The University of Central Arkansas
Department of Physics and Astronomy

Laboratory Manual

PHYS 1410
College Physics I
Spring 2009

Sections
21256: Tuesday
8:00AM—10:40AM
21262: Tuesday
10:50AM—1:30PM

Lab Room:
LSC 114

Instructor:
NJ Austin

Lab Supplies:
hard–bound
quadrille
notebook,
graphing
calculator or
laptop,
PRS InterWrite RF
responder

Text ISBN:
0–13–149579–8

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LABORATORY NOTEBOOK

What type of notebook do I need?
Buy a hardbound, quadrille-ruled lab notebook with sewn-in pages. You must have quadrille pages because you will be using them to make tables and graphs. You must have a hardbound book so that you do not start losing pages partway through the semester. A spiral or glue-bound book with perforated pages will not stand up to the use and abuse.

Where do I get this notebook, and how much does it cost?
They are available at the UCA Bookstore for less than $2. You do not need the super–duper lab notebook with the carbonless duplicate pages.

What goes in my notebook?
Absolutely everything. You should take notes in class in this notebook. You should solve example problems. You should use it to make notes before you come to lab about the topic. You should use it during lab to record and document all that you do. You should use it after lab to complete your calculations and make notes on your sources of error. You should use it to write letters home to your mother thanking her for sending money.
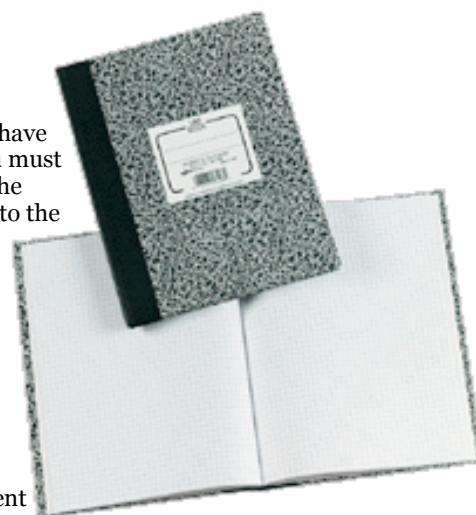
No, really: What goes in my notebook?
Content: meaningful notes, a complete procedure and data set, relevant data reduction, error analysis calculations, and a full explanation of the results obtained.

Organization: this is about how well your book is put together. Data should be labeled (units and uncertainties), calculations should include symbolic formulae, errors should be clearly expressed as relative (%) or absolute (with units), etc.

Let's use this for an example: you are a leading scientist at a cutting edge research university. You have given the task of several critical experiments to your most trusted grad student. Without her results, you cannot publish. If you do not publish, your tenure committee will recommend that you be let go at the end of the academic year. Suddenly and mysteriously, your grad student disappears. She was last seen on a Puerto Peñasco beach during spring break with a bottle of tequila in one hand and her bikini top in the other...

Are you panicked? Should you be? If she has compiled a good notebook, your research project stays right on target. All you have to do is open her book, and you know exactly what she did, how she did it, and what the results were. Any one of your other grad students should be able to pick up her book, and pick up the research right where she left off. There are sketches of the experimental set-ups; descriptions of the methods and instruments used to make measurements; neat data tables with complete labels including units; sample calculations that list the symbolic equation; discussion of possible problems and how they will be addressed in the next experimental trial; and well-documented error analysis. All of this content is recorded neatly, and labeled clearly.

What if my notebook is junk?
If you have to defend your notebook by saying, "Well, it makes sense to me!", then you have not done your job. Your notebook should make sense to anyone who picks it up (who has the same level of subject knowledge--obviously your 4 year old nephew isn't the target audience).

When can I use my notebook?
During lab quizzes: this will be the only resource available to you during lab quizzes; if you can't keep a decent notebook, you only punish yourself. There will be no group quizzes, either, so you cannot rely on your lab partner who can keep an organized notebook. You will either learn to keep a notebook, or keep getting low quiz scores. I can live with either one, but I would prefer you learn to keep a notebook.

You will also be allowed to use your notebook during the problem–solving portion of each exam. This should give you a pretty strong motivation to come to class, take good notes, and solve example problems clearly.

ERROR ANALYSIS REPORT

DATE	LAB ACTIVITY	REPORT DUE
02/03/09	Constant Acceleration	02/19/09
02/17/09	Newton's Laws	03/05/09
02/24/09	Static & Kinetic Friction	03/12/09
03/03/09	Work and Energy	03/19/09
03/17/09	Momentum and Collisions	04/09/09
03/31/09	Centripetal Acceleration	04/16/09
04/07/09	Torque	04/23/09

A sign up sheet will be posted in the lab. You must find a partner and sign up to write an error analysis reports for one of the indicated labs. A maximum of two lab groups per section may sign up for any given lab, on a first-come, first served basis. All of the labs are equivalent, although they obviously do not all stress the same concepts. There are no "easy" or "hard" selections. You may want to choose by due date, in order to work around potential conflicts with due dates in other classes. Once you have made your selection, it is final. Because this is a semester long group effort, you may not change your mind on a whim. Illness or extreme circumstances will be dealt with on an individual basis, and you will be required to provide documentation before changes to the schedule will be made.

Your group will have two weeks to complete the error analysis after you have performed the experiment tin the lab. You should use the format outlined below (same as for Lab 01), and use your practice report as a guide. Use the comments and suggestions provided to give you an idea of what you did adequately the first time and what you need to pay more careful attention to this time. However, you should pay careful attention to any specific guidelines or suggestions specifically included with the lab handout.

Rough Draft

You must complete a draft of the report within the first week, then bring it to discuss with me during office hours. We will go over it together, and I will give you additional feedback to use when finishing up your final draft. I will not pre-grade a report slipped under my door for you to pick up later; you must come in with your group and you should plan to spend about 20 minutes discussing your work. *If you do not come in for a draft discussion, your final report score will reduced by 10%.* If you do not complete the practice report, and fail to bring in a draft for revision, you will not be able to complete this assignment successfully. On the other hand, if you are getting your feedback directly from me, and editing based on my suggestions, you should fully expect to earn a very good score on the assignment. You may bring in more than a single revision for comments; you are free to come in for comments and assistance as many times as it takes up until the due date.

Format

Most formal lab reports follow the same fundamental format, although individual sections may be labeled differently in different contexts. You will not actually be writing a full lab report; you will be concentrating on the data you have collected, and the subsequent reduction and analysis. Your analysis must be typed, with the exception of any sketches, calculations, or graphs. Please do not copy or cut and paste the text of the lab handout into your report. I should not have to tell you that I will immediately recognize text that I have written myself. The sections should be labeled and ordered as follows.

Data

Begin with all of the data collected during the lab. Record all of your measurements neatly, usually in tabular form. Units must be included with each measurement, and uncertainties where appropriate. You must include all data, even if you subsequently determine that it is unnecessary or obviously incorrect.

Reduction

Make the necessary calculations (always show your work and always write down the symbolic formula you are using) or graphs to reduce your data. For example, you may need to transform the raw measurements of distance and time into a velocity. Or you may have a graph that needs to be plotted, then linearly regressed to find a slope and intercept. Graphs may be plotted using whatever software you are familiar with; be warned that if you plot data incorrectly, point penalties are steep. Make sure you know how to use the software (MS Excel is a frequent choice, but it is usually not the best tool for the job; I never use this program to make graphs, so I can't help you out.)

Error Analysis

This is where you make sense of everything. Start by propagating the errors that you have identified and quantified. Each lab will be a little different, and we will discuss methods of error propagation in lab as we encounter them. You will spend time here discussing the effects of random and systematic errors on your results. You will typically need to discuss random and systematic effects separately. A complete discussion (we are into writing paragraphs at this point) will include the source, the size, and the impact of the error on your results, along with suggestions for either eliminating the error entirely, or if it cannot be eliminated, minimizing its effect. There will also be sources of error that you can identify, but cannot quantify. These should be discussed as well.

Conclusions

Tie up any loose ends. Have you adequately accounted for your results? Identify any outstanding issues. Is there is one specific piece of data that defies any effort to explain or account for it? Is there a missing piece of physics that was not measured or taken into account that would explain the results? Do you need to challenge any of the initial conditions or any of the assumptions made going in to the experiment?

ERROR ANALYSIS FOR BEGINNERS

Significant Figures

We will use some simple rules for significant figures. First and most important: just because your calculator will display nine decimal places does not make them all meaningful. Most of the measuring, calculating, and problem solving we will do will be valid to no more than two or three significant digits.

- Leading zeros (0.03) are not significant; they are placeholders. Because you can re-write the number in scientific notation without the zeros (3×10^{-2}), they are not significant digits.
- Trailing zeros are significant. The trailing zero tells you that you could know or measure the number to that decimal place; it just happens to be known or measured to be zero. An object measured with a ruler marked in centimeters can be exactly 3cm long; you would write 3.0cm, though, because the ruler can measure increments of 0.1cm.
- When you add numbers, keep the least number of decimal places in the result.
- When you multiply numbers, keep the least number of sig figs in your result.
- Your final answer should never end up more precise than your original data or measurements.

Precision and Accuracy

Typically, we tend to think that precision and accuracy mean the same thing, and we probably use the words interchangeably. However, they do represent separate and distinct concepts, so we need to have a clear definition for each.

A carpenter building a house needs to be precise to 1/8, or maybe 1/16 of an inch. So a tape measure or T-square marked in inches, subdivided down to an eighth or sixteenth of an inch is an adequate enough tool for him to use. But a machinist milling parts for a jet engine will need a more precise measuring tool—something that can measure much smaller increments, down to a thousandth or even a ten-thousandth of an inch. The carpenter's ruler simply isn't going to be useful to him. However, just because the carpenter's ruler is less precise than the machinist's micrometer does not automatically mean that the machinist is more accurate!

While precision is an inherent property of a measuring instrument, accuracy is related to the use of that tool. A machinist with a very precise micrometer can still make an inaccurate measurement—what if he has aligned the tool improperly, or read the dial incorrectly, or done something otherwise careless? The carpenter, using a less precise tool may be more accurate, if he is using his instrument properly and making his measurement carefully.

In a scientific context, accuracy represents how close a measurement is to a known value. This can be quantified as a percent error. The precision of an experiment is a measurement of its reproducibility. Calculating a percent difference can be a relevant way to quantify the precision of your experimental results. It may seem paradoxical, but a measurement can be precise without being accurate, or accurate without being precise. Examples will abound as the semester progresses.
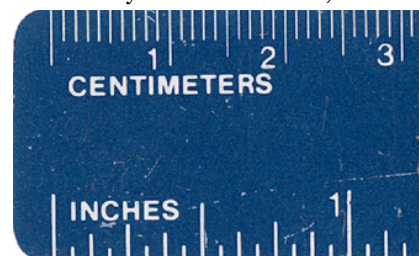
Notice that the precision of the ruler shown depends on whether one uses the inch or centimeter scale to measure.

Experimental Error

Every experiment will have errors associated with it. This does not automatically mean that someone has done something wrong (although someone *may* have done something wrong). For simplicity, we will separate random, systematic, and personal errors.

