Physics 110 - Mechanics

Laboratory Manual

Fall 2025

Physics & Astronomy Department
Knox College
Galesburg, Illinois

Contents

Preface

The goals of physics are to understand nature and make accurate predictions. Physics is often presented as if these goals are achieved by reasoning mathematically from a small set of fundamental laws which look much like mathematical axioms. However, because of this emphasis on mathematical reasoning and logical deduction, it is easy to lose sight of the crucial fact that physics, like the other sciences, is **experimental**. This means that experiments are the basis for the laws of physics and all the predictions we derive from them — the "laws" of physics are in essence just concise summaries of experimental results.

When a theoretical prediction conflicts with an experimental finding, it is the theory which must be scrutinized and likely discarded – so ***it is experiments which constrain theory***. Experiments sort out which theories are possible and which are not. Naturally, the real story is often more complicated than this simple picture: there are examples of great theorists who refused to believe in experiments that seemed to contradict their models and whose intuitions about nature were ultimately vindicated by later, more careful or improved, experiments. There have also been some great theorists who tried this dangerous game and lost. Notwithstanding these interesting complexities of physics research as a human endeavor, the fundamental principle remains that *experiments* are the ultimate basis of our physical knowledge.

Real experiments are a messy business though, and this part of the course is designed to teach you about how they *actually* work. It is almost never easy to disentangle one single phenomenon or principle to be tested from all the other interactions that are always present. Right away we are forced to make approximations, to try to neglect interactions that are hopefully small (like air resistance), and to model others that may not be small (like friction) in ways that we know are imperfect. There is always the issue of choosing an appropriate model—a mathematical description of the experiment that inevitably leaves some things out. Of course, one wants to be sure that what is left out is in fact negligible, or, more precisely, one wants to have some estimate of the size of the errors made.

This brings us to yet another element of experimental work you will be learning about in this course, error analysis or uncertainty analysis, which can be surprisingly intricate. While you will be exposed to issues of experiment design and uncertainty/error analysis, our focus will be primarily on the using the physics you are learning in your lecture section in applied hands-on applications.

This manual begins with information about the course policies, instructions for preparing your lab reports, and detailed disussion of the reporting of measured numbers and experimental uncertainties. After this information you will find descriptions of the planned lab activities for each week.

Laboratory Course Information

Knox College Physics 110 - Fall 2025

Lab Meetings: Wednesdays in room SMC D105

Lab Instructor: Tom Moses
office: SMC D116
office hours: Anytime I am in my office and free (just ask).
email: tmoses@knox.edu
office phone: 309-341-7341

Lab Report Honor Code Policy:

You are encouraged to work together on lab reports; you may consult other students, tutors, or other physics faculty members to obtain insight regarding the lab questions. However, your final write-up must be your own unique product. In particular, **duplicate reports, even from lab partners, are not acceptable** and likewise, **sharing any exact text or plots from your report is not acceptable**.

You additionally are **not allowed to use AI (for example, chatGPT)** to seek solutions to point bearing work (including lab reports). Doing so would be a violation of the Honor Code as you would be presenting work that is not yours for credit.

Lab partners can share measured numbers only with their other lab partners who were personally present when the data was acquired. If you have to miss a lab or leave early, you will need to arrange a time to make up the lab (or the part of the lab that was missed.)

If you have any questions about issues related to the honor code, please ask.

Lab Report Submission:

Lab Reports are due on Friday at 4:00 PM, following the lab on Wednesday. Lab reports should be submitted as a hardcopy submitted in the Lab box in D-wing following the formatting procedures outlined on the following pages.

Please see the next section for instructions on preparing your lab reports.

Policy on Late Lab Reports:

Late labs will get a 10% deduction per business day (work must be turned in by 4:00 PM to be considered in for that day). Naturally, special arrangements can be made (in advance, whenever possible) for sports competitions, illness, etc.

Attendance and Tardiness Policy:

Instructions for the use of the lab equipment and on safety issues are presented at the beginning of the lab period, so it is particularly important to arrive on time for lab. Tardy students will be penalized 10% on the first occasion, and 20% for subsequent occasions. Late arrivals may need to work alone if their lab partner(s) are already well along, at the discretion of the lab instructor.

Preparing Laboratory Reports

Laboratory reports for this course will be rather streamlined, since we want you to focus on understanding the physical ideas rather than on crafting polished scientific reports. That said, reports are expected to follow the guidelines described below.

I. General Information About Lab Reports

Laboratory reports for this course should be submitted as a hardcopy (on paper). Your report may be *neatly* handwritten, or typed (using Word or Google Docs, for example). If a typed version is submitted, you will need to format equations and mathematical symbols appropriately. Whether your report is handwritten or typed, plots must be prepared using computer software (see the guidelines below) and may not be hand-drawn.

Your report should consist of the following three parts:

- **Identifying information** Your name, your lab section (A, B, C, D), and your lab partners names. Write "Lab partners:" in front of your partners names so it is clear who is the author of the report and who was a partner.
- **Answers to the questions** including any calculations, explanations in English, screenshots, or plots. Present your question answers *in order*. In other words, do not attach plots or tables at the end of the report, but include them in the proper sequence with the other questions.
- **Raw data** Include your raw data (the un-analyzed measured numbers acquired in the lab) as an appendix at the end of your report. Label it clearly. Having the raw data available is often helpful in diagnosing problems with the experiment or apparatus.

II. Guidelines for Presenting Answers to Questions

Most questions will require answers that include a numerical answer as well as an explanation or some sort of response. Provide these explanations as clearly worded complete sentences. **When calculations are required, show them in full detail.** If a number of similar repetitive calculations are necessary, it is fine to show one example calculation.

When showing your calculations, always:

- define all symbols used
  (e.g. m_b = mass of ball; m_g = mass of glider; v_o = initial speed of glider, v_f = final speed of glider, etc.),
- specify the units of all quantities including the slopes and intercepts of plotted lines, unless they are truly unit-less
- report numerical values with an appropriate number of significant digits
- include uncertainties, with correct significant figures

III. Preparing and Presenting Plots

Plots and best-fit lines must be prepared using computational tools such as *Google Sheets*, *Excel*, *Mathematica*, *Python*, or similar. Plots made by hand are not acceptable. If you do not yet know how to create plots using computer software and computational tools, please ask—the lab instructor or course teaching assistants can help you.

Guidelines for plots:

- Plots should have a title and appropriate labels on the x- and y-axes including the units of the plotted quantities.

- If it is appropriate to apply a linear fit to your data, you should use the same application for the fit as you use to plot your data. Do not connect the data points with line segments and do not attempt to draw a best fit line by eye.

- Be sure the plot symbol size is appropriate (large enough to be visible and not oddly large).

- For best-fit lines, show the **line** on the plot, report the numerical values of the both the **slope and intercept**, and report the R^2 "goodness of fit" parameter.

- Plots are often considered the most important and convincing element of a scientific report. Make sure yours are large enough to be easily readable.

Reporting Measured Numbers

I. Significant Figures

Reporting a measured number with an appropriate number of digits is important since it implies a certain experimental resolution. In other words, if you report a length of 1.045 mm, you are not just asserting what the length is, but also a confidence that the true length is known to within one thousandth of a millimeter. So, if you display too many digits, you are making a very misleading claim about the precision of your measurement.

Deciding how many digits are appropriate to report is not always simple and can depend on the details of your experiment. Learning to understand it completely is part of mastering your field and the Physics & Astronomy Department covers the mathematical theory in more detail in PHYS 241. However, the method of *significant digits* or *significant figures* is a simple approximate method that works quite well and provides a very good introduction about how to start regularly thinking about this issue. You likely have some familiarity with it already and below is some discussion and examples.

A. Number of Significant Digits in a Measured Quantity

The number of significant digits in a measured number is determined by the resolution of the measuring equipment (i.e. how precise it is capable of measuring) **and** by the magnitude of the quantity measured.

Examples:

A ruler with ± 0.1 mm precision[†] is used to measure a one millimeter long sample.
[†]this effectively means using this ruler you are able to measure to the closest 0.1 mm
$\Rightarrow$ The result is: 1.0 ± 0.1 mm. *(The quantity* 1.0 *mm has* 2 *significant digits).*

The same ruler is used to measure a ten-centimeter long sample.
$\Rightarrow$ The result is: 100.0 ± 0.1 mm. *(The quantity* 100.0 *mm has* 4 *significant digits).*

Vernier calipers (another type of length measuring device) with $\pm$ 0.05 mm precision are used to measure the one millimeter long sample.
$\Rightarrow$ The result is: 1.00 ± 0.05 mm. *(The quantity* 1.00 *mm has* 3 *significant digits).*

Two important notes:

- The *uncertainty* has only one significant digit in most cases.* This is because uncertainties are not precisely known quantities by their nature - as they are an *uncertainty*.
  *there are specific cases where a maximum of two significant digits may be appropriate
- The last significant digit of a measurement or number that is reported is in the same place as the uncertainty (i.e. the tenths place for the first two examples).

B. Propagation of Significant Digits in a Calculation

You will often need to know how to determine the number of significant digits should be displayed in a number obtained from a calculation. This is related to the topic of *propagating* ***uncertainty***, covered in the next section. In essence, the propagation rules for significant digits described below are a simplified rough approximation to a more careful and exact method of propagating uncertainties described later. Because the rules for significant digits are simple to use and give an estimate of how uncertainties propagate, they are worth learning and should always be used unless the more exact method of propagation of uncertainties is used instead.

1. **Adding/Subtracting**

   The number of significant digits in the result is determined by the place of the last digit from operand with the smallest number of significant digits after the decimal point. *(Notice you need to make sure to also properly round your final result.)*

   Examples:

   $$\begin{array}{r} 2.005 \\ 0.04 \\ +13.2415 \\ \hline 15.29 \end{array}$$

   $$\begin{array}{r} 1.954 \\ -0.43 \\ \hline 1.52 \end{array}$$

2. **Multiplying/Dividing or Other Operations (exponentiating, logs, etc.)**

   The number of significant digits in the result is the same as that of the operand with the smallest number of significant digits.

   Examples:

   $2.005 \times 1.04 \times (3.2 \times 10^2) = 6.7 \times 10^2$

   (Note: Writing the above result as 670 *is ok, but it is somewhat ambiguous whether or not the zero is significant. The use of scientific notation avoids this ambiguity).*

   $\sin(1.2\,\pi) = -0.59$

3. **Extra Digits to Avoid Round-Off Error**

   You may, and should, use one or two extra digits in *intermediate steps* to avoid error due to repeated round-offs. (Note: you only need one or two extra digits; using all the digits displayed by the calculator is always a waste of time.) These extra digits should be used in calculations only. Whenever you provide final results or answers to questions the *reported numerical values must have an appropriate number of significant digits.*

II. Units

Measured values you report usually will have units, and the units must be included along with your measured value. Note that some quantities you are familiar with from other contexts (like the slope and y-intercept of a line) typically have units which must be reported in the usual manner.

