PHYS 3A
Lab Manual

First Edition (2022)

CoA Physics Department

NOTES FOR THE FIRST EDITION

This first edition represents a collection of manuals for Physics 4A and 4B labs whose contents align with the topics covered in Physics 3A, mechanics, waves, and thermodynamics. The format in which these manuals are included represents the form of the primary repository for these lab manuals, which are editable Canvas Pages maintained with the associated course shell. It is the intent of the physics faculty of CoA to, in near future, extensively adapt these labs and develop new labs of particular interest to biological science major students.

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Note: Page numbers refer to PDF page numbers for the overall collection. Each lab manual has its own pagination, unrelated to the ToC listing here, generated for the print-out from Canvas Pages.

Lab: Intro to Physics Lab

Note: This is a Newstyle Lab. Read each section of the lab manual carefully before starting to work on that section. Keep an organized record of any measurements you make, or any information you had to discover which was not apparent from the clear text of the lab manual. Make sure to stop at each boxed section of the lab manual and go through the activities in the boxed section. You will turn in a copy of your notes at the end of the lab section, and *a follow-up lab narrative is due next week.*

Welcome to your first physics lab! In this introductory lab, we will introduce general structures and arrangements for physics lab and demonstrate some sources of error you may see in your future labs.

Introductory Notes

If you have taken other science classes before, I hope you will soon see that physics labs are quite different. We say that "physics is the fundamental science," and what it means to me—your instructor—is that physics is the discipline where you learn to do a lot with very little. In other science classes, there are many facts, processes, and formulas to memorize; while there *are* facts, processes, and formulas to memorize in physics too, the emphasis of physics is not on those facts, processes, and formulas themselves but in understanding what the *fundamental laws* are—and how we might be able to derive those facts, processes, and formulas from the fundamental laws.

While I hope *you* will notice the differences soon yourself (and it has been many years since my last chemistry or biology lab, so you are in the better position to tell the differences), following are some key things I want you to note from the first day:

- **Physics lab is more open;** there is more room for experimentation, coming up with your own procedures, and trying out your own things. Of many reasons why physics lab *can* be more open, one important reason—especially important to keep in mind in your other labs—is that physics lab is safer. We rarely deal with chemicals or other dangerous substances; most of our equipment cannot cause grave bodily injury. While I do want you to take care with our instruments—please don’t break them—because your risk of injury is low in general in physics labs, you can afford to be more flexible and more open in terms of lab procedures.
- **Physics lab is more precise and more accurate.** Even in this instructional lab setting with few sophisticated instruments, we can often achieve accuracy within 10% of the accepted numerical result—and with sufficient care and effort, 5% or 1% error is achievable on occasion. I want you to set a high bar for yourself. In physics labs, we deliberately choose situations with few complicating circumstances where this high precision can be achieved—and in the few situations where complicating circumstances remain, we want to better understand the complicating circumstances.

I hope you already understand the importance of experiment to sciences. You have already learned about the "scientific method" and the foundations of empiricism, describing how scientists—and everyone else—come up with hypotheses, design experiments to test the hypotheses, modify the hypotheses based on results of experiments, and iterate (that is, repeat these processes) these steps, improving the initial educated guesses.

At the core of physics problem-solving (or "puzzle-solving", in the language of Thomas Kuhn, a historian of science) is a trial-and-error approach to new situations and problems. "Trial" is the attempt at answering a question or situation that has come up; "error" is the *sophisticated* step in which you try to determine how close—or correct—your answer was. If you decide your answer wasn't quite right (or at least not as right as you would like it to be), then you modify your approach and do the "trial" again, hoping for an improvement at the "error" step. It is an iterative approach (the key feature of the scientific method) which values critical self-reflection.

Our highest goal this semester is to introduce you into physics problem-solving. Some of you might find that this *is* how you have been approaching problems in your life (I hope you will consider a career in physics!); others might find this approach challenging and often times frustrating ("Am I doing this right? Can you just tell me if this is right?"). Physics problem-solving requires *balancing* between logical deductions of mathematical reasoning (think back to when you were first taught about proofs in geometry, or possibly more recently in linear algebra, if you are farther along in your math sequences) and *intuitive* leaps—certain *key* steps in physics problem-solving are often poorly motivated (what this means is, if someone asks *why* I did something, I have no good answer, other than that doing that got me to the correct answer). This balancing is something you have to learn over time, and if by the end of the semester, you begin to understand what it is you are balancing, I will have achieved my goal.

This introduction into physics problem-solving is what we do in *both* physics lecture and lab, but it is far more important in lab. I'll be honest with you: in lecture, we don't really practice what we preach. You don't really get to apply the scientific method in lecture—you are not testing hypotheses when I teach you about Newton's Second Law ($\vec{a} = \sum \vec{F}/m$, for those who have seen it); a lot of time in lecture is spent teaching you about mathematical tools and problem-solving methods—which you *need to know*; you have to know what to "trial" in your trial-and-error approaches. It is in lab where you can *practice* being a scientist and an engineer. While we are not discovering new laws of physics in our physics lab (sorry, the equipment we are providing you with simply are not good enough), we are going through the same processes, reasoning steps, and practices that a practicing scientist or engineer would go through, as they tackle the problems at the frontier of our knowledge (using the state of the art equipment). It is through this lab that we hope you will grow in your thinking as a future scientist and engineer.

So, these are all high ideals—and I understand if these words don't yet have the same meaning to you as it did for me (well, when I was doing research as a grad student). We will start this journey together, and I will provide as many concrete instances as I can, where you can practice being a scientist and an engineer, in anticipation of future careers you will take on, when you move on from here.

Significant Figures, Uncertainty, and Percent Difference

Here is the first concrete example on practicing being a scientist. You have learned about significant figure rules in your earlier math and science classes. This is a version of these rules that you hopefully recognize:

(1) "significant figures" are the number of non-zero digits you have (plus some zero digits that you see that you can infer are significant); (2) when you add or subtract two numbers, you follow the significant figure of the number whose smallest significant figure is larger; (3) when you multiply or divide two numbers, you follow the significant figure of the number which has a smaller number of significant figures. Some examples are below:

- Following are some examples of significant-figure counting of numbers: 137 has 3 significant figures; 305 also has 3 significant figures; 305.0 has 4 significant figures; with 3050, it is ambiguous if it has 3 or 4 significant figures, but if you write it in scientific notation as 3.050×10^3, then it's clear that it has 4 significant figures. And 0.004 has only one significant figure (0.0040 has two significant figures). For examples below, we will stick to numbers that have some digits below decimal, so that there is not an ambiguity regarding number of significant figures.
- When you add 137.04 to 3.142, the answer, following the addition/subtraction rule is 140.18, so that the sum/difference has the same smallest significant figure as the larger smallest significant figure (137.04's smallest significant figure is 4, at hundredths; 3.142's smallest significant figure is 2, at thousandths; so the sum is rounded to hundredths).
- When you multiply 137.04 to 3.142, the answer following the multiplication/division rule is 430.6, so that the product/quotient has the same number of significant figures as the smaller number of significant figures (137.04 has five significant figures; 3.142 has four significant figures; so the product is rounded to have four significant figures).

So these are the rules you have learned and the rules you have been following. Now, as I will be telling you to no longer pay so close attention to these rules ("Down with the rules!"), it is important that you *understand* what these significant figure rules are trying to achieve.

DISCUSSION – Discuss with your partner or group to answer this question: What is the goal of significant figure rules? What do the rules (1) through (3) achieve?

Now, understanding what the rules were trying to achieve, here is why they are inadequate: the range of uncertainties covered by numbers that have the *same* significant figures is potentially large. Consider these two numbers, 1.1 and 9.9. They both have two significant figures. The first number 1.1 covers the range of numbers from 1.050 to 1.149 (they all get rounded to 1.1, when you round to two significant figures). The second number 9.9 covers the range of numbers from 9.850 to 9.949. In many circumstances, the uncertainty you care about is *percent* uncertainty. Given the range of uncertainty (1.050 to 1.149, or 9.850 to 9.949, both covering a numeric distance of 0.099), what percent is that uncertainty of the overall number? It is in calculating this percent uncertainty that you will see that two numbers with the same significant figures can have very different percent uncertainty.

QUESTION and ANSWER – Calculate percent difference from 1.05 to 1.10 and calculate percent difference from 9.85 to 9.90. What range of percent uncertainties could you see in numbers with two significant figures? What range of percent uncertainties could you see in numbers with three significant figures?

In many contexts in this class, you will be told to use three significant figures. It's a "reasonable compromise." Most real numbers you will work with in this class have about 1% uncertainty, and using three significant figures ensure that you do not *increase* uncertainty in your numbers unnecessarily. Sometimes, when significant figure rules say a product should have two significant figures, you might see me retain three significant figures. Or sometimes, for intermediate calculation numbers, you might see extra number of significant figures being retained. This is so that existing *percent uncertainty* in the numbers are preserved and represented, and so that we do not increase the uncertainty unnecessarily.

Finally—for this introductory section—in laboratory context, you are going to see following three terms, sometimes being used interchangeably, sometimes being distinguished from each other: **percent uncertainty**, **percent difference**, and **percent error**. In most situations, they can be used interchangeably without resulting in serious error in meaning, but there are subtle differences in meaning. For example, a particular numerical result might have a zero percent error but *not* have a zero percent uncertainty. I hope you will see illustrative examples throughout this semester!

Part A – Ball Measurements

This first part will provide you with a concrete example of importance of precision and an example of a situation where a given percent error in one measurement results in a different (greater, in this case) percent error in values that are calculated from that measurement. Following are the guiding Research Questions for this part. These are the questions you should answer—with all the necessary details and nuances—by the end of this part. Some description of the setup will follow below.

- **Research Question 1**: Do Nylon Balls (provided) have the same diameter as Stainless Steel Balls (provided)?
- **Research Question 2**: By what percent do volumes of Nylon Balls differ from volumes of Stainless Steel Balls?

We have two different physical objects available that are distinctively different in certain ways but are quite similar in some ways. In the classroom, you will find two containers, one of yellow nylon balls and another of polished stainless steel balls. One is plastic and the other is metal; the stainless steel ball is heavier than the nylon ball. There is one aspect in which they appear to be similar: size. I believe both of these balls are sold as "1-inch-diameter [MATERIAL] balls." What this means is these balls have a *nominal diameter* of 1 inch. So, does this mean these balls do have a diameter of 1 inch? There is a saying in physics: "[It] becomes a purely experimental matter."

We have several different measuring devices at your disposal. Using them (all, any, etc.), determine to your best ability the diameter of one nylon ball and one stainless steel ball. Pay attention to the significant figures ("1 inch", "1.0 inch", and "1.00 inch" carry different meanings; it might just be easier if you are measuring in centimeters or millimeters) and aim for the highest number of significant figures you can achieve given the measuring devices available. If you need help using some of the measuring devices (particularly for the caliper and the micrometer), please call me. The resource note at the end of this lab manual will link you to videos that demonstrate use of caliper and micrometer (in lab, call me; that's probably quicker than watching the video).

MEASUREMENT – Determine the diameters of a nylon ball and a stainless steel ball, to the highest precision possible given the available measuring devices.

Note: There is an aspect of self-learning, or "inquiry-based learning" in these activities. I am deliberately not giving you a detailed set of steps to follow, so that you might figure it out for yourself. Having said that, my goal is not to frustrate you—if you feel stuck at any point, call me and ask me what the next thing to do is. I will figure out where you are and try to give you some ideas on what you could do next.

The diameters you measure above have certain uses. Directly, they are used for quality control (most manufacturers of ball bearings specify not only the sizes of bearings but the tolerances of these sizes, so that their customers know how much—and how little—they can rely on the nominal values). More usefully in a physics lab setting, the value you measure will be the starting point of a calculation. Imagine you are trying to determine the density of a nylon ball. For the density, you need to know its mass and volume. And one of the ways to determine volume of a spherical object is by using this formula you may have seen in geometry: $V_{\text{sphere}} = \frac{4}{3}\pi R^3$, where R is the radius of the sphere. Having measured the diameter, you can calculate the radius easily and use that to calculate the volume of the ball, with better precision and certainty than just relying on the nominal values.

I'm hoping in your measurements above, once you got to high enough precision, you saw a slight difference between the steel ball diameter and the nylon ball diameter. In case your balls had the same *exact* diameter, down to tenths of millimeters, introduce a small error (change the last digit a little) for the purpose of below calculations.

CALCULATION – Calculate the percent difference in the volumes of the nylon ball and the stainless steel ball. Compare this to the percent difference in the diameters of the nylon ball and the stainless steel ball.

There is a way in which these percent differences are related (there is a calculus reason behind it, possibly to be covered in Calculus 2). If you want to know, please ask—knowing this particular reason isn't required for this class; I just want you to know the reason behind **error propagation (https://en.wikipedia.org/wiki/Propagation_of_uncertainty)** .

The measurements you did in this section are the simplest type of measurements (length measurements) in a physics lab. The next section will involve precision measurements of *time*.

Part B – Pendulum Period Measurements

Following are the research questions guiding the activities in this section. While it won't be until Chapter 15 that we can deal with the theory aspects of pendulum oscillations, everything you know about physics *now* is sufficient to perform measurements necessary to answer below research questions (again, with all the necessary details and nuances).

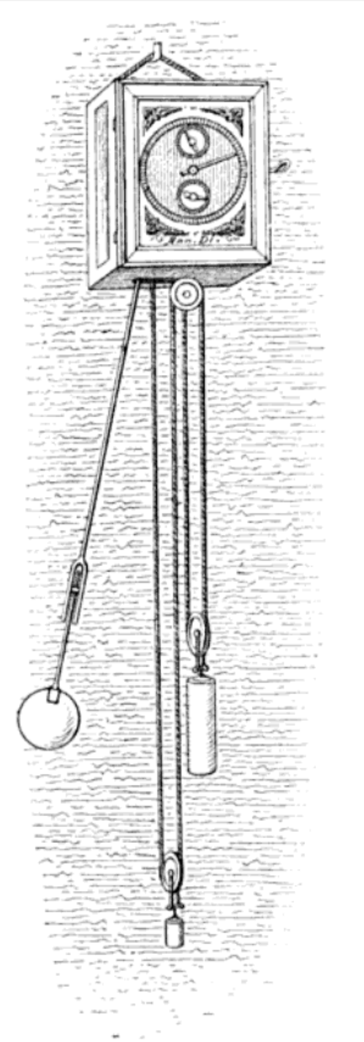
- **Research Question 1**: Does a pendulum swinging in 15-degree arcs have the same period as a pendulum swinging in 45-degree arcs?
- **Research Question 2**: What factors affect pendulum periods?

The pendulum clock, invented by Christiaan Huygens, is inspired by investigations of Galileo into pendulum motion. One (probably apocryphal) story tells of how a young Galileo became curious, looking at the motion of an incense-filled censer (not to be confused with censors he had to contend with later in his life), that the back-and-forth swinging motion seemed to occur at regular intervals. Using his own heartbeat as a timekeeping device, he tried to confirm this observation.

This lab activity is inspired by the same physical setup (minus the incense, which could be irritating to those with allergies). You should find a simple pendulum setup, a small mass hanging at the end of a long string, at your table. The task at your hand is simple: measure the period of the pendulum. What is meant by "period" is the amount of time it takes for the pendulum to make one full back-and-forth swing (in general, "period" is the amount of time it takes for completion of shortest repeating motion). As an open investigation, this can be a little bit too open ("Do something with pendulums."), so I will ask you to focus on the following two questions. In order, first question:

1. Does a pendulum swinging in a small range of motion have the same period as a pendulum swinging in a large range of motion?

You can set a pendulum to move in a small range of motion by giving it a smaller initial angle of displacement from the vertical. The 15-degree arc described in Research Question 1 can be achieved by initially displacing the pendulum by 7.5 degrees from the vertical; when released, the string of the pendulum will cover 15 degrees of motion. A "large range of motion" can be defined in a few different ways. A 16-degree arc is certainly larger, but such a small difference might make effect of a larger range difficult to measure. Research Question 1 uses 45-degree arc as a "large range" (to be achieved by initially displacing the pendulum by 22.5 degrees from the vertical), but if you thought you saw an effect of large range of motion on the period of the pendulum, nothing prevents you from trying larger amplitudes, up to about 180-degree arc or so (possibly smaller, if some mechanical connection/arrangement breaks with larger amplitudes).



You have timekeeping devices provided (and you are welcome to use your own, such as a stopwatch app on your smartphone). Devise your own experiments and take the necessary measurements.

MEASUREMENT – Determine the effect of the size of the oscillations (small or large) on the period of the pendulum motion.

Having investigated the effect of the size of the oscillations on the period of pendulum motion sets you up for the second question:

2. What affects the period of a pendulum?

In particular, what changes can affect this period *strongly*? That is, imagine you wanted to change the period of the pendulum by a factor of 2 (either increase it by 2, causing it to oscillate slowly, or decrease it by 2, causing it to oscillate more quickly). What changes can you make to the pendulum to accomplish this? This is the place where I ask you to exercise your creativity—take a look at pendulum, taking stock of physical parameters that define this pendulum (what parameters are relevant? what parameters *aren't* relevant?). Imagine which of these parameters can be changed, change those parameters, and measure the effect of having changed those parameters.

There is an aspect of art and science to physics investigations. *Science* aspect here is the technical details involved in making the actual measurements. Hopefully having spent your time with Question 1 above, you were able to take a look at your measurement techniques and improve them (ask me if you want my critique!). The *art* here has to do with deciding what to investigate. Multidimensional parameter search is difficult (read more: **Curse of dimensionality** **(https://en.wikipedia.org/wiki/Curse_of_dimensionality)** ; here, "dimension" refers to one measurable aspect, not necessarily having anything to do with physical dimensions, such as three spatial dimensions, or different realms, such as "hell dimension"). There is art in deciding on the right thing to measure; this type of decision-making doesn't occur in a linear or deterministic fashion—so without spoiling the answer, I can't tell you what you should look for. (But if I need to spoil the answer in *individual cases*, I will, so feel free to ask!)

One thing I *can* tell you is how beneficial it is to work on the "science" aspect—if you have a good measurement technique; if you can quickly and efficiently determine, with the necessary degree of precision, what the period of the pendulum is, in a given amount of time, you can try more guesses. That will help you develop the "art" side of physics investigations.

INVESTIGATE – What factors affect the pendulum period significantly?

Lab Narrative

That's it for the in-lab activities. Please turn in a copy of your notes (one *new* way I'm letting people turn in lab assignments: submit it online on Canvas as a high-quality photo of your notes; I can also help you make physical copies, if you don't have a good camera phone). This section will describe the **Lab Narrative** you should turn in next week.

Purpose of the Lab Narrative

The purpose of the lab narrative is to *document your understanding of the lab*. All the details, information, and sections of the lab narrative should contribute to this goal. It might be easier to visualize this goal if you imagine a classmate (or a future Physics 4A student) reading your lab narrative and making sense of what you did and learned in the lab. Feel free to omit superfluous details that you feel does not contribute to documenting how you understood the lab.

When someone—particularly me, your instructor and grader—reads your lab narrative, that someone should feel that you comprehended elements of the lab that you could comprehend within the given time and equipment limitations.

Organization of the Lab Narrative

Following is how I recommend that you organize your lab narrative. You *might* find it necessary to organize it differently; feel free to experiment. The structure given here is the basic structure in which most physics research papers are published in (activity we are trying to model after); it's not a strict guideline you must follow.

- **Introduction**: The introduction section usually gives a background to the experiment, explaining why you are doing the experiment. This might borrow moderately from the lab manual. Introduction is *usually* the last section that should be written (because what you learn from completing the other sections might inform how you write the introduction).
- **Methods and Procedure**: There should be a section in which technical details are described. If someone else wanted to replicate your experiment, what would they need to know? Did you find that you had to wrestle with any particular problem? The procedural details here should give enough details so that others could follow them in order to reproduce your results, but it should skip the boring bits.

- **Results and Analysis / Discussion**: Sometimes information in this section can go alongside Methods and Procedure. Other times, especially if there is a substantial amount of analysis needing to be done, it might be organized into its own section. It's your call, really—does it seem most natural to cite the results of your measurements and what these measurement mean alongside the description of experimental methods, or should the discussion of results be separated out into its own section? Experiments calling for extensive error analysis might need its own results and discussion section, to discuss all possible sources of error.
- **Conclusion**: Conclusion should be written in a way so that if that is the only section someone read, they can quickly get a sense of what you found out in your experiment. It might be a summary of results section; it might boldly state some new (or at least surprising) thing you discovered in your experiment. This is also a good section in which to propose future work—what would you have done, if you had additional time and wanted to further investigate what you were investigating?

Length of the Lab Narrative

There is no particular length requirement on the lab narrative. But just to set proper expectations, for most labs in this course, a high-quality lab narrative including all relevant details and thoughtful analysis can be written in about 3 pages, single-spaced, inclusive of any figures or table of data.

If you feel it's necessary, you may write longer lab narratives, but it is not necessary to write longer lab narratives just to fill space.

Resources and Additional Information

This section is an appendix of information, concepts, techniques, and information that you might find useful for this (and future) lab. I will happily answer any questions *in lab*, but especially in case you feel you need information provided here as you are doing your work outside the lab (either preparing for lab or writing your lab narrative), this is provided here.

A: Percent Uncertainty, Percent Difference, and Percent Error

The terms **percent uncertainty**, **percent difference**, and **percent error** comes up often, and I thought it would be useful to have a single place in which to describe them in some detail, *particularly* moving beyond the simplistic notions of percent error. The simplistic notion of percent error is what you might have seen in previous science labs: "Percent error is the difference between the theoretical value and experimental value, divided by the theoretical value." This simple description is not wrong (just as the significant figure rules you have been following weren't wrong); it just doesn't cover all the cases you might see. Now is the time you learned *why* we calculate percent error and learn different, flexible approaches to expressing experimental uncertainties.

Every physical measurement has an uncertainty associated with it. Sometimes these uncertainties are explicitly stated and easy to infer; other times it takes fair amount of work determining the uncertainty associated with each measurement. Imagine making a measurement of g, which describes gravitational field near the surface of the Earth. The commonly accepted value of g is $g = 9.81\ \mathrm{m/s^2}$. There are different ways of measuring g. One way is to observe motion of an object in free fall and calculate its acceleration. If I did this measurement and obtained a value of $9.8\ \mathrm{m/s^2}$, I can ask and answer three different questions: (1) what is the percent uncertainty in this measurement, (2) what is the percent difference in this measurement, and (3) what is the percent error in this measurement?

The percent difference (2) is the easiest value to calculate with minimal discussion, so I will do that first. With percent difference, often you have two values in mind. In this case, it would be the commonly accepted value 9.81 m/s^2 and the experimentally measured value 9.8 m/s^2. So I take the difference, obtaining 0.01 m/s^2 (note that I am ignoring a significant figure rule to do this; I made the judgment call that this is preferable to reporting a difference of 0.0 m/s^2, following the significant figure rule blindly). To obtain a percent figure, I have to divide this by a reference number, and here, I will choose my experimentally measured value, which gives me 0.01/9.8 = 0.00102 = 0.102%. There are two other numbers I could have chosen as a reference number, either the commonly accepted value, or an *average* of all available numbers. Usually when the percent difference is small, this choice of reference number does not significantly affect your final result, so beyond being explicit about how I am calculating the percent difference, I don't worry so much over which reference number I have chosen.

The percent *error* (3) is more subtle, because you are making a judgment call on which number is the correct, "true" value. If described as percent error, rather than blindly using the commonly accepted value of 9.81 m/s^2, I would need to investigate to see what value I *should have* measured.
The *theoretical* value of g varies depending on your latitude (from 9.832 m/s^2 at the poles to 9.780 m/s^2 along the equator). And there maybe local differences (such as mineral deposits) which affects the "true" value of g you "should have" measured.

I hope my biases are showing with these scare quotes—especially in our context, it's much easier to deal with percent differences. With percent differences, you can simply report difference between two numbers (one you measured, and another that you are using to see if your number is reasonable) without needing to answer the difficult question of what exact number you should have measured. (Having said that, I won't be too strict about enforcing *correct* usage of the term "percent error.")

The percent uncertainty (1) is the one that needs the greatest consideration, and the frank truth here is, I don't have enough information to give percent uncertainty of the value measured, 9.8 m/s^2. I would need to know the details of experimental methods to have an educated guess at the percent uncertainty. Based on significant figure rules, I do hope the percent uncertainty is not much higher than 0.1 m/s^2, because the "8" is supposed to be a significant figure, and if the true value was lower than 9.7 m/s^2 or higher than 9.9 m/s^2, then that "8" is not very significant. The percent uncertainty is not simply a measure of how far your number is from the accepted value (that's "percent difference"). The percent uncertainty expresses how confident ("certain") you are of your measurement. For an example, when I measure length of anything I can put ruler against with a ruler, my uncertainty in that measurement is about 0.5 mm (1 mm being the smallest visible mark on most rulers). If I can't place the ruler right against the object, depending on the setup, my uncertainty might go up a little, maybe as high as 3 mm (depending on my considered judgment on how well I could judge the location of ruler markers with my eyeballs). It doesn't mean I am wrong by 3 mm (or 0.5 mm when I have ruler right up against the object); if I knew how much I was wrong by, I would correct for it. I am simply certain that whatever the correct value is, it is within the 3 mm of the value I am reporting—in other words, my level of uncertainty is 3 mm for that particular measurement where I could not place a ruler against the object.