Random Error

Every measuring tool will have an uncertainty associated with it. This will always be defined as

$$\delta = \pm \tfrac{1}{2}\left(smallest\ division\right)$$

The uncertainty will have the same units as the measurement. For example, the meter stick is marked in increments of 0.1cm. The associated uncertainty, then, of every measurement made with the meter stick will be ±0.05cm. This is because it is reasonable to assume that a careful measurer will not be off by more than half a tick: the object to be measured does not line up exactly with a tick mark on the ruler, so the measurer must decide if the object lies closer to one tick or the other. The worst-case scenario is that the object lies exactly halfway between the ticks, and whether the measurer calls it high or low, the measurement is exactly half a tick off. This uncertainty is considered random because there is no way to know in advance if a measurement will be recorded slightly small or slightly large.

Notice that when a measurer must decide to call a measurement to the nearest tick, he or she is not making a mistake. There is no possibility of a measuring tool that is infinitely precise, and the resulting uncertainty is not in any way the fault of the user. Every measurement made by any instrument will have an uncertainty; *this is not an example of "human error."*

Random error can also occur as a result of the object being measured. For example, if the object has a rough or irregular edge, two measurements of length might be slightly different because the object itself is slightly longer or shorter at a different position. Again, this is *not* the fault of the experimenter, and is *not* an example of "human error."

Because random errors are, well, *random*, it is equally likely that a measurement will be high as low. Multiple measurements, then will have the effect of "canceling" the errors on average. That is, the average value of multiple measurements will be more accurate than any single instance. Two things to remember: first, the *actual* error or uncertainty associated with any given measurement *cannot* be eliminated. It is what it is. Secondly, the effect of the random error is only reduced by taking large

quantities of data. The more data collected, the better the chance for each high value to cancel a low. Realistically, there is never enough time to collect an infinite data set. But you should *always* collect as much data as time permits.

Systematic Error

A systematic error an be related to the tools or the technique of measurement. For an error to be systematic, it must affect every piece of data in the same way. As one example: some rulers are marked with an offset scale. This means that an object must be aligned with the zero on the scale of the ruler, not the end of the ruler itself. If a person made a complete set of measurements using the ruler aligned with the edge, then every single measurement would be recorded too short. Too short, and by the same amount (the distance from the edge of the ruler to the zero). This may seem unlikely, but it is possible (trust me). Another example: a fast-running clock. Every interval of time measured would be recorded as a longer period than it actually was.

Because the effect is uniform, it can often be difficult to spot a systematic error. In some cases, you may be able to remove a systematic error by correcting a method (re–measure and align the ruler properly). However, some systematic errors may be impractical or impossible to remove. You may not have access to a different measuring instrument, or an alternative technique may be so time-consuming that it cannot be implemented in the available lab time. As a result, you have to be prepared to analyze the systematic error and decide if it really matters: Can you still extract the relevant value from your data even with the error present? Can you process the data in a way that makes the systematic error moot (i.e., a relative instead of an absolute comparison).

Personal Error

This is the category in which somebody really *did* make a mistake. This list can be endless, but a few items bear a special mention. Passive acceptance can be a frustrating problem. When your lab partner hands you a AA battery and says, "I measured the diameter and it's 15cm." You think that seems a little big, but you don't want to open your mouth and maybe offend your lab partner, so you just shrug and write it down. After all the data is recorded, you plot a graph and the resulting nonsense makes you realize that your lab partner really does not know how to read a ruler, and *every single measurement is utterly wrong*...now you have to start over, and just about everybody else has already finished up and left the lab. You should also take care against personal bias, in which you assume that you know what the results will be. This can make you careless and insensitive to subtleties that you are not expecting to see. It can also make you dismissive of data you think is "wrong," when it may well be correct, but simply not what you expected to see.

Personal errors may affect your data randomly or systematically. However, because these are the "uh-oh" kinds of errors, you should *always* be double-checking both your measurements and your calculations. You should never leave the lab with junk results that you cannot explain.

Calculating Errors

A percent error is used to compare a measurement or result to what is considered the known or accepted value:

$$\%error = \frac{(accepted - experimental)}{accepted} \times 100\%$$

A percent difference is used to compare two values or measurements, of which neither is assumed to be "correct:"

$$\%difference = \frac{(value_1 - value_2)}{\left(\frac{value_1 + value_2}{2}\right)} \times 100\%$$

Whenever you make a measurement, you should record the uncertainty based on the instrument. If you repeat a measurement multiple times, you should calculate the average value (you know how to take an average):

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

The uncertainty associated with this average value can be either the known uncertainty of the measuring instrument, or something else. If the variation of the values is small–smaller than the known uncertainty–then you should use this as the experimental uncertainty. If the values vary by more than you would expect due to the measuring uncertainty, then you should calculate the standard deviation, and use this as the experimental uncertainty:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

When it is necessary to combine measurements, we will follow two pretty simple rules for error propagation:

▸ When adding or subtracting values, add the absolute uncertainties.

▸ When multiplying or dividing values, add the relative uncertainties.

Let's see how this works with an example. Using a ruler, you measure the dimensions of your calculator.

$l = 12.5$cm

$w = 7.8$cm
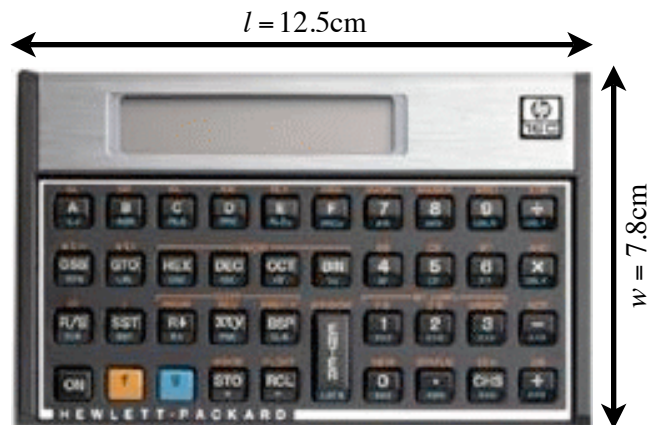
It is 12.5cm long, 7.8cm wide, and 1.2cm thick. Because each of the measurements was made with the ruler, the uncertainty associated with each is the same, ±0.05cm. Express the dimensions as follows:

$$l \pm \delta l = \left(12.5 \pm 0.05\right)\text{cm}$$

$$w \pm \delta w = \left(7.8 \pm 0.05\right)\text{cm}$$

$$h \pm \delta h = \left(1.2 \pm 0.05\right)\text{cm}$$

A calculation of the perimeter of the object requires the addition of values:

$$p = l + l + w + w$$

$$p = \left(l \pm \delta l\right) + \left(l \pm \delta l\right) + \left(w \pm \delta w\right) + \left(w \pm \delta w\right)$$

$$p = 2\left(l + w\right) \pm \left(\delta l + \delta l + \delta w + \delta w\right)$$

$$p = 2\left(12.5 + 7.8\right)\text{cm} \pm 4\left(0.05\right)\text{cm}$$

$$p = \left(40.6 \pm 0.2\right)\text{cm}$$

Determining the area of the object requires the multiplication of values:

$$A = l \times w$$

$$A = \left(12.5\text{cm}\right)\left(7.8\text{cm}\right) = 97.5\text{cm}^2$$

Notice that, because the units on area = cm², you cannot simply add the absolute uncertainties as in the previous example. The relative error, or percent uncertainty will be used:

$$\delta_{\%} l = \left(\frac{\delta l}{l}\right) \times 100\% = \left(\frac{0.05\text{cm}}{12.5\text{cm}}\right) \times 100\% = 0.4\%$$

$$\delta_{\%} w = \left(\frac{\delta w}{w}\right) \times 100\% = \left(\frac{0.05\text{cm}}{7.8\text{cm}}\right) \times 100\% = 0.6\%$$

Notice that the relative uncertainty is a comparison (ratio): you are comparing the uncertainty to the value itself. So, while both measurements have the same absolute uncertainty, they do not have the same relative error. The % error on the width is greater, because the error is a larger fraction of the total value.

To find the uncertainty in the area, add the relative uncertainties:

$$\delta_{\%} A = \delta_{\%} l + \delta_{\%} w$$

$$\delta_{\%} A = 0.4\% + 0.6\% = 1.0\%$$

So, the result for the area has a 1.0% uncertainty associated with it. But how much absolute error?

$$\delta A = \left(\delta_{\%} A\right) A$$

$$\delta A = \left(0.01\right)A = \left(0.01\right)\left(97.5\text{cm}^2\right) = 0.975\text{cm}^2$$

But now consider the sig figs: it is customary to express the uncertainty with one significant figure, unless it has a leading 1. In that case, you should retain the second digit as well. The absolute uncertainty must be rounded:

$$A = \left(97.5 \pm 1.0\right)\text{cm}^2$$

There are more complex methods for error propagation, but these basic rules will serve perfectly adequately for our lab work. For further assistance and self-study, consult the references below.

References

Loktik, Oleg "Error Analysis Tutorial" From *Physics Laboratory Tutorial*.
http://phys.columbia.edu/~tutorial/index.html

Simanek, Dr. Donald E. "Error Analysis (Non–Calculus)"
http://www.lhup.edu/~dsimanek/errors.htm

LABPRO & LOGGERPRO 3.3 REFERENCE

Motion Detector Setup
▸ Make sure that the LabPro interface is connected to a USB port of the computer and is under power.
▸ Connect the Motion Detector (MD) to the Digital Channel DIG/SONIC 1 of the LabPro interface.
▸ If you are using a second MD connect it to the Digital Channel DIG/SONIC 2 of the LabPro interface.
▸ Click on the Logger Pro 3.3 icon on the desktop to run the software.
▸ LoggerPro should automatically detect the MD connected to the LabPro interface and display the icon below the toolbar. If not, click on *Experiment→Set Up Sensors→Auto Detect Sensors*.
▸ The LoggerPro screen will display a window displaying an empty data table, and two windows displaying empty *Position vs. Time* and *Velocity vs. Time* graphs.

To change the Data Collection Time and/or the Sampling Rate
▸ On the main menu, click *Experiment→Data Collection*.
▸ To set the Data Collection time, edit the *Length* cell.
▸ To set the *Sampling Rate*, use the slider or type in the value.
▸ Click *Done*.

To set the room temperature for calibrating the MD
▸ Click on the MD icon below the toolbar.
▸ Click on the icon in the DIG/SONIC 1 box. Go to *Set Temperature…* and enter the room temperature.
▸ Repeat the process for the second MD, if connected.

Dual–Range Force Sensor Setup
▸ Make sure that the LabPro interface is connected to a USB port of the computer and is under power.
▸ Connect the Dual-Range Force Sensor (DRFS) to the analog channel CH 1 of the LabPro interface.
▸ If you are using a second DRFS, connect it to the analog channel CH 2 of the LabPro interface.
▸ Click on the LoggerPro 3.3 icon on the desktop to run the software.
▸ LoggerPro should automatically detect the DRFS connected to the LabPro interface and display the icon below the toolbar. If not, click on *Experiment→Set Up Sensors→Auto Detect Sensors*.
▸ The LoggerPro screen will display a window displaying an empty data table, and one window displaying an empty *Force vs. Time* plot.

