# Physics 101

# Lab Manual

# Spring 2020

Version 1.17

# Lab Schedule

| Date | Lab Title | Openstax Chapters |
|---|---|---|
| January 14-17 | **No Labs** | |
| January 21-24 | Analyzing Forces Involved in Walking | Ch. 4,8,9 |
| January 28-31 | Motion along a Straight Line | Ch. 2 |
| February 4-7 | Free Fall | Ch. 2 |
| February 11-14 | Projectile Motion | Ch. 3 |
| February 18-21 | Newton's Second Law | Ch. 4 |
| February 25-28 | Simple Pendulum | Ch. 1 |
| March 3-6 | Newton's Third Law, Impulse and Momentum | Ch. 4,8 |
| March 10-13 | Work and Energy | Ch. 7 |
| March 17-20 | **No Labs (Spring Break)** | |
| March 24-27 | Buoyancy | Ch. 11 |
| March 31 - April 3 | Ballistic Pendulum | Ch. 8 |
| April 7-10 | Spring-Mass Oscillations | Ch. 16 |
| April 14-17 | Vibrating Strings | Ch. 16 |
| April 21-24 | **Makeup Labs** | |

# Contents

# Lab Syllabus

| | |
|---|---|
| Lab Director | Jacob Turner |
| Office | Webster Hall Room 341 |
| Phone | (509) 335-3398 |
| Email | physics.labs@wsu.edu |

Goals:

To apply what you learn in the lecture, you will need some skills and concepts that are best learned in the laboratory. These skills include model building, data collection and data analysis, laboratory record keeping, and formal reporting of results. You will also need enough statistics to perform elementary hypothesis testing. These skills apply to quantitative work in many fields, including the health- and life-sciences, math, and engineering. Although these activities should improve your understanding of the lecture material, our principle goal is to turn theory into practice.

Most students in introductory physics courses have had lab experience in chemistry and other disciplines. We build on that experience. Your teaching assistants will not be as specific about their requirements as your chemistry teaching assistants may have been. You will often be expected to figure things out on your own in consultation with your lab partner. You will be graded by the rubrics, which can help to provide some guidance, and the written instructions **will not prompt you** to provide all required information. Since you will be working more independently, you will be required to document your work more carefully, with less input from your teaching assistant.

To accomplish these goals, you will be expected to:

- Apply physics in a variety of physical settings.
- Build simple mathematical models.
- Design experiments.
- Document your experimental work, results, and data analysis in lab notes and notebooks.
- Evaluate and compare results using uncertainties.
- Employ representative software packages for data collection and analysis.
- Document your experimental methods, results, and data analysis in a lab notebook.
- Evaluate and compare results using uncertainties.
- Communicate your work in writing (short and long formal assignments).

# Student responsibilities

- **Read the syllabus**. The regulations/guidelines in this syllabus take precedence over any oral commitments that may be made. The lab director is responsible for the final interpretation of these policies.
- **Arrive at your lab on time**. Many important instructions are given in the first 5 minutes of lab. It is vital to be on time to lab. In rare cases, room assignments may be adjusted to accommodate special requirements of a particular lab. Notice will be posted when this happens. Arrival to lab more than 15 minutes late without prior authorization will reduce your final grade by 2% through loss of Exit Ticket.
- **Make sure that all submitted work is your own**. Academic dishonesty is not tolerated and is grounds for failing the course. Should a student have access to legacy lab notes, sufficient changes have occurred in recent semesters that this will be immediately apparent. When working with your lab partner, you may discuss what to include in your notebook, but you must then write those things in your own words.
- Before each lab:
  - **read the lab manual** and related course material, particularly if the material has not already been covered in lecture. Chapters in the freely available OpenStax textbook are referenced for further investigation, YouTube MOOC offerings can also help get you up to speed. Check out MIT OpenCourseWare as well as EdX and Coursera.
  - You are expected to use the week prior to lab familiarizing yourself with all material required for the lab.
  - Some rubric categories require that you complete the work being graded prior to attending lab, this typically means preparing the introduction section for the lab and writing up a Lab Agenda which outlines how you expect the lab to run for the week.
- Bring your Lab Intro and Agenda, calculator, pen/pencil, lab notebook, and scratch paper to lab each week.
- Come prepared to perform mathematical calculations based on the level of math appropriate for the course. This includes algebra, geometry, and trigonometry. All labs also conduct statistical work, which is not covered in any prerequisite courses for these labs. Students may wish to utilize Khan Academy or other resources for help with statistics.
- Do not bring food, tobacco, or beverages into a lab room.

**What is expected of you during each lab**

In lab, you are not required to get to the "end" of the experiments. The goal isn't for you to perform some given action. The goal of the experiment is to get experience with and exposure to experimental techniques and data analysis.

Be deliberate with your approach to all parts of the lab. Doing parts one through three out of a seven part lab incredibly well is better than doing all 7 parts sloppily. And both will be graded on the merits of the work which was completed by the partners. So long as you are making an effort to advance/improve during the full three hours in the lab, you will be capable of obtaining the same experience and advancement as others in the room.

With an introductory experience in performing experimental science, you will not uncover great secrets which rock the foundations of science as we know it. You will not become a high quality researcher. You may however develop habits and approaches which can serve you well on the path to accomplish such feats. Our goal is to have you learn how to observe carefully and record important details, how to design an experiment to test a hypothesis, what the difference is between a hypothesis and a prediction, to train you to be aware of assumptions, to pay attention to accuracy and precision, to quantify and account for error. And finally, our goal is also to help you learn how to communicate the results of your research to others.

# Final lab grades

Lab and Lecture components of this four credit course are only loosely linked. Due to the open ended nature of scientific investigation, the Lab component is evaluated on a Pass/Fail basis. Final grade for the course will be determined completely by performance in Lecture activities. However,a failure of either the Lab or the Lecture will count as a failure of both, and each component will need to be re-taken if the student desires a passing grade (or just takes the course to obtain a better grade).

**A student fails the lab if they score under 70%**. Labs are weighted so that the start of the semester contributes very little to your final grade, and the end of the semester contributes heavily to your final grade. This is designed to permit students to develop familiarity with the expectations of the course.

Each lab has 5 to 15 rubric categories assigned for evaluating the student work. Each rubric can be scored as either No Effort for zero points, Progressing for one point, Expectation for 3 points, or Scientific for 4 points. The maximum score for each lab is calculated based on acquiring Expectation in each Rubric category, meaning that students who put in the work to get evaluated as Scientific acquire extra credit.

As another component of your grade, each week you must complete an “Exit Ticket” before leaving lab for the day. This primarily consists of “put everything how you found it” level of cleaning up your own lab station, but one important item to be aware of is that it includes "Required Level of Effort" as a check. Required Level of Effort covers four checks:

1. Complete the pre-lab assignment
2. Arrive on time (no more than 15 minutes tardy without prior authorization)
3. Complete the lab (stay and work productively the full 3 hours, or reach the end of all lab instructions and exploration of any issues noted during lab)
4. Work well with your partner.

Working well with your partner is determined at the TA’s discretion. A warning will have been issued during the lab session before a student is refused their Exit Ticket due to working poorly with their lab partner. Each Exit Ticket counts as 3% of the final grade.

Although each lab partner in a group will report the same data, *your data analysis, discussion of results, and conclusions must be your own*. The Rubrics should be your guide for ensuring that your work is adequate prior to submitting it. In the last 30 minutes of class, before you leave your lab session and submit your work, review what you have recorded and evaluate yourself using the rubrics. There should be no mystery about what marks you will see when graded work is returned in the next week.

Questions regarding feedback on lab assignments need to be discussed with your teaching assistant within two weeks of receiving the evaluated material (earlier at the end of the semester). Final lab assessments (pass/fail) will be posted on Blackboard 1 week after makeup lab. Errors that affect your physics course grade will be corrected after final grades are submitted to the Registrar, if necessary.

### Summary:

You pass the lab portion of the class if you score a 70% or better in lab. Lab scores are comprised of the following:

- 36% - Exit Tickets (3% each lab)
- 30% - Lab 10, 11, & 12 Rubrics (10% each)
- 21% - Lab 7, 8, & 9 Rubrics (7% each)
- 10% - Lab 4, 5, & 6 Rubrics (3.33% each)
- 3% - Lab 1, 2, & 3 Rubrics (1% each)

Note that Labs 1-3 Rubrics are worth less than the Exit Ticket for the lab. These labs are your time to ask many questions about the Rubrics and work on understanding how to complete the future labs for yourself.

## Attendance Policy

A make up session is available for the final 3 (highly weighted) labs only, and that session is at your normal lab time the session following the twelfth lab. Ensure that your schedule is set to avoid missing any of the final 3 labs. Save your one make up opportunity for unplanned emergency/medical use.

There are no make up opportunities offered for the earlier labs. The make up lab session cannot be used to redo a lab previously attended.

**Do not attend lab if you are ill with something contagious.** Review your Lab Manual and discuss via email with your TA or peers to learn what you can of any new concepts from that missed week. If illness results in missing one of the graded lab sessions, notify your TA as soon as possible to ensure you have material available during the make up session at the end of the semester.

Students with Access Center accommodation for Flexible Attendance need to meet with the Lab Director within 2 weeks of being assigned the accommodation to discuss how it may impact the attendance policy for these labs.

**Exam Conflicts** - If one of your other classes schedules an exam outside of normal hours and it conflicts with your lab session, *the instructor of that other class is required to arrange an alternative time for the exam* with you. This is set forth in WSU Academic Regulation 80 as of Spring 2016. Do not penalize your grade in lab just to take an exam, inform your professors of the regulation if they are unaware of it, and they will arrange an opportunity for you to take the exam without missing lab. But informing your professor of the conflict and arranging an alternate exam is your responsibility.

**Students are not permitted to attend any lab section other than the one for which they are registered.**

# Academic Integrity

Academic integrity is the cornerstone of higher education. As such, all members of the university community share responsibility for maintaining and promoting the principles of integrity in all activities, including academic integrity and honest scholarship. Academic integrity will be strongly enforced in this course. Students who violate WSU's Academic Integrity Policy (identified in Washington Administrative Code (WAC) 504-26-010(3) and -404) will receive no points for the lab in which the violation occurs and a further 5% reduction to their final evaluation in the lab, will not have the option to withdraw from the course pending an appeal, and will be reported to the Office of Student Conduct.

Cheating includes, but is not limited to, plagiarism and unauthorized collaboration as defined in the Standards of Conduct for Students, WAC 504-26-010(3). You need to read and understand all of the definitions of cheating: http://app.leg.wa.gov/WAC/default.aspx?cite=504-26-010. If you have any questions about what is and is not allowed in this course, you should ask course instructors before proceeding.

If you wish to appeal a faculty member's decision relating to academic integrity, please use the form available at https://conduct.wsu.edu.

# Disability accommodations

Students with Disabilities: Reasonable accommodations are available for students with a documented disability. If you have a disability and need accommodations to fully participate in the lecture or lab, call or visit the Access Center in the Washington Building, Room 217 (Phone: (509) 335-3417, e-mail: Access.Center@wsu.edu, URL: http://accesscenter.wsu.edu/ ). All accommodations MUST be approved through the Access Center. Notify both your lecture instructor and the lab director during the first week of lecture concerning any approved accommodations. Late notification may cause the requested accommodations to be unavailable.

As laboratory work is quite different from standard classwork, and we have no examinations, few accommodations apply to labs. Be sure to mention to your TA if you feel one of your accommodations should apply and is not being met.

# Safety resources

General information on campus safety is posted in the Campus Safety Plan. Information on how to prepare for potential emergencies is posted on the Office of Emergency Management web site. Safety alerts and weather warnings are posted promptly at the WSU Alerts site. Urgent warnings that apply to the entire University community will also be broadcast using the Campus Outdoor

Warning System (speakers mounted on Holland Library and other buildings) and the Crisis Communication System (e-mail, phone, cell phone). For this purpose, it is important to keep your emergency contact information up to date on the MyWSU system. To enter or update this information, click the "Update Now!" link in the "Pullman Emergency Information" box on your MyWSU home page).

Safety information that applies to the laboratories appears in the Lab Manual. Your teaching assistant will also present any safety information that applies to the current laboratory at the beginning of the laboratory. Students are expected to conduct themselves responsibly and take no unnecessary risks in the course of their work. Students who disobey the safety instructions of the teaching assistant will be directed to leave the room. All accidents and injuries must be reported promptly to your teaching assistant.

An Emergency Guide is posted by one door of each lab room. Classroom and campus safety are of paramount importance at Washington State University, and are the shared responsibility of the entire campus population. WSU urges students to follow the "Alert, Assess, Act," protocol for all types of emergencies and the "Run, Hide, Fight" response for an active shooter incident. Remain ALERT (through direct observation or emergency notification), ASSESS your specific situation, and ACT in the most appropriate way to assure your own safety (and the safety of others if you are able).

Please sign up for emergency alerts on your account at MyWSU. For more information on this subject, campus safety, and related topics, please view the FBI's Run, Hide, Fight video and visit the WSU safety portal. Each lab room door can be locked from inside in case of a lock down.

## Possible changes

The lab director reserves the right to correct errors in the syllabus and to modify lab schedules and room assignments. The lab director has delegated some authority to modify assignments and due dates to your teaching assistant. This helps ensure that your are graded according the criteria stated during your lab meeting.

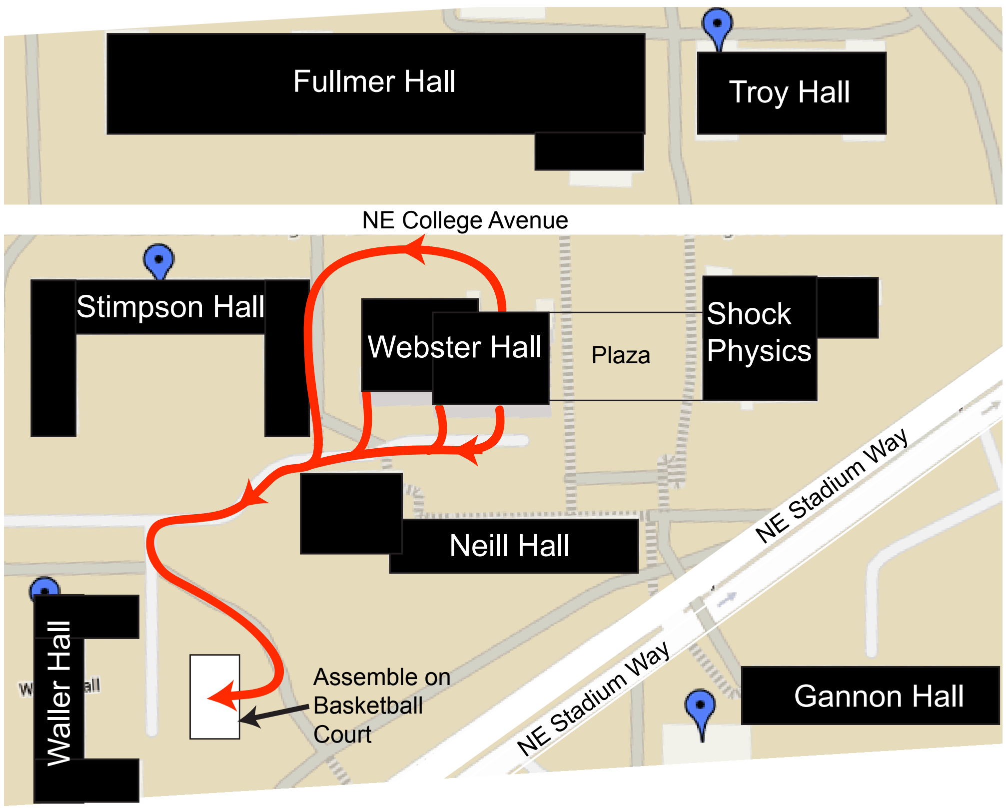



Figure 1. Physics and Astronomy assembly point. In case of a fire alarm, exit the building and gather at the basketball court behind Waller Hall. Use the stairs. Do not use the elevators in case of fire. A department representative will tell us when it is safe to re-enter the building.