In this course we will use the standard ***mks*** (**m**eters, **k**ilograms, **s**econds) system – this is a description of a specific standard within the metric system. A few examples of some important units to make sure you know how to use properly are listed below:

- **Base Units:** *meters, kilograms, seconds*
- m/s – *unit of velocity*
- m/s^2 – *unit of acceleration*
- **Newton** = $\mathrm{kg\,m/s^2}$ – *unit of force*
- **Joule** = $\mathrm{N\,m} = \mathrm{kg\,m^2/s^2}$ – *unit of energy*

III. Uncertainty

A. "Errors" and Uncertainties

Suppose the theory you are testing predicts a value of 2.0 mm for a particular quantity, but your experimental value is 1.5 mm.

Is your experimental value consistent with the theory or not?

This type of situation arises all the time with experiments, where the measured number is not exactly identical with the predicted theoretical value. Therefore, to draw *any* conclusion from the experiment, it is also necessary to know the precision of the measured number. For example, if the measured number and its uncertainty are 1.5 $\pm$ 0.5 mm, the measurement *is* consistent with the theoretical prediction of 2.0 mm; however, if the measured number were 1.5 $\pm$ 0.1 mm, it *is not.* Knowing the uncertainty in your measured number, then, is an essential part of the experiment without which its meaning is unclear. The uncertainty number (the $\pm$0.1 mm) is customarily called *experimental error* or sometimes *experimental uncertainty*, which is a better term since no sort of "error" has been made by anyone — uncertainties are inherent in the measuring process. This can be due to the limitations of the instruments used (note that any instrument will have some uncertainty) or even the statistical uncertainty inherent in the natural phenomenon being measured.

B. Types of Errors

It is important to recognize that uncertainties can show up in an experiment in a surprising number of different ways, and often identifying the major source of uncertainty can be a challenge in itself. An important first step in understanding uncertainty is identifying some of the types of uncertainties/errors to look out for.

The most obvious way uncertainties enter is through the **limitations of the measuring instruments**. For example, if the smallest markings on the ruler are millimeters, the uncertainty of a ruler measurement must be *at least* a half-millimeter or so. This will impact how many **significant figures** you use, as discussed previously. However, the uncertainty of a ruler measurement could easily be *more* than a half-millimeter due to additional sources of uncertainty in your measurement.

Beginning to familiarize yourself with the proper vocabulary of scientific uncertainty is important. This will take some time if it is new to you, but this class is a great way to start. Below are some examples of several different types of uncertainty involving measurement with a ruler, other than the resolution of the ruler markings.

i. Consider measuring the focal length of a lens by focusing light from on a screen and measuring the lens-to-screen distance with the ruler. Different distances, maybe differing by a few mm, might *look* equally in focus to you, so this introduces an uncertainty of a few millimeters. This uncertainty is a ***problem of definition*** as the visual determination of "in focus" has a some range in the definition.

ii. As another example, you measure the width of a tabletop with the ruler and find that you get slightly different measurements depending on which exact part of the table you measure. This is because the table's sides are not quite perfectly smooth and perhaps the table's edges are not perfectly parallel. Therefore, this uncertainty is due to ***model error*** as we *model* the tabletop as a perfect rectangle which is non-exact, causing uncertainty when a real table is measured. Note that this uncertainty could, again, be significantly larger than the uncertainty coming from the ruler's markings.

iii. The way a measuring device, such as a ruler, is read can contribute to error. If you are constrained to view the ruler from an angle rather than perpendicularly, the geometry of the viewing can result in ***parallax error***. In this case, the thicker the ruler and the more oblique your viewing angle, the larger the error will be.

iv. The ruler may have also been manufactured incorrectly, with the markings 1% too close together – then all measurements made with this ruler will be large by 1%. This *non-random error*† is called ***systematic error***. Indeed, there are no perfect rulers, so one can say with confidence that every ruler has *some* degree of systematic error (hopefully much less than 1%, and in fact if it is much less than the millimeter markings, it may in fact be negligible in practice.) Systematic error can be particularly difficult to estimate as it typically requires a careful calibration experiment with improved equipment or techniques. Sometimes equipment manufacturers may specify a probable or guaranteed *maximum* systematic error in an equipment manual; other times an experimenter must undertake a separate *calibration experiment* to test against a known standard. It is important to note that since systematic error is not random, it is typically more difficult to overcome than random statistical errors, which can be reduced by collecting many data values and averaging.

C. Quantifying Random Error/Uncertainty

Random errors, unlike systematic errors (discussed in the last example above), can be determined by repeating an experiment many times. The degree of scatter among the measured values, described by a quantity called the ***standard deviation***, can usually be taken as the measure of the random error.

D. Which Type of Error Do You Have?

When performing real experiments there are many sources of error – some may be systematic in nature and others random, as well as some that don't clearly fall into either category (such as model errors). When asked to identify and consider your sources of error it is important to realize that many potential sources of error may not be significant—the uncertainty in most experiments is dominated by a single largest source of uncertainty. If asked about possible sources of uncertainty, do your best to think quantitatively and to consider the ***relative size*** of your errors in order to identify which is (or are) the most important to include in your error analysis.

As a last word on types of experimental error: You may be tempted to attribute some of the uncertainty in your experiment to *"human error"*, nevertheless this is not an legitimate type of experimental error. Tempting as it may be to reason that since humans are imperfect creatures, our measurements must also bear this limitation, this is not at all what the term "experimental error" means. Making a mistake like writing down the wrong number in your notebook does not count as an experimental error or a source of uncertainty. When you identify a mistake you should, of course, attempt to fix it. If you believe you have made a mistake but cannot identify what exactly it is, do not report this as experimental error, but rather add a comment explaining the situation. Long story short, please do not use the term "human error" in your lab report.

E. Estimating the Size of Uncertainties

Knowing the exact size of an uncertainty can be tricky. Fortunately, we usually only require an estimate and this is usually not too difficult.

- For scale reading measurements (like rulers), $\pm$ half the smallest scale division is often a reasonable estimate for the minimum uncertainty.

- For timing measurements (including velocity or acceleration), it is often convenient to repeat the measurement a few times - the maximum deviation from average (i.e. half of the range) gives a rough, order-of-magnitude estimate of the uncertainty. If you take a large number of measurements the **standard deviation** for the set can be used.

- For other measurements, (for example the uncertainty on a standard mass) you should choose a reasonable uncertainty that you feel you can justify or ask your lab instructor for more information.

F. Propagating Uncertainties in a Calculation

Once you know the uncertainties in the raw measured quantities in an experiment, you may still need to know the uncertainty in some other value *calculated from* the raw quantities.
For example:

> You measure the mass ($m \pm \Delta m$) and the volume ($V \pm \Delta V$) of an object; you want to know the mass-density (ρ) and its uncertainty ($\pm\Delta\rho$).
>
> The mass density is given by $\rho = \frac{m}{V}$. *What is its uncertainty?*

This is the problem of ***propagation of uncertainties*** – figuring how uncertainties are affected when they propagate through a calculation or a series of calculations. There are well-established statistical rules for this but they are only rigorously valid for random uncertainties following the normal, or bell-curve, distribution (although the method generally is *approximately* valid). If you are interested, PHYS 241 (Introduction to Research) or STAT courses are a great way to gain a deeper understanding of how and why this is true! Here, we'll present a simpler approach for estimating the final uncertainties that requires no mathematics knowledge beyond what is needed for the course.

> The final uncertainty in the density ($\Delta\rho$) is given by $\Delta\rho = \frac{1}{2}(\rho_{\max} - \rho_{\min})$, where $\rho_{\max}$ is the **maximum** value for the density consistent with the data and $\rho_{\min}$ is the **minimum** value for the density.
>
> $\rho_{\max} = \frac{m+\Delta m}{V-\Delta V}$ and $\rho_{\min} = \frac{m-\Delta m}{V+\Delta V}$.
>
> Now, take a close look at the + and - signs in the relations above and note that $\rho_{\max}$ is *not* the maximum mass over the maximum volume, but rather the maximum mass over the *minimum* volume. Take a moment to make sure you understand why!

This approach will give a *worst-case estimate*: the density reaches its limiting value $\rho \pm \Delta\rho$ only when *both the mass and volume* are at the appropriate ends of their respective ranges. If the uncertainties in mass and volume were random and uncorrelated, one might expect this to be rather unlikely, and the above procedure would then give an *overestimate* of the uncertainty. On the other hand, if the uncertainties in mass and volume are systematic errors, this worst-case scenario may be most appropriate.

The estimate provided by the method outlined here may be a bit too large but will nearly always will be within a factor of 2 of that calculated by the statistically rigorous approach. So, in most cases this degree of accuracy for our uncertainties will be adequate – clearly, the calculation of uncertainties is sometimes not a very exact science and it is always important to document **how** you calculate your uncertainties, not just your final result.

G. Uncertainty in the Slope and y-intercept of a Linear Fit

(Reference: *J. Higbie, Am. J. Phys., Vol. 59, No. 2, February 1991*)

You will frequently need to calculate results using the slope or y-intercept from a line that you fit through your data. Though the derivation goes beyond the scope of this class, it is easy to calculate the uncertainty in the slope and y-intercept from the standard parameters that are supplied to you with your linear fit when using a program such as *Excel*.

- The uncertainty in the slope (δm) is given by:

$$\delta m = \frac{|m| \tan\big(\arccos(R)\big)}{\sqrt{N-2}} \tag{1}$$

  where m is the slope, R is the square root of the R^2 value (i.e. correlation coefficient) from the linear fit, and N is the number of data points in the data set that was plotted.

- The uncertainty in the y-intercept (δb) is given by:

$$\delta b = \delta m \cdot x_{\text{rms}} \tag{2}$$

  where x_{rms} is the *root mean square* value of the x values (see below).

- The root mean square value of a set of x values can be found as

$$x_{\text{rms}} = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{N} x_i^2\right)} \tag{3}$$

A difficulty sometimes occurs when using standard software like Excel or Google Sheets to display the linear fit (trendline) equation and correlation coefficient. Sometimes, especially when the R^2 value is very close to unity, the above-described method becomes inaccurate, or worse, the software rounds the value of R^2 to 1 and the above formula cannot be used (it results in an uncertainty of zero, which is incorrect.) In that case, you will need to find the values of R^2 (and sometimes the slope or y-intercept) to greater precision than Excel provides by default—that is, you need the software to supply more significant digits instead of automatically rounding. In Excel or Google Sheets, you can use the function "= correl(A1:A10, B1:B10)" typed in any vacant cell (with quote marks omitted) to evaluate the R-value of your data to any desired degree of precision. Here the descriptors A1:A10, B1:B10 indicate the range of the spreadsheet where the data is located (you will have to adjust for the location of your own data). You can use the Format (Cell) command to increase the number of significant digits displayed. Please ask your lab instructor if you need help with this pesky, and not so-very-rare, issue.