Using LabPro Remotely
1. Set up LabPro for remote data collection.
   a) Put fresh batteries in the LabPro.
   b) Set up the sensors, LabPro, and Logger Pro just as you normally would to collect data in Time Based mode.
   c) Instead of clicking the green "GO" button, choose *Remote→Remote Setup* from the Experiment menu. A summary of your setup will be displayed.
   d) Click "OK" to prepare the LabPro.
   e) Disconnect the LabPro from the computer.
   f) If it has not already been saved, save the experiment file so it can be used later to retrieve the data from LabPro.
2. Collect data.
   a) When you are ready to collect data, press the START/STOP button.
   b) When data collection is complete, the yellow LED will flash briefly. You can also stop data collection early by pressing the START/STOP button before data collection is finished.
3. Retrieve the data.
   a) Start Logger Pro if it is not already running. Choose "Continue Without Interface" in the Connect LabPro dialog and click "OK."
   b) Open the experiment file used to set up LabPro.
   c) Attach LabPro to the computer.
   d) If a "Remote Data Available" window appears, click the "YES" button. Click, "OK" which accepts the default to retrieve remote data into the current file. If a window does not appear when the interface is reconnected, choose *Remote→Retrieve→Remote Data* from the Experiment menu and follow the on-screen instructions.
   e) The data will be retrieved.

Using LoggerPro
This software records your data from the LabPro and graphs the results. It is mostly intuitive to use (what do you want to change? Click right on it). You can graph data collected directly using the LabPro, but you can also enter in data manually. Occasionally, we may want to reduce or process our raw data before graphing it. The LoggerPro data table is not a spreadsheet, and does not let you use formulas to process data. You can, however, create an Excel spreadsheet in which you perform any necessary calculations, then copy/paste the final data from Excel to a LoggerPro table. If you are unused to using

a Mac, please do not waste anyone's time complaining about how much you hate Macs; learn how to **ctrl-click** instead of right-click and get on with it.

SO YOU WANT TO	THEN YOU SHOULD	AND YOU OUGHT TO KNOW
Remove the Data Table window	Ctrl-click on the data table and choose **Delete**	Make sure you do not choose **Delete Cells**. This will only delete a particular column and not the entire table.
Insert the Data Table window	Main menu bar click **Insert→Table**	
Remove a specific graph window	Highlight the graph window, ctrl-click and choose **Delete**	
Insert a graph window	Main menu bar click **Insert→Graph**	
Automatically reorganize and rearrange your LoggerPro screen	Main menu bar click **Page→AutoArrange**	
Change the variable plotted on the y-axis of a graph	Click on the y-axis label and choose from the pop-up that appears	Double-click on either axis to open the **Graph Options** window
Change the variable plotted on the x-axis of a graph	Click on the x-axis label and choose from the pop-up that appears	
Group plots with a common x-axis	Select all graphs to be grouped by clicking **Edit→Select All**. Next choose **Page→Group Graphs**	Learn keyboard shortcuts! ⌘A selects all ⌘G groups graphs
Autoscale a plot or group of plots	Click on specific graph to select or ⌘A to select all. Click **Analyze→Autoscale→Autoscale**	⌘U or click on the toolbar icon
Zoom in on a portion of a plot	Click and drag to highlight desired area. Click zoom icon on toolbar	The toolbar is attached to the worksheet window
Manually scale either axis of a plot or group of plots	Grab the axis with a click and hold. Slide to adjust the scale	Double-click on either axis to open the **Graph Options** window
Examine points on a graph	Click on toolbar icon	⌘E
Fit data or portion of data with linear equation	Click and drag to select desired data. Click toolbar icon	Main menu bar click **Analyze→LinearF Fit**
Fit data or portion of data with a non-linear equation	Main menu bar click **Analyze→Curve Fit...**	Click toolbar icon
Store the latest data set	Main menu bar click **Experiment→Store Latest Run**	⌘L
Hide a data set	Main menu bar click **Data→Hide Data Set**	Do not hide the Latest Run!!
Re-display a hidden data set	Main menu bar click **Data→Show Data Set**	Hide, Show, and Delete will let you choose which specific data set you want
Delete a data set	Main menu bar click **Data→Delete Data Set**	
Delete **all** data sets	Main menu bar click **Data→Clear All Data**	This gets rid of **everything**!

LAB 01: CIRCUMFERENCE AND DIAMETER

The Objectives

The purpose of this exercise is simply to get some practice with the techniques of writing an error analysis report. To this end, we will be performing a simple experiment, and paying close attention to how we document what we have done. As a bonus, we get to practice some important analytical skills: graphing data and linear regression.

This experiment is pretty simple, and you should already know the answer. Every scientific experiment starts with a question to be answered or an hypothesis to be tested. In this case, the questions is:

What is the relationship between the circumference and the diameter of a circle?

This is a good question to explore, because we can easily test what we think the answer is. The specific objectives are:

▶ Make accurate, precise, and repeatable measurements using a meter stick and vernier calipers

▶ Make detailed notes on your experimental procedure

▶ Record data neatly, completely, and accurately in your lab notebook

▶ Use *LoggerPro* to construct a graph with correctly labeled and accurately scaled axes

▶ Understand the relevance of a correlation coefficient to a series of linear data

▶ Identify sources of random error and calculate a relative (%) error

▶ Identify sources of systematic error and explain their effect on the results

The Procedure

Measure and record the diameter and the circumference of several cylindrical objects of varying size. You should collect a minimum of ten data pairs from differently sized objects. Document your measuring methods in your notebook.

The Data

Record your measurements in a neat table in your notebook. Label your data with units, and include the uncertainties based on the measuring tool used.

The Reduction

Graph your data. Plot **diameter** on the **x–axis**, **circumference** on the **y–axis**. Use the *LoggerPro* software on the computer (*MS Excel* is also available on the computers, but this is rarely the best choice for scientific graphing). Manuals and instructions for using the *LoggerPro* software are located in the lab.

The Analysis

Error Propagation: Let the *LoggerPro* perform a linear regression on your data. Make sure that you record the equation of the best–fit line in your notebook. When your graph is complete, you may print a copy to attach in your notebook. We can also compare our slope to the expected value (π). Calculate the percent error in your slope (m):

$$\%error = \left[\frac{\pi - m}{\pi}\right] \times 100\%$$

Random Error: Identify the sources of random error that you have quantified. Discuss whether your results have been compromised by these errors, and how you could either eliminate or minimize the effect of these errors. Use the value of the correlation coefficient (r^2) to support your arguments.

Systematic Error: Identify possible sources of systematic error, and where systematic error shows up in your results. Determine whether there is a genuine systematic effect on your data (the correlation coefficient can be useful here as well). Discuss methods for removing or reducing systematic error.

The Conclusions

Unless something went horribly wrong, you should not have anything outstanding to discuss here; comment on whether your experiment concluded successfully. Does your slope correlate with the known value, to within your ability to measure it? Do you have any suggestions for improving the quality of the data, or the accuracy of the results?

You should make sure that you have documented your activities fully in your lab notebook, as you will be quizzed over this experiment next week. You will be allowed to use your notebook as a resource when you take the quiz.

A sample report for this experiment has been posted on the course web. When you are ready to write your formal report later in the semester, you should use this report as an example of appropriate format and content.

References

Gaspar, Joaquim Alves "Using the Vernier Caliper" From Wikimedia Commons. http://commons.wikimedia.org/wiki/Image:Using_the_caliper_new_en.gif

Weisstein, Eric W. "Correlation Coefficient." From *MathWorld—A Wolfram Web Resource.* http://mathworld.wolfram.com/CorrelationCoefficient.html

# LAB 02: VECTOR ARITHMETIC

The Objectives

Because so many of the physical quantities with which we will be concerned this semester are vectors, it is critically important for us to begin to understand how vectors are different from scalars, and how to mathematically manipulate these vectors. Just like any regular numbers, vectors can be added, subtracted, multiplied, or divided. While we are very comfortable doing these arithmetic operations in general, we need some dedicated practice to get good at doing vector math. Because a vector has both magnitude and direction, the processes are a little different than we are used to. Not difficult, just different.

Initially, we will focus on the methods for adding and subtracting vectors. There are several methods, which is convenient, because it will allow us to check what we have done for correctness. Specifically, we will:

▸ Construct accurately scaled vector diagrams
▸ Add vectors using geometric methods
▸ Resolve two-dimensional vectors into rectangular (cartesian) components
▸ Use cartesian components to add vectors arithmetically
▸ Observe the condition for static equilibrium: $\sum \mathbf{F} = 0$

Equilibrium when ring is centered

Pulley position = direction (degrees)

Hanging mass = magnitude (grams)

Leveling screw

The Procedure

4. Level the force table (if necessary) by adjusting the leveling screws on the feet of the table.
5. The **magnitude** of each vector will be the quantity of mass (in grams) hanging from the string.
6. The direction of each vector is specified by the angle (in degrees) at which the pulley is fixed to the table.
7. The table is balanced ($\sum \mathbf{F} = 0$) when the center ring is centered over the pin at the middle of the table.
8. There are four pulleys. If you are setting up and solving a problem involving fewer than four vectors, you should remove the unnecessary pulley. You must leave all the strings attached to the center rings, however. Coil up any unused string and keep them on the table, but out of the way of the vectors you are working with.
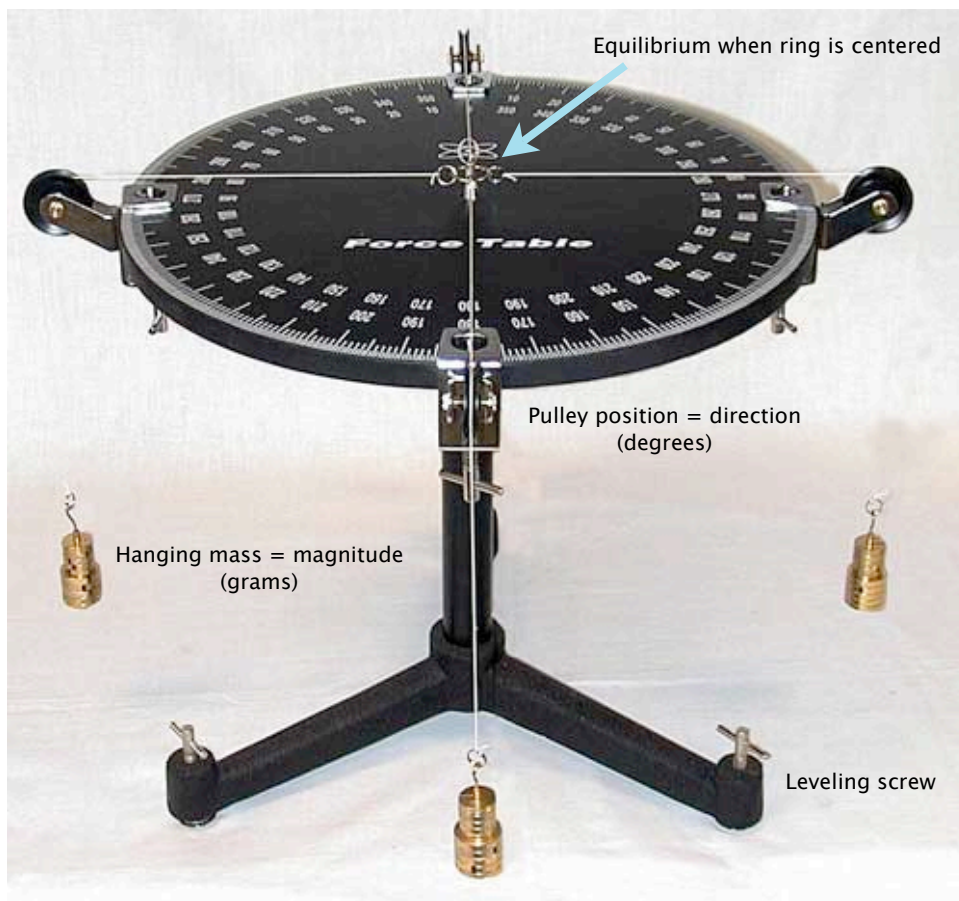
The Data