# Lab Notes and Reports

## Written communication of laboratory work

Records of real research laboratory work take at least two forms. Continual informal notes taken as work happens for posterity, and formal documentation which is intended for publication to a broader technical community to convey findings or encourage collaboration. In the Physics labs we will focus on the former, as we cannot give due treatment to the later for those few who will go on to produce academic reports in the future.

For legal and reference purposes, the primary record of lab work is the lab notebook. The notebook includes notes you make before, during, and after performing an experiment. In an actual lab this can be used to defend patents and otherwise substantiate official positions regarding activity within a lab. For our purposes, the official record impact is in generation of graded content. At the end of each laboratory, you will submit the pages from your notebook to your teaching assistant.

Actual lab work is summarized in technical or academic reports. These reports communicate main results and omit many details recorded in the lab notebook. Because the preparation of proper lab reports require considerable time and effort, we will not require a lab report for these laboratory exercises. A full formal report is often comprised of six distinct sections: An introduction which conveys the intention and value of the work, a background section which frames the work in terms of work by others in the past, a methods section which briefly conveys the details of the work, a data section which conveys the results of experimentation without much analysis by the author, an analysis section which states the author's translation of the data, and a conclusion section to summarize the findings and once more frame the study within the broader academic field, as well as speculate on future work which can be done.

These two forms of communication employ different standards that can be only partially implemented in an instructional lab. As these labs do not give students the freedom to select their research topic or even methods of approach, formal reports are relatively meaningless.

## Lab notes—official record of attendance and work

Although neatness is important, we are interested primarily in the thought process behind your action, not the editing capability in your notebook. However, the content of your lab notes is the main criterion for grading. Lab notes must be sufficiently legible to make it easy for you and others to read and understand exactly what you did. Your notes must include all your raw data, and explain how it was analyzed (for instance, using sample equations). You will often type numerical data into Excel spreadsheets for analysis, but the original numbers must appear in your lab notebook as well. *Your notebook is the official record*—and a backup in case your computer crashes.

With the exception of computer-generated graphs and tables printed during lab, lab notes must be handwritten in pen. Although lab notes are not formal documents, they are legal records. Any attempt to remove information from the record after the fact destroys this value and is considered scientific misconduct. *If you decide that any original data or notes are in error, put a single "X" through it, make short note in the margin explaining why it is in error, then record the new information in a new entry.* Both sets of data must be legible in your lab notes. Your grade will not lowered by including these marked errors. This practice conforms to standard scientific and engineering practice. You are free to work through any derivations that should appear in your lab notes on scratch paper before entering them in your lab notebook.

Each entry in your lab notebook should start with the current date and time in the left margin. Each entry must be recorded at the same time the work is performed. Entries must be sequential. Leaving one or more blank pages or part of a page in your notebook for later work is not acceptable. When you move on to a new page, draw a diagonal line through any large blank areas of the previous page. To work on an earlier lab after you have started work on a later lab, start your addition on first blank page in sequence. Mark the top of the new page, "Continued from page . . . " and another note at the bottom of the old page, "Continued on page . . . ". Many lab notebooks provide spaces for these notes.

Unlike lab reports, lab notes do not have formal sections. It is appropriate to write out questions you have about the lab and one or two sentences of introductory material in your notebook before coming to lab; these entries must be dated at the time of writing. Each step of your procedure must be recorded as you actually perform it. Do not copy procedures from the manual into your lab notes before coming to lab. (When pre-recorded procedures are absolutely necessary, draw a vertical line down the center of the notebook page, with your intended procedure on the left and your record of what you actually did on the right.) Likewise you should record your data as you take the data. There is no data section. To help you avoid missing important points, the lab manual includes some questions about each lab; these questions should be answered in your lab notes where the questions arise in the lab. If you print a graph or data table in lab, attach it to your other notes as close as possible to the handwritten notes that describe the data and how it was collected. Do not collect your computer printouts at the end. Submit your notes in chronological order.

Your lab notes must be sufficiently detailed that you or another student with your background can reproduce your work. The reader must be able to "trace" your work from the original data, through your analysis, to your conclusions. Your notes should leave no doubt about how the data were collected, what sensors and sensor settings were used (if any), and which equations were used to calculate the quantities you report. Define any symbols used in your equations and include appropriate units for numerical data. Sample calculations are often necessary.

Each graph printed during lab should fill a full sheet of paper to allow room for notes. To provide this room, computer-generated graphs should normally be printed in the "landscape" (rather than the "portrait") mode. Landscape mode will print the $x$-axis along the longer dimension of the paper and thus makes most graphs about 50% larger. In some cases it is useful to display computer-generated graphs, for example, showing position, velocity, and acceleration as functions of time, on the same page to facilitate comparison. These graphs should be printed in the mode that most completely fills the page. All graphs must have a *descriptive* title that indicates what is being graphed. ("Graph 1" or "Exercise 1" is not sufficient.) Labels and units are required for both the $x$- and $y$-axes. If you are asked to draw a "curve" through your data points, this should always be a best-fit curve (for example, a straight line if appropriate) that best represents your data. Best-fit lines can be drawn by eyeball and a ruler, or with the help of the computer. If you are asked to calculate the slope (or perform other analysis) of the graph by hand, show the results of this analysis directly on the graph, clearly identifying which points are being used to calculate the desired quantities. When a computer-generated best fit curve is displayed on a graph, the resulting equation (with parameters and uncertainties) should also be displayed on the graph. This allows the reader to evaluate the curve fit results without referring back to the text. Refer to the "Uncertainty/Graphical Analysis Supplement" near the back of your lab manual for more information about using graphs to find mathematical relationships between graphed quantities.

Keeping good records during lab takes time, and it is virtually impossible using formal English, with complete sentences and paragraphs. Record your actions and data in the most clear, efficient way possible. Use phrases instead of sentences. Annotated diagrams—simple sketches with the parts labeled and notes—can save time and be more clear. Descriptive titles for graphs and table columns also help. If an equation is used to describe the data in a graph, write the equation on the graph. Putting it elsewhere usually requires additional text.

In the last 30 minutes of lab is the opportunity in which to be more verbose and to synthesize and refine what is already present within the notes. This is the opportunity to help your reader to understand precisely what has happened, in case your notes up until then had failed to do so.

# Special requirements for lab assignments

## Uncertainty analysis

Many experiments involve a quantitative comparison between values of the same quantity determined by two or more distinct methods. When you compare two values, you must address the question of whether or not they agree within the limits of the expected or measured uncertainties. Methods of uncertainty analysis will be introduced as appropriate throughout the semester for Physics 101 and 201 students. As the semester progresses, you will need to make decisions by yourself on appropriate methods for calculating the uncertainties in your various measured and calculated quantities. Physics 102 and 202 students are expected to be aware of all the uncertainty methods learned in Physics 101 and 201, respectively, and to use them appropriately. The Uncertainty/ Graphical Analysis Supplement near the back of your lab manual defines important quantities, such as the standard deviation, and supplies details about determining uncertainties.

Students are highly encouraged to make use of Khan Academy as a resource to familiarize themselves with basic statistics. This branch of math does use relatively basic mathematical techniques, but has nuance which can catch a new practitioner unaware. Since there is not a statistics prerequisite for the course, it is expected that many students will lack experience with these techniques. However, the value of statistical analysis in scientific research is immense.

# Lab 0. Intro to Work in Laboratory

## Goals

- To get an idea of how experiments are conducted.
- To understand the key ingredients for useful lab notes.
- To be able to use the data acquisition software Capstone.
- To be able to efficiently use Capstone and Excel for data analysis.
- To make quantitative comparisons of results with predictions

## A Quick Note

This manual exists as an electronic document only, we do not provide a print version. During labs, **you may find it useful to open the manual in multiple tabs/windows**, allowing you to keep one copy of the manual on the experiment instructions, and other copies can be opened to supplemental sections. The Appendix sections contain numerous detailed descriptions of how to set up equipment or analyze data which can be of great help during lab.

*Think of the labs more like a shop class than a lecture class*. In a shop class you are given a broad instruction such as "build a birdhouse" and you are expected to know that you will be using a saw to cut the wood to the proper shape, and may use a drill press to put holes in the wood at some point. No instructions tell you precisely what size to make the house, how many walls to use, where to place the holes, or even what type of bird it is intended for. You have access to the tools you will need, and can ask questions whenever you are uncertain about how to use those tools. But ultimately how you accomplish the task is up to you, and there are dozens of ways you can accomplish the task, none of which look precisely the same in the end. Meanwhile in a lecture course you are given problems to solve with known answers, and often those answers are obtained in one or two simple steps using the technique being taught currently in the class, or practicing a technique recently learned. In such lecture courses there is one correct answer and if you cannot obtain that answer quickly you are doing things wrong. Lab is not like lecture classes, Lab is like shop classes. We will give you a task to complete and expect you to use the tools available to figure out how to accomplish that task well.

This manual is not a step-by-step guide walking you through specific actions during each lab. The manual challenges you to think carefully about the physics behind the experiment at hand, and make numerous decisions on your own. When it is reasonable to believe a person can figure out how to perform an action on their own, details will not be provided to prompt the action from you.

And when equipment needs set up, you will not always be walked through the setup procedure. However, the appendix sections do provide detailed discussions of the various sensors you will use, the software required, and the data analysis commonly employed.

This means that a student who fails to consult the appendix may easily get frustrated with the manual for being vague, when the intention is to avoid repetition, and encourage the proper use of reference materials where needed. This omission of precise steps on secondary actions also serves to enhance clarity of the manual for those people who have figured out the equipment, or properly consulted the appendix.

# Introduction

> "*An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer.*" Max Planck

Lab notes should be a shorthand description of the communication with nature. They include the circumstances around the recording of Nature. The formal lab report translates all into an understandable format for the interested outsider.

In undergraduate laboratories, experiments tend to be preconfigured and close to ready to use. However, it is useful to have some knowledge how experiments are conceived and conducted. At times equipment may fail or not function as expected or you are asked to add to the experimental plan. Experimental procedures and problem solving methods drive how and what to keep a record of. Success in the undergraduate laboratories requires the generation of understandable lab notes and more formal lab reports. A significant number of experiments rely upon computer controlled sensors and occasionally computer generated control of experiments. Data are acquired with the aid of the computer and then further analyzed. In this lab tutorial key elements of lab notes will be discussed. The software Capstone (for data collection and data analysis capabilities) as well as Excel will be presented. The laboratory experiments "Motion along a Straight Line" or "Free Fall" will be used as demonstration examples. Returning to lab notes, a method to compare results from different sources will be quantified. The five topics are:

- Experiments
- Lab notes
- Capstone and data acquisition
- Capstone and Excel data analysis
- Quantifiable tools to compare results: the $t'$-score

# Experiments

College is a chance to use the expertise, time, and resources of the school to gain as much experience and exposure to professional experiences as possible. The lab environment should stand out as a phenomenal place to realize this goal, wherein the means is the acquisition and analysis of physical data.

The resources you will use this year are unlikely to match many resources you will have available in the future. Photogates and other sensors we utilize just do not come up that often. However, the experience that this lab sequence is providing you with is invaluable, at least if we successfully communicate our intentions. We are trying to teach you how to support an argument with data. If you want to convince your boss that having the company provide you with a reserved parking space right outside the door will increase profits, you can do that using the data gathering and numerical analysis techniques we teach you in this class, assuming it is true at least.

Focus on this goal in every lab experiment this semester: Use your equipment properly, know the limitations of the equipment, take careful data, and use that data to support a conclusion. Do not get distracted by the minutia along the way. While textbook based classes may appear to care about the "right" answers and how much you can remember, in a lab course unpredictable things can and will happen. Such oddities are not a distraction or mistake, they are simply one more element to account for and either incorporate or overcome.

What specific things we work with from week to week may seem uninteresting, and are likely not activities you will ever find yourself doing again in your life. But they do represented simplified versions of things you find around you on a daily basis.

Each week you are required to perform unit analysis, and draw a Force Diagram. Developing this habit will assist greatly in the lecture and in many other courses or future endeavors.

These following points are keys to consider as you approach any investigation, and each of the labs for this semester especially. Elaboration/example is provided by discussing the upcoming Linear Motion and Freefall labs:

- *What do you want to know?* Start with the title of the lab. What is to be investigated? Here: How does an object move along a path? Can a simple equation of motion of position versus time make predictions?
- *How to simplify the problem as much as possible?* Driving a car or bicycle from home to work may involve a convoluted path and many parameters. Turns, friction, tire pressure, air-resistance, changes in elevation and more play a role. Make it simple: no turns, no friction, no air resistance, horizontal (vertical) motion or a single steady slope.
- *What do you know about this?* Well, you are about to cover the equation of motion in one dimension. Besides time as the input, there are the initial position, speed and acceleration. There is a track (or the fall of the ball towards the center of Earth). There is a slope. The object is a cart (or ball).
- *What will happen?* The equation is the prediction. Given the starting conditions you can predict when the cart will reach the end of the track (the ball will hit the floor). For example: “on a level track the cart will neither slow down nor accelerate”; or: “timing the fall of a rock into a well and listening for the splash lets you calculate the depth of the well.”
- *What’s the plan?*Set up the experiment (which has been done for you). Describe it with a sketch. That should include the essentials only. The cart (ball) and track (the vertical line down) are obvious. What is the orientation of the track? Is it horizontal, i.e. level, or at an angle? Indicate how to measure that. Indicate a direction of positive time or motion. Define the key components and physics parameters (like speed and acceleration). How is the experiment started or triggered? The cart gets a “kick” (the ball is let go without spin). The position is recorded over time. How? Write it down.

