Physics 112 Summer Section 031 Lab Manual

by
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Chapter 1

Introduction

Welcome to the lab portion of your physics class. There are three important goals for doing labs in this course:

1. To get experience with gathering and analyzing technical data, an important part of the scientific method.

2. To develop and improve your technical communication skills.

3. To better understand physics concepts.

Note that only the last item is about physics proper. Wherever you go in life, whatever you do, hopefully this lab will benefit you, regardless of whether or not you ever use physics after graduation.

1.1 About This Manual

This manual is written specifically for students in author's lab sections. Although many of the experiments are similar to those in other labs run by other instructors, they are not exactly the same. Some labs are completely different. If you are not in my lab section, you're looking at the wrong manual.

If you are in one of my sections, there are benefits to having the manual's author running your lab sections. First of all, you can be confident that I know the manual because I wrote it. Second, you can easily obtain a PDF of the manual. In the age of computers, tablets, and smartphones, this can be very helpful. Third, if the manual has errors in it, I can correct them so other people don't suffer through the errors later.

Writing a lab manual is, like many other scientific activities, iterative. Be part of the scientific process. Share your feedback with me about this manual if you possibly can. I'd like to make the manual better for you and for the students who come after you.

Now the legalese: this manual is the personal property of the author, who has created all of its content. I retain the copyright to everything it contains. I am distributing this manual to my students, free of charge, for their personal use while in my lab section. All other use of this manual, including redistribution to others, is prohibited.

1.2 Report format

Reports are an important part of the lab experience. They are due at the end of each lab period (you don't want to take it home, really, trust me) and will be returned, graded, during the next lab assignment. Each lab report will be an individual assignment unless otherwise specified, and will be worth 20 points total. Although reports are individual, you are encouraged to share report elements like tables and plots; make your own copy of everything you need and attach it to your lab report. You can even share ideas and conclusions, but make sure everything you present is written in your own words. Paraphrase prose, but don't ever just copy it.

You have a lot of flexibility as far as doing your report writing, and you are encouraged to use it. Unless otherwise specified, your work can be hand-written or printed out on the lab printer. If you want to use word processors or spreadsheet programs, that's fine. You can also hand write reports on paper of your choosing. Mixed reports, with handwritten and computer-generated sections mixed together, are acceptable. You can use pen if you like when you do handwritten work, but I encourage you to use pencil as it is easier to correct the inevitable mistakes in pencil. When in doubt, however, do whatever helps you produce the best reports.

Physics is a science class. We will use a report format based on the scientific method in our lab reports. The format will be as follows:

1. Cover page (1 point)

   The cover page is a separate page of your report that has basic information about you and your lab report. This information includes your name, the lab title, the date, your lab partners' names, and finally, my name. The goal is to make sure that your report will get to me if I forget it on the lab table. It's so important to have this information that I'm paying for it. The cover page is worth 1 point by itself.

2. Hypothesis/introduction (4 points)

   In the hypothesis/introduction section, I am looking for two things. First of all, I want you to give me an introduction to what you did in the lab. List all the important equations that you use in your work, and so on. I am also looking for a question (a hypothesis) that the lab attempts to answer. Here is an example: "In today's lab, we are seeking to confirm or deny that the acceleration due to gravity is 9.8 $\mathrm{m/s^2}$." Another example: "Is the speed of a wave really equal to its frequency times its wavelength?" Feel free to use equations: "Does $a = gsin\theta$ for a ball rolling on an inclined plane?"

3. Data and analysis (10 points)

   In every lab you collect and present data. If you collect all the data you need to collect and present it clearly, you earn 5 points. You must also analyze the data somehow (enter values into an equation, create a plot, etc.) to reach some conclusion that supports or refutes your hypothesis. This data analysis is also worth 5 points.

4. Conclusion (5 points)

How did it go? Summarize the results of your experiment in the conclusion section. Was your hypothesis supported or refuted by your data and analysis? Science is an iterative process, so in the conclusion you have one final question to answer. What could have made the experiment work better? Suggest ways to improve this experiment (use different lab equipment, collect data a better way, etc.) as part of your conclusion if you can think of any.

1.3 Checking the Hypothesis

Scientific work is about asking questions and finding answers. The question is phrased in your introduction/hypothesis section. The rest of the report, and all of your lab work, is about finding an answer to that question. Don't worry if your hypothesis was wrong; it won't cost you any points in the grading. Your hypothesis should reflect your understanding at the beginning of the lab, nothing more.

As you collect your data and analyze it, think about whether or not it supports your hypothesis. Either answer is acceptable if that's the conclusion your work leads you to. Oftentimes your goal is to show that a formula's prediction agrees with your experimental results. Students often believe that their experimental result leads them to a single number. This is never true because of uncertainty. Uncertainties mean that your data will support a range of possible values for a number.

Your hypothesis is supported if a prediction falls within the range given by your experimental data and analysis. **If your hypothesis is supported, error analysis is not needed!** Your hypothesis is not supported if the prediction falls outside the range given by your experiment. In this case, error analysis is required.

1.3.1 Uncertainty

Uncertainties mean that your experiments will produce a range of values, not just one value. There are several forms of uncertainty you need to keep in mind:

1. Measurement Uncertainty

   When you measure something with a ruler, you cannot say with certainty that it is a specific length. You can't say an object you measured with a meterstick is really 10cm long, for example. All you can really say is that its measured length is within half of the smallest measurement available. Your object is really (10 ± 0.05) cm. Its true length is not precisely known; all that is known is that the measurement lies within the recorded range.

   Record the uncertainties in your measurements whenever it is practical. Use the biggest and smallest values in equations to find the biggest and smallest possible values for calculated quantities. We will call these values the extremes. If you are calculating X from maximum value X_+ and minimum value X_-. Record it as

$$X = \bar{X} \pm \Delta X \tag{1.1}$$

where $\bar{X}$ is the mean of the extremes

$$\bar{X} = \frac{X_+ + X_-}{2} \tag{1.2}$$

and ΔX is half the difference between them, neglecting the sign of the answer, so

$$\bar{X} = \frac{|X_+ - X_-|}{2}. \tag{1.3}$$

2. Statistical Uncertainty

   Sometimes it isn't practical to record measurement uncertainty. Your computer has recorded 1,142 distance values, for example, and it didn't record measurement uncertainty. If you examine the data carefully, however, it seems to fluctuate around some value. This may be a manifestation of measurement uncertainty, or it may be that the quantity being measured does in fact change. You may not know (or care) which of these reasons is the correct one.

   In situations like this one, it is simpler to use statistical uncertainty. For the same quantity X discussed above, $\bar{X}$ is the *mean* of the data

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{1.4}$$

   and ΔX is *standard deviation* of the data

$$\Delta X = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{(n-1)}}, \tag{1.5}$$

   where X_i is one of the n data points that have been collected.

   Computers and calculators know how to find standard deviation, so let them handle the calculation. For example, calculators often refer to standard deviation on their keyboards with the symbols σ or σ_{n-1}. Spreadsheet programs often use the formula STDEV(*range*). Refer to the documentation for the computing platform of your choice for more information, or ask your instructor.

1.3.2 Error Analysis

Error analysis is only needed when quantities determined in your lab do not include the expected value. For example, you don't need an error analysis if you measure the acceleration due to gravity as $9.6 \pm 0.4 m/s^2$ and the accepted value is $9.8 m/s^2$. If you find $9.2 \pm 0.4 m/s^2$, you must do some error analysis, as the accepted value is not included in your range.

In this class, error analysis is simple: find the percent difference Δ between your closest value X_c and the accepted value X. The formula is, simply,

$$\Delta = \left| \frac{X_c - X}{X} \right| * 100\% \tag{1.6}$$

1.4 Conciseness and the Four Sentence Rule

The language of physics is mostly mathematics. We use equations, numbers, graphs, and tables to understand physics concepts. We use prose too, in the form of sentences, paragraphs, and so on, but it is usually not the preferred way to convey information. There are several reasons why. First and foremost, in any science we strive to be concise to help us understand key concepts. When we aren't concise, there's a chance that important physics will be lost in a sea of sentences. Minimizing prose can also better understand complex phenomena.

When you write your lab reports, remember what I call the Four Sentence Rule: anything important you have to say should have four sentences or less in it. If you are writing something that will use more than four sentences, it usually means one of two things:

- You should be using some other method to express your information, like a table, graph, or equation, or
- You don't really understand what you are talking about, and you need to talk to your lab partners or your instructor before you write anything else.

Remember the Four Sentence Rule. If you don't, you might lose points on your reports.

1.5 Units

Units on your data, including quantities like meters, kilograms, and seconds, are an important part of any technical discipline. They help us understand the meaning of the data that we record. Incorrectly recorded units can make your data worthless. Recording and checking units can also act as a "sanity check" for your data. If your units are incorrect on a recorded result, knowing that fact can help you figure out what you did wrong and how to fix it.

When I grade your labs I will be looking for units. Incorrect use of units will result in lost points.

Chapter 2

Sample Lab Report

The following is an example of the format needed for a typical report. It is not for a real report (there has never been a zombie apocalypse, of course), but from reading it you should have a sense of what the ficticious experiment in the manual must have been asking for. Hopefully this will give you ideas for how to do your reports, but it is not meant to be authoritative. If you can think of ways to write better reports, feel free to do so.

Elastic and Inelastic Collisions and Repelling Zombie Attacks

by

Fred Jones

Lab Partners:

Daphne Blake

Unidentified person in a red shirt (deceased?)

Physics 111

Dr. Paul Freitas

July 4, 2014

Hypothesis

A projectile that experiences an inelastic collision with another object has an impulse $\vec{J} = m\vec{v}$, where m is the projectile's mass and $\vec{v}$ is its initial velocity. If the collision is elastic, however, the impulse will be doubled. An object being hit by, say, a rubber bullet will experience twice the average force through the collision as an object being hit with a hollowpoint bullet that would be caught by the target. Thus, rubber bullets should be more effective in knocking over and immobilizing attacking zombies than hollowpoint bullets. In light of the recent zombie attacks on our campus, this topic is suddenly of great interest. Our hypothesis, then, is that it will be twice as easy to knock over attacking zombies with rubber bullets as opposed to hollowpoints.

$$m = 20 \text{ g}$$

$$v = 400 \text{ m/s}$$

Data and Analysis

Trial #	Ammunition Type	Shooter	Number of Rounds Fired	Number of Zombies Knocked Over	Effectiveness (%)
1	Hollowpoint	Fred	100	32	32.0
2	Hollowpoint	Red shirt	116	26	22.4
3	Hollowpoint	Daphne	84	30	35.7
4	Rubber	Daphne	150	106	70.6
5	Rubber	Fred	150	95	63.3

Conclusion

The experiment supported the conclusion that rubber bullets were more likely to knock over zombies than hollowpoint bullets. For shooters Fred and Daphne, their rubber bullet shots were approximately twice as likely to knock over an attacking zombie as their hollowpoint shots. Unfortunately, our third lab group member was overconfident in the hollowpoint rounds, and refused to retreat when it became clear that his shots were relatively ineffective. (In our retreat, we were unable to determine his ultimate fate. Daphne thinks he continued firing hollowpoints until he was overrun.) Daphne's hollowpoint shots were generally more effective, but she learned from our third member's mistakes and switched early to the rubber bullets. No further retreats were required.

Chapter 3

Waves in Stretched Media

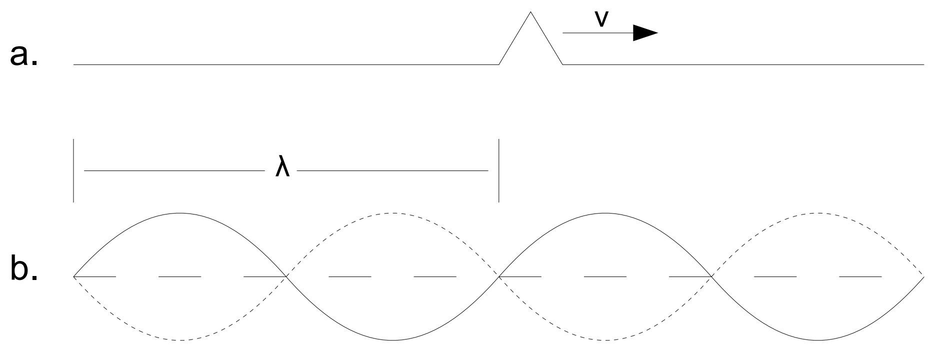

Figure 3.1: Two kinds of waves in a stretched string: a. a traveling wave of speed v and b. a standing wave of wavelength λ at time $t = 0$ (solid), $t = \frac{T}{4}$ (dashed), and $t = \frac{T}{2}$ (fine dashed).

3.1 Introduction

When a physical material is stretched with uniform tension T, waves can propagate through the material. If the tension is uniform through the material, and if the material is basically one-dimensional (like a string or a spring), we can model the material mathematically to show that a wave will propagate with speed v according to the equation

$$v = \sqrt{T/\mu}, \tag{3.1}$$

where μ is the mass per unit length (or *linear density*) of the material.

There are two kinds of waves that are of interest. A *traveling wave* is a disturbance of arbitrary shape that propagates down the length of the material with a constant speed. Ideally it does not change shape as it moves, but external influences and other considerations can cause the wave to spread and flatten to varying degrees. The other kind of wave, a *standing wave*, is caused when two waves with the same size and shape but opposite direction are present in the string. Standing waves are generally sinusoidal (shaped like sine waves), alternating periodically at every point from positive to negative and back again. Sinusoidal waves are defined by two physical properties: the physical distance over which the wave pattern repeats, known as the *wavelength* λ, and the time it takes for the wave pattern to change and change back to its earlier pattern, known as its *period* T.

If you think of a standing wave as two sinusoidal waves traveling in opposite directions, they must have some speed associated with them. It can be shown mathematically that the speed is given by the equation

$$\begin{aligned} v &= \frac{\lambda}{T} \\ &= \lambda f, \end{aligned} \tag{3.2}$$

where f is the *frequency* (inverse of the period) of the wave.

We now have two different expressions for the speed of arbitrary waves in a material, Equation 3.1 and 3.2. Do these two expressions agree with one another, even though the kinds of waves seem very different?

3.2 Apparatus

Long spring, 2 spring scales (10 N or higher), stopwatch, measuring tape, painter's (blue) tape for marking distances.

3.3 Procedures

Your goal is to find the wave speed for a traveling wave using Equation 3.1 and the components of a standing wave separately using Equation 3.2.

3.3.1 Wave Speed From Tension and Density

Find the wave speed using Equation 3.1 using the following procedure. Do this only once. (Other parts of the experiment will be repeated multiple times.)

1. Hang your long spring from a single spring scale. Find the weight of the spring in newtons. Divide by 9.8 m/s^2 to find the mass of the spring in kilograms.

2. Stretch your spring so it is suspended off the floor and can maintain waves. Measure the length in meters; some possible methods include direct measurement (e.g. measuring tape or metersticks) and counting floor tiles (approximately one foot long each). Mark the endpoints of your spring on the floor with blue tape so you can use them again in other parts of the experiment.

3. Calculate the linear density (mass per unit length, or μ) in kg/m.

4. Connect a spring scale at each end. Record the average reading of the two scales as tension T in newtons.

5. Use Equation 3.1 to find the wave speed.

3.3.2 Wave Speed from Frequency and Wavelength

Here you will create standing wave patterns and find the frequency and wavelength of the wave to find the velocity. You should have little trouble creating two to three distinct wave patterns. Find the velocity using the following procedure for all of the patterns whose frequency and wavelength you can easily identify.

1. Hold the ends of your spring at the endpoints you marked in the previous part of the experiment.

2. Have one person holding an end of the spring create a standing wave by shaking their end of the spring gently until a standing wave is created. This may take some practice. If you are collecting data for a second or third standing wave pattern, make sure that your standing wave is different than any previous ones you collected data for.

3. Find the wavelength of the standing wave λ in meters. You can do this by directly measuring the distance between a node and the second nearest node, or by dividing the total distance between the ends by the number of complete wavelengths in that distance. For example, there are 2 wavelengths in the standing wave pattern shown in Figure 3.1.