You will set up and solve several vector addition problems on the table. For each problem, record the following information:

VECTOR	MAGNITUDE (g)	DIRECTION (°)	X—COMPONENT	Y—COMPONENT
A	A	θ_A	A_x	A_y
B	B	θ_B	B_x	B_y
C	C	θ_C	C_x	C_y
R = A + B	R	θ	R_x	R_y

Obviously, if you are adding more than two vectors, you will need additional space on your table. In this example, the vector C is the vector you establish experimentally to balance the table after setting vectors A and B as instructed below. Each problem that you set up will have the form A + B + C = 0, because you are establishing equilibrium in each case. The vector resultant R, then, will be the vector having the same magnitude, but opposite direction as C:

$$\vec{R} = -\vec{C}$$

This means that the direction angle associated with vector R must be adjusted from what you read on the force table:
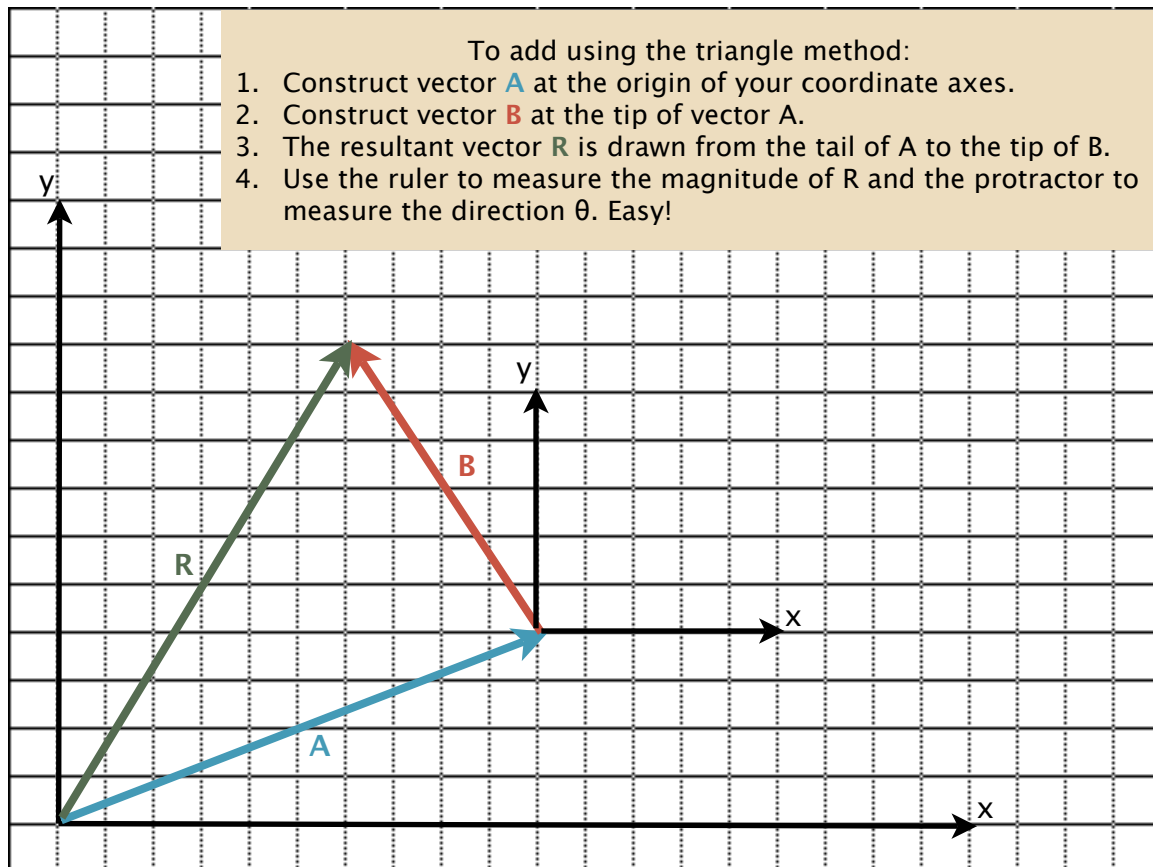
$$\theta = \theta_C + 180°$$

Solve the following vector problems using the force table, then the component and geometric methods:

PROBLEM	VECTOR A	VECTOR B	VECTOR C	RESULTANT
1	100g, 0°	250g, 70°		**R = A + B**
2	150g, 45°	250g, 220°		**R = A + B**
3	200g, 330°	150g, 60°	100g, 135°	**R = A + B + C**
4	250g, 115°	100g, 230°	200g, 315°	**R = A + B + C**

The Data Reduction and Analysis

To resolve vectors **A** and **B** into rectangular components, you must use right-triangle trigonometry. If necessary, you should sketch the triangles in your notebook to insure that you completely understand the idea, and that you are perfectly clear about when to use a sine function and when to use cosine. The actual addition is very simple: keep the x-components together, keep the y-components together. Never mix, never worry. You will also be using the Pythagorean theorem to convert the resultant components R_x and R_y back into a vector expressed as magnitude and direction.

A	B	R	R
$A_x = A\cos\theta_A$	$B_x = B\cos\theta_B$	$R_x = A_x + B_x$	$R = \sqrt{R_x^2 + R_y^2}$
$A_y = A\sin\theta_A$	$B_y = B\sin\theta_B$	$R_y = A_y + B_y$	$\theta = \tan^{-1}\left(\dfrac{R_y}{R_x}\right)$

To add using the triangle method:
1. Construct vector **A** at the origin of your coordinate axes.
2. Construct vector **B** at the tip of vector A.
3. The resultant vector **R** is drawn from the tail of A to the tip of B.
4. Use the ruler to measure the magnitude of R and the protractor to measure the direction θ. Easy!

Once you have recorded the data from the balanced force table, you should construct an accurately scaled diagram of the problem, and complete a geometric solution. An accurately scaled diagram will permit you to read the solution directly from the paper, using your ruler and protractor, without having to calculate anything. You should consult Section 3.2 of your textbook (pages 73–80) for additional diagrams and example problems to illustrate these methods.

The Conclusions

Compare the results of adding the vectors componentwise to the results from the force table and the geometric results. You probably do not have exactly the same resultant vectors in each case. Why? Where does the uncertainty in this experiment lie?

LAB 03: CONSTANT ACCELERATION

The Objectives

The purpose of this exercise is to observe and analyze one-dimensional motion with constant acceleration:

What is the acceleration of an object in free fall?

Some specific objectives:

▶ Observe motion with a constant acceleration
▶ Use the LoggerPro to measure and record motion data accurately
▶ Relate the kinematic equations for constant acceleration to their graphical representation
▶ Prepare detailed graphs, and use them to determine the acceleration of the object
▶ Determine the accuracy of the results by calculating a standard deviation and a percent error

The Procedure

The acceleration of an object is free fall is the acceleration due to gravity:

$$\vec{a} = \vec{g} = 9.8 \tfrac{\text{m}}{\text{s}^2} \downarrow$$

We will measure this directly by releasing an object from rest and recording its position as a function of time. It can also be shown that the acceleration of an object moving down (or up) an inclined plane is directly the result of gravity as well. By measuring the position as a function of time

$$a_x = g\sin\theta$$
$$a_y = g\cos\theta$$

of an object released from rest on an incline, we will have a second method for verifying the value of **g**.

Specifically, we will be using the Motion Sensors attached to the LoggerPro (connected to the computer) to automate the data collection. There are several general techniques that we will always use with the motion sensors:

▶ The LoggerPro software should automatically detect the motion sensor.
▶ The object must be at least 40cm (about 16 inches) from the sensor for accurate data to be recorded.
▶ The sensors are, well, *sensitive*. They will pick up extraneous motion. You will have to practice releasing objects in order get a clean release.
▶ You may adjust the length of the Data Collection interval to suit the actual trial, but you should not set the collection rate to more than 30 data per second. A higher collection rate will not be accurate.

Position the basketball under the sensor and release it from rest. Coordinate with your lab partners so that you do not release before the data collection has begun. Allow the basketball to bounce untouched until the collection interval expires.

Position the motion sensor at the end of the track, and stabilize the track on an incline. Record the incline angle. Release the ball from rest at the top of the incline, making sure to stop the ball before it strikes the sensor. When you have good data, save it and repeat, except this time start with the ball near the bottom of the incline. Give it a push to start it rolling up the incline, then stop it when it comes back down (before it strikes the sensor!) Re-position the incline to a different angle and repeat the experiment for three different angles of incline.

The Data

After you have completed several trials, and are confident that you can perform a clean release, you should start keeping your data sets. You may save your LoggerPro worksheet on the hard drive, using the appropriate Desktop→PHYS1410→Section# folder for your file. Your raw data consists of the tables of position and time values. The remaining columns are calculated values, and therefore part of the data reduction (and the graphs are part of the analysis).

You should have data for both experiments in the same file, so you should name the data sets to distinguish between them. You should have three separate data sets for the three distinct incline angles you tested.

The Reduction

Because the velocity values are calculated and the velocity vs. time graph is automatically generated for you, there are no required calculations of velocity.

Use your v vs t graph to find the acceleration of the ball in free fall. Since acceleration is constant,

$$a = \frac{\Delta v}{\Delta t}$$
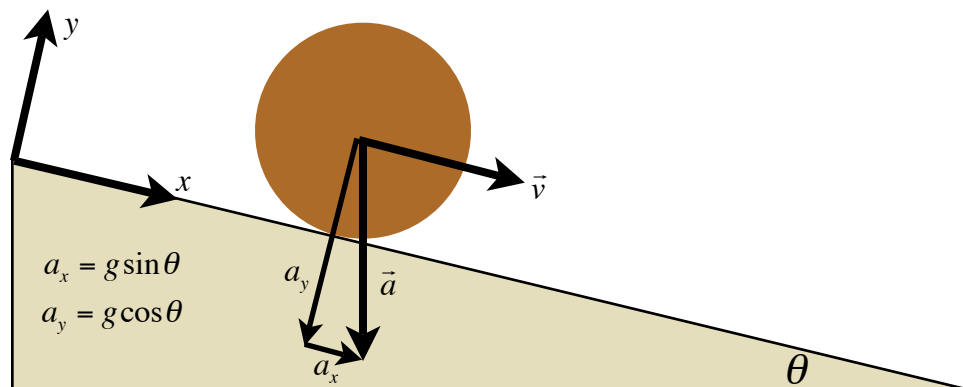
which is the slope of your v vs t curve. If your data includes several bounces, you should find the acceleration of each. Record each of these individual values. This means that you will highlight and curve fit only a selected portion of your data, then highlight and fit the next portion, until you have fit each of the segments.

For the ball on the ramp, your graph will probably be a little messier to look at. By comparing the x vs t graph to the v vs t graph, you should be able to identify the time interval over which the ball was accelerating down the ramp. Find the slope of this portion of the graph, and record it. This is the acceleration in the x-direction, a_x. The value for g can then be calculated:

$$g = \frac{a_x}{\sin\theta},$$

where θ is the angle of the incline you previously recorded. Find the acceleration of the ball and value of g for each of the inclines you tested.

