Physics 111 Summer Section 031 Lab Manual

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Contents

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

Linear Motion Lab

3.1 Introduction and Hypothesis

For motion in one dimension, you can describe the motion of an object using the equations

$$x = x_0 + v_0 t + \frac{1}{2}at^2 \tag{3.1}$$

$$v = v_0 + at \tag{3.2}$$

where x is the position of the object, v is its velocity, t is the time, v_0 is the object's velocity at time $t = 0$, and a is the object's (constant) acceleration. The purpose of this lab is to examine one-dimensional motion that fits this description, and to build familiarity with the lab equipment in the process.

You will use the computer to record your position as a function of time, and try to reproduce three states of motion:

1. Constant position x,

2. Constant velocity v,

3. Constant (non-zero) acceleration a.

Your hypothesis should either be that you can, or cannot, produce these states by walking around the room. Your hypothesis can cover each state individually, or you can make a blanket statement about all three states.

3.2 Apparatus

Computer with Vernier Logger Pro and a motion detector attachment.

3.3 Procedure

Turn on your computer if necessary. Find the motion detector, a green plastic box with a hinged portion, and make sure it is attached by cable to the Dig/Sonic1 port of the Vernier

LabPro interface. Set the motion detector at the end of your lab table, and bend the hinged part so it is vertical. There is also a switch under the hinged part; make sure the switch is set to the man icon instead of the cart icon.

The hinged part of the motion detector has a grate on it that looks like a speaker. This part sends out a series of acoustic clicks that you can hear. It also contains a microphone. The motion detector records the amount of time it takes for it to hear the clicks it makes, and it can use that information to figure out how far away an object is. This process is called echolocation, and it is what bats and submarines use in place of vision. Echolocation allows the Logger Pro software to make graphs of position, velocity, and acceleration as a function of time.

The switch tells the motion detector to look for large or small objects. If it ever seems like it isn't working, flip the switch to the other setting, regardless of what it is currently set to. It can also help to change the angle of the hinged portion.

3.3.1 Constant Position Measurement

Start the Logger Pro software. It should automatically recognize the motion detector. Have one of your lab group members stand in front of the motion detector. The Logger Pro software has an icon that looks like a green play button on a piece of audio equipment. When you click that button, the Logger Pro will begin to record data with the motion detector. That will produce a position versus time plot by default.

Try to make a position versus time plot that shows a constant position for some amount of time. There will, however, be some uncertainty in the position measurement that will cause the plot to look jittery. You can use the Statistics button at the top of the Logger Pro interface to gather statistics for your constant position region. Highlight the portion of the graph that appears to show a constant position for the standing lab partner. Click the Statistics button. A box of data will appear, showing the mean and standard deviation of position for the highlighted region. Print this plot and include it in your report. Make a copy for each member of the lab group.

3.3.2 Constant Velocity Measurement

You can change Logger Pro so it displays velocity versus time instead of position versus time. To do so, right-click on the word Position on the y-axis. A drop-down will appear. Choose Velocity instead of Position. The plot now shows velocity versus time.

Collect data with Logger Pro using the same procedure you used above, but this time, have your lab group member try to move away from the motion detector at a constant speed. In an ideal world, this will produce a flat line on the Logger Pro plot. There will, of course, be some uncertainty in the plot. Again, highlight a region of the plot that shows approximately constant speed and use the Statistics button to measure the mean velocity and the standard deviation. Include a copy of this plot in each lab group member's report.

3.3.3 Constant Acceleration Measurement

Change Logger Pro so it displays an acceleration versus time graph by right-clicking the word Velocity and changing to Acceleration. The plot now shows acceleration versus time. Collect data with Logger Pro while your lab group member tries to move away from the motion detector at a constant acceleration. This involves moving away from or towards the motion detector in a controlled fashion. It will take some time. If at first you don't succeed in capturing constant acceleration, try again, as many times as it takes. Again, use the Statistics button to find the mean acceleration, along with its standard deviation.

3.4 Discussion Points

While writing your conclusion, be sure to include a table of your position, velocity, and acceleration measurements. Their uncertainties should be recorded in the table also. You may (or may not) want to discuss some of these questions in your conclusion:

- How easy was it to produce constant speed, velocity, and acceleration? Which was easiest? Which was hardest?
- Did you fail at any of these measurements?
- How could you make this experiment work better in the future?

Chapter 4

Accelerated Motion Lab

4.1 Introduction

One of the easiest ways to see accelerated motion is to examine the influence of gravity. Near the surface of the Earth, objects accelerate downward at a constant acceleration commonly expressed as g. In the vertical direction, we can say that

$$a = -g = -9.8 \text{ m/s}^2 \tag{4.1}$$

where the sign indicates that the acceleration is downward, not upward. So if we're examining the motion of something that can move vertically, we expect its motion to be described by the equation

$$\begin{aligned} y &= y_0 + v_0 t + \frac{1}{2} a t^2 & (4.2) \\ &= y_0 + v_0 t - \frac{1}{2} g t^2 & (4.3) \end{aligned}$$

where y is the height of the object at time t, y_0 is its height at time $t = 0$, and v_0 is its velocity up or down at time $t = 0$.

You will learn later that $g = 9.8$ m/s^2 is a simplification. The value of g depends on factors like position on the Earth's surface (latitude, longitude, and altitude), as well as geologic features for a specific location. In this lab you will attempt to measure g, along with its uncertainties, several different ways. In your hypothesis, discuss whether or not you think you will find g to be close to the generally accepted value.

4.2 Apparatus

Meterstick, long tape measure, small and large balls, video camera, computer with Logger Pro software, a built-in camera, motion detector, and iMovie video editing software.

4.3 Procedures

You will be measuring g using three different techniques: manual timing of falling objects, photographic timing of falling objects, and finally automated data collection. In the first two methods, you will drop an object from rest and measure the time t it takes to fall from a known height y_0 to height $y = 0$, assuming an initial velocity of zero. Equation 4.3 tells us that

$$0 = y_0 - \frac{1}{2}gt^2.$$

Solving for g yields

$$g = \frac{2y_0}{t^2}. \tag{4.4}$$

4.3.1 Manual Timing of Falling Objects

In the first method, you will drop balls from a tall structure, the parking garage across the way from the Multipurpose Building. You will time the fall with a timer of your choice, and you will measure the distance y_0 traveled by the falling balls (typically this distance is about 11 m) with the long tape measure. With this information, you can use Eq. 4.4 to calculate maximum and minimum values of g. One member of your group will drop the balls from the structure. Another will time the fall. The third member of your group will record the results from the timing as well as the measured drop distance.

Recording the drop distance is easy, but getting the drop times is hard. It takes practice to start and stop the timer at the right time. Record 5 drop times total, but if any of the drop times don't look right, feel free to discard the measurement and do another. Dropping balls from the parking structure doesn't take that long, so make sure you get data you feel confident in. It will help to come up with an estimate of the drop time after you measure y_0. Solving Equation 4.4 for t instead of g yields

$$t = \sqrt{\frac{2y_0}{g}} \tag{4.5}$$

which you can use to get an estimate of t by assuming $g = 9.8\ \mathrm{m/s^2}$.

How you handle uncertainty in this experiment is very important. Even in the best of circumstances your recorded times will not be very precise; each time will look a little different than the others. This lack of precision is uncertainty in t because of your *reaction time*, the time it takes for you to react to seeing either the release of the ball or the ball hitting the ground. Human reaction time is typically about 0.2 seconds. Here we will use statistical methods to account for this uncertainty. For every time measurement you make, you will calculate a value for g. Your final value of g from this technique will be expressed as

$$g = \bar{g} \pm \Delta g, \tag{4.6}$$

where $\bar{g}$ is the average of your computed values of g, and Δg is the standard deviation of these values.

To do this part of the lab, follow these steps:

1. Go to the parking structure. Decide who will drop the balls, who will time the falls, and who will record the data. Send the dropper to the top of the parking structure.

2. Using the long tape measure, measure a convenient distance from the ground to the top of the parking structure. The dropper should find a convienient feature, like the top of a guard rail, that is at the chosen height. The recorder should record this height.

3. Estimate how long it will take for the ball to fall the chosen distance using the equation $t = \sqrt{\frac{2y_0}{g}}$, where y_0 is the chosen height and $g = 9.8m/s^2$. Record this estimate.
4. Have the dropper hold the ball at the chosen height, and loudly count down so the timer can anticipate the drop.
5. Start the timer when the dropper releases the ball. Stop the timer when the ball strikes the ground.
6. Look at the time recorded and compare it with the estimate calculated above. Is it within about 0.2 seconds of the estimate? If not, you may discard the time and repeat the drop.
7. Repeat dropping and timing the ball until you have recorded 5 times. Again, discard any time you don't have confidence in.
8. Return to the lab.
9. For each t_n you recorded for your drops ($n = 1, 2, 3, 4, 5$), use Equation 4.4 to find a potential value of g_n. Record all these values in a data table.
10. Express the value of g by averaging and finding the standard deviation of your 5 g_n values, as shown in Equation 4.6.

Is the expected value of g within the range of values you calculated? If not, find the percent difference between the closest observed value and the expected value using Equation 1.6. Present your results in a neat, easy-to-read manner.

4.3.2 Photographic Timing of Falling Objects

Here you will use a video camera to record a ball falling from halfway up a meterstick to the table top (i.e. $y_0 = 0.50$ m). You will use video editing software to find the time of the fall precisely, and use Equation 4.4 to find g. By using a video camera that shoots 30 frames (or pictures) per second, we should be able to measure the time of the fall with greater precision.

To set up your computer to take data:

1. Face the lab computer toward the end of the lab bench.
2. Click on the Finder icon on the Launcher (bottom of the screen). Choose Applications (under Favorites), then double click the iMovie application.
3. You need iMovie to show the exact frame number of selected frames. Choose iMovie — Preferences, then click Display time as HH:MM:SS:Frames if it isn't already selected. Close the Preferences dialog.

Your goal is to find five different values of g from five different recordings. For each data collection attempt:

1. Choose File | Import from Camera.

2. Stand a meterstick on the end of the lab bench. Have someone hold a ball so its bottom is at the 0.50 m (50 cm) mark.

3. Click Capture.

4. Drop the ball, let it bounce on the table at least once.

5. Click Stop to stop recording.

6. Click Done.

7. Find the item you just recorded in the lower right pane. Select the whole item so it is surrounded by a yellow boundary. Drag this selected region to the upper left iMovie pane.