4. Find the period of a single oscillation T by timing a larger number of oscillations (like 15 or 20) and dividing that measured time by the total number. Remember that one oscillation is the time it takes for a point on the spring to go across and back to its original position from its maximum deflection.

5. Calculate the frequency of oscillation f by taking the inverse of the period found in the previous step.

6. Find v using Equation 3.2.

3.3.3 Finding Wave Speed Directly

To find the wave speed directly:

1. Stretch your spring between the marks made earlier.

2. Create a wave pulse by plucking the spring sideways. Start your timer at the same time the pulse is generated.

3. The pulse will go down the stretched spring and reflect back. Time the pulse as it travels over at least four lengths of your spring.

4. Compute the wave speed by dividing the distance traveled by the measured time.

3.4 Notes on Data Presentation

You will want to present your wave speeds from all the techniques you used so they can be compared side-by-side. A table can be very helpful.

Chapter 4

Sound from Half-Open Pipes

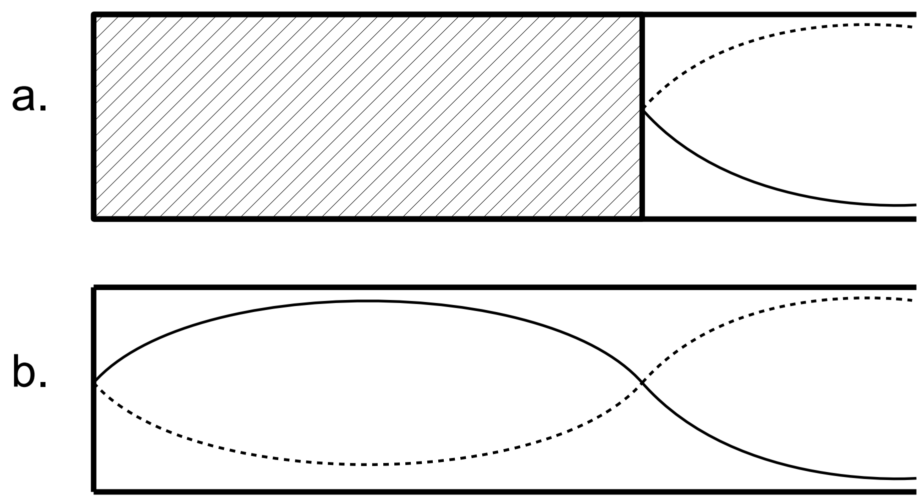

Figure 4.1: A standing wave of wavelength λ in a pipe of length a. $L = \frac{\lambda}{4}$ and b. $L = \frac{3\lambda}{4}$

4.1 Introduction

Sound in air is an example of a wave traveling through a medium. We can think of air as a collection of molecules loosely connected together, like the coils in a spring. If we can press them together quickly and release them, they will try to return to their equilibrium position, but in doing so, they will exert a force on the molecules next to them, pressing them together and moving the pulse sideways. This will create a *longitudinal wave* that will continue moving through the air. In the case of sound, this longitudinal wave is called a *sound wave*.

When air molecules have boundaries, interesting things can happen. Imagine an air molecule near a wall. An air molecule pushing on it toward the wall cannot move it as much as a molecule away from a wall could move. The molecule will push back against its neighbor. For this reason, if you imagine a sound wave heading toward a wall, it is impeded by the wall and will bounce back away from the wall. This is called a *reflection*. If a sound wave goes down a tube and hits a wall, the reflected wave can add to the original incident wave to create a standing wave, just like the ones you can see in stretched media like strings and springs. In fact, even a patch of dense air created by a standing wave can cause a reflection.

Not every wave can create a standing wave. For a tube or pipe closed at one end with length L, the allowable wavelengths λ_n of sound waves that can create a standing wave are given by the equation

$$\lambda_n = \frac{4L}{n}, \tag{4.1}$$

where n are odd integers like 1, 3, and 5. You can tell when a standing wave is present in a tube because it will *resonate*, filling the air around it with sound of wavelength λ_n.

In this experiment, you will use a tuning fork of a known frequency f (stamped on the fork) to create a standing wave in a half-open pipe. The bottom of the pipe will be filled with water, closing off that end of the pipe. The water level is adjustable by moving a reservoir up and down. You will strike the tuning fork and hold it above the opening of the tube, then adjust the water level until the sound of the tuning fork is greatly amplified, possibly even filling the room. You will record the height of the water column L_1 by seeing where the meniscus of the water column lies on the meterstick attached to the pipe. You will then move the reservoir up or down to find another nearby resonance point, the next nearest one in fact, and record the second water column height as L_2. The difference between these heights is one-half a wavelength of the sound, so

$$\lambda = 2|L_1 - L_2|. \tag{4.2}$$

Because the speed of sound v is given by the equation $v = f\lambda$, we can conclude that

$$v = 2f|L_1 - L_2|. \tag{4.3}$$

A commonly-used model for the speed of sound in air uses the formula

$$v = 331.4 \text{ m/s} + 0.60\left(\frac{\text{m}}{\text{s}\cdot\ \text{C}^\circ}\right)T, \tag{4.4}$$

where T is the temperature of the air in degrees Celsius. How will your results from Equations 4.3 and 4.4 compare?

4.2 Apparatus

Pipe with variable water height and meterstick, water, three tuning forks with frequencies higher than 256 Hz.

4.3 Procedure

Find the temperature of the room T and use Equation 4.4 to estimate the speed of sound in the lab. Record this value (and your calculation) in your report. You will use this value for comparing the speed of sound found with each tuning fork.

Next, do the following for each tuning fork you have:

1. Record the frequency of your tuning fork in your data table.

2. Estimate values for L_1 and L_2. By using Equation 4.1 and the equation $v = f\lambda$, you can conclude that
$$L_1 \approx \frac{v}{4f} \tag{4.5}$$
and
$$L_2 \approx \frac{3v}{4f}. \tag{4.6}$$
You must now find exact values for these numbers experimentally.

3. Adjust the water height to the approximate value of L_1 given above.

4. Ring the tuning fork and hold it above the tube so that, if the fork was wide enough, it would block the tube. Listen to the volume of the tone the fork emits, not the ringing overtone. Ask your instructor for help if you have trouble differentiating the two sounds.

5. Find the exact value of L_1 by raising and lowering the water level in the tube by raising or lowering (respectively) the water reservoir. If the tuning fork dies off, strike it again and keep experimenting until you have a reasonably precise value for L_1. Record this value.

6. Adjust the water height to the approximate value of L_2 given above.

7. Ring the tuning fork and hold it above the tube so that, if the fork was wide enough, it would block the tube. Listen to the volume of the sound.

8. Find the exact value of L_2 by raising and lowering the water level in the tube by raising or lowering (respectively) the water reservoir. If the tuning fork dies off, strike it again and keep experimenting until you have a reasonably precise value for L_2. Record this value.

9. Calculate v using Equation 4.3.

4.4 Discussion points

Does the prediction of Equation 4.4 fit within the range of all of the values of v you found experimentally? Discuss your answer in your report's conclusion section.

Chapter 5

Measuring the Speed of Sound

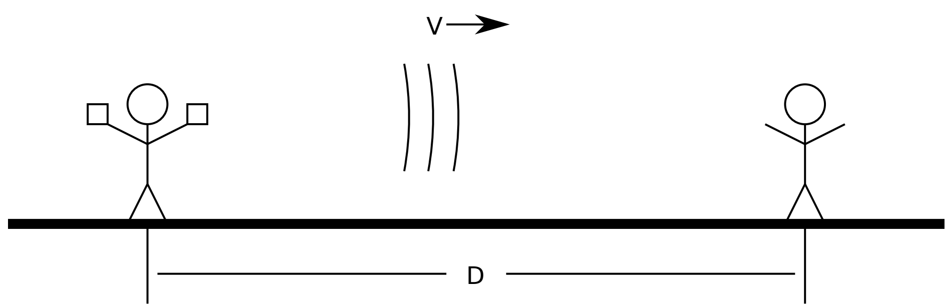

Figure 5.1: Two stick figures measuring the speed of sound the simplest possible way.

5.1 Introduction

Sound is a common example of a wave in physics. Sound waves in air all travel at one speed (more or less), the *speed of sound*. The textbook value given for this speed, which we will refer to here as v, is 340 m/s, but this is a very simplistic approximation. The speed varies with temperature. One model for this temperature dependence was given in Equation 4.4, namely

$$v = 331.4 \text{ m/s} + 0.60 \left(\frac{\text{m}}{\text{s} \cdot \text{ C}^{\circ}} \right) T, \tag{5.1}$$

where T is the temperature of the air in degrees Celsius.

The goal of this experiment is to measure the speed of sound two different ways. The first method is the simplest: one person will stand a large, known distance away from an observer with a stopwatch, as shown in Figure 5.1, and make noise by banging wooden blocks together. The observer with the stopwatch will start timing when he sees the blocks strike one another, and stop the stopwatch when he actually hears the sound. The speed of sound, then, is found from the equation $v = D/t$, where t is the time it takes for sound to cover the distance D.

The second method involves spacing two microphones a distance D apart in the laboratory. Using audio mixing software (in this case, the open source program Audacity), one can find the time t it takes for a sound to cross over one microphone and reach the other. Again, $v = D/t$. This method takes up much less space than the other method, and can be done indoors.

Will these two methods validate Equation 5.1 within uncertainty?

5.2 Apparatus

Thermometer, stopwatch or other electronic timer, cell phone (optional), notebook and pencil (for data collection), two wooden blocks, long (100 m) tape measure, two microphones, audio mixer, and a computer with appropriate recording software (like Audacity).

Note: Logger Pro with two pressure transducers can be used instead of the mixer and ordinary microphones. Due to low sampling rates, however, this setup is *not recommended*. If you use Logger Pro for this experiment, check your work frequently and discard anomalous results.

5.3 Procedure

There are two separate procedures in this experiment: an outdoor measurement and an indoor measurement. For each procedure by itself, calculate $v = D/t$ for each value of t you collect. Express your speed of sound with uncertainty from each technique as $v = \bar{v} \pm \Delta v$, where $\bar{v}$ is the average of your observed speeds of sound and Δv is the standard deviation of these values. Finally, calculate an expected value of v using Equation 5.1. Does this value fit within uncertainties indicated by your data, or at least the range of values you observed?

5.3.1 Outdoor Measurement

1. There are three roles in this lab: noisemaker, timer, and recorder. Divide these responsibilities among the members of your lab group. If necessary, the timer and recorder can be the same person.

2. Have the noisemaker carry the wooden blocks and the optional cell phone. The timer will carry the stopwatch or other timing device (most cell phones have an integrated timer). The recorder will carry the notebook and pencil. Your lab instructor will carry the thermometer and the tape measure. You may carry additional belongings with you if you do not want to leave them in the laboratory.

3. The instructor will read the outside temperature. Recorders will record this temperature.

4. Follow the instructor to the sidewalk in the middle of the T-lot parking lot.

5. The instructor will note a line on the sidewalk for the timers and recorders to stand on. The group will then use the tape measure to mark out another line on the same sidewalk a distance D (about 200 m) away. The noisemakers will move to the second line.

6. One of the noisemakers should call one of the timers, recorders, or the lab instructor with their cell phone. This experiment is easier when members of the same group can communicate.

7. The timers should reset their timing devices, and the recorders should be prepared to record times. When timers and recorders are ready, they should tell the noisemaker that they can begin the experiment.

8. The noisemakers should hold their blocks straight out from their sides, then bang them together over their heads slowly and steadily, repeating the entire motion many times. This motion should be like clapping along with a band at a concert, but more slowly.

9. When timers see the wooden blocks come together, they can start their timers. When they actually hear the sound of the blocks, they should stop their timers.

10. Recorders should write down the time t found by the timers.

11. Repeat from Step 9 onward until the recorder has recorded 5 or more times.

12. After all data has been collected, the noisemaker can stop making noise and can return to his lab partners. Once all lab groups are finished collecting data, the class can return to the laboratory.

13. Analyze your data as described above.

5.3.2 Indoor Measurement

1. Record the air temperature in the laboratory.

2. Your instructor should have set up his computer, mixer, and microphones for data collection. Measure the distance between the microphones.

3. Each group will take turns collecting data for this experiment. When it is your turn, have one group member pick up a pair of wooden blocks and stand behind the closest microphone.

4. Start a stereo sound recording using the computer.

5. Clap the blocks behind the nearest microphone, so the blocks and the two microphones are all on the same line.

6. Watch the computer display. When the sound of the blocks appears on both tracks of the recording, stop recording.

7. Select the region of the recording where the sound is heard by both microphones. Use the Zoom feature to focus the display on only this region.

8. Select to highlight the time of the recording from one peak on one recording to the second peak on the other. The time that it took the sound to go from one microphone to the other is now selected.

9. Read the number of samples in the highlighted region off the display. Convert this number to a time by dividing the number of samples by the sampling rate (usually 44,100 samples/s).

10. Undo all of your recent operations with Control-Z until your recording disappears.

11. Repeat the procedure from Step 4 onward until you have at least 5 observed values of v.

12. Analyze your data as described above.

Chapter 6

Young's Double Slit Experiment

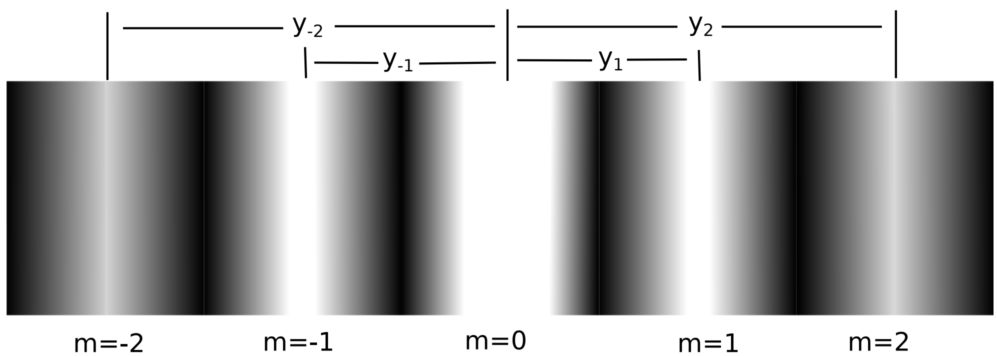

Figure 6.1: A double slit interference pattern. Note the dimming of the fringes away from the center; this is caused by the narrowness of the slits.

6.1 Introduction

Young's double slit experiment is a classic experiment demonstrating the wave nature of light. Imagine shining a light of known wavelength λ, such as a laser, through a pair of narrow slits in a barrier. By doing a careful analysis of the path difference taken by light going through each of the slits, one can show that the light will create an *interference pattern*, an interchanging series of light and dark spots (or *fringes*) on a projection screen placed at a distance L away from the slits. The pattern will look like the one shown in Figure 6.1.

Let us assume that the distance to the screen L is much greater than the distance between the slits d. The brightest points in the pattern will appear at an angle θ governed by the equation

$$m\lambda = d\sin\theta, \tag{6.1}$$

where m is an integer (0, ±1, ±2, etc.) known as the *order* of the fringe. When the angle θ is small, one can show that $\sin\theta \approx \tan\theta \approx \frac{y_m}{L}$, where y_m is the distance between the zeroeth order fringe and the mth order fringe. Equation 6.1 can be simplified to

$$m\lambda = \frac{dy_m}{L}.$$

We generally know the wavelength of lasers very precisely; the value is printed very precisely on the laser itself in most cases. What we may not know, however, is the distance between our slits. We can determine it by solving for d:

$$d = \frac{m\lambda L}{y_m}. \tag{6.2}$$

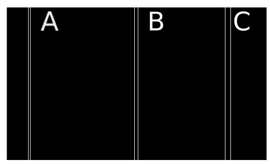

Figure 6.2: An example of three different double slits (A, B, and C) with different distances d between the slits. When printed on transparency paper, these slits can be used to demonstrate double slit interference by shining a laser through the slits.