You can see expressions of this type of uncertainty when you look up physical constants. For example, when I look up G, this is the value I see: $G = 6.67430(15) \times 10^{-11}\ \mathrm{m}^3 \cdot \mathrm{kg}^{-1} \cdot \mathrm{s}^{-2}$. What this means is, those who compiled this result are confident that the first four digits, 6.674 are correct. The last two digits, 3 and 0 represent the best estimate, and the number in the parentheses represents the level of uncertainty. According to those who compiled this result, the value of G may be as small as $6.67415 \times 10^{-11}\ \mathrm{m}^3 \cdot \mathrm{kg}^{-1} \cdot \mathrm{s}^{-2}$, or as large as $6.67445 \times 10^{-11}\ \mathrm{m}^3 \cdot \mathrm{kg}^{-1} \cdot \mathrm{s}^{-2}$ (within some confidence intervals, for those of you who took statistics).

This is the considered, *correct* notion of uncertainty, and "percent" part simply turns this figure into percentage terms, by dividing the uncertainty by a reference number (usually your best estimate). So in the example of G above, the percent uncertainty in the accepted value of G is $0.00015/6.67430 = 2.25 \times 10^{-5} = 0.00225\%$.

In our labs, we often use the percent difference as a way to guess at the percent uncertainty. This is a mere shortcut (we have limited time in lab); study of experimental uncertainty requires more consideration.

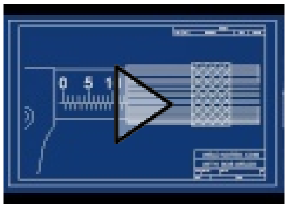
B: Measurements with a Caliper/Micrometer

In lieu of written descriptions in use of a caliper or a micrometer, let me refer you to these videos. I can also demonstrate these techniques in lab (and this is where the information is not very useful outside of a lab setting, unless it's to tell you that you did it wrong in lab).

How to read a metric Vernier caliper (https://youtu.be/vkPlzmalvN4)

(https://youtu.be/vkPlzmalvN4)

How to read a micrometer (https://youtu.be/StBc56ZifMs)



(https://youtu.be/StBc56ZifMs)

C: Measuring Your Reaction Time

The human reaction time is a common source of error whenever manual measurement of time interval is involved. This is one particular source of error you need to be mindful of, as you are performing the pendulum measurements. Below procedure describes how you can measure your own reaction time, with the equipment available in lab. If you just want a quick number you can use, the typical human reaction time involving visual information (you see a meter stick falling) and hand movement (you close your fingers) is about 0.2 second.

Procedure (an example data table you can use with this procedure is provided below):

a. Have your lab partner hold a meter stick between your thumb and forefinger.
b. The thumb and forefinger should be about 2 cm apart (about twice the thickness of the meter stick) so that they do not touch the meter stick.
c. Record the location of the thumb and forefinger before dropping the meter stick (Starting Point, in the table).
d. Your lab partner will drop the meter stick without warning. Try to catch the meter stick as quickly as possible. If you catch it before the meter stick is dropped or if your arm moves as you catch the meter stick, repeat the measurement. You can brace your arm using the table to make sure that your arm will not move down as you catch the meter stick.
e. For each successful measurement, record the end finger position (Ending Point, in the table).
f. Calculate the distance traveled, and convert it to meters. Record it on the table as Distance Traveled.
g. The following is a kinematics formula we will cover in class. For an object in freefall, starting from rest, the distance traveled is given by, $d = (1/2)gt^2$, where $g = 9.8\ \mathrm{m/s}^2$. Solving this expression for time t gives, $t = \sqrt{2d/g}$, and plugging in the numbers (d being distance traveled in meters) gives the reaction time, t. Use this to fill in the last column.

Below table provides enough space for 5 trials. By averaging the 5 trials, you can obtain a better estimate of your reaction time, *and* the spread of the points will give you a way to estimate an uncertainty of your reaction time (think through it).

Trial	Starting Point (cm)	Ending Point (cm)	Distance Traveled (m)	Reaction Time (s)
1				
2				
3				
4				
5				

Note: This is a Newstyle Lab. Most other labs you will see in the semester are Oldstyle Labs, which will appear quite a bit more structured. Please do follow instructions in those other labs; what remains the same with Newstyle Labs and Oldstyle Labs are my expectations—remain flexible and be open to creative problem-solving in physics labs; if you aren't sure of something, always ask!

Lab: Motion

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report.*

Introduction

We start our study of physics with a discussion of motion because the simple setting allows us to challenge common misconceptions and misunderstandings and start building a correct physical intuition (to get a sense of how difficult motion is to grasp intuitively, consider that Greek philosophers like Aristotle had this completely wrong). In some sense, we are not covering any new physics (I haven't taught you a single law of physics yet), but a good grounding in the study of motion will give you a vocabulary to describe the laws of physics that we will cover.

In this lab, we introduce some instruments you will use for this and other labs this semester, and we will look at the motion of a cart under several different situations (ranging from simple to slightly more complicated) to confirm what you know correctly regarding motion and to dispel any conceptual misunderstandings.

Part A: Motion on a Level Track

At your station, you should see a track lying flat on the table. Use the provided level to make sure that the track is indeed level. You should also see a motion detector, connected to DIG/SONIC 1 channel of LabPro, which is connected to a laptop. If the program Logger Pro is not already running on the laptop, run it by double-clicking on the shortcut named "VelocAccel" on the Desktop.

Some quick instructions about Logger Pro:

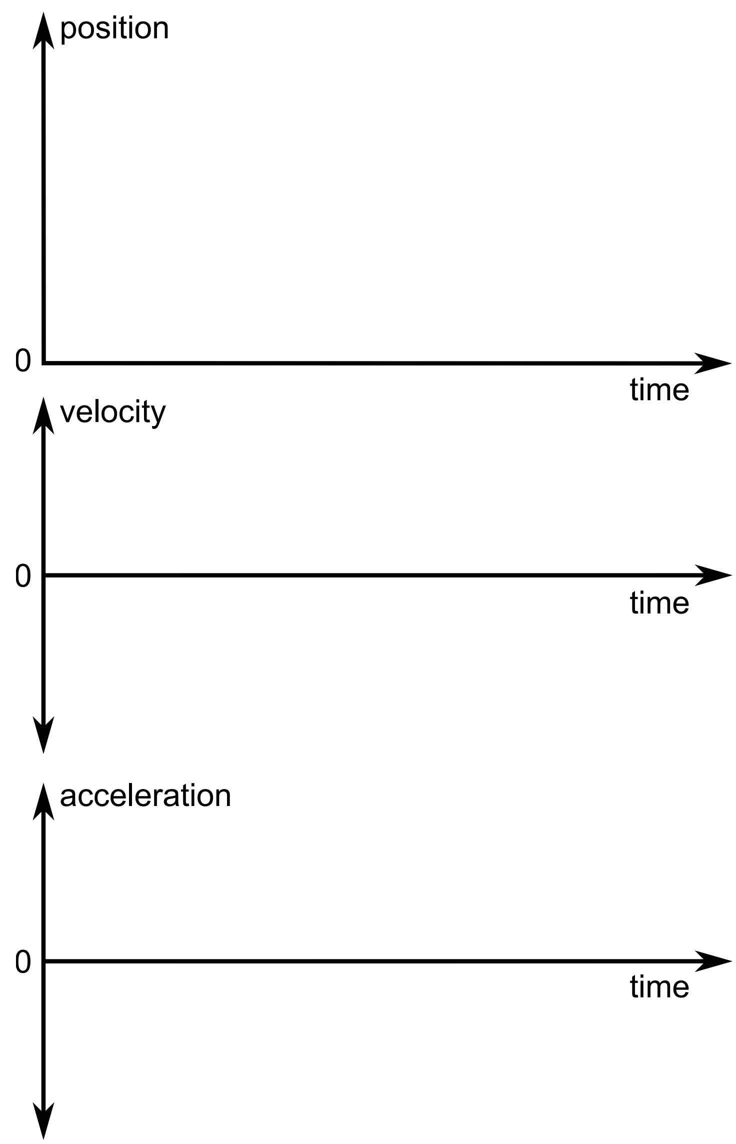
- It should connect to the motion detector automatically (if it asks, click "Connect"). Call me if it doesn't.
- When you hit the large green button called "Collect," the program will start gathering data. You can click it again to stop, or you can let it continue to run (the data run will end in 5 to 10 seconds, depending on the setting). Instead of clicking the "Collect" button, you can also press the space bar.
- To adjust properties of axes, double-click or right-click on different parts of the graph.
  Explore (Call me if you have questions)!

Some notes about Motion Detectors:

- We have two kinds. They work mostly the same way - by producing ultrasonic waves, and when these waves reflect from an object and come back to the motion detector, it measures the amount of time it takes for the round trip and uses it to calculate a reading of position. That is, **the Motion Detector measures position**.
- So it's important that: the motion detector is aimed at the object whose position you want to measure (the beam is pretty narrow), and that you (or your hand) don't come between the motion detector and the cart.
- The motion detector can only measure object positions at distances of 15 cm or greater. At shorter distances, the round-trip time is too short to be measured reliably.
- There is a short delay between when you hit "Collect" and when the motion detector starts to gather data. You can tell by listening for rapid ticking of the motion detector.
- Explore! Play around with the equipment. If you have any questions, call me.

Take some time to become familiar with this setup. You will be using both the motion detector and the Logger Pro software for several labs this semester, and it's worth spending 5 to 10 minutes becoming familiar with their use. Call me if you have any questions.

When you are ready, place the cart on the level track (about 15 cm from the detector), start collecting data, and push the cart away from the motion detector, so that it reaches the other side in about 1 to 2 seconds. Catch the cart on the other side so that it does not collide with the rail. Look at the graph on Logger Pro, and if necessary, repeat the measurement so that you have graphs that you expected to see. Make sure they look smooth.



Q1: Sketch the position, velocity, and acceleration graphs you see in Logger Pro in the space provided on the right (feel free to tear out this page and include it with your lab report). Sketch the whole graph (from the beginning to the end) and *mark* the portion of the graph that represents the motion of the cart from the time when it was released from your hand to when it was caught in your hand.

What feature do you expect to see in each graph? Briefly describe in your lab report the features expected.

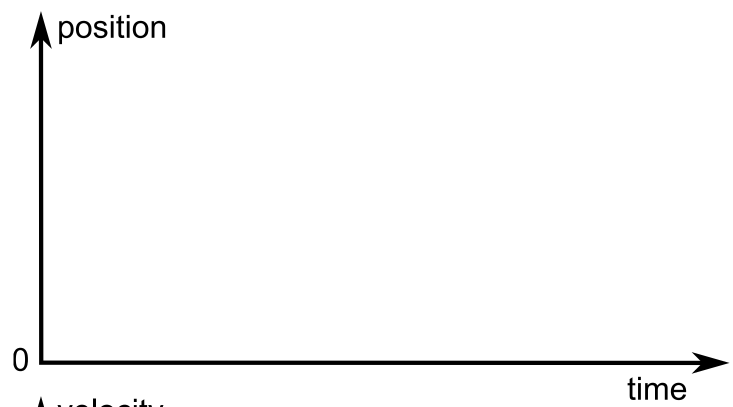
The graph you see in Logger Pro is not perfect because of measurement errors and noise. Using a distinct writing instrument (pen on pencil or different colored pen), sketch the graph you expect to see if there's no noise. [For bonus points: Can you explain why the noise appears to be greater on velocity and acceleration curves than the position curve?]

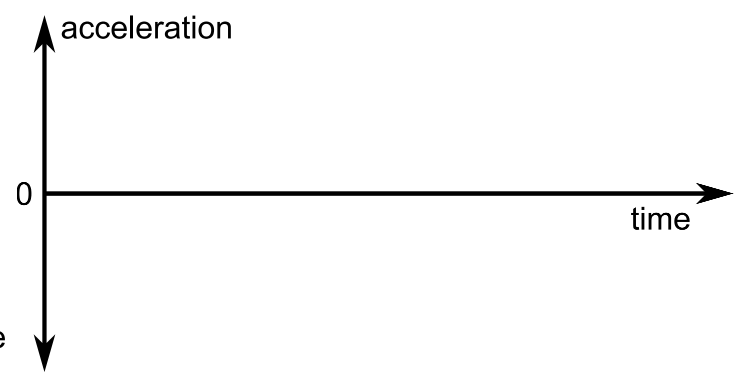
Q2: What kind of acceleration does the graph in Q1 represent? Explain how you would measure this acceleration from the velocity graph.

Part B: Motion on an Inclined Track

Let's make it interesting. Instead of pushing the cart along a level track, raise one end (the end with the motion detector) of the track. We will let the cart roll down the track, starting from rest. Raise one end of the track by about 5 cm. The exact amount does not matter, only that your track should have a very gentle slope, so that it takes the cart several seconds to roll down. Answer the questions below in your lab report ***before* proceeding with any measurements**.

Q3: How do you expect your position, velocity, and acceleration curves to look different, compared to the curves you sketched in Q1? Write down these differences in words in your lab report, and sketch the shape of the expected curves (please don't draw noise!) on the axes on the right.





Q4: Do the measurement:

- Start "Collect" (remember the delay)
- When the motion detector starts collecting data, release the cart.
- Catch the cart at the bottom so it does not collide against the rails.

Do the position, velocity, and acceleration curves look as you expected? Describe any difference from Q3 in words on your report. Using a distinct writing instrument (pen or pencil or different colored pen), sketch the position, velocity, and acceleration curves on the same axes on the right (make sure that any significant difference is clearly shown; if the curves you see are exactly as you expected, the two sets of curves will more or less overlap—plus noise).

Q5: Using the data you collected, measure the acceleration of the cart. There are several different ways to do it (either using the velocity curve or the acceleration curve). Describe your method briefly in your lab report and give the measured acceleration (remember units!). Your method must give a result more precise than 0.05 m/s^2 (that is, your measurement uncertainty has to be less than this). Ask me if you are not sure how to do that.

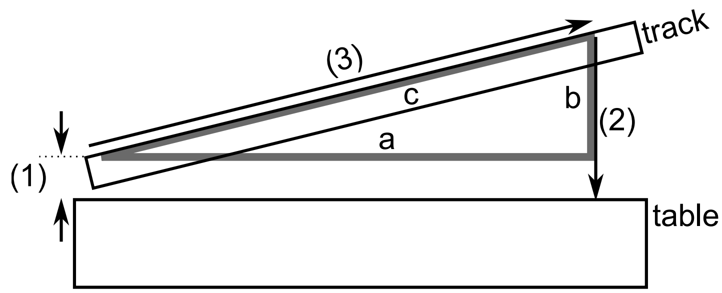
We can use this setup to measure ***g***, the gravitational acceleration. This is the formula you'll learn to derive in a few weeks:

$$a = g \sin\theta,$$

where ***a*** is the acceleration of the cart (as measured in Q5) and ***θ*** is the angle the track makes with the horizontal (use the table as a reference; it is close enough). If you measure the acceleration of the cart at a few different angles, then a graph of values of ***a*** vs. **sin *θ*** should appear linear (according to the formula above), and the slope of this graph will give you the numerical value of ***g***, the gravitational acceleration. So, follow the exercise below to measure ***g***.

Let's make one measurement at the current position of the track (very gentle slope). I will walk you through all the measurements you will need to make. Please do it carefully and call me if there are any questions, as you will repeat it 4 more times for a total of 5 measurements. You already measured the acceleration in Q5, so we will use that value (if you couldn't measure it precisely, call me!). Now you need to measure the angle , and what you should realize is:
(1) the setup makes it awkward to measure the angle with a protractor, and (2) the measurement with protractor would have too large an error/uncertainty.

So, you are going to use trigonometry to *calculate* the angle instead. Consider the diagram of your setup on the right. You will make three length measurements: (1) height of the track at the "bottom", (2) height of the track at the "top", and (3) length of the track between the "bottom" and "top". You can actually choose some points to be the "bottom" and "top"; they do not have to be the actual bottom and top.



Using these measurements, find out the lengths **b** and **c** as labeled in the figure, and use $\theta = \arcsin b/c$ (from SOH-CAH-TOA). Call me if you have any questions.

One additional note: We do have a vertical protractor that is designed to measure angle for setup like this. Call me and ask for it, if you want to try using it to double-check the angles you calculate. One question I want you to consider if you choose to use the vertical protractor: "Which method provides a more accurate and/or more precise measurement of track angle?"

Q6: Repeat the above measurement at least 4 times with 4 different angles that the track makes with the horizontal (make sure to cover a good range of values of θ) to fill out the table on the right (the first row should be your result from above). Note anything interesting you observed in your lab report.

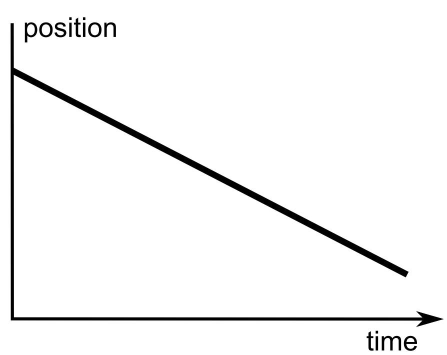
Trial	accel (m/s^2)	θ (deg or rad; indicate unit used)	sin θ
1			
2			
3			
4			
5			

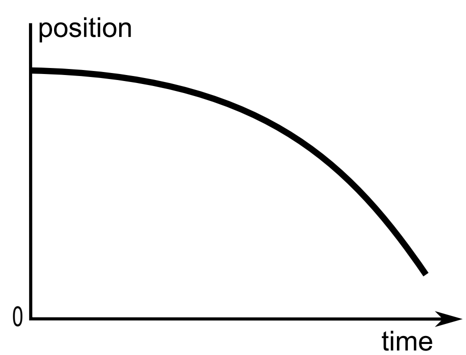
Q7: Using the values of acceleration as **y** values and **sin *θ*** as ***x*** values, fit a best line (of the form $y = mx + b$) to the plot of acceleration vs. **sin *θ***. You can do this numerically on most graphing calculators and some scientific calculators using a function called “linear regression.” Write down this best-fit-line function in your lab report with the parameter values from the linear regression. The slope (***m***) is your measurement of ***g***, the gravitational acceleration. (Call me if no one in your group knows how to do linear regression on a calculator.)

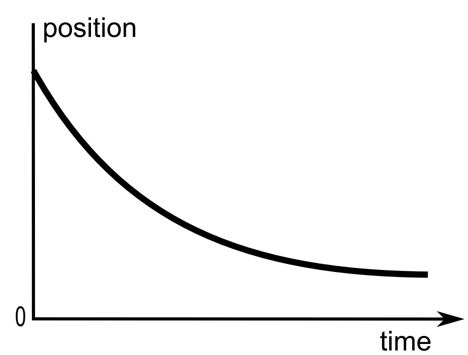
Additional Questions

Q8: You measured the value of the gravitational acceleration ***g*** in Q7. As you might know, the accepted value of ***g*** near the surface of Earth is about 9.8 m/s^2. Calculate and give a percent error for the ***g*** you found in Q7. (Note: As a general rule, lab results in this class are expected to be accurate within 10%. Or, to put it another way, when you get a result that is off by more than 10%, you need to either: (1) fix it, if possible, or (2) explain the large error by properly attributing it to plausible sources of error---and, please, don't say "human error." Call me for help if necessary.)

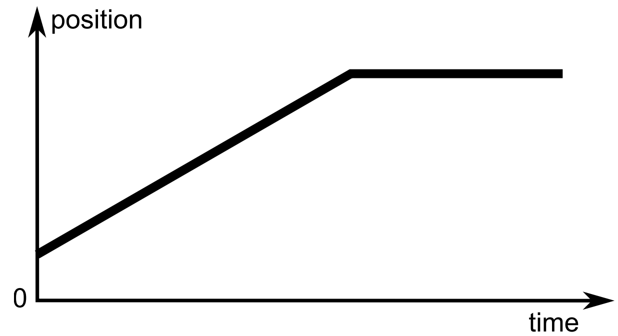
Q9: For each of the position graphs below, briefly describe in your lab report an experimental setup which would produce the position graph you see. (If you are not sure, you are in luck! You can test your ideas on the lab equipment that you still have access to.)



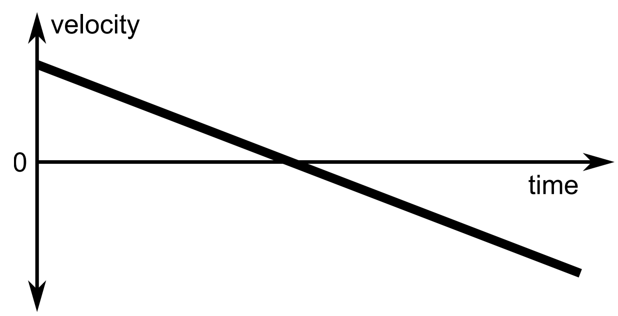




Q10: Check your understanding. For the position graph shown below, sketch velocity and acceleration graphs in your lab report.



Q11: Check your understanding. For the velocity graph given below, sketch position and acceleration graphs in your lab report. [Hint: pick a few points to do a spot check. Is the value of acceleration consistent with the instantaneous slope at that point on the velocity curve? Is the value of the change in position consistent with the area under the curve up to that point on the velocity curve?]



Appendix: Materials List

Equipment needed per group

- 1 x inclined track setup (track, bar mounted vertically with table clamp, and track clamped to bar)
- 1 x Motion Detector setup (Motion Detector, Lab Pro, and Laptop, with VelocAccel.cmbl file)
- 1 x dynamic cart
- 1 x level
- 1 x ruler
- 1 x meter stick
- (Optional) 1 x "ACE magnetic protractor"

Equipment needed for class

- some scientific calculators capable of linear regression (as backup for groups without any)

Lab: Projectile Motion

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report.*

Introduction

Projectile motion describes the motions of many objects on Earth: a football thrown by a quarterback, a basketball shot from the 3-point line, a baseball on its way to a home run (in fact, you can include every single ball sport here), or a bullet from a sniper's gun. When objects move under the influence of only gravity, the result is a pattern of motion we call projectile motion, and the analysis of projectile motion is one of first illustrations of the predictive power of physics problem-solving.

In lecture, we have already covered the features of projectile motion, and you may have even seen a few examples of projectile motion, with all the mathematics worked out. In this lab, we will approach the problem from the other direction. You will record a video of a ball and analyze the video with the help of software. In doing this analysis, you will see the connection between common projectile motions you see every day and the mathematical features of projectile motion discussed in lecture.

Part A: Projectile Motion – Tennis Ball

You have a tennis ball, digital camera/camcorder, and a computer for this part. You will record the motion of the ball with the camera; transfer the video file to the computer, and analyze the video. You will need a minimum of four people for this part.

First, record the throwing of a tennis ball from one person to another (standing 1 to 2 meters apart), while the third person records the video, and a fourth person (also in the video) holds a meter stick, hanging down. A few pointers:

- Take the time to set up the shot. Is the frame of the shot straight? Is everyone in the shot? Will the entire path of the ball be visible in the shot? Is the shot well-focused and not blurry? Is the *ball* reasonably sharp and not too blurry? If anything does not look good, you will need to re-take the shot before moving onto analysis.
- If you have a good camera phone, you can use your own phone. For groups without a good camera phone, I have a camcorder and a couple digital cameras capable of recording video.
- For the videographer: You need to hold the camera perfectly steady for a few seconds. If you find this difficult standing, you might want to sit down and brace your elbows against the table.
- For the person holding the meter stick: Use the meter stick to also record the "vertical" direction. Instead of holding the meter stick rigidly, let it hang from your (raised) hand straight down. This will show for the camera which direction is directly downward.

Record one throwing of the ball. Review the video to make sure it's well-focused and not blurry; if it is blurry, try taking another recording. When you have a good recording, transfer the video file to the laptop.

On the laptop, open Logger Pro by double-clicking on the **Acceleration.cmbl** file on the Desktop. You should see a page with a data table, and three graphs. Import your movie by choosing from the top menu, ***Insert*** → ***Movie …*** . Navigate to the video file that you saved, and click ***Open***.

a. You will see a window open containing your movie. If necessary, using the controls at the corner of the movie window, resize the window to fill the page. Using the controls on bottom left corner, advance your movie up to the point when the ball just left the thrower's hand, either by using the ***Play*** button or the ***Next frame***
b. On the right side of the window, you will see a number of analysis buttons (if not, click on ***Enable/Disable video analysis*** button on the bottom right corner). Set the origin of your coordinate system by clicking ***Set Origin*** and clicking at the bottom of the ruler. If necessary, rotate the coordinate axes using the yellow dot (click and drag), until the vertical axis is perfectly aligned with the ruler.
c. Set the scale: click on ***Set Scale***, then using the cursor, click and drag from the bottom of the meter stick to the top. In the dialog box, enter "1 meter" as the distance.
d. Now track the ball: Click on ***Add Point*** button, then using the cursor, click on the position of the ball (consistently track the center of the ball). The program will advance the movie by a frame; click on the position of the ball again, continuing until just before the ball is caught (you will need to click about 20 times or so, depending on the throw).
e. To resize the movie window, choose from the top menu, ***Page*** → ***Auto Arrange***.
f. The top right graph will show "X" and "Y" positions of the ball as a function of time. The middle right graph should be blank. To show the "X Velocity" and "Y Velocity" on the graph, double-click on the graph, click on the "***Axes Options***" tab, and select "X Velocity (m/s)" and "Y Velocity (m/s)." Click ***Done*** when done.
g. We will use the bottom right graph to show the accelerations. First have the program calculate acceleration by: (1) choose from the top menu ***Data*** → ***New Calculated Column ….*** Change the "Name" to "X Acceleration" (short-name "aX"); (2) click on the blank space below "Expression" and click on ***Functions*** → ***calculus*** → ***derivative***; (3) then click on ***Variables (Columns)*** → ***X Velocity***. Before clicking ***Done***, go to "Options" tab to change color to match the colors for "X" so far. When done, click on ***Done***. Repeat these steps for the "Y Acceleration" (replacing "Y" for "X" in the steps above). Now, to show the "Acceleration" on the graph, double-click on the bottom right graph, click on the "***Axes Options***" tab, and select "X Acceleration" and "Y Acceleration" to show the accelerations. Click ***Done*** when done.