8. Mouse over the clip in the upper left pane to find the exact frame where the ball started falling. The editing software will show the time of this frame, which we will call t_1. Record this time. The second to last number shown is the number of seconds, and the last number shown is the frame number, which can be converted to a decimal by dividing by the frame rate of 30 frames per second (FPS). For example, 2:24 is 2.00 s + $\frac{24}{30}$ s = 2.80 s.

9. Now find the exact frame where the ball hit the table. The editing software will show the time of this frame, which we will call t_2. Record this time as described above.

10. Find $t = t_2 - t_1$.

11. Use t in Equation 4.4 to find g for this trial.

Once you have five values of g, record them in your report as

$$g = \bar{g} \pm \Delta g, \tag{4.7}$$

where $\bar{g}$ is the average of the values you found, and Δg is the standard deviation of these values.

Does the expected value of g fall between within the uncertainties of the values you found? If not, find the percent difference between the closest value and the expected value using Equation 1.6.

4.3.3 Automated Data Collection

Here you will use a computer with Logger Pro and the motion detector to automatically record the position of a falling object at small, regular intervals. At the end, you will use Logger Pro's statistics functions to find an average value for the object's acceleration during its fall. Here is the procedure:

1. Close Logger Pro if it is already running to avoid the possibility of miscalibration. Open it from the Launcher at the bottom of the screen.

2. Find the switch under the hinged portion of the motion detector. Make sure it is set to the ball/cart setting.

3. Hold the basketball under the hinged portion of the motion detector.

4. Start collecting data, and drop the ball.

5. Stop collecting data after the ball has bounced, if necessary. Your plot should show at least one parabolic arc that ends where the ball contacts the floor.

6. Click the word Position on the y-axis to reveal a context menu. Select Acceleration.

7. Your plot should now show flat lines where the parabolic arcs once were. Highlight each flat line and click on the Statistics button. A box will appear showing statistical data, including the mean and standard deviation values you need to express g (with uncertainty) in your report.

8. In your report, record the mean acceleration and the standard deviation from the statistics that appeared on the plot.

9. Print a copy of your plot for each member of your lab group. This plot is part of the Data/Analysis section of your report.

Could 9.8 m/s^2 be within the range of values for g found using the automated collection procedure?

Chapter 5

Vectors and Forces

5.1 Introduction

5.1.1 Vectors and Unit Vectors

Like many other sciences, physics is highly mathematical. We express things of interest, like speed and temperature, in terms of single numbers by themselves. Another name for a number by itself is a *scalar*. Sometimes a single number by itself is not enough, however. If you want to fly from Boise to Salt Lake City, is it enough to fly 300 miles? No, you also need to travel in a specific direction as well, in this case, 130.68 degrees East of North.

We can get that sense of direction by using a different mathematical construct, a *vector*, instead of a scalar. We indicate that a quantity is a vector by putting an arrow over it ($\vec{F}$). We can think of vectors as arrows with a certain length, or magnitude, and a certain direction. Your texbook, Knight, discusses vectors this way in great detail. Vectors are often discussed in terms of *components*, which Knight does not cover well. To describe a vector in components, we first break up our directions into unit vectors that are orthogonal, or independent, of one another. One example is the positive x and positive y directions in a two-dimensional Cartesian coordinate system. We first define a *unit vector* in the positive x direction, which we call $\hat{\imath}$. We also define another unit vector $\hat{\jmath}$ that is in the positive y direction. Both of these unit vectors have a length of 1 unit. If we think of them as pointing East and North, we can see that they are independent of one another. How far East must you go before you go any amount North of where you are? You can't, you need to be able to go North as well as East.

It is easy to convert vectors described by magnitude and direction into unit vectors. Look at the force table on the lab bench in front of you. It has angles on the top like a protractor. Let's say that $\hat{\imath}$ is in the 0 degree direction and that $\hat{\jmath}$ is in the 90 degree direction. Let's also say we have some vector quantity $\vec{F}$ whose magnitude is F and whose direction is an angle θ from the x-axis. We can show with trigonometry that

$$\vec{F} = F(\cos\theta\hat{\imath} + \sin\theta\hat{\jmath}). \tag{5.1}$$

By using unit vectors this way, addition and subtraction of vectors becomes easy. Simply add like components together. Say, for example, we want to add another vector $\vec{F'}$, whose magnitude and direction are F' and θ', to $\vec{F}$. The sum can be expressed simply as

$$\vec{F} + \vec{F}' = (F\cos\theta + F'\cos\theta')\hat{\imath} + (F\sin\theta + F'\sin\theta')\hat{\jmath}. \tag{5.2}$$

If you have n forces, you can easily extend the formula above to include them:

$$\vec{F}_{net} = \sum_{i=1}^{n} \vec{F}_i = \sum_{i=1}^{n} (F_i\cos\theta_i)\hat{\imath} + \sum_{i=1}^{n} (F_i\sin\theta_i)\hat{\jmath}. \tag{5.3}$$

Now let's look at Equation 5.2 again. Let $\vec{F}'$ be a net force from one or more known forces, and let $\vec{F}$ be some other force that cancels it out. In other words,

$$\vec{F} + \vec{F}' = 0.$$

Remember that $\hat{\imath}$ and $\hat{\jmath}$ are independent of each other. That means that all of the coefficients of $\hat{\imath}$ and $\hat{\jmath}$ must be zero. We can now solve for $\vec{F}$:

$$\vec{F} = -\vec{F}' = -F'\cos\theta'\hat{\imath} - F'\sin\theta'\hat{\jmath}. \tag{5.4}$$

Oftentimes you are given a vector in terms of unit vectors. For example, let

$$\vec{F} = F_x\hat{\imath} + F_y\hat{\jmath}, \tag{5.5}$$

where F_x and F_y are numbers. You can express this in terms of a total force F at an angle θ by using the following relationships derived from trigonometry:

$$F = \sqrt{F_x^2 + F_y^2} \tag{5.6}$$

and

$$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right). \tag{5.7}$$

5.1.2 Objective and Hypothesis

When you hang weights from the strings on the force table, you are creating force vectors whose magnitude is the mass of the hanging weight (including the hanger) times g. Hanging weights from multiple strings creates multiple forces on the ring at the center of the force table. If the sum of these forces is zero, the ring can be placed so it is not touching the central pin and it will stay there when released at rest.

In this lab, you will be told what forces to create on the force table. You will add them all together using the unit vectors described above to find another force that will balance the others out. You will then use the result of Equation 5.4 to add another force to the ring in the table's center. If your prediction is correct, you can position the ring at the center of the table, and it will stay there, because the sum of the forces on the ring is zero.

For your hypothesis section, state whether or not you think Equation 5.4 is correct.

5.2 Apparatus

Force table, 3 weight hangers, string, weights.

5.3 Procedures

In your lab work you will try to cancel out three different force combinations:

1. 0.98 N at 0° and 0.98 N at 90°
2. 2.94 N at 0° and 3.92 N at 90°
3. 0.98 N at 120° and 0.98 N at 240°

To test your hypothesis, follow these steps:

1. For each force in the case you are considering, figure out how much weight to hang from the string. (Hint: divide the force in Newtons by g to get a weight in kilograms, which you can convert to grams easily.)
2. Set the pulley for each force at the specified angle.
3. Pull each string so it drapes over the pulley, and hang the right amount of weight to reproduce the specified force.
4. Use Equation 5.2 to find a single, equivalent force to the other forces.
5. Use Equation 5.4 to find a single force that will counteract the other forces.
6. Use Equation 5.6 to find the magnitude of the counteracting force. Divide it by 9.8 to figure out how much weight to use in kilograms.
7. Use Equation 5.7 to find the direction of the counteracting force.
8. Hang a weight of the specified magnitude at the position specified in the steps above.
9. Pull the center ring so it is centered on the center pin. Hold it still, then let go. When it stops, does it rest against the pin? If not, your force calculation is correct. If it touches, recheck your calculations above and try again.

There is no error analysis in this lab.

Chapter 6

Atwood's Machine Lab

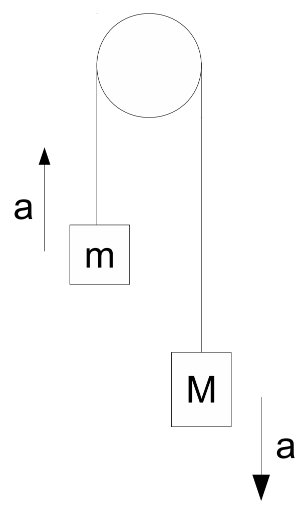

Figure 6.1: Atwood's machine

6.1 Introduction

Atwood's machine consists of two objects, one with mass m and one with mass M, connected by a string and a pulley. Elevators are typically an example of an Atwood's machine. When the masses are free to accelerate, if we assume that mass m is less than mass M, we can use free body diagrams to analyze Atwood's machines to calculate the acceleration of the two objects. Because they are connected by a string that does not stretch, the two masses accelerate at the same rate but in opposite directions as shown in Figure 6.1. For the purposes of this lab, we assume the string and the pulley so light that they are massless and frictionless.

In Figure 6.2 we see a free body diagram for the two masses in the Atwood's Machine. We can sum all the forces on mass m to find that, in the vertical direction,

$$ma = T - mg. \tag{6.1}$$

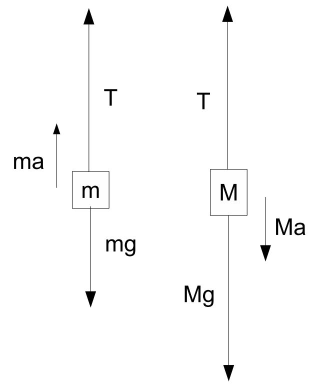

Figure 6.2: Free body diagram for Atwood's machine

For mass M,

$$Ma = Mg - T. \tag{6.2}$$

If we solve these two equations algebraically (e.g. solve the first one for T and plug that result into the second) we find that

$$Ma = Mg - ma - mg. \tag{6.3}$$

We can now solve for a:

$$(m + M)a = (M - m)g$$

or

$$a = \frac{(M - m)}{(M + m)}g. \tag{6.4}$$

We will attempt to verify this result in our experiment.