In this experiment, you will be given a copy of the slits shown in Figure 6.2 printed on appropriate transparency paper. When you shine a laser through one of the pairs of slits (labeled A, B, and C) you will be able to project an interference pattern on a screen. You will measure y_m repeatedly and use it to calculate the slit separation d. The slide was designed to have the slit pairs for A, B, and C at distances of 0.25 mm, 0.50 mm, and 0.75 mm apart respectively. Are they?

6.2 Apparatus

Double slit slide, laser of known wavelength, slide stand, paper screen, tape, long tape measure, small ruler, laser of known wavelength, optical bench.

6.3 Procedure

1. Find and record the wavelength of your laser printed on the tag attached to its power cord.

2. Mount your laser, if necessary, on the end of your optical bench closest to the wall.

3. Place the slide stand on your optical bench so the laser beam goes through it, adjusting the stand's height and the laser's height and orientation as needed. Do not add the double slit slide yet.

4. Turn on your laser so it shines on the wall opposite your lab station. Find the spot on the wall and attach a piece of paper to the wall so the spot can be seen clearly. Adjust the optical bench as a whole if necessary to make attaching the screen to the wall more convenient. Try to keep the beam perpendicular to the wall.

5. Darken the room so interference fringes can be easily seen.

6. Attach your double slit slide to the slide mount, using tape or any other convenient attachment method, so the beam goes through one pair of double slits. You will know the beam is adjusted properly if you see a number of small fringes very close together. If your beam goes through only one slit, you will see a much broader fringe pattern. If this happens, move the slide sideways until you you see additional dark fringes in the broad fringes you saw previously.

7. Record the specific slit pattern (A, B, or C) you are currently using on your screen.

8. Find the brightest spot in the interference pattern. Make a pencil mark above its center and label this point with a 0, as it is the $m = 0$ fringe.

9. Use a long tape measure to find L, the distance from the slide mount to the $m = 0$ fringe on the screen.

10. Mark the centers of the fringes to the immediate left and right of the zero order fringe marked previously. Label them as "$m = 1$," "$m = -2$," and so on. At some point, these fringes will become too dark to see because of single slit interference. This is normal. You shouldn't need the fringe locations at or beyond this point.

11. Replace your paper screen with another blank screen and repeat the previous steps until you have data for all three slit patterns.

12. Create a data table with the following column headers: Pattern (A, B, or C), m, y_m (m), and d (m). You may do your table and its calculations by hand, or you may use a spreadsheet program instead if that works better for you.

13. Fill in your table with information from your paper screens. Measure each y_m with a ruler as needed, and calculate each value of d using Equation 6.2.

14. For each slit pattern (A, B, or C) record the average value of d and the associated uncertainty (standard deviation).

6.4 Discussion points

Did your experimental values of d for each slit pattern agree with the values given in the introduction within the uncertainties of your data? If not, calculate a percent difference between your nearest possible experimental value and the expected value. Do you have any ideas about why the data differs? Do you have any ideas for how can this experiment be improved?

Chapter 7

Ray Tracing, Images, and Refractive Indices

7.1 Introduction

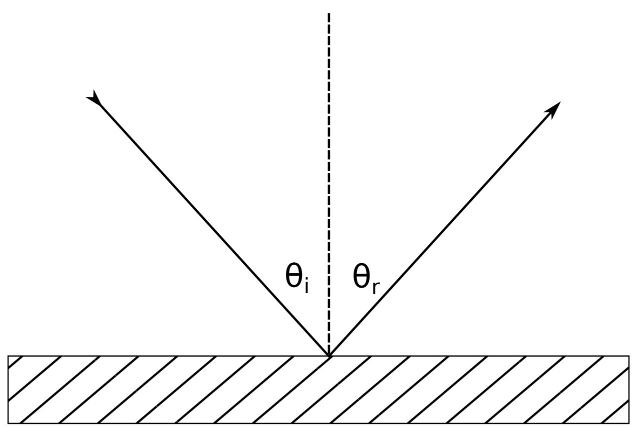

Figure 7.1: Reflection of light from the front of a surface.

Classical optics is the study of the two most obvious ways light can interact with surfaces: *reflection* and *refraction*. Reflection is the simplest of the two phenomena. When a light ray encounters a surface at an angle of incidence θ_i (see Figure 7.1, the ray will reflect (bounce off) the surface at an angle of reflection θ_r according to the Law of Reflection:

$$\theta_i = \theta_r. \tag{7.1}$$

The Law of Reflection leads to interesting consequences. For example, a flat mirror will create a *virtual image* of objects placed in front of it

Refraction is a slightly more complicated phenomenon. The speed of light v in a transparent material is lower than the speed of light in a vacuum c. We usually express v in terms of a material's *index of refraction* n, a dimensionless number greater than 1. The exact

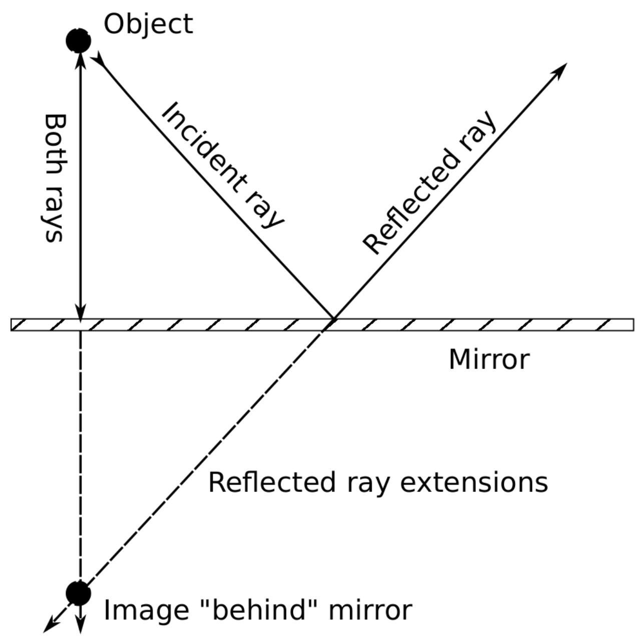

Figure 7.2: An image appearing “behind” a plane mirror.

relationship is

$$v = \frac{c}{n}.$$

If we assume that a ray of light will always take a path between two points that minimizes the amount of time it takes for the trip, a concept known as *Fermat's Principle*, mathematics will lead us to deduce Snell's Law, which states that for a beam with an angle of incidence θ_1 on a surface, the angle of transmission θ_2 can be found using the equation

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \tag{7.2}$$

where n_1 is the index of refraction on the incident side of the surface and n_2 is the index of refraction on the side where the beam is transmitted. (Reflection may also occur at the surface according to the Law of Reflection, Equation 7.1.)

In this experiment, you will use a laser to create a visible ray that you can trace through reflections and refractions on real materials like mirrors and prisms. You will mark the path of these rays on paper with a pencil, and use a protractor to find angles of incidence, reflection, and refraction as needed. You will attempt to find the real and virtual image locations of objects in your mirrors. You will also use your results to find indices of refraction for your prisms.

7.2 Apparatus

Pin board, pins, thumbtacks, paper, ruler, protractor, laser with spreading lens, plane mirror with stand, circular metal mirror, transparent glass prisms.

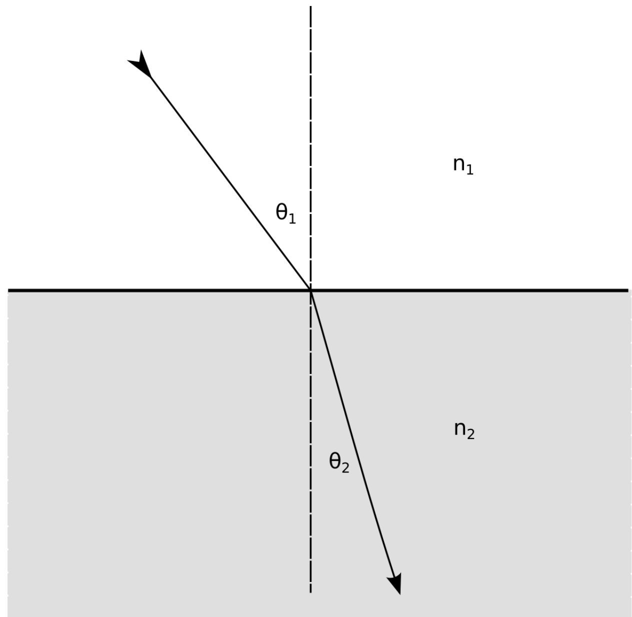

Figure 7.3: Refraction of light into a surface.

7.3 Report Structure

This lab uses a lot of drawings prepared by your group collectively. It is not practical to reproduce these drawings for individual reports. One single group report is all that is required for this set of experiments. Make sure that all requested information is on the pertinent drawings (angles, calculations, etc.).

Your report will have the following pages:

- Cover page, including names of all lab group members
- Plane Mirror drawing
- Circular Mirror drawing
- Transparent Prism drawing(s)

7.4 Procedures

In this set of lab exercises, you will find image locations from a plane mirror and a curved mirror, and find the index of refraction of two glass prisms.

7.4.1 Plane Mirror

When you look in a flat or plane mirror, like the ones found above sinks in bathrooms, you see a virtual image of real objects in the mirror. Mathematically one can show that virtual images in the mirror appear to be the same distance from the mirror as the object that created them. Is that true? Here you will use ray tracing to find out.

1. Place a piece of blank paper on your pin board. Pin the paper to the board at the corners with thumbtacks.
2. Place the plane mirror in its stand at the center of the paper. Use a pencil to trace the location of the front surface of the mirror, taking care not to move the mirror.
3. Place a pin about 5 cm away from the mirror. Circle the pin hole with a pencil.
4. Turn on the laser.
5. Place the laser and beam spreader behind the pin and shine the laser on the pin. You should be able to see a ray going through the pin and onto the mirror, where it reflects away from the mirror. These are the incident and reflected rays.
6. Sketch over the incident and reflected rays with pencil. Your traced rays should be solid lines. Add arrowheads to the rays to show the direction of the rays.
7. Repeat the previous two steps, moving the laser and beam spreader each time, until you have five sets of incident and reflected rays traced on your paper.
8. Remove the mirror and turn off the laser.
9. Place a ruler over each reflected ray so the ruler extends behind the location of the mirror. Use a dashed line to extend the reflected ray behind the mirror. You are marking where the reflected rays appeared to be coming from on the other side of the mirror, if that were physically possible.
10. Find the location where the extended (dashed) lines appear to converge behind where the mirror was. Circle this location. This is the image location of the virtual image of the pin produced by the mirror.
11. Use a ruler to measure the distances between the pin location and the mirror (the *object distance*) and the convergence point of the reflected ray extensions (the *image distance*). Estimate uncertainty in your image distance if the ray extensions don't appear to converge precisely to a single point. (They shouldn't converge precisely; no one can draw that well.)
12. Do your object and image distances agree within your uncertainty? Answer this question briefly somewhere on your drawing.

7.4.2 Circular Mirror

Here you will first measure the *focal distance* f of your circular mirror, which is the distance from your mirror to the point where parallel rays incident on the convex side of the mirror converge. Next, you will measure the distance to the virtual image produced by the convex side of the mirror by parallel incident rays. In either case, theoretical calculations predict that the focal distance is given by the equation $f = \frac{R}{2}$, where R is the radius of curvature of the circular mirror. Will your observations support this calculation?

1. Place a new piece of paper on your pin board.
2. Stand your curved mirror at the center of your paper. Trace around the outside of the mirror, both the convex and the concave sides. The location of your mirror should be marked well enough that you could remove the mirror and later replace it at exactly the same spot.
3. On the concave side of the mirror, draw a line perpendicular to the mirror's surface at the mirror's center.
4. Draw two lines parallel to the first line on either side of that first line. There should now be five lines drawn on the concave side of the mirror. Put arrow heads on the lines toward the mirror. These lines represent your incident rays.
5. For each incident ray, use the laser and beam spreader to cover your it and create a reflected ray visible on the paper. Sketch over this reflected ray, and add an arrowhead pointing away from the mirror.
6. After all the reflected rays are drawn, look for a region of the paper where all the reflected rays seem to converge (approximately). This is the focal point. Mark this spot on the paper.
7. Measure the distance from the focal point to the closest point on the mirror, where the first ray meets the mirror. Write this distance on your paper.
8. Remove the mirror temporarily.
9. Extend all of your incident rays on the concave side through the mirror's usual location to the convex side. Place arrowheads on these rays pointing toward the mirror's usual location. These will be incident rays for the convex side of the mirror.
10. Replace the mirror exactly where it was before.
11. Again, use the laser and the beam spreader to illuminate the incident rays on the convex side so the beam covers only the incident ray markings. You will see reflected rays; trace those rays with a solid line and put arrowheads on them pointing away from the mirror.
12. Remove the mirror again.
13. Use a ruler to extend your convex-side reflected rays to the concave side. These rays should all appear to intersect in approximately one location. Mark this location, and measure its distance from the mirror along the axis of symmetry if you haven't already done so.

14. You must now find the radius of curvature of the mirror. To do so, place the mirror at the edge of its old location, such that it appears to have the same center as it did in its original location. Mark the outside (concave) surface of the mirror with a dashed line.

15. Repeat the previous step until you have made at least half of a complete circle with the mirror, one segment at a time.

16. Use the ruler to find the diameter of your circular arc. Record the diameter D and radius R of your circular arc on your drawing.

17. Compare your focal distance f and your radius R. Is $f \approx \frac{R}{2}$? Find the percent difference.

7.4.3 Transparent Prism(s)

Here you will trace a ray incident on a side of a glass prism. By marking where the ray exits the prism, you can find the complete path of the ray through the prism. You can then use a protractor to find the angles of incidence and refraction at each surface of the prism. Using Snell's Law, Equation 7.2, you can then solve for the index of refraction of your glass prism by assuming that in air, $n = 1$. The index of refraction of glass is often about 1.5. Is that true here?

1. Place a new, blank sheet of paper on your pin board, and secure it with thumbtacks.

2. Place one of your prisms (your choice) in the middle of your paper. Trace around the edge of the prism so you can remove it and replace it exactly if necessary.

3. Use the laser and beam spreader to shine a beam into the prism through a polished surface. (Warning: not all surfaces are polished.) The incident angle (angle from a line perpendicular to the prism's surface) should be about 30°. If your incident ray exits the prism near a corner or is reflected internally from the prism before exiting, move your beam elsewhere.

4. Trace the incident ray, and the final ray exiting the prism. Place arrowheads on these rays indicating their direction.

5. Remove your prism from your paper.

6. Draw normal lines (lines perpendicular to your prism's surface) at the points where the beam enters and exits the prism. Your normal lines should be easily distinguishable from your rays, and should allow you to easily measure angles of incidence and refraction.

7. Finish tracing the ray through the prism by drawing a straight line between the beam entry and exit points with a ruler or straight edge.

8. At each surface where the beam enters or exits the prism, find θ_1 and θ_2 with a protractor. Write these numbers clearly on your drawing.

9. Using Snell's Law, Equation 7.2, solve for the index of refraction of your prism. Write each value on your drawing very clearly near the interface that produced each value.

10. If your prism was square or rectangular, are the first incident and final transmitted rays approximately parallel? If your prism was triangular, does your drawing remind you of a classic rock album cover? If so, which one?

11. If time permits and you wish to do so, you can add additional rays with different incident angles to your drawing as described above. You can also do another drawing for your other prism(s). Only one drawing with one ray tracing is required, however.

Chapter 8

Lenses and the Thin Lens Equation

8.1 Introduction

Lenses are, in their simplest form, pieces of transparent material (like glass or polycarbonate) with spherically-shaped surfaces. By changing the radii of the surfaces, one can define the properties of the lens. The two most common types of lenses are *converging* and *diverging*. They each have different optical properties.

