

Chapter 1: Seeing the Light

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All handouts are to be considered as drafts for a future publication.

COURSE OUTLINE

We selected as the theme of this semester the subject of *light* both because it is a fascinating phenomenon in its own right and because studies of the characteristics and behavior of light lead naturally to investigations of other important physical phenomena, including particles, waves, energy, electricity, and magnetism. People have always been intrigued by light, and “sun worshipers,” in one form or another, are common even today.

Humans are aware of the importance of light primarily because our sense of sight plays such an important role in our interaction with the world around us. Before we move into some of the more basic (but sometimes more abstract) aspects of light, therefore, we will spend a little time gaining some insights into the processes through which we see. As we go on to study other phenomena, we will return from time to time to see how our accumulating knowledge can help further our understanding of how our senses operate to keep us in contact with the rest of the world.

The most fundamental question about light is also probably the most difficult one: What is it? There are two quite different answers that have been developed and investigated over the centuries; one describes light as a *wave*, the other suggests that it is a stream of tiny *particles*. Since neither waves of light nor its particles can be seen directly, the only way to decide about these two models of the nature of light is by studying its actual behavior. We will therefore devote time early in the course to investigating the behavior of light in some detail. A substantial portion of the course will also be devoted to gaining a better understanding of the behavior of more readily observed kinds of waves, some of the characteristics of simple particles, and comparisons of these with the results of experiments we do with light itself. In trying to understand how some of the phenomena that we find characteristic of light might fit with a particle description, we will see whether the bouncing of steel balls follows the same pattern as the reflection of light from a mirror. To better understand why the idea of light as a wave was developed, we will study the behavior of waves that we can see and measure directly: waves in shallow pools of water, waves on springs and on ropes. These investigations will provide us with additional tools in our search for an understanding of the connections between wave phenomena and the behavior of light.

We note that both waves and particles have the ability to carry *energy* from one place to another. Ocean waves can do tremendous damage to structures along the shore; hailstones can make sizable dents in strong metal roofs. Light, likewise, carries energy; the production of electricity using solar cells and the winds created by the movement of heated masses of air are two examples of such energy, transmitted to earth in the form of light from the sun, 93 million miles away. We therefore will spend some time investigating some of the many forms of energy,

how one form can be changed to another, and how energy can be carried from one place to another.

As we become more familiar with light, we will learn about some related phenomena: infrared and ultraviolet radiation, radio and TV transmissions, x-rays, and microwaves. This study will lead us to some experiments with electricity and magnetism, and to an appreciation of how these phenomena further add to our understanding of light.

Finally, we will return to the wave/particle question, making some measurements which will allow us to contemplate the depth and richness of the understanding we have achieved.

EXPERIMENTS. As noted in our introductory handout, the experiments are designed to be done in “research teams” of four or five students each. Be sure to designate a *research coordinator*, a *data and discussion recorder*, and a *report coordinator* for the activities of this chapter. These roles will be rotated among the members of your team as each new chapter is started, so that everyone gains the experience and shares the responsibilities for all aspects of the team’s research as the semester unfolds.

EXPERIMENT 1.1. Can you trust your eyes?

A great many “optical illusions” have been developed over the years. Some of them may be familiar to you, while others may be new and unexpected. We have collected a few of them in a separate handout. As your team considers each one, you should record your honest impression of the drawing as appears to you, as well as your guess as to the true facts in the situation depicted. Then describe and carry out some ways to measure or otherwise determine, as accurately as possible, the properties being questioned in the drawing. Finally, indicate the team’s guesses or hypotheses as to what may be the reasons for any observed discrepancies between appearances and measured result

Figure 1. Which horizontal line is longer, and by how much? After you have made a guess, use a metric ruler to measure both lines. Are you surprised at the result? What makes them appear to be so different? Propose different hypotheses and try to test them. How different in length would you have to make the lines so that they appear to be equal? Is the effect the same if the drawing is held vertically?

Figure 2. Another “length” illusion is shown in Fig. 2. Is the hat taller than the width of its brim? (Consider the height to be the distance from the top of the hat to the center of the slightly curved bottom line.) Measure the lines to see what the facts actually are. Make hypotheses and test them if possible.