- *Time management* No experiment can consume infinite time. Having a sense of what will happen (see the predictions) allows for judgment calls. Decide about where to place measurements along a range of options. Should you focus on one end or the other or change a parameter in equal steps? Where should data acquisition be focused? “Record the cart motion once, three times or 100 times?” “Push gently or hard?” “Focus on the time between first and second bounce of the ball or elsewhere”.
- *Execute the plan* Start the data recording. This is where the Capstone program comes into play (see below). Trigger the cart’s motion (let go of the ball). Repeat several times. Write down what is done: Kick towards sensor on level track, take 1, take 2, etc. (Drop the ball, take 1, 2, etc.). Write down what happens: “the cart jumps the track (the ball is spinning)”, “the cart stops mid track” are some. Print out the data. Label stuff.
- *Analyze the data* Given the physics equations from above, can you “fit” the motion. What are the fit parameters. Note them down. Do not forget units and uncertainties. This, too, involves Capstone. You may have to combine multiple takes and average. This is where Excel comes in handy.
- *Compare to hypothesis* Did the cart “neither slow down nor accelerate on the level track”? Yes, or no. Would that depend on how carefully you look? This is, where quantitative methods of comparing come in handy (see below for t’-scores).
- *Draw conclusions* Write down the findings. Such as: “The ball dropped with a constant acceleration of $9.8 m/s^2$. That value is known with an uncertainty of $0.1 m/s^2$.”; or “the cart did slow down after all; the acceleration was $-0.02 \pm 0.01 m/s^2$.” And “Friction was not eliminated completely”.
- *What can/should be done in further experiments?* Once you know how to do things, you also can find ways to do it better. That should go here. Sometimes, you can do it right away. That’s a modification to the plan. Now jump back to the step of “Execute the plan” for the next iteration.

That’s it. Just keep in mind to post timestamps. One per page is sufficient. At every step is better. Print outs should be big, in landscape and full page. Add labels, so you and your grader know what belongs where.

# Lab notes

The notes are the written record of your actions, measurements, and observations. Science relies upon data and concrete, verifiable facts. "Having it all in your head" is never acceptable. Thus if something is not in your notes, then it did not happen. Even if the manual told you to do something, and you clearly must have done so in order to obtain information which IS in your notes... if you did not record it, nothing counts. Someone with no access to the Lab Manual who comes across your notes should know what you did, why you did it, and everything that they would need to do in order to repeat it.

- *Headings*: Start with the number and title of the laboratory. List your name, your WSU ID, your lab partner’s name, the class and section number (for example PHYS 101 lab 03) and the date. This is invaluable if your notes are lost, or if you need to later prove you were present due to clerical errors in attendance tracking.

- *Timestamps*: List the current time on the right margin of your notes at least once per page. Many labs have different components. List the times at their start points. Timestamps (and dates for longer efforts) help in the organization. External events may contribute to outcomes but are discovered only later. Correlation becomes possible with good time keeping.
- *Be brief*: These are not novels. These are memory aides for you (and the exam) and recipes and procedures to reproduce the experiment. Full paragraphs should not happen at any point.
- *Introduction*: In a **bullet list**, note down the initial steps of an experiment. Start with what is to be investigated. End up at an outline of the plan. Your TA's introductory notes and the materials from lecture, textbook, and lab manual can help.
- *Sketches*: "A picture is worth a thousand words." Sketches, free-body diagrams and drawings are worth more. They leave out all but the essential parts. Make them **big**. Half page sizes are good. Add labels. "Cart", "motion sensor" and arrows with "this way in time and positive direction" are examples. Most of us cannot draw straight lines freehand. If a specific slope is important, note that down. We do not expect artistic masterpieces, so supplement with words whenever your images are inadequate to portray important detail.
- *Math*: Don't just write down equations. Besides an equation using the value "$p_{cart}$", write down that "$p_{cart}$" is the momentum of the cart. After all, it could be "power". "F" may be a force but could denote friction. In algebra, include steps. Basically, imagine your physics book math without any annotation. Would that be comprehensible?
- *Taking data*: When recording the motion of a cart along a track, write in you notes what is done: "First run: give cart a push to let it travel from the right towards the sensor". If the data are printed, add labels to the printout for easy correlation.
- *Graphs*: Make them **big**. Full page landscape is the standard. Leave plenty of room to add annotation later.
- *The actual experiment*: Not all of the data collected on the computer may be equally relevant. Only the parts that help the question to nature are of interest. Highlight this part and say so in your notes. For example "the experiment takes place from time = 5 sec to time = 21 sec, as highlighted by the shaded box". If you start the recording of "the basketball falling over time" and then position and let go of the ball, the first part until the ball drops is not part of the **actual experiment**. It's part of the setup. Once the ball bounces out of the field of view of the sensor the actual experiment is over. The rest until the stop button is hit is not part of the actual experiment. When the cart stops mid-track or hits the end of the track, that may be the end of the **actual experiment**.
- *Relevant in a graph*: Axes must be labeled and have correct units. If you are graphing inverse mass, the units are "1/kg". Label the graph so you and your grader can correlate the graph with the specific notes in the report. The **actual experiment** part should cover at least 50% of the graph area and be pointed out. At times, a separate overview graph may show a full set of data once.
- *Fits and other analysis in graphs*: Line fits will be made to find best matches of functions with datasets. Again, the highlighted sections are important. Results should also be in the lab notes and not just on the graph. Provide the equation of the fit whenever possible (it should always be possible).
- *Results*: Do not records a billion digits unless relevant. This is called significant figures. Any result has a value, an uncertainty and units. You may measure the length of the track and write down to the nearest millimeter. Nobody would even think of using micro or nanome-

ters. The tape measure and the viewing angle play a role. So the nearest precision is a millimeter. That's the uncertainty. "The track is $1.234 \pm 0.001m$ long" is the example. More digits are meaningless.

- *I am going to write it up neatly later*: is not an option. These are not memoirs. These are the life tapes of what is going on in the experiment. Do not leave space for filling in the blanks later.
- *Summary and conclusions*: A summary is not "we measured a lot". A summary repeats the key results and findings that answer the initial question. "The basketball falls with constant acceleration. The acceleration is $9.8 \pm 0.1 m/s^2$." "The cart does not travel with constant velocity along a horizontal track. Friction, even though small, is the cause. It is equivalent of a deceleration of $0.015 \pm 0.004 m/s^2$." "The equation of motion in 1 dimension predicts the motion within uncertainty of xxx." Up until the summary, your notes are a jumbled mess, and contain lots of extra information. It is now that you sort through the information in order to ensure the reader of the work is getting the bigger picture.

At this point, experiment and notes thought to be complete... you need to look at your Rubrics for the lab. Read over the rubrics and make sure that you have performed something which can be evaluated for each assigned rubric category at least once. In those cases where you have done an action multiple times (like graphs), ensure that every instance is showing your absolute best work. If you included 12 graphs, and 11 of them were flawless, but for one of them you failed to label the axes... you would be evaluated as "Progressing" instead of "Scientific"

# Capstone data acquisition

A lot of what you need to know in Capstone is how to set up the specific sensors being used for the week. We will cover new sensors as they are introduced. For now, the important thing that will be used every time is how to display the data from the sensors on the screen so that you can record and later analyze the measurements from each sensor.

When you launch Capstone, it loads with a few template options available to click on, shown in Figure 1. It is uncommon that one of these templates is precisely what you want to use, but the first three options may occasionally suffice.


Figure 1. From left to right, 1) A table with graph, 2) A graph with two digital displays, and 3) two digital displays.

When you want to have a more specific layout, you will be looking at the sidebar on the far right as in Figure 2.

To use one of these displays, you will drag the icon to the center panel of the screen and release. Once you have the display element on screen, all that is left is to assign labels and data. Some-


Figure 2. The primary options of interest in Capstone Displays toolbar

where, you will see Figure 3 inside the display element. Click on that to get a menu, where you can select which data you want to use.

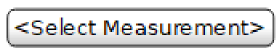



Figure 3. Click on this to get a dropdown and assign data to a display element.

Note that on a Graph display, you will have two places to assign data, one set of data per axis, as well as a spot in the lower left to assign a Title to your Graph, shown in Figure 4.

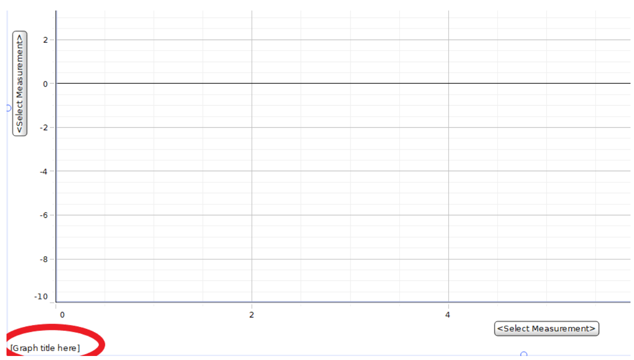



Figure 4. Always set a Title on your Graphs to help your reader.

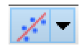
A few buttons along the top of your graph can be of great use. Looking at Figure 5, button a will auto-scale your display to zoom as far in as possible while still getting all data in view, button b will insert a selected best fit line, button c will add a coordinate reading tool (useful for finding specific values along the graph), and button d will let you place multiple data sets along the Y axis (useful for overlapping graphs to make comparisons).

On page 132 there is a decription on how to use DataStudio, the precursor to Capstone. Most of that information remains relevant and can be of use in the new software as well.

A few other notes not yet fleshed out with images:

- *Start the program and layout*: Double click on the little blue and white brick icon and the maximize the display to full screen. Around a mostly blank central white page on all for sides

(a) Autoscale data



(b) Apply a Best Fit Line

(c) Use Coordinates Tool

(d) Add another set of data on the Y Axis

Figure 5. Various options at the top of a graph display.

are your main control options. In order of use, start on the **left** with **hardware** configuration and **data parameters**; on the **right** select **display options**; on the **bottom** row buttons for **start/stop recordings** and related parameters. Finally, on the **top** icons are located for **data highlighting**,**analysis**, **fitting**, and **output printing and saving**. There is also an option or keeping a **journal** of the session for later printing or saving. All data can be saved or exported for safekeeping on flash-drives or importing into Excel.

- *Select and configure a sensor*: At the top on the left, the **hardware** button opens subscreens to select the sensor(s) of the day. Little **gear wheel** icons offer options for fine tuning.
- *Adjust significant digits*: Next down on the **left** is a **triangle rainbow** button where significant digits can be set up. Similar adjustments can be made elsewhere as well.
- *Analyze datasets*: Some of the **top** of the graph options allow to **highlight** (select) regions with the actual experiment data as defined earlier. Then you may perform statistics or fitting operations. On the graph you may pan and zoom to optimize the display as required for the lab notes and reports.
- *Prepare the display for printing*: On the very top list of tabs, **file** lets you set up the print format (must be landscape) and print graphs. Before printing, add labels. Several areas on the display allow for that. You may also drag a **textbox** onto the graph. This lets you correlate the printout with a location in your notes (and makes your grader happy).
- *Multiple measurements*: Capstone lets you take multiple runs. Just restart the recording and a new display starts. The older data are still present. A little rainbow triangle on the top bar lets you toggle through older **runs**.
- *Keeping a log*: Capstone offers the option to maintain a **Journal**. The button is at the top. It takes snapshots of the central display and maintains all in chronological order.
- *Record and saving activities*: Computer crashes and power outages happen. Note your findings in the lab notes. Print graphs. Save your data temporarily in the thaw-space on the computer's hard drive (or permanently on your flash-drive). Do not depend on the computer to keep your data. Crashes happen. You do not want to start all over.
- *What if the computer crashes?* Did you save your work and log it in your notes? No? **You just learned the hard way why you keep records on paper.** Restart the lab with.

# Capstone and Excel data analysis

Capstone offers a large range of options to fit datasets on display in your graphs. It lets you select subsets of the full dataset and analyze them exclusively. Little boxes appear and show the results. Thin lines graphically represent the analysis outcome. Excel — originally developed to help with tasks in business — offers some additional capabilities for data analysis. Results from multiple measurement runs can be combined on spreadsheets to be graphed together as a function of your controlling parameters. Simple linear regression analysis can be performed on these results. More complex math can be performed on your columns of data. You may have some experience in using Excel. Some less common operations are covered here.

- *Graphs*: On the top bar of tabs go to **insert** and find **scatter**.
- *Axes labels*: Excel is not as convenient as Capstone for that. But, all the options are available.
- *Error bars*: Excel has powerful graphing options. You can add error bars to your graphs.
- *Linear regression*: This is the important one! **Do NOT use trendline.** On the top bar of tabs go to **data**. At the very right side under **Data analysis** a window pops up. Scroll down to look for **Regression**. This version will let you select x- and y-datasets, and fit a linear function. The results for intercept and slope will also carry an uncertainty. This is crucial. You must have uncertainties to finish your notes. Also, choose the options to display the results on a separate sheet to avoid overwriting existing data.
- *Record results*: Do not depend on Excel sheet print outs. Record the results in your lab notes. Annotate them so your grader understands what you did!
- *Graphs*: The same rules as for Capstone graphs apply. Excel requires more legwork to maintain units and suitable axes ranges.

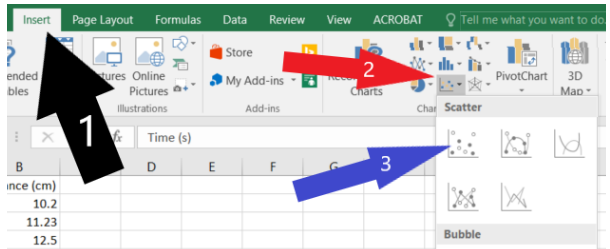
Microsoft Excel has quite a large suite of tools available for working with data. Since there are no prerequisite courses for this lab which have trained students to use Excel, experience levels will vary heavily. So the precise elements of Excel which will be required of students are based on what the Teaching Assistant desires to spend time teaching.

Whether by Excel or another program, you will need to produce graphs and perform calculations in the course. It is ideal to use whichever tools your Teaching Assistant is supporting, but in case you are incapable of making a graph in any other manner, this manual will present instructions for doing so in Excel.

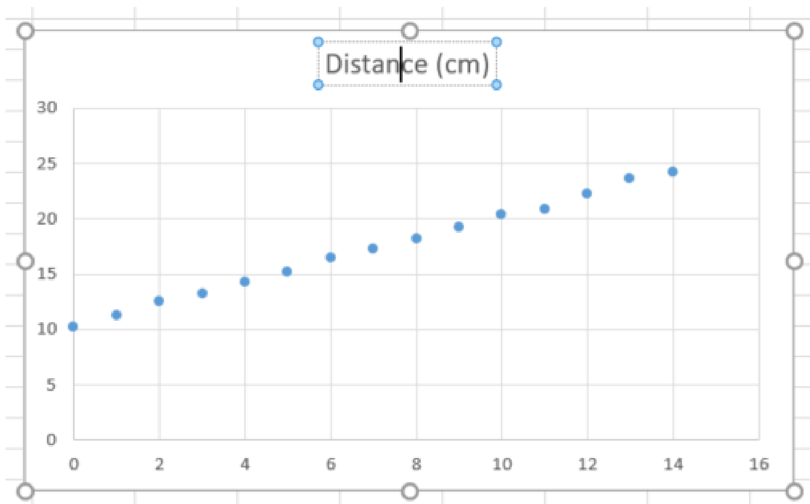
First, enter your data into Excel. Remember to take the time to place labels (including units) so you can make sense of the data at a later time.

| | A | B |
|---|---|---|
| 1 | Time (s) | Distance (cm) |
| 2 | 0 | 10.2 |
| 3 | 1 | 11.23 |
| 4 | 2 | 12.5 |
| 5 | 3 | 13.21 |
| 6 | 4 | 14.23 |
| 7 | 5 | 15.21 |
| 8 | 6 | 16.4 |
| 9 | 7 | 17.31 |
| 10 | 8 | 18.18 |
| 11 | 9 | 19.25 |
| 12 | 10 | 20.34 |
| 13 | 11 | 20.8 |
| 14 | 12 | 22.26 |
| 15 | 13 | 23.6 |
| 16 | 14 | 24.21 |
| 17 | | |

Now, select your data which you want to graph, and go to Insert->Scatter Plot.