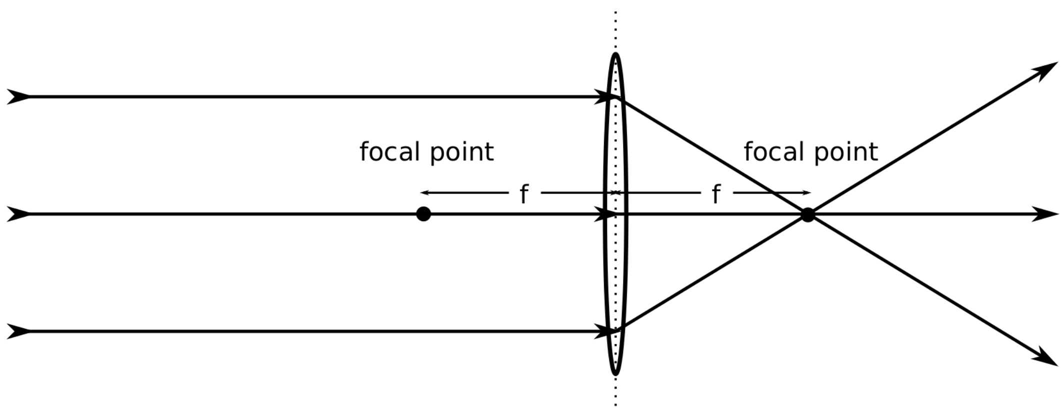

Figure 8.1: A converging lens focusing parallel rays at its focal point.

A converging lens will take incident parallel to the axis of symmetry (or *optical axis*) of the lens and force them to converge to a single point known as the *focal point* on the opposite side of the lens from the incident parallel rays. Each lens has two focal points, one on each side of the lens. Both are on the optical axis of the lens. The distance along the optical axis between the lens (assumed to be very thin) and the focal point is known as the *focal distance* f.

Converging lenses are frequently used to project images on screens. Movie projectors have a converging lens to do the final projection. This ability to create real images is useful for finding the focal length of a converging lens. If you take a converging lens, you should be able to make an image of something very far away and project it on a screen. The distance between the projection and the lens is then the focal length. Figure 8.1 shows how such a projection might work.

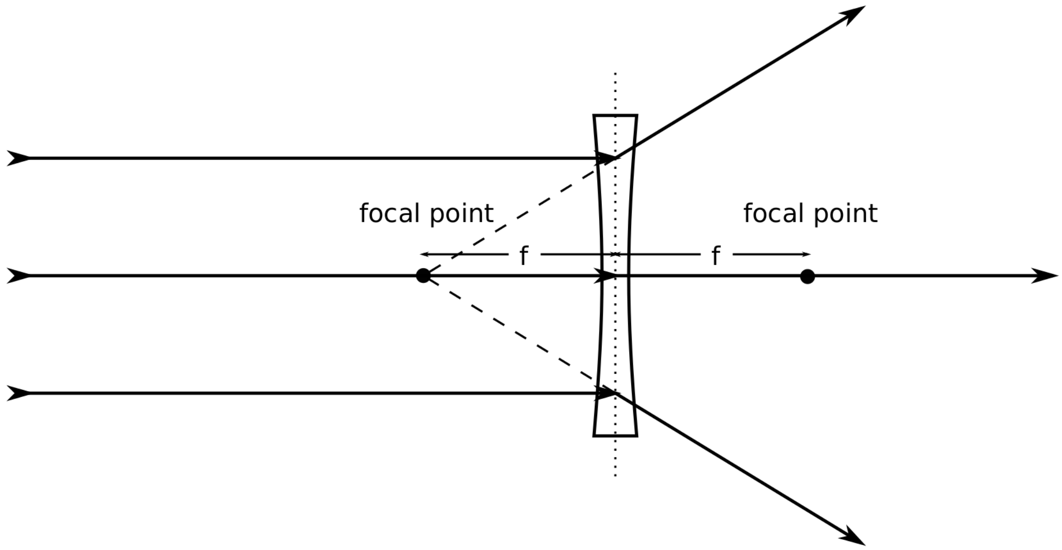

Figure 8.2: A diverging lens making rays parallel to its optical axis appear to originate from the focal point on the same side as the incident rays.

A diverging lens does the opposite of what a converging lens does: it makes rays parallel to its optical axis spread out or diverge. Although this sounds useless, this divergence has many practical uses because of how the rays diverge. They do so in such a way that they appear to originate from a focal point on the opposite side of the lens, as shown in Figure 8.2. As with converging lenses, diverging lenses have a focal length. A diverging lens has a negative focal length, however, while a converging lens has a positive focal length.

Perhaps the largest practical application of diverging lenses is eyeglasses. People who are nearsighted are unable to focus on things at great distances. Light rays from these distant objects are basically parallel. By making these parallel rays appear to come from a much closer focal point, diverging lenses make it possible for nearsighted people (like the author of this lab manual) to focus on distant objects. Diverging lenses move far objects in closer in a sense. Another important property of diverging lenses is that, when placed up close to a converging lens, they create a combination lens with different properties, as we will see below. This can be used to correct optical defects in a lens, for example.

Both converging and diverging lenses create images. Converging lenses create *real images*, while diverging lenses create *virtual images*. Real images are real in that they can be projected on a screen. Virtual images can't be projected on a screen, but otherwise behave like a real image. Real images are upside-down relative to the object that created them, and are usually described as *inverted*. Virtual images are not inverted, and generally described as *upright*. Image locations can be determined using the *thin lens equation*:

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f} \tag{8.1}$$

where o is the distance between the object and the lens, i is the distance between the image and the lens, and f is the focal distance of the lens.

Images are generally not the same size as the objects that created them. (If you take a picture of the Moon, is your image of the Moon the same size as the Moon itself, or is it something smaller that can actually fit within a camera body?) The size of the image relative to the object is known as its *magnification* m, which is given by the formula

$$m = -\frac{i}{o}. \tag{8.2}$$

There are some conventions worth noting. In the work we do here, o is always positive. For a real image i is positive and for a virtual image i is negative. As mentioned earlier, f is positive for a converging lens and negative for a diverging lens. A negative magnification means a real image, and a positive magnification means a virtual image.

We can use Equation 8.1 together with Equation 8.2 to find the focal lengths of both converging and diverging lenses. For example:

- By measuring object and (real) image distances explicitly for a converging lens, we can use those distances to calculate the focal point.
- For a converging lens, an object that is essentially infinitely far away (like the Sun or even the horizon) will produce an image at the focal point.
- For a diverging lens, an image that is half the apparent size of the object means that the object distance is one half the focal length of the lens.

Sometimes two lenses with different focal lengths f_1 and f_2 are placed against one another. They will behave together as if they were a different lens with an equivalent focal length f_{eq}, where

$$\frac{1}{f_{eq}} = \frac{1}{f_1} + \frac{1}{f_2}. \tag{8.3}$$

This can be useful to weaken a lens to some degree, as in the case of bifocals, or to correct optical problems in a lens.

We can use Equation 8.3 to calculate the focal length of a diverging lens. We can place the diverging lens next to a converging lens with a shorter focal length; this will result in a lens combination that is equivalent to a converging lens. By measuring the focal length of this combination, we can solve Equation 8.3 to find the focal length of the diverging lens if the focal length of the converging lens is already known.

In this experiment, you will use the simplest techniques described above to find focal lengths for converging and diverging lenses. You will then use Equation 8.1 and 8.3 to attempt to verify your results. Will these simple techniques work?

8.2 Apparatus

Optical bench, two converging lenses, diverging lens, lens stand, lighted object, screen, ruler, blank paper, graph or lined paper, and adhesive tape.

8.3 Procedures

There are two parts to this lab exercise. In the first you will find the focal length of two converging lenses using two different techniques. In the second part, you will find the focal length of a diverging lens using similar methods.

8.3.1 Converging Lenses

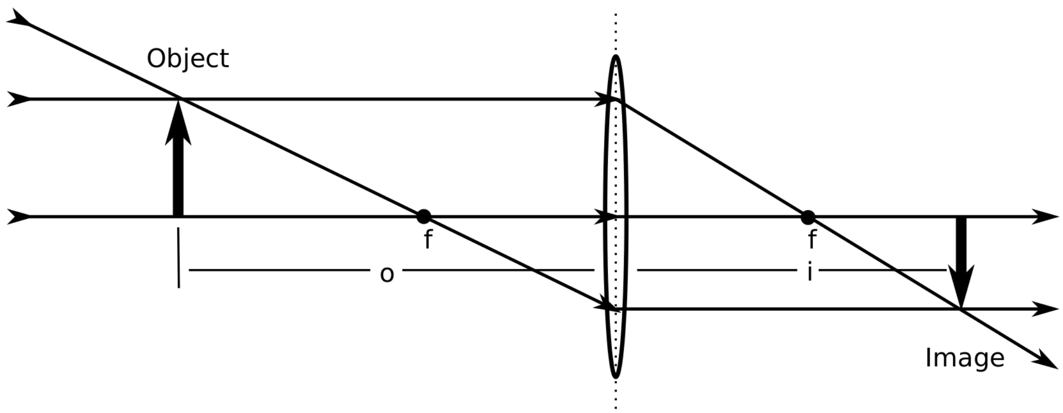

Figure 8.3: A real image produced by a converging lens.

1. Ask your lab instructor to partially darken the room.
2. Take both of your converging lenses to the window without the blind on it. Hold each lens up near the window.
3. Hold a piece of paper such that your lens is between the paper and the window. Move the paper until you see an image on the paper of the most distant object you can reasonably see.
4. Use a ruler to find and record the lens-to-paper distance.
5. Put down the paper. Pick it up again. Return to Step 3 to find a second value for the lens-to-paper distance. Your result will be different than the first because there are, in reality, a range of different possible values where the image will be in focus.
6. The average of your lens-to-paper values is the focal length of the lens determined by this method (the distant object focal length), and half the difference between them is the uncertainty. Record these numbers.
7. Switch converging lenses and return to Step 3 to find the focal length with uncertainty for your second lens.
8. Return with your lenses to your lab station.

9. Place one lens on a lens stand.

10. Place the lighted object at one end of your optical bench, and your screen at the other end. Both the lighted object and the screen should be located such that their center marks are at convenient locations (0 cm, 150 cm, etc.) on the scale that runs the length of the optical bench.

11. Set the lens between the lighted object and the screen such that a real image of the object appears on the screen. Position your lens so the part of your object at the marked location on the scale (like the filament in the light bulb at the center of the object box) is best focused.

12. Record the object and image distances, and find the focal length of the lens using Equation 8.1.

13. Without moving the lighted object or the screen, move your lens to another location to create an image on the screen. Repeat Step 12.

14. Replace your first converging lens with your second lens.

15. Repeat the procedure from Step 11 onward, finding two values for the focal length for the second lens in the process.

In your report, compare the focal lengths you found on the optical bench with the ones you found by imaging distant objects. Do the two different sets of values overlap within their uncertainties? If not, find a percent difference for the closest optical bench and distant object values.

8.3.2 Diverging Lenses

1. Pick up your diverging lens. Examine your piece of graph paper through it. Notice that the lines on the paper appear smaller the farther away you hold the paper.

2. Hold the paper a distance away from the lens such that the distance between parallel lines on the paper appears to be half the distance it normally is.

3. Use a ruler to find and record the lens-to-paper distance.

4. Put down the paper. Pick it up again. Return to Step 2 to find a second value for the lens-to-paper distance. Again, your second result will be different than the first by some small amount.

5. The average of your lens-to-paper values is the focal length of the lens determined by this method (the hand focal length), and half the difference between them is the uncertainty. Record these numbers.

6. Pick up a converging lens and use it to examine the graph paper as if the lens were a magnifying glass. Note how the lens behaves.

7. Place your diverging lens up against the converging lens and see if the combination of lenses behaves like a magnifying glass. If not, try your other converging lens. If neither combination of lenses behaves appropriately, see your instructor.

8. Tape your combination lens together by wrapping tape around their edges.

9. Place your combination lens in a lens holder.

10. Set the lens holder between the lighted object and the screen such that a real image of the object appears on the screen. Position your lens holder so the part of your object at the marked location on the scale (like the filament in the light bulb at the center of the object box) is best focused.

11. Record the object and image distances, and find the equivalent focal length of the combination lens using Equation 8.1. If in doubt, use the exact center of the lens combination as the location of the combination lens.

12. Use Equation 8.3 to find the focal length of the diverging lens by itself. Use your focal length for the combination lens and your average focal length of the converging lens in your calculations.

13. Without moving the lighted object or the screen, move your lens holder to another location to create an image on the screen. Repeat from Step 11 onward to produce a second estimate of the focal length of the diverging lens.

14. Record the average of your two focal length estimates as the focal length of your diverging lens produced by this method (the bench focal length), using half the difference between the values as the uncertainty of the bench focal length.

Do your two bench calculations for the focal length of the diverging lens agree with your hand estimates within their uncertainties? Discuss your results in your report. If the two sets of values do not overlap, find the percent difference between the closest bench estimate and hand estimate.

Chapter 9

Electrostatics

9.1 Introduction

Electrostatics is the study of static, non-moving electric charges. The earliest electricity experiments were really electrostatics experiments. Scientists like Benjamin Franklin, better known in the United States for his work in early-American politics and diplomacy, spent countless hours doing electrostatics experiments in order to learn the basic properties of electric charges, how to store electricity, and the basic physical principles involved in electric phenomena.

Generating a static electric charge in our day is not terribly difficult. Here are some examples:

- Rub a balloon in your hair or on an article of clothing made of wool, polyester, or another insulating fiber.
- Turn on an older, cathode ray tube based television set. The screen will become electrically charged after it has been on for a short time.
- Slide down a plastic slide on a dry day. You yourself will become electrically charged, and your hair will stand on end when you reach the bottom of the slide.

You can likely think of other examples, and early electrical pioneers certainly did. You are in a science class. How can you study these electric charges?

Modern experimenters use a variety of electric and electronic devices, like voltmeters and oscilloscopes, to study electrical phenomena. These devices weren't available in the 1700s, however, and the scientists of that time period learned a lot about electricity from much simpler devices. In this experiment you will do the same. You will use modern, everyday materials like plastic cups, styrofoam, paper clips and aluminum foil to study static charges.

Your principal instrument in this experiment is an *electroscope*, a device used to capture and measure the intensity (qualitatively) of an electric charge. You will have an opportunity to measure the charge from a number of different static electricity sources. Which ones do you think will be the most charged? Will your electroscope prove your predictions?

9.2 Apparatus

Clear plastic drink cups with lids, paper clips, aluminum foil, balloons, CRT television set displaying arbitrary content (a menu screen is fine), Wimshurst generator, wires, alligator clips.

9.3 Procedures

There are two parts to this experiment:

- Building an Electroscope
- Collecting Electric Charge Data

Note that the two parts have equal weight. This experiment is as much about designing and building your instrument as it is about using it. You should develop an appreciation for engineering as much as science in this lab exercise.

9.3.1 Building an Electroscope

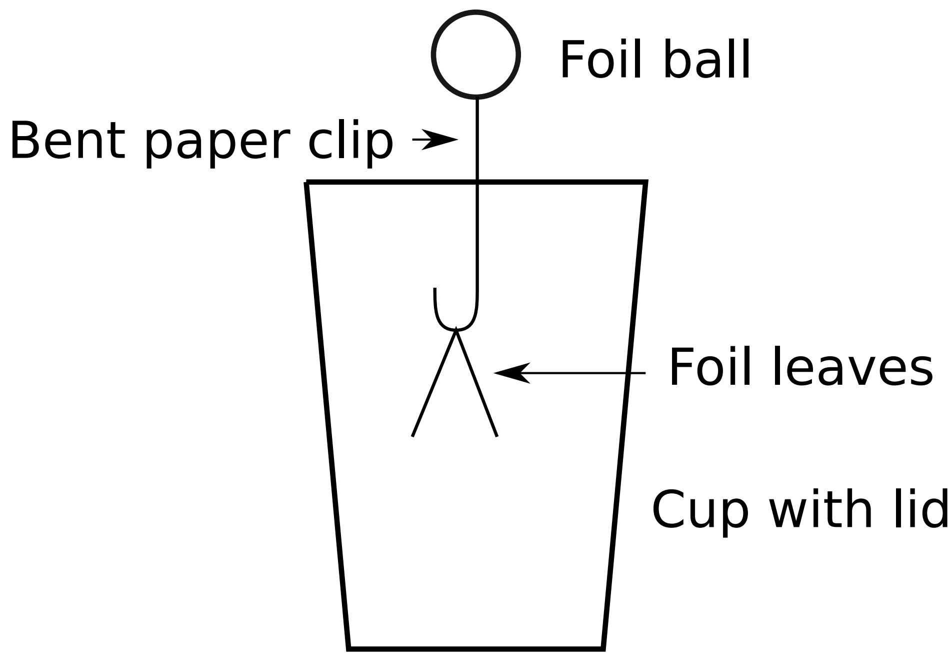

Figure 9.1: A simple electroscope.

