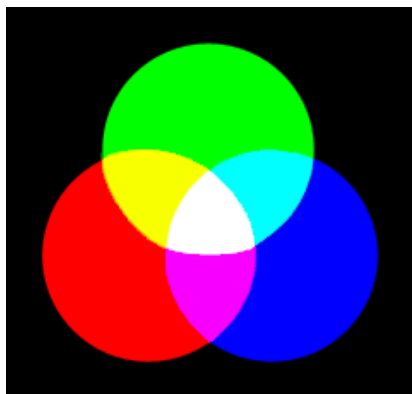


Figure 10.4: Colors adding together in a light projection box.

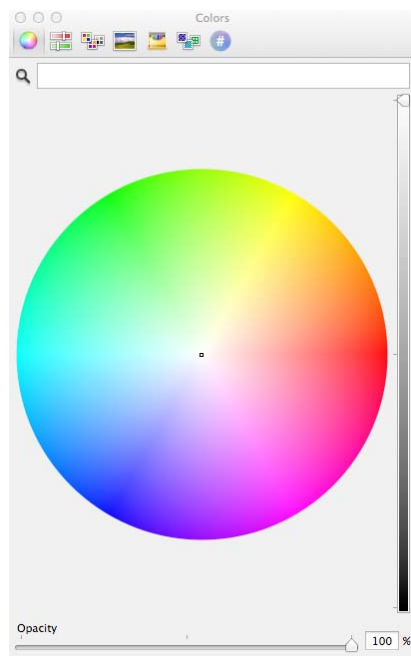


Figure 10.5: RGB color selection on a computer appropriate for viewing on a screen (additive).

process: light from a source, like the sun, falls on the surface of an object (or set of pigments) and is reflected. But not all wavelengths are reflected; just some reach our eyes which we interpret as the color of that object as in Fig. 10.4. The painter’s job is to mix the right pigments together in order to cause other humans to “see” the color he or she desired. Said more specifically, the painter chooses the pigments necessary in order to take out the wrong colors from light that reflect from the surface, leaving the desired color. So color is not an attribute of just the object: it’s a combination of the reflection or absorption of light (atomic physics) and our interpretation of that light through our highly-evolved eyeballs (physiology).

The **subtractive primaries** are a convention following a long history of painting and printing. They are now usually Cyan, Magenta, and Yellow (from this point on, we’ll call them C, M, and Y). Painters like them because

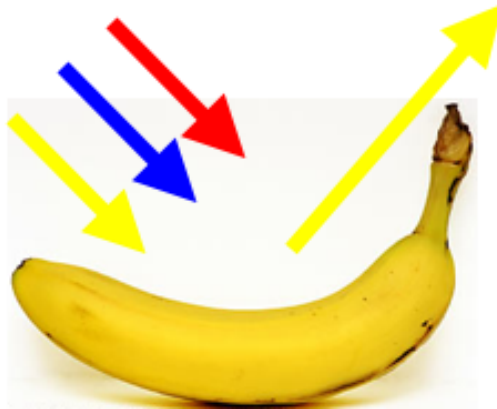


Figure 10.6: This is another way to make yellow: all colors fall on the surface of the banana and are absorbed except the yellow.

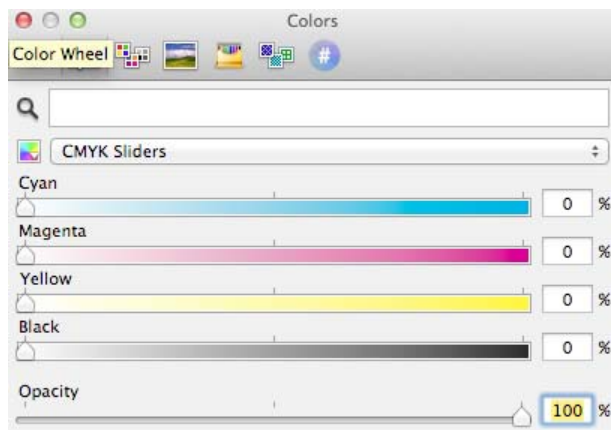


Figure 10.7: You've seen this on your computer as well. It's the color selection appropriate for printing (subtractive).