Now take a look at the picture of the Gateway Arch in St. Louis. Any thoughts?

Figure 3. Study figure 3 in the handout. Start by focusing on the thin diagonal lines. Do they appear to be parallel? How can you find out? Are there different ways of viewing the figure that make the true facts easier to see? Can you think of reasons why this illusion is so compelling? Does knowing the actual situation make any significant difference in how you view the drawing?

Figure 4. This figure shows a simple set of black squares. Are there white lines between the squares? What is going on where these "lines" cross? What happens when you look directly at any of the crossings?

Figure 5. *This figure will be investigated in Experiment 1.4.*

Figure 6. Shown here are four different-colored squares with smaller grayish squares at their centers. Which of the grayish squares is the lightest? Which is the darkest? Are they all pure gray, or do some have color tinges? After carefully noting how each member of the group sees these gray squares, see if you can find a way to eliminate the effect of the surrounding colors and compare the grays directly with one another.

Analysis: Do the measurements and careful observations agree with what you first saw when you looked at each of the figures? Is there any reason to believe that the measurements give a truer answer than your first impressions? Were you able to figure out what was going on that confused your eye or your brain? Not all of these illusions have easy explanations, but each of them tells you something useful about the vision process.

EXPERIMENT 1.2 Where do the colors come from?

What you will need

light box and power supply
slits ("beam formers")

plastic or glass prisms

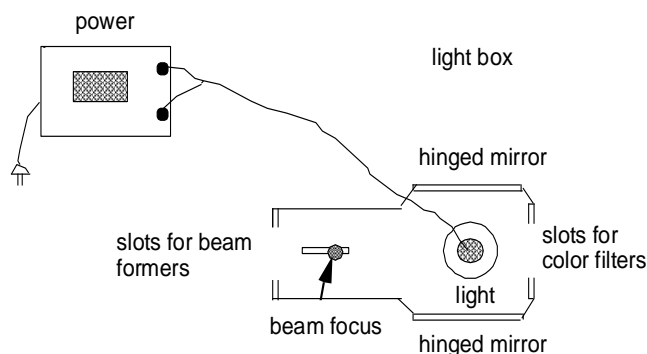


Fig 7. Schematic diagram of the light box, indicating connection to power supply.

Attach the wires from the power supply to the light box and plug the cord on the supply into the wall socket or distribution strip on your lab bench. Fig. 7. shows, schematically, how the box should be connected. Use a beam former with three or four slits at the end of the box closest to the focus knob, and adjust the knob's position so that the beams of light appear to be parallel. Now, substitute a single, narrow slit, so that only one beam emerges from the light box, and shine it through one of the prisms as shown in Fig. 8. You will be able to see the beam best if you put all of the equipment on top of a sheet of white paper.

What does the light do when it enters the prism? What happens when it exits? Find a position and orientation for the prism where the emergent beam shows the spectrum of colors noted above. Can you see all of the colors mentioned above? In particular, can you find the odd ones like lilac and olive? Think of other colors that are familiar to you – perhaps members of the class are wearing clothing in these colors – that do not appear to be in the white-light spectrum revealed through the use of the prism.

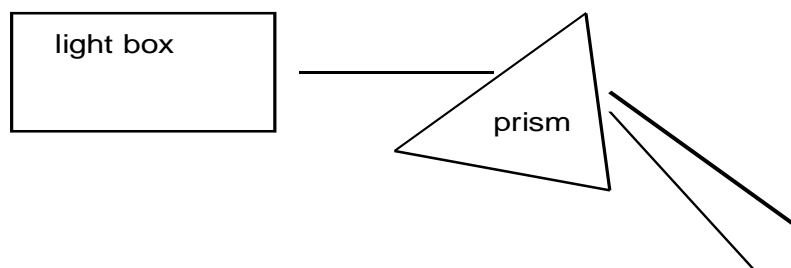


Fig. 8. Setup for viewing white-light spectrum with prism.