6.2 Apparatus

Computer with Logger Pro software and a Rotary Motion Sensor (RMS), twelve pennies, and two capped pipe segments attached together with string.

6.3 Procedures

Use the following procedure to verify Equation 6.4:

1. If your computer is running Logger Pro, exit the program and reopen it from the Launcher, Desktop, or Start button.

2. Make sure that the Rotary Motion Sensor is connected to the analog CH 1 port. (If it is plugged into another port, make sure you reference the appropriate interface in the steps below.)

3. The Rotary Motion Sensor must be configured before use. To do so, click on the small icon in the upper left corner of the Logger Pro window that looks like the LabPro interface box. Click on the button for the CH 1 interface and select Rotary Motion Sensor.

4. Click on the Equation dropdown. Choose Position.

5. Click on the Calibrate tab. Change the pulley diameter to 0.05 and the units to "m".

6. Click Apply to apply the changes. If you fail to click Apply, the settings will not be saved or used.

7. Click Done, then close the LabPro setup dialog.

8. One Logger Pro plot should display "Position (m)" on the y-axis. If it shows anything else, go back to Step 3 and work through the configuration process again.

9. Place 12 pennies in one of the containers and none in the other. Screw the caps on both containers.

10. Weigh each container and record the mass of each container.

11. Hang the containers by the connecting string from the large (5 cm diameter) Rotary Motion Sensor pulley. Hold both containers steady. Neither should be moving vertically or swinging from side to side.

12. Have one group member hit the Collect button on Logger Pro. Release the two containers shortly thereafter, before data collection ends.

13. Stop data collection if need be. Note the time on the plot when the free motion of the containers ended (e.g. a container hit the floor or the upper pulley). Do not use data at or after this time.

14. On Logger's Velocity plot, there should be a linear region of the data with a fairly constant slope. Select that region and use the Linear Fit button to get an idea of the acceleration of the two containers. The slope of the best fit line is the acceleration of the containers.

15. Click on the word "Position (m)" in the other plot if it is showing. Select "Acceleration (m/s^2)" to change the plot to an acceleration plot.

16. The acceleration plot should show a flat line where the sloped line is on the velocity plot. Select this flat line, then click the Statistics button. Record the mean and standard deviation in the box that appears. These are your acceleration and uncertainty to use in your report.

17. Use the masses of the containers found in Step 10 to calculate the acceleration using Eq. 6.4. If this calculated value does not fit within the uncertainty of your recorded value, calculate the percent difference between the predicted value and the closest recorded value using Equation 1.6.

18. Move two pennies from the heavier container to the lighter one and repeat from Step 10 until you have data for the two containers being approximately equal in mass.

Chapter 7

Centripetal Force Lab

7.1 Introduction

For an object to be moving in a circle at a constant speed, it must experience a force toward the center of the circle (a *centripetal force*). Your textbook tells you that the magnitude of this force is given by the equation

$$F_c = \frac{mv^2}{r}, \tag{7.1}$$

where m is the mass of the object, r is the radius of the circle it is moving around, and v is the constant speed of the object. If the object moves around the circle in a time T, it is simple to show that

$$v = \frac{2\pi r}{T},$$

so

$$F_c = \frac{4\pi^2 mr}{T^2}. \tag{7.2}$$

This force must be exerted through some physical object like a rod, a string, or a spring.

The goal of today's lab is to verify that Eq. 7.1 is true. You will spin an object of known mass m that is held to the axis of rotation by a spring. Spin the object so it spins over a marker rod, so that the radius of its circular path will be known precisely. You will measure the time it takes for the weight to move around a circular path using the video camera, and you will calculate the amount of centripetal force using Eq. 7.2, including uncertainty. You will then use weights to stretch the spring the same amount as the weight stretched the spring while the object was moving. You can then calculate the amount of stretching force using the equation

$$F_c = Mg \tag{7.3}$$

where M is the amount of mass you hung to stretch the spring and g is the acceleration due to gravity at Earth's surface ($9.8\ \text{m/s}^2$).

For your hypothesis, do you think that Eq. 7.2 and Eq. 7.3 will agree when you account for uncertainty? Will the range of values the two equations produce overlap? If you don't think they will overlap, why not? Is there an equipment problem you think will ruin the experiment, for example?

7.2 Apparatus

Centripetal force aparatus, balance, masses, mass hanger, computer with iMovie video editing software and a built-in video camera.

7.3 Procedures

Use the following steps to record your data:

1. Remove the hanging mass m from the aparatus. Use a digital scale to determine its mass. Record the value in kilograms, then re-hang the weight on the aparatus. Do not attach it to the spring yet.

2. Loosen the thumbscrews that hold down the metal distance indicator to the base of the aparatus. Move the indicator until it is 0.16 m (or 16 cm) away from the center of the axis of rotation of the aparatus. Re-tighten the thumbscrews, securing the indicator in place.

3. Loosen the thumbscrew that holds the arm to the top of the aparatus. Move the arm until the hanging mass hangs down directly over the indicator. Tighten the arm's thumbscrew, then attach the spring to the hanging mass. The spring will pull the mass inward slightly.

4. Loosen the thumbscrew that secures the counterweight to the aparatus. Move it until it is about the same distance from the center of rotation as the hanging mass. Retighten the thumbscrew. Now test your aparatus. You should be able to spin the device, having one of your lab partners hold it at the base, without it vibrating too much if the counterweight is positioned appropriately. If the device can't be spun fast enough to have the hanging weight hang over the indicator without the device falling over, you may need to reposition the counterweight. Repeat this step until the device is balanced well enough to perform the experiment.

5. Start spinning the aparatus by rotating the axle with your fingers. Practice keeping the weight directly over the indicator. If it pulls in to far, spin it a little more, and if it goes past the indicator, stop spinning.

6. Position the computer so its video camera can see when the weight is hanging directly over the indicator.

7. You are ready to record data when you have mastered the spinning motion and your mass is spinning at a constant rate. Record at least five orbits of the weight around the center of the aparatus. Stop recording.

8. Use the editing software to find the start and end times for several individual rotations. Record the period T (difference between start and end times of a rotation) for at least five rotations of the hanging mass.

9. Find the force F_c, with uncertainty, as follows. Find the smallest possible F_c by calculating it with Equation 7.2, using the largest possible value of T from your data recorded in Step 8. Find the largest possible F_c similarly, but using the largest value of T you recorded instead. Record F_c with its uncertainties as described under "Measurement Uncertainty" in Section 1.3.1.

10. Attach the string to the hanging mass. Hang it over the pulley on the end of the aparatus, and attach a weight hanger of known mass to the string.

11. Add mass to the weight hanger until the hanging mass is hanging straight down over the indicator rod.

12. Calculate the force being applied to the spring using the mass recorded above and Equation 7.3. Is this calculated value within the uncertainties of the value of F_c calculated using Equation 7.2?

13. If the indicator is less than 0.21 m (21 cm) from the center of the axle, loosen the thumbscrews that hold down the metal distance indicator to the base of the aparatus and move it another 0.01 m (1 cm) away from the center of the axle. Re-tighten the thumbscrews and repeat the experiment starting at Step 3 above.

14. Data collection is complete after you have data for r = 0.21 m.

7.4 Discussion Points

For each value of r in your experiment, you should have a value for the centripetal force found two different ways. Do these values agree to within the uncertainties of the experiment? If not, did you notice any problems with the equipment or the procedure that could explain your data better? Can you think of any ways to improve this experiment? Discuss these questions in the Conclusion section of your report.

Chapter 8

Torque Lab

8.1 Introduction

So far you've learned how to deal with multiple forces through free body diagrams. Specifically, if you have a system in static equilibrium and all the forces in the system are being applied in one place, you know that the net force on the system is zero:

$$\sum_i \vec{F}_i = 0. \tag{8.1}$$

Now what if the forces are being applied in different places? It is now possible for a system to rotate and experience angular acceleration as well as linear acceleration. To have static equilibrium we expect that angular acceleration will be zero as well. One can show that for this condition to occur, the *net torque* on the system will also be zero, i.e.

$$\sum_i \tau_i = 0 \tag{8.2}$$

where

$$\tau_i = r_i F_i \sin\theta_i. \tag{8.3}$$

For any conceivable axis of rotation, the sum of the torques around that point must be zero. In Equation 8.3, r_i is the distance between the point where force F_i is being applied and the axis of rotation in question, and θ_i is the angle between the two vectors.

In this lab exercise we will show that static equilibrium does in fact occur when the net torque about an axis of rotation is zero. You will be applying torques to a meterstick by hanging masses at specific places. At least one of these points will be chosen so that, according to your calculations, the sum of the torques about the pivot point (point of rotation) of the meterstick will be zero. Once you hang your masses, the system is in static equilibrium if the meterstick balances at the pivot point.

8.2 Apparatus

Meterstick, stand, three pivot clamps, mass hangers and an assortment of masses, digital scale, string, computer with Logger Pro and force probe (or a spring scale), protractor.

8.3 Procedures

Before you begin, you must know a few quantities. Find the mass of your meterstick with the digital scale. Find the mass of a pivot clamp by itself as well, which we will call m_c below. You may find their masses individually and record them, taking care to use the correct value for each use, or you may simply assume that they all have about the same mass. Also, connect the pivot clamp to the meterstick and find its center of mass. This is the point where the meterstick balances. Ideally this would be at the 50 cm mark, but there can be variations due to construction and wear.

When using the pivot clamp, be sure to attach it so its sharp edges point down. (They look like a knife edge, but they aren't nearly as sharp.) When the clamp is used to hold the meterstick in the stand, the sharp edges will sit in the stand, and when the clamp is used to hold hanging weights, the metal loop will hang from the rounded edges. The thumb screw should face up, and the mark in the pivot clamp will point to the distance from the end of the meterstick.