you can get the truest black using these three colors (which you'll do).²

Filters

A filter is a semi-transparent film which passes some wavelengths and not others. Let's deal with the Additive Primaries (R, B, G) and the Subtractive Primaries (C, Y, M) only. Remember: **White light is a mixture of all of the colors**, a controversial fact first worked out by Isaac Newton. So if you pass white light through a filter that removes all wavelengths but R then you'd call that a Red Filter. Likewise, for B and G. Filters are not perfect: a red filter doesn't pass only a single wavelength, but rather a band of wavelengths which are reddish. You'll measure these bands in this lab.

Let's picture the effects of filters on the Additive and Subtractive Primaries in Figs. 10.8–10.9. In each picture, white light is incident from the left, passes through a filter, and only particular wavelengths of light emerge on the right. The little spectrum window (on the far right) shows the effects on the spectrum of visible light.

Fig. 10.8 shows what happens when white light is passed through filters that are the additive primary colors (R, G, B). Notice that if you pass white light through a red filter only “red” (or the reddish wavelengths of) light is transmitted. In addition it might not be too surprising that if you pass red light through a red filter, all you get is red light out. But what happens if you pass red light through a blue filter? The blue filter only transmits light with wavelengths around 400-500 nm, but “red” light has wavelengths around 600-700 nm. Does any of the red light make it through a blue filter?

The Subtractive Primary colors (C, M, Y) can also be fashioned into filters, but here something different happens because both the physics and our perception is different. Fig. 10.9 shows the results when white light enters from the left and passes through:

... a cyan filter — to produce cyan colored light. It does that by removing the longest wavelengths (reddish) leaving the rest, which is represented in the top picture as green and blue arrows. (Look at the color wheel: the cyan filter removes its complementary color on the opposite side of the wheel, i.e. red.)

²Sometimes you see printers using CMYK, where K stands for “key”, which is not black, per se, but a printer-specific designation for the black “key” plate that prints the detail and is, in fact, black.