Excel will place a title on your graph, often taking one of the labels from your data. This is rarely what you want the title to be, so change the title by double clicking on it. Then simply type in an appropriate title.




You should include labels for the axis in every graph so that a reader can understand the data without any other input. To add axis labels, click on the graph anywhere, and three options will show along the upper right of the graph area, click the + icon, and check the box for "Axis Titles"

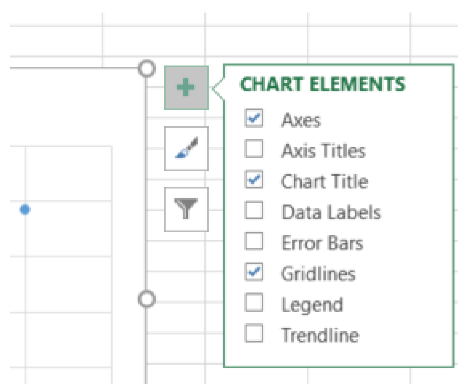
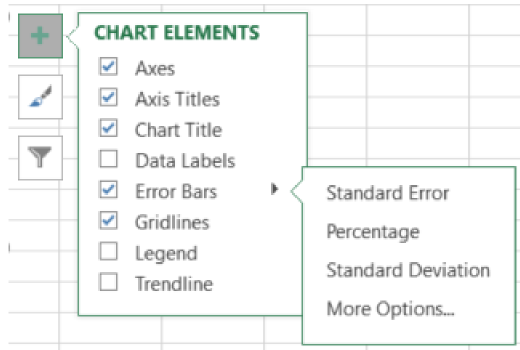
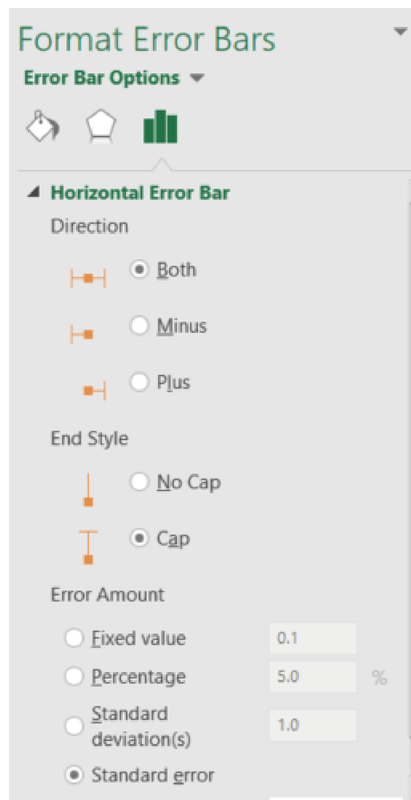



Figure 6. Enable Axis Labels, and then set the labels appropriately (include units!).

In that same menu area where you enabled Axis Titles, you can also enable Error Bars and Legend. Excel will automatically calculate Error bars using standard deviation, which is often acceptable but you can change the error bars if a different calculation is desired for the experiment. However, Excel will also add horizontal error bars, which are meaningless in most experiments, and so you need to hide those. If you expand the options next to Error Bars, you will be able to choose "More Options..."




By default, it opens up showing the options for the Horizontal Error Bars, which is what we want to eliminate. Enable the "Fixed Value" for Error Amount, and set the value to 0. Also select "No Cap" for End Style.




You should now have a graph which is acceptable for most data display requirements.

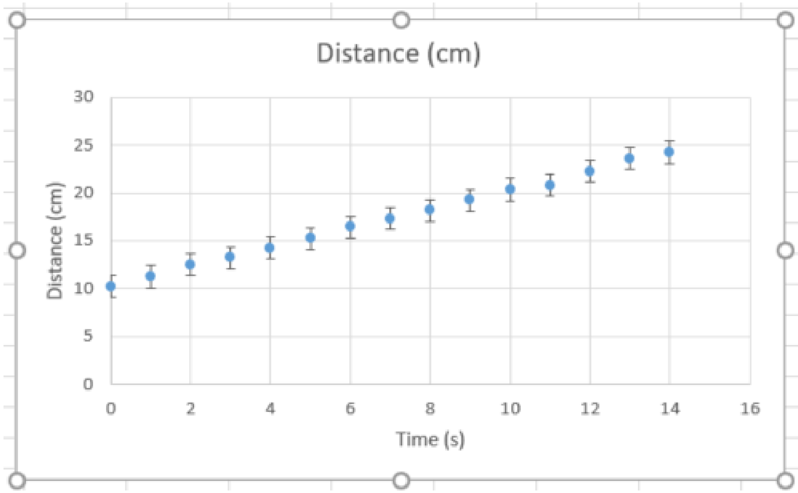
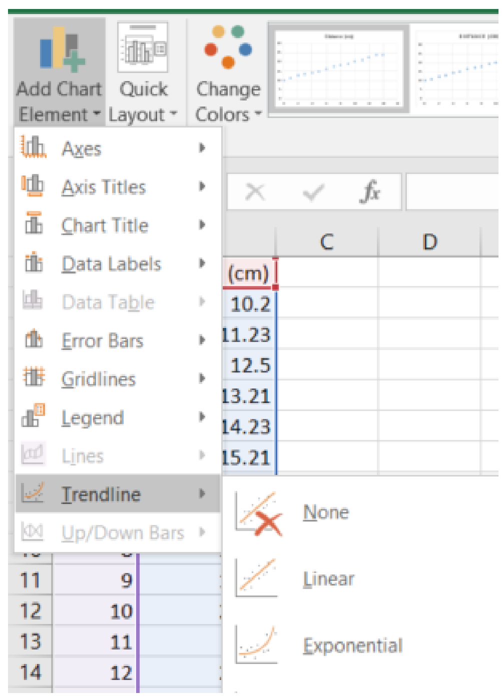



Figure 7. An acceptable graph for most display requirements.

In some cases you will also be required to include a best fit line. This is available from the "Add Chart Element" dropdown, under "Trendline." The choice of Linear or Exponential is typically all you need to know, and it is determined by knowing what kind of data you expected to be measuring.




If you double click on the Trendline, you can find an option to add the equation to your graph. This and adding a legend when graphing more than one data set can help improve your graph's ability to communicate information.

Page 141 contains further notes regarding Excel, and goes into detail which may be beyond what your teaching assistant requires for the semester if they have another software package they prefer to use.

## Quantifiable tools to compare results: the $t'$-score

The end product of measurements and their analysis are a set of results. Quantitative results are values with uncertainty and units. For example, the acceleration of the basketball in free fall or the near lack of acceleration of a cart on a horizontal track. The final remaining task tends to be to bring these results into perspective. How do they compare to the initial predictions. The gravitational acceleration in Pullman is approximately $9.80 m/s^2$. Your result may be $g = 9.75 \pm 0.05 m/s^2$. Clearly the values are different. Should we contact the School of the Environment? The USGS? Unlikely. Chances are, their values are more precise. The equipment and methods here are not. So how can you judge, how reliable and trustworthy the results are? One way would be to look at the different datasets and extract how much they vary from run to run. From mathematics and thermodynamics it is known how to deal with statistical random fluctuations. That is the basis of quantifying the reliability and the underpinning of listing uncertainties. The uncertainty says that in 68 out of 100 cases a repeat of the experiment will result in a new value that is no more than one uncertainty away of the old value. In the above measurement of g the chance is 68% that the next measurement is gnext is within the range from 9.7 to $9.8 m/s^2$. Or, turned around, the chance of randomly measuring another value outside of this window is 32%. Double (triple) the window range and the chance drops to 5% (0.7%) of randomly measuring something outside the range. If gnext were less than 9.6 or larger than $9.9 m/s^2$ this is a random outliner result in 7 out of 1000 measurements. The $t'$-score is simply the distance (absolute value of the difference) of one result (your lab result) from another result (or your prediction at the onset) $\Delta$ in comparison to the uncertainty $u$. The higher the $t'$-score the more likely something is different or the prediction was wrong or something unforeseen in the measurement deviates from the plan.[1]

$$t' = \frac{\Delta}{u(\Delta)} = \frac{\Delta}{\sqrt{u(m_{F/a})^2 + u(m_{bal})^2}} \tag{1}$$

The denominator is a tad more complicated. Typically, the result and the "compare to" values both have uncertainty. They must be combined. In statistics this is done in quadrature. Add the squares and then take the square root. In the labs here the critical value for $t'$ is 3. If $t'$ is smaller, there is agreement, if it is larger, something is different. In prize winning physics to convince the audience that something new was discovered or a theory proven wrong the $t'$ must be larger than 5. The chance of a statistical effect drops below 1 in a million.

In manipulating equations, a great deal of algebra is required. If you are not comfortable with re-arranging equations then you need to start practicing immediately. Attempting to memorize every re-arranged variation of every equation will quickly overwhelm you with pointless memorization, and make it impossible to see how the basic physical principle work.

To analyze your data, you will constantly be using statistical analysis, sometimes beyond the *t'*-score. This branch of mathematics is unlikely to have been covered for any student previously, though it is of use to everyone at some point in their life.

[1] N. T. Holmes and D. A. Bonn, "Quantitative comparisons to promote inquiry in the introductory physics lab," Phys. Teach. **53**(7), 352 (2015). DOI: 10.1119/1.4928350

In addition to the instructions from your teaching assistant, I urge all students to practice and refine their skills by using the resources available from Khan Academy.

There is a lengthy presentation about Uncertainty on page 124.

# Lab 1. Analyzing Forces Involved in Walking

## Goals

- To simplify and describe a human body walking.
- To practice assigning forces with directions to objects and systems.
- To describe how the forces relate to the act of walking.

## About Labs

Some college level lab courses encourage students to produce formal documents for each lab, asking you to spend a week after the lab session preparing this document. Students are required to include specific sections like an Introduction and Conclusion, sometimes also an Abstract. This exercise is meant to prepare students for the sharing of research in journals. However, an Introduction and a Methods section mean very little when everybody had to do the same thing in the same manner. Often in such labs the students have no idea what they did or why they did it, and so these sections involve much parroting back what was in the manual and little development of understanding.

There is still value in the effort of crafting a scientific document. You learn about precision in language and organization of thought. However, in these labs we seek to help students understand the procedure of research more than the reporting of research. As such, your week of time outside lab which can contribute to success within the lab comes *before* each lab session rather than *after* it.

Read the lab procedures for the upcoming week. Most of this will make little sense to you. However, there are few labs which can be done by students at the introductory level, and there exists a great deal of documentation about them online. After reading through the manual you should know enough to perform a search to find more details. It is expected that you arrive at the lab with a good sense of not just what we will be doing in the lab, but also of what equipment will be used and what results should occur. Having confidence that you know what results will occur before you even start the lab means that you have the opportunity to be surprised if the results are different than you anticipated, which can lead to meaningful exploration and learning.

While you are researching the topics which will be used in lab and how other people have done labs on similar topics, you can build an introduction for your lab manual which says what you expect to need to know and how you expect lab to function. This will prevent the retroactive introduction which is the same for everybody issue mentioned earlier. It will also prepare you to answer the Rubric SL.A.a when it asks about improvements for the lab with better insight.

In addition, your week prior to lab will include reading the rubrics for each lab.

**Rubric Awareness**

Rubrics are included in the Appendix section with full descriptions on how to exceed or fail to meet the Expectation mark which is required. Additionally, the rubrics relevant to each specific Lab are listed at the end of that lab. Knowing the rubrics helps you to know how to perform the lab.

For these first two labs boxes like this will help draw your attention to the rubrics at key points.

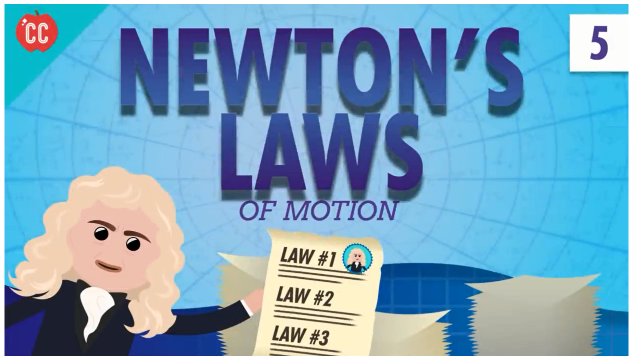
We reduce the grade value of the first labs because you are still learning how to perform scientific investigations and we do not expect you to do well immediately. Like solving any math equation, science has multiple paths from question to answer. But unlike math equations, there are also multiple equally worthy answers, to include sometimes having no answer at all. This wide range of potential processes and outcomes means that any overly prescriptive grading mechanism (like assigning specific point values to key phrases) detracts from the research by forcing students to try and "solve" the game of acquiring their desired grade.

## Introduction

A force is an interaction. The force of gravity is an interaction between a mass and a gravitational field. A force of friction is an interaction between two surfaces. As vectors, forces also have directions. The directions of the force will always lie along a straight line between the two interacting bodies and either point toward one another (Attractive forces) or away from one another (Repulsive forces). Gravity always acts towards the center of the object creating the gravitational field. On Earth gravity acts towards the center of the Earth. On the moon gravity acts towards the center of the moon. Similarly friction acts opposing the direction of motion and along the surfaces.

Forces are an important part of describing systems and processes. This lab is meant to serve as an introduction to observing and recording forces. It is very likely you have not covered this material in the lecture, or if you have that it is still new enough you are working to get accustomed to the concept. This lab will use some very simple applications of Newton’s Laws (you will spend much time on these in lecture), and some heavy repetition to ensure you develop a solid sense of not just what forces are, but how we deal with them in Physics. The repetition will also develop familiarity with Newton’s Laws and with drawing Force Body Diagrams. These Laws and Diagrams are incredibly powerful tools to solve problems throughout introductory Physics.

Please watch the Video 1.1 on Newton’s Laws for a brief introduction to Newton’s Laws of motion.