8.3.1 Two Hanging Masses

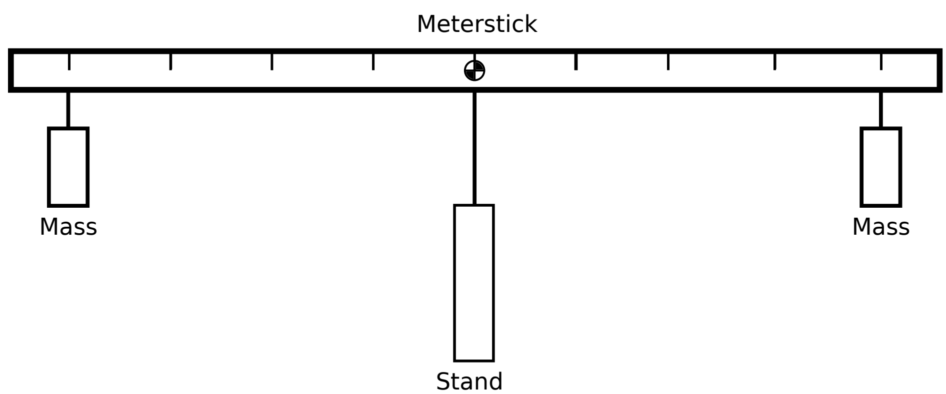

Figure 8.1: A meterstick with two masses hanging from it. The sum of the torques on the meterstick is zero.

1. Set the pivot clamp on the meterstick such that the meterstick is balanced. The meterstick will sit at pretty much any angle you set it at, and it won't move quickly away from that position.

2. Attach a pivot clamp to the left side of the meterstick, 20 cm away from the balance point. Hang a 100 g (0.100 kg) mass from the pivot clamp.

3. Use Equation 8.2 to predict where a 200 g mass should be hung to balance the meterstick. Set $\theta_1 = 90°$, $r_1 = 0.20$ m, $m_1 = 0.100 \text{ kg} + m_c$, $\theta_2 = -90°$, $m_2 = 0.200 \text{ kg} + m_c$, and $F_i = m_i g$ in the two-term sum and solve for r_2. *Show all your calculations in your report.*

4. Place a pivot clamp on the meterstick at the location you predicted in the previous step. Hang 200 g from the pivot clamp. Does the meterstick balance?

5. Repeat the previous two steps for a 300 g (0.300 kg) mass.

8.3.2 Three Hanging Masses

1. Attach pivot clamps at 10 cm and 20 cm away from the balance point, both on the same side. Now hang 100 g of mass from each pivot clamp.

2. Use Equation 8.2 to predict what mass must be hung from a point 40 cm from the pivot clamp, but on the opposite side from the two 100 g masses. Remember to use the mass of a pivot clamp with metal loop (m_c) in your calculations.

3. Place a pivot clamp 40 cm from where the meterstick sits on the stand, on the opposite side of the stand from where the 100 g weights hang. Hang the amount of mass you calculated in the previous step from the pivot clamp. Does the meterstick balance? (If you can add or subtract 5 g from the mass hanger to make the meterstick flip to the other side, this is close enough, and you can consider the meterstick balanced.)

4. If you did not achieve balance, why not? Recheck your calculations. If you find an error, repeat the previous steps with your new calculated mass to check for balance. (You do not need to record erroneous data in your report. Delete it, erase it, or cross it out with a single line, whichever you prefer.)

8.3.3 One Hanging Mass

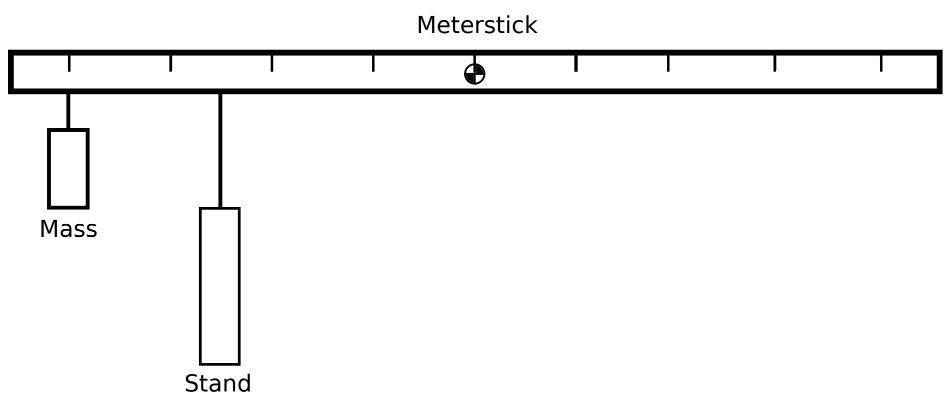

Figure 8.2: A meterstick with a single mass hanging from it. The mass of the meterstick itself creates a torque at the meterstick's center, keeping the sum of the torques equal to zero.

Here the weight of the meterstick becomes important. You will move the pivot clamp away from the meterstick's balance point and hang some amount of mass on the short side to balance it out. This is just like the case of two hanging masses, except one of the masses is the meterstick itself. You will assume that all of the mass of the meterstick is at its balance point, also known as its center of mass or center of gravity.

1. Move the pivot clamp on the meterstick 25 cm to the left of its balance point.

2. Attach a pivot clamp to the left side of the meterstick, 10 cm away from the stand.

3. Use Equation 8.2 to predict where a how much mass should be hung on the pivot clamp to balance the meterstick. *Show all your calculations in your report.*

4. Hang the amount of mass you calculated in the previous step from the pivot clamp. Does the meterstick balance? (If you can add or subtract 5 g from the mass hanger to make the meterstick flip to the other side, this is close enough, and you can consider the meterstick balanced.)

5. If you did not achieve balance, why not? Recheck your calculations. If you find an error, repeat the previous steps with your new calculated mass to check for balance.

8.3.4 Zero Hanging Masses

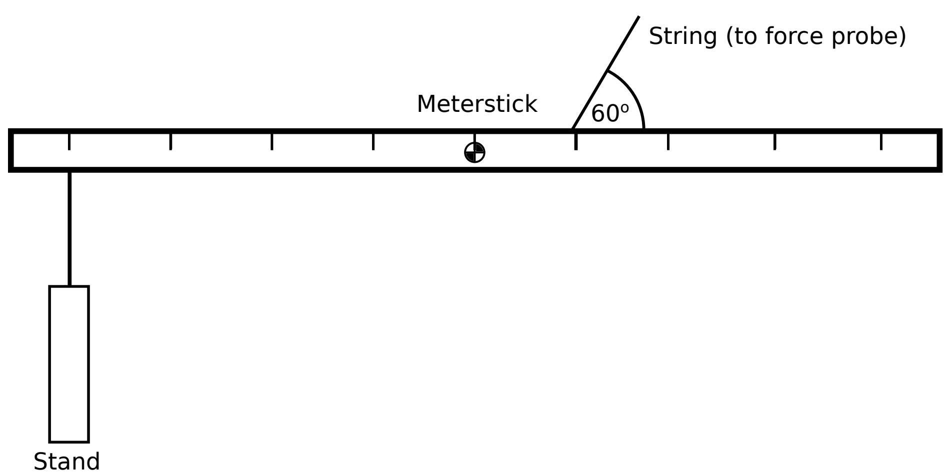

Figure 8.3: A meterstick with no masses hanging from it. A string attached to the Logger Pro force probe (or a spring scale) keeps the sum of the torques equal to zero.

Here the weight of the meterstick will provide a torque around the pivot point on the meterstick. You will use several upward forces, one vertical and one at an angle, to counteract that torque and keep the meterstick in rotational equilibrium.

1. Place the pivot clamp for the meterstick 40 cm to the left of its balance point. Set the stand on the floor, and the pivot clamp in the stand.

2. Place a second pivot clamp, with a metal loop, 10 cm to the right of the balance point. Attach a string to the clamp.

3. Move the stand so the second pivot clamp is directly under the force probe or spring scale. Wrap the string around the hook on the force probe so it holds the meterstick level. The probe should be pointing straight down.

4. Use Equation 8.2 to predict where a how much upward force is required on the pivot clamp to balance the meterstick. *Show all your calculations in your report.*

5. Start Logger Pro on the computer if you need to. Read the amount of force on the force probe from the lower left corner of the display (or use the spring scale). Compare this reading with your calculated value from the previous step. Record the percent difference. Is the value low enough that it suggests your calculations were correct?

6. Loosen the string on the hook. Move the stand sideways until the string is at a 60° angle from the meterstick instead of a 90° angle. Have one lab parner hold the stand if need be. Tighten the string so the meterstick is level with the floor.

7. Use Equation 8.2 to predict where a how much upward force is required on the pivot clamp to balance the meterstick. *Show all your calculations in your report.*

8. Read the amount of force on the force probe from the lower left corner of the display or the spring scale. Compare this reading with your calculated value from the previous step. Record the percent difference. Is the value low enough that it suggests your calculations were correct?

Chapter 9

Springs Lab

9.1 Introduction

Springs are important devices that we use every day. Cars ride on springs. Computer keyboards use springs to push keys back out after they have been pressed. Retractable pens use them. Many types of scales use springs of various sorts, including digital scales. The list can go on and on and on. By learning more about springs, you can learn how many common mechanical devices work.

There are many forces at work in nature, many of them very complex. For example, solid matter is held together primarily by a large number of electric forces acting on each individual atom in the solid. Still, most solids can be modeled by assuming that each atom is held in place by a single spring of a certain strength. Many properties of matter, including strength of materials, heat and sound conductivity, or even superconductivity, can be explained using this assumption. So, if you understand springs in general, you're in a good position to learn about many more complex physical phenomena. Learn springs and you can learn everything.

From a physics perspective, a spring is a simple device that exerts a force when you push or pull it. The amount of force it provides is proportional to the amount it is stretched or compressed, and that force opposes the stretching or compressing force applied to it. Mathematically, we can describe a spring force using Hooke's Law, which states that

$$\vec{F} = -k(\vec{x} - \vec{x_0}),$$

where $\vec{F}$ is the vector force exerted by the spring, $\vec{x}$ is the location of its end while the force is being exerted, $\vec{x_0}$ is the location of its end while no force is being exerted, and k is a property of the spring known as the *spring constant*. The units of the spring constant are Newtons per meter, or N/m. Oftentimes our spring forces are one-dimensional, and we choose coordinates where $x_0 = 0$, so we get the much simpler equation

$$F = -kx. \tag{9.1}$$

What happens if we attach two springs together? They act like they are a single spring with a different spring constant. For example, if you attach two springs end-to-end, the force exerted by either spring is identical when they are both pulled or pushed. So, if springs with spring constants k_1 and k_2 are connected end-to-end (also known as *connected in series*), we can show that the two springs together act like a single spring with spring constant k_{series}, where

$$k_{series} = \left(\frac{1}{k_1} + \frac{1}{k_2}\right)^{-1}. \tag{9.2}$$

When springs are connected side-by-side (or *in parallel*) with one another, we can show mathematically that, because they must both be stretched the same amount (x_1 and x_2 are the same), the two springs together must act like a single spring with spring contstant $k_{parallel}$, where

$$k_{parallel} = k_1 + k_2. \tag{9.3}$$

The goal of this experiment is to learn more about springs empirically. You will take some simple spring scales, which consist essentially of a spring and some attachment hooks, and do some simple experiments to find spring constants for each one from Equation 9.1. You will also then connect the two scales in series and in parallel, and attempt to find equivalent spring constants for these combinations. Will your results match those found from Equations 9.2 and 9.3? Include your prediction in your hypothesis.