Using a clear plastic cup, a lid, a bent paper clip, and some aluminum foil, attempt to create an electroscope similar to the one shown in Figure 9.1. Refer also to the example your instructor has made. Note that the foil leaves in the figure above are shown spread apart. When you first make your electroscope, the leaves should be hanging parallel to one another.

When you touch the foil ball to a statically-charged object, charge will collect in the device at the foil leaves, causing the leaves to spread apart as shown.

Don't be afraid to change your electroscope once you've built it. If you think the device will work better if you change it, give it a try. Just be sure to use the exact same device for collecting data with all of your different charge sources.

9.3.2 Collecting Electric Charge Data

Here your goal is to collect as much electric charge as you can from several different sources, including:

- A charged balloon
- The television screen
- The Wimshurst generator (with instructor help)
- A glass rod rubbed with silk
- A plastic rod rubbed with wool

If you can think of another interesting charge source, feel free to add that to the list. (I'm sorry we don't have a plastic playground slide.)

After you collect charge from each source into your electroscope, take a look at the foil leaves inside it. Note the angle between the two leaves, and write down whether it is approximately zero, small (less than 45°), medium (45° to 90°), or large (greater than 90°). The larger the angle, the more charge the electroscope has collected.

After your data is collected, make a list of all the charge sources from those that provided the least charge to those that provided the most. Is this the ordering you would have expected prior to the experiment?

Chapter 10

Electric Potential and Field Lines

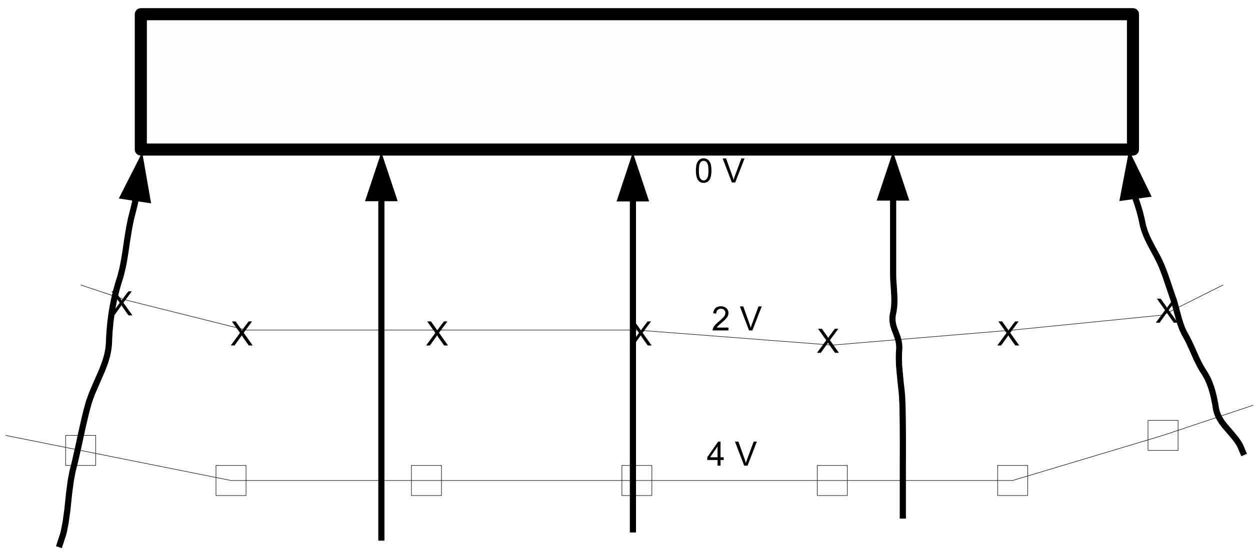

Figure 10.1: Example of an electric potential map with field lines

10.1 Introduction

The force on an electric charge q is proportional to the electric field in the space around it:

$$\vec{F} = q\vec{E},$$

where $\vec{F}$ is the force vector and $\vec{E}$ is the electric field vector. When a charge moves in a conducting material, it needs a force to move it, so there must be an electric field as well to keep a charge moving. It is sometimes useful to know which way the electric field is pointing in a given region of space.

Unfortunately, tools for mapping electric field strength and direction are not commonplace. A much more common electrical meter is a voltmeter, which finds the electric potential difference (or voltage, hence the name) between two points. Voltmeters are part of every digital multimeter, an inexpensive tool you may already own (simple ones cost only a few dollars). There is a relationship between potential difference and electric field strength, namely

$$E = \frac{\Delta V}{\Delta x} \tag{10.1}$$

where ΔV is the (small) change in potential between points a (short) distance Δx apart. Electric field is always directed from high to low electric potential, perpendicular to the curves of equal electric potential (or *equipotentials*), so we can use a map of electric potential to determine electric fields in a given region of space. Know the electric potential and you can deduce the electric field.

In this experiment you will place metallic cylinders in a tray of water and apply a potential difference, or voltage, to the cylinders. One cylinder will be at a potential of 10 V, and the other will be at 0 V, and both cylinders will sit on a piece of paper. Because of the potential difference, charge will flow between the cylinders, which means there must be an electric field at every point in space between them. You will use the voltmeter in a digital multimeter to map numerous equipotentials (places with the same electric potential, like 2 V) between the cylinders. You will use a special pencil that writes underwater, a *film marker*, to mark numerous points at the same electric potential. Later you will connect these points together with lines to show where the equipotentials are. Once you have five or more equipotentials (including the cylinder surfaces, all parts of each one being at the same electric potential) you will use this information to show numerous electric field lines between the two cylinders.

Your final electric potential and field maps are for the two-dimensional surface where your paper lay during the experiment. One can also show that these maps also apply to infinitely-long, straight cylinders as well. In other words, you can map electric fields and potentials for some classic physics examples in three-dimensions (one isolated line charge, two parallel line charges, two parallel plane charges, and a line charge near a plane charge) with your two-dimensional experiments.

This experiment does not easily lend itself to individual reports, as it involves painstaking work on wet pieces of paper. You won't have time to make a plot for each lab group member. Your final report will be a group report, not an individual report. Also, producing electric field maps takes plenty of time by itself. There will be no need for a conclusion section.

10.2 Apparatus

Plastic tray, water supply, paper, film marker, digital multimeter, 5 cookie-cutter-like metal cylinders (large round, two small round, and two long rectangular), two long metal probes (lengths of copper wire), power supply, 2 red and black long wire lead pairs (one red and one black lead per pair), 3 alligator clips, and drying line with paper clips to hold the wet paper maps during the drying portion of the experiment. And *lots* of paper towels.

10.3 Procedures

Complete this basic set-up procedure and use it for all of your scenarios:

1. Fill your plastic tray with 2-3 cm of water if it isn't already filled.
2. Turn on your power supply and adjust the coarse and fine voltage adjustment knobs until the power supply reads 10 V.
3. Plug one black lead into the negative (-) terminal on the power supply.
4. Plug one red lead into the positive (+) terminal on the power supply.
5. Plug one red lead into the voltmeter plug on the multimeter. (Ask for help if necessary.)
6. Plug one black lead into the common plug on the multimeter. (Ask for help if necessary.) Connect the other end to the negative (-) terminal on the power supply.
7. Plug an alligator clip into the loose end of all three unconnected leads.
8. Clip the red lead from the multimeter to one of the two probes about two inches from one end.

In this experiment you will examine the following scenarios:

A. Isolated line charge (one large round cylinder and one metal probe)

B. Two parallel line charges (two small round cylinders)

C. Two parallel plane charges (two rectangular cylinders)

D. Line charge near a plane charge (one small round cylinder, one rectangular cylinder)

For each scenario, complete this procedure:

1. Describe the scenario at the top of a clean sheet of paper (e.g. "Isolated Line Charge," "Scenario A", etc.).
2. Immerse your sheet of paper face-up in the tray of water. Tap it down gently until it rests flat at the bottom.
3. Place the two cylinders for your scenario on the paper, emerging from the water as described below for each scenario:

   A. Place the large circular cylinder down around the center of your page, and use a metal probe instead of a second cylinder.

   B. Place the cylinders across from each other around the center of the page.

   C. Place the rectangular cylinders parallel to one another, centered on the page center.

   D. Place the round cylinder so it is directly above the center of the rectangular cylinder, centered on the page center.

   If you are uncertain where to place your objects, talk to the instructor.

4. Clip one lead from each power supply terminal to each cylinder. Hold the leads if necessary to prevent the cylinders from falling over through the course of the experiment.

5. Turn on the multimeter. Set it to operate as a DC voltmeter that can read up to 10 V. (Each multimeter is different; ask your instructor for help if necessary.) Test your multimeter by touching the probe to the cylinder connected to the red lead from the power supply. The multimeter should read 10 V.

6. Use your film marker to trace the perimeter of each cylinder onto the paper beneath them. Write the electric potential of each cylinder (0 V or 10 V) next to each perimeter. These are your first two equipotentials.

7. Place your multimeter-attached probe in the water between the two cylinders. Find a point at 2 V. Mark that point on the paper with an "X" using your film marker. (You will use other distinct symbols to indicate points at other electric potentials. This will make drawing the equipotentials easier.)

8. Find numerous other points where the electric potential is 2 V, and mark those points with an "X" also. You are done when you can look at the points you have plotted and you can easily connect them to fill in a sketch for the entire 2 V equipotential. Find points all around each cylinder if you can do so. (You will "connect the dots" later, after your paper has dried.)

9. Repeat the previous two steps for 4 V, 5 V, 6 V, and 8 V. Use a different marking symbol (like squares, dots, circles, and triangles) to mark the points to make the different equipotentials distinct from one another.

10. Turn off the power supply, disconnect the leads to the cylinders, and remove them from the water, placing the wet cylinders on a paper towel to minimize the mess. Remove your paper from the water and hang it on a drying line until it is completely dry.

Collect data for all four configurations. Once your papers are dry, finish your plots by adding electric field lines as follows. For each configuration:

1. For each voltage, sketch lines to connect adjacent data points. Your equipotential for that voltage is now complete.

2. Make five evenly-spaced marks on the 0 V equipotential, which is the outline for one of your cylinders. For circular cylinders, your points should be evenly spaced around the circle. For rectangles, put your points on the long, flat edge facing the other cylinder.

3. For each point you made in the previous step, use a regular pencil to start drawing a line perpendicular to the 0 V equipotential. Extend this line toward the 2 V equipotential, gradually turning the curve as needed to make the curve cross the equipotential at a right angle. Keep drawing the curve until you reach the 10 V equipotential. If need be, erase your curve and start over to get a better curve. Practice makes perfect.

4. Add several arrow heads to your curves pointing from the 10 V equipotential toward the 0 V equipotential. Your electric field lines are complete.

On each map, add a marker to indicate some location where the electric field is strongest. Your electric field lines will be closest together at this location. Also, mark a region where the electric field is weakest, meaning where the electric field lines are furthest apart or possibly even nonexistant.

Chapter 11

Resistors and Ohm's Law

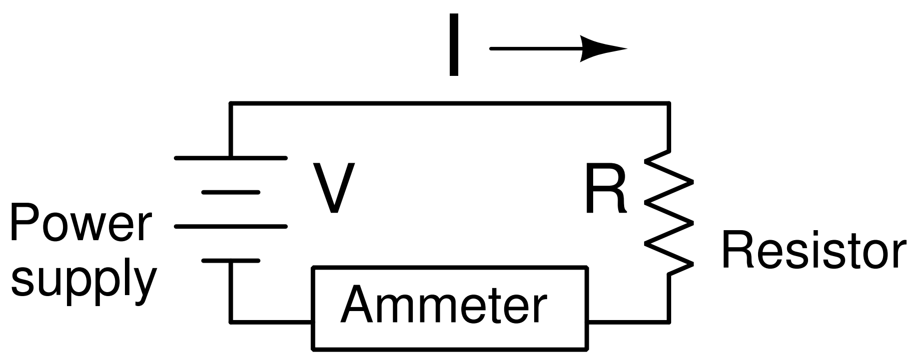

Figure 11.1: A simple resistor circuit

11.1 Introduction

For most materials that conduct electricity to any degree, there is a simple relationship between the current I that flows through them when an electric potential (or voltage) V is applied across them. That relationship is known as *Ohm's Law*, and is usually given as

$$V = IR. \tag{11.1}$$

The quantity R is the material's *resistance*, and it is measured in volts per amp, or ohms (Ω).

Perhaps the most common component in any electric circuit is the *resistor*, a piece of conducting material whose resistance is known to a certain precision. A common type of resistor, the through-hole axial lead reisistor, looks like a piece of painted plastic with wires (or leads) sticking out of each end, as shown in Figure 11.2. The painted bands tell you what the rated resistance is of the device. Each band represents a specific number, and the total resistance of a resistor is given by the formula $R = N_1N_2 \times 10^{N_3} \pm \Delta R$, where N_i is the number represented by the ith painted band. The uncertainty of the resistance ΔR is

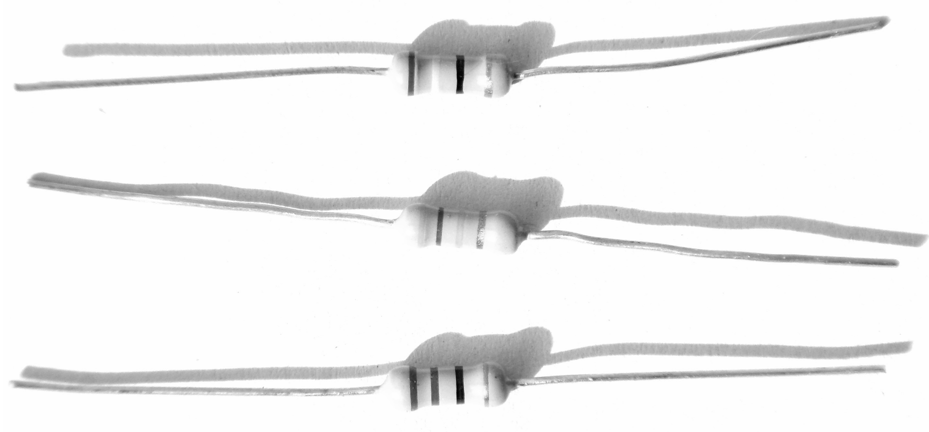

Figure 11.2: Some common through-hole axial lead resistors

given by the number represented by the tolerance band color. Tolerance bands have different colors (like gold or silver) than the other bands, and they appear last or second to last. If you are unsure how to read resistor bands, identify the tolerance band and place it to your right. If you don't find one, put the most space on the resistor on your right. Table 11.1 shows all the different possible band codes you need to know in this experiment.

In this lab, you will read the bands of a resistor to determine the rated values, with uncertainty, for each of three resistors. You will then determine the resistance of each resistor two other ways for comparison. The first method involves recording the current I passing through each resistor for five different applied voltages V between 0 V and 18 V. You will then plot V vs. I (remember, it's always plot Y vs. X) using a spreadsheet program and then fit the data with a trendline (best-fit line). The slope of the trendline is R. Finally, you will use the Ohmmeter function of a digital multimeter to find resistance more directly.

11.2 Apparatus

Three resistors of varying values, wire leads, alligator clips, digital multimeter, computer with spreadsheet program like Microsoft Excel or OpenOffice/LibreOffice Calc.