Referring to the graphs you see, answer the following questions in your lab report.

Q1: Describe the position graphs ("X" and "Y"). What qualitative features (that is, features that can be described without using numbers) do you see that you expected to see for projectile motion? What quantitative features (features that are described with numbers) do you see that agrees with how you saw the actual throw? Name at least two of each (but name more, if you can).

Q2: Verify some of the expected features of the projectile motion: (1) What is the ***Y Velocity*** when the ball is at the top of its arc? (2) Does the ***X Velocity*** vary significantly? (3) What are the values of ***X Acceleration*** and ***Y Acceleration***?

Q3: Using the numbers you can look up in the graph, estimate the initial velocity (magnitude and direction) of the ball. Do the numbers make sense? That is, does the speed sound reasonable (to compare “m/s” to “miles/hour,” you can double the number in “m/s”; it will be approximately close to the speed in “miles/hour”)? And given what you remember of the throw, does the angle above horizontal sound reasonable? Show your work and answers in your lab report.

By using ***File -> Save As…*** (choose a unique name and save on the Desktop), save your data for the analysis questions at the end of the lab. You will need a clean version of ***Acceleration.cmbl*** for the next part.

Part B: Projectile Motion – with Air Resistance

Although we ignore air resistance for most of the discussion of projectile motion, anyone who has gone skydiving (or played badminton outdoors on a windy day) can tell you that you can’t always ignore air resistance. So, you are now going to analyze motion where air resistance will be significant.

Grab a new latex rubber balloon, blow a little bit of air in it, and tie it off. Keep the balloon small (make it about 10 to 15 cm in diameter, or possibly smaller); making the balloon too large will make air resistance too significant and make some of the questions below difficult to answer.

Make a recording of the balloon toss, just like you did with the tennis ball (follow the same precautions as before). Double-click on ***Acceleration.cmbl*** on the Desktop to open a new Logger Pro window (click on “Start an additional copy”), and analyze the motion following the same procedure as in Part A.

Once you are finished with the analysis, answer the questions below in your lab report.

Q4: Measure the Y Acceleration of the balloon in the balloon toss and compare it with the Y Acceleration of the tennis ball toss. If you notice anything unusual with your balloon data, note it in your lab report. (If you notice anything unusual with the *tennis ball* data, it could mean that you are making a mistake that you should fix.)

Q5: Considering your data, what is the direction of the force due to air resistance? Is it always opposed to gravity? If not, describe and estimate (that is, give directions in angles!) the direction of force due to air resistance. If you find that the direction of force due to air resistance is changing throughout the balloon toss, pick two (2) representative points and give the direction of air resistance at those two points.

Analysis Questions

Using the data you saved in Part A, answer the analysis questions below. You will be using Logger Pro to answer some of the questions—so make sure the whole group participates for those questions.

Q6: In earlier exercise, you used Logger Pro's video analysis tool to define coordinate axes. You can use this to estimate initial speed (answered by hand in Q3). This is how you do it:

1. Enable video analysis (it might still be enabled from last time), and click on ***Set Origin***
2. Click and drag the yellow dot on the X axis to rotate the axes. As the axes rotate, you will see the position, velocity, and acceleration values change (both in the table and in the graphs), as the software recalculates the values of the ***x*** and ***y*** components of $\vec{x}$, $\vec{v}$, and $\vec{a}$ for the new axes.
3. Set the orientation of the axes so that, for the moment when the ball left your hand, the Y Velocity is zero and the X Velocity is at a maximum (with respect to axes orientation).

Apply these steps to the data from Part A to find the initial speed of the ball. Compare your answer using this method to your number in Q3. Show your work and notes in your lab report.

Q7: Even with the method above, the velocity graphs you see on Logger Pro remains that—a graph of velocity components, not speed (i.e. Y Velocity does not remain at zero, it changes over time). In order to graph the speed as a function of time, you need to add a new calculated column. Find a formula for speed in terms of variables that are available ("X", "Y", "X Velocity", "Y Velocity", "X Acceleration", and "Y Acceleration") and create a new calculated column (refer to Step (g) in Part A). Here are some tips on entering formulas on the keyboard:

1. Use "+", "-", "*", or "/" for "add", "subtract", "multiply", and "divide" (most everyone probably knows this).
2. Use "^" for exponentials. For example, $2^3 (= 8)$ would be entered on keyboard as "2^3" (hopefully many people already know this—if not, this is the standard way to express exponentials with keyboard characters).
3. For most other things, look under "Functions" for special functions. For example, you can find logarithms (both "ln" and "log") and square roots ("sqrt") there.

When you have added a "Speed" calculated column, graph it (use *Insert -> Graph* to add a new graph) and call me, so that I can see your modifications and initial your lab report. **Lab reports without my initial on this part will lose points.**

Also answer in your lab report: (1) Does the speed graph look as you expected it to look? List one or two qualitative features you might have expected to see that you do see on the speed graph. (2) Can you calculate acceleration based on the speed graph? If yes, calculate acceleration based on the speed graph (show your work below). If no, explain why not.

Q8: In Q7 above, did you remember to fix the coordinate axes from Q6? If you did, try rotating the axes back to how it was in Q6. If you did not remember to fix the coordinate axes, try "fixing" the coordinate axes by making the Y axis vertical again. Does this affect the result of the analysis in Q7? Explain why not. (i.e. What is special about speed, in the context of vectors and coordinate axes?)

Q9: Evaluate and *correct* this statement: “In projectile motion, the speed of the object is always changing, but the velocity is not always changing.” (Keep the scope of the statement; avoid making the statement correct by making it claim less. For example, if you make the statement say "In projectile motion, the speed of the object may be always changing, but the velocity may not be always changing," the statement may be correct, but because it is a much *weaker* statement than before, it shall not be considered a correct answer here.)

Additional Analyses

Try out this analysis if you have some time left after answering Q9 in your lab report.

Sometimes in experiments, you have to figure out a way to remove systematic errors from the data (whenever possible, we try to minimize systematic effects in experiment design, but sometimes you don’t find them until later and it may not be possible to re-do the experiment with improved design). The effect of air resistance you have seen in Part B is one such systematic error.

Q10: Suppose that the goal of the experiment was to measure the gravitational acceleration. Figure out a way to analyze your balloon data, so that you can accurately (see your answer to Q2 for comparison) estimate ***g*** from your balloon data alone. Give a description of the method you found and the justification for the method. Calculate a value of ***g*** using the method and give a percent error. (Note: “It gives the correct value of ***g***” cannot be your justification. In experiments, there are such things as a result being *accidentally* correct. Only when a result was *expected* to be correct and *is actually* correct, it can be relied on.)

Appendix: Materials List

Equipment needed per group

- 1 x meter stick
- 1 x tennis ball
- 1 x latex rubber balloon
- 1 x video camera [or cell phone with video camera] (and a way to transfer video to computer)
- 1 x laptop with Logger Pro installed

Lab: Dynamics

Note: For the "lab report," answer all questions marked as ***Q1, Q2,*** *etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report.*

Introduction

So far, we have explored motion (velocity and acceleration) in lab, but we have stayed away from what *causes* the motion. That is the subject of today's lab, "dynamics," or a study of forces.

As we have covered in lecture, force causes motion. Or, to be more precise, *net* force causes *acceleration*, according to Newton's Second Law,

$$\sum \vec{F} = m\vec{a},$$

where m stands for the mass of the object, $\vec{a}$ is the acceleration (with direction in mind), and $\sum \vec{F}$ is the sum of all individual forces acting on the object (i.e. the net force).

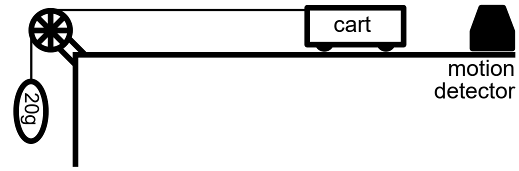
In this lab, we will explore a simple situation (although you will see some things moving up and down and other things moving left and right, this situation can be essentially considered as a 1-dimensional motion) involving forces on an object and measure its motion (position, velocity, and acceleration), to help cement your understanding of Newton's Second Law—this is the foundation of a very important set of topics we will be spending the next month or so studying.

Part A: Cart & Hanging Mass - Prediction and Measurements

We will be using the motion detector and cart set up that you have used for the 1D kinematics lab. The key difference, as you see on your table, is that the track is level, and there is a mass hanging from the cart over a pulley.

Equipment Reminders

- The motion detector detects the cart by bouncing an ultrasonic wave from it. Keep it at least 15 cm away (any closer, and detector cannot measure time difference well), and keep other objects and your hand out of the path of wave.
- Do not allow cart to strike the rails or other objects. If it does strike, check and fix the alignment of the motion detector.
- Remember how to use Logger Pro (or if you don't, call me over for a quick overview/review).



Q1: Using the Standard Strategy (covered in lecture) and Newton's Second Law, derive a formula for the acceleration of the cart, assuming the mass and the cart are released from rest. Use the symbol $\boldsymbol{M_C}$ for mass of the cart and $\boldsymbol{M_H}$ for mass of the hanger (do not plug in a number for $\boldsymbol{g}$ yet and keep the expression symbolic). Show your derivation and result in your lab report.

Q2: Plug in the following numbers for a prediction of the acceleration. You will perform the measurement and verify how close this prediction was: $\boldsymbol{M_C}$ = 500 g, $\boldsymbol{M_H}$ = 20 g, and $\boldsymbol{g}$ = 9.8 m/s^2. Give your predicted acceleration in m/s^2.

Q3: After you hit "Collect", release the cart from about 15 cm from the motion detector and catch it before it hits the pulley, measuring the position of the cart (and the program will also calculate its velocity and acceleration). Measure the acceleration as accurately as you can, using Logger Pro, and give your answer below. Be sure to describe how you measured your acceleration. Also calculate a percent error with Q2 to estimate how close to the prediction this result is.

We are going to change the setup of the experiment a little bit. Instead of releasing the cart from rest, you are going to give the cart a brief push away from the pulley (towards the motion detector) and let it go. Ideally, the cart will come as close as 15 cm from the motion detector and then roll away. If the position graph "flat lines" during any portion of the motion (usually happens when the cart is too close), try it again with a gentler push so that the cart does not come so close to the motion detector.

Q4: ***Predict before doing experiment:*** Once the cart has left your hand (and before you caught it again), will the acceleration of the cart be affected by how strongly you pushed? Give your answer below (yes or no) and explain your answer. Please be sure to discuss your prediction and the reasoning with your group (are there *parts* of cart's motion where the acceleration depends on strength of your push?).

We are going to do the following experiment to see if our prediction was correct. Do three trials (three times with a "gentle" push and three times with a "hard" push), measuring the acceleration using Logger Pro (make sure that the uncertainty of your measurement is less than 0.05 m/s^2) as you have done several times before (if there are any questions about best way to measure acceleration using Logger Pro, call me). You can distinguish between "hard" and "gentle" pushes by noting how far the cart moves before turning around. If any push did not come out the way you intended (maybe an intended "gentle" push became too "hard"), ignore any such result and re-do it, until you get three *usable* results.

Q5: ***Measure***: Following the procedure above, measure accelerations a total of 6 times, to fill out the table on the right. Calculate the average for both types of runs.

Q6: Estimate the uncertainty of your measurements. Discuss below how you arrived at your estimate. Your estimate of uncertainty does not need to be precise (one or at most two significant figures are enough), but it does need to be based on some objective criteria. (Call me if you are not sure how to estimate uncertainty of your acceleration measurements—there are different ways to estimate the error, based on how you measured your acceleration.)

Run	Acceleration with “hard” push (m/s^2)	Acceleration with “gentle” push (m/s^2)
1		
2		
3		
avg		

Q7: Does the acceleration of the cart depend on how strongly you pushed the cart with your hand? [Please note that the question does not ask if the average in column 1 above is a different value than average in column 2.] With your answer to Q6 in mind, what does it mean (numerically) for acceleration of the cart to depend on how strongly you pushed the cart?

Q8: ***Compare***: Does your result in Q5 (use the average value) agree better with your prediction in Q2, or does your result in Q3 agree better with your prediction in Q2? Use the percent error (calculate it, if it’s not already done) to see which result agrees better with the prediction and give an explanation for why it agrees better.

Part B: Cart & Hanging Mass - Analysis

Considering the experiments in Part A, answer below questions.

Q9: For the **cart**, after you finish pushing the cart:

- As the cart moves away from the pulley (answer below with "toward pulley" or "away from pulley"):
  - What is the direction of the velocity?
  - What is the direction of the acceleration?
  - What is the direction of the net force?
- As the cart moves back towards the pulley (answer below with "toward pulley" or "away from pulley"):
  - What is the direction of the velocity?
  - What is the direction of the acceleration?
  - What is the direction of the net force?

Q10: For the **hanging mass**, compare the upward tension force (from the string) and the downward weight on the hanging mass:

a. After you finish pushing the cart, as the hanging mass is *still moving up*, is the tension force greater than, equal to, or less than weight of hanging mass? In your lab report, draw the free-body diagram of the hanging mass and explain your answer based on Newton's Second Law.
b. While the hanging mass is *moving back down*, is the tension force greater than, equal to, or less than weight of hanging mass? Does any of your explanations from above change?

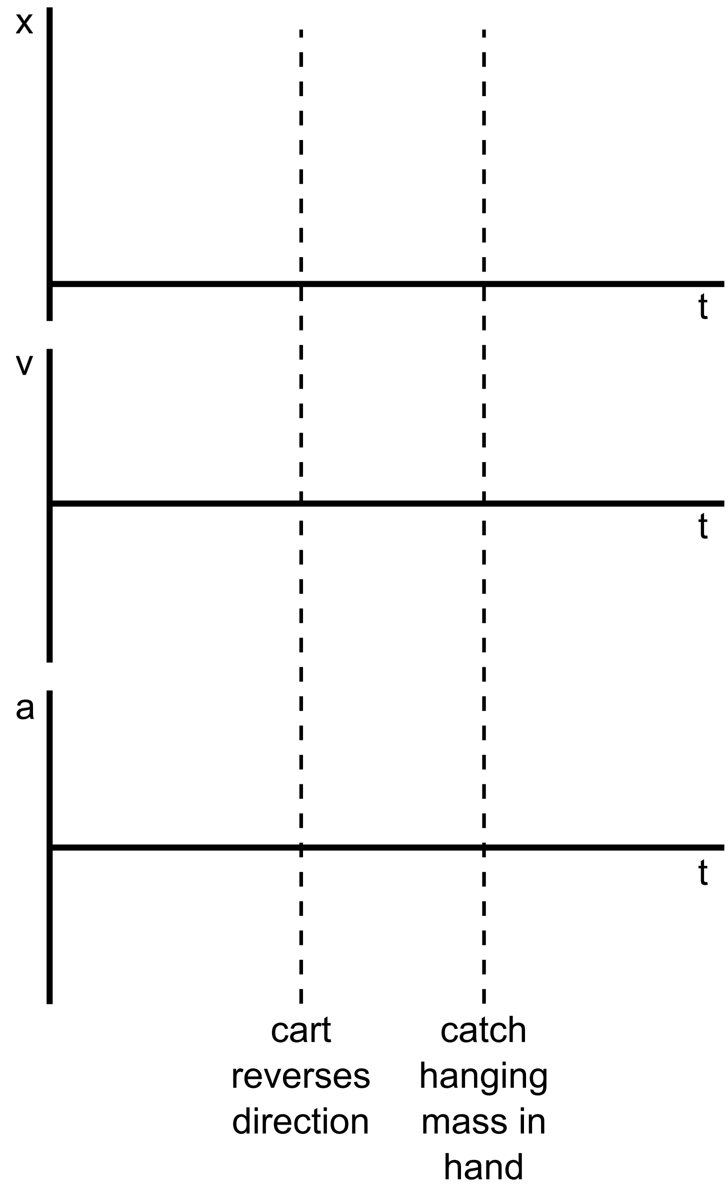
When you are done with Q9 and Q10, call me to discuss your answers and get my initials on your lab report. **Lab reports without instructor initials will lose points.**

Q11: In your lab report, derive an analytical expression for tension (in terms of $\boldsymbol{M_C}$, $\boldsymbol{M_H}$, and $\boldsymbol{g}$). Confirm that your expression for tension is consistent with your answers to Q10 above.

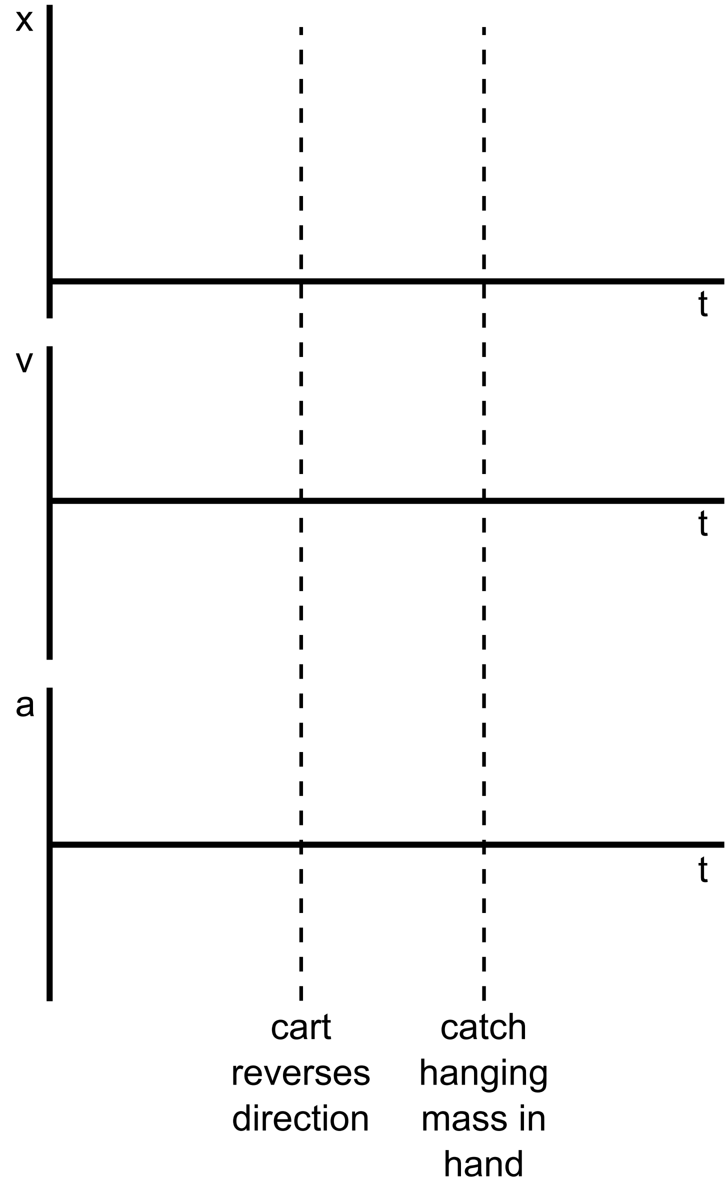
Part C: Additional Exercises

Let's make it interesting. Repeat your previous experiment, with the following twist: When the cart is moving back toward the pulley, "turn off" the tension by catching the hanging mass in your hand. Allow the string to go slack (but make sure it doesn't get in the cart's way).

Q12: ***Before*** you do the experiment, on the graphs to the right, make a ***prediction*** on how the position, velocity, and acceleration curves will appear. Make sure to line up the curves vertically, using the provided guides.



Q13: ***After*** you do the experiment, on the graphs to the right, draw a sketch of what you see on Logger Pro software. Make sure to line up the curves vertically, using the provided guides.



Q14: Explain the features you see in your graphs. If your prediction was substantially different from your result, explain why (and demonstrate your *understanding* of how things happen the way they actually happen).

Additional Discussion Questions

Q15: Answer this question *quickly without any calculation*: A car cruises down the highway at constant velocity 50 mph. The backward force of wind resistance and friction have a combined strength of 5000 newtons. The traction of the tires with the road causes a forward force on the car (the engine is making this all happen, of course). Is this forward force less than, equal to, or greater than 5000 newtons? Answer in the next 5 seconds, and move onto the next question.

Q16: Did you answer “equal to 5000 newtons” or “greater than 5000 newtons”? Many people *intuitively* answer “greater than 5000 newtons” (it’s great if you didn’t; if you did, please pay close attention to this exercise). The correct answer is that, for the situation described above, forward force is equal to the backward force. Explain why this is the correct answer (what do you know about the car? make sure to use Newton’s laws).

The questions below are particularly for those who answered “greater than 5000 newtons” in Q15. It is very important at this stage that you confront your intuition and reshape it to be consistent with Newton’s Second Law. Below is a suggested approach:

- Before reaching the cruising speed of 50 mph, as the car was speeding up, was the forward force greater than, equal to, or less than the backward force? Explain.
- Evaluate this statement: “Net forward force is needed to make an object move forward.” Point out parts of this statement that are correct, *and* point out parts of this statement that are incorrect (or at best, misleading).

Lab: Forces in Equilibrium

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report (be sure to make it clear which name is yours).*

Introduction

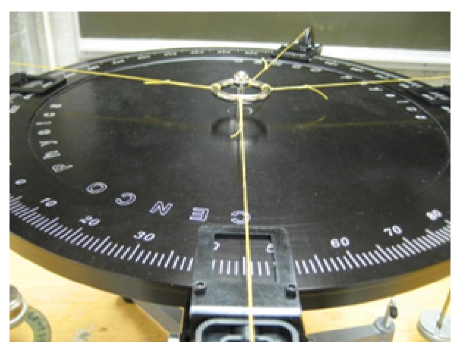
The purpose of this lab is to illustrate working with different representations of force vectors. These approaches also work as a model for working with other vector quantities that will be introduced later in the semester.

For most of Physics 4A, when we work with vector forces ($\vec{F}$) in problem-solving, we work with them in component form. However, this is not the only available mathematical approach to handling vectors (and there are situations where more graphical approaches yield a simpler path to the solution). In this lab, you will see those different representations and see how they are consistent with the component representation of vectors, as you determine the “equilibrant,” the vector force $\vec{E}$ which, when added to other forces on the object, makes the net force ($\sum \vec{F}$) equal to zero. (Don’t worry about memorizing this word; you won’t see it again in Physics 4A.)

Part A: Equipment Check

Look at the equipment you have available at your table. You should have:

- force table (pictured on right)
- level (for leveling the force table)
- 3 x 50-gram mass hangers
- a slotted mass set, containing: 2 x 200 g, 2 x 100 g, 3 x 50 g, 4 x 20 g, and 2 x 10 g.



Also, rulers, protractors, and graph paper are available for the class (you should have writing instruments).

Equipment Check:

- Using the provided level, make sure your force table is level.
- Check the alignment of pulleys by looking at the string and the angle marking.

If any of the pulleys look broken, call me so that I can either help fix it or give you a replacement pulley.

Q1: You are going to be measuring out forces of magnitudes 2.50 N and 1.60 N (and a third, yet unknown force between 0.5 N and 3.00 N). Describe in your lab report how you would do it using the equipment provided. Describe in detail. Which of the slotted masses will you use?

Part B: The Experiment

You are going to determine the equilibrant $\vec{E}$ experimentally.

First, set up the forces $\vec{A}$ and $\vec{B}$ on the force table as specified below (Note: Use ***g* = 10 m/s^2**):

- $\vec{A} = 2.50\,\mathrm{N}$, at 66° (use the angle markers on the force table; if your force table has two sets of markers, pick one and be consistent)
- $\vec{B} = 1.60\,\mathrm{N}$, at 163°

Using the string and the hanger, apply these forces on the ring. The ring will try to move to one side and be stopped by the pin in the center.

To determine $\vec{E}$ experimentally, you are going to find the magnitude and direction of the third force $\vec{E}$ which, when added to $\vec{A}$ and $\vec{B}$ (by applying it as a third force on the ring), will make the net force equal to zero (and you can tell when this happens, because the ring will remain centered on the force table).

It is going to be easy to determine the direction of $\vec{E}$ first. Follow the below directions to determine $\vec{E}$ (direction and magnitude) experimentally, after setting up forces $\vec{A}$ and $\vec{B}$.