Are you convinced by what you have seen so far that the colors are really present in the white light, and that they are just treated differently enough by the prism (for example, bent by slightly different amounts) so that you can see them separated out? That's what most of us learned long ago. But, for the sake of argument – scientific argument – consider, for a moment, the alternative hypothesis that the colors are, instead, a property of the *prism*. This would be another way of explaining what you are seeing, and not any more far-fetched than the more familiar idea of separation of colors already present in the white light – if we had only the present experiment to go on! (Discuss this, and see whether and why you agree or disagree.) One way to probe the validity of these two different hypotheses about the origin of the colors would be to see if you can find a position for a second prism whereby the separated colors can be re-combined. What position might be most likely to do this? If the combination of colors again looks white, which of the hypotheses would be a better description of the way light and prisms really interact? If the second prism always adds color, what outcome would you expect for this two-prism experiment?

EXPERIMENT 1.3 Are three colors enough?

What you will need

Macintosh computer with “color” utility, or Windows computer with “color wheel” software; small lens or magnifying glass (15X is a reasonable magnification for this purpose)

In grade school, most of us learned that a great variety of colors -- perhaps every color imaginable -- can be created through the use of just three *primary colors*. This concept was taught to you in connection with paints or crayons, rather than colored beams of light. However, the idea of primary colors is also valid in connection with light. How many colors does a television screen or a computer monitor actually produce?

The "color wheel" provides a nice little laboratory to explore several properties of color vision, including the notion of primary colors. The computer should be set up with this utility displayed when you are ready to start the experiment, but if not, it can be found by using the mouse to select “control panels” from the Apple menu, “color” or "appearance" from the additional selections this reveals, and then “other” from the “highlight color” list. The screen will show a circle on the right side and a set of variables on the left. If the color wheel is dark, or all black, use the mouse to slide the “intensity” lever in the right-hand column to the top. At this point, you should see a circle with bright, *saturated* colors around the rim, and progressively more washed-out colors as you look more toward the center. The numbers beside each variable are directly related to the colors you see on the wheel; you can change the numbers and see where the corresponding color is on the wheel, or you can select, with the mouse, any color on the wheel and see the corresponding numbers for each variable.

1.3a. SOME THINGS TO TRY. The numbers in the lower-left corner of the display are the most important ones to understand. They correspond to the variables labeled “red,” “green,” and “blue.” These three colors are the only ones that can be controlled on the computer. Take a good look at the screen, and note the large number of colors actually visible. Take a lens or magnifying glass and closely inspect a portion of the screen that appears white. What do you see? You can inspect other areas of the screen as well. Use the mouse to point to the area on the rim of the color wheel that shows the purest red you can see, and press the mouse button. Now look at the numbers beside the variables “red,” “green,” and “blue.” What do you find? Similarly, select the purest green on the wheel, and note the values of the color variables. Without selecting blue, what do you think the values for the three variables will be for this third case? Test your hypothesis by clicking the mouse within the little boxes that contains the numbers for each of the three colors, deleting whatever number is in each box, and typing in your guesses. (Note that the range of numbers for each color on these computers is 0 to 65535, with 0 representing the complete absence of the indicated color and 65535 representing the brightest possible value of the color for the monitor you are using. Color wheels on other computers may use a 0 to 255 scale, or 0 to 100.) After typing in all three numbers, *click the mouse in the top half of the color-sample box that appears in the upper left portion of the window.* (Hitting the “enter” key, instead, selects this color and returns you to the computer’s operating system, and you have to restart the color wheel program.) The color equivalent of the three numbers you typed in should appear in the box, and also be selected by a little circle at the position of that color within the color wheel.

1.3.b. COMBINATIONS OF PRIMARY COLORS. We have investigated the numerical equivalents for the three controllable colors. Now, how about looking for combinations of the three? Try colors on the rim of the circle between any two of the three controllable colors. Look at the numerical values, and at the amounts of red, green, and blue light visible in a magnified view of the rectangular color patch. Does it make sense to call the three controllable colors “primaries”? Experiment with different combinations of the three controllable colors. Where, on the wheel, do mixtures of any two of these lie? (Set the third color to 0 to test this question.) Are there any surprises when you mix two of the primaries? What happens to the location of the color when you add a bit of the third primary? What happens to its appearance? Take a look now at two of the variables in the upper left part of the panel, “brightness” and “saturation.” You can change the values for the primaries and see how these other two variables change. Alternatively, you can select different locations on the color wheel, or you can change these two additional variables by hand (insert numbers in the corresponding on-screen boxes) and see how the other quantities are affected. What are the most saturated colors? How about the *least* saturated?