11.3 Procedures

Use your power supply, multimeter, wire leads and alligator clips to create the circuit shown in Figure 11.1. For each resistor, perform the following procedures:

1. Record the rated value of each resistor using the painted bands and Table 11.1, including the uncertainty.

2. Connect the resistor into the circuit using the alligator clips.

3. Turn on your power supply. Record the current I flowing through your resistor for at least 5 different values of applied voltage V between 0 V and 18 V.

Color of Stripe i	Meaning
Black	$N_i = 0$
Brown	$N_i = 1$
Red	$N_i = 2$
Orange	$N_i = 3$
Yellow	$N_i = 4$
Green	$N_i = 5$
Blue	$N_i = 6$
Violet/purple	$N_i = 7$
Grey	$N_i = 8$
White	$N_i = 9$
Gold	$\Delta R = \pm 5\%$
Silver	$\Delta R = \pm 10\%$
None	$\Delta R = \pm 20\%$

Table 11.1: Resistor stripe codes and their meanings

4. Enter your data into a spreadsheet program, and plot V (y-axis) versus I (x-value). Find the slope of the trendline that best fits the data. Record this slope as one observed value of R.

Finally, use the ohmmeter function of your multimeter to find a second observed value for the resistance R of each resistor.

11.4 Analysis and Conclusions

You have now determined the resistance of your three resistors two different ways, using a V versus I plot and using an ohmmeter. How do these values compare with the rated value for each capacitor? In your analysis and conclusion, answer these questions:

- Did your two observed values for the resistance of each resistor fit within the range of possible values indicated by its colored bands? If not, what was the percent difference between your observed value and the closest possible value the resistor was rated at?
- What was the percentage difference between your two experimentally-determined values? If you have reason to believe one method produced a better result than the other, explain why.

Chapter 12

Capacitors

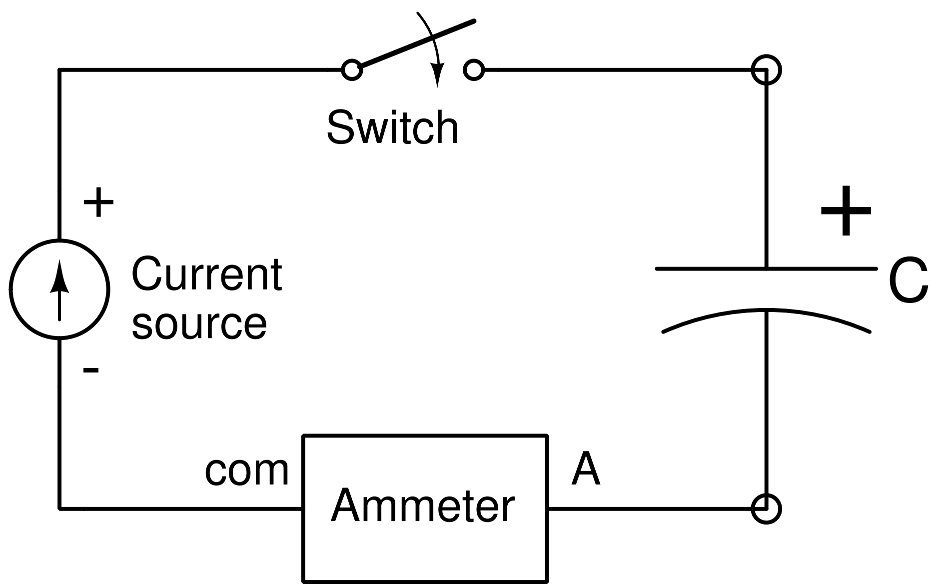

Figure 12.1: Schematic of your charging capacitor

12.1 Introduction

A capacitor is a device used to store electric charge. When a voltage V is applied across its terminals, a charge Q builds up on the positive plate according to the equation

$$Q = CV \tag{12.1}$$

where C is a property of the capacitor known as its *capacitance*. The capacitance of a specific capacitor depends on many parameters of the capacitor, such as the size of its conducting plates, the distance between them, and the materials in between.

You can measure the capacitance of a capacitor directly by connecting it to a *current source*, an electronic device that can provide a constant change in electric charge per unit time (current) as long as its applied voltage is below a certain maximum value. When the voltage needed to apply the desired current reaches this value, the current source shuts off. The power supplies in the lab can function as current sources when they are set in that mode. If a capacitor is connected to a current source set to provide a current I at time $t = 0$ when $Q = 0$, then at a later time t

$$Q = It \tag{12.2}$$

If we set Equations 12.1 and 12.2 equal to one another, we discover that at a time t when the voltage reaches its maximum value V,

$$C = \frac{It}{V} \tag{12.3}$$

By recording the time it takes, with uncertainty, to charge the capacitor with a known current and maximum voltage, we can thus find its capacitance with uncertainty. (Assume that the uncertainty in I and V is negligible.)

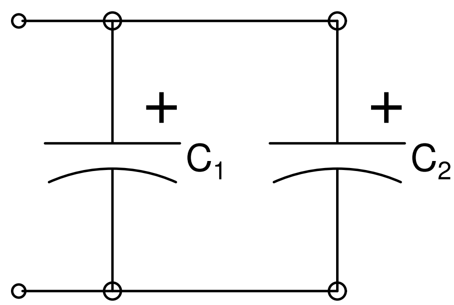

Figure 12.2: Two capacitors (C_1 and C_2) in parallel

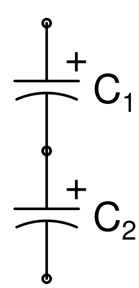

Figure 12.3: Two capacitors (C_1 and C_2) in series

It is possible to use multiple capacitors together so they act collectively like a single capacitor with some different capacitance. For example, imagine two capacitors with capacitances C_1 and C_2 are connected as shown in Figure 12.2. By assuming that the voltage across each capacitor is the same, you can show that the two capacitors together act like a single capacitor of capacitance C_{eq} whose capacitance is given by the formula

$$C_{eq} = C_1 + C_2. \tag{12.4}$$

You can also connect two capacitors end-to-end, as shown in Figure 12.3, to make a different equivalent capacitance. By assuming the charge across each capacitor is the same, you can conclude that

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}. \tag{12.5}$$

You will attempt to verify these equations in this experiment.

12.2 Apparatus

Power supply, 2 polar electrolytic capacitors (nominally $41,000$ μF), stopwatch, digital multimeter, wires with banana plugs (including shorting leads), electrical switch resembling a Morse code key.

12.3 Procedures

12.3.1 Setup

To set up for this experiment, you must first set up the power supply to act as a 0.100 amp current source:

1. Turn all current and voltage adjustment knobs to zero (counterclockwise).
2. Connect a cable between the positive (+) and negative (-) terminals on the power supply. (Under other circumstances this short circuit can damage equipment, but your supply is built to handle this connection without a load appropriately.)
3. Turn the coarse voltage adjustment up 1/4 turn or so.
4. Flip the switch next to the display on the power supply to the “Amps” setting.
5. Turn on the power supply. Turn the coarse and fine current adjustment knobs until the display reads 0.100 A.
6. Disconnect the lead between the positive and negative terminals.
7. Flip the switch on the power supply from “Amps” to “Volts.”
8. Turn the coarse and fine adjustment knobs until the display reads 18 V. (Changing the voltage setting again will not be necessary.)

9. Flip the switch next to the display back to the “Amps” setting.

Next, connect leads to create the circuit shown in Figure 12.1. To follow DC wiring conventions, use red wires to connect the power supply positive terminal, the switch, and the positive terminal on your first capacitor. Use black wires to connect the capacitor’s negative terminal, the digital multimeter, and the power supply’s negative terminal. All multimeters are different, so don’t hesitate to ask your instructor how to do the multimeter connections.

Note that your capacitors are *polar*. They are designed to have higher voltages connected only to the positive (+) terminal. Make sure that the positive terminal of the power supply connects only to the positive terminals of the capacitors.

12.3.2 Finding the capacitances

You must find the capacitances of a) each capacitor individually, b) their serial combination, and c) their parallel combination. In the case of the combinations of capacitors, think of them as a single capacitor. Connect the capacitors together appropriately first, then add a short red lead to the positive terminal of the combination and a short black lead to the negative terminal of the combination. Finally, connect the power connections to make the circuit look like the one shown in Figure 12.1.

Use the following procedure to find the capacitance of each test case:

1. While the switch is open, touch the red and black shorting leads together to discharge the capacitor(s). Electrical arcing will occur, along with a loud popping noise. This is normal.

2. Close the switch and start the timer simultaneously. The multimeter will display a constant value of I (approximately 0.100 A, or 100 mA) in a short amount of time. Record this value.

3. Stop the timer when the current reading on the multimeter starts to drop abruptly, or when the LED lights on the front of the power supply change color. Record this value of t.

4. Use Equation 12.3 to calculate the capacitance or equivalent capacitance of your test case.

Record at least five values for capacitance or equivalent capacitance for each test case. Your observed values are the average of your highest and lowest values, and the uncertainty is the absolute value of the difference between this average and the highest or lowest value.

In your conclusion, answer the following questions:

a Does the rated value of each capacitor ($41,000\ \mu$F) fit within the range of your observed values?

b Calculate equivalent capacitances using your observed capacitances of each capacitor (ignoring uncertainty) and Equations 12.4 and 12.5. Do these values fit within the range of observed values you obtained?

If either answer is no, find the percent difference between your closest observed value and the expected value and record this percent difference in your report.

Chapter 13

Energy and Efficiency

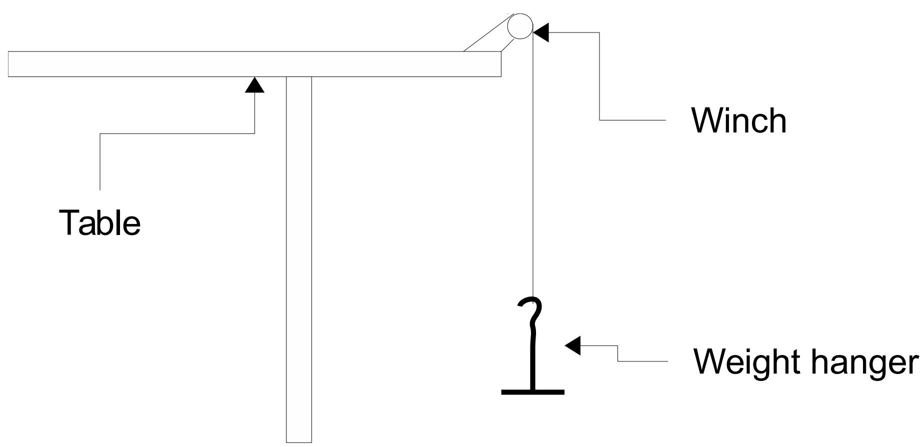

Figure 13.1: An electric winch

13.1 Introduction

There are many kinds of machines that change one form of energy to another. When we look at such devices, we are often interested in their *efficiency*, which measures how much energy is lost in the conversion. We can judge the relative merits of different energy conversion devices in part based on their efficiency. Efficiency e is defined mathematically as

$$e = \frac{W_{out}}{W_{in}}, \tag{13.1}$$

where W_{out} is the total amount of work we get out of the device, and W_{in} is the work supplied to the device. Ideally, efficiency should equal one, but in all real world situations, it is less than one. Often much less.

Let us now consider a device that converts electrical energy to gravitational potential energy: a winch. A winch is simply a motor or engine that turns a shaft, causing a line to wind around its axle and raising a load from a lower height to a higher one. For a winch, the amount of work it does raising an object of mass m to a height h above its starting point is mgh, where g is the strength of acceleration due to gravity (9.80 m/s^2). For electric winches operating at a steady, constant rate, the work they do in a time t is equal to t times the winch's *power* P, which is defined as

$$P = VI, \tag{13.2}$$

where V is the supply voltage and I is the electric current supplied by the device. So,

$$\begin{aligned} e &= \frac{mgh}{Pt} \\ &= \frac{mgh}{VIt}. \end{aligned} \tag{13.3}$$

How efficient are winches in reality? Is their efficiency close to 1? How close?

In this experiment, the goal is to learn more about the efficiency of a real device, the winch. This experiment will also help develop intuition about the power supplied to electrical devices.

13.2 Apparatus

A small electric winch (a motor attached to gears and an axle), digital multimeter, string, alligator clips, wire leads, power supply, weights, weight hangers, meterstick, and a stop watch.

13.3 Procedures

Set up the apparatus as follows:

1. Connect a red wire lead to the positive (+) terminal of the power supply. Attach an alligator clip to the other banana plug on the red lead.

2. Clip the alligator clip on the red lead to the red wire on the winch.

3. Connect a black wire lead to the negative (-) terminal of the power supply. Connect the other end to the COM terminal on your digital multimeter.

4. Connect another black lead to one of the A terminals (mA, 10 A, etc.) terminals on the digital multimeter. Attach an alligator clip to the other banana plug on this black lead.

5. Clip the alligator clip on the black lead to the black wire on the winch.

6. Turn all of the current and voltage knobs on the power supply all the way down (counterclockwise).

7. Flip the power supply display switch to the Volts setting.

8. Turn the coarse current adjustment knob up halfway, so its indicator faces straight up.

9. Turn on your digital multimeter. Make sure it is in an appropriate DC ammeter setting. Ask the instructor if you need help understanding how to use the ammeter setting (all the multimeters are different).

10. Unwind the string completely from the axle of the winch by pulling it sideways.

11. Attach a weight hanger to the string.

12. Turn on the power supply and turn up the voltage using the coarse voltage adjustment knob until the string begins to wind around the axle of the winch at a steady, comfortable pace. Read the ammeter, and make sure you can come up with a good average reading.

13. When the weight hanger rises to the maximum height you would like it to go, turn off the power switch on the power supply. Unwind the string to bring the weight hanger back to its lowest point.

You are now ready to collect data, which consists of values of m, h, V, I, and t for each run.

To record your data, first make some sort of table to contain it. (A spreadsheet program is an excellent tool for making tables.) The table columns should be m, h, V, I, t, and e, and the column headers should contain appropriate SI units (kg, m, etc.). Use the following steps to fill in the table:

1. Record m, the mass of the weight hanger plus any weights it is holding.

2. Record h, the change in height the weight hanger will experience during your run.

3. With the weight hanger at its lowest point, turn on the power supply and the stopwatch simultaneously.

4. Record V from the value on the power supply.

5. Record I, the average current from the ammeter while the weight hanger is being lifted by the winch. (The number will fluctuate a little; make your best estimate.)

6. When the weight hanger rises to its maximum desired height (say, 0.5 m above its starting point), stop the stopwatch.

7. Turn off the power supply and unwind the string from the axle until the weight hanger is at its lowest point again.

Don't be afraid to make test runs, where you vary parameters like V during the run to get it to work the way you want it to. You only need to record data you trust; if you think something is wrong, fix it and try again.

Each run should be a little different. Your first run should have just the weight hanger. For the next run, add a significant amount of weight to the hanger but don't change the voltage on the power supply. For the next run, increase the voltage to get the run time to be approximately equal to that of the first run.

13.4 Questions for Conclusions Section

In your conclusion section, talk about what happened to the efficiency when

- The mass m being lifted by the winch increased.
- The speed of the lift increased when the voltage went up.

Did the efficiency change substantially? If there was a change, was it the way you might have expected, or was it opposite?

Chapter 14

Magnetic Field in a Coil

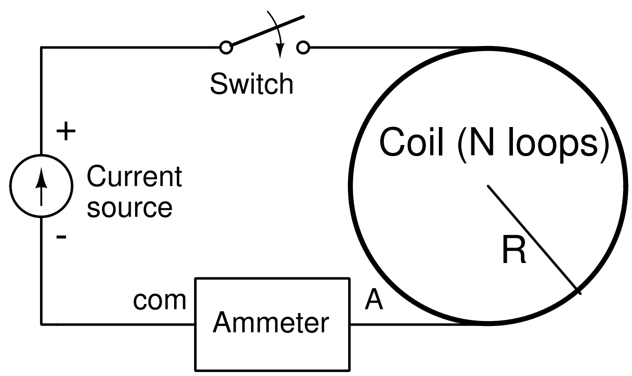

Figure 14.1: Circuit schematic for measuring magnetic field in a coil of wire

14.1 Introduction

When you run a current through a circular coil of wire, it creates a magnetic field in the region of space around the coil. At the very center of the coil, the formula for the magnetic field strength B measured in tesla (T) is given by the formula

$$B = \frac{\mu_0 N I}{2R}, \tag{14.1}$$

where μ_0 is the magnetic permeability of free space $(4\pi \times 10^{-7}\ \frac{\mathrm{T{\cdot}m}}{\mathrm{A}^2})$, I is the current in amps, N is the number of loops of wire in the coil, and R is the radius of the loop in meters. Note that the formula is proportional to both N and I.

