PHY 252 Introductory Physics Laboratory II

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Experiments

Experiment 1

Color

1.1 Objectives

- Use the digital spectrometer to disperse white light into a continuous spectrum of color and determine the range of wavelengths in the visible spectrum.
- 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.

1.2 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 the language stuck with use.

1.3 Key Concepts

As always, you can find a summary on-line at Hyperphysics[1] . Look for keywords: light and vision, color, color vision, additive color mixing

1.4 Theory

How do we see color?

White light is composed of light of all wavelengths in the visible range (400–700 nm). Our color vision comes from the fact that we have three different kinds of color receptors ("cones") in our retina. One kind of cone is most sensitive to red; another is most sensitive to green; and the third to blue (though there is overlap — see Fig. 1.1). These three colors are called the **primary colors**, as they are typically combined to create other colors. If our cones were sensitive to a different set of colors, those colors would have been our primary colors. All receptors are sensitive to a range of colors, e.g. "blue" to violet, indigo, and blue. What color we see is dependent on how much the cones are stimulated with respect to each other. 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 three primary colors with different intensities, we can generate all possible colors.

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 object. The red light at 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, and absorbs everything else. These represent two kinds of color mixing, additive and subtractive, respectively.

[1] `http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html`

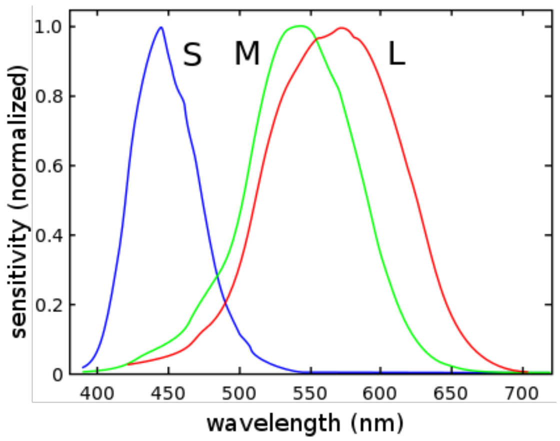


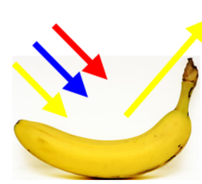
Figure 1.1: Sensitivity vs. wavelength for each of the human eye's three cones[3], labeled S, M, L, and colored according to the primary color they are most sensitive to. (Image credit: Vanessaezekowitz on en.wikipedia)

Additive color mixing

When color combinations are additive – like in an older CRT ("cathode ray tube") display, 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. 1.2 shows the additive color primaries at work. (You'll do this.)

The color wheel that you see on your computer, as in Fig. 1.3, 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 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** 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 wave-

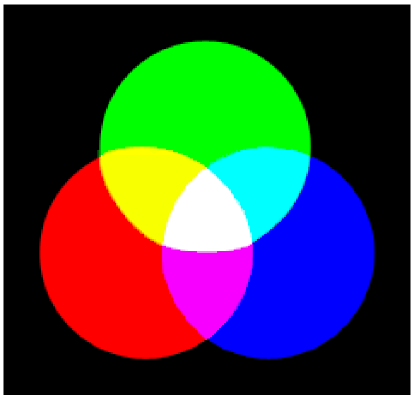
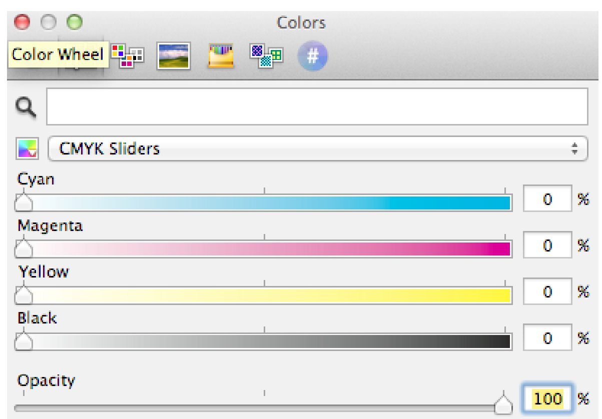


Figure 1.2: Colors adding together in a light box.