9.2 Apparatus

Two spring (fish) scales, two metal bars, one bar clamp, ruler.

9.3 Procedures

One of the metal bars should be attached to the table with the bar clamp. Attach it so the bar is vertical if it isn't there already.

You will need to take force measurements as part of your experiments. The spring scales are labeled to display either Newtons (a true force measurement) or grams (a mass measurement). Be sure to read from the Newtons side of the scale.

9.3.1 Single Springs

Here you will find the spring constant of each scale individually. If the scales are the same model by the same manufacturer, one might think their spring constants should be identical. Is that true? For each scale, do the following:

1. Zero the scale. Turn the hexagonal plastic nut at one end until the plastic plunger lines up with the 0 on the Newtons scale.

2. Use a ruler to measure the distance between the 0 N and 1 N marks on the scale. (Uncertainty is plus or minus 0.5 mm.)

3. Use Equation 9.1 to find the maximum and minimum values of the spring constant. (Assume the force is negative, so you don't need to worry about the sign in Hooke's Law.) Record these values in your report.

4. Repeat the previous two steps for two other force values that can be easily read from the force scale.

5. Record the maximum and minimum values of k for this scale in your report.

6. If your two scales are not identical, repeat the previous steps to determine the spring constant of your second scale.

9.3.2 Springs Connected in Parallel

How strong do two strings attached side-by-side feel when pulled?

1. Connect both spring scales to the bar attached to the table. The scales should be one above the other.

2. Hook both scales to the other metal bar, held in the hand of one of your lab group members.

3. Pull the non-fixed bar so the two scales both stretch about 3 cm. Keep the loose bar parallel to the other bar so the two scales stretch the same amount.

4. Record the amount of stretch, with uncertainty, as x. (Uncertainty is 0.5 mm.)

5. While keeping the springs in the scales stretched to about 3 cm, read both scales to determine the amount of force on each spring. Add the two values together. Record this sum, with uncertainty, as F. (Do the scales read the exact same number? Use their difference as the uncertainty.)

6. Use Equation 9.1 to find the value of $k_{parallel}$. To find the largest possible value of $k_{parallel}$, use the largest value of F possible and the smallest possible value of x. Use the smallest F and the largest x to find the smallest k. Record $k_{parallel}$ with its uncertainties, as described in Equation 1.1.

7. Use Equation 9.3 to find the predicted value of $k_{parallel}$ with uncertainties. (Use the smallest possible values of k for the smallest possible $k_{parallel}$ and the largest possible values of k for the largest possible $k_{parallel}$. Record this information as a value of $k_{parallel}$ with uncertainty.

8. Do the predicted and observed values of $k_{parallel}$ agree within uncertainty? Discuss this comparison in your report. Find a percent difference if agreement within uncertainty is not possible.

9.3.3 Springs Connected in Series

1. Connect one spring scale to the bar attached to the table. Connect the other spring scale to the first spring scale. Pull the two scales taut to keep them from falling apart.

2. Pull the two scales so they are parallel to the ground (approximately) and their force measurements can be read easily.

3. Read the two scales from the Newtons side. Record their two slightly differing readings as F with appropriate uncertainty, as described in Equation 1.1.

4. For each scale, use a ruler to measure the distance between the 0 N mark and the force indicator. Add these two values, and record them in your report as x with uncertainty of 1 mm.

5. Use Equation 9.1 to find the value of k_{series}. To find the largest possible value of k_{series}, use the largest value of F possible and the smallest possible value of x. Use the smallest F and the largest x to find the smallest k_{series}. Record k_{series} with its uncertainties, as described in Equation 1.1.

6. Use Equation 9.2 to find the predicted value of k_{series} with uncertainties. Use the largest possible values of k to find the largest possible k_{series} and the smallest possible values of k for the smallest possible k_{series}. Record this information as a value of $k_{parallel}$ with uncertainty.

7. Do the predicted and observed values of k_{series} agree within uncertainty? Discuss this comparison in your report. Find a percent difference if agreement within uncertainty is not possible.

Chapter 10

Momentum and Inelastic Collisions

10.1 Introduction

The momentum vector $\vec{p}$ of an object with mass m and vector velocity $\vec{v}$ is given by the equation

$$\vec{p} = m\vec{v} \tag{10.1}$$

For two objects, their total momentum is simply the momentum of each object added together:

$$\vec{P} = \vec{p}_1 + \vec{p}_2. \tag{10.2}$$

Momentum generally conserves through a collision of objects: $\vec{P}$ is the same before and after a collision.

Let's consider a collision between two objects. Momentum conserves, but there are a lot of ways that can happen. Imagine a car crash, for example, where one car hits another stopped at an intersection. The two cars in the collision can stick together, drifting away from the collision site with some speed less than that of the moving car before the collision. This is a *perfectly inelastic collision.* The cars can also separate after the collision, which is known as an *elastic collision.*

In this experiment we will concern ourselves only with perfectly inelastic collisions. You will cause a moving lab car with mass m_1 and speed v_i to collide with a stationary car of mass m_2 on a level track. Thanks to magnets or hook-and-loop fasteners (a.k.a. Velcro) the two cars will stick together and roll away as one after the collision with speed v_f. We can look at the momentum of the cars in the direction of the track and rewrite Equation 10.2 as

$$m_1 v_i = (m_1 + m_2) v_f.$$

Solving this equation for v_f gives

$$v_f = \frac{m_1}{m_1 + m_2} v_i. \tag{10.3}$$

Will this relationship hold true within uncertainty?

10.2 Apparatus

Computer with Logger Pro and the motion detector attachment, levelable metal track, two carts with magnets or hook-and-loop fasteners to connect them after a collision, digital scale, blue tape or other method for attaching weights to one cart.

10.3 Procedures

1. The first time you perform this experiment, remove any equipment, weights, old tape, and other material from the two carts until they are identically configured and as close to "stock" as possible.

2. Place the motion detector at the end of the ramp. Flip the hinged part to face down the track, and flip the switch beneath to the ball/cart setting.

3. If necessary, turn on the computer and/or start Logger Pro. It should show a position versus time plot and a velocity versus time plot.

4. Connect the two carts with the magnets or hook-and-loop fasteners. Place both carts in the middle of the track and release them while they are at rest.

5. Do the carts roll to either side? If so, adjust the track level using the track's or the table's leveling feet. (Ask for help if necessary.) Make the track as level as you reasonably can.

6. Clean the track of any obvious dirt or debris so the carts can roll freely. Test roll the carts to make sure the track is clean enough.

7. Separate the two carts. Find the mass of each cart with the digital scale. (Initially the two carts should weigh approximately the same.)

8. Place one cart at the center of the track. Have a lab group member hold it if necessary.

9. Place the other cart near the motion detector, oriented appropriately so the carts will stick together after a collision.

10. Start recording data in Logger Pro by clicking the record (green "play") button. Give the cart near the motion detector a gentle push toward the resting cart at the middle of the track.

11. If the resting cart is being held, release it before the moving cart collides with it. Make sure the two carts stick together during the collision. Repeat the collision with a lower initial velocity if the carts don't stick together.

12. Stop recording data (click the red "stop" button) once the two carts are near the end of the track. (If they hit the end, make sure you ignore any data recorded after the carts hit the end of the track.)

13. Select as large a region of the velocity plot as possible corresponding to the time before the collision. The plot should be mostly flat, aside from some jitter, in this region. Click the Statistics button. Record the mean and standard deviation of the velocity for the selected region as v_i with the standard deviation as the uncertainty in the measurement.

14. Select another large a region of the velocity plot corresponding to the time after the collision. Click the Statistics button. Record the mean and standard deviation of the velocity for the selected region as v_f with the standard deviation as the uncertainty in the measurement.

15. Calculate v_f using Equation 10.3. Use the cart masses recorded earlier and v_i used in the experiment. Be sure to include the uncertainty of v_i to get an uncertainty for v_f. Do the range of values covered by v_f include any part of the range of values you found experimentally? If not, calculate a percent difference between the closest values of the theoretical and experimental values.

16. If your target cart (the one that is stationary at the beginning of the experiment) has less than 400 g of weight taped to it, tape an extra 200 g of mass to the top of the target cart and repeat the experiment from step 7.

Chapter 11

Elastic Collisions

11.1 Introduction

In the previous lab exercise we studied inelastic collisions, where two objects collide and stick together. In this experiment we will study several different kinds of *elastic* collisions, where the colliding objects are essentially completely free to fly apart from one another.

In the first collision type, two wheeled carts will gently collide. The first cart (call it cart 1) moves with some speed v_{1i} into a stationary cart (cart 2) with initial velocity $v_{2i} = 0$. One cart will have a post attached to a spring extended toward the other cart; when the carts collide, the spring will act as a bumper to keep the carts from damaging one another. Kinetic energy from the first cart will stretch the spring in the process, and eventually almost all of that energy will be returned to the two carts. This is an elastic collision: essentially none of the energy will be lost to the environment.

Because energy and momentum conserve in this one-dimensional collision, we can express these quantities mathematically and solve for the final velocities of cart 1 (v_{1f}) and cart 2 (v_{2f}). Your textbook tells you that

$$v_{1f} = \frac{m_1 - m_2}{m_1 + m_2} v_{1i} \tag{11.1}$$

and

$$v_{2f} = \frac{2m_2}{m_1 + m_2} v_{1i}, \tag{11.2}$$

where m_1 and m_2 are the masses of carts 1 and 2 respectively.