The Analysis
Calculate an average value for g based on the values you obtained for each individual trial. The experimental uncertainty of this average value must be found by calculating the standard deviation:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(g_i - \overline{g}\right)^2}$$

where g_i is each individual value, and $\overline{g}$ is the average value.

Compare your average to the known value of g, and calculate your percent error.

The Conclusions
You should think about and answer these questions in your notebook as preparation for your quiz next week:

1. For the free–falling basketball, what is the shape of the position vs time graph? Relate this to the kinematic equation for position as a function of time.
2. Explain how you would know, without having observed the experiment, that the basketball had bounced. What do your graphs have to tell you about this?
3. What would your graphs look like if you had started by throwing the ball up and letting it fall back down, instead of just letting it drop from rest?
4. Why is the slope of the v vs t graph negative for the ball, regardless of whether it was rolling up or down the incline?
5. Do you get a more accurate result with the freely falling ball, or with the ball on the incline? Can you think of any reason why one technique might be more accurate than the other?
6. How could you improve the results of the incline experiment?
7. Why do we need to use the standard deviation to find the uncertainty in our result?

LAB 04: NEWTON'S LAWS

The Objectives

This week, we want to explore Newton's laws of motion. Some specific objectives:

▸ Measure and record motion data accurately
▸ Analyze motion in the context of applied forces
▸ Identify the forces acting on the system, and the forces acting on specific elements of the system
▸ Prepare free-body diagrams to predict experimental results
▸ Graphically determine the relationship between applied force and acceleration
▸ Compare the predicted and actual accelerations to determine which sources of error have the greatest impact on the results
▸ Examine the systematic effects of errors caused by an incorrect or incomplete set of premises or initial conditions

The Procedure

The experimental set up is a basic Atwood's machine. When the system is released from rest, the hanger (m) will be pulled down by gravity. Because it is attached to the cart (M), wherever m goes, M has to follow. The acceleration of the system will be determined using the motion sensor equipment. The sensor will record position as a function of time, from which we know we can determine the acceleration by finding the slope of the velocity vs time plot.

You will perform multiple trials in which you gradually transfer masses from the cart to the hanger. The total system mass (m + M) will remain constant, but its distribution will change as M decreases and m increases. You should perform a few practice runs, then make sure to save your data runs as you transfer mass from M to m.

The Data

Your raw data consists of the position vs time data for each trial. Make sure that you have noted how much mass is located at both M and m for each trial you run. Save the individual trials, save the data file in the appropriate folder on the computer.

The Analysis

1. Carefully draw a free–body equation for each mass. Use these force diagrams to write Newton #2 for each mass, in terms of the forces you have identified. Solve to predict the system acceleration. Calculate the **predicted acceleration** for each trial, and record it.
2. For each trial, the slope of the velocity vs time graph is the system acceleration. Fit a best line, and record the slope. This is the **experimental acceleration** for each trial. How well do these values match the predictions?
3. Your free body analysis of the problem indicates that, if Newton #2 is correct, your combined trials should prove it:
$$F = (m + M)a$$
$$y = mx$$
corresponds to
Prepare a graph of your results with **F** on the **y–axis** and **experimental average acceleration** on the **x–axis**. Your free–body equations show that the force causing the entire system to accelerate is gravity pulling on the hanger:
$$F = mg$$
4. Determine the **slope** of the best–fit line and its **y–intercept**.
5. Compare the total system mass (m + M) to the experimental value of your slope:
$$\%error = \left[\frac{(m + M) - slope}{(m + M)} \right] \bullet 100$$
6. Identify sources of random error, and whether you can quantify them or not. Are your results seriously compromised by random error? How do you know?
7. Is your analysis of the forces complete? If not, what is missing? How significant is this oversight? How does this affect the relationship between your actual and predicted accelerations? Random or systematic effect?
8. Is your assumption of $v_o = 0$ valid? If $v_o \neq 0$, what is the impact? Does this show up in your actual or predicted acceleration? Explain exactly how this could happen, and exactly what the consequence of this would be. How can you use your graph to determine whether a missing force or non–zero v_o is the culprit?

The Conclusions

Comment on whether your experiment concluded successfully. If you have not already, suggest how the procedure or prediction could be modified to bring the actual and predicted accelerations into closer correlation.

LAB 05: STATIC AND KINETIC FRICTION

The Objectives

This week, we want to further explore Newton's laws of motion. Our previous analysis indicated to us that we needed to consider the effect of kinetic friction on our moving cart. Using a set up similar to last week's, we will be able to answer the question: *What are the coefficients of static and kinetic friction between a pair of surfaces?*

Some specific objectives:

▶ Incorporate the direct measurement of force into our automated data collection
▶ Continue the analysis of motion in the context of applied forces
▶ Identify the forces acting on the system, and the forces acting on specific elements of the system
▶ Prepare free-body diagrams to predict experimental results
▶ Graphically determine the coefficients of static and kinetic friction for a pair of surfaces
▶ Examine any random or systematic effects on the results
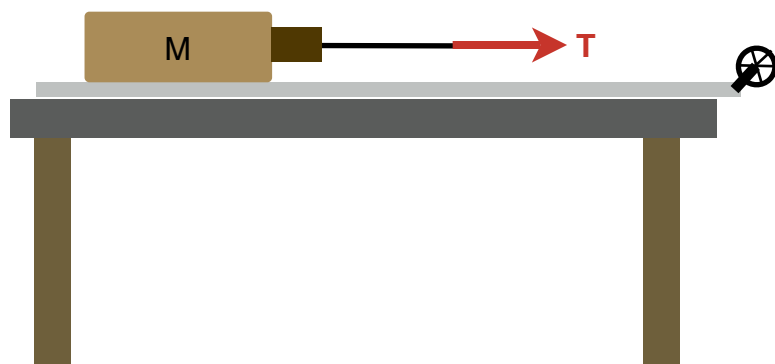
The Procedure

The experimental set up is similar to the Newton's Law set-up from last week. However, initially, we will not be using a hanging mass to pull our cart. To measure the coefficient of static friction, attach the force sensor to the front of the cart, and tie a length of cord to the sensor. The sensor will then record the applied force, which will be the tension in the cord. By slowly increasing the amount of applied force until the cart begins to move, the maximum static friction can be measured directly. The maximum amount of static friction will occur just at the instant before the cart begins to move.

For a given cart mass M, you should repeat the trial several times, recording at least five values for T_{max}. You will perform multiple trials in which you gradually add mass to the cart. You should have at least **four different cart masses**, with **five trials** at each mass.

To measure the coefficient of kinetic friction, set the motion sensor on the track, just as we did last time. You will be recording position and force simultaneously with each trial. This week, we are not concerned with keeping the system mass constant. You will be adding mass to the cart, and the force sensor will be recording the value of the tension in the cord.

When the system is released from rest, the cart should experience constant acceleration as it moves down the track. This acceleration and the measured tension will be used to determine the coefficient of friction.

You should add mass to the cart in 0.500kg increments, and repeat. You may have to add mass to the hanger to insure that the system will move when released. Keep track of how much mass you hang, even though we will not be using the value directly.
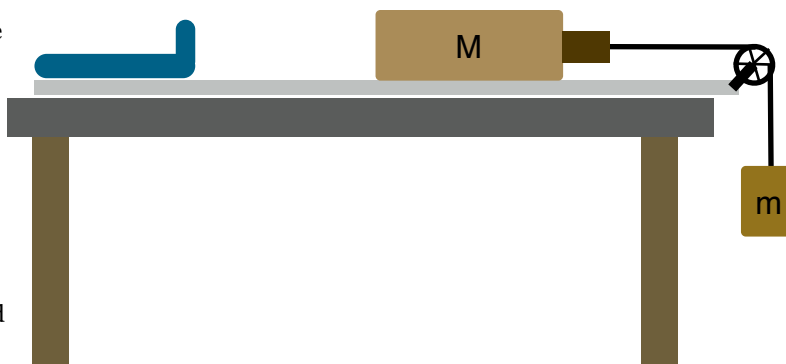
The Data

Because we are running so many static trials, you do not need to retain every single set of data. If you have a trial that produces a particularly good graph, save that. Your static data consists of a table of recorded mass (cart + any extra mass) and the resulting maximum force of tension. Plan to spend some time carefully collecting good quality data. Not every trial will be acceptable.

You will want to save the trials for the kinetic measurements. Make sure to record how much cart mass (M) and hanger mass (m) corresponds to each trial. Your kinetic data should include the masses, the average tension while the cart accelerated, and the acceleration. Both tension and acceleration will be extracted from our graphs. Make sure to save individual trials, and also save your entire worksheet in the proper folder on the hard drive.

The Analysis

1. Carefully draw a free–body equation for the static mass. Use the force diagram to write Newton #2 in terms of the forces you have identified. Solve to predict the coefficient of static friction μ_s. Based on your mass and tension data, you should be able to construct a graph (T vs N) to find a value for μ_s.
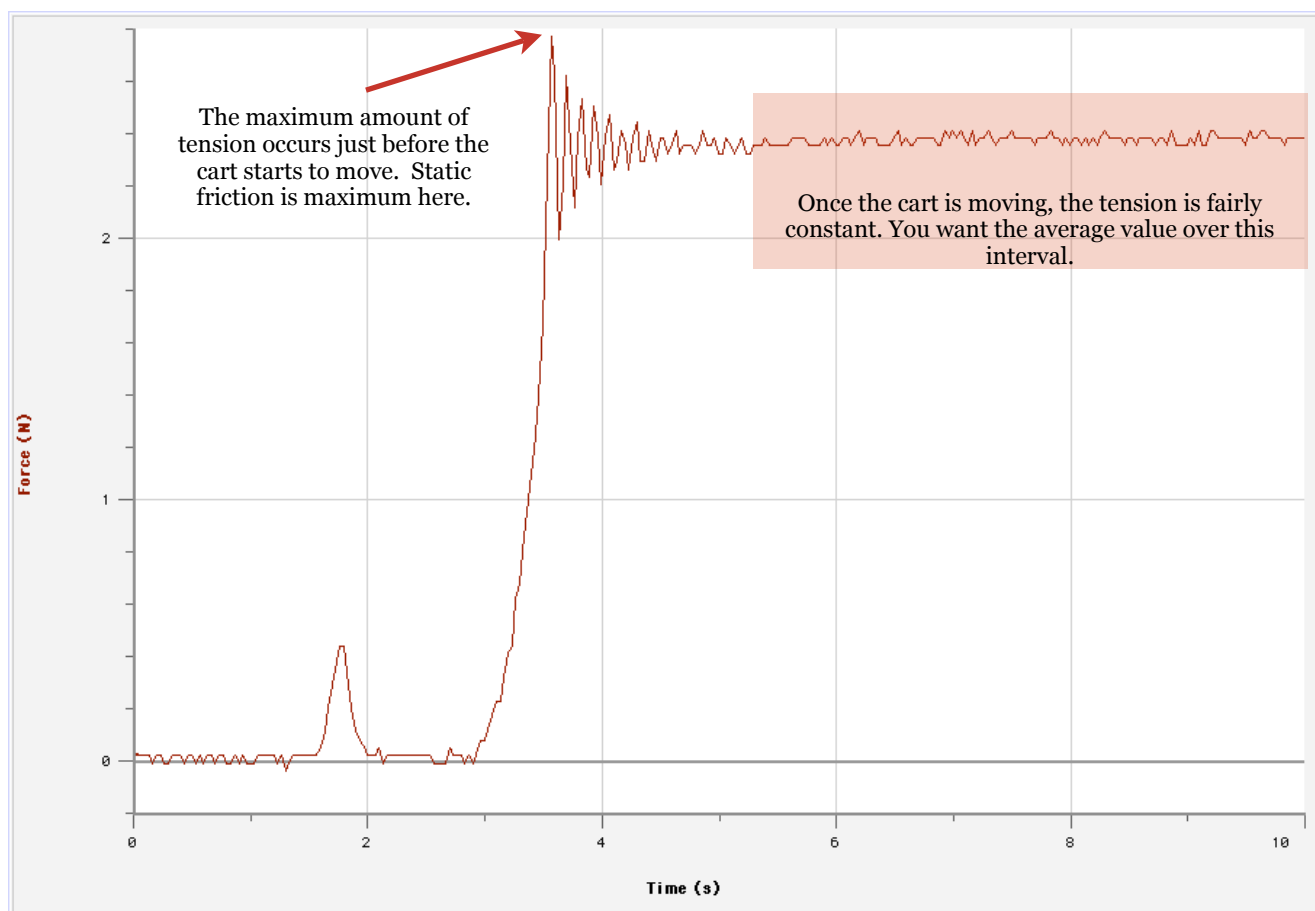
2. For the kinetic trials, draw a free–body equation and write Newton #2. Notice that in this case, the tension does not match the force of friction! Solve algebraically for the kinetic coefficient μ_k.
3. Use the tension and acceleration data to calculate a coefficient for each trial. Find the average value, and calculate the standard deviation to give you the uncertainty.
4. Identify sources of random error, and whether you can quantify them or not. Are your results seriously compromised by random error? How do you know?