Further Reading

Students interested in further reading on the subject of error analysis are directed to John Taylor's excellent and highly accessible text *An Introduction to Error Analysis*.

PHYSICS 110 - EXPERIMENT 1

INVESTIGATING MOTION AND USING IOLABS

1 Introduction

In this lab, you will be exposed to many of the physics concepts and experimental techniques that will be revisited throughout the term in lab. This week, you will be introduced to tools we will be using this term: the *iOLab device* and accompanying software, and the process of plotting data using *Google Sheets, Excel* or other computer plotting software.

For many of you, this experiment introduces new software to learn as well as many new ideas. Recognize it is OK if you do not master it all on this first exercise, but you *must* focus energy on building these skills as you will need them throughout the term. In addition to building skills with the software and hardware, this lab will also reinforce what you are learning in class about displacement, velocity, and acceleration. A good scientist needs to understand their tools as well as the theory behind experiments in order to be successful in the laboratory. Even if some of these steps seem simple, please take the time to do them carefully as there are many subtle details to learn.

2 Procedure

A. Exploring Position, Velocity, and Acceleration using the iOLab (Wheel)

(i) Log in to a lab computer and launch the **iOLab App**.

(ii) Turn on the iOLab the device then initiate the `Wheel` *sensor*.

(iii) Place the iOLab device on a relatively smooth surface face-down (i.e. on its wheels). Press the `Record` button Record in the **iOLab App** then begin to roll the iOLab device across the surface watching how the device records the one-dimensional *position* from the starting position as well as *velocity* and *acceleration*.

(iv) Note the that *zero-point* of *position* can be reset while you are running the experiment by pushing the `Rezero sensor` button.

(v) By default the experiment is set to run indefinitely, however you should click the `Stop` button Stop when you are not taking data. You may simply click `Continue` when you wish to start taking data again.

(vi) At any time if you wish to start over you may click the `Reset` button Reset CAUTION: this will erase the data you just took from the screen. However, your data runs are automatically saved and can again be found using the `Local resources` function but may be a little tricky to retrieve. If you want to find the saved data, your data file is saved to the folder Documents/IOLab-workfiles/rawdata and the filename indicates the data and time.

(vii) You also may save your current data and start a ***new*** data-collection run by clicking on the `Add run` button 

.

(viii) Try several simple practice experiments such as rolling the cart up an incline, along a flat surface, etc. . Take time to adjust how your data are displayed (e.g., zooming in to a region, adjust the range, taking average over a region, etc.). You will need to display your data in a multitude of ways during the term.

B. Experiments

1. Push the cart with a roughly constant velocity along a smooth surface. This can be a part of a longer run, but you will need to change the range such that the region with constant velocity is clearly visible.

    - Using the measurement tools in the *iOLab Application* determine the velocity you pushed the cart with using the **position graph**. Assume an uncertainty of 5% on your velocity derived through this method. Take and save a screenshot showing your measurement.
    - *Using the same section of data*, now look at the **velocity graph**. Again using the measurement tools determine the velocity (given by μ in the iOlabs graphs) and appropriate uncertainty (given by σ). Take and save a screenshot showing your measurement. In Windows, a convenient tool for taking a screenshot of part of the screen is SnippingTool.
    - Again using the same section of data, now look at the **acceleration graph**. Determine the value and uncertainty of the acceleration from the plot (same method as above) and save a screenshot.
    - Use these data to answer Question 1 (include the screenshots with your answer)

2. Place the cart at the top of a notable downward incline with the y-axis of the *iOLab cart* pointed down the incline and release it from rest (take care not to let the device fall off a tall ledge or similar; it can break!).

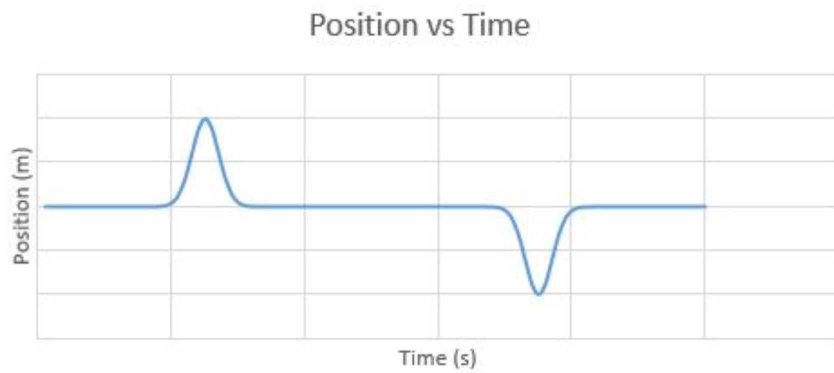
    - To begin, look at the velocity graph and highlight the portion where the cart was rolling down the incline. This should be easy to identify if you consider what should be occurring as the cart rolls down the incline.
    - Can you determine the velocity of the cart using the same methods you used in the previous experiment? Why or why not?
    - Take a screenshot to support your answer.
    - Answer Question 2.

3. Repeat the procedure from Experiment 2 of having the cart roll down a smooth incline in the positive y-direction, now from **two different starting heights** (so you will have

data from three different heights altogether.)

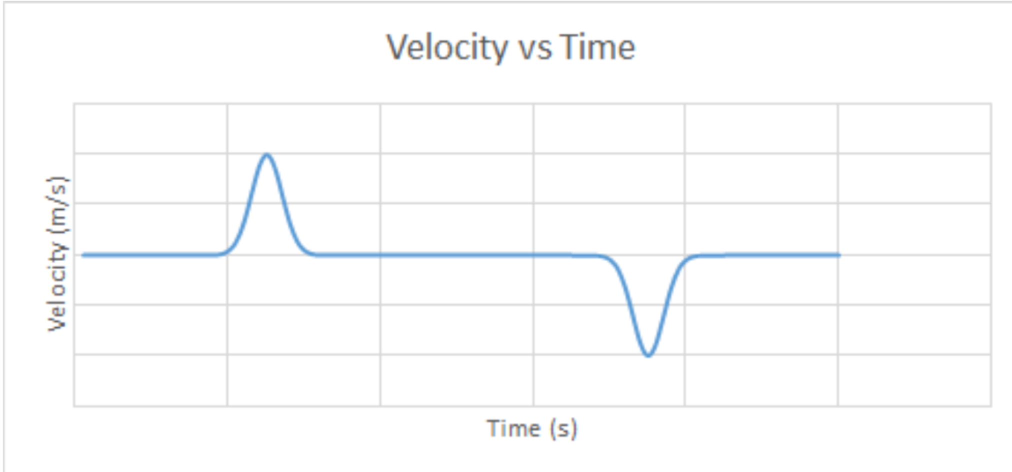
Determine the ***maximum speed*** of the cart for each starting height, which should be when the cart reaches the bottom of the incline. ***Make sure to also record each starting height****, i.e., the distance between where the cart is released and where it either leaves the incline or is stopped.*

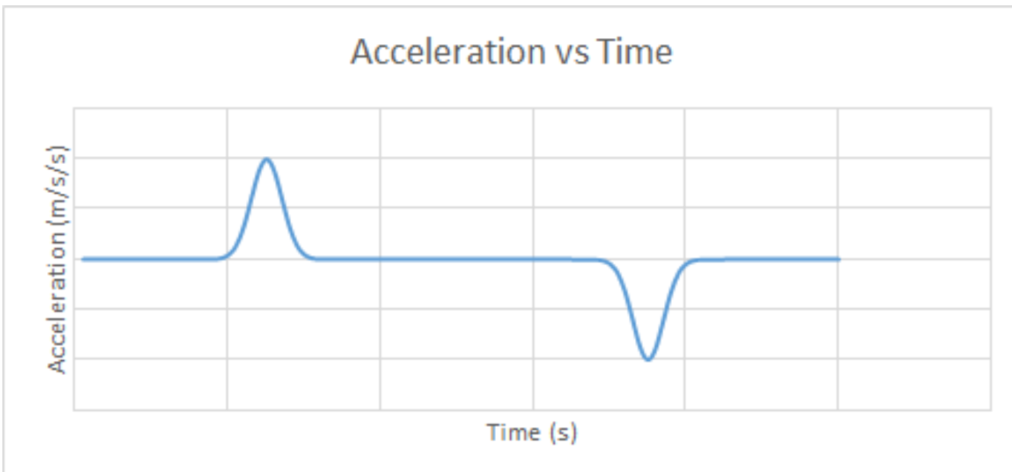
- Make a table showing your measured starting height (h), maximum speed (v_{max}), and maximum speed squared (v^2_{max}) for each case.
- Answer Question 3 (include your data table with your answer)



4. Adjust the display of the iOLab app display so that it shows only the cart's position, not the velocity or acceleration graphs. With the cart on the horizontal lab bench, figure out how to move the cart so that its position graph looks like the example shown above.
   - Take a screenshot of your resulting graph.
   - Answer Question 4 (include the screenshot of your position graph).

5. Repeat Experiment 4, but moving the cart so it reproduces first the v vs. t graph shown above, and then the a vs. t graph.
   - Take a screenshot of your resulting graphs.
   - Answer Questions 5 and 6 (include the screenshots of your position graphs).





3 Questions

If you have not already, make sure to read over PREPARING LABORATORY REPORTS. Your LAB REPORT must include the answer to each of these questions as complete sentences with requested responses or numerical results explained completely in the proper context of the experiment.

> *For example, if a question says: "3. In Procedure C, what current did you determine to be flowing through the resistor?"*
> *You would want to write an answer similar to: "3. We found the current through the resistor to be* 35.2 ± 0.1 *mA." Make sure you also always answer all parts of the question asked.*

1. Referring to the data in Experiment 1.
   a. What value did you determine for the average speed using the position graph? Include uncertainty, reporting your answer in the form $X \pm Y$, where X is the measured value and Y is its uncertainty, using proper units and significant digits. Explain how you determined the value and include a screenshot. Recall

that the uncertainty in the slope value in this question may be considered to be ±5% of the slope value supplied by the iOLab software.

b. What value did you determine for the average speed and its uncertainty using the velocity graph? Express similarly to part (a). Explain how you determined this value and include a screenshot. Recall that the uncertainty in the velocity determined from the velocity plot is given by the σ parameter reported by the iOLab software.

c. Are your two results for the average velocity consistent with each other within the uncertainties?

d. Do your acceleration data in this region confirm that the velocity was *constant*? Report the value of acceleration and its uncertainty as determined from the acceleration vs. time plot and explain briefly. Include your screenshot.

2. Referring to the data in Experiment 2:

   Are you able to determine the velocity of the cart using the same methods as the Experiment 1? Explain clearly why or why not. Include a screen shot as part of your explanation.