Figure 1.3: RGB color selection on a computer.

lengths are reflected; just some reach our eyes which we interpret as the color of that object. 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 reflects from the surface leaving the desired color.



So color is not an attribute of just the object: it's a combination of the reflection of light (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, or CMY. Painters like them because you can get 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 I 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 those bands in this lab.

Let's picture the effects of filters on the Additive and Subtractive Primaries in Figs. 1.4–1.5. In each, white light is incident from the left passes through a filter, and only particular wavelengths emerge on the right. A little spectrum window shows the effects.

Maybe not too surprising, if you pass red light through a red filter, all you get is red. What happens if you pass red light through a blue filter?

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

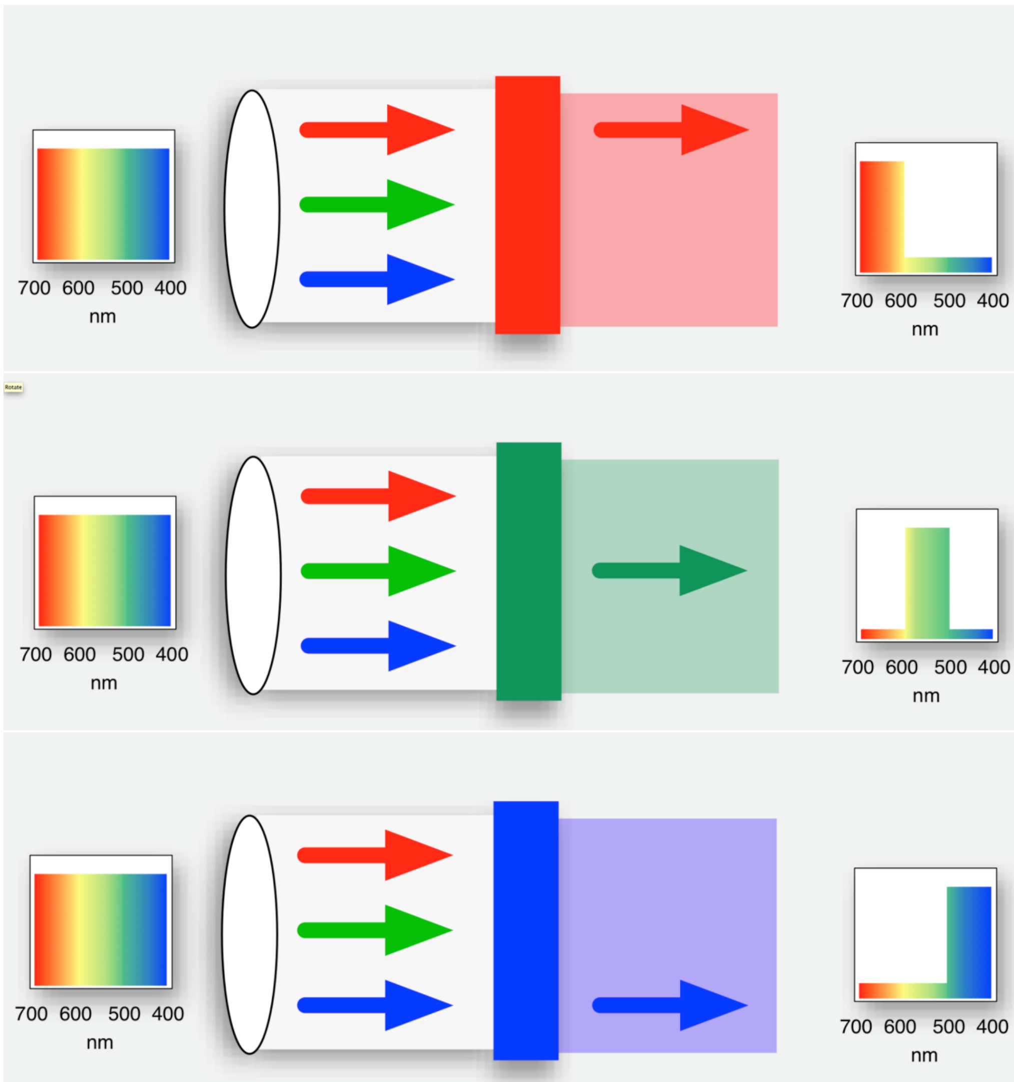


Figure 1.4: White light is incident on red (top), green (middle), or blue (bottom) filters.