The Conclusions

Comment on whether your experiment concluded successfully. If you have not already, suggest how the procedure or prediction could be modified to bring the actual and predicted accelerations into closer correlation.

An Example Graph

Below is an example of a force vs time plot. This is real data collected using the same set up that you will be using. However, not all of your graphs are going to look this good. Certainly not all of mine do. Anyway, this shows you pretty clearly what you are looking for. The value of the maximum tension gets you the static coefficient, and the flat part of the graph shows you where there was constant force (and thus constant acceleration).

The maximum amount of tension occurs just before the cart starts to move. Static friction is maximum here.

Once the cart is moving, the tension is fairly constant. You want the average value over this interval.

LAB 06: WORK AND ENERGY

The Objectives

What is the relationship between the release height and travel distance of a bowling ball?

Specifically:

▸ Observe energy conversion from potential to kinetic
▸ Observe the relationship between kinetic energy and work
▸ Analyze the work-energy theorem quantitatively
▸ Design and collect a data set that addresses multiple random error issues
▸ Perform statistical and graphical analysis on the data
▸ Examine experimental results for evidence of missing physics or inaccurate assumptions
▸ Determine the accuracy of the results

The Procedure

We will use a bowling ball rolling down a ramp to observe the transformation of potential energy to kinetic. When the ball leaves the ramp, it will roll across a rough carpet. As the friction between carpet and ball does work on the ball, it will slow down and eventually stop, its kinetic energy dissipated.

If we assume no energy lost on the ramp, then the amount of potential energy to begin is the same as the amount of work required to stop the ball. By comparing the release height to the travel distance, we can verify the relationship.

The Data

Measure and record the ball release heights and horizontal travel distances. Details of the measuring process will be discussed in class. The entire class will collect and share a single data set.

The Reduction

1. Calculate the average horizontal distance for each recorded release height.
2. Prepare a graph of the **release height (y–axis) vs. the distance (x–axis)**.
3. Find the slope and intercept of the best-fit line.

The Analysis

### Error Propagation

4. For each release height, calculate the standard deviation in the horizontal distance data:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}$$

This is the formula for the standard deviation of a sample set of data containing N members, where x_i represents each individual data, and x the average of the set.

The standard deviation represents the spread of the data: for normally distributed data, you would expect 68% of the values to fall within ±1σ deviation of the average value, and you would expect 95% of your data to fall within ±2σ deviations. This is similar to the % difference that we have previously calculated, but more statistically accurate.
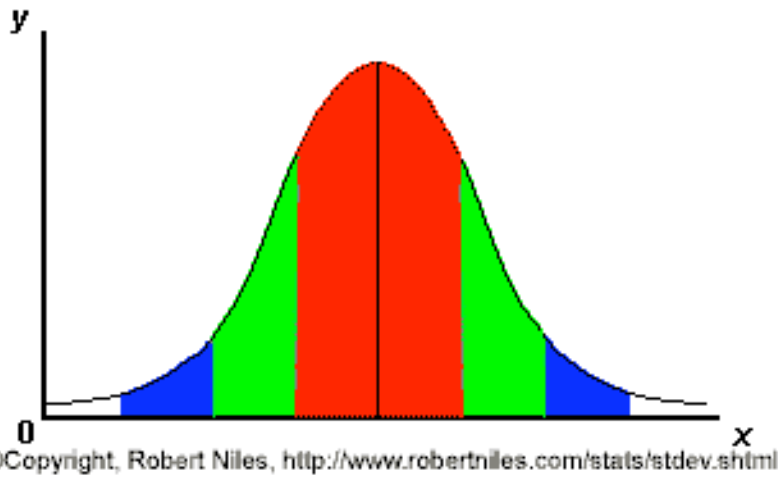
Random Error

Discuss the effect of measuring error on your results. Which has a bigger impact, an error in measuring height or an error in measuring distance? Why? Explain why it was necessary to perform multiple trials at each release height, and collect data for multiple release heights.

Systematic Error

What should the y-intercept of your graph be (hint: if the release height is zero, how far across the carpet should the ball roll?)? Why isn't this your graphical intercept? Does your calculated range of intercepts include this value?

Explain how systematic measuring error in the release height could result in the observed intercept. Based on the technique you actually used, is this a possible cause of your intercept?

Is the assumption that no energy is lost as the ball rolls down the ramp valid? If energy is lost, explain how this affects the horizontal distance traveled by the ball. Could this systematic effect be responsible for your graphical intercept? Explain.

The Conclusions

Comment on whether your experiment concluded successfully. Does your slope seem really small (considering that last week's cork on aluminum was about 0.35 and waxed wood on snow is about 0.10)? Any ideas? Have you adequately explained your graphical intercept? Are there any data points that seem to need an extra explanation, or was there any data that you eliminated when you performed your calculations?

LAB 07: COLLISIONS

The Objectives

A perfectly elastic collision is one in which both momentum and energy are conserved. This type of collision is difficult to stage and observe in the lab, but we will create a collision that comes very close to perfect elasticity. However, the observation and the collected data may seem to contradict each other. Part of this exercise will be about reconciling observations that seem to be mutually exclusive. Partially elastic or perfectly inelastic collisions are far easier to stage, and we will be observing several of these types of collisions as well. Our specific objectives include:

▸ Observe the differences between elastic and inelastic collisions
▸ Analyze momentum and energy conservation quantitatively
▸ Examine experimental equipment and techniques for sources of error
▸ Perform error analysis to determine the accuracy of the results

The Procedure

Work in groups of four. There are two independent experiments to perform: air track collisions and ballistic pendulum. Because there is a single air track, only one group may use that apparatus at a time. The data are acquired quickly, so you will not have to wait very long for a turn. In the meantime, perform the ballistic pendulum experiment.

Air Track Collisions
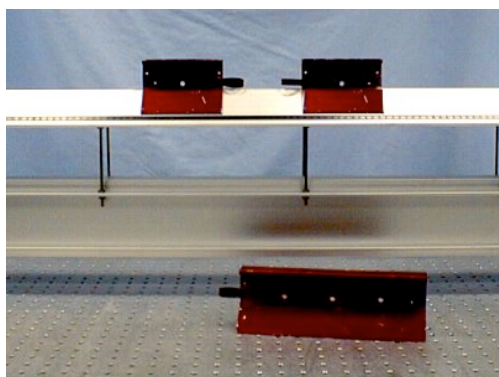
Separate the photogates on the air track to create a collision interval. The first cart should be placed before the first gate, and the second cart should be placed in the collision interval between the gates. Make sure that the air blower is running before you slide the cart on the track. Sliding the cart when the blower is off will damage the track.

For the elastic collision, both carts must be flagged. The first cart will pass through the first gate before the collision, and the second cart will pass through the second gate after the collision. Arrange the carts so that the metal bumpers will collide, then stage the collision. Repeat twice more.

For the inelastic collision, remove the flag on the second cart. The first cart will pass through both of the gates, so only one flagged cart is necessary. Arrange the carts so that the velcro bumpers will stick together on collision, then stage the collision. Repeat twice more.

The Data and Reduction

Record the mass of each cart and each flag. Record the time before and the time after each collision.

Calculate the velocity, momentum, and kinetic energy for each trial of each collision, before and after. Pay careful attention to units here. Notice that, because each flag is 5 cm long, that the velocity will always be

$$v = \frac{0.05\text{m}}{t}$$

where t is the time it takes for the flag to pass through the photogate.

If you have not already, organize the information into a neat and easy to navigate table (one for each collision staged):

CART	MASS (KG)	TIME T_1 (S)	TIME T_2 (S)	VELOCITY V_1 (M/S)	MOMENTUM P_1 (KG·M/S)	VELOCITY V_2 (M/S)	MOMENTUM P_2 (KG·M/S)	KINETIC ENERGY K_1 (J)	KINETIC ENERGY K_2 (J)
A									
Flag A									
B									
Flag B									

The Analysis

Based on our initial assumptions, what qualitative observation supports our assertion that the elastic collision is, in fact, perfectly elastic? For each elastic trial, calculate the change in momentum as a percent lost or gained. Calculate the change in the kinetic energy (as a percent lost or gained) for each elastic trial. Use a table to summarize your results.

For each inelastic trial, calculate the change in momentum as a percent lost or gained. Determine the energy lost as a percentage of the original kinetic energy. Predict and calculate the theoretical energy loss for a perfectly inelastic collision (this requires some symbolic algebra!). Again, summarize the calculations in a neat table.

Ballistic Pendulum

For the ballistic pendulum, a steel ball is launched by releasing a compressed spring. The projectile becomes embedded in the bob of a pendulum (a plastic block), which swings up as a result. The projectile gun has three settings for the spring compression. You should fire the steel ball three times at each spring compression setting.

The Data

You will need to measure and record the mass of the steel projectile ball (m), the mass of the block (M), and the length of the pendulum cord (L). At the lowest setting (spring compressed the least), fire the steel ball into the block and record the height angle θ. Reset the pendulum and repeat twice more, then repeat for the other spring compression settings. As always, present your data in a neat and organized table.

The Reduction and Analysis

Use momentum conservation at the instant of collision:

$$p_1 = p_2$$
$$mv_1 = (m + M)v_2,$$

and energy conservation after the collision:

$$K_2 = \tfrac{1}{2}(m + M)v_2^2$$
$$U_3 = (m + M)gh_3$$
$$K_2 = U_3,$$

to derive an expression for the launch velocity of the projectile in terms of the variables you have measured (m, M, L, θ).

For each setting, calculate the average angle to which the block rose. Use this value to find the launch velocity for each of the projectile gun settings.

Compare the calculated launch velocities to the known values by calculating the percent error. Connect this to the perceived loss of momentum during the collision.