In this experiment, you will attempt to verify this proportionality for both N and I. You will use a magnetic field sensor attached to a computer running Logger Pro to measure the magnetic field at the center of your loop. Unfortunately, the magnetic field sensor is difficult to calibrate; the default reading on the computer is probably not measuring field strength accurately in tesla. However, its reading should be proportional to the true value, so we can use its results to verify whether or not the magnetic field strength is proportional to N and I as predicted.

14.2 Apparatus

Computer with Logger Pro, magnetic field sensor, field sensor mounting block, power supply, digital multimeter (ammeter), Morse code-type switch, long wire for coil, wire spool/pipe, wire leads, alligator clips.

14.3 Procedures

14.3.1 Setup

Use the following procedure to assemble your loop circuit:

1. Wrap the wire around the spool ten times. Make sure that the loops of wire are close together. They can be on top of one another.

2. Insert the field sensor mounting block (a block of wood with a channel cut down the middle) into the wire spool.

3. Using a black lead and an alligator clip, if necessary, connect one end of the loop to one of the ammeter terminals of the digital multimeter.

4. Connect the COM terminal of the digital multimeter to the negative (-) terminal of the power supply using another black lead.

5. Connect a red lead to the other end of the wire loop using an alligator clip, and connect the other end of that lead to a terminal on the switch.

6. Connect another red lead from the second switch terminal to the positive (+) terminal on the power supply.

7. Insert your sensor into the channel in the mounting block. Slide the sensor until its hooked end rests in the plane of your coil of wire. Alternately, if the mounting block is not available, tape your sensor to the bottom of the spool such that the dot on the hooked end of the sensor is approximately at the center of your coil.

8. Turn on your power supply. Set the switch near the display to the amps setting.

9. Set the coarse voltage adjustment knob to vertical. Set the fine voltage adjustment knob to 0

10. Hold the switch closed. Set the coarse and fine current adjustment knobs so that the ammeter reads 3 A. When you are finished, open the switch.

11. Turn on your computer and Logger Pro, if necessary.

12. Disconnect any sensors other than the magnetic field sensor from the LabPro interface box, a green plastic box connected by cable to the computer. Make sure that the magnetic field sensor is plugged into CH1.

13. Click the small icon that looks like the LabPro box in the upper left corner of the Logger Pro window.

14. Click the button in the CH1 pane, then select Choose Sensor — Magnetic Field.

You are now ready to collect data.

14.3.2 Proportionality with Current

The magnitude of the magnetic field detected by the detector should be shown near the upper left corner of Logger's display. At first, your magnetic field sensor is measuring whatever portion of Earth's magnetic field is in the same direction as the sensor. You will "zero away" Earth's magnetic field in your experiment when you collect data.

Use the following procedures to collect data about how the magnetic field depends on current:

1. Click the zero button on Logger Pro to eliminate any magnetic field reading not coming from your wire loop.

2. Close the switch. Your magnetic field reading should jump to a fairly constant value. Record the current and an average magnetic field reading, either by watching the number in Logger Pro and recording an average value or by recording data for a few seconds and averaging the value using the Statistics button.

3. Turn down the current until it is 0.5 A lower than before.

Repeat these steps until you have data for $I = 0.5$ A. Make a plot of B versus I for these data points using a spreadsheet program, and fit a line (a "trendline") to the data. Attach the plot of this data, including the linear fit, its equation, and its correlation coefficient, to your report. In your opinion, is a line a good fit for this data?

14.3.3 Proportionality with Number of Loops

You will now record the magnetic field at the center of your loop as a function of the number of loops for 6 values of N, starting with $N = 10$ and working down one loop at a time. To set up for this experiment, close your switch and turn up the current until it is at 3.0 A again.

Use the following procedure:

1. Click the zero button on Logger Pro to eliminate any magnetic field reading not coming from your wire loop.

2. Close the switch. Your magnetic field reading should jump to a fairly constant value. Record the current and an average magnetic field reading, either by watching the number in Logger Pro and recording an average value or by recording data for a few seconds and averaging the value using the Statistics button.

3. Unwind one loop from your spool. Make sure that the wire leads entering and exiting the loop are perpendicular to the plane of the loop as much as possible.

You are finished collecting data when you have recorded the magnetic field at the center of the loop for $N = 5$. Make a plot of B versus N similar to your previous plot, including the best fit line, its equation, and its correlation coefficient. In your opinion, is a line a good fit for this data?

Chapter 15

Earth's Magnetic Field

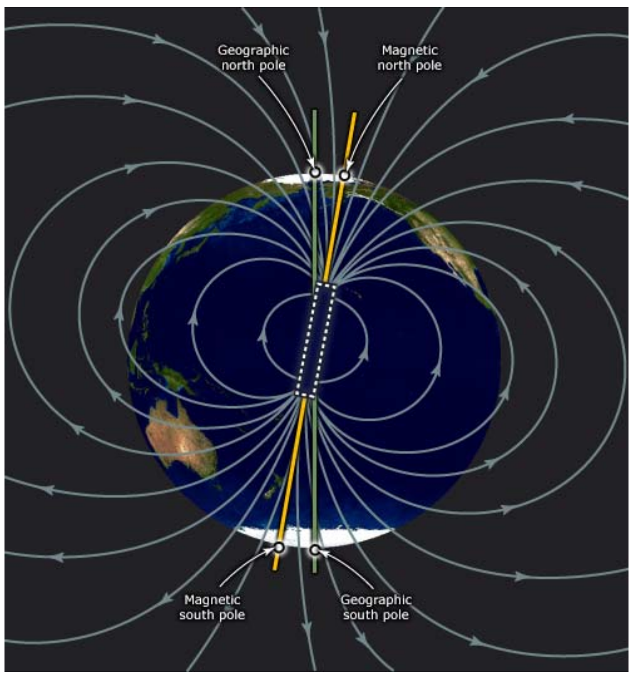

Figure 15.1: Global view of Earth's magnetic field lines (source: http://www.TeAra.govt.nz/en/diagram/9213/earths-magnetic-field)

15.1 Introduction

Like a bar magnet, Earth has a magnetic field surrounding it. Field lines emerge from Earth's magnetic south pole and re-enter at the magnetic north pole, as shown in Figure 15.1. For many centuries now, we have used this magnetic field for navigational assistance using instruments like the compass. Unfortunately, the axis of these poles is offset from Earth's rotational axis by an angle of about 11.5°, so magnetic and true north are rarely the same. We can compensate for this offset by making detailed maps of Earth's magnetic field using simple instruments like the compass, its vertically-mounted cousin the dip needle, and current-carrying coils of wire. If we know how Earth's magnetic field behaves in a given part of the Earth, we can still use a compass for navigation, even if it doesn't point true north. To have a complete map, we need to know the magnetic field vector $\vec{B}$ at a given location.

We can find the direction easily enough using a dip needle; the needle points in the direction of the field, and we can measure its angle ϕ relative to the horizon directly. This value is known as the *inclination* of the magnetic field. Orient the plane of the dip needle in the magnetic north-south direction, in the same direction a compass points, then read the angle directly. Measuring the magnetic field strength B is a little harder. We can measure the horizonal component using a coil. Simply line up the coil so its plane, again, is in the north-south direction, as you did with the dip needle. Place a compass in the middle of the coil, then read its deflection angle θ as you vary the current I in the coil. One can show that the magnitude of the field in the coil B_c is given by the formula

$$B_c = \frac{\mu_0 N I}{2R}, \tag{15.1}$$

where μ_0 is the magnetic permeability of free space ($4\pi \times 10^{-7}\ \frac{\mathrm{T\cdot m}}{\mathrm{A}^2}$), I is the current in amps, N is the number of loops of wire in the coil, and R is the radius of the loop in meters. Using trigonometry, we can show that

$$B_c = B_h \tan\theta. \tag{15.2}$$

We can also show, again using simple trigonometry, that

$$B_h = B \cos\phi. \tag{15.3}$$

We can now solve Equation 15.2 for B_h and substitute this result into Equation 15.3:

$$\begin{aligned} B &= \frac{B_h}{\cos\phi} \\ &= \frac{B_c}{\tan\theta\cos\phi} \\ &= \frac{\mu_0 N I}{2R\tan\theta\cos\phi}. \end{aligned} \tag{15.4}$$

In this experiment, you will use Equation 15.4 to find the total magnetic field strength at your current location. You will change the amount and direction of current flow in your coil to change the angle θ a compass needle at the center of your coil points. You can then enter this information into Equation 15.4, along with a known value of ϕ, to find the total magnetic field strength. You will also look up a value produced by a commonly-used geomagnetic model through the Internet. Does the model value agree with your observations within uncertainty?

15.2 Apparatus

Compass, dip needle, power supply, multimeter/ammeter, alligator clips, variable-turn coil, and three wire leads (one long red lead and two black leads, one of the same length as the red lead), computer with Web browser.

15.3 Procedure

Use the following procedure to measure the total magnitude of Earth's magnetic field. Note that for best results, your lab station should be in a place free of large quantities of ferromagnetic materials like iron or steel. Unfortunately, your lab station will most likely be in a building with a steel frame, or on an outdoor concrete pathway made of steel-reinforced concrete. If you are inside a building, perform the experiment as close to an exterior wall as possible. If you are outside, try to get as far away from concrete as possible.

15.3.1 Set up

To set up your coil for your experiment:

1. Take one long red lead and a black lead of identical length. Twist the two wires together many times, as if you were making a rope.
2. Connect alligator clips to one end of each colored lead.
3. Connect the red lead to the positive (+) terminal on the power supply.
4. Connect the black lead to the ammeter terminal on the digital multimeter. Ask for help if necessary.
5. Connect the COM terminal on the multimeter to the negative (-) terminal on the power supply with another black lead.
6. Clip one alligator clip to the leftmost terminal on the coil, and the other clip to the rightmost terminal. You can move one or both of these clips later to change the effective number of turns N in your coil.
7. Turn the coarse voltage adjustment knob to about half its maximum value (straight up).
8. Turn the fine voltage adjustment knob and both current adjustment knobs all the way to the left.
9. Flip the switch next to the display on the power supply to the Amps setting.
10. Place your power supply as far away from the coil as possible, and try to make the wire leads connecting to the coil run straight out (perpendicular) from the coil.
11. Place your compass at the center of the horizonal bar in the middle of your coil. Its center should sit directly on top of the crosshair markings at the center, and the north-south line of the compass should run straight across the coil.
12. With no current running through the coil, turn the coil until the needle points north-south.

15.3.2 Collect reference data

1. Open a Web browser, like Opera, Safari, Chrome, or Internet Explorer, on your computer.

2. Navigate to the National Oceanographic and Atmospheric Administration's magnetic field calculator page at `http://www.ngdc.noaa.gov/geomag-web/`.

3. Click the Magnetic Field tab.

4. Use the search page to find your exact location (using either ZIP code or country/city combination), then click the Calculate button.

5. Record the accepted values of the inclination (ϕ) and the total field (B). Use these values for comparison in the rest of the experiment.

15.3.3 Collect experimental data

Your instructor should have set up a dip needle somewhere in the lab room for you to examine. Compare the inclination on the dip needle to that you found on the NOAA site, taking care to correct the dip needle reading if it measures from the vertical instead of from the horizonal. It should agree roughly with the NOAA value. Note that you should use the NOAA value in all calculations, as the dip needle may not be on a level surface.

Your goal is to collect at least 4 measurements of B. For each measurement:

1. Turn on your power supply. Record the current I, including its sign. (The first time you run the experiment, I is positive. If you ever reverse the flow by changing where you plug in the leads, for example, I is negative.)

2. Wait for the compass needle to settle down. When it does, record θ.

3. Count the number of turns of the coil between the alligator clips. Record this number as N.

For an easy way to create a new data set, unhook the alligator clips and connect them to the coil opposite the way you used them in the previous run. I will have an opposite sign from the previous run, as will θ. The absolute value of θ will also be different, mainly because it is difficult to align the compass precisely with the coil.

Chapter 16

Diffraction and Spectroscopy

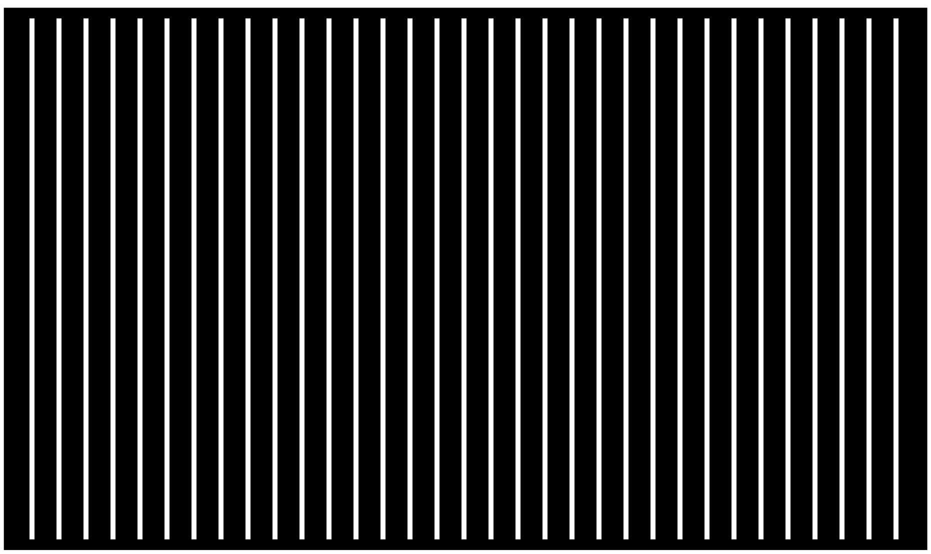

Figure 16.1: A magnified view of a diffraction grating. The distance between adjacent slits is d.

16.1 Introduction

In this experiment, you will create and use a primitive spectrometer in the lab, and use it to identify the wavelengths of light in the emission spectrum of hydrogen. Before you can perform this experiment, you must first understand how your spectrometer operates. You must also learn more about spectroscopy in general. This introduction will help you learn the fundamentals.

16.1.1 Diffraction Gratings

In an earlier experiment we studied the interference of light as it passes through a single pair of narrow, closely-spaced slits in an opaque slide. The interference maxima, or bright bands, in the interference pattern occurred at angles θ according to the formula

$$m\lambda = d \sin\theta, \tag{16.1}$$

where d was the distance between any two adjacent slits, λ was the wavelength of the light being used, and m was an integer describing the order of the fringe (0, ±1, ±2, etc.).

It turns out there's nothing particularly special about the double slit experiment. You get similar results for three slits, four slits, or any higher number of slits for that matter. The maxima all occur according to the formula above, the only difference is that the bright bands become brighter and narrower when more slits are added. What happens when you have an infinite number of these slits? It turns out that the interference pattern becomes a *diffraction pattern*, a series of bright lines with broad dark areas in between them. The bright lines, or interference maxima, still appear according to Equation 16.1. The series of slits that produces a diffraction pattern is called a *diffraction grating*.

Diffraction gratings have many uses. When light of multiple colors, like ordinary white light, is shined on a diffraction grating, the grating scatters the component colors at different angles according to Equation 16.1. In other words, a diffraction grating functions much the same as a prism would. (Diffraction gratings are now much less expensive to produce than prisms, and so they have replaced prisms in many scientific instruments.) This ability to split light into its component wavelengths allows us to perform interesting experiments.