Q2: Hold the third string in your hand, and move it around the force table, trying to keep the ring centered on the force table. You should find that in most circumstances, you cannot keep the ring centered on the force table regardless of what magnitude of force you apply. So move the third string around until you find a position where you *can* make the net force go to zero (that is, keep the ring centered on the force table). Have at least 3 people in your group make this measurement in angle, and write down the results in your lab report. Aim for an error of about ±1° or less (or perhaps within ±0.5°).

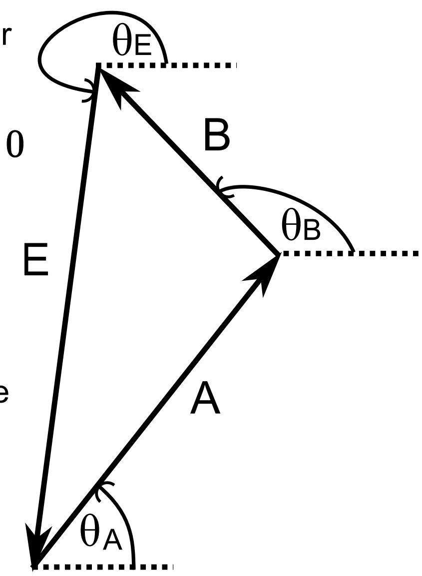
Q3: At the average value of the angles you determined in Q2, place a clamp for the pulley. By trial and error (by placement and removal of masses), determine the magnitude of the force $\vec{E}$. This is the experimental value of the equilibrant, which satisfies the condition, $\vec{A}+\vec{B}+\vec{E}_{\mathrm{expt}}=\mathbf{0}$. Write down this magnitude in your lab report, and call me to demonstrate your forces in equilibrium and get my initials on your lab report.

Note: Lab write-ups without instructor's initials will lose points. Make sure to call me to discuss your result (and your error estimate) here and get my initials.

Part C: Calculation of E

In this part, you are going to calculate using three different methods: (1) by use of a carefully drawn vector diagram, (2) calculation using vector components, and (3) calculation using geometry (law of cosines and law of sines). Each method should take up one full page in your lab report. Follow the directions below:

Q4: **Vector Diagram**: Draw a vector diagram on a provided graph paper showing the vector sum $\vec{A}+\vec{B}$, and then close the triangle. This is a graphical representation of the equilibrant relationship, $\vec{A}+\vec{B}+\vec{E}=0$, and the last side of the triangle is $\vec{E}$. Measure its magnitude and direction. See the figure on right for label of angles.



Use the graph paper only for direction reference; use a ruler to measure all distances.

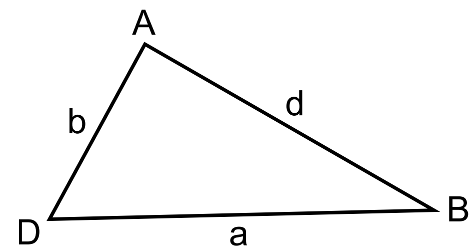
Notes: For best results, draw as large a vector diagram as would fit on the graph paper (if it feels too large, it's probably the right size). For angle measurements and marking, extend the baseline so that you can make accurate angle measurements with the protractor (within 0.5° accuracy). Clearly label all your vectors and include a scale for conversion of length in the diagram to newtons. *Use the margins on the graph paper for recording your results.*

Q5: **Calculation Using *x* and *y* components**: Since $\vec{A}+\vec{B}+\vec{E}=0$, $\vec{E}=-(\vec{A}+\vec{B})$. You can break $\vec{A}$ and $\vec{B}$ down into ***x*** and ***y*** components and add them by components to find the ***x*** and ***y*** components of $\vec{E}$.

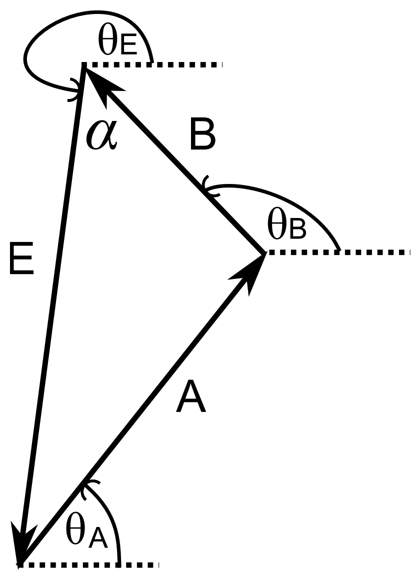
Using a separate piece of paper for your lab report, calculate the magnitude and direction of $\vec{E}$ (for direction, give angle θ_E, as shown on the figure for Q4).

Q6: **Calculation Using the Law of Cosines and the Law of Sines**: You can calculate the magnitude and direction of vector $\vec{E}$ *without* breaking any vectors into components by using geometric relationships (and a couple theorems derived in geometry). Recall the Law of Cosines and the Law of Sines.

Using the quantities labeled in the triangle on the right (here, lower-case symbol represents the length of the side; upper-case symbol is the angle inside the triangle),



- Law of Cosines: $d^2 = a^2 + b^2 - 2ab\cos D$, and
- Law of Sines: $\frac{\sin A}{a} = \frac{\sin B}{b} = \frac{\sin D}{d}$.



You can follow the steps below to calculate the magnitude and direction of vector $\vec{E}$ (refer to the figure on the left):

1. Find the angle opposite to side ***E***. Draw larger sketch and auxiliary figures, if necessary.
2. Using the magnitudes ***A*** and ***B***, and the angle opposite ***E***, find the magnitude ***E***, using the law of cosines.
3. Now that you know ***E*** (and the angle paired with ***E***), now you can use law of sines to find the angle marked as α (which is paired with side ***A***).
4. Once you have α, work through the remaining geometric relationship to express θ_E in terms of α and calculate the numerical value of θ_E for the direction of $\vec{E}$.

Use a separate piece of paper for your lab report to show your work and calculate $\vec{E}$, magnitude and direction.

Q7: For full credit, draw up a table in your lab report (organize it in the way that best represents your results in this lab) to:

- Summarize the magnitude and direction of $\vec{E}$, as determined experimentally, graphically, and through 2 different, independent calculations.
- Report the percent deviations in the magnitudes of the experimental and graphical values relative to the calculations.
- Report the difference in the directions (in angle) of the experimental and graphical values relative to the calculations.

Lab: Circular Motion

Note: This is a Newstyle Lab. Read each section of the lab manual carefully before starting to work on that section. Keep an organized record of any measurements you make, or any information you had to discover which was not apparent from the clear text of the lab manual. Make sure to stop at each boxed section of the lab manual and go through the activities in the boxed section, keeping necessary notes and recording, particularly of numerical values. For the in-lab report, follow the instructions at the end of the lab manual.

Introduction

Force analysis is at the heart of mechanics. While you will learn principles and techniques that will allow you to work out answers more quickly (look ahead to introduction of energy and momentum this semester), the ability—real and theoretical—to analyze forces to derive motion directly is what undergirds these principles. In previous labs involving forces and mechanics, you had to make this limiting assumption that friction is negligible. We have also not had a chance to directly observe effects of centripetal force in a lab setting.

We will address both of these omissions in this lab.

Equipment

Rotating Platform – This low-friction rotating platform will be at the center of measurements you will design and perform to achieve goals in this lab. The "low-friction" description applies to the axle, supported by ball bearings. The top surfaces have as much friction as you expect metal surfaces to have, and we have a few different tapes you can apply to obtain different friction coefficients.

Tabletop Objects – We have a few different objects available which will be useful in different parts of the lab. The stainless steel ball can show features and dynamics of circular motion in a low-friction environment. The metal cubes can be used for investigating friction coefficients between metal and different types of surfaces. The slotted mass set can be used to test if some of the effects being investigated depend on mass of the object.

Video Camera – Certain measurements in this lab are easiest to make using video cameras. Unlike in a previous lab, you will not need to make detailed position and distance measurements, but the video recording gives an excellent way to measure time interval differences between events. A good smartphone camera can be used for this; a few digital cameras are also available for the class.

Tapes – a few different types of tapes are available. The bare platform top can be used as a smooth metal surface; we have cellophane tape, masking tape, and electrical tape that can be applied to the platform top to investigate friction coefficient between metal (tabletop object) and cellophane, paper, or vinyl.

Part A: Circular Motion

Circular motion can be used to demonstrate Newton's Second Law, $\vec{a} = \sum \vec{F}/m$, that net force causes acceleration, resulting in a change of velocity, and that in the absence of a net force, an object *maintains its velocity*. The rotating platform gives an ideal circumstance where you can challenge your intuitive notions about Newton's Second Law and how it relates to rotating bodies or bodies in circular motion. The exercises below will also help develop some familiarity with the capabilities and limitations of these rotating platforms.

GOAL– The main objective of this part is to become familiar with the rotating platform, which will be used for the remainder of the lab. At the end of this part, check yourself by asking yourself these questions: (1) "How well can I perform different activities/tasks using this rotating platform?" (2) "How well do I understand limitations of this rotating platform? What are some ways in which this could be more ideal?"

The rotating platform can be spun up in different ways. One way is by holding the edge of the platform and pulling your hand towards you, giving the platform a good amount of speed in one stroke of arm motion. There is another way to spin up the platform that is more controllable. You can use friction between your finger tip and the top of the rotating platform. As your fingertip is in contact with the top of the platform (one finger or several fingers), if you move your hand in a circular motion around the center of the platform, you will see the platform spin up gradually. You may be able to spin up the platform to a faster final speed using the second method over a period of several seconds than you can spin it up with one stroke. Try these methods, and see if you can find other ways to spin up the rotating platform in a way where you retain a good amount of control (also, try different methods for *slowing down* the rotating platform).

When you feel you have a good amount of control in spinning up (and slowing down) the rotating platform, move onto the remainder of this part to observe and analyze circular motion of stainless steel balls.

TASK–Study circular motion of a single stainless steel ball on the rotating platform.

We can use the rotating platform to put a single stainless steel ball into a circular-ish motion while subject to a very small number of forces. This will help us see what forces are at work in a circular motion. You can put the stainless steel ball into motion in a number of different ways. You might start by placing the ball at rest on the surface (the platform may not be perfectly level; make sure the ball doesn't start rolling on its own) and then spinning the platform. Or you might set the platform spinning first, and then gently set down the stainless steel ball (make sure the ball doesn't bounce). The small amount of friction between the platform and the stainless steel ball ("rolling friction") will set the ball in motion, and the ball will roll off the platform eventually (be ready to catch the ball).

Perform this motion (a few times if necessary) and record your observation.

QUESTION/DISCUSSION – How did the ball move? In a couple sentences, using diagrams if necessary, describe how the ball moved.

There is *a lot* going on as the stainless steel ball circles the center of the rotating platform. It's easy to miss some details or misinterpret the visual cues. Repeat the motion performed earlier, but this time, video-record the motion using a digital camera held over the rotating platform, recording the motion from a "bird's eye" view. Watch this video in slow-motion; if necessary, use the available laptop to import the video into a Logger Pro project. The Logger Pro video analysis tool allows you to advance the video a single frame at a time.

QUESTION/DISCUSSION – How did the ball move? Does anything in your previous answer need to change?

When you have observed the motion using a recorded video and discussed the observation as a group, please call me. I will review your discussion with you and initial your lab notes/in-lab report. If you have to move on to the next part, please be sure to call me as **lab notes/in-lab report without my initial will lose points.**

Part B: Centripetal Force

With the familiarity gained with the rotating platform in Part A, we will now move on to investigate the centripetal force in this part, using the rotating platform. By now, most of you are familiar with the relevant formulas—the centripetal acceleration is given by $a_c = v^2/R$; the centripetal force is given by $F_c = mv^2/R$. The task that some students might be struggling with is the task of connecting these formulas to the physical phenomena that you observe (e.g. "Where do you label the centripetal force mv^2/R in your FBD?"). So, to help you make those connections, we are going to do a simple —at least what appears simple—experiment, with variations.

At the core, this is the experiment: you will place a mass (one of the metal cubes or the slotted masses) on the rotating platform, off-center. Then you will spin the platform, until the mass just begins to slide. The variations you can include involve parameters for centripetal force above. You can change R (distance from center); you can change v (tangential velocity of mass) by changing how fast you spin the platform; you can change the mass, too.

In the spirit of this Newstyle Lab, I won't give a lot of detailed steps and procedures. You have the equipment (that you feel some level of familiarity with); you have the basic procedure; and I will now give you some basic questions that you should try to answer. See questions below and try to figure out how to answer them with experiments using the rotating platform.

Caution: Try to catch the masses when/if they fall off the platform. Keep away fragile objects and devices, in the event you don't catch the masses in time and they go tumbling across the table.

TASK – Using the equipment available in lab, answer below conceptual questions.

1. As you gently rotate the platform (gently enough so that the masses do not slide) where do you see the effect of the centripetal force? Describe how you would measure the centripetal force in this scenario.

2. As you increase the rotational speed of the platform, what happens with the centripetal force? Describe what features of the motion allows you to draw this conclusion.

3. In all cases, if you spin the platform fast enough, the masses will slide. Explain why the masses slide—what happened to the centripetal force?

4. Suppose you take two masses (as much as possible, identical to each other), place them at different distances from the center (one nearer and one farther), and start to spin up the platform. Which mass will start to slide first? And why? (Do the experiment and see—if the result is different from what you predicted, make sure you understand why.)

5. What is the centripetal force on an object placed directly at the center, $R = 0$?

If you get stuck on any part, do please call me. While you should spend some time thinking through the problem, do not waste too much time (no more than 5 minutes or so) being stuck on a difficult question in lab.

Part C: Friction and Centripetal Force

Now that you feel comfortable about the conceptual aspects of this setup, now is the time to make some measurements. As you hopefully understood in Part B (and partially in Part A), there is a connection between the friction force keeping the block in the same place on the rotating platform and the centripetal force as given by mv^2/R. When a block just begins to slide is when there is a maximum possible static friction force on the block, and by connecting these relationships together, you can derive a formula for the coefficient of static friction based on the quantities you can measure in this lab.

Write down this formula. (You actually should have done this exercise—or a version very similar to it—as part of your prelab. Use this opportunity to review your derivation and fix any conceptual or mathematical errors made.)

RESEARCH QUESTION – Measure and investigate friction coefficients between different materials.

The activities (and specific goals) in this part are left open on purpose. You should at least measure *one* coefficient of friction between one pair of materials. But finishing the lab at that point is quite a bit anticlimactic (what does that single number mean? Is it a "good" measurement or a "bad" measurement?). You should aim to go further. Having made one set of measurements you should decide on what "further research" is needed and pursue that in the remaining time. I do have some notes and suggestions, and I am available to consult (as always), but please make this part your own.

Some considerations as you complete this part:

1. First focus on developing good experimental procedures. You have several quantities you need to measure. Some will be easy (like R); others will take a fair bit of thinking and trial-and-error. Use what is available to you; ask me for anything you wish you had; make use of the video analysis capability through Logger Pro.
2. There are different directions you can go with "further research." One set of suggestions: you can go "deeper" or "wider". *For "deeper"*: you could stick to one particular pair of materials and investigate that one friction coefficient in varying sets of circumstances, perhaps looking at how repeatably friction coefficients can be measured, or what unexpected factors might affect the value of the friction coefficient. *For "wider"*: you can measure friction coefficients with different pairs of materials, perhaps to better understand ranges of values of friction coefficients. Don't be limited by these suggestions and pursue what seems interesting to your group.
3. **Be mindful of one limitation: time**. Leave enough time to complete your in-lab report. See in-lab report instructions below; keep in mind how long it might take to complete them, and leave enough time at the end of measurements so that you are not rushed.

In-Lab Report Instructions

With these *Newstyle Labs*, what we hope *eventually* to do is not have any in-lab report but give people enough time to complete a lab narrative in the week after the lab. But for the time being, we are limited by the fact that most labs this semester are *Oldstyle Labs*, with the gradebook set up best for the combination of prelab exercises and in-lab reports.

With this in mind—and knowing that time during lab is limited—what I am hoping to have you turn in is something between lab notes and lab narrative. In lab notes, relevant information might be written in a way only you can understand. In lab narrative, the presentation of material is well-organized, with proper introductions and conclusions (but writing this out takes time; more time than you have in lab). The in-lab should be somewhere in the happy medium—organize the information enough so that I can understand what is written, but don't worry about a little bit of disorganization and gaps in presentation.

So, for the in-lab report, look over your notes. Do you see evidence of completion for all the boxed tasks, activities, and questions above? If not, make sure to write something short down, so that the evidence of completion can be clearly seen for grading. For the questions in boxes, have you answered them in a way that someone else—me—can understand the answers well?

Take the time to look over your notes and fill in any gaps needed. No introduction of conclusion is required for the in-lab report (although you are welcome to add your reflection on the activities). Turn in your notes with gaps filled in as your in-lab report.

Lab: Conservation of Energy

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report (be sure to make it clear which name is yours).*

Introduction

We spent a fair amount of time this semester on the study of forces. As you begin solving more complex problems using forces (i.e. Standard Strategy), this mathematical approach becomes unwieldy. So we are now introducing a second set of approaches to help us tackle these new problems. In this second set of approaches (this is the second half of what we call “mechanics,” or “dynamics”), instead of focusing on individual interactions, we focus on what are called “conserved quantities.”

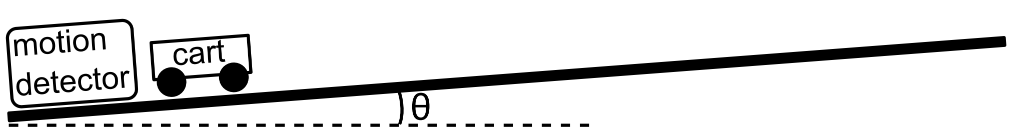
Energy is the first of these conserved quantities we introduce, and in this lab, you will see a relationship between the change in energy of an object and the work done on the object.

Part A: Inclined Track

We will be using the motion detector and cart set up that you have used for the 1D kinematics lab and the dynamics lab. Start out by setting the track at an incline (similar to the 1D kinematics lab).

Equipment Reminders

- The motion detector detects the cart by bouncing an ultrasonic wave from it. Keep it at least 15 cm away (any closer, and the detector cannot measure time difference well), and keep other objects and your hand out of the path of the wave.
- Do not allow the cart to strike the rails or other objects. If it does strike, check and fix the alignment of the motion detector.
- Remember how to use Logger Pro (or if you don’t, call me over for a quick overview/review).



Q1: Examine the setup at your station. You have an inclined track, a cart, and motion detector positioned at the bottom of the track (see figure above). Set the incline at a moderate incline (the high end at about 10 cm from the table), and measure the angle of the incline. *[Note*: *You will need to use trigonometry to calculate the angle . Call me if you are not sure what you should measure.]*

Q2: Mechanical energy of the cart is given by the sum of its kinetic energy and potential energy,

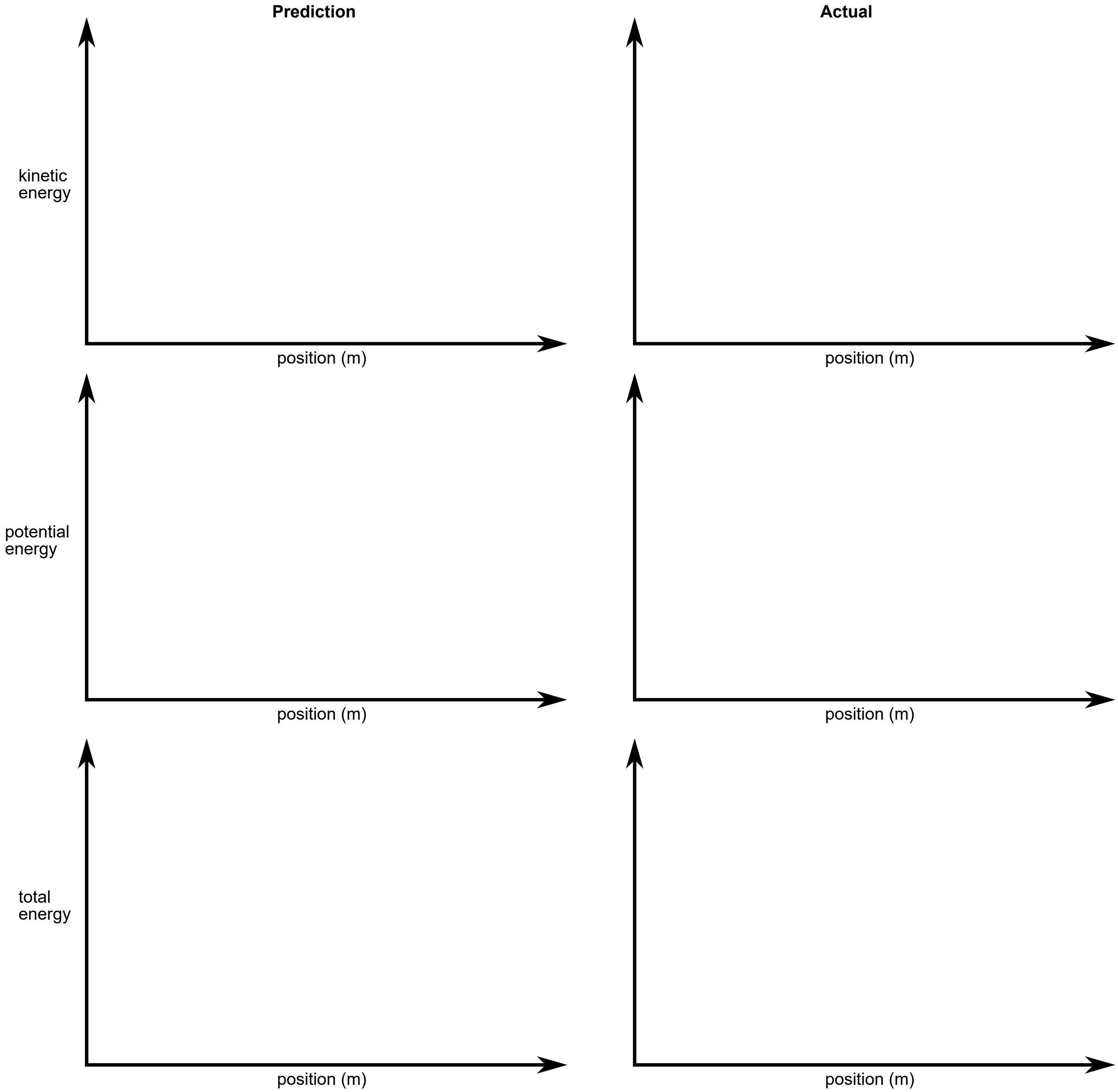
$$\textbf{total mech. energy} = \mathrm{KE} + \mathrm{PE}_{\mathrm{grav}} = \frac{1}{2}mv^2 + mgh.$$

Measure and record below the constant parameters you will need for the energy calculation. In the expression for energy above, there are two variables, ***v*** and ***h***. Throughout the cart's motion, these two numbers change, and you will need a way to update them. The speed ***v*** is directly calculated by Logger Pro (so you just use the value provided by Logger Pro). Find a way to relate the height ***h*** to some measurement made by the motion detector. Describe your result in the lab report.

Q3: Come up with an expression for the kinetic energy (**KE**) and the potential energy (**PE**), in terms of the constant parameters you can measure, and the variables measured by the Motion Detector and Logger Pro. Write down this derivation in your lab report.