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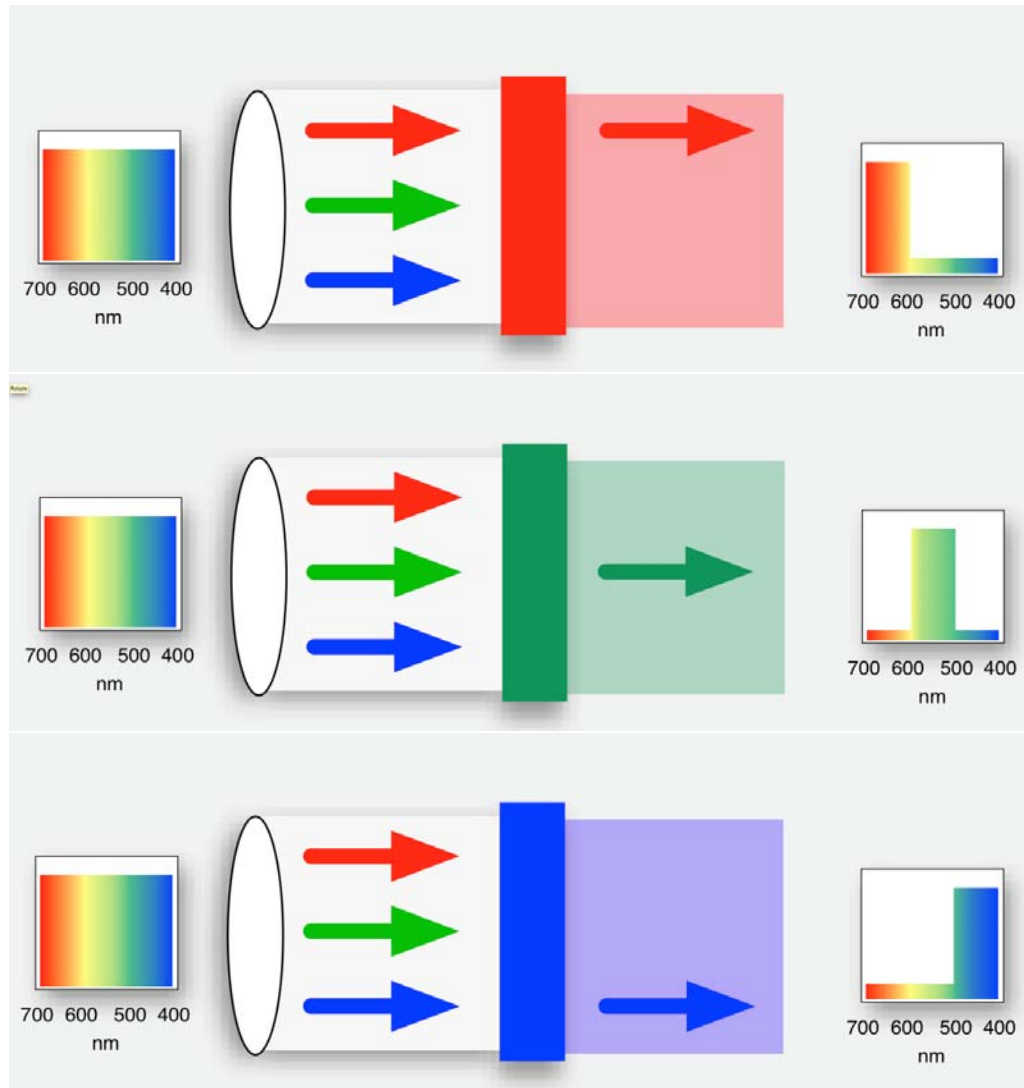


Figure 10.8: White light is incident on red (top), green (middle), or blue (bottom) filters.

... a magenta filter — to produce magenta light. It does this by removing the middle wavelengths (greenish) leaving the rest which is represented in the middle picture as red and blue arrows. It too removes its complementary color on the opposite side of the wheel.

... a yellow filter — to produce yellow light. It does this by removing the shortest wavelengths (bluish) leaving the rest which is represented in the bottom picture as red and green arrows. Likewise, it removes its complementary color from the opposite site of the wheel.

A table that will be very useful for answering the questions at the end of this lab is shown in Table 10.1. Remember that white light is made by combining red, green and blue light (the addition of the primary colors). In the table, each row is a subtractive primary color (C, M, Y) and the columns are the additive primary colors (R, G, B). The table can be used to understand both subtractive and additive color mixing. A few examples are given here:

- The table shows that each subtractive primary (C, M, Y) absorbs one additive primary color (R, G or B), as indicated by the color that is shaded. For example, cyan absorbs red but transmits (or reflects) green and blue.
- You can get one additive primary color by combining two subtractive primary colors. For example, a mixture of magenta and yellow would absorb both green and blue, allowing only red to be seen.
- You can add two additive primary colors together to get one of the subtractive primary colors. For example, if you want to make the color cyan you can add green and blue together. This effect is how you see yellow in Fig. 10.3, notice that the bottom row in the table tells you that red plus green will make yellow.

Notice that the subtractive primary colors can be thought of as adding two additive primary colors together or subtracting one additive primary from white light. For example, magenta can be made by adding red and blue together (additive color mixing) or by absorbing red from white light (subtractive color mixing).