3. Referring the data in Experiment 3.

   a. Explain how you determined the starting heights and maximum velocities.

   b. Using *Google Sheets, Excel*, or something similar, plot v_{max}^2 vs. h. Plot using mks units.

      When asked to make a plot of A vs. B – "A" is always on the y-axis and "B" is always on the x-axis

   c. Fit a line to your plot and display the fit on your plot. Include your plot.

   d. Do your data suggest that v_{max}^2 is linearly correlated to h? Explain.

   e. What are the units of the slope of the line you plotted? Given this answer, what quantity do you suspect we are able to derive from this slope? (e.g. velocity, energy, momentum, etc.)

      ***Why** we are plotting v_{max}^2 may not have been presented yet in class. This question is first about working through the procedure and software/concepts. Second, it is about how **dimensional analysis** can be a useful tool.*

4. Referring to the data in Experiment 4:

   Explain how you moved the cart to create the desired position vs. time graph and why that method makes sense. Include your screenshots.

5. Referring to the data in Experiment 5.:

   Explain how you moved the cart to create the desired...

a. velocity vs. time graph and why that makes sense.

b. acceleration vs. time graph and why that makes sense.

PHYSICS 110 - EXPERIMENT 2
Measuring Acceleration

1 Introduction

In last week's experiment, we began investigating the motion of an object moving in one dimension. We will continue those investigations in this week's experiments, where we will make measurements on accelerating systems and determine the value of g, the acceleration due to gravity at the surface of the Earth.

2 Procedure I - Free Fall

Perhaps the most straightforward way to determine the acceleration due to gravity is to measure the acceleration of a freely falling object. You will perform such an experiment using photocell gate (i.e. photogate) detectors for timing. The photogate consists of a light emitter and a light detector separated by a distance. The light emitter produces an invisible beam of infrared light which is received by the detector. When an object, such as a falling ball, passes through the photogate, it blocks the light beam. Computer-controlled electronics can measure the time that the beam is blocked or the time delay between successive interruptions of the beam.

In this experiment, you will drop a ball so that it falls through two photogates in succession (see Figure 1). The ball falls a distance y_1 before reaching the first photogate and then continues falling through a total distance y_2 before passing the second photogate. You will measure the time interval T between the passing of gate 1 and gate 2. Knowing y_1, y_2, and T, you can deduce (as you were to do for the Prelab) the acceleration due to gravity, g.

1. **Set Up Apparatus**
    - Photogates emit an infrared (IR) beam on one side and detect that beam on the other side of the gate. They work by periodically checking to see if the beam is blocked/unblocked and recording the time when the state of the gate (blocked/unblocked) changes.
    - The photogates are mounted on a vertical rod with photogate 1 on top and the photogates in good vertical alignment. Use a meterstick to ensure good vertical alignment of the photogates. Position the horizontal "drop indicator bar" directly above photogate 1, as shown in Figure 1.
    - Connect the top and bottom photogates to the Dig/Sonic1 and Dig/Sonic2 slots, respectively, of the Vernier LabPro interface. Open the LoggerPro software. Click on the LabPro icon (the blue-green rectangle in the upper left of the screen) and verify that LoggerPro has automatically recognized the photogates. Right-click on photogate 1 and set it to “Photogate timing”. Do the same for photogate 2. Then close the LabPro window.

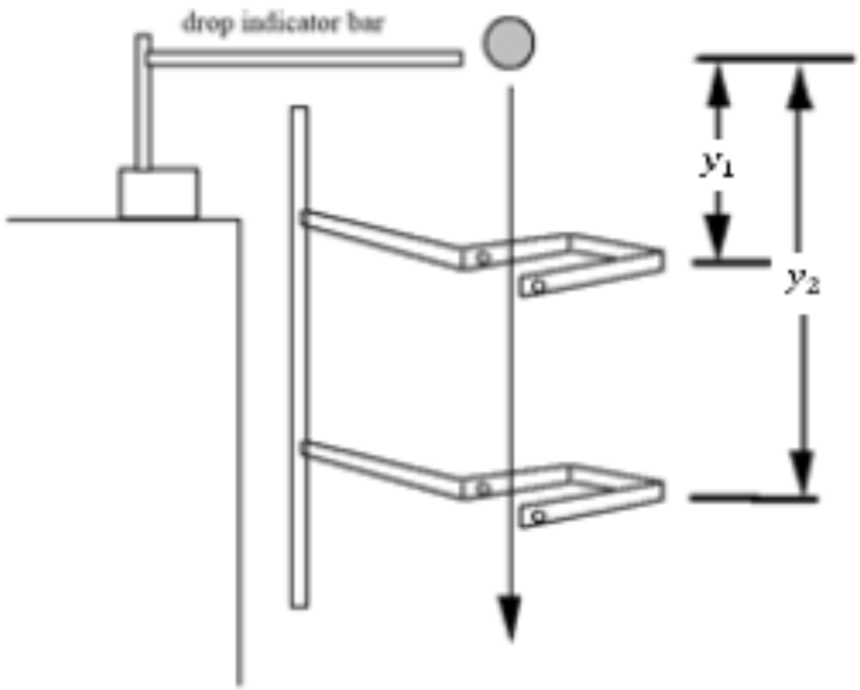


Figure 1: Diagram of experimental set up.

2. **Verify the photogates are working**
   You should see three columns of data: `time`, `GateState1` and `GateState 2`.

   - A GateState value of 1 indicates the infrared beam is blocked. The time associated with a gatestate of 1 indicates the time interval between the click of the collect button and when the beam was first blocked.
   - A GateState value of 0 indicates the photogate is not blocked. The time associated with a gatestate of 0 indicates the time interval between when the beam was again detected after being blocked.

3. **Set-up Data Collection**

   - Under the `Experiment` heading, select `Data Collection` and set the experiment time to 60 sec and the sample rate to 1000 samples/sec. *What does the sample rate tell us about the uncertainty of our time measurement? What if the sample rate were 1 sample/sec?*
   - Click `Collect`, and then pass your hand between each of the gates. Verify that the gate states are as you expect and that the time intervals are reasonable.

4. **Perform the Experiment**

   - Holding the ball at the level of the "drop indicator bar", drop the ball through the photogates. **Be sure that the ball passes cleanly through both photogates**–if the ball bounces off the sides of one of the gates the results will be poor and you should repeat the experiment.

- Measure and record the distances y_1 and y_2 and their respective uncertainties. Determine and record the time interval T for the object passing from one gate to the next. Take at lease four more runs and record the time values you obtain in a table.

3 Procedure II - Acceleration on a Ramp

With an analysis only incrementally more difficult than for the free fall experiment, one can determine the acceleration due to gravity by measuring the acceleration of an object sliding or rolling down a ramp. The analysis of this problem will be discussed soon in class, but at this time we are concerned with the measurements.

1. Using a meter stick, take measurements to determine the angle of the ramp and its uncertainty.
2. Launch the iOLab App and turn on the iOLab cart. Select the `Wheel` option and show the acceleration chart only. On the chart's `Settings`, select Autoscale. Set the run time to 5 seconds.
3. Orient the cart at the top of the ramp with its y-axis pointing downhill. Click the record button and let the cart accelerate downhill.
4. Select the region of the resulting graph in which the acceleration (a) was more or less constant, and record the average value and standard deviation of (shown as μ).
5. Repeat three more times and find the average value and standard deviation of a_{downhill}.
6. Repeat steps 3-5, but launch the cart uphill on the ramp and find the average value a_{uphill}.

4 Questions

1. Figure 1 shows a diagram of the set up for first experiment. The ball is released at height y_1 above the photocell gate and a distance y_2 away from a second photocell gate. We measure the time T taken to traverse the distance between the photocell gates. Derive an ***algebraic expression*** for g in term of y_1, y_2 and T.

   Hint: It will be useful to express the time it takes to travel from the release point to the first photocell gate (through the distance y_1) as t_1 and the total time from the release point to second photocell gate as t_2 and then recognize that $t_2 - t_1 = T$.

2. (a) Show your data table for the five ball drop trials. Also calculate the average value of the time T taken for the ball to travel from the upper to the lower photogate. Assume the timing has a systematic uncertainty of $\pm 0.002s$. Report the average value of the time difference in the standard form of *value* $\pm$ *uncertainty*, that is $\bar{T} \pm \Delta T$, using proper significant digits and including units.

   (b) Calculate the acceleration due to gravity g from your data. Then calculate the maximum value value of g consistent with your experiment, taking into account the uncertainties in y_1, y_2 and

$\bar{T}$, showing your calculation. The uncertainty can be taken to be $\Delta g = g_{\text{max}} - g$. Report your answer for the acceleration due to gravity and its uncertainty in standard form.

(c) What is the percent difference between your results and the accepted value of g (9.80 m/s^2)? Note that it is customary to round percent differences to one (or at most two) significant digits. *Percent Difference* is found by taking the difference between your measured and accepted value divided by the accepted value. Or, mathematically:

$$(\frac{\text{measured - accepted}}{\text{accepted}}) \times 100\%$$

(d) Are your results consistent with the accepted value? Explain. Note that the two numbers agree if they are within 2× the uncertainty width, that is, if $|g_{\text{experiment}} - g_{\text{accepted}}| < \Delta g$.

3. (a) Calculate $sin(\theta)$, the sine of the angle between the ramp and the horizontal, using your distance measurements of the inclined ramp. Then calculate the maximum possible value of $sin(\theta)$ consistent with the uncertainty in your measurements. Show your calculations. As usual, take the uncertainty in $sin(\theta)$ to be the difference of those two values, and report $sin(\theta)$ and its uncertainty in standard form.

(b) Consider your iOLab cart data. Given that the cart's friction is not negligible, should a be larger for the uphill or the downhill runs? Explain. (Hint: What should the direction of the frictional force be in each case?)

(c) Average your final values for a_{uphill} and a_{downhill}. Average the uncertainty values also, and report your experimental value for a and its uncertainty in standard form.

(d) It is plausible that $\bar{a}$ should give you the acceleration the cart would have in the absence of friction. Without friction, we expect an acceleration of $a = g\sin(\theta)$. Use your data to determine $g_{\text{experimental}}$ and its uncertainty. Note that to find the uncertainty, you'll need to find the maximum value of g consistent with the uncertainties in a and in $sin(\theta)$. Show your work. Report your final answer for g and its uncertainty in standard form.

Is your result consistent with the accepted value of 9.8 m/s^2? What is the percent error?

PHYSICS 110 - EXPERIMENT 3
Introduction to Forces

1 Introduction

You will be performing two different experiments studying the nature of acceleration as a vector using an inclined plane. You will be introduced to a new tool on your iOLab devices, the `force sensor`. Introductions to each of the experiments are presented below.