The Subtractive Primaries can also be fashioned into filters, but here something different happens – both the physics and the perception is different. Fig. 1.5 shows those results. The 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 as green and blue. (Look at the color wheel: the cyan filter removes its complementary color on the opposite side of the wheel – red.)

. . . 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 as red and blue. 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 as red and green. Likewise, it removes its complementary color from the opposite site of the wheel.

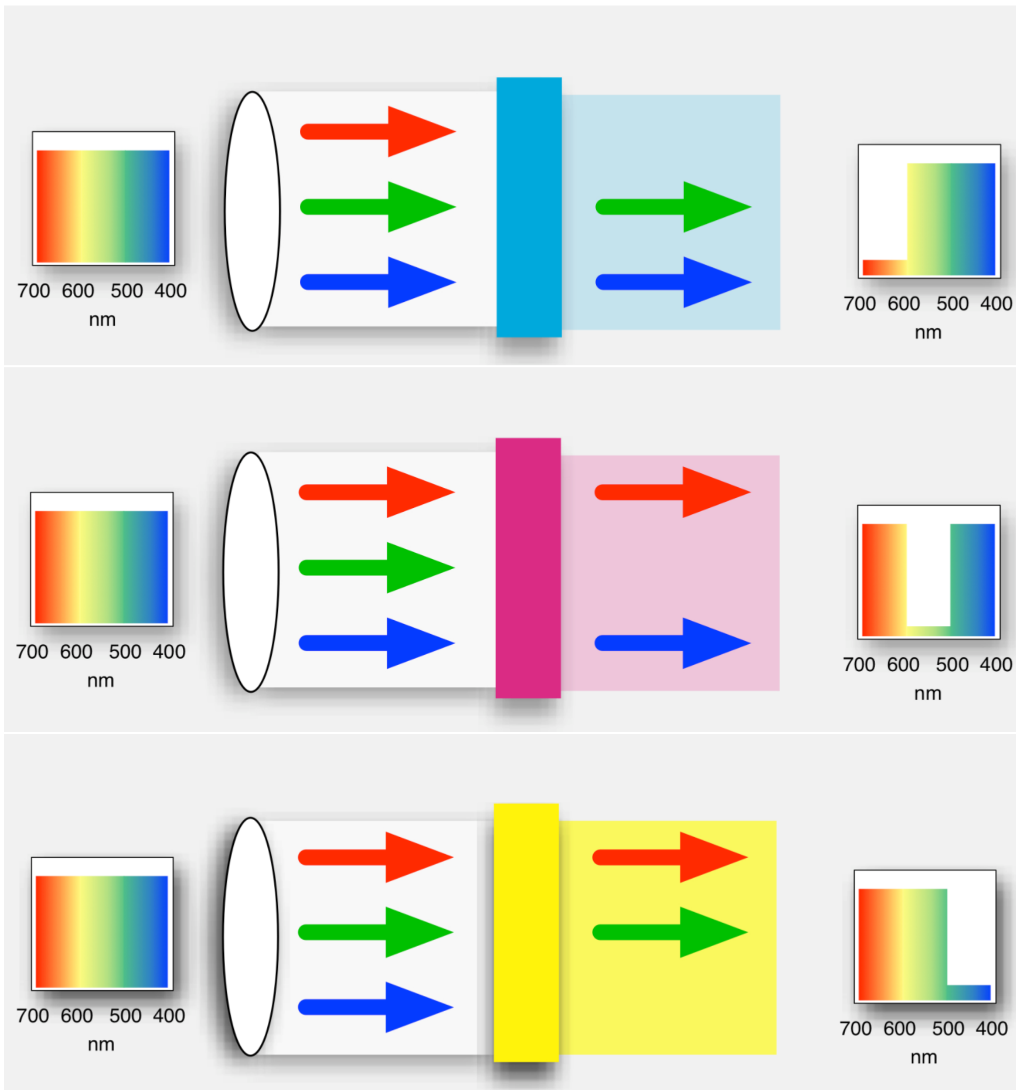


Figure 1.5: White light is incident on cyan (top), magenta (middle), or yellow (bottom) filters.