Video 1.1. Newton's Laws: Crash Course Physics #5 by PBS Digital Studios

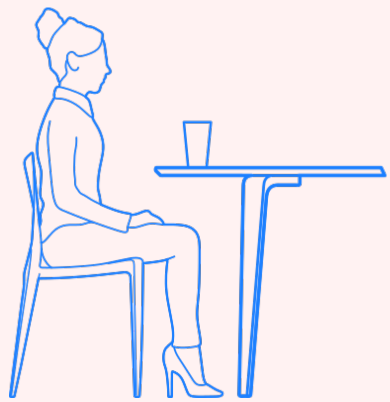
## Drawing the Body

Since we are concerned about the connection between the moving body and the forces on the system, the lab will focus on the details of the lower body. The upper body will be simplified. Simplicity is required for faster simple analysis and avoidance of distraction. Details are required for in-depth analysis.

For this lab use a single box for the torso, head, and arms as simplifications. If you find a need to be more detailed during the lab, you may increase the detail and explain the need for it at that moment. For the lower body you should draw representations of the thigh, the calf, and the foot on each side of the body. A single box with a label is all you need to have to represent each segment of the body. Clarity to the reader is valued, artistic ability is not required. This process of representing a complex reality with a simplified representation is known as modeling, and it is vital to much physics work.

**Examples to Illustrate**

To ensure that expectations are made clear, but avoid forcing students to copy one approach to solving the lab, these textboxes will demonstrate FBD drawings of grabbing up a glass on a tabletop. Pay attention to the style of approach. You do not need to copy precisely what is done, for example later in the lab the examples will draw up a table to illustrate the steps used in making the drawings. Using a table and choosing which columns to place in a table are decisions you may make for yourself. If they add clarity then you should do so, if you have no idea why they are there, then they likely will not add clarity for you.
To set up the scenario for the case of grabbing a glass: You start seated at a table, with your hands on your lap and a glass on the table in front of you.



I am going to decide that in this case the only body parts which are important are the upper arm, forearm, and hand. For simplicity I will not cover the fingers for how to grasp the glass. This means that the elements which I need to draw are as follows:

| BODY | UPPER ARM | FOREARM | HAND |
| --- | --- | --- | --- |

Again, these are the elements I anticipate needing at the start. If I discover that I need more detail I can add it later. For your assignment in the lab, a good start may be thigh, calf, and foot, along with the generalized torso for the remainder of the body.

## Choosing when to draw a Diagram

This is the point in the lab where groups will significantly diverge from one another. Any time that a portion of your simplified representation would move, we know from Newton's Second Law that there must be a net force on that part of your body. You must carefully observe while you and/or your partner go slowly through the motion of taking a step and decide at what points in time each portion of your body must move in order to take a step (accidentally losing your balance or scratching your nose does not add to your needed sketches, we are only interested in the motion which cannot be avoided to successfully move your body with standard walking action).

More importantly, any time that the direction of motion changes, you now have new forces in play on that body part. So not only do you have to determine which body parts are moving at any moment, but also pay attention to when the direction of motion changes.

In the course of these motions you are swinging the parts of your body, which brings in the physical principle of torque. However, if we simplify all swinging action to an approximation of straight line movement we can avoid getting involved in rotational motion at this time (we will get to rotation later in the semester though). This is a reasonable approach if we consider each tendon and joint to function like a pulley, which can change the direction of force application.

**Rubric Awareness**

Ignoring Torque like this is one of the things we want you to talk about with rubric CT.A.a. This rubric asks you to compare what you record in your lab notebook against reality and point out where you have simplified reality in order to be able to record it or just to focus on an easier portion of the whole of what is happening at the time.

**Examples to Illustrate**

In our example case of lifting up a glass on a table, we start with the arms resting on our lap. Breaking down the motion to get a grip on the glass could go this way:

1. Bend at the elbow to lift forearm and hand
2. Rotate at the shoulder to lift upper arm
3. Extend elbow back to extend forearm and hand
4. Grab glass with hand

Now, doing these motions and NO other motions at all would be quite awkward for normal motion. The goal is not to explain exact real motion, which has many parts moving in different directions at once, and frequent changes in direction for each body part. Instead the goal is to describe an option for motion which we can describe.

In an attempt to describe actual motions I would take, broken down to the steps in which direction of motion changes for any part of the body:

1. Rotate wrist to turn hand from resting on knee to having palm perpendicular to the ground, while rotating shoulder to raise arm
2. Stop rotating wrist while continuing to rotate shoulder
3. Extend elbow while continuing to rotate shoulder
4. Grab glass with hand

In these cases I come out to the same number of total steps, but have multiple actions happening during each step which I will have to keep track of in the drawings later. Stepping through the first set of instructions which were simplified is a little awkward, but I can clearly decide between each step what is happening. For the more realistic second set is is more fuzzy as to when I move from one step to the next, and I have a feeling when I try to actually perform the motions that there are other steps which should be mentioned as well, depending on precisely where I start my hands and the glass in my simulation.

Take your time in describing carefully precisely how all parts of the body which do move must move. Remember that "move" here doesn't just mean you actively compress or extend a muscle connected to that body part, since very often your feet will just be "along for the ride."

Feel free to use your own terminology for body parts (some of you are likely pre-med and may be particular about getting anatomy correct and detailed), and to consult web based resources as desired for details on muscle connections. Do keep in mind that we are seeking a simplified representation though, and so long as you are consistent we will not be evaluating for medical rigor. But do make sure that your reader is able to understand your terminology by combining terms with descriptions or graphics.

If you have trouble feeling if a muscle is active have your partner help you balance while you maintain position to contract and relax the muscle. If there is tension in the muscle, then you are using it. Placing a hand on your leg can often help you to feel muscles move beneath your skin. Please only attempt to feel your own muscle movements.

If you are doing the lab properly, you will feel rather silly as you work to figure out how your body performs movements which you have taken for granted since you were 5 years old and never thought through since. Stand up, take slow steps, try to force muscles you said are doing nothing to do nothing. Take only portions of steps repeatedly to feel how the muscles really move.

Observe as best as you can which forces or muscles are necessary to proceed from one stage to another. Write them down as well as well as a short description.

## Drawing Diagrams

At each of the stages you describe for taking two full steps, you will draw multiple force diagrams, including in each force diagram an arrow for each of the forces on that part of your body (gravity and muscles). Each force can be represented as an arrow from the center pointing in the direction of the force, like weight of the body part itself will be drawn going downwards (gravity based force).

The forces from muscles will be tougher, as these would go around the joints. Fig 1.2 is an example of a lower right leg. The boxes are black, the joints are gray, the weights are in blue, and the forces exerted by the muscles are in green. Reminder: This is not the kind of drawing you will provide as your final FBD, it is merely illustration of the changes in direction for forces across joints. In this diagram, weight forces start with 'W' while forces from muscle contractions start with 'F'. All of the labels here end in 'r' since they are for the right side. The 'ls' is the quadriceps for the leg-straightening. The 'fp' is the foot pull up (as opposed to the foot push down). Use any naming convention that you want. But include enough information that it can be understood by anyone reading your work. Where needed for clarity, you can include side on and front on drawings since you can't draw a 3D motion path on 2D paper.

Note: your forces can have angles. Fig 1.2 for simplicity only has vertical and horizontal forces. You will most likely have some angle. Name the angle if necessary. Include it in your diagrams. You don't have to measure it.

Fig 1.2 is shown as only one leg for showing finer details. When noting things down write down all forces you can observe. Decide on relevance later. Fig 1.2 also does not include every force, and shows multiple body parts at once. We would expect you to draw each body part in isolation with all forces acting upon that body part detailed as required by both Newton's Second Law and Newton's Third Law. According to Newton's Third Law, you would need to have all forces manifest as pairs of forces, so when the muscle connecting your thigh to your calf contracts, there is one force drawn on the calf pointing up toward the thigh, and an equal force drawn on the thigh pointing down toward the calf. These two forces pointing toward one another indicates a contraction of the connecting muscle. How would an expanding muscle apply the forces?

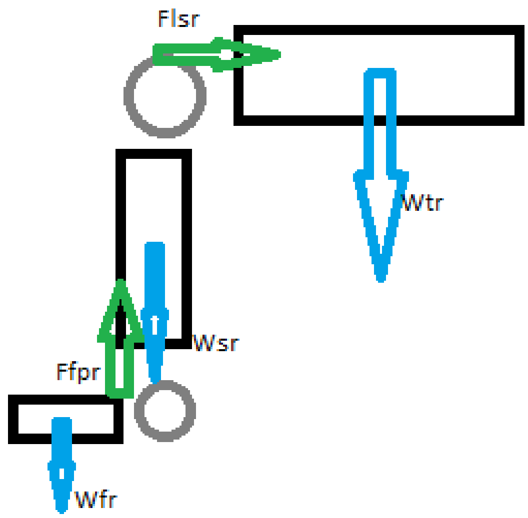
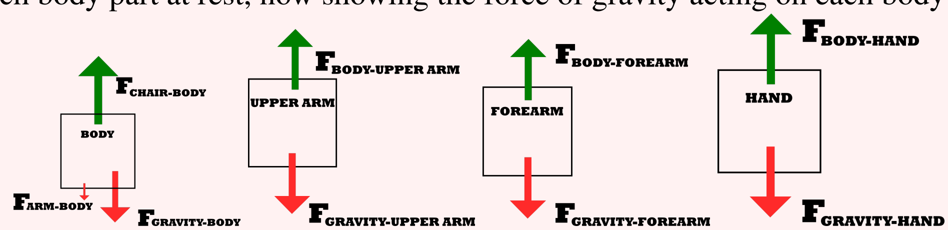



Figure 1.2. Diagram of representation of a bent right leg.

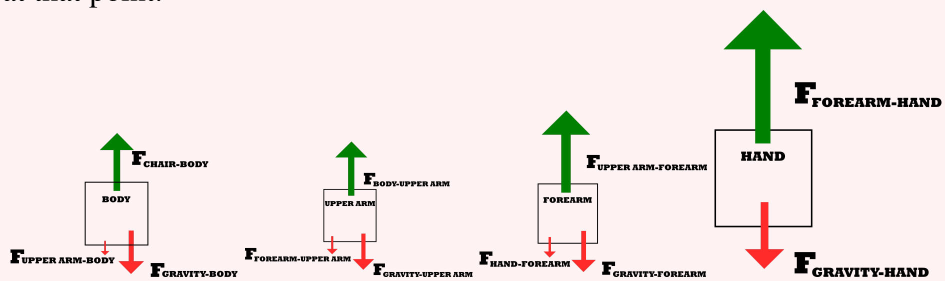
**Examples to Illustrate**

To show the FBDs we expect to see, I will work with the simplified motion example from the first list in the previous example box.
First, each body part at rest, now showing the force of gravity acting on each body part:




Notice that I group together all of the forces on the body from the upper arm, forearm, and hand as simply "Force from arm on body" doing this would require also explaining that I have done so, which is most easily done by including the formula $F_{ARM-BODY} = F_{BODY-UPPERARM} + F_{BODY-FOREARM} + F_{BODY-HAND}$.
The force from the upper arm on the body happens at the shoulder, while the force of the forearm and hand on the body happen along the leg where they are resting. Likely the force from the upper arm splits in some manner between the shoulder and leg, but such precision is not relevant at this time.
Also note that the arrows drawn down if added together are equal to the arrows drawn up for each body part. This is because every body part is stationary, and so the sum of forces needs to be zero according to Newton's Second Law. Also notice that each force appears twice on the diagram to satisfy Newton's Third Law. There is the force between the body and the hand shown on the hand as $F_{BODY-HAND}$ but it also shows on the body as a part of $F_{ARM-BODY}$. Similarly, all of the forces of gravity on the various body parts also appear combined in the force of the chair on the body. Is that symmetry clear without having an equation? Would it be appropriate and/or helpful to include that equation with the diagram?

For that matter, is it absolutely clear which arrows add to zero by graphics alone, or would equations help to make sure the reader can understand that intention?
Step 1 was: "Bend at the elbow to lift forearm and hand." So now I need to draw each of those same diagrams, modified to show an imbalance in forces for those body parts which do move, and also keeping in mind that the support for the hand which opposes gravity will no longer be the body, as it is being lifted off of the leg and will only physically contact the forearm at that point.




$F_{CHAIR-BODY} = F_{UPPERARM-BODY} + F_{GRAVITY-BODY}$
$F_{BODY-UPPERARM} = F_{FOREARM-UPPERARM} + F_{GRAVITY-UPPERARM}$
$F_{UPPERARM-FOREARM} > F_{HAND-FOREARM} + F_{GRAVITY-FOREARM}$
$F_{FOREARM-HAND} > F_{GRAVITY-HAND}$

With these graphics and the explaining formulas we see an imbalance of forces on the forearm and hand, with balanced forces on the main body and upper arm. This matches our description for the first step which had a rotation at the elbow causing the forearm and hand to raise up off of the leg. Note that the support against gravity for the hand and forearm now come through the upper arm, along with the extra force from contracting the bicep. We could draw each of those forces individually to help make it clear that we have support against gravity in addition to a further lifting force without the need for equations.
Since we are working in an idealized realm of physics with no friction losses, lifting your arm results in a greater force down on the chair than just the weight of the person. In real application you cannot change your weight on a scale by raising your hands to any noticeable degree. This is a combination of how little force we actually need to move our limbs at the slow speeds we move them, and losses to friction and heat which would occur to stabilize the body.
I will not illustrate all four steps for the sake of brevity. This example should suffice to make expectations clear, if not please ask your TA for further directed support. Each step would include a similar set of four force diagrams, giving careful consideration to Newton's Second and Third laws at each step.

**Rubric Awareness**

Our second rubric for this lab is IL.B, which asks you to draw Force Diagrams and describes some key elements of them. The lab itself focuses heavily on these drawings, so this callout is just reminding you rubrics exist and in future labs you should check them regularly.

**Verification**

Repeat the stages you decide upon for walking at least three times. Feel/Look for any inconsistencies. Feel along your own body for where the muscles you indicate forces from actually move. Does each motion you feel correspond to a force drawn during the appropriate step in the drawing? If you notice anything different, write it down. Additional drawings may be necessary, add them where needed.

# Newton's 2$^{nd}$ and 3$^{rd}$ Laws

It is important to review your work explicitly to not just check for errors, but also to reinforce concepts. Go back through your depictions and identify when a force is justified by Newton's Second Law, when it is justified by Newton's Third Law, and in which cases there was a change in direction due to lever or pulley type action in the body.

**Examples to Illustrate**

Here is an example of how to record this double-checking action for the FBDs used so far in the example:

| Stage/part | Newton's 2$^{nd}$ | Newton's 3$^{rd}$ | Torque present |
|---|---|---|---|
| Rest / Body | Stationary, net force zero | Interaction to support all parts of arm | |
| Rest / Upper Arm | Stationary, net force zero | | |
| Rest / Forearm | Stationary, net force zero | | |
| Rest / Hand | Stationary, net force zero | | |
| 1 / Body | Stationary, net force zero | Interaction to support Upper Arm | |
| 1 / Upper Arm | Stationary, net force zero | Interaction to support and lift Forearm | Lifting Forearm via lever action |
| 1 / Forearm | Rising, net force up | Interaction to support and lift Hand | |
| 1 / Hand | Rising, net force up | | Moving up via adjacent Forearm |

## Newton's 2$^{nd}$

These are all the forces that are causing a change in motion. For your step taking maybe a hip flexor will pull your leg forward, at another stage in motion maybe you would then have your calf push your foot down and you are pulled forward with a gravity imbalance. Note that you can add mid-stage steps if your earlier descriptions were end points with motion happening between stages.