2 Procedure

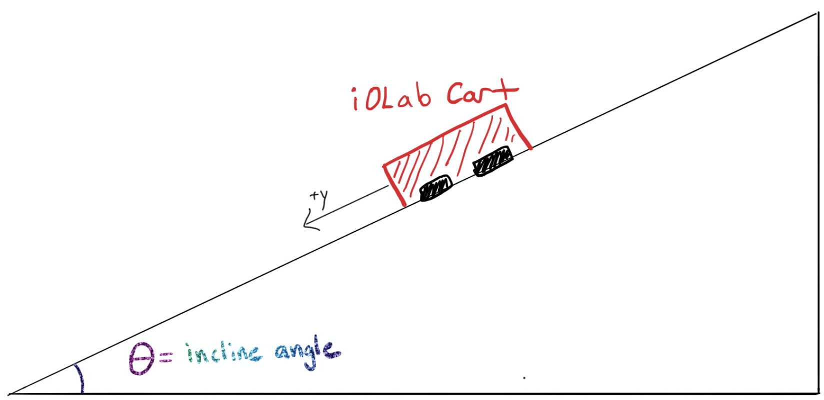


Figure 1: The inclined plane set-up with incline angle θ.

The Inclined Plane I - Gliding (with small friction)

A. Introduction

We would now like to study *the inclined plane* and an object gliding without friction, as an ideal system for studying one-dimensional, translational motion. Your iOLab cart rolls on wheels with smooth bearings that are not frictionless, but when rolling on a smooth surface over a short distance, the friction in the bearings is relatively minimal and we can get a fairly good approximation to ideal "frictionless results", though you will see they are not perfect.

We say our cart exhibits translational motion as all the points on it move together at the same velocity (i.e. the cart isn't rotating). You may have noted that the *wheels* of the car are *rotating* so the motion is not entirely translational. However, you'll also notice the wheels have *very little mass* and this means that the the carry very little rotational inertia and rotational kinetic energy (which you will learn about later), and thus the rotational contributions to the motion are very small and we will consider the motion as a pure translation. This is a good example of how we can use a simplified model (neglecting friction and rotational motion) to gain insight into a not-so-simple physical system.

B. Perform Experiment

i. Set up an inclined plane (like you did in Experiment 1 and as shown in Figure 1). You will need to **determine the angle.** Measure that angle as before by making measurements of length and height using a meter stick. Be careful and clear about what measurements you are taking.

ii. We will be now rolling the carts down the incline and measuring the acceleration of the cart using the `Wheel` sensor. Connect and sync the iOLab with your computer. Place the iOLab cart on the incline wheels-down with the y-axis pointing down the incline, but keep your hand (or something) in front of it so that it doesn't yet roll down the incline.

iii. Initiate the `Wheel` sensor and make sure the velocity plot is on. You will not need the position or acceleration plot for this experiment.

iv. Begin recording data. Release the cart and let it roll to the bottom of the incline, being careful to catch the cart at the bottom. Please protect the cart and its good wheel bearings from unnecessary jolts!

v. Before proceeding take a moment to change the limits on your data (i.e. zoom in) such that the region where the cart was smoothly gliding down the incline is clearly displayed. This will be easily identified as a region of constant acceleration where the velocity is increasing linearly.

vi. Drag the cursor over the linear region and the software will display the measured data. Record the value for the slope (denoted s and expressed in units of m/s^2.) Then repeat 3 more times. Record your four values of acceleration.

vii. Repeat this procedure four more times using different incline angles (that is, for a total of five different incline angles.)

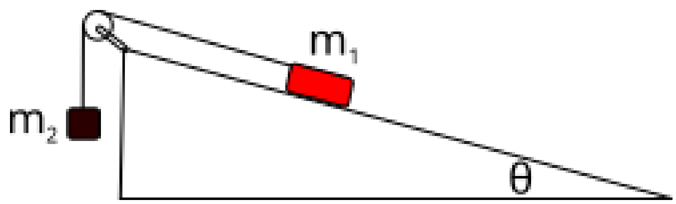


Figure 2: Set-up for the force balance experiment.

The Inclined Plane II - Force Balance:

A. Introduction

We would now like to further study the forces at work by attaching a hanging mass and *balancing the forces* on the iOLab. In order to do this we will again need to build an inclined plane, attach a pulley and also attach a string conecting the iOLab to a suspended mass over the pulley.

B. Perform Experiment

i. Connect a string to your ioLab cart, place your cart wheels-down on the inclined plane (with an angle of at least 20 degrees), and pass the string over the pulley as shown in Figure 2 above.

ii. Add masses to the hanging string until you balance the forces such that the iOLab does not move either up or down the incline. Explore the range of masses that will satisfy the "balanced" condition. Half of this range will be your uncertainty. Record the maximum and minimum suspended masses (which is equal to the respective tensions in the string).

iii. Add a 50 g mass to your cart and repeat the experiment. Repeat the experiment for added masses of 0, 50, 100, 150, and 200 grams.

3 Questions

1. Report your measurements from Experiment I in a table with columns for the measured dimensions of the incline, $\sin(\theta)$, where θ is the angle the incline makes with the horizontal, and $\bar{a}$, the average acceleration at each incline height.

2. (a) Assuming the cart is sliding down the incline frictionlessly, derive an algebraic expression for g, the acceleration due to gravity, in terms of $\bar{a}$ and θ. Show all the steps.

   (b) Make a plot of $\bar{a}$ vs. $\sin(\theta)$. Explain clearly how you can use the properties of the linear fit on your plot to determine the numerical value of g.

   (c) Calculate the uncertainty in the value of g obtained from your plot, using the method from page xvii (Uncertainty of the Slop and Y-Intercept of a Linear Fit). If the R^2 value on your plot exceeds 0.98, you should use the method described on page xvii to obtain the R-value from Excel or Google Sheets to greater numerical precision (use about 6 significant digits). Show your uncertainty calculation. Then report your final value for g and its uncertainty in standard form (that is, in the form $g \pm \Delta g$ with proper significant digits and units.)

(d) Are your results consistent with the expected value for g ($9.80\ \mathrm{m/s^2}$)? Explain. Do the assumptions of the model used (negligible friction and rotational dynamics) appear to be justified?

3. (a) Refering to Figure 2, draw well-separated force diagrams showing the forces on m_1 (the iOLab cart) and m_2 (the hanging mass). Label each force vector and describe in words each force vector. To "describe" a force, you must state whether the force is *contact* or *gravitational*, which agency is exerting the force, and which mass the force is acting on.

   (b) Balancing force components along the incline, derive an expression for m_1 as a function of m_2, g, and the incline angle θ.

4. (a) Replace m_1 in your expression above with $m_1 + \Delta m$, where m_1 denotes the mass of the ioLab cart and Δm denotes the added mass. Suppose a plot were made with m_2 on the y-axis and Δm on the x-axis. Show that the result would be a straight line and derive algebraic expressions for the slope and y-intercept. (*Algebraic expressions* means that you should express the slope and y-intercept in terms of symbols like m_1, g, and θ and not use numbers.)

   (b) Now make the above-described plot and display it in your report. Find numerical values for the slope and y-intercept. Also find the uncertainties in the slope and y-intercept, using the method described on page xvii. Show your work. Report your experimental values for the slope and y-intercept and their uncertainties in standard form.

   (c) Using the values obtained above, determine the mass m_1 of the ioLab cart, and its uncertainty. Show your work. Report your experimental value for the mass of the cart and its uncertainty in standard form.

PHYSICS 110 - EXPERIMENT 4
INCLINED SEMI-ATWOOD MACHINE

1 Introduction

This week, we will revisit the static equilibrium experiment investigated in last week's lab. By increasing the hanging mass so that the balance condition is upset, the equilibrium is disrupted and the system undergoes uniform acceleration. We will use Newtonian dynamics to analyze the accelerating system.

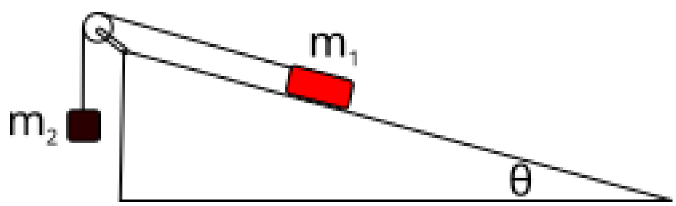


Figure 1: Set-up for the inclined semi-Atwood experiment.

2 Procedure

1. Your set-up should consist of the ioLab cart on an incline with a string from the cart running over a pulley to a hanging mass as shown in Figure 1 above.

2. Make measurements with a meterstick to determine the angle θ your incline makes with the horizontal. Record your measurements and their estimated uncertainties.

3. Weigh your ioLab cart on a triple beam balance and record its mass and the estimated uncertainty.

4. Place the cart on the incline, pass the string over the pulley, and add the smallest mass to the mass hanger so that the cart, when released from rest, accelerates smoothly up the incline. A reasonable approach would be to find the mass that balances the cart in static equilibrium, and then add about 20 g of additional mass. You could choose a bit more or less in order to minimize the number of mass disks piled on hanger.

   Be careful not to let the cart drop or collide roughly with the pulley–please catch the cart gently and protect its good wheel bearings.

5. Start the ioLab software, choose the `Wheel` sensor, and select the velocity vs. time plot. Release the cart from the bottom of the incline, allowing it to accelerate upward toward the pulley (and catch the cart before it strikes the pulley!) Use the software zoom tools to zoom in on the linearly increasing range of the acceleration, then use the analysis tool to drag over the linear region and display the slope. The slope is denoted "s" and given in units of m/s^2. Record the slope. Repeat four more times, recording each value of the slope, then find the

average. This will be the average acceleration of the cart for your initial value of hanging mass m_2.

6. Repeat the above procedure four more times, each time adding 20 g to the hanging mass m_2.

3 Questions

1. Display your data in a table with columns for the hanging mass m_2, the average acceleration $\bar{a}$, and the value of $(m_1 + m_2)\bar{a}$.

2. (a) Starting with well-separated force diagrams for m_1 and m_2, set up and solve Newton's equations to derive an algebraic expression for acceleration a in terms of the parameters m_1, m_2, acceleration due to gravity g, and the incline angle θ.

   (b) Suppose one were to plot the quantity $(m_1 + m_2)a$ on the y-axis vs. m_2 on the x-axis. Show that such a plot must be linear and find algebraic expressions for the slope and y-intercept of the plot. Hint: From your solution in part (a), rearrange terms so that the quantity on the y-axis, $(m_1 + m_2)a$, appears on the left side. Can you arrange the terms on the right side in the form $const \times x + const$, that is, in the form $mx + b$?

3. (a) Make the plot described in the previous question. If the R^2 value is above 0.98, be sure to use the method described on p. xvii to find the value of the linear correlation coefficient R to greater numerical precision.

   (b) Find the uncertainty in the slope and y-intercept values, using the method described on p. xvii. Show your work. Report the numerical values of slope and y-intercept along with their uncertainties in standard form.