What combination of the three primaries would you expect is needed in order to produce white? If you haven’t tried this or seen it already, try it on the computer. Now, refer back to your earlier results. Select one of the primary colors, for example blue, and recall the values of the three primaries that correspond to that one color. Then look at the most saturated mixture of the *other two primaries*, in our example red and green, with the third one set to zero (full-scale green, full-scale red, zero blue). What is that color? Where does it appear on the color wheel, in relationship to the color you started with? These pairs of colors are called *complementary* colors. What do you get when you mix two colors that are complements of each other?

EXPERIMENT 1.4 What can we learn about our vision process just by staring?

EQUIPMENT

white paper

colored broad-tip pens

Examine **Figure 5** in the supplementary handout. There is a white cat on a black background on the left, and a small mouse on a white background on the right. Stare at the dot in the center of the cat for at least one minute, and then shift your eyes to stare at the dot in the middle of the white background on the right. What do you see? It may take a little while, but you should see something besides the white background in a few seconds. This effect is known as an *afterimage*. It is indicative of a certain fatigue (technically, a kind of “bleaching”) of the visual receptors that sets in when a fixed pattern is viewed for more than a few seconds in normal room lighting conditions. The receptors that have more light on them (what part of the picture would they have been viewing?) become, for a period of time, less sensitive than usual. When you then look at an all-white area, the fatigued receptors cannot respond as fully as those that were not as stressed, and do not therefore send your brain signals that indicate as strong a white area as do the less-stressed ones.

Now, try this experiment again, but this time after staring at the cat, shift your gaze to a light-colored wall across the room instead of looking at the white panel on the paper. How does this second observation differ, if at all, from what you saw when you shifted to the white rectangle on the paper in front of you? Can you think of an explanation of both what happens when you stare at a white area after looking at the picture, and also what may account for the differences when the white areas are at different distances from you?

In this experiment, how much fatigue would you expect the red-sensitive receptors to experience compared to the green or blue ones? You should be able to guess the answer to this question knowing what you now do about white light. Now, we will do a similar experiment but use colored objects rather than black-and-white ones. First, you will make a simple drawing, with a few large red areas and a few large black ones. You will then stare at your drawing for about a minute, and after that gaze at a blank piece of white paper. Before doing this, however, think about what you learned about color relationships in your color wheel experiments. If your red receptors become fatigued, how do you suppose your eye will respond to white light? That should give you some idea of the color to expect if there is any afterimage at all. Make the hypothesis first, and give a reason if you have any idea. Then do the experiment. What do you see? Do the results match your hypothesis? What is the relationship of the color of the afterimage to the original red? Can you refine the reasoning that helps you understand what is taking place in your eye?

Now try the experiment again using different colors. You will get best results if you do not use a lot of colors in any one picture, and if the colored areas are not very small. Can you begin to predict how the afterimages will look?

ARTISTIC FOOTNOTE

Artists often consciously utilize principles developed by scientists to produce the particular effects they desire. Somewhat less well-known is the fact that scientists sometimes pick up important insights from the work of artists. In the late 1800's, French impressionist Georges Seurat adapted the newly-emerging knowledge about color perception, and the eye's ability to mix neighboring spots of color so as to produce the effect of a different color, into a new painting style his contemporaries soon dubbed *pointillism*. Instead of covering his canvases with broad swaths of color, in wide or narrow brush strokes, he meticulously painted tiny dots of color, interspersing two or more different colors that could produce in the eye of a beholder standing at some distance from the painting a completely different perception from what might be seen if the individual dots were viewed close-up. More recently, Jasper Johns created a set of works based on afterimages; perhaps the best known of these is a painting that has the form of an American flag, but done entirely in the colors complementary to those of the actual flag. Why might he have done that?

QUESTIONS AND ACTIVITIES. *Answers or results are due one week after the day we finish this chapter in class. Some of the activities should involve other students who are not taking Discovering Physics. We want them to participate in the scientific adventure, too!*

1.1 What are the primary colors you learned as a child? Do they work well? Why do they seem to give different results for various mixtures than when light is mixed? Hint: how do paints and crayons differ from light beams? More accurate primaries for pigments are used in the printing industry, and can be found in the color cartridges of every ink-jet printer. What are these colors, and why are they better for production use than the ones we all learned in kindergarten? The "colorsub" web program listed below may be helpful in working this out.