Error Analysis

Random Error

Is the air track experiment really about identifying random errors and reducing their effects? Are the large losses of momentum and energy seen with the air track the result of random errors whose effects could be reduced by collecting more data? What about the ballistic pendulum experiment? Is the much smaller discrepancy between the measured launch velocity and the known launch velocity the result of random measuring errors? Could collecting more data substantially reduce the difference between the measured and predicted launch velocities?

Systematic Error

Obviously nothing here was conserved that should have been, and the actual energy loss during the inelastic air track collision far exceeds the prediction. Discuss whether this is the result of the experimental technique, or whether there is some missing physics that need to be included in the analysis (or possibly both).

The Conclusions

Comment on the overall success of these experiments. If you have not already, suggest some ways in which the experiments could be improved to better demonstrate the principles of conservation.
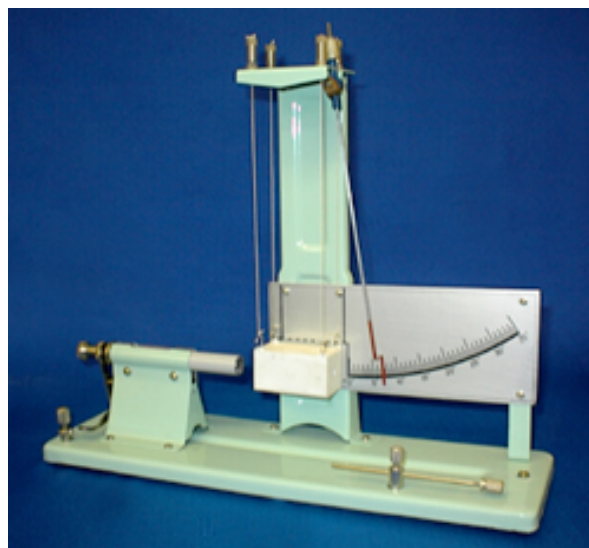
LAB 08: CENTRIPETAL ACCELERATION

The Objectives
We will be using Newton's laws and the concepts of angular motion to answer the question:

What is the elastic constant (stiffness) of a spring?

Specifically:

▸ Use Newton #2 to describe the forces acting on an object in equilibrium
▸ Observe and measure the period of circular motion
▸ Determine the centripetal acceleration of a moving object
▸ Analyze circular motion in terms of applied forces
▸ Compare methods for determining the constant of a spring
▸ Examine experimental equipment and techniques for sources of error
▸ Perform error analysis to determine the accuracy of the results

The Procedure
The apparatus shown can be used in two different ways to determine the constant of the spring. As shown, the pendulum is in static equilibrium. The cord on the right (passing over the pulley, attached to the mass hanger) can be detached, which permits the central vertical axis to spin freely.

The Data
Measure and record the unstretched length of the spring. Measure and record the mass of the pendulum. Measure the reaction times of the timers using the stopwatches. These remain constant for both methods. Watch your units: mass in kg, length in m, time in s.
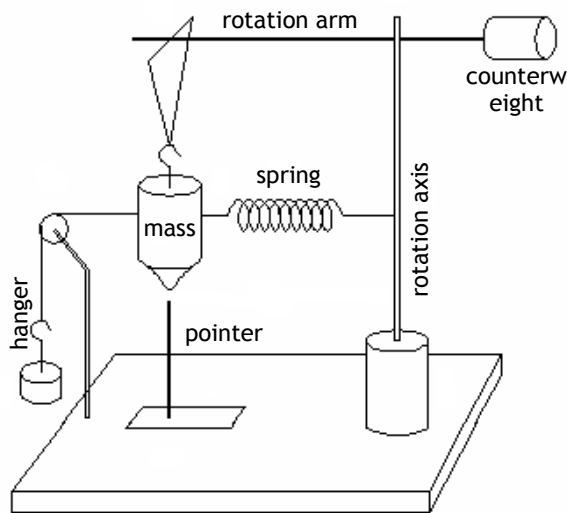
Static Method
As shown on the sketch, alignment is critical. The pendulum mass should be hanging vertically. Without either the spring or the cord attached, allow the pendulum to hang. Align the pointer directly underneath. Re-attach the spring and cord. Add mass to the hanger until the pendulum is again hanging in the vertical position (as marked by the pointer).

Record the total mass added to the hanger. Measure and record the amount by which the spring has been stretched.

Sketch a force diagram of the stationary pendulum in equilibrium when the spring is attached. Use this to determine the spring constant k. Show your work.

Dynamic Method
For the dynamic method, measure and record the radius of the circular motion as shown. Detach the cord and the hanger, and spin the rotation axis. Spin up to speed, when the pendulum is properly aligned with the pointer. Again, alignment is very important. Keep the axis spinning at the rate which maintains the alignment. Notice that, because the pendulum is aligned exactly as before, the amount by which the spring stretches is also the same (and does not need to be remeasured).

Record the period of motion for each trial. You should measure the amount of time it takes for some whole number of complete revolutions (5? 10? 100?), and you should have each timer record multiple measurements (3? 5? 100?).
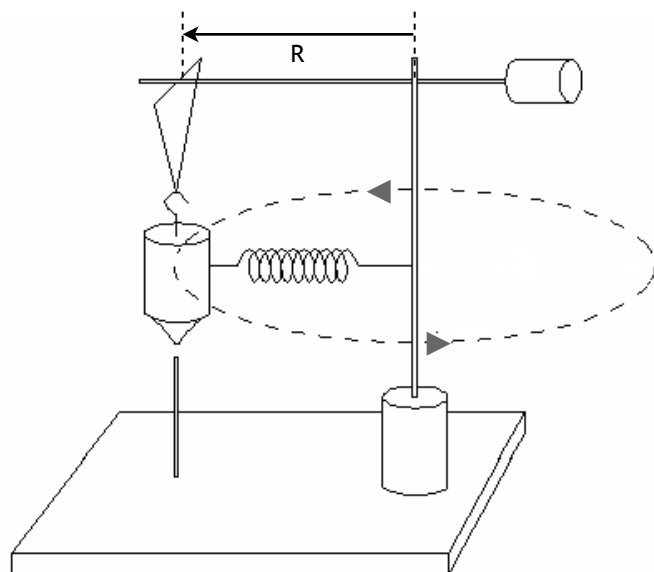
Dynamic Reduction

1. For each dynamic time trial, calculate the period of the motion:

$$T = \frac{t}{n}$$

    where T is the period of one complete revolution, t is the total measured time interval, and n is the number of complete revolutions observed.

2. Calculate the average period of motion over all trials.

3. Sketch the free body equation of the pendulum in motion. Use it to write Newton #2 for the pendulum, and calculate the spring constant. Show your work.

The Analysis

Error Propagation

4. Determine the experimental uncertainty (based on the known uncertainties in the measured values used to make the calculation) in the value of k for the static trial.

5. For the uncertainty in the period, take the average reaction time as the absolute uncertainty in the average total time. Then the absolute uncertainty δT in one period is

$$\delta T = \frac{\left(\text{average reaction time}\right)}{n}$$

    where n is the total number of revolutions measured.

6. For the dynamic trial, determine the experimental uncertainty (based on the known uncertainties in the measured values used to make the calculation) in the value of k.

Random Error

Identify the sources of error in the experiment, and discuss how they effect the results. Which method results in a more accurate and reliable spring constant? Explain.

Systematic Error

Do you have any reason to think that your results are subject to systematic error?

The Conclusions

Comment on the overall success of the experiment. If you have not already, suggest how the experiment could be modified to improve the results.

LAB 09: TORQUE AND STATIC EQUILIBRIUM

The Objectives

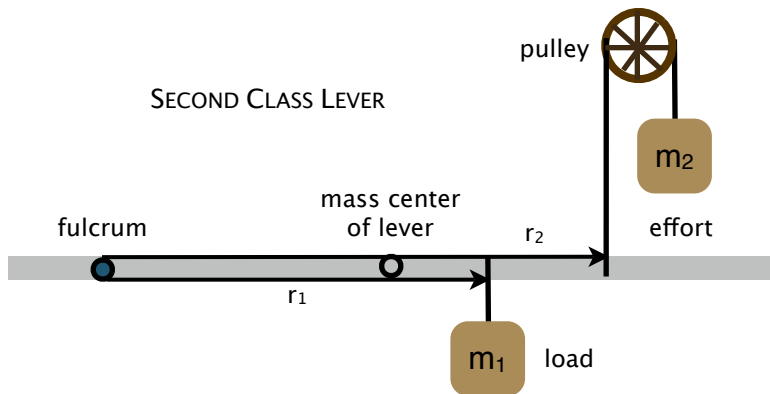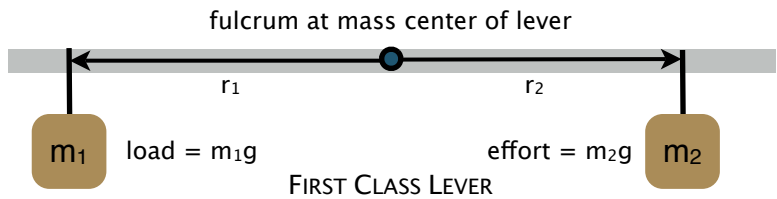There are four basic components to a lever system:

7. a rigid structure (the *lever*)
8. a pivot point (*fulcrum*) for that rigid structure to rotate about
9. a mechanical force (called a *load* or resistance) acting on the rigid structure that attempts to cause it to rotate and
10. another mechanical force (called an *effort*) acting on the rigid structure that attempts to prevent it from rotating.

Using a meterstick for a lever, one can position a fulcrum anywhere along its length. Similarly, one can apply a load anywhere, then determine the required effort to prevent rotation. The three classes of levers are defined by the positions of the load and effort relative to the fulcrum.

The *mechanical advantage* of a lever is simply the ratio of the load to the effort and can have a value greater than, less than, or equal to one.
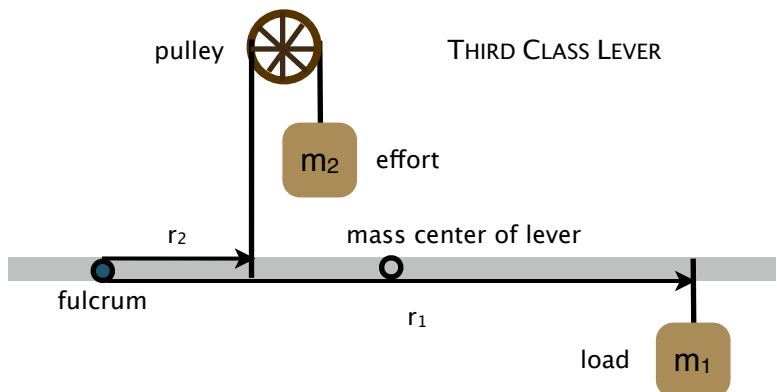
Our specific objectives:

▸ Determine the mass center of an irregular object
▸ Apply the definition of torque and the associated sign conventions for rotational motion
▸ Identify and apply the conditions for static equilibrium
▸ Construct and observe the differences between first, second, and third class levers
▸ Define mechanical advantage and develop a graphical method for determining it

fulcrum at mass center of lever

r_1 r_2

m_1 load = $m_1 g$ effort = $m_2 g$ m_2

FIRST CLASS LEVER

SECOND CLASS LEVER

pulley

m_2

mass center of lever

fulcrum r_2 effort

r_1

m_1 load

The Procedure

▸ Measure and record the mass of the meterstick. Attach a pivot clamp to serve as a fulcrum (measuring the mass of this clamp is not necessary).
▸ Find the mass center of your meterstick by balancing it without any added mass. Adjust the fulcrum clamp until the stick is level and balanced, then record its position on the stick.
▸ Set up a First Class Lever, using a 100g load (you must include the mass of the hanger clamp here!) located 5cm from the left end of the meterstick. Balance the lever with a 150g effort (including clamp) located to the right of the fulcrum.

pulley   THIRD CLASS LEVER

m_2 effort

r_2 mass center of lever

fulcrum r_1

load m_1

▸ Using the sign convention that the **fulcrum** is the **origin** and to the to the right is positive, record the positions r_1 and r_2 of the load and the effort.
▸ Move the load m_1 5 cm to the right (closer to the fulcrum). Reposition m_2 for equilibrium, and record the new values of r_1 and r_2. Continue to move m_1 in 5cm increments until you have at least five data pairs of r_1 and r_2 values.
▸ Reposition the fulcrum to 10 cm from the left end of the meterstick. Construct a Second Class Lever as shown in the diagram above, making sure not to switch the hanger clamps. Attach the 100g load 40cm to the *right* of the fulcrum. Balance the lever by attaching the effort hanger 5 or 10 cm from the right end of the meterstick, and adding mass until the system is in equilibrium. Make sure to record the amount of mass m_2.