4. (a) From your finding for the slope of the plot, what value do you determine for g, the acceleration due to gravity? Is your measured value in agreement with the accepted value of 9.80 m/s^2? Explain.

   (b) If your value differs from the accepted value, can you suggest a probable source of systematic error that could account for the discrepancy?

5. (a) Calculate $sin(\theta)$, the sine of the angle between the ramp and the horizontal, using your distance measurements of the inclined ramp. Then calculate the maximum possible value of $sin(\theta)$ consistent with the uncertainty in your measurements. Show your calculations. As usual, take the uncertainty in $sin(\theta)$ to be the difference of those two values, and report $sin(\theta)$ and its uncertainty in standard form.

   (b) Use the numerical value you obtained for the y-intercept of the plot to calculate $sin(\theta)$. Your calculation will also involve g and m_1 and their uncertainties. You may use the accepted value of g for this question and assume that it has negligible uncertainty. Is the value of $sin(\theta)$ you calculated consistent with the value calculated in part (a)? Explain. Roughly speaking, two measured values are called consistent if they differ by less than twice their uncertainty (which you may approximate as the sum of the two uncertainties.)

PHYSICS 110 - EXPERIMENT 5
ACCELERATING SYSTEMS

1 Introduction

This week, you will perform an experiment, shown in Figure 1 below, similar to last week's but with two novel features: sliding friction will be important, and the moving masses will have related but distinct accelerations. Since the iOLab cart will be sliding rather than rolling, we'll use its on-board accelerometer sensor to measure accelerations. In the analysis of the experiment using Newton's laws, you will be able to determine the acceleration due to gravity g and the coefficient of kinetic friction μ_k.

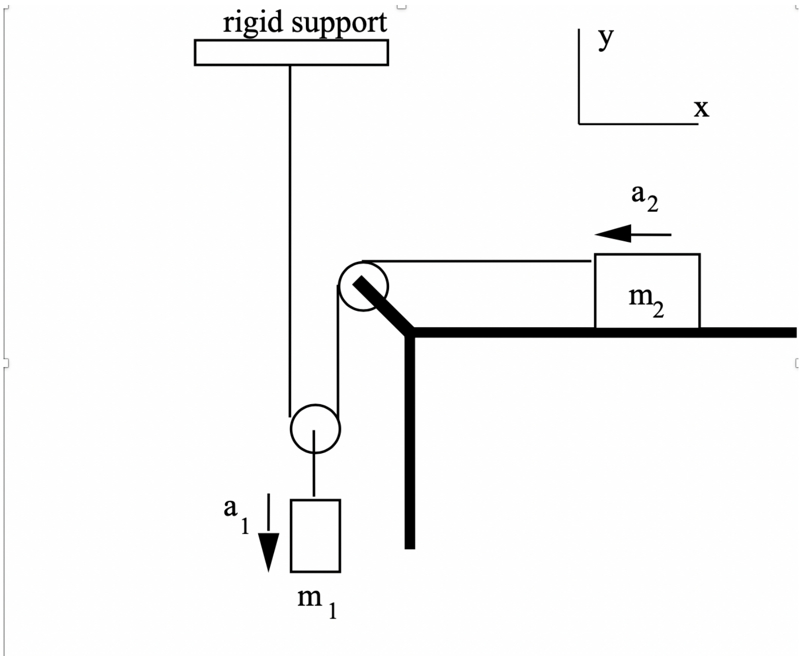


Figure 1. The two-mass system of Experiment 4.

2 Procedure

A. Calibration and Set-Up

i. This week we will introduce the accelerometer sensor housed within the iOLab cart. First, you must calibrate the accelerometer: in the iOLab app, with the iOLab device turned on, click on the gear icon and go down to `Calibration` → `Accel - magn - gyro`.

ii. Follow the directions in the prompts to calibrate the accelerometer. Be sure to use a level surface when calibrating the device.

iii. Use the triple beam balance to measure the mass of the iOLab cart.

iv. Use the triple beam balance to measure the mass of the hanging pulley. Don't forget to include this mass and the 50g mass hanger when you calculate m_1.

v. Arrange the apparatus so the string passes over the fixed pulley and under the moving pulley as shown in Figure 1.

B. Add 150g to the mass hanger. **Record the total mass of m_1 and its estimated uncertainty**. Carefully rub down the surface of the table on which the iOLabs cart will slide with a clean dry cloth. (This step is to help ensure the friction remains constant for successive measurements.)

C. Put the cart on the opposite end of the table from your hanging mass and set it down on the felt pads (*not the wheels!*) and hold it in place so it doesn't slide. Make sure your string is running over the pulleys as desired.

D. Turn on the accelerometer and make sure you are recording the acceleration component in the y-direction in which the cart will be moving; turn off the other acceleration component measurements for clarity.

E. Press Record and release the cart and let it slide across the table stopping it with your hand before it reaches the table edge. **Please be sure to gently catch the cart and do not let it fall off the edge of the table.**//

Make sure the cart is sliding smoothly across your table; if it slides with lots of starts and stops add a bit more mass and try again.

F. The plot of acceleration vs. time will exhibit a roughly constant section corresponding to the sliding motion of the cart across the table. Use the zoom tools to zoom in on this region, and use the analysis tool to select the region and display the measured values. Record the mean acceleration and it uncertainty during the time the iOLab cart slid across the table. Repeat this measurement 5 times, and find the average value of the acceleration and its uncertainty.

G. Repeat the above procedure with a total of 5 different suspended masses with added mass from 150 g to 350 g, ()typically) placed on the mass hanger. For each suspended mass, make a table entry showing the hanging mass (m_1), the acceleration of the iOLab cart (a_2), and the uncertainty of each.

3 Questions

1. Display your data in a table with columns for the hanging mass m_1, the average acceleration $\bar{a_1}$, and the value of $(m_1+4m_2)\bar{a_1}$. Your values for m_1 should include the mass of the moving pulley, the mass hanger, and any additional mass used. Note that acceleration $a_1 = a_2/2$; see Question 2b for discussion of this point.

2. (a) Starting with well-separated force diagrams for m_1 and m_2, set up Newton's equations for each mass. Note that the masses have distinct accelerations; denote them by a_1 and a_2.

   (b) Observe that when the falling mass descends a distance x, the iOLab cart slides a distance $2x$. This is true during any interval of time, so the accelerations are related by the *equation of constraint* $a_2 = 2a_1$. Using this relation, solve the force equations to derive an algebraic expression for acceleration a_1 in terms of the parameters m_1, m_2, acceleration due to gravity g, and the coefficient of kinetic friction μ_k.

   (c) Suppose one were to plot the quantity $(m_1+4m_2)a_1$ on the y-axis vs. m_1 on the x-axis. Show that such a plot must be linear and find algebraic expressions for the slope and y-intercept of the plot. Hint: From your solution in part (a), rearrange terms so that the quantity on the y-axis, $(m_1+4m_2)a$, appears on the left side. Can you arrange the terms on the right side in the form $const \times x + const$, that is, in the form $mx + b$?

3. (a) Make the plot described in the previous question. If the R^2 value is above 0.98, be sure to use the method described on p. xvii to find the value of the linear correlation coefficient R to greater numerical precision.

   (b) Find the uncertainty in the slope and y-intercept values, using the method described on p. xvii. Show your work. Report the numerical values of slope and y-intercept along with their uncertainties in standard form.

4. (a) From your finding for the slope of the plot, what value do you determine for g, the acceleration due to gravity? Is your measured value in agreement with the accepted value of 9.80 $\mathrm{m/s^2}$? Explain.

   (b) If your value differs from the accepted value, can you suggest a probable source of systematic error that might account for the discrepancy?

5. Use the numerical value you obtained for the y-intercept of the plot to calculate the coefficient of kinetic friction mu_k. Your calculation will also involve g and m_1 and their uncertainties. For this calculation, use the experimental value of g and its uncertainty that you found above. Does your result for mu_k appear reasonable?

6. Consider the system shown in Figure 1. Suppose $m_2 = 200.0$g, the coefficient of static friction is 0.400, and the coefficient of kinetic friction is 0.300.

   (a) If the system is in static equilibrium, what is the largest possible value of m_1?

   (b) In the above situation, if m_1 is given a slight, brief push, the friction becomes kinetic rather than static. What is the acceleration of a_1 in this case? Show your calculation.

PHYSICS 110 - EXPERIMENT 6
The Conical Pendulum

1 Introduction

The conical pendulum consists of a mass at the end of a string; the upper end of the string is fixed and the mass orbits in uniform circular motion as shown in Figure 1, while the string sweeps out the surface of a cone. By investigating the dynamics of the conical pendulum, we will be able to verify the theory of rotational dynamics presented in class. With the other experimental parameters known, we can use the conical pendulum to measure g, the acceleration due to gravity, providing a quantitative test of the theory of rotational dynamics. The upper end of the string is tied to the force sensor and we can use it to measure both the horizontal component of the force required to keep the mass moving in a circle and the orbital period T, the time it takes to complete its circular orbit.

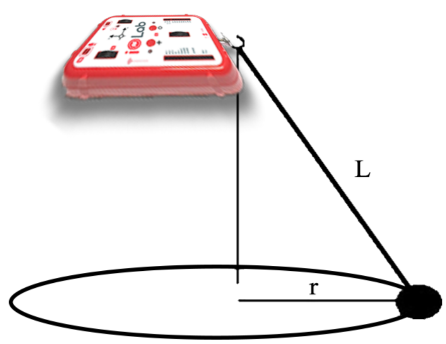


Figure 1: Schematic of the conical pendulum.

A. Procedure

We will be using the force sensor in the iOLab this week. The iOLab force sensor, connected to the small eyebolt on the negative y side of the device, can detect force in only a single direction at a time. This will provide sufficient information to learn a great deal about the system.

1. Open the iOLab Program and turn on your iOLab. Check the `Force Sensor` box and perform a calibration by clicking the gear icon ⚙▾ and selecting `Calibration` → `Force` and following the directions.

2. The eyebolt on your device should be connected to a string about 50 cm long fastened to a small brass ball. Carefully measure the length of the string from its attachment to the eyebolt to the center of the ball using a meterstick. Record your result and its estimated uncertainty.

3. Measure the radius r of the reference circle drawn on paper (this will be the orbital radius of your pendulum) and also its uncertainty. *Note:* The uncertainty in r will **not** be determined by the precision with which you can measure the circle, but instead the precision with which you can get the pendulum to accurately follow the circle, which you will need to estimate reasonably. It would be OK to revisit this estimate after trying to operate the pendulum and seeing how it goes.

4. Make sure the sensor is properly zeroed as well by holding it horizontally (as you will be in the experiment) with no mass and clicking the `Rezero Sensor` button at the bottom of the force vs. time graph. You can rezero at any point during the experiment to ensure that your `Force Sensor` is properly zeroed.