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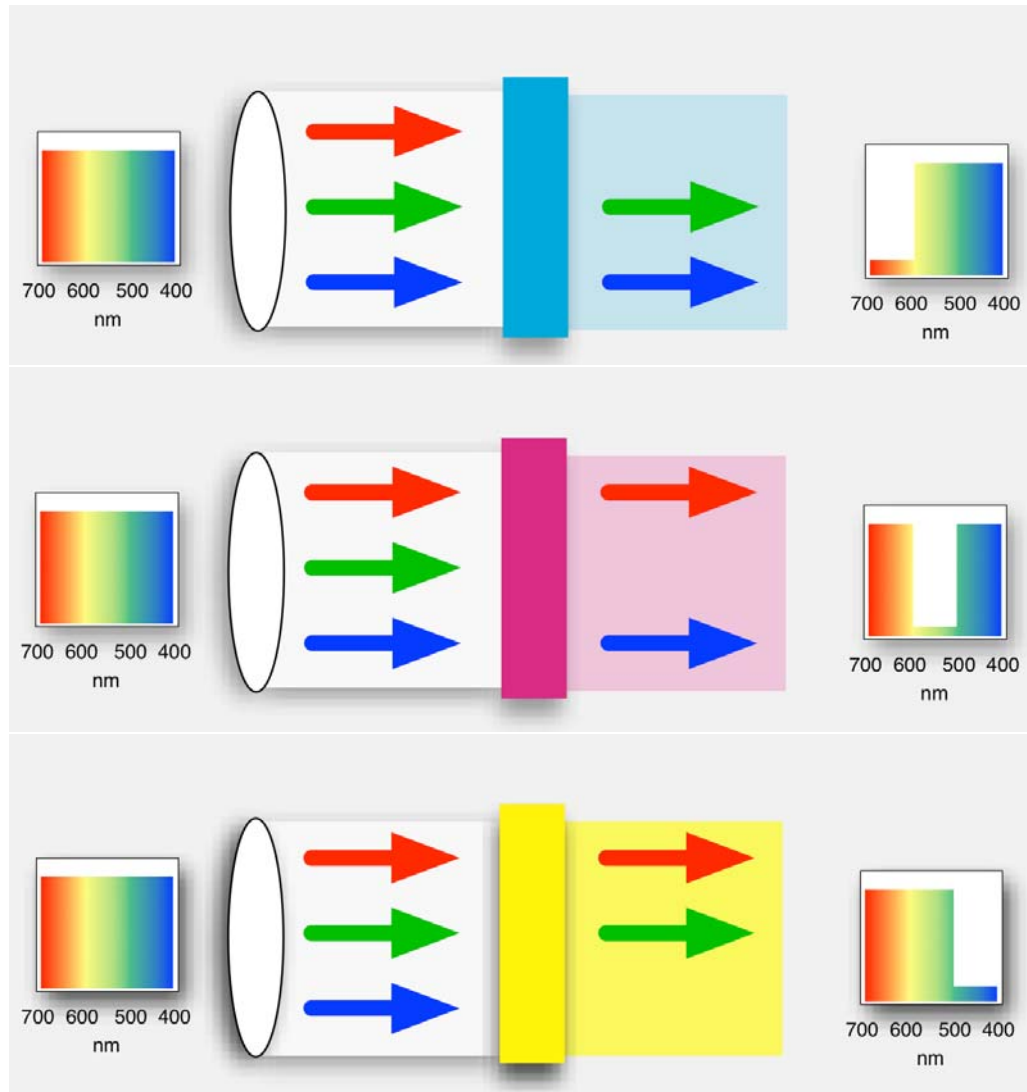


Figure 10.9: White light is incident on cyan (top), magenta (middle), or yellow (bottom) filters.

| white light (contains all wavelengths) | red long λ | green medium λ | blue short λ |
|-------------------------------------------|-----------------------|---------------------------|-------------------------|
| <i>subtractive primary:</i> | | | |
| cyan (absorbs red) | red | green | blue |
| magenta (absorbs green) | red | green | blue |
| yellow (absorbs blue) | red | green | blue |

Table 10.1: For a given subtractive primary color that subtracts from white light, this table shows which colors are absorbed and which are reflected/transmitted. Colors with a gray background and in bold are absorbed.