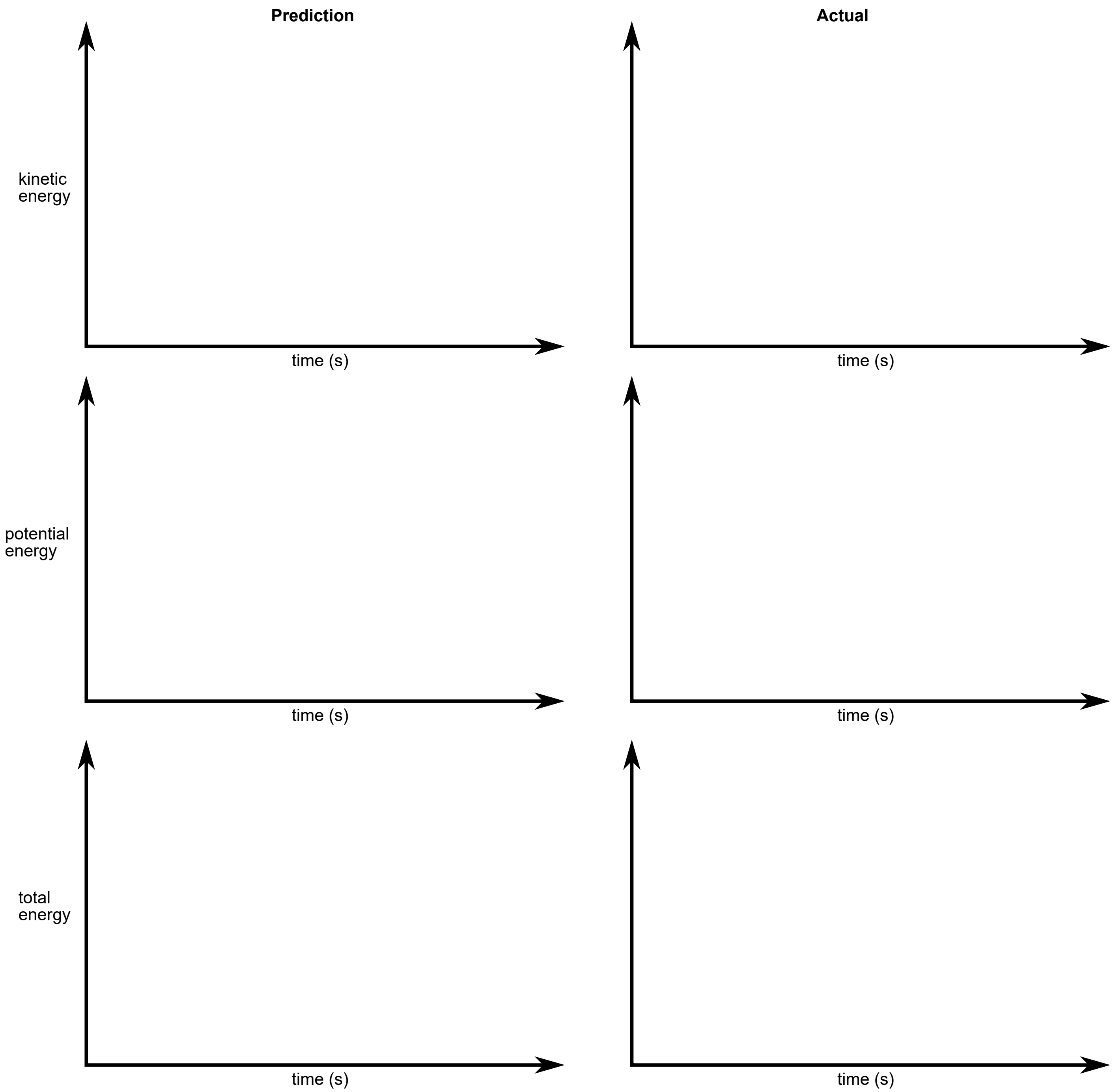
The expressions you derived above have already been entered into Logger Pro. If it is not already open, open the file *ConsEnergy.cmbl* in the *4A Lab* folder. Check User Parameters (*Data -> User Parameters*) and enter the values you measured/calculated above in Q2. Check the calculated column expression for kinetic energy and potential energy. Go to *Data -> Column Options -> Kinetic Energy* and click on "Column Definition" tab. The definition is in the "Expression" column; make sure it agrees with your expressions. Repeat this for *Potential Energy*. As you check the expressions entered into Logger Pro, make sure that you understand what is being plotted for energy on your graphs.

Q4: **Experiment – Rolling the cart Downhill**. You are going to measure/calculate the energies of the cart as it rolls downhill, starting from rest. Before you do the experiment, make a prediction in the plots on the left side first, using the plot provided below. As a *function of position* (not time), how should the graphs of kinetic energy, potential energy, and total energy appear?



Do the experiment (release the cart from the top; catch it at the bottom) and record your results on the right-side graphs. Note the energy and position scales on the axes. How well does your prediction agree with results? Does the total energy change? (If it does, you may have mis-entered some parameters. Call me!)

Q5: **Experiment – Rolling the cart Uphill**. This time, you will measure / calculate the energies of the cart as you roll it uphill (and the cart returns to original position). Before you do the experiment, make a prediction in the plots on left side first, using the plot provided below. This time, *as a function of time*, how should the graphs of kinetic energy, potential energy, and total energy appear?



Do the experiment (roll the cart uphill so that it returns without hitting the pulley at the top; catch the cart at the bottom) and record your results on the right-side graphs. Note the energy and time scales on the axes. How well does your prediction agree with the results? Does the total energy change?

Use your second experiment (rolling the cart uphill) to answer the below questions in your lab report.

Q6: Consider the changes of energies throughout the cart's motion: (1) At which point of the motion does the cart have maximum kinetic energy? (2) At which point of the motion does the cart have maximum gravitational potential energy? (3) As the cart moves from the point of maximum kinetic energy to maximum gravitational potential energy (or vice versa), what happens to the total energy of the cart?

You can use the changes in potential energy of the cart to calculate its kinetic energy and speed at any point. Follow the instructions in the next question and show your calculations in your lab report:

Q7: Choose a point on your energy graphs after the cart clearly left your hand. Refer to this point as "bottom" to answer these questions: (1) What is the difference between the potential energy of the cart between the top of its motion and at the "bottom" of its motion? (2) Assuming mechanical energy is conserved, what is the kinetic energy of the cart at the "bottom"? Do not look up the value of kinetic energy but calculate it from measurements of potential energy of the cart. (3) What is the speed of the cart at the "bottom"? (Again, do not look up the value of the cart's speed from the Logger Pro graphs, but calculate it from your results in (1) and (2) in this question.)

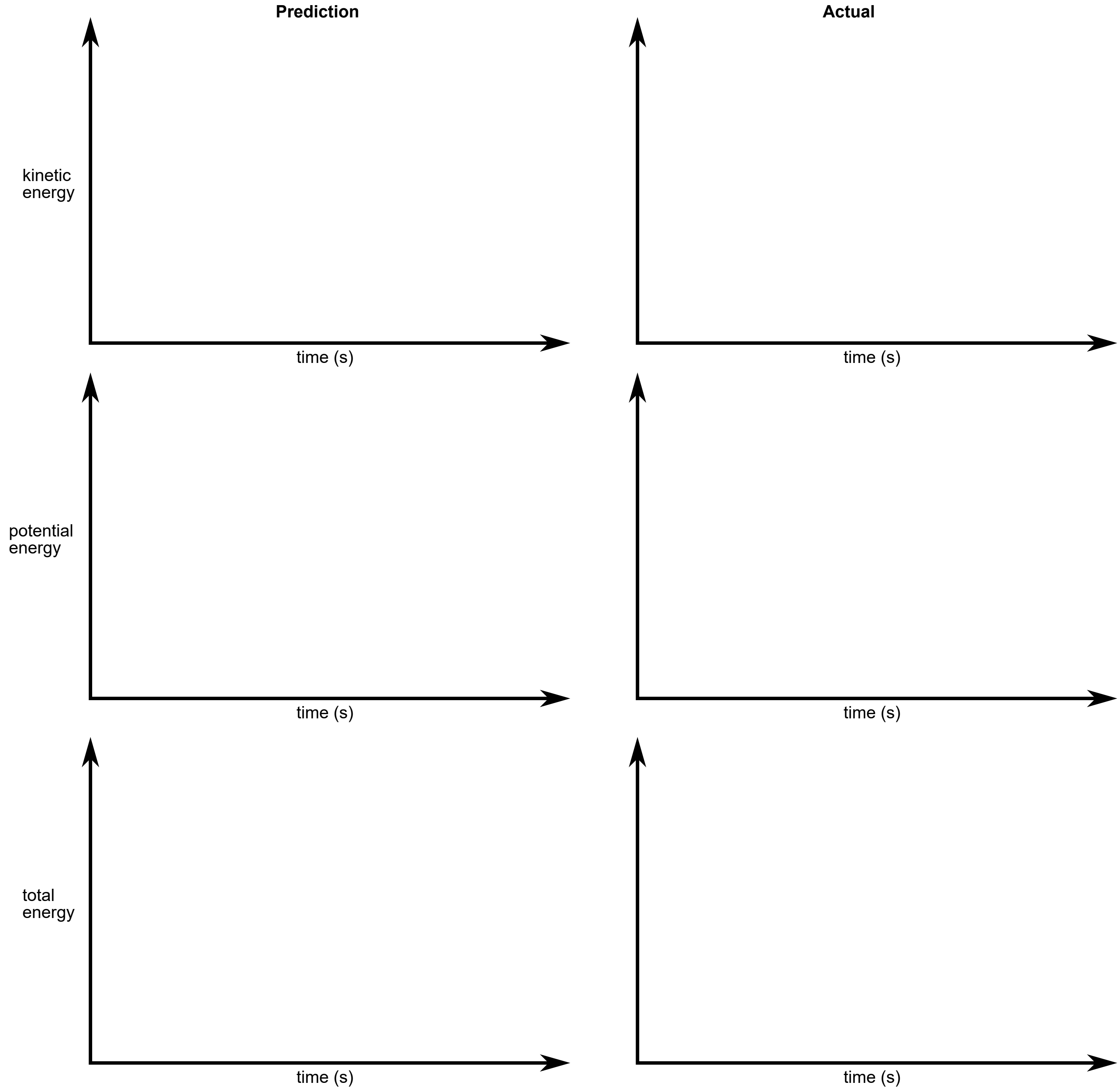
Q8: Look up the velocity of the cart at the "bottom" in your Logger Pro data. Calculate and give the percent error between the measured velocity of the cart at the bottom and the velocity calculated in Q7.

Part B: Work and Energy

Increase the angle of the incline by raising the raised end of the track to about 10 cm from the table. Attach a 20-gram hanger to the cart using the string attached to the cart and hang the hanger over the pulley. Make sure that the incline is steep enough that the cart will roll down when released.

[Note: Make sure to update the angle User Parameter after making the increasing the angle of the incline.]

Q9: **Experiment – Rolling the weighted cart Uphill**. You will measure / calculate the energies of the cart as you roll it uphill (and the cart returns to its original position). Before you do the experiment, make a prediction in the plots on left-side first. As *a function of time*, how should the graphs of kinetic energy, potential energy, and total energy appear? How should these graphs be different before?



Do the experiment and record your results on the right-side graphs. Note the energy and time scales on the axes. Does the total energy change? If it changes, why do you think it changed? Explain briefly in your lab report.

Considering the experiment in Q9, answer the questions below in your lab report. Remember that work done is $W = \vec{F} \cdot \vec{d}$. When you are done answering questions Q10 through Q13, call me for a brief discussion about your answers and get my initials on your lab report. **Lab reports without instructor initials will lose points. Make sure to call me to discuss your answers here and get my initials.**

Q10: Describe in which part of the motion the total energy was increasing or decreasing.

Q11: When the total energy was increasing, was the work being done by the tension force on the cart positive or negative? When the total energy was decreasing, was the work being done by the tension force on the cart positive or negative? Explain your answer (how do you know the work being done was positive or negative), and explain how the sign of the work being done relates to the change of energy (increase or decrease).

Q12: We believe that the total energy (of the universe, including all forms of energy) is conserved. When the total energy of the cart increases, where is this extra energy coming from? When the total energy of the cart decreases, where is this energy going to?

Q13: From your graph, figure out the difference between the maximum total energy and minimum total energy (in joules). Numerically show in your lab report that this difference is accounted for in the difference of total energy of the 20-gram hanger between the two states.

Part C: Additional Considerations

For this lab, we ignored the effects of friction (and friction should have been negligible for the carts you used). How would your energy curves (as a function of position) be different, if friction had been significant in Part A, as you rolled the cart downhill (for example, if a friction coefficient of 0.2 was effective between the cart and the track)? Sketch your predictions in your lab report in graphs similar to Q4, and note the expected similarity and difference in the energy curves as a function of position from when friction was insignificant.

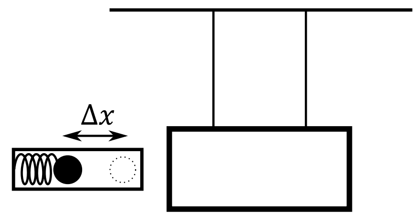
If you want to try it out (and check your predictions), ask me for a cart exhibiting significant friction with the track to try it out.

Lab: Ballistic Pendulum

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report (be sure to make it clear which name is yours).*

Introduction

This lab is based on a classic setup dealing with conservation of energy and momentum (see the figure on the right). This is one of the key examples for the application of conservation laws (and the considerations you need to put into it); make sure you can both *derive* and use the formulas in this lab.



As a reminder:

- Energy (that is, mechanical energy) is conserved when the net work done by non-conservative forces is zero.
- Momentum is conserved when the net impulse due to external forces is zero.

In the ballistic pendulum setup, energy will be conserved in some parts (but not all parts), and momentum will be conserved in some parts (but not all parts). So start by recognizing the parts where energy and/or momentum are conserved.

Part A: "Pre-Lab"

Following is what will happen in this lab. You are going to use the launcher to fire a projectile into a catcher. As the catcher catches the projectile, it will swing upward like a pendulum (hence "ballistic pendulum"). The experimental setup will allow you to measure height h by which the catcher rises, and using that measured height, you will calculate what the launch speed v_0 of the projectile was. If it helps you form the mental images of this problem, try firing the ballistic pendulum a few times to get a sense of it, but hold off on any measurements until after you complete Q1 and Q2.

Q1: In your lab report, derive an equation for the initial velocity v_0 of the projectile, given the final height h of the catcher. Pay attention to how you should define the height h—is it the distance from the table? If not, where is it measured from? In which parts of the motion is energy conserved? In which parts is momentum conserved? Explain your answers and choices. [*Note: steps in this derivation should be similar to what you have done for Prelab Question 1; the key changes are in which quantities are treated as known and which are treated as unknown.*]

Q2: Determine how to measure the maximum swing height h of the projectile and the catcher. Look at your setup carefully to see if there is anything you can use to mark the maximum height h. [*Note: While there is more than one way to measure maximum height h, all acceptable methods will measure h with better than 10% accuracy.*]

Q3: Measure all other necessary constant parameters for calculating v_0. You can find these parameters in your derivation of the formula for v_0 in Q1 (if you did it correctly, the only other dynamic parameter in the formula should be h, and the rest should be constant parameters).

Part B: Ballistic Pendulum

On the launcher, choose a range setting (short, medium, or long range) to use. You may also have a choice of the type of ball (nylon or steel) to launch, but using the steel ball is recommended for better accuracy in your final results. Make sure the launcher and the catcher begin level and aligned, and verify after each trial that the alignment remains good. Use the measurements you make in this part to calculate the initial speed v_0 of the projectile.

Q4: Do the first trial, measuring the maximum height h. In your lab report, show your work for the numerical calculation of v_0. Make sure to write down: (1) the range setting and type of ball used, (2) the measurement of h, and (3) the calculation of v_0 from h and other measured parameters. Show your work: (1) if the measurement of h involves more than one direct length measurement, show it in your lab report; (2) both in intermediate results and the final number calculation, show the units you are using. To avoid unnecessary introduction of error, use $g = 9.8\,\mathrm{m/s^2}$.

Q5: Repeat the trial two more times (for a total of 3 measurements of v_0) and write down the result in your lab report. Calculate an average of your three trials. You will use this average for later comparison. [*Note: Make sure your results do not vary wildly. If your three measurements of v_0 vary a lot, that is an indication that you are making some mistake which needs to be fixed. Call me if you are not sure.*]

Part C: Ballistic Projectile

In this part, you will measure the initial speed v_0 independently of the methods you used in Part B above, so that you can compare the two results and get a sense of accuracy of the initial speed v_0 you determined. Make sure to use the same settings as in Part B (same ball type and same range setting).

Q6: In this part, you are going to measure the range D of the projectile, launched horizontally at some height H from the floor, and you will use this range D to calculate the initial velocity v_0. Derive the formula for v_0 (in terms of D and h and any other constant parameters) from 2D kinematics (following steps similar to Prelab Question 2). Show your work in your lab report, and ask me questions!

Q7: Carry out three measurements to measure the range D, where the ball lands after being launched horizontally at a height H. You will be provided with a carbon paper to assist in your measurement of D (call me, so that I can provide the carbon paper and explain the procedure). Write down your three measurements in your lab report. Using the average of these three measurements as D, calculate initial speed v_0. Show your work (show units; use $g = 9.8\ \mathrm{m/s^2}$).

Part D: Additional Questions

Please answer questions below.

Q8: Calculate the percent difference of your results in Q5 and Q7. Does the percent difference seem reasonable? Identify potential sources of error (and please, do not say “human error”) that could result in the percent difference you calculated. Be quantitative in your reasoning. For example, if you see a 5% error, could air resistance affect the path of the ball enough to introduce a 5% error? [*Note: An error greater than 10% requires a detailed explanation to avoid losing points. If you have error greater than 10% here, try: (1) Repeating some of the measurements with improved procedures (if there is time), or (2) identify enough sources of error (with percent error contributions estimated) to add up to 10% error. Ask me questions!*]

Q9: Explain: (a) In the collision of the ball and the catcher, how do you know that mechanical energy is lost? (b) In the swing up of the ball and the catcher after the collision, how do you know this process does not conserve momentum? [*Note: If you answered these questions in Q1 already, repeat your answer here. If you did not answer these questions already in Q1, answer them now.*]

Lab: Rotational Inertia

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report (be sure to make it clear which name is yours).*

Introduction

Rotational inertia plays the same role in rotation that mass (a.k.a. "inertia") plays in translational motion. That is, rotational inertia resists angular acceleration, or expressed in equation form,

$$\sum \tau = I\alpha,$$

where $\sum \tau$ is the net torque, α is angular acceleration, and I is the rotational inertia (this is the rotational version of Newton's Second Law).

While we can write down many equations and formulas for rotational inertia (sometimes called "moment of inertia"), we will use this time and equipment available in the lab to help build your intuition for rotational inertia, both the factors that go into determining rotational inertia and the role rotational inertia plays in rotational motion.

Part A: Hands-On Exercises

All the measurements in this lab will be made using the rotational inertia apparatus pictured on the right. So, let's take a little time getting familiar with the apparatus.

Image by Capilano University

The apparatus should already be set up at your table, with two masses placed in a symmetrical fashion. Gently rotate the apparatus, rotating it back and forth to get a sense of its "inertia" (resistance to change in motion). Also gently set the apparatus in rotational motion and let it rotate for a bit to get a sense of whether there is a significant friction in the apparatus.

For the questions below: First, move the masses in as close to the center as possible and repeat the above exercises. Answer the questions below and follow the directions.

Q1: Measure the distance between the center (the point at which the horizontal bar is fixed at the vertical rotating rod) and the center-of-mass of each mass. Record the distance in centimeters in your lab report.

Rotate the masses a little bit to get a sense of their inertia. Then, move the masses as far out along the horizontal rod as possible. Rotate the masses a little bit after moving out to get a sense of their inertia again.

Q2: Estimating roughly, how much harder was it to rotate the masses? To rotate it by the same amount (same angular accelerations), did it take twice as much effort? Five times? Ten times? After writing down your estimate, record the distance between the center and the center-of-mass of each mass again in your lab report.

We will do a more quantitative measurement of rotational inertia in the next section, but what you wrote down in this section will serve as a gauge of your intuitive feel for rotational inertia. (If they agree with what you find out at the end of this lab, great! If they do not agree well, try to figure out where you went wrong and use your new knowledge to reshape your intuition.)

Part B: Measuring Rotational Inertia

We are going to measure the rotational inertia of the apparatus (at several different positions of masses) by using conservation of energy. *You* will write down the detailed procedure, but below is a summary of what you need to do:

Idea: Although you don't know much about the setup, it seems (or should seem) like energy is conserved in the setup. By hanging a mass over the pulley and letting it fall, you can transfer a known (or calculate-able, at least) amount of energy to the rotating masses. If rotational inertia behaves like mass does in translational motion, then,

$$\mathrm{KE}_{\mathrm{rot}} = \frac{1}{2} I \omega^2,$$

where ω is angular velocity, as before.

Things to Measure: You are going to need to know the change in energy of the hanging mass. Measure the potential energy change by measuring the change in height (from an initial height until the mass contacts the ground). Also you are going to need to know the final velocity of the hanging mass (needed for calculating the kinetic energy of the hanging mass—negligible—and the angular velocity of the rotating masses—not negligible). I will describe a procedure for calculating the final velocity of the hanging mass using nothing but a ruler and stopwatch.

What to Calculate: You are trying to calculate the rotational inertia in the above expression, or solving for I,

$$I = \frac{2\mathrm{KE}_{\mathrm{rot}}}{\omega^2}.$$

This means you need to measure and calculate quantities needed for $\mathrm{KE}_{\mathrm{rot}}$ (using the assumption of conservation of energy, this is the same amount of energy as the amount of mechanical energy lost by the hanging mass as it falls), and you need to measure and calculate quantities needed for ω (this is where you need the final velocity of the hanging mass).

This is how to calculate the final velocity of the hanging mass: (1) First, measure the *average* velocity of the hanging mass, for the duration of the fall ($v_{\mathrm{avg}} = \Delta x/\Delta t$, by definition). (2) Since the hanging mass is falling at constant acceleration, we can use the constant-acceleration kinematics formula, which says, $v_{\mathrm{avg}} = (v_i + v_f)/2$, or in this case, since $v_i = 0$, $v_f = 2v_{\mathrm{avg}}$. That's it! Once you measure the average velocity for the duration of the fall, in this case, the final velocity is double the average velocity.

Q3: In your lab report, write out a detailed procedure for your measurement of the rotational inertia I. It should include: (1) Any factors that might affect the rotational inertia, such as distance of the masses to the center (measure from center-of-mass of the masses). (2) Measurement and/or determination of any constant parameters needed for calculation (as examples, you would need to measure the diameter of the rod that the string wraps around, and you would need to determine how much mass to hang for the measurement). (3) Direct measurement of any variables needed for calculation (such as initial height of the hanging mass and the time to fall). You may need to repeat direct measurements both to calculate an average of multiple measurements and to have an idea of your measurement uncertainty.

As you write out your procedure, make sure to include enough details so that someone else can repeat your exact measurements, if they wanted to. Clearly indicate the value of I that you determined, in correct units. (The easiest way to avoid unit mistakes is to convert *all* measured quantities to meters, seconds, and kilograms—basic SI units—before any calculation.)

Q4: Repeat the procedure two more times (for a total of 3 measurements of I, for different positions of the rotating masses (for best results, try them at the closest to the center, medium distance to the center, and farthest from the center). Write down the results in your lab report. Make sure to indicate the masses' distance to the center for each . You will need this for a later question. Make sure to note anything interesting or unusual you observe.

Part C: Analysis

From Part B, you have three measurements of rotational inertia I at different distances x_{mass} of the masses. The rotational inertia I should have been clearly different for the three measurements (and each “measurement” might consist of an average measurement, in terms of time to fall, etc.). Answer the questions below.

Q5: To summarize, please fill out the table of the rotational inertias ($I(x_{\text{mass}})$) as a function of positions of the masses (x_{mass}) at the end of this lab manual. Only 3 measurements are required, but you are free to make more measurements as you feel necessary. (You can also make a copy of the table in your lab report and avoid having to turn in this lab manual.)

Q6: Based on your data, what would you guess is the rotational inertia I proportional to, other than mass? (In your measurements, you did not vary the mass.) Explain your answer.

Q7: If there is time, calculate a percent error for your measurement of $I(x_{\text{mass}})$ for the largest value of x_{mass}. The theoretical value for rotational inertia in this geometry, approximately, is $I_{\text{theo}} = Mx^2_{\text{mass}}$, where *M* is the *total* of the rotating masses. [Approximations involved: (1) we are treating the cylindrical mass as a point mass; (2) we are ignoring the rotational inertia of the rod.] How does your experimental result compare to the theoretical “prediction”? [Note: You will have to take the masses off and measure their mass for this calculation.]

$I(x_{\text{mass}})$	x_{mass}
1.	
2.	
3.	

Lab: Static Equilibrium

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report (be sure to make it clear which name is yours).*

Introduction

An object at rest is in a state of static equilibrium when the net force and the net torque on it are zero. That is, static equilibrium holds when:

$$\sum \vec{F} = 0 \text{ and } \sum \vec{\tau} = 0.$$

In this lab, you will make measurements and analyze several situations dealing with static equilibrium.

Part A: Balancing Ruler

At your table is a setup that can be used to balance a meter stick on a single point of support. The point of support can be moved by loosening and tightening the clamp. When you feel comfortable with the setup, move on to the measurements and questions below.

Q1: The single point of support at which you can balance the meter stick is its center of mass. Balance the meter stick at a single point of support and measure the location of its center of mass (X_{CM}). In your lab report, record the position X_{CM} to within an accuracy of 0.5 mm (that is, 0.05 cm).

Q2: Answer the following questions in your lab report: When the meter stick is balanced on its center of mass, what is the magnitude of the torque due to the weight of the meter stick, calculated about the point of support? Explain your answer, in at least two different ways. [Hint: (1) What are the two different ways torque can be expressed; (2) What is the lever arm for the gravitational force?]

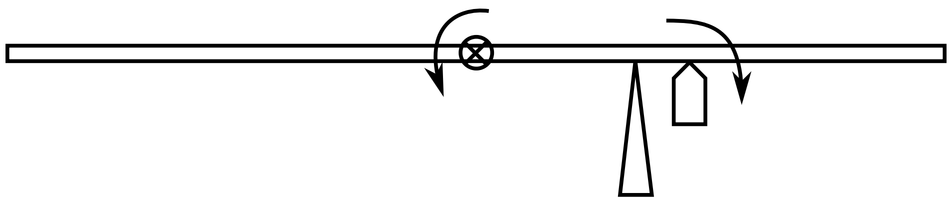
In the below exercises, you are going to determine the mass of the meter stick by using the torque from a known load.

- Slide the meter stick in its clamp, so that it is supported off-center. Move it to at least less than the 30-cm mark, or greater than the 70-cm mark (or farther!).
- With a loop of string, suspend a mass so that the system of the stick and the load is in static equilibrium (that is, balanced nearly horizontally).