1.2 Devise various hypotheses that could explain why most people do not guess the relative weight of the two objects seen in class. What was the main purpose of this demonstration?

1.3 Try some of the optical illusions in this chapter on your friends. See if they have any additional ideas as to what causes the effects.

NOTE: Figures 1, 2, and 3 are reproduced from "The World's Best Optical Illusions," by Charles H. Paraquin, © 1987, Sterling (New York). Figures 5 and 6 are reproduced from "Seeing the Light," by David Falk, Dieter Brill, and David Stork, © 1986, Wiley (New York).

Useful websites

It is difficult to find a color wheel on the web as good as the one provided for this lab. Here is one that at least has the colors right – although its interactivity is not very intuitive:

www.alterfin.com/mirror/colorWheel/alterShockWheel.html

This site has a nice interactive demonstration of color mixing of the light primaries:

<http://mysite.verizon.net/vzeoacw1/coloradd.html>

This application, as well as the following one, requires installation of a "Flash" plug-in for your web browser. If you don't have it, it can be found at

http://www.macromedia.com/shockwave/download/download.cgi?P1_Prod_Version=ShockwaveFlash

And this one, from the same author, shows how *pigments* mix:

<http://mysite.verizon.net/vzeoacw1/colorsub.html>

Warning! On the screen, the mixing of "pigment" colors is actually a *simulation*, since the computer monitor is actually shining light directly toward your eyes using its RGB phosphors. However, if you print out some of the screens you see while you are playing with the various mixtures, the printout will be the real thing, as it will then be using the actual pigments.

Drawings for Chapter 1

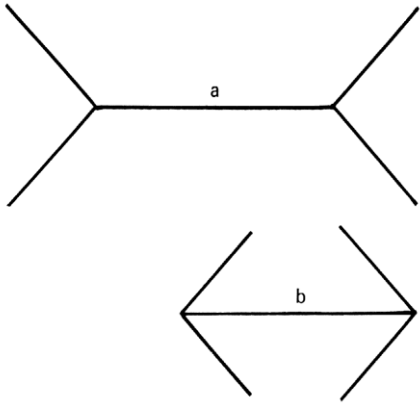


Figure 1.

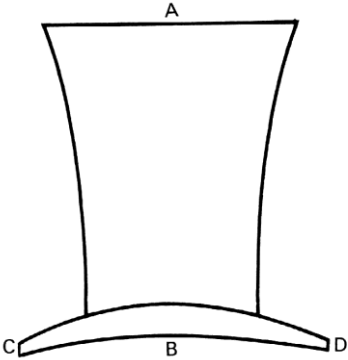


Figure 2.

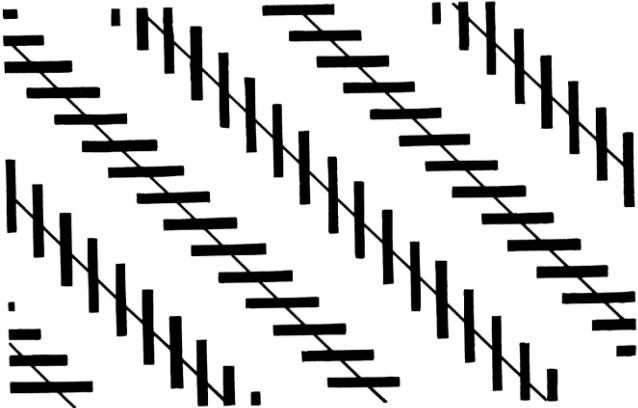


Figure 3.