In this experiment you will attempt to validate Equation 11.1. You will use Logger Pro with a motion detectors to measure the speed of cart 1 both just before and just after a collision. In reality, some amount of energy will be lost from the cart system to things like sound and heat. Still, will the percent differences between theory and experiment be small?

11.2 Apparatus

Cart track, two carts (one with a spring post), computer with Logger Pro, one motion detector, one 100 g mass, adhesive tape, digital scale.

11.3 Procedures

You will perform the following experiment three times to reflect the following scenarios:

a. $m_1 = m_2$ (approximately),

b. $m_1 > m_2$, and

c. $m_1 < m_2$.

To make one cart more massive than the other, simply tape the 100 g weight to the cart that should be more massive. Switch the carts to change which cart is more massive. To make the carts approximately the same mass, remove all weights, tape, and other foreign substances from both carts so they weigh approximately the same amount.

1. Adjust the masses of the carts as described above to match the scenario (a, b, or c) you will be experimenting on.
2. Press the button on top of one of the carts to extend the bumper post.
3. Place the carts next to each other in the middle of the track with the bumper post between them.
4. Put the motion detector at the end of the track closest to the wall and the computer. Flip up the hinged section so it points toward the carts, and flip the switch to the cart setting.
5. Start Logger Pro, or restart it if it is already running.
6. Change the y-axis label on the plot from Position to Velocity.
7. Move the cart nearest the motion detector about a quarter meter or so toward the detector.
8. Click the record button on Logger Pro. Once the motion detector starts making noise, flick the cart closest to the motion detector *gently* toward the other cart.
9. As the carts collide, note the approximate time of the collision on the Logger Pro plot. Stop Logger Pro data collection once the collision is complete and the carts are far apart from one another.
10. You should be able to see flat regions (approximately) before and after the collision. If you can't see flat regions, return to Step 8 and repeat the collision.
11. Highlight the flat region just before the collision. Click the Statistics button to generate statistical data for the region. Record the mean in your report as v_{1i}.
12. Use the value of v_{1i} recorded in Step 11 in Equation 11.1 to find an expected value for v_{1f}.

13. Highlight the flat region just after the collision. Click the Statistics button to generate statistical data for the region. Record the mean in your report as the observed value of v_{1f}.

14. Find a percent difference between your observed and expected values and record this percent difference in your report.

Chapter 12

Rolling Objects Lab

12.1 Introduction

When an object rolls down a plane at an angle θ from the horizonal, we expect total energy E to conserve, so at any time

$$E = U + K + K_{rot}.$$

Here K is translational kinetic energy and K_{rot} is rotational kinetic energy. If the object has mass m, radius r, starts at height h, ends at height 0, and starts at rest, then

$$mgh = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2,$$

where g is the acceleration due to gravity ($9.80 \ \mathrm{m/s^2}$), I is the object's moment of inertia, ω is its angular velocity, and v is the velocity of its center of mass. We know that $v = \omega r$, so

$$mgh = \frac{1}{2}(m + \frac{I}{r^2})v^2.$$

The velocity is straight down the ramp. We are given h, the initial height of the rolling object, but it is more interesting to know d, the distance it has rolled down the ramp. They are related by trigonometry: $h = d\sin\theta$. Also, we expect the acceleration down the ramp a to be constant, so $v^2 - v_0^2 = v^2 = 2ad$. We can use these results to find that

$$\begin{aligned} mgd\sin\theta &= \frac{1}{2}(m + \frac{I}{r^2})(2ad) \\ &= (m + \frac{I}{r^2})ad, \end{aligned}$$

which simplifies to

$$a = \frac{mr^2}{mr^2 + I} g\sin\theta. \tag{12.1}$$

We can solve this equation for θ to find that

$$\theta = \sin^{-1}\left(\frac{a}{g}\frac{mr^2 + I}{mr^2}\right). \tag{12.2}$$

This is our goal in this lab exercise: find the slope of a ramp by measuring the acceleration of objects rolling down the ramp.

To calculate θ, then, it looks like we need to know an object's mass, radius, and moment of inertia, which is tabulated in your textbook. When you look up formulas for I, however, you will see that they are generally expressed as $I = Cmr^2$, where C is some number like $\frac{2}{5}$. We can plug this result into Equation 12.2 to simplify it to

$$\theta = \sin^{-1}\left(\frac{a(1+C)}{g}\right). \tag{12.3}$$

In reality, all we really need for most objects is to know what their shape is (solid sphere, hollow sphere, thin cylinder, etc.). Their mass and size don't really matter, it would seem.

Is Equation 12.3 true? Can you measure the acceleration of a rolling object of a known type and use this information to calculate the slope of your inclined plane? How well will your results from different objects agree?

12.2 Apparatus

Inclined plane, computer with Logger Pro and motion detector, billiard ball, bocce ball, racquetball, hollow cylinder, and solid cylinder. Note that the cylinders should be large enough to be easily tracked by the motion detector; cylinders smaller than a racquetball should not be used. *Do not use any wooden objects, as they are not well-balanced.*

12.3 Procedures

To begin, make sure your plane is inclined appropriately. It needs to stay tilted at the same level for all the objects in your experiment. Do some test rolls with one of the spheres; it should roll straight down the plane without hitting the sides. Ask your instructor for help if you can't get the ball to roll appropriately. Also, make sure your plane is clean. Eraser shavings tend to collect on these ramps for some reason. Wipe the surface clean if you need to.

Before using any object, make sure it is appropriately balanced for the experiment. Billiard balls are an excellent example of a well-balanced object. Note that as they roll down the slope, the noise they make is very consistent. All your other objects should have the same consistency. If any of your objects make a substantial bumping noise every time they roll over, they are not well-balanced. Clean the surface of the object and try another test roll. If cleaning doesn't help, you might want to replace the object with another one.

For each object listed above:

1. Place the motion detector at the top of the inclined plane. Flip the hinged part to face down the slope, and flip the switch beneath to the ball/cart setting.

2. Turn on the computer and open Logger Pro (if necessary).

3. On the plot of velocity versus time, click the "Velocity" label on the y-axis. Choose "acceleration" from the menu to make the plot an acceleration versus time plot.

4. Do a test roll of your object down the slope to make sure it behaves the way you expect. For the cylinders, make sure they start off perpendicular to the slope of the plane so they roll straight down the plane as much as possible.

5. Have one group member hold the object at the top of the slope while another member clicks the collect (green "play") button on Logger Pro. When the object gets to the bottom of the slope, stop collecting data (click the red "stop" button).

6. Select a flat portion of the acceleration plot. Click the statistics button. Record the mean and standard deviation of the acceleration in the highlighted region as the acceleration and its uncertainty, respectively.

7. Look up the moment of inertia of the object you are testing. You may use your textbook for this purpose, for example, or resources found on the Internet. Record the coefficient of mr^2 as C.

8. Find the greatest and least possible values of your slope using the greatest and least possible values of a in Equation 12.3. Put your results in a table in your report, so you can easily compare these values with values from other objects.

In your conclusion, talk about how well your values of θ agreed with one another. Did the ranges of possible values from all of your objects overlap? Do you trust values from some objects more than others, and if so, why?

Chapter 13

Ballistic Pendulum Lab

13.1 Introduction

A ballistic pendulum is an interesting variant of an ordinary pendulum. It is designed to capture a projectile (like a bullet) fired at the pendulum in order to determine its initial velocity. Ballistics pendulums have often been used in police crime labs, specifically the ballistics lab (hence the name), to help identify critical information about firearms that may have been used in crimes.

Here is how a ballistics pendulum works. When a projectile with mass m is first captured in a ballistics pendulum with mass M, the projectile is trapped by the pendulum in an inelastic collision. If the pendulum has no initial velocity, and the projectile has speed v at capture, conservation of momentum tells us how to relate the pendulum's final speed V to v:

$$mv = (m + M)V. \tag{13.1}$$

After the capture, we expect the pendulum will swing up to some maximum height above its initial position h and then stop. (A gear will engage at this height to prevent the pendulum from swinging back, making it easier to measure the maximum height of the pendulum.) We expect energy to conserve through this process, so the kinetic energy of the pendulum just after the capture should be the same as the gravitational potential energy of the pendulum when it reaches its maximum height:

$$\frac{1}{2}(m + M)V^2 = (m + M)gh, \tag{13.2}$$

where g is the acceleration due to gravity, 9.8 m/s^2.

We can now solve Equation 13.1 for V and substitute the result into Equation 13.2, yielding

$$\frac{1}{2}\left(\frac{m^2}{(m + M)^2}\right)v^2 = gh, \tag{13.3}$$

which simplifies to

$$v = (1 + \frac{M}{m})\sqrt{2gh}. \tag{13.4}$$

So, if we know how high the pendulum goes after capturing a projectile, we can deduce the initial speed of the projectile using Equation 13.4.

In this experiment, you will fire a steel ball bearing horizonally from a launcher and determine its speed two different ways. In addition to using the ballistic pendulum as described above, you will also fire the ball across the room and mark its landing point with a piece of carbon paper. You will use a tape measure to measure how far it flew from its launching point. If the ball bearing falls a total vertical height y, one can deduce that it fell that height in a time $t = \sqrt{\frac{2y}{g}}$ due to simple kinematics considerations. If it also traveled a horizonal distance d, then its initial velocity must have been d/t, or

$$v = d\sqrt{\frac{g}{2y}}. \tag{13.5}$$

You will calculate velocity values, with uncertainties, using both of these techniques independently. Will the results agree within uncertainty?

13.2 Apparatus

Ballistic pendulum with ball bearing and loading plate, target board, carbon paper, regular paper, tape measure.

13.3 Procedures

Warning: this experiment involves firing a heavy steel ball bearing at a wooden target board, causing a loud knocking noise with every impact. The noise can be startling if you are not expecting it.

13.3.1 Loading and Firing the Launcher

This experiment requires that you measure v using two methods: the kinematic method and the ballistic pendulum method. Both methods involve repeatedly loading and firing the launcher. Here is the procedure for loading and firing:

1. Place the loading plate on the metal post on the launcher.
2. Your launcher may or may not have multiple launch settings. Hold the back of the launcher and press the plate firmly until the launcher clicks the first time. (Stopping at the first click, or setting, will guarantee consistent firings.)
3. Remove the loading plate.
4. Slide the ball bearing onto the post. Your launcher is ready to fire.