## Newton's $3^{rd}$

These are all the pairs of forces acting on opposition.. You can state them as paired forces, or as interactions. The simplest seeming one is the Normal force and the weight of the entire body, though when both feet are on the floor you have to distribute the body weight between them. For example all the weight is on one foot after lifting the other off of the ground, and therefore so is the entire normal force (since your torso and head are not dropping to the ground, somewhere the gravitational force on those body parts must be balanced out).

### Torque

Though we are allowing for simplification of torques, you need to always be aware in science of the times when you simplified (or in other words: Ignored something on the assumption it wouldn't matter in the end). Sometimes when you face unexpected results in experiment, the answer is that one of your simplifications should not have happened because you ignored something which did have a significant impact. We will be dealing with cases similar to a pulley, where the muscle pulls with a tendon around a joint (like the tricep pulling your arm straight) and with direct pulls (like the bicep pulling your arm into a bend). In both cases, the limb being manipulated is acting as a third class lever, giving a larger range of motion at the cost of an increased power requirement to accomplish movement.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 1 Analyzing Forces Involved in Walking:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

☐ Straighten up your lab station. Put all equipment where it was at start of lab.

☐ Required Level of Effort.

☐ Complete the pre-lab assignment ☐ Arrive on time

☐ Work well with your partner ☐ Complete the lab or run out of time

| CT.A.a | | IL.B | |
|---|---|---|---|

---

Lab 1 Analyzing Forces Involved in Walking:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

☐ Straighten up your lab station. Put all equipment where it was at start of lab.

☐ Required Level of Effort.

☐ Complete the pre-lab assignment ☐ Arrive on time

☐ Work well with your partner ☐ Complete the lab or run out of time

| CT.A.a | | IL.B | |
|---|---|---|---|

# Lab 2. Motion in a Straight Line

## Goals

- To understand how to calibrate equipment.
- To understand how to determine limitations of equipment.
- To understand how to interpret the sign (+,–) of velocity and acceleration.
- To observe how the acceleration of an object behaves when the direction of the object's motion reverses.

Each week, **stop work on the lab with about 30 minutes left in the class session**. We are **not** scoring you for completion of all lab activities, but for doing quality work. Use this final 30 minutes of the class session to review the rubrics which apply to the week and check that you have performed at the level you desire.

Our requirement is that students perform at the EXPECTATION level in our rubrics. This allows for mistakes at roughly a 75% score rank if this were a classical assignment. It would be fantastic if you could all score at SCIENTIFIC, which is flawless performance. But you are introductory students, and expecting a flawless performance is not realistic. Plus it is always better to have a view of the next steps in your progress, and I do hope that each of you continues to improve your skills in scientific experimentation, even if you never purposefully engage in physics research again.

Like solving any math equation, science has multiple paths from question to answer. But unlike math equations, there are also multiple equally worthy answers, to include sometimes having no answer at all. This wide range of potential processes and outcomes means that any overly prescriptive grading mechanism (like assigning specific point values to key phrases) detracts from the research by forcing students to try and "solve" the game of acquiring their desired grade.

For this week, there will be text boxes interrupting the flow of the lab to explain when you would need to pay attention to the rubrics, and how you would satisfy them. These boxes are going to be placed at points in the lab where the rubric applies, but typically when you are dealing with rubrics you have evaluated all of them prior to lab so you have a general sense of what is required, and then at the end of the lab you go through and ensure you met requirements by finding those places where rubrics applied in particular.

## Introduction

**Rubric Awareness**

Rubric CT.B.a applies right at the start. Read the whole lab procedure in the week prior to lab, and do some extra research (either by reading your textbook or looking online) on the topics we will be examining. You are writing the introduction section to satisfy your Exit Ticket requirements at the same time as you fulfill CT.B.a, and it is best if you clearly identify a portion of the introduction for rubric CT.B.a. We aren't looking for you to just re-state the title of the lab. We want to know that you understand why we are doing *this* experiment today, and what are the important things for you to know while you do the experiment. If you are not sure what the purpose of the lab is, being distracted by irrelevant details or failing to notice critical ones is very possible.

The other portion of your introduction written prior to attending lab is SL.A.a. Or at least half of it. You are asked to describe the experiment itself for SL.A.a, which can be done through reading the manual and looking at other experiments on the subject online. The final portion of SL.A.a is to suggest improvements to the lab, which will have to wait until after you have been able to use the lab equipment and figure out ways in which it fails to provide ideal knowledge. Knowing how other people perform similar labs can help considerably in deciding how the lab you perform could be better.

Often SL.B.a can be satisfied at the same time as CT.B.a, as descriptions of the equipment may be useful in describing what we will do with the equipment. But in cases where you do not know what gear we will be using, and cannot find any details about gear typically used in labs on this subject, SL.B.a would be appropriately addressed later in better detail.

CT.B.b can also be satisfied before attending lab, though on occasion you will realize the need to add a few variables to your list when you find that your research was not quite adequate to prepare you for lab.

One difficulty which new learners of physics deal with is that you have lived your life in the physical world, and discussed the physical world. This has lead to using scientific terms in non-technical manner. Take the word "Slow" and think about what that means. Is it velocity, or acceleration? Well, if I say "That car is slow" then I mean velocity. But if I say "That car should slow down" then I mean acceleration.

Words like velocity and acceleration you may not have used as often when speaking with people casually, but you have almost certainly heard before and thus will have a self created definition in your mind, even if not consciously. What you learn in lab and class has to work against any aspects of your personal definitions. Let me state outright that nobody can tell the difference between a constant linear velocity and a constant linear acceleration by eye at the scale which exists in the lab room.

## Motion along a straight, horizontal track

Before continuing, make sure that the cart track is level. The track has a screw at one end (the end nearest the edge of the table) that can be turned to raise and lower the track until the track is level. Your teaching assistant will describe how to use a spirit level to make sure the track is properly leveled.

It is worth developing some familiarity with what the cart is able to measure, and ensure that you trust the measurements it makes. Set up the cart on your track and add a Digits display to Capstone showing you position. While recording, move your cart along the track a fixed value as measured by the markings on the track and verify that the position displayed on Capstone agrees.

**Rubric Awareness**

While we will not always encourage you directly in the manual to experiment with your equipment to find the limitations and capabilities, that is the entire essence of Rubric SL.B.a. You can find many details about the limitations of gear online. With simple devices like a meter stick you can tell the limitations by simple inspection of the instrument. But for electronic devices running through a computer interface it is vital to both do research online about the equipment and to interact with the equipment to determine requirements for effective use of the tool.

This is an appropriate place to address rubric WC.A (sketching). Every time the setup on your lab table changes, a new sketch is appropriate. Or at least a small sketch revising a portion of the initial full table sketch. Just a maximum, minimum, and angle does not construct a full picture of your setup to a reader. You need to include a sketch and written description of how the gear is arranged in order to do that. The written description can also include math expressions, analogies or alternative scenarios. The important key is to make sure your representation shows all of the important information and contains no errors. Or that when there are limitations to your representation (which always happens with analogies) that you explain clearly what those limitations are.

For a sketch, we are not judging you on artistic capability, but we are judging you on information delivery. If you just draw a couple of vaguely rectangular blobs, but you label them well, then you have done a fantastic job with your sketch. Meanwhile if you make a photo-realistic drawing of your entire lab room, but I cannot tell where on your track your measurements start and end, you have a terrible sketch.

Throwing all of your numbers into your sketch can get confusing and messy fast. This is why simple labels can be of great help. I can mark the sensor at the end of the track with a large MS, and then write next to the sketch that MS is the motion sensor, which is angled to point parallel to the track surface, with the distance from the mesh screen to the starting edge of the track being 3.43 cm, and the center of the mesh located 4.72 cm above the surface of the track. Now there is no chance of confusing these numbers as measurements for the track or cart, which are each labelled with different indicators and described in detail elsewhere on the page.

Return to informal observations, this time making note of position, velocity, and acceleration as the cart sits still or moves. Velocity cannot be confirmed through a second measure, but you should be able to make sense of the values in general (if it said the velocity was 5,980 m/s, I would hope you realize there is a problem with that. You are likely able to decide other less ludicrous values are inappropriate as well. The whole track is 2m long, so if the cart takes 2 seconds to move across the track you know roughly what velocity you should read). If you are able to trust the displays of both position and velocity, then it is finally reasonable to look at the data shown for acceleration, which you are unlikely to have the intuition to know if it is reliable or not, and so must rely upon your confidence in the sensor as established by the other two measures.

## Application and Expectation

The informal observations were founded only in sense-making. "Look at the data, does that match what you expect?" To bring application and further solidify confidence in the equipment, you need to make predictions and then verify. Note that you are now outside of the informal observation period, and so should be making more copious notes in your lab Notebook. Make sure that you provide sufficient detail to know what the relevance of the data is if you look back at this lab in 12 weeks.

Once again, start with position. reset your cart by turning recording off and back on, and then move your cart (without checking the sensor readings) to obtain a position reading of 0.578m (you may need to increase precision to get the decimal places required here). Once you have moved the cart 0.578m, check the reading on Capstone for agreement. If there is no agreement, then something about your understanding of how the equipment functions is faulty, or the equipment itself is. Repeat this until you are able to rely on the output of the sensor. And for the last time I will remind you: Be recording what you do and why, then the data obtained in your notebook.

With position "mastered" you should move to velocity. To make a prediction here, you need to first establish the range of motion available on your track, then choose a total time of travel to aim for (between 0.5 seconds and 1.5 seconds is reasonable). Push the cart from one end to the other, at the appropriate force required to get the cart to travel the total distance in the travel time you are aiming to obtain. Does the measured velocity times the time of travel match the range of your motion (final position minus initial position) along the track? Here you are not looking for as precise of an outcome as you obtained with position, as the graphs of velocity and acceleration should make it clear that you did not have a single value for velocity the entire duration of travel. But if you select your data set to consider from only the region where velocity appears to have a straight slope, it should come out close in calculation.

Change in position is velocity. Change in velocity is acceleration. Change in acceleration is jerk. Change in jerk is snap. Change in snap is crackle. Change in crackle is pop. One can continue this progression, but for most practical purposes we stop after reaching the concept of acceleration. Acceleration is proportional to force in Newton's Second Law, which is our main tool for predicting motion. Our goal is to understand how acceleration, velocity, and position are related for the simple case of motion along a straight path. We will explore more complicated motions later.

## Motion along a level track

Before continuing, verify that the cart track is still level.

### Observe and describe motion

**Rubric Awareness**

At this point you should be familiar with all of the equipment in the lab for this week, and how the equipment is used. That makes it the appropriate time to look back at the list of variables you made for Rubric CT.B.b and decide if you missed any, also review what you said for SL.B.a to make sure you really understand how to use all of the measurement tools and have delivered that information in your notes.

For Rubric CT.B.b, you need to understand dependent variables (those values you have to measure, and you can change what the value will be by changing something else in the experiment), and independent variables (those values you get to choose and set, you directly control what number will be used during setup of the trial run). You need not always list out "this is my answer for CT.B.b..." to satisfy this rubric, seeing which values are recorded tells the grader your answer to this rubric. But there is much to be said for making it easy for a grader to see that you have met expectations. Recording data which turns out to be irrelevant to the lab doesn't penalize you in this evaluation, so long as you make a note that the data proved irrelevant to show the grader that you realized the waste of time.

Rubric SL.B.b sounds at first like it is asking you to record what the lab manual already stated. That is not the intention. When we ask you to describe how to use the equipment to make your measurements we are looking for a great deal of specifics. You don't "measure the distance from the cart to the sensor" to get a value for position. No, you "measure the distance from the edge of the cart nearest to the motion sensor to the mesh screen on the motion sensor by placing a piece of tape on the track just below the leading edge of the cart and then holding a meter stick so that the zero-marked edge of the meter stick is firmly placed on the mesh of the motion sensor, being careful not to damage the mesh screen in the process." This second description tells me what primary and secondary tools were used, what you were being careful of, how you were ensuring accuracy, and where on each object the measurement was being made.

Place the cart at the end of the track closest to the computer and give it a gentle but quick push so it travels the length of the track in about one second. Leave Capstone off at this point. Observe the motion *after you are no longer touching the cart* and the cart is coasting along the track, but has not yet hit the bumper at the other end of the track. Describe the motion of the cart in words. From your observations describe the relationships between *position and time* and *velocity and time* by drawing graphs of position and velocity as functions of time. Using the same time scale for each graph, show the qualitative (no actual numerical values) behavior of the motion that you have just observed. Use a straightedge where appropriate. **Include some words to explain the reasoning behind each of the graphs that you draw. You may wish to use arrows pointing to special**

**features of your descriptions along with corresponding explanations of why you included those features.** You are expected to NOT use Capstone at this point. Doing the graphs on your own now will allow you to decide if the graphs shown in Capstone align with what you expect to see or not. Should the graphs in Capstone not agree with what you draw during this step, it indicates a problem with the equipment, or a problem with your understanding (which helps you figure out where to focus your studies).

Rubric Awareness

Rubric IL.A involves recording information you acquire from the lab equipment. The IL.A rubric applies every time you take data from your lab setup, and every time you write down observations to provide context to that data. There have been opportunities before now where you should have been recording observations, but now you absolutely must have something recorded. Be sure to record it carefully, including units and labels for variables.

The manual asked you to include graphs here, which brings us to Rubric WC.B. You will be printing most graphs out from Capstone, but even if you set up all of the displays in Capstone properly, the final printout will not contain all information which facilitates a reader's proper understanding of a graph.

At this moment you are expected to not be using Capstone at all, and making freehand graphs which approximate what you observe. Be sure that each axis is labeled with what value you are assigning to that axis, what units that value is expressed in, and numbers at an appropriate scale. For these freehand drawings the numbers will be understood to be approximations, not assignment of actual values measured. The X axis (horizontal scale) should always be the independent variable (the value you have control over, to include time).

Normally in a graph you are showing actual recorded data. Having the data connected via lines in such a case is inappropriate, as any line across the graph is meant to say "The values along this line are completely valid possible results," and to show such information it is more accurate to calculate and draw a trend-line, not simple connect-the-dots lines which bounce around like mad on real data.

In addition to raw numbers and trend-lines and axis labels, it can help considerably to make note of key events on a graph. If the graph crosses zero, did you observe something interesting happening at that time? If the graph reaches a local maximum or minimum, did that correspond to a physical observation? Also, some experiments will have you clicking record before initiating the actual test. When this happens and your graph includes data prior to the start of your trial, it helps the reader to know at what point on the graph the trial really starts (as well as when it ends if you continued to take data past the end of the trial and it shows up in your printed graph as well).