Table 1.1 demonstrates subtractive color mixing. White light is incident. Therefore, it contains red, green and blue light, the addition of primary colors. Each row shows a primary subtractive color. The table shows that each subtractive primary absorbs one additive primary color, as indicated by the shading. A mixture of magenta and yellow would absorb both green and blue, allowing only red to be seen.

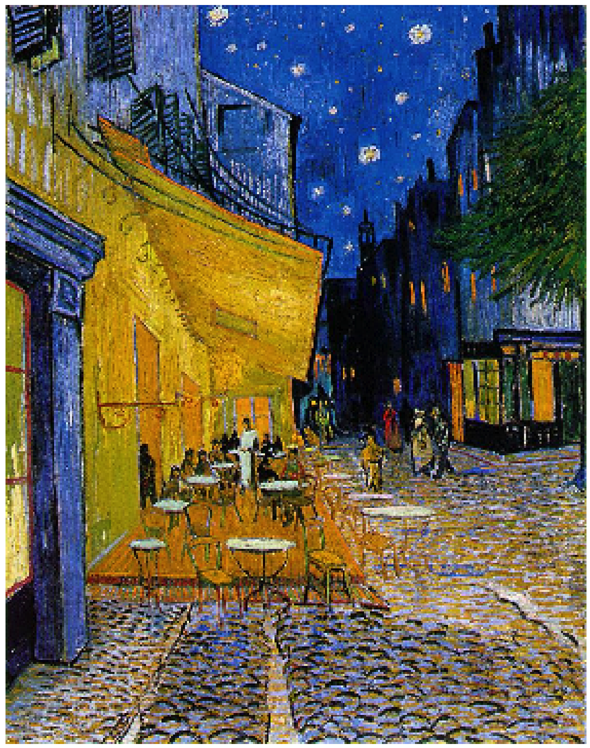
The same chart can be used to predict the result of additive color mixing. Blue and green is the same as white light with red absorbed. Looking for the shading on red leads you to the cyan row, so blue + green = cyan.

The subtractive primary colors can be thought of as adding two additive primary colors or subtracting one additive primary from white light.

white light (**contains all wavelengths**)	**red** long λ	**green** medium λ	**blue** short λ
subtractive primary:			
cyan (absorbs red)	red	green	blue
magenta (absorbs green)	red	green	blue
yellow (absorbs blue)	red	green	blue

Table 1.1: For a given subtractive primary color that subtracts from white light, this table shows which colors are absorbed and which are reflected/transmitted. Colors in a gray background 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)

1.5 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.

1.6 Equipment

- digital spectrometer with integrated sampling system (Ocean Optics USB650 Red Tide, Fig. 1.6)
- computer with Logger *Pro* installed
- one cuvette (sample holder, clear box) (clear tube in Fig. 1.6(a))
- set of additive-primary (RGB) and subtractive-primary (CMY) color filters
- projector box
- light box

(a) Cuvette (clear box) sitting on top

(b) Cuvette inserted.

Figure 1.6: Digital spectrometer with integrated sampling system, shown with cuvette both uninserted and inserted.

1.7 Procedure

Setup

1. Connect the SpectroVis Plus spectrometer to the USB port of the computer. Start the data-collection program Logger *Pro*, and then choose `New` from the `File` menu.

2. Calibrate the spectrometer.

   a) In Logger *Pro*, from the drop-down menus, choose `Experiment` ▶ `Sensors` ▶ `Calibrate`.

   b) Place an empty cuvette in the spectrometer; make sure to align the cuvette so that the clear sides are facing the light source of the spectrometer (the frosted sides should be parallel with the long edge of the whole device). When the warmup period is complete, select `Finish Calibration`. Select `OK`.