5. Now, practice holding the iOLab device horizontally as shown in Figure 1 and making the ball orbit in uniform circular motion above the reference circle. You will find that it is surprisingly easy to do so and you will not have to move your hand much (although slight, almost unconscious motions are occurring to supply the small amount of energy lost to air resistance and maintain the orbit.) When you are reasonably good at this, you are ready to acquire the data from the force sensor.

6. When you are ready to acquire data, start the ball orbiting over the circle and when the orbit is as desired, begin collecting data by clicking `Record`. Let the ball complete 10 or more orbits, then stop recording by clicking `Stop`. The plot of force vs. time should look like a sine wave. Before proceeding, discuss the following questions with your lab partner(s).
    - Why is the plot sinusoidal?
    - How can the force vs. time plot be used to find the horizontal component of the tension in the string?
    - How can the orbital period be deduced from the force vs. time plot?

7. To analyze your data, select the analysis tool (bar graph icon) and drag the cursor over the region of data between the center of one peak and the center of another peak. Ideally, measure over several complete peaks, perhaps 10 or more. The display will show the total time. Dividing the total time by the number of complete periods will yield the period T of a single orbit. Record this result. Then take a screenshot of your force vs. time plot to be included in your report.

8. Next, you will measure the vertical distance from the top of a peak to the bottom of an adjacent peak, which corresponds to the component of force in Newtons measured by the force sensor. Use the zoom tools to zoom in on one peak and adjacent trough near the center of your data. Then, with the analysis tool selected, you will see the force reading corresponding to the cursor position on the screen. Move the cursor to read the force at the top of a peak and at the bottom of the adjacent peak and take half the difference, which will be the horizontal force (amplitude of the sine wave) in Newtons.

9. Perform a total of at least 3 trials of the experiment. If the values of T or F_h for a given trial differ by more than 10% from the average of your other trials, reject that trial and try again.

2 Questions

1. Display your data in a table with columns for the orbital period T and horizontal force amplitude F_h for each trial. Display also the average of your trials. As a rough estimate of your uncertainty, you can use the maximum difference between the an individual trial and the mean. Report your findings of the mean period T and the mean horizontal force amplitude F_h and their uncertainties in standard form. Also report your measurements for the length L of the pendulum and radius r of the orbit and their uncertainties in standard form.

2. Writing the component equations of motion in the vertical and radial directions, derive an algebraic expression for the period T of the mass's circular motion in terms of the quantities g, r, and L, where g is the acceleration due to gravity, r is the radius of the circular orbit, and L is the length of the pendulum. *Note:* Do not include the angle θ of the pendulum with respect to vertical in your final answer–you can eliminate this parameter using geometry.

3. (a) Using your experimental data and the expression derived above, calculate the acceleration due to gravity g. Also calculate its uncertainty. Show your work. Report your experimental value for g and its uncertainty in standard form.

   (b) Find the percent difference between your experimental value for g and the accepted value of 9.80 $\mathrm{m/s^2}$. Is your experimental value consistent with the accepted value? If not, can you suggest a possible explanation?

4. Derive an algebraic expression for the mass m of the ball in terms of the horizontal component of the tension force (F_h) in the string, the orbital period (T), and the radius (r) of the orbit.

5. Using the expression you derived above and your experimental measurements of F_h, T, and r, calculate the mass of the ball. Does the value you calculated seem plausible? Explain briefly.

6. Is it physically possible to whirl a pendulum around in a horizontal plane with the string perfectly horizontal (assume that your hand does not get in the way)? Explain. (This is a *thought experiment* - please do not try it.)

7. Include your screenshot of the data plot from the lab.

PHYSICS 110 - EXPERIMENT 7

Conservation of Mechanical Energy in a Dynamic System

1 Introduction

In this lab we will reexamine the familiar dynamical system of the semi-Atwood machine shown in Figure 1 from the perspective of *mechanical energy conservation*. When released from rest, the system accelerates, gaining kinetic energy. The principle of mechanical energy conservation asserts that in the absence of non-conservative forces like friction acting on the system the sum of its kinetic energy and potential energy is constant. This implies that, for the two-mass system under investigation, the amount of kinetic energy gained should equal the amount of gravitational potential energy lost. We will use the principle of mechanical energy conservation to determine the unknown mass m_2.

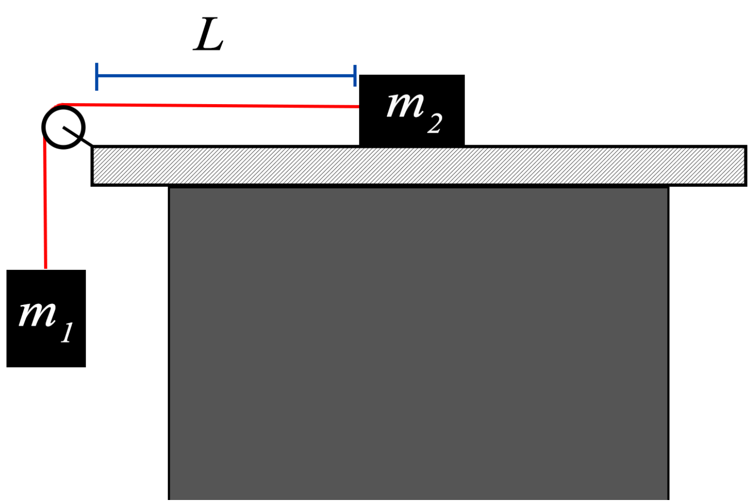


Figure 1: Experimental set-up; m_2 is the `iOLab` cart.

2 Procedure

This week we will be measuring velocity of m_2 (the cart) using the `wheel sensor` on the iOLab.

A. Turn on the iOLab application, connect your device and select the `Wheel` sensor, and uncheck the `Acceleration` plot so that just the `Position` and `Velocity` plots are displayed..

B. Weigh the cart on the triple-beam balance. The paperclip mass is 0.39 ± 0.01 g. Record these masses.

C. The cart will have a string tied to it (this ***should not*** be attached to the force sensor). Attach the paperclip to that string and add to it a hanging mass of 20 g. Pass the string over the pulley and start the iOLab cart back at least 50 cm from the edge of the table on its wheels.

D. Press `Rezero Sensor` under the x-axis of the position plot **before** releasing the cart from rest.

E. Start data collection and release the cart from rest, rolling toward the pulley. **Catch the cart gently before it strikes the pulley**.

F. Using the iOLab graphs, record the velocity of the cart when it has moved 50.0 cm from its starting position. To do so, you will need to use the zoom tools to expand the appropriate regions of both plots, then move the cursor along the position vs. time plot to identify the time coordinate when the position reaches exactly 50.0 cm, then move the cursor along the velocity vs. time plot to identify the velocity coordinate at that moment.// Record the mass used (including the paperclip) and the velocity obtained.

G. Repeat the above measurement twice more. Record each velocity measurement, and then the average of your three velocities measurements.

H. Repeat the above procedure for masses of 40, 60, 80, and 100 g.

3 Questions

1. (a) Display your data in a table with columns for the mass m_1 (including paperclip) and velocity v for each trial. Display also the average of your trials.

   (b) Display another table with columns for the mass m_1, average velocity v, inverse mass $1/m_1$, and inverse velocity squared $1/v^2$.

2. Write the equation of energy conservation for the system shown in Figure 1, equating the system's energy at the moment of release and the moment when each mass has moved by a distance L. Use only the symbols m_1, m_2, L, v, and g, where g is the acceleration due to gravity.

3. (a) Suppose a plot were made with $1/v^2$ on the y-axis and $1/m_1$ on the x-axis. Using the equation you derived above, prove that such a plot must be linear and derive expressions for its slope and y-intercept, expressing your answers only in terms of the variables m_1, m_2, L, v, and g.

(b) Make and display the plot described above. If the R^2 value is above 0.98, be sure to use the method described on p. xvii to find the value of the linear correlation coefficient R to greater numerical precision.

(c) Find the uncertainty in the slope and y-intercept values, using the method described on p. xvii. Show your work. Report the numerical values of slope and y-intercept along with their uncertainties in standard form.

4. (a) Using the slope relation from Question 3a and numerical value you found in Question 3c, determine the mass of the iOLab cart m_2 and its uncertainty. You may use the accepted value of $g = 9.80\ \text{m/s}^2$. Explain your reasoning. Report your experimental result for m_2 and its uncertainty in standard form.

   (b) Report the measured value of m_2 you obtained using the triple-beam balance, along with its estimated uncertainty, in standard form.

   (c) Are the measurements of the cart's mass consistent? If they are not consistent, can you suggest a possible explanation?

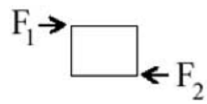
5. (a) Using the y-intercept relation you found in Question 3a, evaluate the predicted y-intercept.

   (b) Is your value for the predicted y-intercept consistent with the experimental value you reported in Question 3c? Explain.

PHYSICS 110 - EXPERIMENT 8
Torque: Rotational Equilibrium and Dynamics

1 Introduction

Earlier in this course you learned that for a body to be in static equilibrium, the sum of the force vectors acting on that body must be zero (i.e. $\sum_i F_i = 0$). However, that is not the only necessary condition for an object of nonzero size (i.e. anything but a point mass) to be in static equilibrium. A glance at the following object will illustrate this:



Suppose the above mass has two forces acting upon it which add up to zero. By Newton's Second Law, the object will not accelerate along a line, **but it will begin to rotate**. The two forces create a ***torque*** on the mass, and the result of this torque is an angular acceleration which leads to rotation. This fact can be expressed as the rotational analog to Newton's second law:

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

where τ is the torque, α is the angular acceleration and I is the rotational inertia (known as the *moment of inertia*) of the object. In this week's lab we will do one experiment to study ***rotational equilibrium*** and a second experiment to study ***rotational dynamics***.

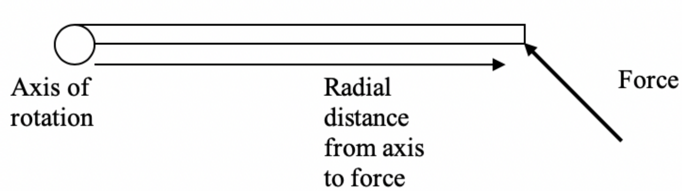
2 Procedure

I. Rotational Equilibrium

A net torque causes an angular acceleration (changing rate of rotation) about some axis of rotation. The magnitude of a torque is given by

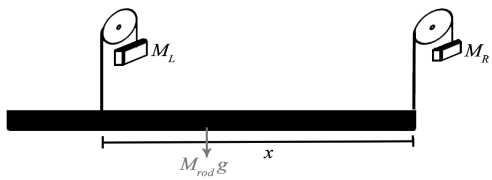
$$\tau = R\,F\,\sin(\phi),$$

where R is the radial distance from the axis of rotation to the point of the force's application, F is the magnitude of the force, and ϕ is the angle between the two. It should be clear that the maximum torque will occur when a given force F is applied perpendicularly to the radial arm R (i.e. tangentially). This explains why it is easier to open a door when you push farther from the side with the hinges—you get a larger torque for the same applied force.