Q3: Record the location of the support and the mass and location of the load (with better than 0.05 cm, or 0.5 mm accuracy). Only one trial is required, but record all values below carefully and accurately. Record in your lab report: (1) the position of the support point (X_{support}), (2) the position of the additional load (X_L), and (3) the mass of the additional load (M_L). You will need these three quantities for the following calculations.

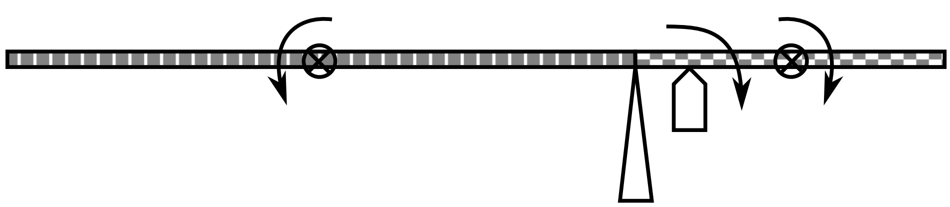
Below, you are going to calculate the mass of the ruler (M_R) by using your measurements in Q1 and Q3 above. There are two different ways to do this calculation. Follow the instructions below to do the calculation in each way, and answer the comparison question (Q6). *Note: Record enough significant figures for intermediate calculations and your final result. You should keep at least 4 significant figures for intermediate calculations and write your final result with about 3 significant figures (*use your judgment *if you need to keep more or less).*

Q4: In the first method, you analyze the picture this way (see figure below): The ruler's weight (with the weight of the ruler imagined as acting at the single point of its center of mass) generates a counter-clockwise torque, and the load's weight generates a clockwise torque. The mass of the ruler is the value that will cause these two torques to balance each other out.



Carry out the calculation in your lab report. Keep all quantities (X_{CM}, X_{support}, X_L, and M_L) in terms of symbols as you go through the algebra, and hold off on plugging in the numbers until the very end, when you have an analytical expression for M_R. Follow the Standard Strategy (draw FBD, etc.), and show all your work in your lab report.

Q5: In the second method, you analyze the picture this way (see figure below): The portion of the ruler to the left of the support point generates a counter-clockwise torque, and the portion of the ruler to the right of the support point generates a clockwise torque. With the ruler asymmetrically placed, the additional clockwise torque due to the weight of the load adds to the clockwise torque to balance out the greater counter-clockwise torque from the greater portion of the ruler.



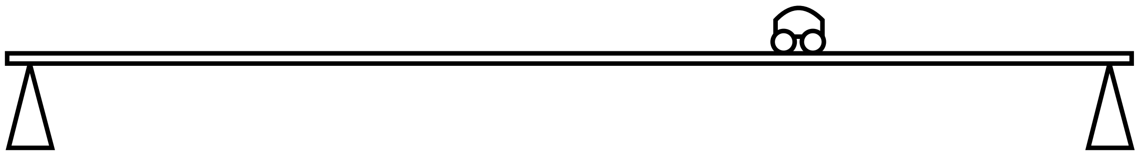
Carry out the calculation in your lab report. Keep all quantities in terms of symbols as you go through the algebra, and hold off on plugging in the numbers until the very end, when you have an analytical expression for M_R. Call me if there are any questions for the calculation. Follow the Standard Strategy (draw FBD, etc.), and show all your work in your lab report.

Q6: In Q4 and Q5 above, are your results identically the same, or are they slightly different? If they are slightly different, explain in your lab report why they are slightly different. Also, in your judgment, which of the two methods are better (in terms of accuracy first, and then in terms of ease of calculation/concept), the method in Q4 or Q5? Explain why in your lab report.

Q7: Measure the mass of the meter stick directly (make sure to take off the support clamp). Which method (Q4 or Q5) gave you a result that was closer to the true value?

Part B: The Simplest Bridge

A meter stick with mass M_R is supported at positions $X_L = 10.0\ \mathbf{cm}$ and $X_R = 95.0\ \mathbf{cm}$. A load with mass $M_L = 1.382\ \mathbf{kg}$ is placed at a position of 65.0 cm.



Q8: Calculate the magnitude of the support forces (F_L and F_R) acting at positions X_L and X_R. Show your work in your lab report. *Note: the mass of the meter stick, M_R, will be written on the board for your use in the calculation.* [Hint: Use the Standard Strategy: draw FBD of the bridge with all the forces acting on it, and enforce $\sum F = 0$ and $\sum \tau = 0$.]

Q9: Measure the support forces in the setup (numbered #2) at the front of the room (set up in the way described for Q8). Compare the measured forces with the calculated forces. Calculate percent errors for the forces and comment on the size of the error. (Is it small and reasonable? If it is large, what are some sources of errors? Can you fix it?)

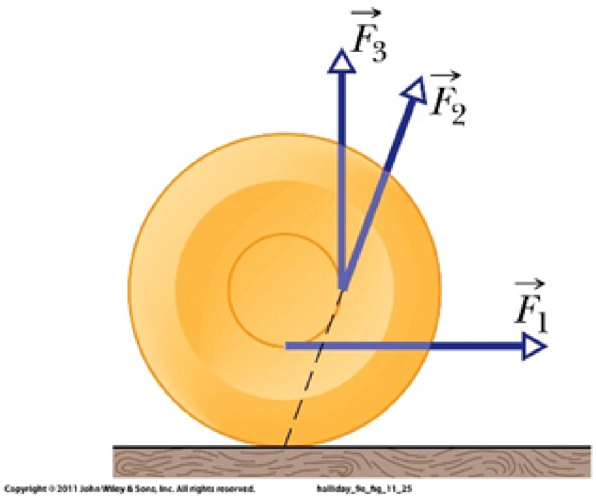
Part C: Additional Conceptual Questions

In the remaining time in the lab, consider and answer the questions below. There are setups around the room that will help you consider the question.

Q10: A two-pan balance is used to determine the mass of a can. Look at the balance and see how it works. If you took the can (along with the balance and the standard masses) to the Moon, would it still be in balance with the standard masses in the right-hand pan? Answer and explain in your lab report. [Note: Look for the setup labeled #3.]

Q11: The system of the fisherman-and-fish is in a “stable equilibrium,” meaning when given a small displacement away from equilibrium, the system returns to its equilibrium orientation. In your lab report, sketch a diagram, with the fisherman-and-fish tilted a little to one side, and explain why they move back toward equilibrium. [Hint: Find the center-of-mass of the fisherman-and-fish; Also see the illustration of stable, unstable, and neutral equilibrium at the end of this lab manual. The setup is labeled #4.]

Q12: A spool, rests on its lower edge (see below).



What direction does the spool rotate if you pull with force indicated in the direction of $\vec{F}_1$, $\vec{F}_3$, and $\vec{F}_2$? (The last one is a bit tricky; look carefully at the diagram to pull in the correct direction.) For each case, sketch a diagram and label the lever arm, the force, and the direction of the net torque (clockwise or counterclockwise). [Hint: Watch carefully as the spool begins to rotate. Where on the spool is the fixed pivot point? Drawing the lever arm from a convenient center of rotation will help illustrate the direction of the torque. The setup is numbered #5.]

Appendix: Stable, Unstable, and Neutral Equilibria

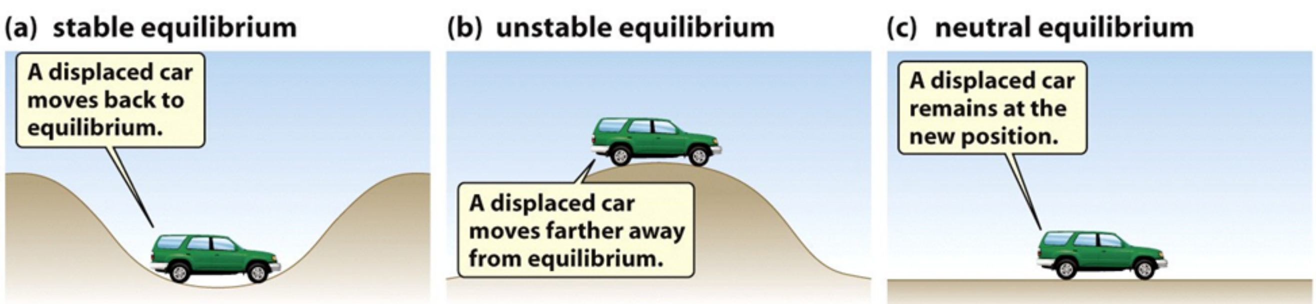


Figure 14-4 Physics for Engineers and Scientists 3/e
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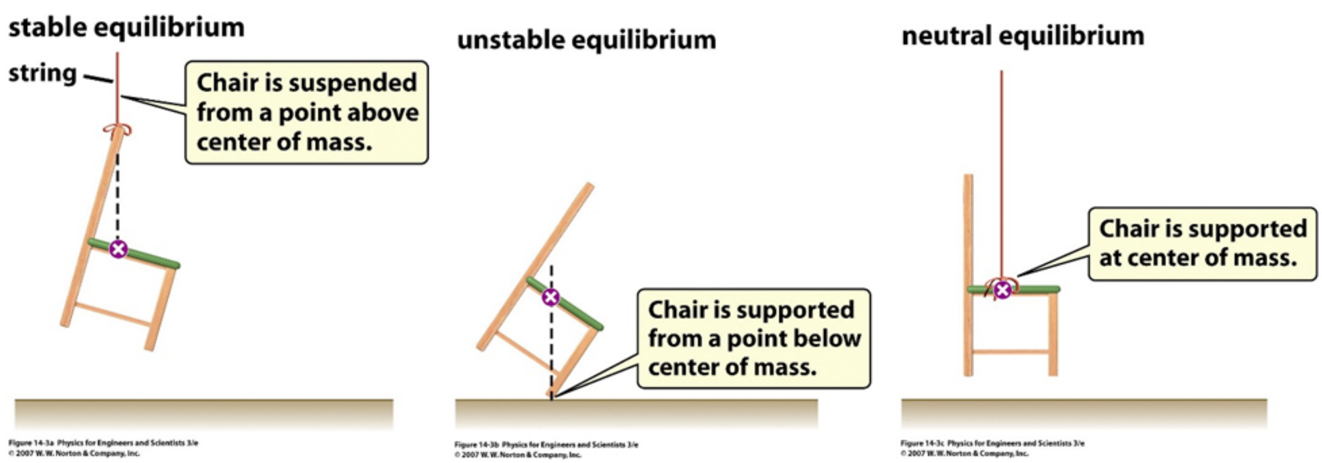


Lab: Oscillations

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report (be sure to make it clear which name is yours).*

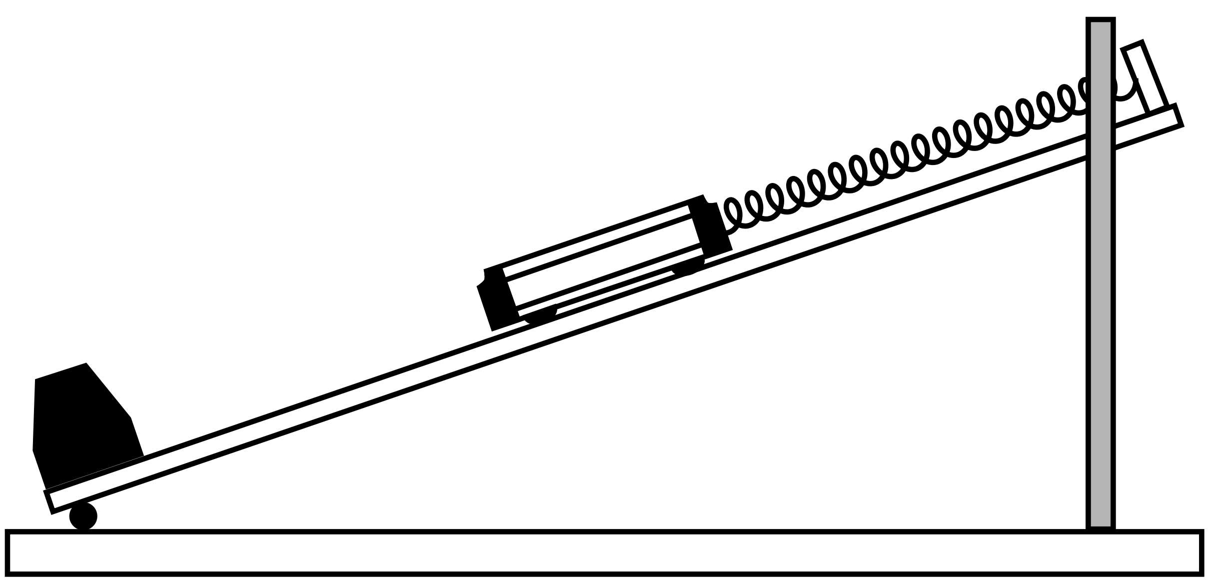
Introduction

Simple harmonic oscillation (SHO) describes the motion of a mass hanging from a spring when it oscillates back and forth after being displaced from the equilibrium position. In this lab, we will focus on a few features of SHO motion that we want you to start developing your intuition for.

We leave more mathematically rigorous treatments such as equations of motion to the lecture, but as a note for your ongoing study in physics and engineering, SHO motion is one of the most important types of motion to analyze. This is because nearly all motion involving conservative forces about a stable equilibrium can be approximated as a simple harmonic-oscillator motion Examples of SHO motion are endless in physics, engineering, quantum mechanics, chemistry, biology, and so on.

Part A: Period of SHO Motion

You should have a setup similar to the diagram below at your table. A cart is fastened to the top of an inclined track using a spring, with additional masses placed on the cart to cause the spring to stretch by about 10 cm or so. A motion detector is placed at the bottom of the track to measure the position of the cart (this will be used in the next part.)



Q1: **[Vocabulary Check]** Push the cart up the incline slightly and let go. Observe the oscillatory motion that the cart undergoes. In your lab report, describe the motion of the cart, and in describing the motion of the cart, define the following two key terms: **amplitude** and **period**.

To help you think through what you are going to measure in this lab, be sure to make predictions and explain your predictions before you make measurements.

Q2: **[Prediction]** How would you expect the period to depend on the amplitude of oscillation? Give a brief answer in your lab report and explain your reasoning conceptually. *[Note: To resist the temptation of changing your prediction if you turn out to be wrong, write this part in pen. You are never graded on the correctness of your prediction, but you* ***are*** *graded on your reasoning process, which will appear very confused if you do not do this part properly.]*

Now that you have made the prediction, we will test it. Use a watch or stopwatch (use an app on your smartphone or use the provided stopwatch) to determine the period. In order to increase the accuracy of your measurement, you can measure the time for 3 to 5 oscillations and divide by the number of oscillations to calculate the period of a single oscillation.

Q3: Displace the cart a few centimeters from equilibrium (no more than 5 cm) and release it. Record the displacement in centimeters. With a small initial displacement, determine the period of oscillation. Repeat the measurement for a total of three trials. Record your results in your lab report. Keep a careful and organized record of all your measurements (example: trial number, time measured, number of oscillations, etc.) and show at least one sample calculation. Calculate an average period P_1 of all three trials and record it in your lab report.

Q4: Displace the cart by the maximum amount you can displace it. You can do this by sliding the cart up the track until the spring is about to go slack. Record the amount of maximum displacement in centimeters. With a large initial displacement, determine the period of oscillation, following the same procedure as Q3. Calculate an average period P_2 of all three trials and record it in your lab report.

The following question (Q5) will help you answer the next question (Q6) more meaningfully. Carefully answer it; call me if you are not sure.

Q5: What is the uncertainty in your measurement of P_1 and P_2? Answer this considering: (1) How much error/uncertainty in time is introduced each time you start/stop the stopwatch? (2) Given how much this affects the total time measurement, what is the uncertainty in the calculation of a single period? (3) You have performed three trials (which hopefully gives you a spread of numbers for period in Q3 and Q4). How does the uncertainty estimated in (2) compare with the spread of three trials? Write down your answer in your lab report and show work. *[Note: You need not be very precise in the estimate of your uncertainty, but you should be sure of your uncertainty to within an order of magnitude.]*

Q6: For most measurements, your P_1 will be slightly different from P_2. Given the uncertainty estimated in Q5, is your P_1 meaningfully different from P_2? Make a note in your lab report about how the period of oscillation depends (or does not depend) on amplitude.

Let's try to make sense of the above result (especially if your result in Q6 does not agree with your prediction in Q2; but do answer the questions below even if they agreed).

Q7: With larger amplitude, the cart has a longer distance to travel in each oscillation. What does it mean for the average speed of the cart if it travels this longer distance in the same amount of time as it travels the shorter distance in smaller-amplitude oscillation? Explain your answer briefly.

Q8: Consider dynamics of the motion of the cart to explain your answer in Q7 from the other direction. Using forces and/or energies involved in large-amplitude oscillation, explain why the average speed (or the maximum speed) should be larger in the larger-amplitude oscillation.

Make sure your Q7 and Q8 answers are not identical (they are both approaching the same answer from different directions, so although the conclusions are the same, the reasoning process should be different), and when you are ready to discuss your answers, call me to discuss and get my initials on your lab report. **Lab reports without instructor initials will lose points.**

One other parameter you can change for the oscillation of the cart in your setup is the angle of the track. Answer the next few questions, keeping adequate notes in your lab report.

Q9: Measure the current height of the top of the track from the table. Lower the angle of incline of the track by lowering the height of the track (by a substantial amount; at least 10 cm, or more). Record the change in height, and make observations of anything that changed with the decrease in the angle of incline.

Q10: **[Prediction]** Now that the cart is oscillating on a gentler incline, how will its period be different, if at all? Explain your reasoning in your lab report.

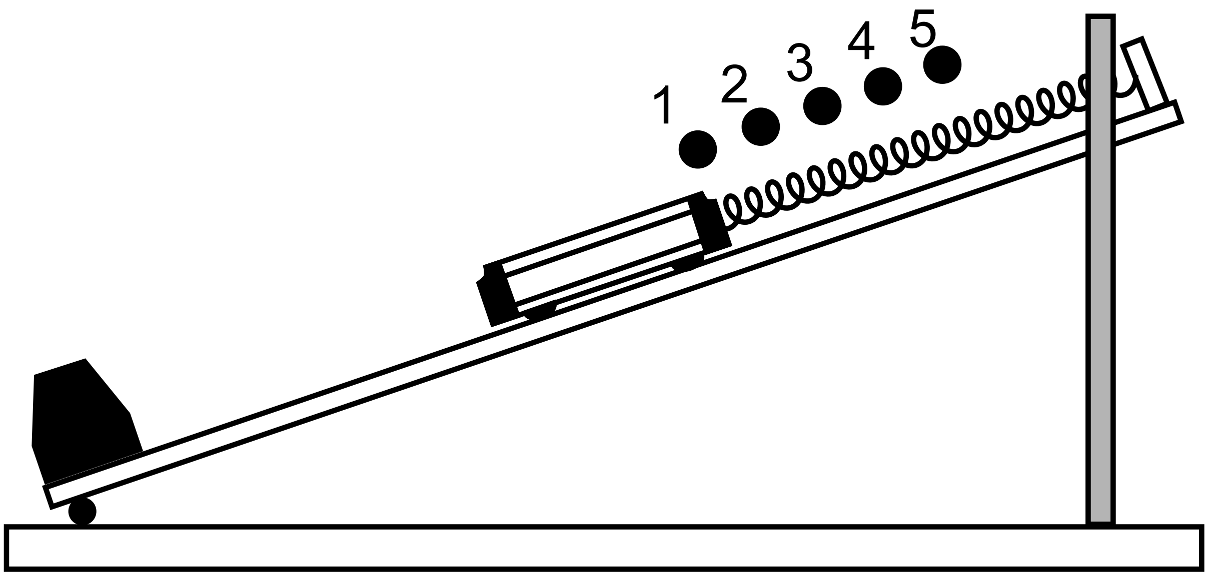
Q11: **[Measurement]** Measure the period of oscillation of the cart. Use similar procedures as what you used in Q3 and Q4, keeping detailed, well-organized notes in your lab report. Calculate the average period P_3 using three trials measuring the period, and record it in your lab report.

Q12: Considering the uncertainty in the calculated value of period (has it changed substantially from Q5?), is your new average period P_3 meaningfully different from P_1 or P_2? Explain your answer.

Part B: Oscillation Kinematics

In this part, we are going to look at the kinematics of SHO motion in detail (which will hopefully help you develop an intuition for the SHO equation of motion and the solutions to the differential equation).

First, a short question to answer for the diagram below.

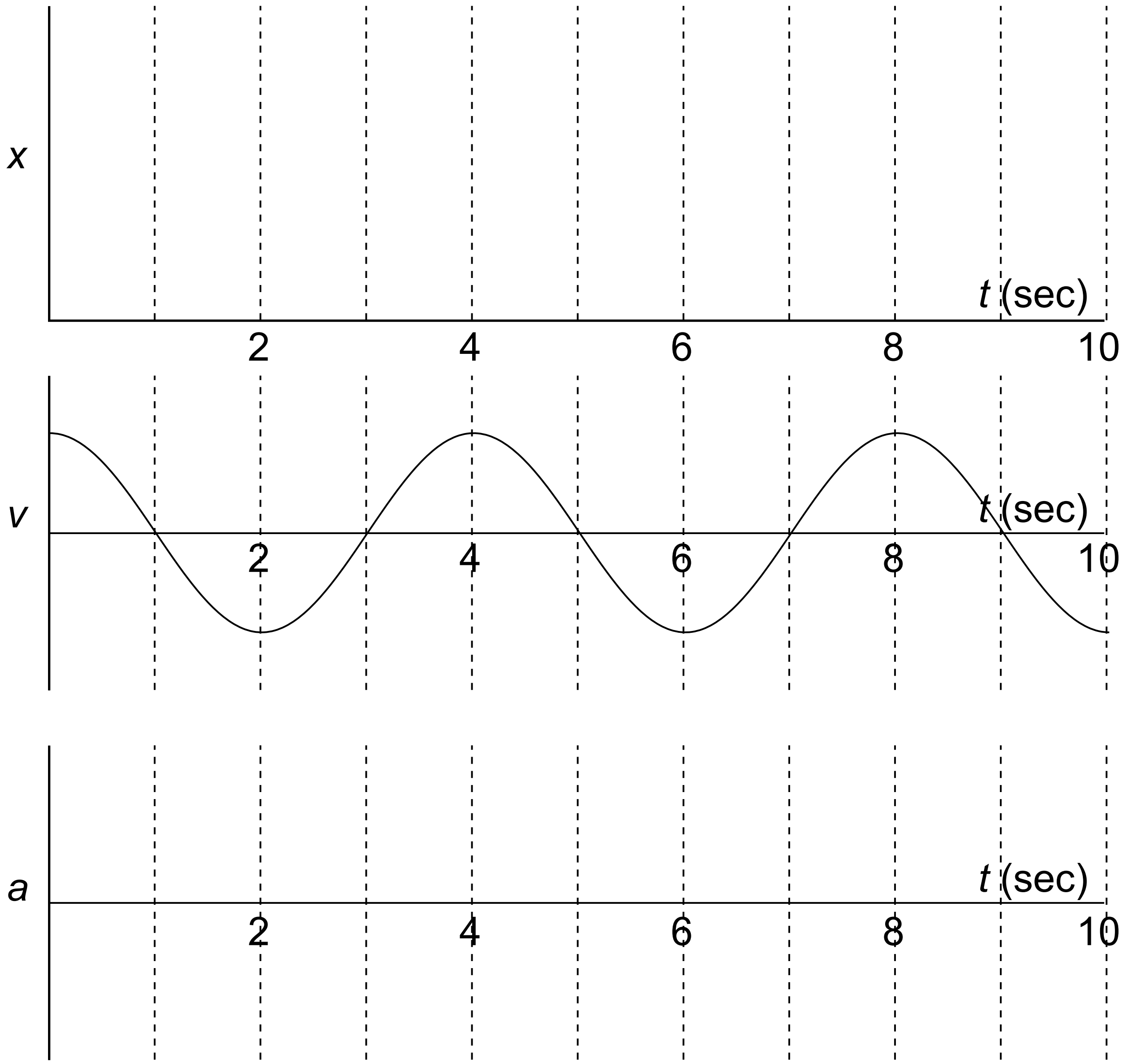


Q13: Consider the five labeled points in the diagram above. Points 1 and 5 are the endpoints/turning points, which are the highest and lowest points reached by the cart. Point 3 is the equilibrium position of the cart where it settles when it is just hanging instead of oscillating. At what point or points will the cart's speed be greatest? Explain why (either using forces or energy) in your lab report.

Now we are going to finally use the motion detector which you should find at the bottom of track (call me if your setup is missing a motion detector). Turn on the computer, open Logger Pro, and open the file *Oscillations.cmbl* (call me if you have trouble finding the file or Logger Pro).

Q14: Set the cart to oscillate and track its motion using the Logger Pro software and the motion detector (call me if you are not sure how). The *Oscillations.cmbl* file should be set up to plot the position and velocity of the cart with the same horizontal axes. Using the position plot, identify the points where the cart was at the labeled points 1 through 5 (roughly). Look at the values of velocity at these position to verify your answer in Q13. Write down your *brief* observations and explanations in your lab report.