Now start the cart at the end of the track farthest from the computer and give it a gentle but quick push *toward* the computer. Draw graphs showing your descriptions of the position and velocity as functions of time using a consistent time scale for both graphs as above. You still should not be using Capstone.

Suggestion: Draw the position and velocity graphs for motion toward the sensor and motion away from the sensor in one vertical column on a single page of your lab notebook. They could look something like this (but all four in a line):

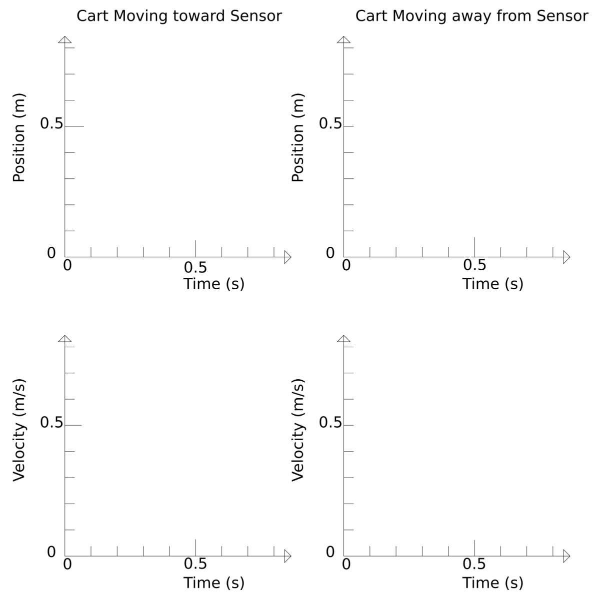



Figure 2.1. Graphs of Position and Velocity against time aligned vertically with proper axis labels.

What can you say is similar about your sets of graphs? What is different? Do those similarities and differences make sense for what happened? Would the reader of your lab notes be able to say which pair of graphs belongs to which direction of travel?

## Acquire position, velocity and acceleration data

Set up the Capstone software to display graphs of position, velocity, and acceleration as functions of time. General instructions for configuring Capstone to record and display data are available at the beginning of the Computer Tools Supplement, but you should have an option to select which will pre-configure these three graphs.

Position the cart on the end of the track near the computer with the LEDs and power button facing toward you, click on the “Record” button in Capstone, then give the cart a quick push away from the computer so it reaches the other end of the track in approximately one second. Re-scaling the resulting graphs both horizontally and vertically to show only the region of interest during the “free” motion of the cart. Then print out the graphs in “landscape” format on a single piece of paper. Write a descriptive title across the top of your graph and add any other appropriate annotations.

**Rubric Awareness**

At this point you are recording actual measured data values, which invokes Rubric IL.A. A good rule of thumb is that if you are showing more than 3 numbers, you should have the information in a table. And if you are trying to show a change over time (a trend), you should have the information in a graph. Your sketches up to this point also constitute data and would be included in evaluating your IL.A performance for the lab as a whole endeavor. At any point, having a number floating by itself is completely meaningless. Numbers need to have units, and should always be assigned to variables and labels so that the reader knows when the number was acquired and what it relates to within the lab.

Rubric QR.B also begin to comes up at this point. While taking data and recording it to present to your reader, you need to be looking for patterns in that data. Noticing that the position value gets smaller as the cart travels in a particular direction would be identification of a very simple pattern in this data, that would satisfy a portion of QR.B. But you need to represent this mathematically as well, which can be done by indicating a point on the track which indicated the 0.0m position, and that the end of the track corresponds to X.XXm positive or negative value in position.

And finally with the pattern identified and represented by math, you want to explain the pattern with words. This fulfills SL.B.b, so long as you use those words to bring up concepts from your research prior to lab. In the case of position measurements it is a simple matter of how the device was programmed to display the information obtained. It uses a tachometer to measure how many times the wheel rotates, and has a stored constant telling it the circumference of the wheels.

The other patterns you would observe in the course of this lab may require a bit more work for finding a formula and explanation, but should not require much more effort. Each graph you produce is meant to illustrate some pattern, but you are encouraged to make note of any other patterns you observe. You could note that velocity does not remain perfectly constant when pushing the cart along the level track, and then find if the loss in velocity is related to distance travelled or time of travel. These observations move beyond the scope of the written lab procedures, but are still covered by the rubrics for evaluation, which illustrates the reason why we use rubric evaluation for the labs instead of looking for you to record specific values and perform selected math operations.

Use the Capstone software to calculate the average velocity during the “free” motion of the cart by averaging a number of velocity values and finding the standard deviation of the values as an uncertainty estimate. This is done by selecting the velocity-time data you wish to average with the cursor and clicking on the “Σ" symbol at the top of the graph window; a drop-down menu of options is displayed. Check the standard deviation option, and leave the other checked options checked. Refer to the Uncertainty/Graphical Analysis supplement at the back of your lab manual for more information on the standard deviation, what it means and how it is defined and calculated.

**Rubric Awareness**

This standard deviation value is the beginning of your data analysis for the lab, which brings us back to Rubric SL.B.b. You want data analysis to be happening as you go along through the lab, which makes automated analysis like what Capstone offers quite valuable. Data analysis can help you to realize when the data you recorded is meaningless and a trial should be attempted again. This can happen due to equipment failure, mistakes in setup or execution, and due to failing to account for variables which are relevant to the lab (recall Rubric CT.B.b). Having standard deviation for data sets, averages for multiple trial runs, trendlines for graphs, and t-tests for data acquired on known values or to compare trial runs for similarity are the most common analysis techniques which will come up during these labs. Knowing which analysis is appropriate and making a decent attempt at applying the analysis is what we are looking for here. So if you take an average of values for a system which was undergoing change (average position of cart moving across the track), then we have a problem. But if you still don't understand what a t-test is for, you should talk with your TA but you aren't going to be dropped in your evaluation score.

The average cart velocity can also be computed from the slope of the position versus time graph. Use the Capstone software to find the slope of the position-time graph and the uncertainty of the slope during the “free" motion of the cart. First use the cursor to mark the region of interest on the position-time graph and then click on “fit" at the top of the graph window to choose the type of fit to make to your data. If the displayed precision of the position measurements is less than one standard deviation, you should increase the displayed precision. Your teaching assistant can explain the procedure.

Repeat the experiment for the case of motion *toward* the computer, starting from the end of the track away from the computer. Again, be sure to have the LEDs and power button facing toward you on the cart. Print out the resulting graphs after making the adjustments described above, and compute the average velocities using the same two methods.

If you have time, try to determine why it is important to pay attention to the location of the LEDs and power button on your cart.

### Compare questions and data

Address the following questions in a summary paragraph before you move on to the next experiment:

1. How do the general shapes of your descriptions and experimental position-time, velocity-time, and acceleration-time graphs compare? Were your expectations borne out by the experiment (Compare your drawn graphs to your measured ones)? Explain why or why not.
2. Does the sign of the acceleration on the experimental acceleration-time graph make sense? Use the definition of acceleration to help answer this.
3. Are the averages determined by the two methods above consistent? Use the uncertainties derived from your data to make the comparison.

**Complete your work with the horizontal track before moving on to the sloping track!**

## Motion along a sloping track

Raise the end of the track near the computer 8–10 cm above the tabletop by placing the wooden block on edge under it. Make sure the spring-loaded plunger on one end of the cart is extended and facing downhill to cushion the impact at the bottom of the ramp.

## Motion of cart moving down the ramp

### Observe and describe motion

Do not use Capstone to record. Observe the motion as the car is released from rest at the top of the ramp. Focus on the one-way trip down the ramp: ignore the bounces at the bottom end of the track. Describe the motion of the cart in words. On a single page of your lab notebook, draw graphs of what you expect the position, velocity, and acceleration functions to be for the cart from the point of release until the instant before the cart hits the bumper at the bottom of the ramp. Use the top of the track as the origin of the position-time graph.

**Rubric Awareness**

Rubric IL.B applies here (Force Diagrams). The manual did nothing to prompt you to draw one in the words written. Instead it is the experimental setup and your objective which indicate the need of a Force Diagram. Any time you are working on an angle, you should be trying to figure out how gravity is going to work with the experiment. To do that, a Force Diagram is the most useful tool available. You could have included quite a few Force Diagrams prior to now, as they are never a bad choice to include in a sketch of the experimental setup. Essentially everywhere something experiences motion, a Force Diagram is useful. Any time the direction of motion changes, a Force Diagram is useful. Remember: Force Diagrams are one of the best tools available for solving problems throughout mechanical physics.

Your Force Diagram should indicate what object you are representing forces for, a simple label accomplishes this the best. Even if you are a fantastic artist, you never know how hard it will be for your reader to notice what you have drawn out of context from the lab setup. Once you have established which object you are drawing forces for, you then need to indicate which forces act on that object and draw arrows in the appropriate directions and with appropriate relative scale to one another for each force. All forces should be drawn as arrows to or from the center of mass for the object. Even though the actual force likely applies along the side of the object (such as friction on the wheels), the FBD is only interested in representing direction for the object treated as a point-mass.

Including an axis is also quite important. Often this is accomplished simply by drawing the gravitational force, since that indicates which direction is down for all experiments performed on Earth. In rare cases it may be important to indicate your horizontal axis as well though. There are times when an object is on a ramp where you do not want to use gravity as your vertical axis, but instead want to use the surface of the slope as your horizontal axis. Right now is a case where you must decide between those two options.

### Acquire position, velocity, and acceleration data

Use the Capstone software to record the position-time, velocity-time, and acceleration-time graphs for the above motion. Print and label the graphs as described above.

Use the Capstone software to calculate the average acceleration during the "free" motion of the cart (after your release or push) by two methods: by averaging a number of acceleration values and by taking the slope of the velocity-time graph. For each measurement, record an uncertainty estimate for your acceleration measurement. This will be the standard deviation of the mean of your acceleration values in the first case and the standard error of the slope in the second.

**Compare descriptions and data**

Address the following questions in a summary paragraph before you move on to the next experiment:

1. How do the general shapes of your descriptions and experimental position-time, velocity-time, and acceleration-time graphs compare? Were your expectations borne out by the experiment? Explain why or why not.
2. Does the sign of the acceleration on the experimental acceleration-time graph make sense? Use the definition of acceleration to help answer this.
3. Are the averages determined by the two methods above consistent? Use the uncertainties derived from your data to make the comparison.

## Motion of cart moving up the ramp

Position the cart at the bottom of the ramp and give it a quick push up the ramp so that it does not bump into the end stop at the top of the ramp. Focus on the one-way trip up the ramp until the cart comes to rest. Draw graphs showing your descriptions of position, velocity, and acceleration as functions of time on another sheet of paper. Then acquire position, velocity, and acceleration data during this motion using Capstone. Address the three questions above in a summary paragraph before you move on to the next experiment.

## Motion of cart moving up and down the ramp

Again, position the cart at the bottom of the ramp and give it a quick push up the ramp so that it does not bump into the end stop at the top of the ramp. This time focus on the two-way trip up and down the ramp until the cart hits the bumper at the bottom of the ramp. Draw graphs describing the position, velocity, and acceleration as functions of time on another sheet of paper. Then acquire position, velocity, and acceleration data during this motion using Capstone and address the three questions above.

Finally, describe the measured acceleration as the cart slows down, stops momentarily, and speeds up again at the top of the track. Consider especially the time when the velocity is momentarily zero.

# Summary

Write a brief conclusion comparing your position, velocity, and acceleration measurements in the various configurations.

**Rubric Awareness**

The end of the lab is when it is appropriate to complete your work on rubric SL.A.a. This rubric asked you how you can improve on the experiment, and it is asking you to think about how your data could have been absolutely flawless. Was it easy to read position of the cart consistently? If it is not, then your measurements for position would have been slightly off due to the uncertainty in making readings.

Or you can make note of the noise in acceleration readings from Capstone. Or, would you have been able to figure out more clearly how velocity and position function if you had a longer track? This rubric is rather wide open since there are any number of ways in which your experiment could have given you better data or run more smoothly. The goal is to identify major shortcomings or significant improvements, but so long as you are thinking about how to improve the data you are working well on the concept of experimental design thinking.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.a**<br>Is able to analyze the experiment and recommend improvements<br>Labs: 2, 3, 5, 11, 12 | No deliberately identified reflection on the efficacy of the experiment can be found in the report | Description of experimental procedure leaves it unclear what could be improved upon. | Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none. |
| **SL.B.a**<br>Is able to explain operation and limitations of measurement tools<br>Labs: 2, 3, 6, 11, 12 | At least one of the measuring tools used in lab lacks a clear identification of precision/limitation | All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed | All measuring tools identified with precision/limitation of each tool listed. Description of how to measure using some tools may be incorrect/vague, or precision may not be adequately justified. | All measuring tools are identified with proper precision values and thorough discussion of limitations. Descriptions on how to make measurements are complete and could be understood by readers with no prior familiarity with the measuring tools. |
| **SL.B.b**<br>Is able to explain patterns in data with physics principles<br>Labs: 2, 3, 6, 8, 11, 12 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.B.a**<br>Is able to describe physics concepts underlying experiment<br>Labs: 2, 3, 6, 9, 11, 12 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |
| **CT.B.b**<br>Is able to identify dependent and independent variables<br>Labs: 2, 3, 6, 12 | No attempt to explicitly identify any variables as dependent or independent | Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified | The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent. | All physical quantities relevant to the experiment are identified as dependent and independent variables correctly, and no irrelevant variables are included in the listing. |
| **QR.B**<br>Is able to identify a pattern in the data graphically and mathematically<br>Labs: 2, 3, 6, 9, 11, 12 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.A**<br>Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 2 Motion in a Straight Line:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Remove the wooden block from under track so that the track rests flat on the table.
- ☐ Place the Motion Sensor level with the track so it can properly record cart motion.
- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.A.a | |
| SL.B.a | |
| SL.B.b | |
| | |

| | |
|---|---|
| CT.B.a | |
| CT.B.b | |
| QR.B | |
| IL.A | |

| | |
|---|---|
| IL.B | |
| WC.A | |
| WC.B | |
| | |

---

Lab 2 Motion in a Straight Line:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Remove the wooden block from under track so that the track rests flat on the table.
- ☐ Place the Motion Sensor level with the track so it can properly record cart motion.
- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.A.a | |
| SL.B.a | |
| SL.B.b | |
| | |

| | |
|---|---|
| CT.B.a | |
| CT.B.b | |
| QR.B | |
| IL.A | |

| | |
|---|---|
| IL.B | |
| WC.A | |
| WC.B | |
| | |

# Lab 3. Free Fall

## Goals

- To determine the effect of mass on the motion of a falling object.
- To review the relationship between position, velocity, and acceleration.
- To determine whether the acceleration experienced by a freely falling object is constant and, if so, to calculate the magnitude of the acceleration.
- To calculate the appropriate uncertainties and to understand their significance when analyzing data.