16.1.2 Spectroscopy

Your lab station has several glass tubes filled with elemental gasses: mercury and hydrogen. You can run an electric current through the gasses, causing their electrons to move from lower energy to higher energy states. These higher energy, or *excited*, electrons with energy E_n will only stay in these states for a short time before dropping back to lower energy states E_m. The quantities n and m are integers known as *quantum numbers* that describe an electron's energy. In this case, $n > m$ and $E_n > E_m$.

To drop from higher energy E_n to lower energy E_m, electrons must get rid of their excess energy $E_n - E_m$ by emitting small packets of light called *photons*. Every type of atom will emit different wavelengths of light during this process. By splitting up the light from these excited gasses and identifying its component wavelengths, a process called *spectroscopy*, we can gather information useful for identifying the gasses.

Quantum mechanics tells us that for hydrogen, these photons must have energies ΔE given by the formula

$$\begin{aligned} \Delta E &= E_n - E_m \\ &= 13.6\text{eV}\left(\frac{1}{m^2} - \frac{1}{n^2}\right), \end{aligned} \tag{16.2}$$

where 1 eV is one *electron volt*, the amount of energy an electron acquires in crossing a potential difference of one volt. Quantum mechanics also tells us that

$$\Delta E = \frac{hc}{\lambda}, \tag{16.3}$$

where λ is the wavelength of the emitted photon and h is a physical constant known as *Planck's Constant*. If we combine Equations 16.2 and 16.3, we can conclude that

$$\lambda = \frac{hc}{13.6\text{eV}} \left(\frac{1}{m^2} - \frac{1}{n^2} \right)^{-1}. \tag{16.4}$$

If we use Equation 16.4 to calculate wavelengths we can actually see, ones with wavelengths of 400-700 nm, we discover that we are only interested in cases where $m = 2$ and $n > 2$. We are left with the *Balmer Series*,

$$\begin{aligned} \lambda &= \frac{hc}{13.6\text{eV}} \left(\frac{1}{4} - \frac{1}{n^2} \right)^{-1} \\ &= \frac{1}{R} \left(\frac{1}{4} - \frac{1}{n^2} \right)^{-1} \end{aligned} \tag{16.5}$$

where R is known as Rydberg's Constant and has the value of 1.097×10^7 m^{-1}.

If we examine the light from an excited hydrogen gas sample through a diffraction grating, we should be able to see different wavelengths of light, or colors, from the sample scattered at different angles. When we use the angles and Equation 16.1 to calculate the wavelength of the light, we would expect our results to agree with Equation 16.5. Do they?

16.2 Apparatus

Discharge lamp, mercury tube, hydrogen tube, two metersticks (one white), ring stand, diffraction grating, lens holder, and masking tape.

16.3 Procedure

In the first part of the procedure, you will assemble your spectrometer from the parts provided. Next you will calibrate your spectrometer by finding a key number, the slit spacing d of the diffraction grating, through the observation of the emission spectrum of mercury. With this information in hand, you will proceed to the final part of the experiment to measure the wavelengths and uncertainties of as many components of the emissions spectrum of hydrogen as you can. You will then compare these values with the closest values calculated using Equation 16.5. Do your results agree with the calculated values within uncertainty?

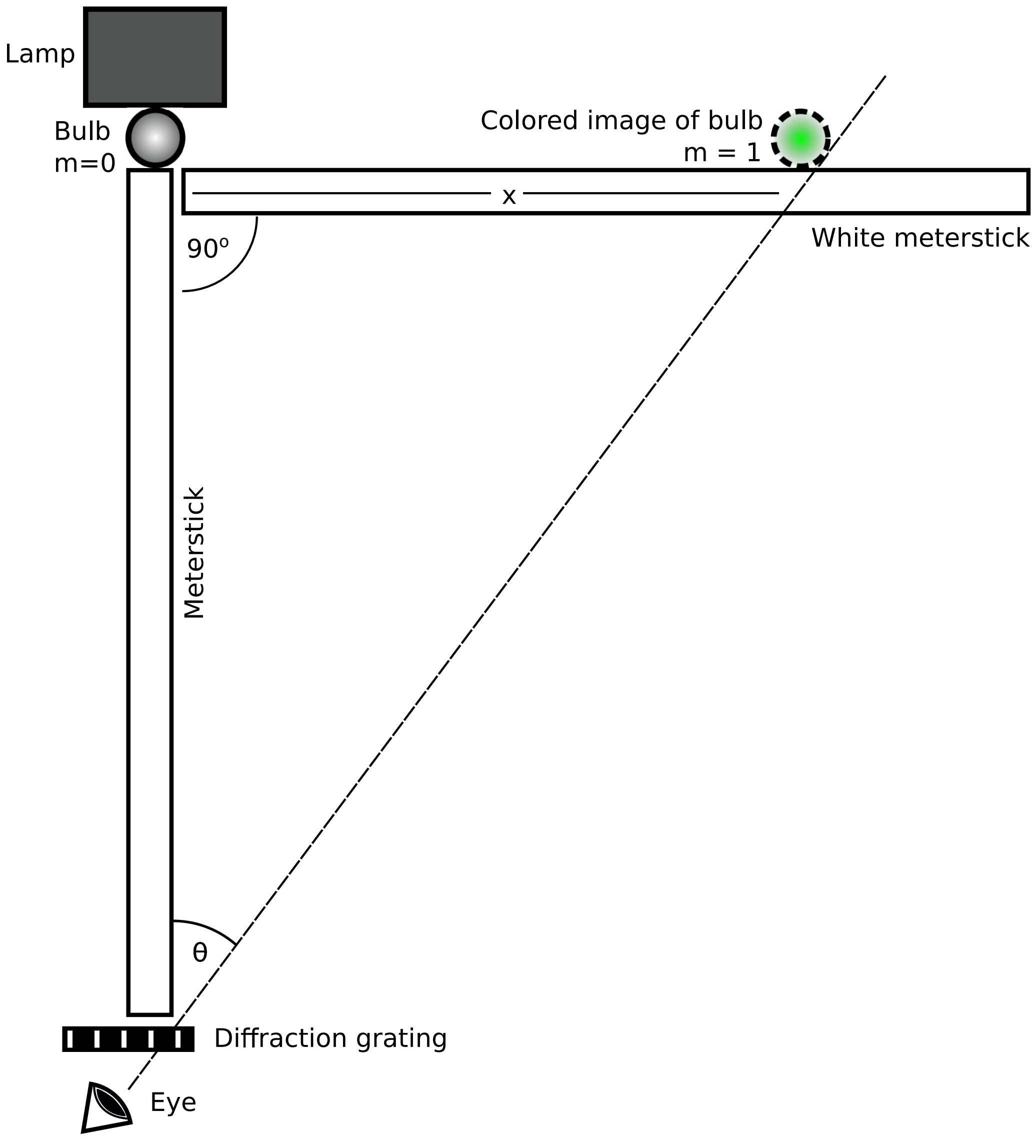

Figure 16.2: A completed spectrometer.

16.3.1 Building Your Spectrometer

1. Place your discharge lamp on your lab table. Place a meterstick on the table in front of the lamp, so its end is located at the bulb of the lamp. If one of your metersticks isn't white, use that meterstick here.

2. Put your diffraction grating in the lens holder, and place the lens holder at the other end of the meterstick.

3. Attach your white meterstick to the ring stand at the 50 cm mark. Adjust the ring stand so the meterstick is about as high off the table as the center of the bulb in the discharge lamp.

4. Move the ring stand so the white meterstick is perpendicular to the other meterstick. Its 0 cm end should appear to be just touching the right edge of the bulb in the discharge lamp when viewed through the diffraction grating.

Now that your spectrometer is completed, it is important that you don't move any of its major components, either deliberately or accidentally, during the rest of the experiment. If you do, try to put them back as best you can.

16.3.2 Calibration

Before you can use your spectrometer to examine the spectrum of hydrogen, you must first calibrate it. In this case, calibration means finding the slit spacing d for your diffraction grating.

1. If necessary, carefully remove the existing bulb from your discharge lamp and replace it with the mercury bulb.

2. Turn on your discharge lamp and ask your instructor to dim the lights in the lab.

3. Look through the diffraction grating at the discharge lamp. What you are seeing is the $m = 0$ maxima in the diffraction pattern created by the diffraction grating.

4. Now look through the diffraction grating to the right of the $m = 0$ image of the glowing lamp. You should see several colored images of the lamp. These are the higher order maxima in the interference pattern.

5. Locate the rightmost edge of the first green image of the glowing bulb, as shown in Figure 16.2. This is the $m = 1$ maximum for the green wavelength in the the mercury spectrum. The markings on the white meterstick should also be visible through the diffraction grating.

6. Record the location on the meterstick x of this rightmost edge of the first green image of the bulb as precisely as possible. Your measurement should have three significant digits, and should be in meters.

7. Trigonometry tells us that the tangent of θ is $x/(\text{ 1m})$. The wavelength of this green light λ is known to be 546 nm. Solving Equation 16.1 for d tells us that

$$d = \frac{546\text{nm}}{\sin(\tan^{-1} x)}. \tag{16.6}$$

   Calculate and record d.

8. Have all other members of the lab group perform from Step 4 onward. You should have two or three different values of d. No two values should be identical.

9. Calculate and record a value of d with uncertainty using the average and the standard deviation of all of your group's observed values of d.

16.3.3 Spectroscopy of Hydrogen

Here your goal is to record the visible wavelengths of the emission spectrum of hydrogen, and compare your results (with uncertainty) with calculations of the wavelengths using the Balmer Series, Equation 16.5.

1. Turn off your discharge lamp. Carefully remove the mercury bulb from your discharge lamp and replace it with the hydrogen bulb. Turn the lamp back on. Find the central maximum in the diffraction grating.

2. Look for a colored image of the glowing bulb to the right of the last image you examined. Have each member of the lab group record x, the location of the right edge of the image on the white meterstick. Again, these results should not all agree.

3. We must now calculate the wavelength of this color light. We know $m = 1$, so

$$\lambda = d \sin(\tan^{-1} x). \tag{16.7}$$

   Use this equation twice to find the largest and smallest possible values of λ. To find the largest value, plug the largest possible values of d ($\bar{d} + \Delta d$) and the largest value of x found by your group. To find the smallest value, plug in the smallest possible value of d ($\bar{d} - \Delta d$) and the smallest value of x found by your group.

4. Repeat from Step 2 onward for all the visible colors in the emission spectrum of hydrogen that you can see. You should have 3 or 4 wavelengths total.

5. Calculate the first 3 or 4 wavelengths predicted by Equation 16.5. Plug in $n = 3, 4, 5$ (and if you were able to see 4 lines, $n = 6$) and record the computed values.

6. Compare your observed values with the values computed from the Balmer Series. Do each of the computed values fit within the uncertainties of one of your observed values? If not, calculate the percent difference between your nearest observed and computed values.

Chapter 17

Radioactive Decay and Random Processes

Atoms come in two types: *stable* and *unstable*. A stable atom will stay the way it is indefinitely. The most common variety (or *isotope*) of hydrogen, ${}^1_1H$, is a stable isotope. Unless something happens to it, it will remain ${}^1_1H$ forever. Unstable isotopes, like the carbon isotope ${}^{14}_{7}C$, will eventually decay to other elements. It is impossible to say exactly when a particular atom of an unstable isotope will decay, but eventually it will.

We can talk about large numbers of atoms with reasonable certainty. If we have a large number of atoms (like one billion) of an unstable element in a sample, we know that after a certain amount of time, half of those atoms will have decayed. This time is known as the *half-life* of an isotope. Mathematically, we can say that if we know the half-life $t_{\frac{1}{2}}$ of an isotope and the initial number of atoms N_0 of that isotope, there should be a number of atoms of that isotope N after time t given by the formula

$$N(t) = N_0 \left(\frac{1}{2}\right)^{t/t_{1/2}}. \tag{17.1}$$

We can use this information to estimate the *probability*, or chance, that an undecayed atom will decay in a given time interval. The probability $P(t)$ of an atom decaying in a given amount of time t is proportional to the number of atoms that have decayed during that time interval, so

$$\begin{aligned} P(t) &= \frac{N_0 - N}{N_0} \\ &= 1 - \left(\frac{1}{2}\right)^{t/t_{1/2}}. \end{aligned} \tag{17.2}$$

We can use this information to simulate the decay of a collection of atoms. The simulation will resemble a board game. If we know the probability that an atom will decay in a given time interval, we can define one turn of our game to be that time interval. We can then generate a random number through some random process, like flipping coins. Our random number will be the probability of that particular coin flip outcome occurring. If that number is less than or equal to the probability of our atom decaying, the decay process occurs, and we can mark the atom as decayed using a wooden token. If not, we try again on the next turn.

Today we will consider a two-step decay process of krypton isotope $^{76}_{36}Kr$. The first step is the beta decay process of krypton to bromine,

$$^{76}_{36}Kr \rightarrow \beta^{+} + \ ^{76}_{35}Br, \tag{17.3}$$

has a half-life of 9.7 hours. The decay product $^{76}_{35}Br$, however, is also unstable. The bromine isotope decays through beta decay to selenium,

$$^{76}_{35}Br \rightarrow \beta^{+} + \ ^{76}_{34}Se, \tag{17.4}$$

with a half-life of 17.2 hours. Let us define our turn to be 3.5 hours. If we do that, we can calculate that the probability of a krypton-bromine decay is 0.22, and the probability of a bromine-selenium decay is 0.13.

It turns out that these probabilities are easy to replicate with coin flips. The probability of two flipped coins landing heads is one in four, about the same as the probability of a krypton-bromine decay. The probability of three flipped coins landing heads is one in eight, about the same as the probability of a bromine-selenium decay.

Using this game-style process, you will model a system of four krypton atoms. On each turn, you will do an appropriate flip of two (for krypton) or three (for bromine) coins to see if the atom decays. If it does, you will change the atom's token. If not, you won't. (Selenium is stable, and will not require any coin flipping.) At the end of the turn, you will count the number of krypton, bromine, and selenium atoms remaining and record those numbers in a table. You will also record the number of krypton atoms you would expect to have left according to Equation 17.1. The simulation is over when all of your atoms have decayed to selenium or when 25 turns have elapsed.

For large N_0, the number of krypton atoms should follow Equation 17.1. Here, $N_0 = 4$, which is not a large number by any measure. Do you think your number of krypton atoms will follow the exponential decay predicted by Equation 17.1?

17.1 Apparatus

Four three-sided decay tokens, three pennies, a small plastic cup.

17.2 Procedure

1. Create a data table, either on an ordinary piece of paper or in a spreadsheet program. (A spreadsheet can do repetitive calculations for you.) Use these column headers:
   - Turn number
   - Time (h)
   - # of Kr atoms (predicted)
   - # of Kr atoms (observed)

- # of Br atoms (observed)
- # of Se atoms (observed)

2. Place your four wooden tokens in front of you with the Kr symbol facing you. All of your atoms are now krypton atoms, and your turns are about to start.

3. Record the current turn number n in your table, along with the current time $t = (3.5\ \text{h})n$.

4. Calculate the expected number of Kr atoms that should be remaining according to Equation 17.1 and record the number in your table to two significant digits.

5. For each atom you still have, give them a chance to decay. If your atom is:

   - Kr: place 2 pennies in your cup, shake the closed cup, and pour them on the table. If they both show heads, turn that atom's token to the Br side.
   - Br: place 3 pennies in your cup, shake the closed cup, and pour them on the table. If all three show heads, turn that atom's token to the Se side.
   - Se: do nothing (selenium is stable).

6. Record the total number of tokens that are showing Kr, Br, and Se in your table.

7. If all your atoms are Se or you have completed turn 25, your simulation is completed. If not, add one to the turn number, return to Step 3 and continue the simulation.

17.3 Discussion Points

Discuss the following in your report:

- Did all of your krypton atoms decay, at least to bromine, by the time 25 turns had elapsed?

- Did the number of krypton atoms per turn agree reasonably well with the predictions of Equation 17.1? If not, does this constitute an experimental error of some sort, or is this just something that can happen?

- If other people in the lab obtained different results than you did, what does this mean? Did they do something wrong?

- If you repeat the experiment using the same procedures, do you expect to obtain the same results?