Van Gogh was the master of complementary colors, especially yellows with blues. One of the things about complementaries is that we see stark contrasts between them and we perceive a sense of stability. No physics here, it's physiology and psychology — artistic genius.



The Café Terrace on the Place du Forum, Arles, at Night
by Vincent van Gogh (1888)

10.5 In today's lab

In this experiment, we will use subtractive color mixing by filters rather than by pigments, since filters are more easily manipulated in the laboratory. You will measure the bands of light that the filters allow through (transmit).

10.6 Equipment

- Digital spectrometer from the previous lab, but with an absorptometer with integrated sampling system that creates light internally and passes it through insertable filters for digitization (Ocean Optics USB650 Red Tide, see Fig. 10.10)
- Computer with *Logger Pro* installed
- One empty cuvette³ for calibration (the clear tube in Fig. 10.10(a))
- Set of 3 additive primary (R,G,B) filters each in their own cuvettes, 3 subtractive primary (C,M,Y) color filters in theirs, an empty cuvette for calibration and one cuvette with two filters in the same tube (there should be a total of 8 cuvettes at your bench). **Do not open the cuvettes!**
- Light projection box at the front of the room
- LED desk lamp

³A “cuvette” is a glass or plastic holder designed to hold objects destined for spectroscopic analysis. It’s pronounced “coo-vette” as in “corvette.”



(a) Cuvette (clear box) sitting on top

(b) Cuvette inserted.

Figure 10.10: Digital spectrometer with integrated sampling system, shown with cuvette both uninserted and inserted.

10.7 Procedure

Setup

1. Start the data-collection program *Logger Pro* and choose **New** from the **File** menu.
2. Make sure the power supply for the fan is plugged into the part of the digital spectrometer that is labeled “USB-ISS-UV-VIS”.
3. Connect the spectrometer to the USB port of the computer. Wait a few seconds for the light and fan to come on inside the spectrometer (you will hear a click as the shutter opens and then the fan should come on). If you find that nothing appears on the computer screen when you try to collect data then unplug and plug back in the USB cable to the spectrometer with *Logger Pro* already running.
4. Calibrate the spectrometer:
 - a) Place the empty cuvette in the square hole in the top of the spectrometer (see Fig. 10.10); make sure to align the cuvette so that the frosted sides are parallel with the long edge of the whole device (this ensures that the clear sides are facing the light source of the spectrometer).

- b) In *Logger Pro*, from the drop-down menus, choose **Experiment**
▶ **Calibrate** ▶ **Spectrometer: 1**.
- c) When the warmup period is complete, select **Finish Calibration**.
- d) Select **OK**.

Absorption spectra of filters

For each of the additive primary color filters (R, G, B):

1. Insert the cuvette with the desired filter into the sample holder, press the “Collect” button in *Logger Pro*, and observe the spectrum that results. If the spectrum is not visible or is cut off at the top of the graph, right click on the y -axis label **Absorbance**, select **Autoscale**
▶ **Autoscale**.

Note that the plot is an **absorption spectrum**. The larger the absorption value the more that wavelength is absorbed by the filter and NOT detected by the spectrometer. A value close to zero means that the wavelength was nearly totally transmitted. Notice that this is the opposite of what you did in the last lab where you were looking at emission spectra. In this experiment a peak means that that wavelength is missing (it was absorbed) and a zero value means it can be seen (it was transmitted). Keep this in mind when you fill in the table in Question 1.

2. Write down your observations for each filter in the table under Question 1. Describe which colors are **transmitted** and record the wavelength ranges of the resulting absorption spectra. Note that you may see a continuous band of colors (the “main” band), then a gap, and a narrower range of colors.
3. Print out the curves from the R, G and B filters all on 1 graph. You can do this by hitting “collect” when starting the next filter and choosing the option to keep the previous result in the dialog box.
4. Label each curve by going to **Insert** ▶ **Text Annotation**. A text box will appear and you can grab the end of the line with the mouse and point it at the curve that you’ve referenced.