Absorption spectra of filters

For each of the additive-primary color filters,

1. Place the filter in the cuvette, insert the cuvette into the sample holder, press the "Collect" button in Logger *Pro*, and observe the spectrum that results.

> Note that the plot is the **absorption spectrum**. A value close to one means that the wavelength in question was absorbed by the filter and not detected by the spectrometer. A value close to zero means that the wavelength was nearly totally transmitted.

2. Describe the colors transmitted. Record the wavelength ranges of the resulting absorption spectra. You may see a continuous band of colors (the "main" band), then a gap, and a narrower range of colors. Record these in Question 1 and answer Questions 2–3.

3. Place each of the three subtractive-primary color filters (cyan, magenta, and yellow) in the cuvette. Observe the resulting spectra in

Logger *Pro*. Plot qualitatively the intensities of the transmitted colors in the graphs below. Label horizontal axis with the colors you see. Assign the intensities qualitatively (e.g., 5 = no change with or without the filter, 0 = color gone completely with filter). Fill in the plot like a histogram.

Additive color mixing

In this part of the experiment you will use the "projector box" to observe additive color mixing. The projector box is the large black box located at the side or in the back 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, we can see what color we produce where they overlap. You can make accurate predictions for these colors using Table 1.1. Make your predictions first, then observe using the projector box, recording both in Question 4 and answering Question 5.

Subtractive color mixing

Now we will see how color by subtraction works differently. Here we will use the white light boxes located in the middle of the lab bench. By stacking several color filters on top of each other, we can see what the resultant color is. This light is **very** bright so you may want to cover up the rest of the light box (where the filters don't cover) with a book or piece of paper to see the results clearly. Some of the filters are not very efficient (as we saw earlier) so you may want to use more than one of the same color (i.e. in the first one, stack two reds and two blues together). Make your predictions first, then observe using the projector box, recording both in Question 6 and answering Questions 7–9.

1.8 Questions

1. Record your observations below:

filter	**colors transmitted (note gaps)**	**range transmitted (main band)** wavelength (nm)	
red			
green			
blue			

2. For an ideal "red" filter, what colors would be absorbed?

3. How well do the filters match the colors you would expect to see in red, green and blue light?

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. Record your predictions and observations in the following table.

filter mixture	**predicted color**	**observed color**
red + blue		
red + green		
cyan + magenta		
cyan + yellow		
magenta + yellow		
cyan + magenta + yellow		

7. Why does the red+green and red+blue give different results in this part of the experiment than in the part with the projector box? Explain what caused the results for RED + GREEN to be different in each case (that is, explain how each case worked).

8. Explain the results for cyan + yellow.

9. Explain any differences between predicted and observed colors.

10. Describe the qualitative difference between additive and subtractive color mixing with a practical example from everyday life of each.

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

12. According to theory, blue filters absorb which color(s)?

13. And yellow absorbs?

14. So a blue filter combined with a yellow filter should give?

15. Look at this situation (blue + yellow filters) with the ceiling light. What color do you see?

16. Does the color you observe match your prediction? If it doesn't, then why? What wavelengths must the filters let through?

17. Check this with the spectrometer. What did you find?

Bibliography

[1] P.J. Mohr, B.N. Taylor, and D.B. Newell. The 2010 codata recommended values of the fundamental physical constants. (Web Version 6.0). This database was developed by J. Baker, M. Douma, and S. Kotochigova. Available: `http://physics.nist.gov/constants` [2012-07-03] National Institute of Standards and Technology, Gaithersburg, MD 20899., 2011.

[2] Rainbow Symphony, Inc. Diffraction Gratings Slides — Linear 500 line/mm. Available `http://www.rainbowsymphonystore.com/difgratslidl1.html`, 2012.

[3] Andrew Stockman, Donald I. A. MacLeod, and Nancy E. Johnson. Spectral sensitivities of the human cones. *J. Opt. Soc. Am. A*, 10(12):2491–2521, Dec 1993.