▶ Using the same sign convention as before, record the positions r_1 and r_2 of the load and the effort. Slide the load 5cm to the *left*, and rebalance the effort. Continue to decrease r_1 in 5cm increments until you have at least five data pairs of r_1 and r_2 values.

▶ Repeat the experiment once more, constructing a Third Class Lever. Begin with the 100g load located 5cm from the *right* end of the meterstick, and position the effort clamp 50cm from the fulcrum. Measure and record the mass m_2 required to balance the lever, then move m_1 to the *left* in 5 cm increments until you have at least five pairs of data.

The Data
If you have not already, summarize all of your data in a neat table. Setting up an Excel worksheet is advisable, since the data reduction will be quick and simple if you can type a formula once, then copy and paste it down a column.

The Reduction
Using the sign convention that a *positive* torque creates a *counterclockwise* rotation (*negative* torque creates *clockwise* rotation), calculate the individual torques acting on each type of lever. You should remember to include torque due to the meterstick itself if the pivot is not located at the mass center of the stick.

The Analysis
1. For each type of lever, draw a complete free-body diagram. Include all forces acting on the lever, then identify which forces actually create a torque with respect to the pivot.
2. For the second-and third-class levers, examine the effort in particular. Notice that the clamp exerts a *downward* force while the tension in the string exerts an *upward* force at the same point. Summarize the torques algebraically, and if necessary, edit your spreadsheet to account for the weight of the effort hanger and its torque.
3. For each type of lever, prepare a graph of r_2 (y–axis) as a function of r_1 (x–axis). Perform a linear regression, and compare the resulting equations of the lines to your algebraic summaries of the torques. Identify the physical meaning of the slope and intercept of each graph, and compare those values to the values predicted by your torque summaries.
4. Are the deviations in your graphical results random, or do you detect some systematic effect? You should be able to construct a qualitative argument from examining your graphs, and you should be able to support your arguments quantitatively by calculating percent error values for both slope and intercept.
5. For the anatomical examples shown on the right, identify the type of lever illustrated. Comment specifically on the relationship of load and effort (think about muscle strength).
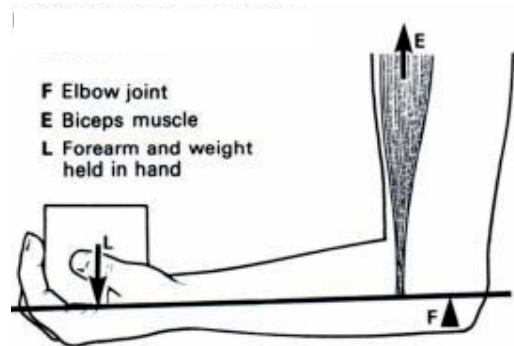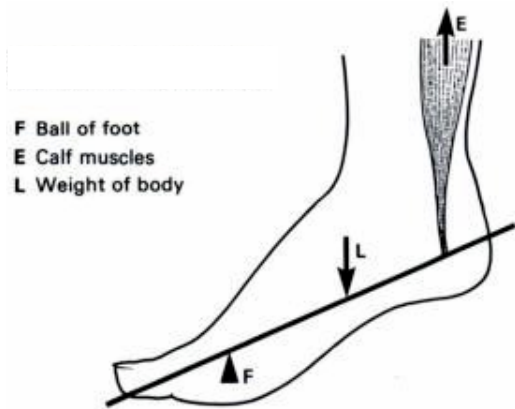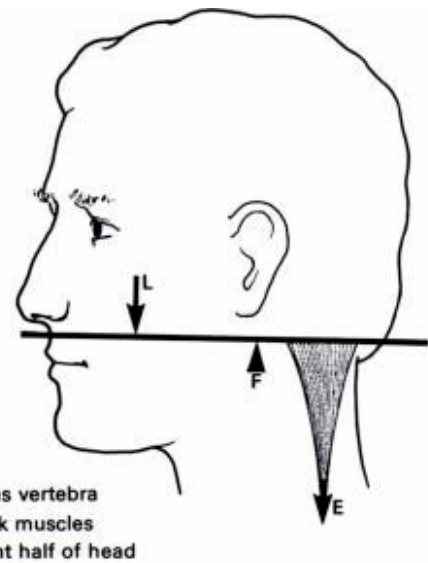
The Conclusions
Comment on any outstanding issues with data or results, and suggest methods for improvement if appropriate. Briefly address how the graphical method could be used to facilitate the design of a mechanical system requiring the use the levers.

F Atlas vertebra
E Neck muscles
L Front half of head

F Ball of foot
E Calf muscles
L Weight of body

F Elbow joint
E Biceps muscle
L Forearm and weight
   held in hand

LAB 10: THERMAL EXPANSION

The Objectives

You are certainly aware that heat causes many materials to expand. You may notice that railroad tracks are not one long, solid piece, but many pieces. A gap must be left between adjacent pieces, to allow for thermal expansion. You will also see expansion gaps on bridges. If you have ever installed wood flooring, you will also remember that it is important to leave an expansion space all the way around the perimeter of the room (shame if that floor was to buckle on a hot day!).

How much an object expands depends on several parameters: what the object is made of, how big it was originally, and how much its temperature has been increased. The greater the original length, the more an object will expand. The greater the increase in temperature, the greater the expansion. But not all materials of the same size will expand by the same amount when increased by the same temperature. The coefficient of thermal expansion depends on the type of material: the greater the coefficient, the greater the expansion for a given length of material and given temperature increase.

What is the coefficient of thermal expansion for brass?
What is the coefficient for iron?

Our specific objectives include:

▸ Observe the linear expansion of several metallic samples
▸ Determine the coefficients of thermal expansion for two metallic samples
▸ Compare the coefficients for different types of metallic samples
▸ Examine experimental equipment and techniques for sources of error
▸ Perform error analysis to determine the accuracy of the results

The Procedure

▸ Use the calipers to measure the diameter of each rod. Measure in several places along the rod, and use the average value for calculations.
▸ Each rod is etched with a circumferential groove. Measure the length from the groove to the end of the rod. You must measure and record each rod separately. The lengths are not uniform.
▸ Because the actual increase in length ΔL is too small to measure directly, an indirect method will be used. It is not difficult, but can be fussy. Details will be provided in class.
▸ You should measure and record the expansion of two brass rods and two iron rods. If you need a "do over," you must get a fresh, cold (room temperature) rod. Do not try to re-use a warm rod.

Temperature = T_0

Temperature = $T_0 + \Delta T$

L_0 ΔL
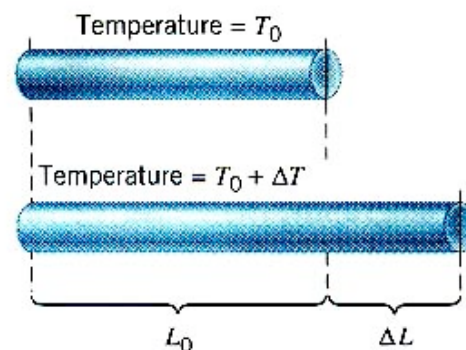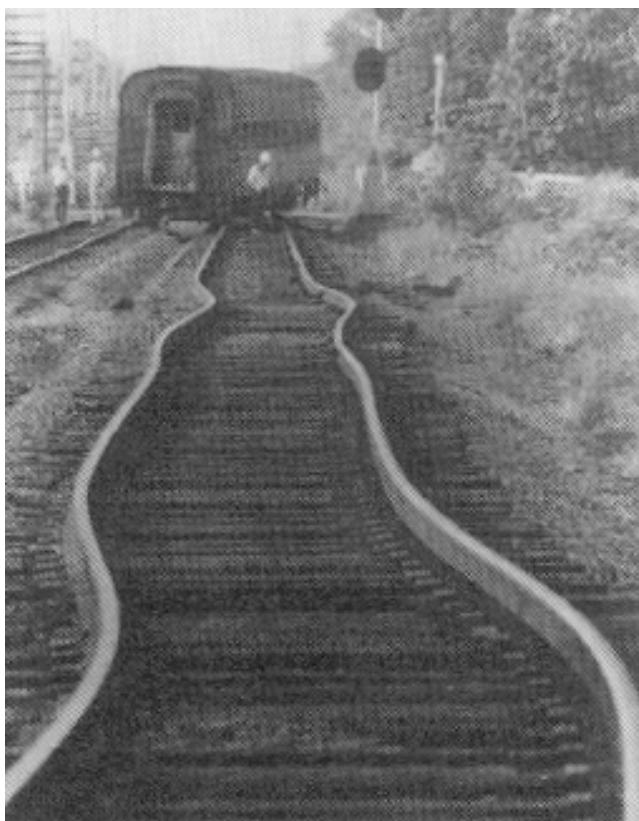
The Data

Keep the data for each rod organized separately:

ROD	DIAMETER (cm)			AVERAGE DIAMETER (cm)	LENGTH L_0 (cm)	INITIAL TEMPERATURE T_O (°C)	FINAL TEMPERATURE T_F (°C)	EXPANSION ANGLE (°)
BRASS								
BRASS								
IRON								
IRON								

The Reduction

1. Convert the expansion angle θ into the linear expansion *ΔL* (in cm) for each rod:

$$\Delta L = \left(\frac{\theta}{360°}\right)(\pi d)$$

where *d* is the average diameter of the rod.

2. Use the expansion equation to determine the coefficient α for each rod:

$$\Delta L = \alpha L_o\left(T_f - T_o\right)$$

3. Average the values for the brass rods, then average the iron rods.

The Analysis

4. Compare your experimental values to the accepted values by calculating your percent error:

$$\alpha_{brass} = 1.92 \times 10^{-5} / °\text{C}$$

$$\alpha_{iron} = 1.14 \times 10^{-5} / °\text{C}$$

5. Examine your experimental methods for sources of random error. List these potential sources and the impact they might have on your experimental results. Is testing two rods sufficient for an accurate determination of the expansion coefficient? If you combine your results with the other lab groups, will the overall class average improve?

6. Do you have any reason to suspect that your results may be systematically compromised? Compare your results with other lab groups, and determine whether a pattern emerges. If you detect a systematic effect, return to your procedure and try to determine how it might have occurred.

The Conclusions

Comment on any outstanding data (good or bad), suggest methods for improving your experimental results.