Just as an object at rest must have a net force of zero in order have no translational motion, the object must have a net torque of zero to experience no rotational motion.

Consider a rod of length L being supported horizontally by two strings, one at its right end and one a distance x from the right end (see the figure below). Including the force due to gravity, there will be three forces acting on the rod. (Note that the force of gravity can be considered as acting at the center of the rod at the rod's center of mass.) These three forces, depending upon where they are with respect to the axis of rotation, may also create torques on the rod.



Torque is a vector quantity, hence it has both magnitude and direction. If a torque tries to induce a clockwise rotation about a given axis, the direction of that torque is into the page (we will call it *negative* in this case). A torque directed out of the page will be positive as it would lead to a counterclockwise rotation. **For a body to be in static equilibrium the sum of the forces must be zero and the sum of the positive and negative torques must also be zero.** In the first experiment you will experimentally determine what masses (M_L and M_R) are necessary to apply forces F_L and F_R that keep the suspended rod in equilibrium.

1. Weigh a meter stick. Your apparatus will have a suspended meter stick with an extra 100 g hanging from its midpoint, and two clamps (22.70 ± 0.05 g each) attached to strings connected to M_L and M_R.
2. Position the string pulling up with force F_R so it is at the right end of the rod. Position the right pulley above that point so that the string is vertical.
3. Position the string pulling up with force F_L so it is 5 cm in from the left end of the rod (i.e. $X = L - 5$ cm), and reposition the left pulley so it is above that point with the string vertical.
4. Adjust the mass on the left and right mass hangers so the rod is **horizontal** and in equilibrium. Experiment to find the *range of masses* that will satisfy this equilibrium condition (i.e. figure out the uncertainty in your values of M_L and M_R.)
5. Repeat steps (3) and (4) with F_L 10 cm, 15 cm, 20 cm, and 25 cm from the left for a total of five positions.

   Fill in Table I below.

$X \pm \delta X$ (cm)	$M_L \pm \delta M_L$ (g)	$M_R \pm \delta M_R$ (g)	$(M_L + M_R) \pm \delta M$ (g)

II. Rotational Dynamics

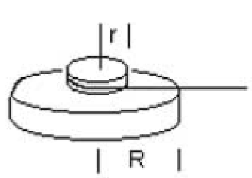
Just as an unbalanced force will create a linear acceleration in the direction of the force, an unbalanced torque will create an angular acceleration in the direction of the torque (i.e. parallel or anti-parallel to the axis of rotation). The angular velocity ω of an object is defined as the rate of change of its angular position ($\omega = \frac{d\theta}{dt}$) in radians/second - recall that 2π radians = 360°. Likewise the angular acceleration α of an object is the rate of change of that object's angular velocity ($\alpha = \frac{d\omega}{dt}$). Angular acceleration is measured in radians/sec^2.

If an unbalanced, or net torque τ_{net} is applied to an object, the object will experience an angular acceleration which is proportional to the net torque: $\tau_{net} = I\alpha$. This is the rotational analog to Newton's second law of motion. The constant of proportionality I in this equation is a measure of the object's rotational inertia - or resistance to angular acceleration -just as the mass M is a measure of an object's resistance to translational acceleration.

For an object of mass M and radial dimension R measured from the axis of rotation, its rotational inertia will always have the form $I = CMR^2$, where C is a dimensionless constant less than or equal to 1.

In this second experiment you will determine the rotational inertia I and the constant C characteristic of a cylindrical disk rotating about its center.

(a) Measure and record the mass of the solid plastic disk. The radius R of the disk is 12.70 ± 0.03 cm and the smaller radius r at which the tension in the string causes a torque on the disk is 1.50 ± 0.03 cm. (Note this is the top-most and narrowest of the spindle slots.)



(b) Note that the bearings for this experiment provide a nearly frictionless environment

for your disk, which can rotate freely. You will use the photocell gates to measure its angular velocity ω as a function of time while a constant torque is being applied.
Determine the angular displacement $\Delta\theta$ the disk makes while the photocell gate is blocked:
measure the width of the photogate "blocker" and the radius out from the center of the disk to the photogate.
Width:__________ Radius: __________ $\Delta\theta$ (radians) = width/radius = __________.
You *may* enter the $\Delta\theta$ into LoggerPro as the width of the blocker in radians, so the program is able to automatically calculate angular velocity in rad/sec as you will see below.

If you then measure the time Δt during which the gate is blocked, you'll be able to calculate the angular velocity as $\frac{\Delta\theta}{\Delta t}$.
You alternatively can have Logger Pro calculate the angular velocity for you: click on the Logger Pro icon, then click on the Photogate icon. Select the `Set Distance or Length` option, and enter the above width in radians, and adjust the units from m to rad. The velocity data column will now show the angular velocities for the times in which the gate is blocked.

(c) Start the Logger Pro software running in the `Gate Timing` mode and set the experiment duration to about 40 seconds.
Recall that to set-up Logger Pro, you'll need to click on small green icon in the upper left of the screen to display the sensors, click on the Photogate sensor, and select `Gate Timing` from the drop-down menu; to set the experiment duration, choose `Experiment`, then `Data Collection`, and enter the desired experiment duration. Also, set the Experiment to measure 1000 samples/second.

(d) After the Logger Pro is set up, hang 40 grams over the pulley on the 1.3 ± 0.1 gram paperclip, center the "gate blocker" in the photocell gate, and release the disk from rest. The computer will then tell you the Δt's for times at which the disk has rotated through 2π, 4π, 6π, 8π, and 10π radians. Record these five times.

Then repeat the above procedure for masses of 60 g, 80 g, 100 g, and 120 g. Be careful to delete data from any rotations occurring after the descending mass has hit the floor.

3 Questions

I. Rotational Equilibrium

1. Display a data table with columns for the distance x, left mass M_L, right mass M_R, total mass $M_L + M_R$, and the quantity $\frac{L}{2x}$. Report units and uncertainties for measured quantities. Report also the meterstick length and mass (without added masses or hangers) and their uncertainties, in standard form.
2. Referring to your data table, what should you expect for the sum of the masses in the $(M_L + M_R)$ column? Are your experimental results in the $(M_L + M_R)$ column consistent with your expectations? Explain.
3. a. Write the torque balance equation for all torques acting about the right end of the

meterstick. Taking note of this relation, show that if M_L were plotted on the y-axis and $\frac{L}{2x}$ were plotted on the x-axis, the plot would be a straight line. Derive algebraic expressions for the slope and y-intercept of the line in terms of the variables of the problem.

b. Make and display the plot described. Determine the slope and y-intercept and their uncertainties. Show your work. Report the slope and y-intercept and their uncertainties in standard form.

c. Using your results for the slope, determine and report the mass of the meterstick and its uncertainty. Is the value consistent with the value reported in Question 1? Explain.

d. Is the y-intercept value determined from the plot consistent with the predicted value from part (a)? Explain.

II. **Rotational Dynamics**

1. For each value of hanging mass m, display a table showing the rotation angle θ, the measured time that the gate was blocked, and the squared angular velocity ω^2. The rotation angle will take the values 2π, 4π, 6π, 8π, and 10π radians. Report your measured values for the radius and width of the gate blocker, along with their uncertainties, in standard form. Show one example of how you calculated the angular velocity ω.

2. For each value of hanging mass m, plot a graph of ω^2 vs. θ. From the slope of each graph, determine the angular acceleration α. Use rotational kinematics to show how the slope is related to α. Show one example of your calculation of α. You need not find its uncertainty.

3. Display a table showing columns for the hanging mass m (including mass hanger paperclip), angular acceleration α (determined in the previous question), $1/m$, and $1/\alpha$.

4. a. Plot $\frac{1}{\alpha}$ vs. $\frac{1}{m}$, and find the numerical values of the slope and intercept of a straight-line fit to the data. Find the uncertainty in the slope, and report the value of the slope and its uncertainty in standard form.

   b. On the next page is shown the derivation of the following equation:

$$\frac{1}{\alpha} = \left(\frac{C\,M\,R^2}{g\,r}\right)\frac{1}{m} + \frac{r}{g}.$$

   Taking note of the above equation, use your plot to determine the constant C and its uncertainty. Show your work. Does the value of C you found experimentally agree with the theoretically predicted value of $\frac{1}{2}$ (see Chapter 10 of Giancoli)? Explain.

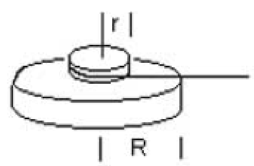
   c. Find the percent difference between your experimental value and the theoretical value of C.

Below we will show that

$$\frac{1}{\alpha} = \left(\frac{C\,M\,R^2}{g\,r}\right)\frac{1}{m} + \frac{r}{g}.$$

.

Consider the wheel to the below in which
r = the radius of hollow disk about which the string was wound, and thus the radius at which a torque due to tension in the string is applied
R = the radius of the large solid disk
α= angular acceleration of the disk M = mass of the disk
g = acceleration due to gravity



' We begin with the rotational analog of Newton's second law, applied to the large solid disk:

$$\tau_{net} = I\alpha$$

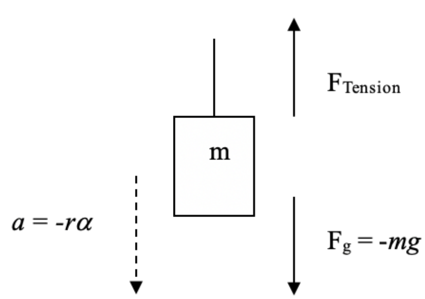
where I is the rotational inertial and generally defined to be $I = CMR^2$ in which C is a constant that depends on the geometry of the mass distribution. This is the constant you are to find.

τ is the net torque on the disk due to the tension force F_T in the string. In general, torque is given by:

$$\tau = rF_T\sin(\theta)$$

and in this case, the radial arm is r. The angle between r and the tension force is 90°.

To find the tension force F_T, we consider the falling mass:



Using Newton's second law:

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

$$\vec{F_T} + \vec{F_g} = m\vec{a}$$

$$F_T - mg = -mr\alpha$$

$$F_T = mg - mr\alpha$$

Therefore, from the definition of torque the net torque is

$$\tau_{net} = I\alpha = CMR^2\alpha$$

Setting the torque expressions equal to each other, moving $mr^2\alpha$ to the other side, and dividing by $mgr\alpha$ yields:

$$\frac{1}{\alpha} = \left(\frac{C\,M\,R^2}{g\,r}\right)\frac{1}{m} + \frac{r}{g}.$$