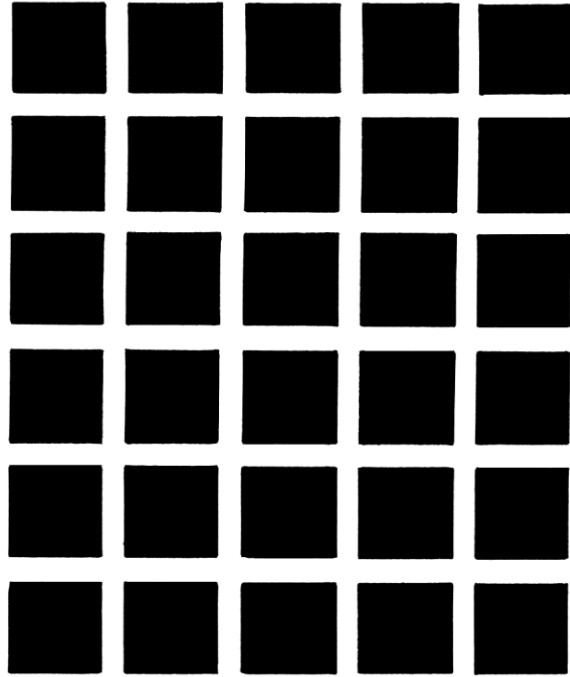


Figure 4.

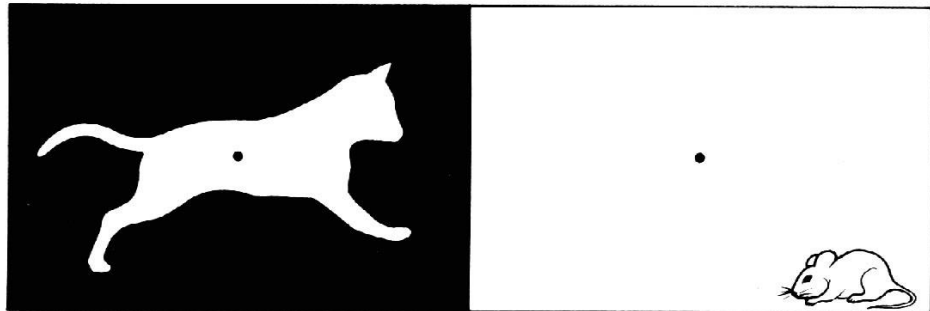


Figure 5.

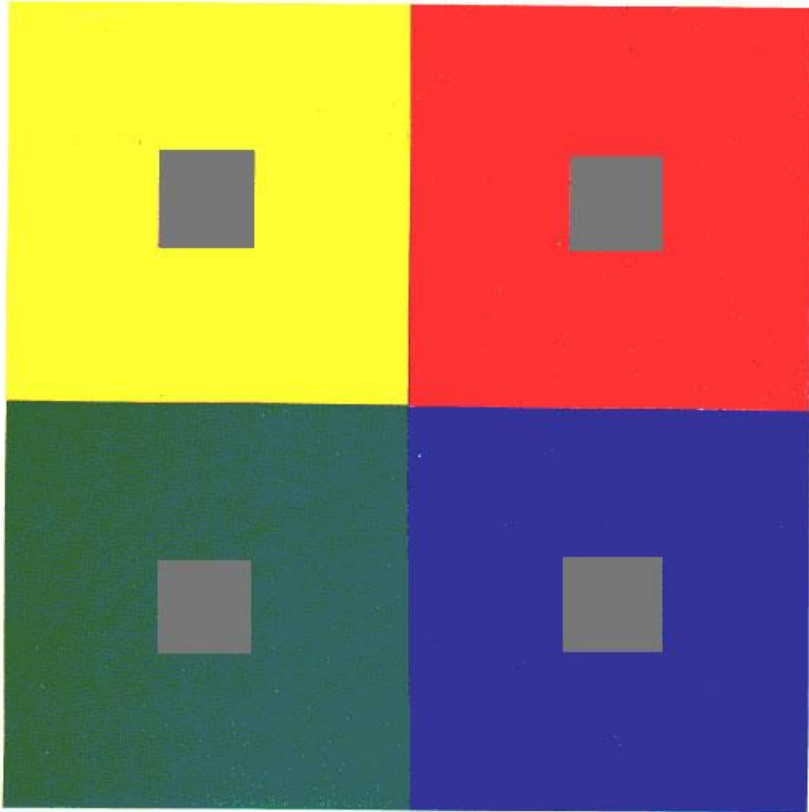


Figure 6.



Gateway Arch,
St. Louis, Missouri