Fire the ball bearing by pressing the flat metal button on top of the launcher.

13.3.2 Kinematic Method of Determining v

1. Find the mass of your ball with the digital scale.

2. Place your ballistic pendulum on your table facing toward the table on the opposite side of the room.

3. Stand your target board vertically against the end of the lab table across the room from your own table.

4. Load the launcher.

5. Test fire the launcher and note where the ball bearing lands. It should strike the target board somewhere convenient. If necessary, relocate your launcher and do another test firing to confirm the ball bearing is striking the target board in a convenient place.

6. Tape a piece of white paper on your target board approximately where the ball bearing was striking it.

7. Tape a piece of carbon paper so it covers the white paper on the target board.

8. Load and fire your launcher. The ball bearing should strike the carbon paper, leaving a black mark on the white paper underneath. Repeat this step until you have at least five marks on your white paper.

9. Measure the distance from a point on the floor directly beneath the launcher to the base of the target board. Record this distance d.

10. Measure and record the height of the launcher above the floor and record this value in your report as y_l.

11. For each black mark on your white paper, measure and record the height of this mark above the floor. Write this height next to each mark on the paper. Also, record these values in your report as y_t.

12. For each value of y_t, find a value of y using the equation $y = y_l - y_t$.

13. Use these values of y and d in Equation 13.5 to find the speed v of each launch.

14. Record an overall value of v for this experiment as

$$v = \bar{v} \pm \Delta v, \tag{13.6}$$

where $\bar{v}$ is the average of your individual values of v and Δv is the standard deviation of these values. This is the speed of the ball at launch with uncertainty as found by the kinematic technique.

13.3.3 Ballistic Pendulum Method of Determining v

1. Remove the ballistic pendulum from the launcher and find its mass with a digital scale.
2. Place the steel ball inside the pendulum. Find the center of mass of the ballistic pendulum by balancing it on your finger. Mark the location of the center of mass with a pencil line on the pendulum if it isn't already marked.
3. Reattach the pendulum to the launcher and remove the ball. Measure the height of the center of mass of the pendulum above the table top.
4. Load and fire the ball into the pendulum, using the loading and firing instructions above.
5. Measure the final height h of the pendulum's center of mass.
6. Calculate the initial velocity v of the ball using Equation 13.4 above.
7. Repeat from Step 4 onward until you have at least 5 values of v.
8. Record an overall value of v for this experiment as

$$v = \bar{v} \pm \Delta v, \tag{13.7}$$

   where $\bar{v}$ is the average of your individual values of v and Δv is the standard deviation of these values. This is the speed of the ball at launch with uncertainty as found by the ballistic pendulum technique.

13.3.4 Analysis

Do the ranges of values of v determined using your two techniques overlap? If not, find a percent difference between the closest values with uncertainty included. Discuss the difference in your report.

Chapter 14

Densities Lab

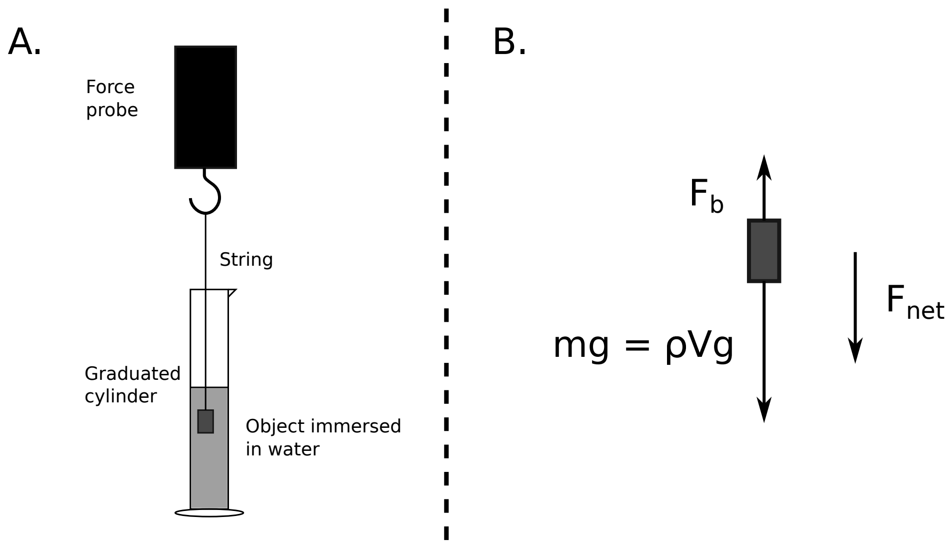

Figure 14.1: A. Weighing an object in water. B. A free body diagram of an underwater object.

14.1 Introduction

Density is the mass per unit volume of a material, often expressed as either kg/m^3, g/cm^3 or (equivalently) g/mL. (One milliliter is one cubic centimeter by definition.) The easiest way to find the density ρ of an object, assuming the density is the same everywhere inside the object, is to use the simple equation

$$\rho = \frac{m}{V}, \tag{14.1}$$

where m is the object's mass and V is its volume. For simple shapes like a cube, the volume can be found with a ruler and some simple mathematics. If the shape is irregular, you can find the volume by immersing the object in water and measuring how much the water's volume changes.

There is another way to find the density of an object. According to *Archimedes' Principle*, there is a buoyant force F_b on objects in fluids equal to the weight of the fluid displaced, or pushed aside, by the object. Imagine we have an object of uniform density ρ immersed in a fluid with density ρ_f. Assume that the object's density is higher than the fluid's, and that both are much higher than the density of air, similar to what is shown in Figure 14.1. The free body diagram shows that

$$\begin{aligned} F_{net} &= mg - F_b \\ &= \rho V g - \rho_f V g, \end{aligned} \tag{14.2}$$

where g is the acceleration due to gravity. If we were to weigh the object in the fluid, say by attaching a string to the object in the fluid and to a scale outside the fluid, the weight of the object in the fluid W_f would be equal to F_{net}. Outside the fluid, the object's weight W would simply be mg, or $\rho V g$.

We can rewrite Equation 14.2 in terms of W and W_f as

$$W_f = W - \rho_f V g. \tag{14.3}$$

Dividing both sides by W yields

$$\begin{aligned} \frac{W_f}{W} &= 1 - \frac{\rho_f V g}{W} \\ &= 1 - \frac{\rho_f V g}{\rho V g} \\ &= 1 - \frac{\rho_f}{\rho}. \end{aligned} \tag{14.4}$$

Solving for ρ tells us that

$$\rho = \frac{\rho_f}{\left(1 - \frac{W_f}{W}\right)}. \tag{14.5}$$

Thus if we can weigh an object both inside and outside a fluid of known density (water has a density of 1.00 g/mL) we can find the density of the object.

14.2 Apparatus

Three objects made of different, non-wooden materials, with at least one having a regular shape whose volume can be calculated, string, small ruler, computer with Logger Pro and force probe, long and short metal bars, clamps to attach bars to table and to each other, small and large graduated cylinders, digital scale, and water.

14.3 Procedures

You will calculate the densities of each object two or three ways.

- ρ_1: mass divided by calculated volume (if possible),
- ρ_2: mass divided by observed volume, and
- ρ_3: calculation using Equation 14.5.

The goal in this experiment is to compare these values with one another and with tabulated values, found either in your textbook or on the Internet.

One can use density measurements to help identify materials. Do you think that the method based on Archimedes' Principle is reliable for this purpose?

14.3.1 Setup

1. If necessary, attach the long bar to the table using an appropriate clamp.
2. Attach a short crossbar to the long bar using another clamp. The crossbar should be over the table, not over the floor.
3. Slide the force sensor over the crossbar and attach it tightly with the thumbscrew.
4. Fill the large graduated cylinder with water if necessary. Use the drinking fountain near the restrooms down the hall.
5. If Logger Pro is running on the computer, restart it. The computer should show a reading for the force sensor in the upper left corner, above the Lab Pro icon, and the graph should be showing an empty force versus time graph.

14.3.2 Data Collection

Here are the step-by-step procedures for collecting data. For each of your three objects:

1. Find the mass of the object, in grams, using the digital scale.
2. If the object has a regular shape, measure the object with your ruler. Measurements should be in cm, and should be made to the nearest half millimeter (or 0.05 cm). Calculate the object's volume in mL (or cm^3; same thing). Assume your uncertainty in the volume is ± 0.001 mL.
3. Calculate the largest and smallest possible values for ρ_1 using your recorded mass and the smallest and largest values for volume (respectively) calculated theoretically. Record these values in your data table.
4. Tie a string around your object. Tie a loop to the other end of the string.
5. Zero the force sensor.
6. Hang your object from the force sensor. It should be suspended in air a few inches above the table.

7. Collect data for several seconds.

8. Select a flat region on the force versus time graph. Click the Statistics button. Record the mean value as the weight of the object in air W.

9. Fill your small graduated cylinder to about the halfway mark if necessary.

10. Record the volume of water in the cylinder in mL as V_1.

11. Place the small graduated cylinder under the hook on the force probe. Hang your object in the water in the small graduated cylinder. You may raise or lower the crossbar as needed, or turn it so the object does not touch the side of the graduated cylinder.

12. Record the volume of water in the cylinder again as V_2.

13. Record the volume of your object V as $V_2 - V_1 \pm \Delta V$, where ΔV is the uncertainty of measurement of your small graduated cylinder (usually stamped at the top of the cylinder).

14. Calculate the largest and smallest possible values for ρ_2 using your recorded mass and the smallest and largest values for volume (respectively) obtained from your small graduated cylinder. Record these values in your data table.

15. Use Logger Pro to record force data for a few more seconds, while the object is hanging in water.

16. Select a flat region on the force versus time graph. Click the Statistics button. Record the mean value as the weight of the object in fluid W_f.

17. Calculate a value for ρ_3 using Equation 14.5. (Assume uncertainties for this measurement are negligible.)

18. Remove your object from the water and examine it. What is it made of? Aluminum, steel, and lead are common materials for these objects. Ask your instructor for an opinion if you have doubts.

19. Find a commonly accepted value for the density of your material in your textbook or on the Internet. Record this value in your data table.