Q15: Shown below are axes for position (***x***), velocity (***v***), and acceleration (***a***) graphs, lined up vertically so that they share the same horizontal time (***t***) axis. An instance of the velocity graph is provided on the axes below. Sketch position and acceleration graphs so that they are correctly lined up vertically relative to the given velocity graph. If necessary, use the setup in Q14 to verify that your graphs are sketched correctly. [Hint: The program also calculates acceleration; you simply need to change the vertical axis option to plot acceleration in addition to (or instead of) position or velocity.]



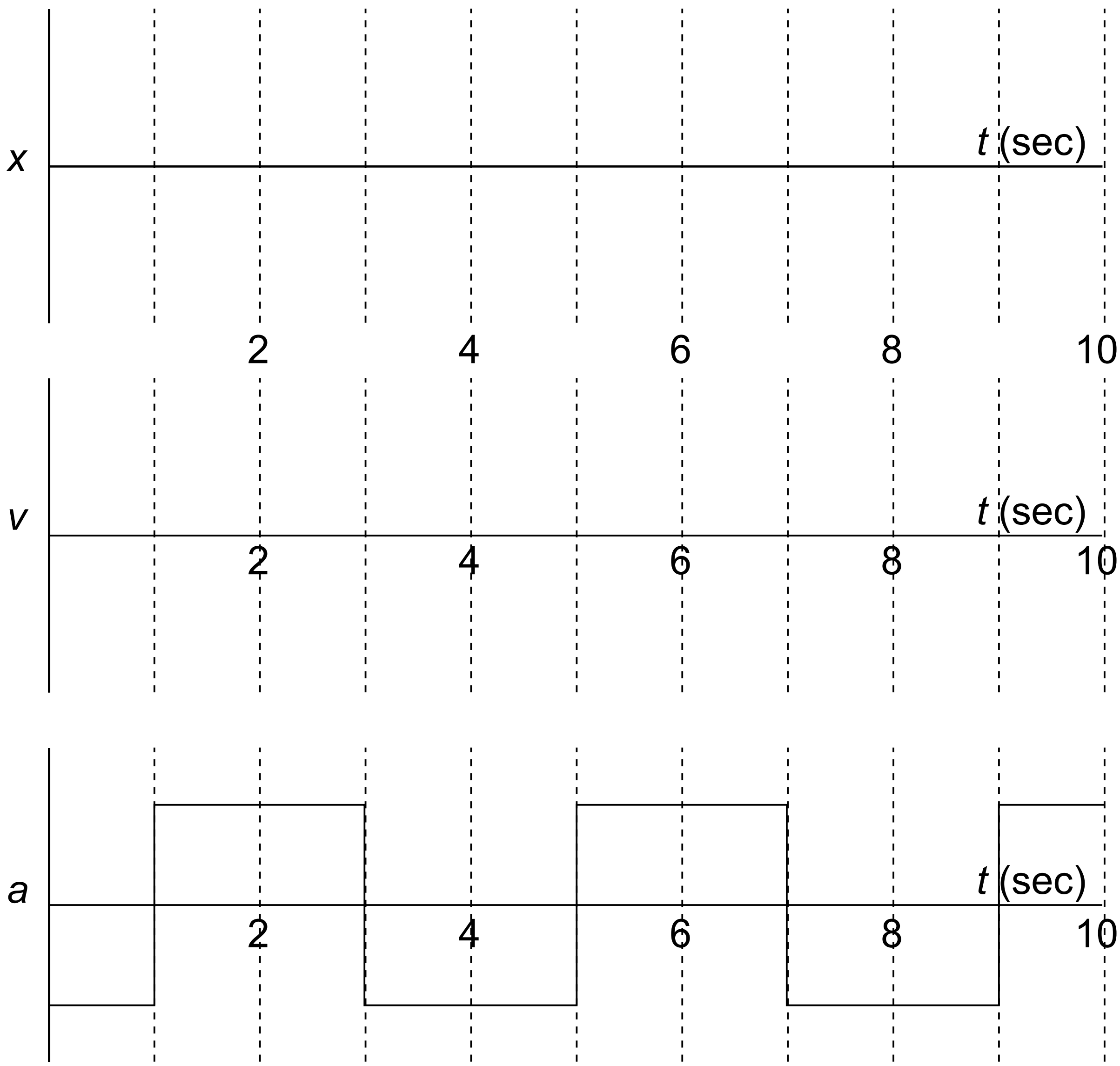
Considering your answers in Q14 and Q15, answer the two questions below.

Q16: At the endpoints of its motion, the cart is momentarily at rest but has a large acceleration. Explain in simple, non-mathematical terms how the cart can have a large acceleration and zero velocity. Give another example of motion with zero velocity and non-zero acceleration.

Q17: At the midpoint of its motion, the cart is moving, and the net force on it is zero. So, why doesn't the cart remain at constant velocity? What forces act on the cart?

SHO motion is the first example (call it a "case study") of detailed analysis of kinematics including expressions for ***x(t)*** and ***v(t)*** which involves time-varying accelerations. For this reason, the kinematic equations that we covered early this semester (of the type $x = x_0 + v_0 t + \frac{1}{2}at^2$ or $v = v_0 + at$) do not apply in this case. The question below highlights this difference.

Q18: Shown below are axes for position (***x***), velocity (***v***), and acceleration (***a***) graphs, lined up vertically so that they share the same horizontal time (***t***) axis. An instance of an acceleration graph which most closely relates to constant-acceleration motion and still results in oscillatory motion is given below. Using your knowledge of kinematics, fill in the velocity graph and the position graph. Assume that both velocity and position start at zero.



The graph above represents oscillation, but it does not represent *simple harmonic* oscillation. SHO results only from a net restoring force that is proportional to the displacement (i.e. spring force, among many others).

Extra: Measurement of Spring Constant

Note: Only complete this section if you are otherwise finished with the lab. This is an additional measurement exercise which relates to your measurements in Parts A and B above.

With the measured value of the period, you are now actually in a position to calculate the spring constant of the spring you are using. From our discussion of spring SHO motion, the natural frequency of oscillation is related to mass ***m*** and spring constant ***k*** by $\omega_0 = \sqrt{k/m}$ (note that ω_0 is actually *angular* frequency). Since the period is the reciprocal of frequency and frequency (***f***) is related to angular frequency by $\omega = 2\pi f$, we have,
$P = \frac{1}{f} = \frac{2\pi}{\omega} = 2\pi\sqrt{\frac{m}{k}}$.

For the optional exercise here,

1. Solve the above equation for the spring constant ***k*** and find a numerical value. The total mass of the cart and the load is 1.5 kg (0.5 kg cart and 1 kg load). (What is the SI unit of the spring constant ***k***?)
2. Come up with a way to measure ***k*** directly (that is, without using an oscillatory motion) by application of Hooke's Law ($F = -kx$). Measure ***k*** directly and compare this directly measured value with that found above.

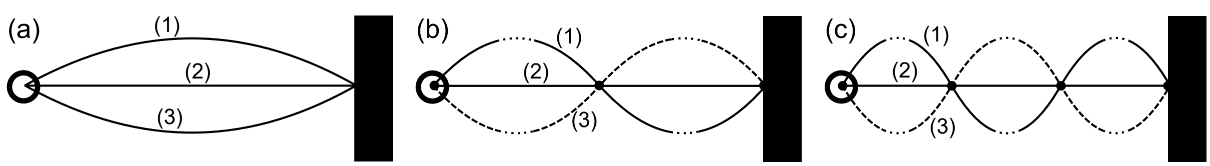
If you see significant difference between (1) and (2) and cannot explain it, call me. I will give you some ideas on what to test for.

Lab: Standing Waves in Sound

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report (be sure to make it clear which name is yours).*

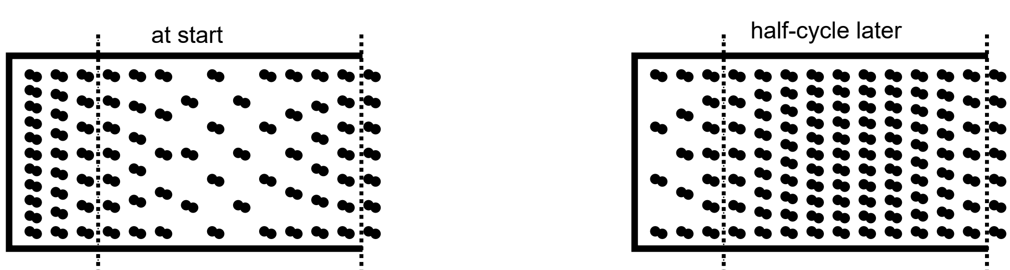
Introduction

Standing waves are the result of the superposition of two traveling waves, traveling in opposite directions in the same medium. The interference between the two traveling waves gives rise to the distinctive shape of a standing wave. For example, the diagrams below show several different standing waves on a string (each diagram shows three snapshots; (1) at the beginning of a period, (2) a quarter period (and three quarters of a period) later, and (3) a half period later). At a few locations, you can see the two waves destructively interfering, so that, over a whole period, the string at this point does not move. This point is called a **node** (and the points on the string that move the most are called **antinodes**).



The waves shown above also show nodes at each endpoint, because each endpoint is being held at the location. So, for this particular standing wave, the endpoints must be nodes. For each setup for a standing wave (or "resonance"), the conditions on endpoints are specific for the setup, and we call these conditions **boundary conditions**. Boundary conditions determine the shape of the standing wave; it is very important to know clearly what they are for the standing waves in your setup.

The standing waves in this lab won't be visible like the standing waves on a string. Instead, standing waves of sound may be represented as below, as varying density of air molecules.



Another way to represent the same physical thing is showing the varying pressure, as a function of location along the tube, as shown below.

Make sure you understand the representation of sound waves before proceeding with the lab. In the lab, we will determine the speed of the sound wave (with frequency f and wavelength λ) using the relationship,

$$v_{\mathbf{wave}} = f\lambda$$

Part A: Prelab Warm-Up

Answer the question below in your lab report in preparation for the measurements and analysis for this lab.

Q1: Based on the representation of sound waves (in terms of pressure) above, what is the boundary condition at the closed end of the tube? At the open end of the tube?

Q2: In this lab, you will set up and hear standing waves in a vertical tube. We adjust the length of the tube by changing the water level (making the water level higher to shorten the tube length, and lower to lengthen it). If the wavelength of your sound wave is $\lambda = 1.0\mathrm{m}$, what is the shortest length of the tube that would allow for a standing wave in the tube? What are the next two shortest lengths of the tube? To help you answer this question, sketch in your lab report the first three lengths of the tube that would give a standing wave of wavelength λ. What are the lengths of the tube in terms of the wavelength λ?

Part B: Experiment and Measurement

Now you are ready to take the measurements. Observe your setup. Make sure you understand the operation of each part before you proceed. Your setup can be described in four parts:

1. Vertical half-open tube (a column of air, open at the top and closed at the bottom by water)
2. Water can for adjusting the water level (connected to the tube by a hose)
3. Speaker just above the tube for producing sound (with a pure sine tone generated by the function generator)
4. Microphone set just over the top of the tube and connected to laptop with Logger Pro running (in Logger Pro, click "Experiment > Data Collection > Repeat")

The half-open tube should be directly below the speaker to allow sound waves to enter the tube. When you set up a standing wave, you will see that that the amplitude has become maximal in Logger Pro. You should also hear the sound become noticeably louder, but rely on Logger Pro to pinpoint the maximum.

Q3: Set the frequency of the function generator at 500 Hz. You should hear a tone coming from the speaker. Set the “amplitude” knob of the function generator so that you can barely hear the tone from the speaker (it will become louder when it is on resonance). Hit "collect" in Logger Pro to visualize the sound wave. Sketch what you see, taking care to label and provide a scale for the axes.

Q4: Hit "collect" in Logger Pro and adjust the water level. Pay close attention to the amplitude of the sound in Logger Pro (it should be changing in response to the water level). Find the water levels that yield maximal amplitudes and record them in your lab report in centimeters (try to find 3 or more such water levels; if that’s not possible, find at least 2). Your ears should also register that the sound is louder at these locations. Record the maximal amplitudes in your lab report and compare them to the amplitude of the sound wave you sketched in Q3.
Note: You may use the centimeter marking on the side of the tube itself.

Answer the short questions below in your lab report.

Q5: Do the lengths follow the pattern you determined in Q2? Keep in mind that, depending on your tube setup, you may not be able to get the shortest resonance length.

Q6: Do the values you measure precisely agree with the prediction? This is the question: if you found all resonance lengths, starting from the shortest, is the second resonance length exactly 3 times the first resonance length, and is the third resonance length exactly 5 times the first resonance length (or 5/3 times the second resonance length)? Make your observation (but do not spend too much time on this question and move on).

Q7: It turns out because of “**end correction** (https://en.wikipedia.org/wiki/End_correction)” effects, the node (in pressure) is not at the very top of the tube, but slightly above (how far above depends on the radius of the tube); this should explain the discrepancies you see above. In order to cancel out this end correction effect, you can take a difference between two of your measurements (how does this difference relate to the wavelength?). Determine the wavelength of the 500 Hz sound wave and record it in your lab report. Show your work, based on your measurements in Q4.
Note: If you were able to find three resonances, you can take two different differences—e.g. difference between second and first resonance lengths *and* difference between third and second resonance lengths—to obtain better results.)

Q8: Change the function generator to a higher frequency (make it significantly higher than 500 Hz above) and repeat the measurements and calculations you did for 500 Hz. Record your measurements and work in your lab report.

Part C: Analysis

Q9: In Q7 and Q8, you determined the wavelengths (λ) of the sound wave. Combining this information with the frequency (f) measurement from the function generator, you can find the speed of the sound wave, given by the relationship: $v_{\text{sound}} = \lambda f$. Find the speed of the sound wave for frequencies 500 Hz and the second, higher frequency. Record your calculation in your lab report (show your work!) and comment on any difference or similarity between the two results (are they as expected? Was there anything surprising?).

Q10: The speed of sound waves can vary depending on temperature and humidity. The speed of sound waves in dry air is given by, $v = \mathbf{331\,m/s} + (\mathbf{0.6\,m/s}\cdot\ ^\circ\mathrm{C}) \times T$, where T is temperature measured in degrees Celsius. In your lab report: (a) Calculate the theoretical sound wave speed. (b) Compare it to the experimental sound wave speeds found in Q9 above. (c) Calculate percent differences and explain any errors that you see. In addition, try answering: Can you attribute the error to measurement errors in Q4 and Q8? What are your largest sources of error? Are frequency measurement errors larger or are wavelength measurement errors larger? Explain.

Optional Exercises

Do these exercises if you have some time left after answering Q10 in your lab report.

In Q4 we found resonances by adjusting the length of the tube. Here we hold the length fixed and change the frequency instead.

Q11: Adjust the water level in the tube until there is around 30 cm of air space at the top of the tube. Measure and record the exact length of the air space. Vary the frequency of the sound using the function generator, and identify resonances using Logger Pro as we did in Q4. Record the frequency for each of the first four resonances. [Hint: the lowest resonance should be a little below 300 Hz]

Q12: Compare the approach employed in Q11 to that of Q4. If our goal is to determine the wavelength(s) of the tone(s) we used (and any quantities subsequently calculated from wavelength), is one approach preferable over the other? Why?

Lab: Calorimetry Manual

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report.*

Introduction

Calorimetry is a measurement of heat transfer. Let's review some important concepts for the discussion of calorimetry (for those who took high-school or general chemistry, this will be a review):

- **Heat**, in the technical meaning of the word in physics and chemistry, is a transfer of thermal energy.
- For a given substance, there is a relationship between heat transfer and change of temperature. We call this **specific heat capacity**. Specific heat, a constant value for a given substance, is given in units of **joule/(kelvin·kilogram)**. Experimentally we find that amount of heat transfer needed is proportional to mass of sample (more material requires more heat for same temperature change) and to temperature difference (more heat is needed for larger temperature change).
- Using the relationship between specific heat capacity and temperature change, you can calculate for the amount of heat transfer by making temperature measurements.

So in calorimetry, amount of heat transferred is not directly measured, but it is calculated from measurement of temperature changes (and some knowledge about the material). The basic expression for amount of heat transferred (***Q***) is given by,

$$Q = c \cdot m \cdot \Delta T$$

where ***c*** is the specific heat capacity of the substance, and ***m*** is the mass of the sample, and ***ΔT*** is the temperature change ($\Delta T = T_{\text{final}} - T_{\text{initial}}$). Many calorimetry measurements make use of the fact that when two things at different temperatures are in thermal contact, they come to a thermal equilibrium (the two things reach the same final temperature), and in this process, heat outflow (Q_{out}) of a hotter substance must equal heat inflow (Q_{in}) of the colder substance, since energy is conserved: $Q_{\text{out}} = Q_{\text{in}}$.

In the next two parts, you will consider your setup and design experiments to determine unknown quantities.

Part A: Sample Identification

In this part, you are given a metal cube of unknown composition. Your goal here is an educated guess for the composition of the metal cube.

Q1: Brainstorm! In your lab report, list some material properties you can measure to identify the composition of the metal cube. Try to focus on properties you can measure or calculate using equipment in the lab, and list at least one property that can be measured using calorimetry (this is a calorimetry lab, after all). Work with your group.

Post-brainstorm Note: One property you can measure using calorimetry is specific heat capacity. For measuring specific heat capacity of the metal cube, you have following equipment and material available:

- hot and cold water (and beakers to keep them in, and beaker tongs to carry them with when hot)
- rod and thread to suspend the sample
- insulated (double-walled) aluminum cup
- thermometer in rubber stopper to measure temperature in aluminum cup

Q2: Considering the equipment and material available to you, design a calorimetry experiment that will allow you to make necessary measurements to calculate the specific heat capacity of the sample. Describe your procedure briefly in your lab report. Some things to consider and questions to address: (1) Your aluminum cup is insulated but not *perfectly* insulated; what kind of measurement errors will come from this imperfection? (2) Do you want to place a hot metal cube in cold water or a cold metal cube in hot water? Which is better and why? (3) For best measurement, do you want to mix a large amount of water with metal cube, or a small amount of water? Why?

If necessary, check your design of the experiment with me before making the measurements (in Q4).

Q3: In the experiment you designed in Q2, you should be making temperature measurements. Now you need mathematical expressions to relate these measurements to heat transfer (***Q***) and, eventually, specific heat capacity. Derive a formula for the specific heat of the metal sample, keeping in mind that the only numbers available to you are: (1) temperature measurements, (2) mass and volume measurements, and (3) known physical constants. You may find the expression $Q = c \cdot m \cdot \Delta T$ useful. Show your derivation and result in your lab report. (*Note*: You did a problem like this in your homework. If no one in your group is familiar with this calculation, call me!)

BEFORE PERFORMING EXPERIMENT

Safety Note: Be careful when handling hot water. Handle the hot-water beaker only by using beaker tongs. Tongs themselves may get hot, so only handle them by the handles. (Physics labs are generally safe with minimal risk of injuries; this lab is an exception, so please be careful.)

Q4: Perform the experiment you designed in Q2. Repeat your experiment 2 to 3 times, so that you have a sense of your experimental error. For each trial, calculate specific heat capacity of the metal using the formula you derived in Q3. In addition to your measurement uncertainties, difference between trials will give you sense of your experimental error. In your lab report, record your measurements and calculations. Show at least one set of complete calculations.

Q5: The table below shows the known specific heat capacities of different elemental metals. Using your results in Q4 and the table, make an educated guess for the composition of the metal cube. If you think more than one metal may fit, refer back to your answer to Q1 for additional measurements you can make (hopefully easily), which will distinguish between different candidate materials.

Write your answer, reasoning, and any additional measurements in your lab report.

element	***c*** (J/kg/K)
aluminum	904
potassium	757
calcium	631
scandium	567
titanium	520
vanadium	489
manganese	479
iron	449
chromium	448
nickel	445
cobalt	421
zinc	388
copper	384
gallium	371
rubidium	364
arsenic	328
strontium	300
yttrium	298
zirconium	278
niobium	265

Specific heat capacities of some elemental metals (source: Wolfram|Alpha)

Part B: "Red Hot" Calorimetry

In this part, you will estimate the temperature of an iron sphere that is glowing red hot using calorimetry measurement.

Note: There is one Meker burner setup (and two iron spheres) for the whole class. Please plan out your measurement so that you will have enough time with this shared equipment.

Safety Note: Although physics labs are rarely dangerous (or cause a risk of bodily harm), this lab is an exception. The iron sphere will glow red—if it even touches you briefly you will get a bad burn. The metal tong will also get very hot very quickly. Always cool the metal tong with cold water after using. If you have question about safety of any particular equipment, ask me; don't risk it. The iron sphere should reach red-hot glowing temperature starting from room temperature in about 3 minutes or less. If this does not happen, call me to adjust the burner or the sphere. Please do not do it yourself as it could be unsafe.

The measurement procedure for this part is given below; think through the same considerations as in Q2 and if you should change anything to help make more accurate measurement of the temperature of red-hot glowing iron sphere.

Measurement Procedure: Make measurement of initial temperature of water in aluminum calorimeter. When ready, first note the color of the iron sphere (you will use this for error estimate), and drop the red-hot glowing iron sphere into the calorimeter and make measurement of the equilibrium temperature.

You will also need the mass of the iron sphere, as well as mass or volume of water, to answer the question below.

Q6: Calculate the initial temperature of the iron sphere. Start by doing the derivation similar to Q3 (except that you want to solve for the initial temperature of the iron sphere). Give the derivation and calculation of numerical value of the initial temperature of the iron sphere in your lab report. Since equipment is limited for this part of lab, take only one measurement (provided that your result seems reasonable; if not, repeat as necessary).

Additional Questions

Consider and answer questions below in your lab report.

Q7: Using the known specific heat capacity of the material you identified in Q5 as the theoretical value, calculate the percent error of the specific heat capacity you measured in Q4. Does your answer sound reasonable? If not (or, even if so) identify specific sources of error that are responsible for error and the magnitude of error due to these sources.

Q8: Estimate the percent error for your result in Q6, using: (1) either or both of the tables below, and (2) comparison with results that other groups obtained. Does your answer sound reasonable? List some sources of error for your result in Q6 (in particular, can you think of any sources of error that were *not* present in Part A?).

Color	**Temperatures** (°C)
Black red	426 to 593
Very dark red	593 to 704
Dark red	704 to 814
Cherry red	815 to 870
Light cherry red	871 to 981
Orange	981 to 1092
Yellow	1093 to 1258
Yellow white	1259 to 1314
White	1315+

Colors observed in steel, according to Chapman's "Working Technology" (1972)

Color	**Temperature** (°C)
Red: just visible	525
Dull red	700
Dull cherry red	800
Full cherry red	900
Clear cherry red	1000
Deep orange	1100
Clear orange	1200
Whitish	1300
Bright white	1400
Dazzling white	1500

Stirling Consolidated Boiler Company's "A Book of Steam for Engineers" (1905)

Appendix: Materials List

Required Equipment for Both Parts

- 1 x aluminum calorimeter (per group)
- 1 x thermometer (per group)
- several balances (for the whole class)

Part A

- Large pot of water, kept hot
- Access to tap water (cold water)
- 1 x beaker (per group)
- 1 x beaker tong (per group)
- 1 x metal cube sample (per group)
- rods and threads (for the whole class)

Part B (for the whole class to share)

- 2 x iron sphere
- 1 x metal tong
- 1 x Meker burner

Lab: Heat Engine Cycle Manual

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report.*

Introduction

It is all too easy to take the description of heat engines and refrigerators as very theoretical and abstract, with little connection to the principles of mechanics you learned in Physics 4A (and which I keep reminding you, through models like the kinetic theory of gas, underlies everything we do in thermodynamics).

The goal of this lab is to help you draw connections between P-V diagrams (which admittedly can seem very abstract) and processes that occur in real life. As an engineer and/or scientist, it is important that you develop an intuitive feel for the analytical tools we use, like free-body diagrams in Physics 4A, and P-V diagrams in thermodynamics. Once you have an intuitive feel, problem-solving will come more easily.

Required Equipment

- Heat engine apparatus
- A set of masses for applying known pressure
- Hot water (boiling water + tap water), tepid water (tap water), and cold water (ice water) reservoirs

Equipment Notes

- The seal made by the piston in your heat engine apparatus is not very good. Only place and remove small weights (small pressure difference), and do the procedure as quickly as possible to **minimize air leakage** during experiment.
- Keep the hot water at your group between 40 to 70° Near-boiling water is available at the front; use tap water to cool it down to about 70°C. Keep an eye on the temperature.
- Relevant equipment measurements:
  - **Piston inner diameter = 32.5 mm**; Piston and platform **mass = 35.0 g**
  - **Aluminum can inner diameter = 38 mm**; **Aluminum can inner height = 150 mm**

Pre-Lab Equipment Check

Look at your heat engine apparatus and do the following simple calculations and procedures to make sure you understand the setup and the capability of your equipment. You are not required to record anything, but it is *strongly recommended* that you do not skip these checks.

Check 1: Look at the three tube clamps in your apparatus. See if you can set all three so that air flows freely between the aluminum can and the piston but no gas flows into or out of the system. Test it by pulling gently on the piston and watching it go back when you release it.