5. Answer Questions 2–3.
6. Repeat steps 1 – 4 from above for each of the subtractive primary color filters (C, M, Y) and print their curves on 1 graph.

For this part of the lab you will turn in 2 graphs taken with the spectrometer: one for the additive primaries (R, G, and B) and one for the subtractive primaries (C, M, and Y). Make sure to label all of the curves.

Additive color mixing

In this part of the experiment you will use the light projection box to observe additive color mixing. The projection box is the large black box located in the front of the room. It contains three different independent light sources. The knobs on the sides let you adjust the intensity of each of the lights independently. For example, by adjusting the knobs so that the blue light is off and the red and green lights are of equal intensity, you can see what color is produced where they overlap. You can make accurate predictions of what colors to expect using Table 10.1. When answering the questions for this section: **make your predictions first**, then observe the result using the projection box. Record both in the table given in Question 4 and then answer Question 5.

Subtractive color mixing

In this section you will experience subtractive color mixing and understand how it differs from additive color mixing. Here you will use the LED desk lamp (which is approximately white light) on each table and different colored filters (which can be found at the front of the room in manilla envelopes). First, write down the expected (theoretical) color for each filter combination in Question 6. (There is only one correct answer for each theoretical color, which can be determined by using Table 10.1 plus Figure 10.8 and Figure 10.9.) After writing down the expected color, then observe what is the resultant color by stacking several filters together and letting light from the desk lamp pass through them. You will need a few pieces of each color as some of the filters are not very efficient (as you saw earlier in the lab). For example, when completing the first line of the table try stacking

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two red and two blue filters together. Answer Questions 7–12. For Question 10 you will use the cuvette with 2 filters in it and print out the graph from the spectrometer.

10.8 Questions

1. Record your observations below:

| filter | colors transmitted (note gaps) | range transmitted (main band) | | |
|---------|--------------------------------|-------------------------------|-----------------|-----|
| | | min | wavelength (nm) | max |
| red | | | | |
| green | | | | |
| blue | | | | |
| cyan | | | | |
| magenta | | | | |
| yellow | | | | |

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2. If you had an ideal “red” filter, what colors would be absorbed?

3. How well do the R, G and B filters match the colors you expected?
Would you say that the filters are “ideal”?

Additive color mixing

4. Record your predictions and observations in the following table.

| light mixture | predicted color | observed color |
|----------------------|------------------------|-----------------------|
| red + green | | |
| red + blue | | |
| green + blue | | |
| red + green + blue | | |

5. How well did your predictions agree with your results? Explain any differences.

Subtractive color mixing

6. First record the expected theoretical color (using Table 10.1 plus Figures 10.8 and 10.9) and then your observations in the following table.

| filter mixture | theoretical color | observed color |
|-------------------------|--------------------------|-----------------------|
| red + blue | | |
| blue + yellow | | |
| cyan + magenta | | |
| cyan + yellow | | |
| magenta + yellow | | |
| cyan + magenta + yellow | | |

7. Why does “red + blue” give different results in this part of the experiment compared to the part with the projector box? Explain what caused the results for red + blue to be different in each case (that is, explain how each case, additive vs. subtractive, works).

8. Explain the results for cyan + yellow.

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9. For blue + yellow, did the color you observe match your prediction? If it didn't, then why not? What wavelengths of light must the filters let through?

10. Check this with the spectrometer by using the cuvette that has two filters (a blue and a yellow) in it. Did you accurately estimate which wavelengths the filters would let through? If not, which wavelengths did the filters let through? Print out the graph from the spectrometer.

11. Give a practical example from everyday life of additive and subtractive color mixing. (You must give a different example than the stop sign and stop light from the write-up.)

12. Why is it harder to think of examples of additive color mixing?