14.3.3 Questions for Conclusion Section

- Do your values of ρ_1 and ρ_2 agree with each other within uncertainties? If so, their extreme values should overlap to some degree.
- Do your values of ρ_3 agree with the associated values of ρ_1 and ρ_2?
- What is the percent difference between ρ_3 and your generally accepted value for the same material?
- Is using Archimedes' Principle to determine densities a good way to identify materials? Why or why not?

Chapter 15

Thermal Expansion

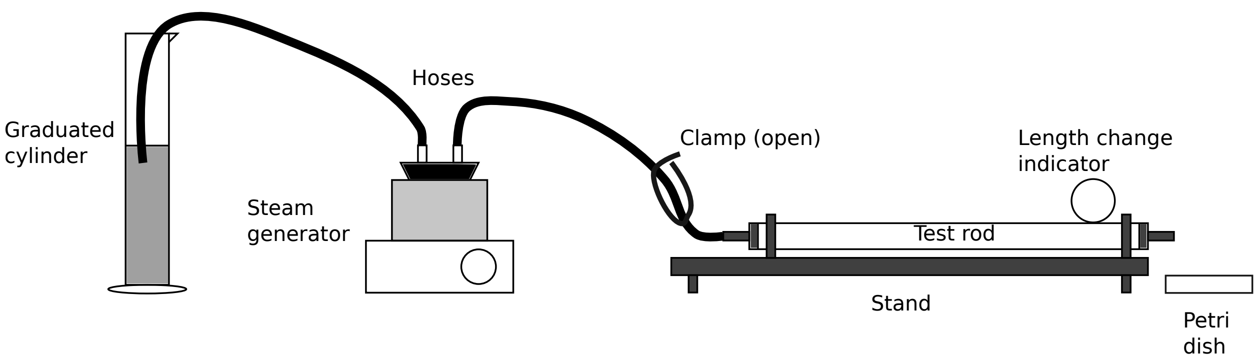

Figure 15.1: Apparatus for thermal expansion testing

15.1 Introduction

Materials tend to change in size when they change in temperature. Metals tend to follow a very simple linear model. If a metal has length L_0 at temperature T_0, its length L at temperature T is often well-described by the equation

$$L = L_0 + \alpha L_0(T - T_0) \tag{15.1}$$

where α is a property of the metal known as its *coefficient of linear expansion*. Temperature and length changes are assumed to be small; this model fails when temperatures approach the melting temperature of the metal, for example. Note that this equation doesn't have any real physics in it; all we are saying is that the length of our metal is directly proportional to its temperature.

We can solve Equation 15.1 for α to find that

$$\alpha = \frac{(L - L_0)}{L_0(T - T_0)}. \tag{15.2}$$

Coefficients of thermal expansion are important in many disciplines, like structural engineering, and values have been tabulated for many materials. Some examples are shown in Table 15.1.

Material	α ($\times 10^{-6}$/°C)
Copper	17.6
Steel	11.3 – 13.5
Aluminum	23.4

Table 15.1: Linear expansion coefficients for various materials

In this exercise, you will attempt to verify some of these values. You will pass steam through long samples of these three materials and measure the changes in temperature and length of the material. You will then calculate α and compare your values to the values in Table 15.1. Uncertainty measurements will not be used here; simple percent differences will suffice.

15.2 Apparatus

Steam generator, two hoses, hose clamp, three test rods (copper, steel, and aluminum pipes with hose couplings at both ends), test rod stand with integrated thermistor and length change indicator, digital multimeter, wire leads, graduated cylinder, meterstick, petri dish, pot holder.

15.3 Procedures

15.3.1 Assembly

To assemble your test apparatus for data collection:

1. Open your steam generator. Make sure it is about half-full of water. Add or remove water as needed, then close the generator.

2. Partially fill the graduated cylinder with water.

3. Attach one hose (without a clamp) to a coupling on the top of the steam generator. Submerse the other end of the hose just slightly into the water in the graduated cylinder. If the hose end is too deep in the water, steam pressure in the generator may rise high enough to pop the stopper off the generator. If this happens, raise the hose higher in the water. If necessary, relocate the graduated cylinder so it can stand freely without tipping over.

4. Attach the second hose to the other coupling on the steam generator. Place a clamp on this hose as shown in Figure 15.1 and close the clamp to pinch the hose closed.

5. Turn on the steam generator, and turn the heat to its highest setting.
6. Attach the digital multimeter to the thermistor with the wire leads. Set the multimeter to the ohmmeter setting, usually to the 200 kΩ setting. (All multimeters are different; ask your instructor for help if necessary.)

You are ready to collect data when bubbles begin to appear in the water in the graduated cylinder.

15.3.2 Data collection

For each test rod:

1. Identify and record the type of metal that the rod is made of. Copper is orange in color. Aluminum has the haziest finish. Steel has a mottled appearance due to the zinc coating on its exterior. Don't be afraid to ask for assistance if you aren't sure what material your rod is made of.
2. Drain any water present in the test rod and the petri dish into the graduated cylinder.
3. Place the test rod in the stand. There are thin metal guide rods that will help you place the rod in the stand appropriately. Place them in their slots on the test stand.
4. Pull the knob on the length indicator so the rod finishes dropping into place. Release the knob; the dial indicator should now be in contact with an L-shaped attachment on the test rod.
5. Turn the outer ring on the length indicator until the dial points to the 0 mark.
6. Attach the clamped hose to one hose coupling on the test rod. (Do not open the clamp yet.)
7. Place the petri dish under the free hose coupling on the test rod.
8. Unscrew the thumbscrew at the middle of the test rod, removing it if necessary, until the thermistor's ring or spade connector can be attached to the test rod. Re-tighten the thumbscrew to hold the connector firmly in place.
9. Read the multimeter display (it usually displays in thousands of ohms). On the table attached to the stand, find the starting temperature T_0 of your test rod by looking up the thermistor resistance. Interpolate the temperature as best you can.
10. Measure the initial length of the test rod L_0 with the meterstick.
11. Open the hose clamp. Steam should begin to flow through the test rod. If necessary, move the hose end in the graduated cylinder down slightly to obtain greater pressure.

12. Watch the multimeter display and the length change indicator. As the temperature of the test rod rises, the length of the rod will change and the resistance of the thermistor will fall. At some point, the test rod will reach an equilibrium temperature around 80°C. When it does, you are ready to collect more data. This step can take some time. While you wait, watch the length change indicator carefully to see if it goes completely around the dial. (It generally does for the aluminum test rod, but not for the others.)
13. When the temperature is more-or-less stable, look up the final temperature of the rod T on the table on the stand using the resistance measurement on the digital multimeter.
14. Record the change in length of the rod using the length change indicator. Note that as the rod lengthens, the dial turns backwards. Each division on the dial is 1/100th of a millimeter.
15. Use your recorded data and Equation 15.2 to find α, the coefficient of linear expansion for your rod.
16. For the aluminum and copper rods, find a percent difference between your α and the tabulated values above. If your rod is steel, does your coefficient fit into the range of values given in Table 15.1? If not, find a percent difference between the closest tabulated value and your value.
17. Close the hose clamp to cut off steam to your test rod.
18. Remove the hose from the rod's hose coupling.
19. Disconnect the thermistor from your rod.
20. Using the pot holder (your rod is *hot*, be careful!), lift your rod off the stand.
21. Pour any water in the rod into your graduated cylinder.
22. Set the rod down on the table to cool.
23. If you haven't collected thermal expansion coefficients for all three materials, choose another test rod and return to Step 1.

Chapter 16

Pendulum Lab

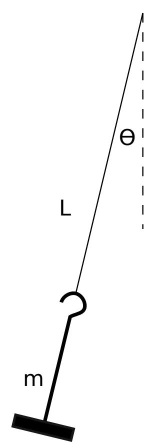

Figure 16.1: A simple pendulum.

16.1 Introduction

A pendulum is, in its simplest form, a weight of mass m (sometimes called a bob) attached to the end of a light string or rod of length L, as shown in Figure 16.1. It can be shown mathematically that the period T, or time of one complete oscillation, of a pendulum displaced by only a small angle ($< 15°$ or so) from vertical is given by the formula

$$T = 2\pi\sqrt{\frac{L}{g}}. \tag{16.1}$$

Note that the period is only related to two physical quantities: the length of the pendulum and the rate of gravitational acceleration. It has nothing to do with the initial angular displacement θ, or even the mass m of the bob.

Today's experiment will be an attempt to verify this relationship for a pendulum oscillating at small angles.

16.2 Apparatus

Long rod, table clamp, second clamp, string, meterstick, stopwatch, protractor, weight hanger and weights, computer with iMovie software and built-in camera.

16.3 Procedures

You will perform three experiments in this lab exercise, finding the period of the pendulum multiple times for each experiment. Start with $L = 0.50$ m, $\theta = 5°$, and $m = 50$ g or 100 g (the mass of your weight hanger) for all runs. (You will reuse this inital data for all parameter variations.) You will change the following parameters:

- Mass m: add a 50 g weight to the hanger
- Angle θ: increase to $\theta = 10°$
- Length L: increase to $L = 0.75$ m, then to $L = 1.00$ m.

After each run, you will calculate the period of the pendulum using Equation 16.1.

16.3.1 Setup

1. Start the iMovie video capture and editing software.
2. Attach your rod and your table clamp to the table near the middle of the table.
3. Attach about 1 m of string to the upper clamp on the long rod as directed by your instructor.
4. Tie a loop at the bottom of the string, then hang your weight hanger from the loop.
5. Examine the video in iMovie. The pendulum should be close enough to the computer so the pendulum motion is easily visible. If not, reposition the computer and/or the pendulum.

16.3.2 Data Collection

Perform this procedure for every parameter variation described above.

1. Change the mass of the bob and the length of the pendulum as needed.
2. Record all parameter data for this run.
3. Hold the protractor at the top of the string, so its center is at the pivot point of the pendulum.
4. Deflect the pendulum to the desired angle θ, then let it go.

5. Start recording video.
6. Allow the pendulum to swing through at least five oscillations, or complete periods. For example, when the pendulum swings from one side to another *and back again*, that is one oscillation.
7. Stop recording video.
8. Use the video editing software to find the period (time) of at least five pendulum oscillations. Record these times in a data table. Clearly associate these times with specific values of m, θ, and L as needed.
9. Calculate your expected value for the period of the pendulum using Equation 16.1.

Did changing your parameter change your period noticeably? Do the range of values you found experimentally cover, or potentially include, this value?