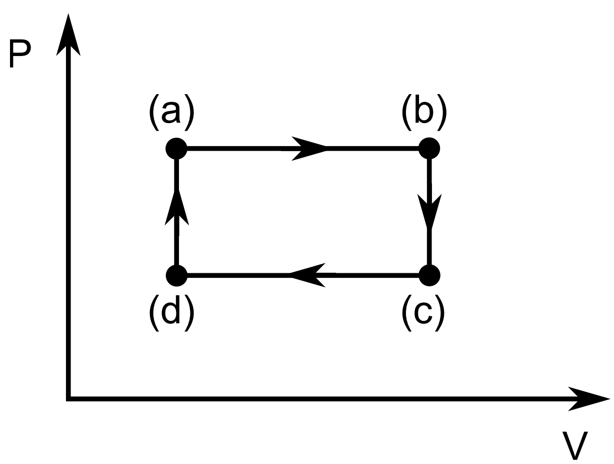
Check 2: Calculate the volume of aluminum can, and the maximum volume of the piston. If the apparatus was sealed as in Check 1 above with piston at minimum volume, and the piston was pulled out to maximum volume, what would be the pressure inside?

Check 3: Perform the procedure in Check 2. When you release the piston, does it return to the original position? Why do you think it does not return to the original position? (This is why you will use placement/removal of weights in actual lab, rather than pushing/pulling on piston.)

Make any necessary notes in your lab report.

Part A: Thermodynamic Process I

Consider the P-V diagram shown below. The pressure and volume of the working gas (air in the sealed heat engine apparatus) will cycle through **(a)**→**(b)**→**(c)**→**(d)**→**(a)**, etc.



Your heat engine is initially prepared in the state **(a)** through following steps (do this when you are ready to do the experiment):

- Leave the aluminum can at room temperature (use tap water).
- Place 100 grams on the platform.
- Seal the heat engine apparatus with the piston positioned low (about 20 mm height)

After this, the gas in the heat engine apparatus will correspond to state **(a)** in the diagram. Now you will figure out how to make the gas inside the piston undergo the cycle shown.

Q1: Using your heat engine apparatus and available thermal reservoirs (hot, tepid, and cold), how will you make the gas go along path **(a)→(b)**, and path **(b)→(c)**, and path **(c)→(d)**, and then back to **(d)→(a)**? Write down your plan in your lab report. (Hint: Name each of the processes. What quantity is kept constant in the process? To bring about the change in the other quantity, what else must change and in what direction? *Caution:* You must be able to measure pressure and volume as you perform your procedure.)

Q2: Do the procedure you described in Q1 (quickly, before the gas leaks through the piston). Did everything work as you expected? Write down any modifications needed or any surprising/interesting findings in your lab report. Note how far the piston moved in the process **(a)→(b)** (measure it in millimeters).

Q3: For each of the process, answer whether positive, negative, or zero work was done by the gas in the heat engine apparatus (an example table for suggested organization is shown below; please record your answer in your lab report). Explain your answer. If non-zero work was done, point out the mechanical change that occurred external to the gas, as a result of the non-zero work ("Where did the energy go?").

Process	Work Done	Explanation	Mechanical Change External to Gas (if non-zero work done)
(a)→(b)			
(b)→(c)			
(c)→(d)			
(d)→(a)			

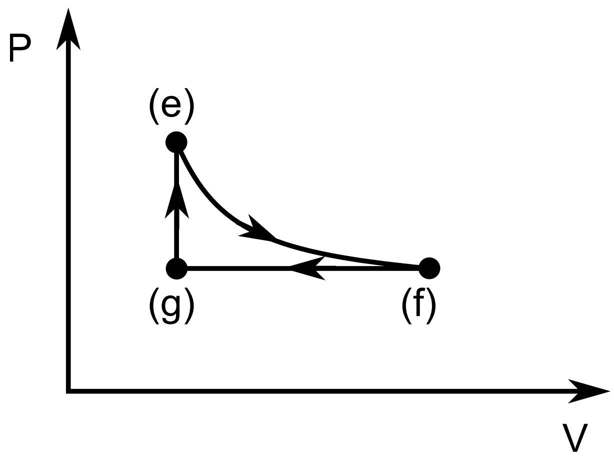
When you have recorded a complete table in your lab report (and you have discussed the result within the group to make sure you all understood the processes; I will ask questions!), call me to get my initial. **Lab reports missing instructor's initial will lose points**.

Q4: For each of the four processes above, what is the direction of heat transfer? State whether heat was added to the gas or taken from the gas.

Q5: In a heat engine, net heat is added to a system (heat added is greater than heat taken, over a cycle), and the system uses some of that energy to do work. Explain how your heat engine apparatus acted as heat engine in this **(a)(b)(c)(d)** cycle. What did your heat engine accomplish as a result of the work done by its working fluid?

Part B: Thermodynamic Process II

Consider the P-V diagram shown below. The pressure and volume of the working gas (air in the sealed heat engine apparatus) will cycle through **(e)**→**(f)**→**(g)**→**(e)**, etc.



Your heat engine is initially prepared in the state **(e)** through following steps (do this when you are ready to do the experiment):

- Place the aluminum can in the hot water bath.
- Place a total of 100 grams on the platform (you may want this in 10, 20, 50 gram masses)
- Seal the heat engine apparatus with the piston positioned low (about 20 mm height)

Your heat engine will be prepared in state **(e)**. Now you will figure out how to make the gas inside the heat engine apparatus undergo the cycle shown.

Q6: For the process **(e)**→**(f)**, the product PV is constant. Using your heat engine apparatus and available thermal reservoirs, how will you make the gas go along path **(e)**→**(f)**, and path **(f)**→**(g)**, and path **(g)**→**(e)**? Write down your plan in your lab report, paying particular attention to the process **(e)**→**(f)** (if PV is constant, what else is constant, and how will you achieve it?).

Q7: Regarding this part of the lab, suppose one of your friends comments: "Since the temperature stays constant along the path (e)→(f), the gas neither absorbs nor loses heat along that path, meaning that the internal energy of the gas stays constant." Do you completely agree with this statement? Sort out parts of the statement that are correct and the parts that are incorrect. What mistaken assumption is your friend making?

Q8: Along path **(f)**→**(g)**, the gas loses internal energy. Along path **(g)**→**(e)** the gas gains internal energy. Which of these two changes in internal energy is bigger in magnitude? (Hint: Is there any change in internal energy along path **(e)**→**(f)**?)

Q9: Explain how the apparatus works as a heat engine in this cycle. What is the result of the work being done by the heat engine? Note how far the piston moves in the process (measure it in millimeters).

Additional Questions

Consider and answer questions below in your lab report.

Q10: Estimate how much net work was done over one cycle. Make separate estimates for Part A and for Part B. Use the measurements of piston displacement in Q2 and Q9 to help you estimate the work done. [Hint: Consider two ways of calculating the mechanical work done, in the context of thermodynamics. Which way is easier, given the experimental measurements available?]

Q11: In very generic terms, efficiency can be defined as, $\mathbf{efficiency} = \frac{\mathbf{what\ you\ want}}{\mathbf{what\ you\ pay}}$. The idea is to describe what percentage of what you “pay” can be turned into what you want. For the heat engine cycles like those you saw in Part A and Part B of this lab, how would you define efficiency? In other words, what physical quantity are you trying to get out of the engine cycle (what you want)? What physical quantity do you need to provide, in order to get what you want (what you pay)? [Hint: Do some sanity checks for your definition. Is your efficiency always less than 100%? Is higher efficiency something you would want?]

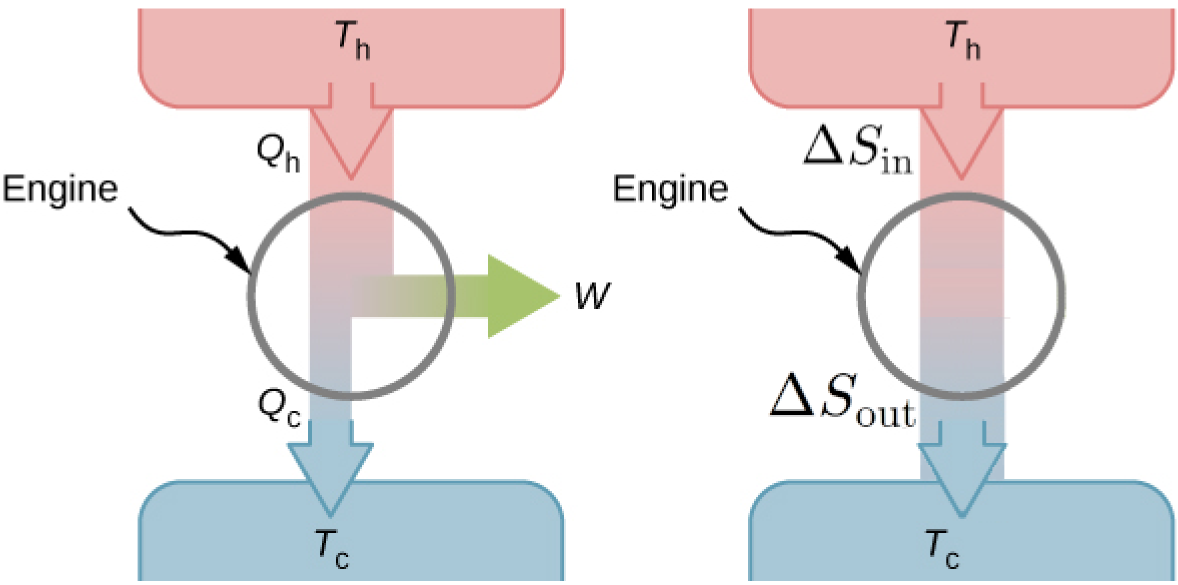
Worksheet Lab: Entropy Manual

*Note: For the "lab report," answer all questions marked as **Q1, Q2,** etc. on separate pieces of paper to turn in. Use the space provided in the lab manual for graphs or answers required to be formatted in a particular way. Please follow all directions and answer all questions. You only need to turn in your answers for the lab report. Write your name and your group partners' names on your lab report.*

This lab is based on UC Berkeley Physics 7B Worksheet Lab, "Entropy and Second Law."

Questions for Discussion

Q1: Shown below are schematic figures for the energy and entropy of a heat engine (OpenStax *University Physics Vol. 2*, Figure 4.4, and a modified version of that for entropy transfer). The one on the left shows schematic diagram of energy transfer; the one on the right (or below the first figure) shows transfer of entropy.



a. What is the relationship between $\Delta S_{\rm in}$ and $\Delta S_{\rm out}$? Why is it not possible to develop a cyclic engine that converts heat entirely into work? Why *must* some heat ($Q_{\rm out}$) be ejected from the system?

b. In a Carnot engine, $Q_{\rm in}$ enters the system only along isotherm $T_{\rm H}$, and $Q_{\rm out}$ leaves the system only along the isotherm $T_{\rm L}$. Use your result of (a) to find $Q_{\rm out}/Q_{\rm in}$ in terms of $T_{\rm H}$ and $T_{\rm L}$.

c. An efficient engine converts as much heat as possible into work, ejecting as little heat as possible. Can you explain why a Carnot engine gives the greatest possible efficiency? [*Hint: $Q_{\rm in}$ enters the system only at the highest temperature of the cycle. $Q_{\rm out}$ leaves the system only at the lowest temperature of the cycle.*]

Q2: A cyclic heat engine uses an ideal gas as its working substance. Which of the following are true?

- (T / F) | For a complete cycle, the change in entropy of the gas is zero ($\Delta S_{\text{gas}} = 0$).
- (T / F) | For a complete cycle, the change in entropy of the gas is zero ($\Delta S_{\text{gas}} = 0$), but only if the engine operates reversibly. If the engine operates *irreversibly*, then $\Delta S_{\text{gas}} > 0$.
- (T / F) | For a complete cycle, the change in entropy of the universe is zero ($\Delta S_{\text{universe}} = \Delta S_{\text{gas}} + \Delta S_{\text{environment}} = 0$).
- (T / F) | For a complete cycle, the change in entropy of the universe is zero ($\Delta S_{\text{universe}} = \Delta S_{\text{gas}} + \Delta S_{\text{environment}} = 0$), but only if the engine operates reversibly. If the engine operates *irreversibly*, then $\Delta S_{\text{universe}} > 0$.

Q3: A box with total volume V_0 is divided in half by a partition. On the left-hand side of the partition, there is a sample of ideal gas with initial pressure P_0 and initial temperature T_0. On the right-hand side of the partition, the box is empty.

The partition is then suddenly removed, and the gas expands freely to fill the entire box. Soon the gas is in thermal equilibrium again.

a. Intuitively, what do you think happens to the entropy of the gas when it expands freely? Does the entropy increase, decrease, or stay the same? Justify your answer.
b. Suppose that two students, Carolina and Meghan, are asked to find the change in the gas's entropy for this process.

- Carolina wants to find the change in entropy as follows: $\Delta S = \int_{\text{initial}}^{\text{final}} \frac{dQ}{T} = \int_{\text{initial}}^{\text{final}} \frac{0}{T} = 0$, where Q=0 since no heat flows in or out of the gas during the free expansion.
- Meghan, on the other hand, wants to find the change in entropy like so: $\Delta S_{\text{ideal gas}} = \frac{d}{2} N k_B \ln \frac{T_f}{T_i} + N k_B \ln \frac{V_f}{V_i} = 0 + N k_B \ln \frac{V_f}{V_i} = N k_B \ln 2$, where $\ln(T_f / T_i) = 0$ since $T_f = T_i$.

  Whose method is correct? Why?

Q4: One form of the Second Law of Thermodynamics states that in any closed system, the entropy never decreases ($\Delta S_{\text{closed system}} \geq 0$). Qualitatively speaking, this means that closed systems tend to evolve towards more and more disordered states. (For example, think of ice cubes melting in a thermos bottle filled with water.)

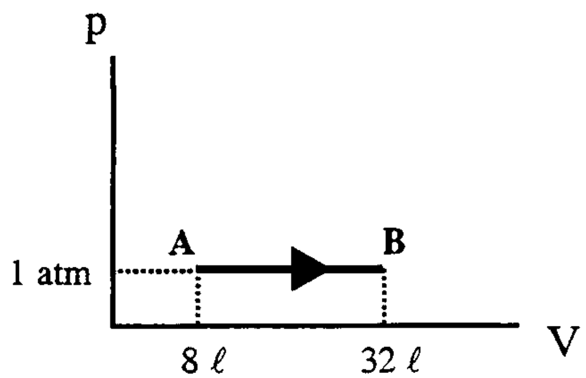
It is sometimes claimed that the existence of life violates the Second Law. The reasoning is that living systems can evolve towards more and more ordered states. (For example, think of a chicken's egg developing into a baby chick.)

Can you explain this apparent contradiction?

Problems

NOTE: In a typical discussion section at UC Berkeley, students usually work through the problems during the discussion section, either individually or in groups. The GSI monitors the progress and conversation among the students and either assists individually or brings the section together for a discussion on a common issue that develops in the course of the section.

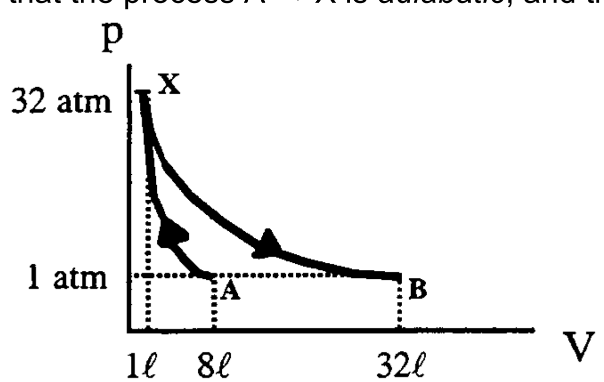
Q5: Two moles of monatomic ideal gas, under a constant pressure of 1 atmosphere, expand from an initial volume of 8 liters to a final volume of 32 liters.



(This is a reversible transformation.)

a. Is heat flowing into the gas or out of the gas during this transformation? (You needn't calculate anything in detail; just decide whether the heat flow is in or out.)
b. What is the change in entropy of the gas during this transformation? Is the sign of your answer consistent with your answer from part (a)?

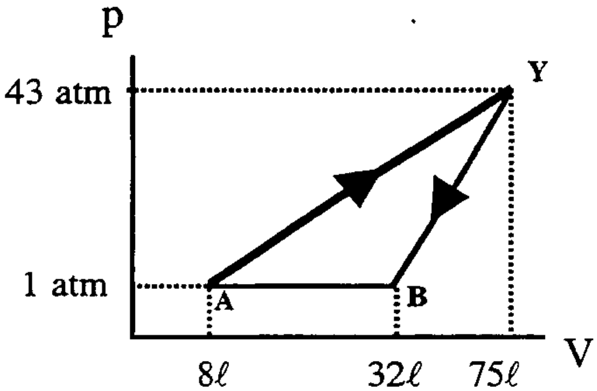
   Now consider a *different* path from A to B, this time via point X. The point X has been chosen so that the process A → X is *adiabatic*, and the process X → B is *isothermal*.



c. Find $\Delta S_{\mathrm{A}\to\mathrm{X}}$ using the basic rule for reversible processes,
   $\Delta S_{\mathrm{A}\to\mathrm{X}} = \int_A^X \frac{dQ}{T}$.
d. Next, find $\Delta S_{\mathrm{X}\to\mathrm{B}}$, again using the basic rule for reversible processes:
   $\Delta S_{\mathrm{X}\to\mathrm{B}} = \int_X^B \frac{dQ}{T}$.
e. Now add your answers for $\Delta S_{\mathrm{A}\to\mathrm{X}}$ and $\Delta S_{\mathrm{X}\to\mathrm{B}}$ to find the total change in entropy $\Delta S_{\mathrm{A}\to\mathrm{X}\to\mathrm{B}}$.

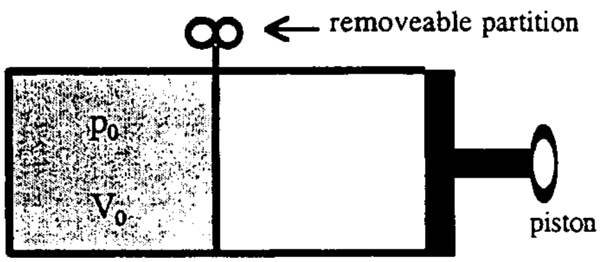
f. How do your answers for $\Delta S_{\mathrm{A}\to\mathrm{B}}$ and $\Delta S_{\mathrm{A}\to\mathrm{X}\to\mathrm{B}}$ compare? Why is this?

Suppose we consider yet another path from A to B, this time via point Y.



g. What is the total change in entropy $\Delta S_{\mathrm{A}\to\mathrm{Y}\to\mathrm{B}}$ for the total path A→Y→B?

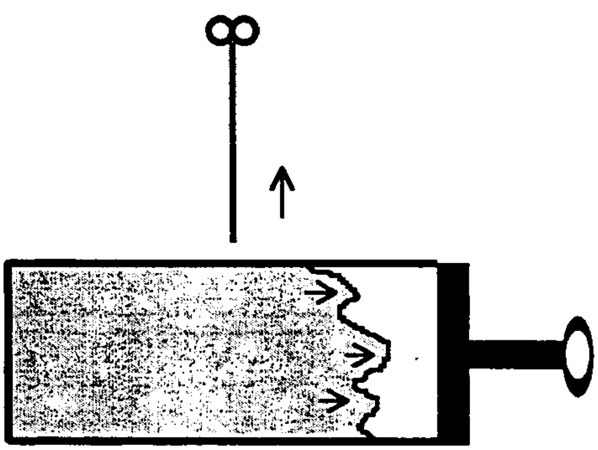
Q6: The device shown below consists of a chamber with volume $2V_0$. This chamber has a removable partition in the middle. (Notice that the right-hand wall of the chamber is actually a piston.)



A

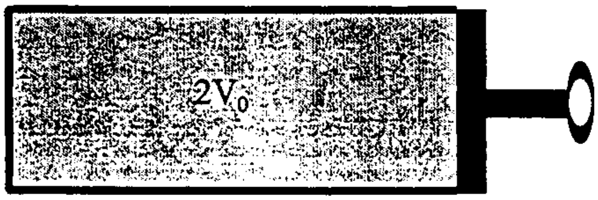
As shown in the figure A above, the partition is initially in place, and an ideal diatomic gas is confined to the left-hand side, occupying volume V_0. The gas is under an initial pressure p_0. Meanwhile, the right-hand side of the chamber is vacuum.

In the first step of the process, the partition is suddenly removed. As a result, the gas expands freely to fill the chamber. This is shown below in figure A→B.



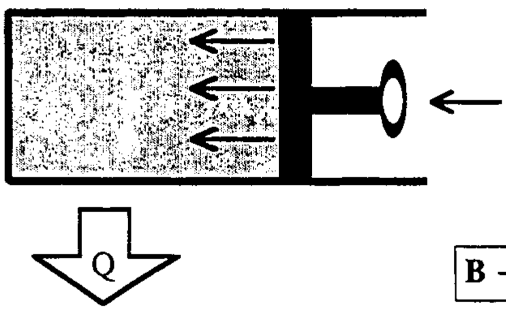
A → B

Soon the gas is once again in equilibrium, but now at volume $2V_0$. This is figure B.



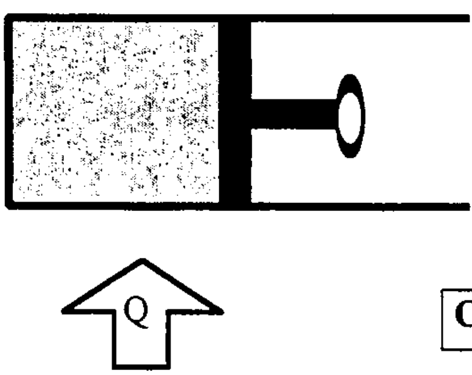
B

As the next step, the piston compresses the gas back down to the original volume V_0, but heat is drawn out of the gas also, so that the pressure remains constant during this process.



B → C

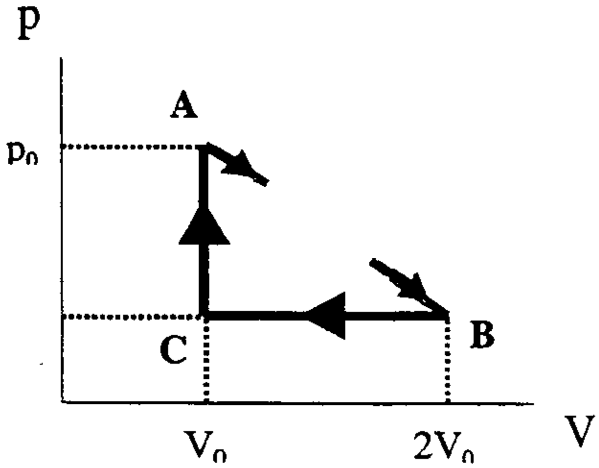
As the third and final step, heat is added to the gas at constant volume, until the pressure returns to the initial value p_0.



C → A

At this point the partition can be re-inserted, and the piston can be drawn back to its initial position. We are now ready to repeat the cycle.

Here is a pV diagram for this cycle.

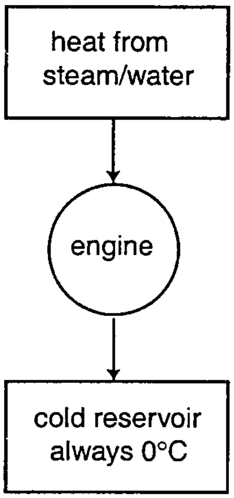


a. Explain why the temperature of the gas at B is the same as the temperature at A.
b. Using this fact, find the pressure at B.
c. Why is this device *not* an engine? (Hint: What can you say about W_{net}?)
d. How much entropy is added to the *gas* during each step? (i.e. find $\Delta S_{\text{A}\to\text{B}}$, $\Delta S_{\text{B}\to\text{C}}$, $\Delta S_{\text{C}\to\text{A}}$ for the gas)
e. What do these entropy changes add up to? Why?
f. How much entropy is added to the *environment* during each step? (i.e. find $\Delta S_{\text{A}\to\text{B}}$, $\Delta S_{\text{B}\to\text{C}}$, $\Delta S_{\text{C}\to\text{A}}$ for the environment)
g. What is $\Delta S_{\text{universe}} = \Delta S_{\text{gas}} + \Delta S_{\text{environment}}$ for the whole cycle?
h. Are these results consistent with your answers for **Q2** above?

Q7: You have 50 kg of steam at 100°C, but no other heat source to maintain it in that condition. You also have a cold reservoir at 0°C that will stay at 0°C at all times.

Suppose you operate a reversible heat engine with this system: the steam condenses and then cools until it reaches 0°C, and the heat released in this process is used to run the engine. (The steam/water itself remains in the upper container at all times.)

[For water: $L_v = 2256 \text{ kJ/kg}$, $c_w = 4190 \text{ J/kg} \cdot \text{C}$]



a. Calculate the total entropy change of the steam as it condenses to water and cools to 0°C.
b. Find the total amount of work that the engine can do. Explain your reasoning in a few sentences, in addition to carrying out any calculations. [Hint: How much heat must the engine expel to the low temperature reservoir?]