## Introduction

When an object is dropped from rest, its speed increases as it falls—that is, it accelerates. In this experiment you will characterize the motion of freely falling objects using an ultrasonic motion sensor. As with last week, a significant part of the experiment entails understanding the relationship between the acceleration, velocity, and position of an object. You will also employ the concepts of mean (or average) value, standard deviation, and standard deviation of the mean of a measured quantity. An introduction to these concepts is given in the Uncertainty/Graphical Analysis Supplement at the back of the lab manual.

## Effect of mass on the motion of a falling object

At your lab station locate the small yellow plastic ball and a steel ball of the same diameter. After recording the masses of the balls, hold the balls at the same height and drop them together. Note which ball (if either) reaches the floor first. Use the padded catch box to minimize damage to the floor by the steel ball. If the balls strike the floor at different times, consider how accurately you can release the balls at the same time. An experiment with two identical balls can indicate how small differences in release time affect your results.

Note that it is rare for students to be able to release the two balls such that they will indeed both hit the ground at the same time. So spend some time working carefully to determine if you can devise a method of dropping which will reliably result in the same time difference (or simultaneity) of landing. It is common for people to drop differently with their dominant hand than they do with their off-hand, so does the fall give the same result if you switch hands? How about if your lab partner drops instead of you, does the result change then?

Scientists have to devise methods which are consistent regardless of who performs the experiment, and often will work to vary environmental or experimental configurations which they believe are unimportant to the experiment in order to check for "hidden variables" (things which do impact your results, but were not initially considered relevant and thus ignored).

If you change the height at which the balls are released, does the result change?

Record the conditions and the observed results for each trial that you do. Based on your findings summarize your observations. What can you conclude regarding the effect of the mass on the motion of the falling balls?

Try dropping another object such as a pen or pencil along with the steel ball. How do the motions compare now? What conclusions can you draw from your observations?

Be sure that the notes you make in lab are sufficient for you to repeat the experiment later in the semester if asked to do so.

# Characterizing the operation of the motion sensor

Consult the Computer Tools Supplement at the back of the lab manual to learn how to connect the **motion sensor** to the computer interface box at your lab station. Knowing the name of your sensor is important to being able to properly set them up, as well as looking at where the cables connect to the PASCO 850 Interface. Once the sensor is connected, set up the Capstone software to simultaneously display graphs of position, velocity, and acceleration as functions of time.

The motion sensor works by sending out a sound wave pulse, and then listening for the same sound to return after reflecting off of a surface. This places two limitations on the sensor: A minimum range, which is half of how far sound can travel in the time between starting to generate the sound and being prepared to receive a return signal, and a maximum range, which is half of the distance sound can travel in the time between pulse generation (controlled by what you set the recording rate to).

I want you to be able to form arguments with the data from this sensor, that also means I want to know you believe the measurements from the sensor to be accurate. How can you ensure that when the sensor says a velocity was 0.38 m/s it was correct? Can you check in any other way to see if the velocity was not actually 0.35 m/s or 0.41 m/s?

## Calibration and Testing of equipment

Add a *digits* display to the Capstone program, and set it to display position (by clicking on the *measurement* button and selecting position). Turn on your sensor by clicking the *Record* button on the bottom left of the screen.

At this point, your instructions are to "play" with your setup. Figure out how the sensor works, convince yourselves that it **does** work. And then find the limitations of the sensor. By holding the basketball beneath the sensor, figure out what the minimum range of the sensor is. Do this by displaying a Digits display set to show position, and by using a meter stick to verify the measurement. Hold the basketball very close to the sensor and move it away until the position begins to change.

Verify that the position reading is accurate (where is it measuring from and to?), continue to move the ball away from the sensor and verify that position updates appropriately. Once satisfied that the sensor work, begin to move the basketball back toward the sensor, make note of when the position reading ceases to update accurately. *Remember: Everything you do is to be described in your notebook with sufficient detail that someone unfamiliar with the lab (no access to the lab manual) would be able to repeat your actions to verify they get the same data. So record a description of your setup, your actions before and during measurements, and your data.*

The reason we are doing this play with position displayed is simple: That is the only one of the three values you can verify with a second measure that you already have faith in, and have a similar precision in measuring the values. That being a meter stick.

Do not stress about recording absolutely everything you do during this exploratory phase. However, if you figure out something significant (like equipment limitations or capabilities), it is worth recording what you learned, and what supports that being true.

Different sensors in the room will have different minimum ranges, and each sensor will have different maximum ranges at different times based on your selected recording rate. Every time that you use one of these sensors, start by figuring out these limitations. Any attempt to measure outside of the minimum to maximum range means the data is useless.

Now take some data while moving the Basketball up and down under the motion sensor. Display this position, velocity, and acceleration data in a table. Starting from the position data in this table, determine how Capstone computes the velocity as a function of time. Which position values are used to calculate the velocity at a given time? Repeat this process for the acceleration calculation. Which velocity values are used to calculate the acceleration at a given time? Use this to determine which position values are used to calculate the acceleration at a given time. Show sample velocity and acceleration calculations in your lab notebook, taking care to label the time at which each position value used in the calculation was recorded.

Use this information to determine how fast the motion sensor can respond to changes in velocity and acceleration. If the velocity of an object suddenly (instantaneously) changes from one value to another, how long will it take the velocity reported by Capstone to reach the new value? How is this change reflected in the value of acceleration reported by Capstone? If the acceleration of an object instantaneously changes from one value to another, how long will it take the acceleration reported by Capstone to reach the new value?

Finally, determine how far away from directly beneath the sensor you are able to obtain an accurate measurement of the posiition of the ball. Does this distance from alignment change along with distance from the sensor (Can you be further off center when near to the sensor than you can when far from it, or vice-versa?)

# Characterizing free fall with a motion sensor

## Data acquisition

Hold the basketball under the motion sensor such that the top of the ball is greater than the minimum distance for your sensor. Make sure that hands, feet, stools, backpacks, and such are removed from the target area so the motion sensor "sees" only the basketball. Click on the "Start" button of Capstone to start the data taking process. Wait a few seconds before quickly removing your hand(s) and releasing the ball. Allow it to fall to the floor and bounce twice. Then click the "Stop" button to terminate data acquisition. Expand the graphs to display only the motion during the fall and through the second bounce. Check with your TA to make sure that you have a good set of data. If necessary, repeat the data taking process until satisfactory data is obtained. You may need to adjust the record rate in Capstone to get clean readings on acceleration. Be aware that changing your record rate may change your maximum range. Print out a copy of the three graphs on a single page in the "landscape" format to include in your notes.

## Qualitative analysis

Observe the acceleration-time graph. Expand the graph vertically so that the acceleration during free fall occupies most of the graph. Ignore the noisy regions during each bounce, when the ball contacts the floor. This means your data will NOT include the "peaks" of the bounce on the position graph, only the smooth curve between those peaks. Remember that velocity and acceleration update a few data points later than position due to how the sensor calculates the values. Avoiding the data around the point of contact with the floor is not cherry picking data, it is merely isolating the data we consider to those points we are 100% confident will demonstrate the physical scenario of interest (free fall).

What conclusions can you make regarding the acceleration of the basketball during the initial fall and between the first and second bounces?

After the first bounce, the ball is moving upward toward the motion sensor and slowing down before it speeds up again and bounces the second time. Explain the sign of the acceleration (negative or positive) during this interval both as the ball slows down while moving upward and speeds up while moving downward.

Is the velocity-time graph consistent with the observed acceleration during each segment of the ball's motion? Compare them using the definition of acceleration in terms of velocity.

## Quantitative analysis

The value of the basketball's acceleration can be found from the position data, from the velocity data, or from the acceleration data. If the kinematic equations describe the path of the basketball, each data set should give the same acceleration.

1. Use the position vs. time graph to determine the average acceleration between the first and second bounce with Capstone's curve fit function. Select some of the position data between

the first and second bounces using the "Highlight range of points in active data" (pencil) tool from the tools along the top of the graph. Be sure to select only data in the region where your velocity and acceleration data are consistent. From the kinematic equation, we expect the position of basketball to be described by an equation of the form $y = At^2 + Bt + B$: the quadratic equation. With the data selected, choose "Quadratic" from the Curve Fit menu (icon shows red line through blue points) along the top of graph. From your knowledge of the kinematic equations, compute the acceleration of the basketball in free fall from the constant $A$ in the curve fit. Capstone also displays the uncertainty in $A$. Use this uncertainty to compute the uncertainty in the acceleration. This uncertainty is called the standard error, and is equivalent to the standard deviation of the mean computed for a list of averaged numbers. (If the precision of your acceleration value is less than its standard deviation, ask your TA for assistance in obtaining more significant digits. Always make sure that your printout clearly identifies which data points were used in the curve fit. If Capstone does not make it clear, identify them by hand after you print the data.

2. Use the velocity vs. time graph to determine the average acceleration and its uncertainty between the first and second bounces. From the kinematic equations, we expect the velocity of the basketball during free fall to be described by an equation of the form $v = At + B$: a linear equation. Select the velocity data between the first and second bounces and choose "Linear" from the curve fit menu to obtain the slope of the velocity-time graph (the constant $A$). On your printout, identify the data points used to determine the acceleration. The uncertainty in this acceleration measurement is equal to the "standard error" reported by Capstone in the curve fit window.
3. The acceleration vs. time shows the acceleration value direction. One can simply select the data between the first and second bounce and check the mean and standard deviation buttons under the $\Sigma$ button along the top of the graph. Again, identify the data points used to determine the mean acceleration. The uncertainty in the mean value is calculated by dividing the standard deviation by the square root of $N$, where $N$ is the number of data points used to calculate the mean. You will have to count the points by hand. Capstone will compute the uncertainty for you if you use the "User Defined Fit" function in the Curve Fit function, then enter an equation of the form $y = A$ into the Curve Fit in the Tools Palette on the left side bar.
4. Print your graphs again, with the annotations requested so far included on them.
5. Did the acceleration values determined in this experiment agree with your expectations? Do they agree with each other? Use the quantitative test for consistency described in the "Uncertainty and Graphical Analysis: Using uncertainties to compare measurements or calculations" section of the lab manual. Briefly, we conclude that two measurements, $a_1$ and $a_2$, with uncertainties $u(a_1)$ and $u(a_2)$, are consistent if $t' = |a_1 - a_2| / \sqrt{u(a_1)^2 + u(a_2)^2} < 3$. You will need to compare the three accelerations measurements you made from the position, velocity, and acceleration data, respectively. You should also compare these measurements with the "expected" value of $a = g = 9.80$ m/s$^2$.
6. Are some acceleration values "better" (more precise or more accurate) than others? Explain your reasoning.

## Conclusion

Discuss what you have discovered about objects in free-fall. What did you expect to find? Did your experiment agree with your expectations? Did the various methods of determining the acceleration of falling objects give the same values? Discuss and explain, using your results for the experiment. You may wish to summarize all your experimental numerical results in a small table here, making it easier to refer to them in this part of your notes. How does the concept of uncertainty assist us in making logical conclusions?

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.a** Is able to analyze the experiment and recommend improvements<br>Labs: 2, 3, 5, 11, 12 | No deliberately identified reflection on the efficacy of the experiment can be found in the report | Description of experimental procedure leaves it unclear what could be improved upon. | Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none. |
| **SL.B.a** Is able to explain operation and limitations of measurement tools<br>Labs: 2, 3, 6, 11, 12 | At least one of the measuring tools used in lab lacks a clear identification of precision/limitation | All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed | All measuring tools identified with precision/limitation of each tool listed. Description of how to measure using some tools may be incorrect/vague, or precision may not be adequately justified. | All measuring tools are identified with proper precision values and thorough discussion of limitations. Descriptions on how to make measurements are complete and could be understood by readers with no prior familiarity with the measuring tools. |
| **SL.B.b** Is able to explain patterns in data with physics principles<br>Labs: 2, 3, 6, 8, 11, 12 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **CT.B.a**<br>Is able to describe physics concepts underlying experiment<br>Labs: 2, 3, 6, 9, 11, 12 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |
| **CT.B.b**<br>Is able to identify dependent and independent variables<br>Labs: 2, 3, 6, 12 | No attempt to explicitly identify any variables as dependent or independent | Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified | The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent. | All physical quantities relevant to the experiment are identified as dependent and independent variables correctly, and no irrelevant variables are included in the listing. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.B**<br>Is able to identify a pattern in the data graphically and mathematically<br>Labs: 2, 3, 6, 9, 11, 12 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 3 Free Fall:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.a | | CT.B.a | | WR.C | |
| SL.B.a | | CT.B.b | | IL.A | |
| SL.B.b | | QR.A | | IL.B | |
| CT.A.a | | QR.B | | WC.B | |

---

Lab 3 Free Fall:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.a | | CT.B.a | | WR.C | |
| SL.B.a | | CT.B.b | | IL.A | |
| SL.B.b | | QR.A | | IL.B | |
| CT.A.a | | QR.B | | WC.B | |

# Lab 4. Projectile Motion

## Goals

- To determine the launch speed of a projectile and its uncertainty by measuring how far it travels horizontally before landing on the floor (called the range) when launched horizontally from a known height.
- To predict and measure the range of a projectile when the projectile is fired at an arbitrary angle with respect to the horizontal.
- To predict the initial firing angle of the launcher for a prescribed range value.
- To determine quantitatively whether the measured ranges in (2) and (3) are consistent with the desired range values.

## Introduction

When objects undergo motion in two (or even three) dimensions rather than in just one, the overall motion can be analyzed by looking at the motion in any two (or three) mutually perpendicular directions and then putting the motions "back together," so to speak. In the case of projectiles, the horizontal and vertical directions are usually chosen. Why is this choice made? Ignoring the effects of air resistance, an object moving vertically near the surface of Earth experiences a constant acceleration. We know this by experiment. Likewise an object moving horizontally experiences zero acceleration. Any other choice of perpendicular directions would have nonzero, constant values of acceleration in both directions. When we write the descriptions of the motion in mathematical terms, the horizontal/vertical choice of directions results in the simplest description.

Under what conditions can the effects of air resistance be ignored? One condition is that the object's speed is not too high, since the effect of the air resistance increases with speed. If two objects are the same size and shape, the lighter one of the two will experience the larger effect on its motion due to the air. (Imagine a ping-pong ball and a steel ball bearing of the same size.) In designing this lab, care has been taken to ensure that air resistance has a negligible effect on the trajectory of the projectile. When conditions are such that air resistance cannot be ignored, the motion is more complicated.

## Mathematical preliminaries—Equation for range

To accomplish the first two of our stated goals, we need a general mathematical relationship between the horizontal range of the projectile and the initial height, initial velocity, and launch angle. See Figure 4.1. You will need to solve the appropriate kinematics equations for motion with constant acceleration in the horizontal and vertical directions simultaneously. Rather than writing the equations in terms of the angle, $\theta$, it is suggested that you use the symbols $v_{0x}$ and $v_{0y}$, where $v_{0x} = v_0 \cos\theta$ and $v_{0y} = v_0 \sin\theta$, to simplify the algebra. You need to solve for the range, $R$, in terms of $v_{0x}$, $v_{0y}$, $h$, and $g$. The details of this derivation must be included in your lab notes.

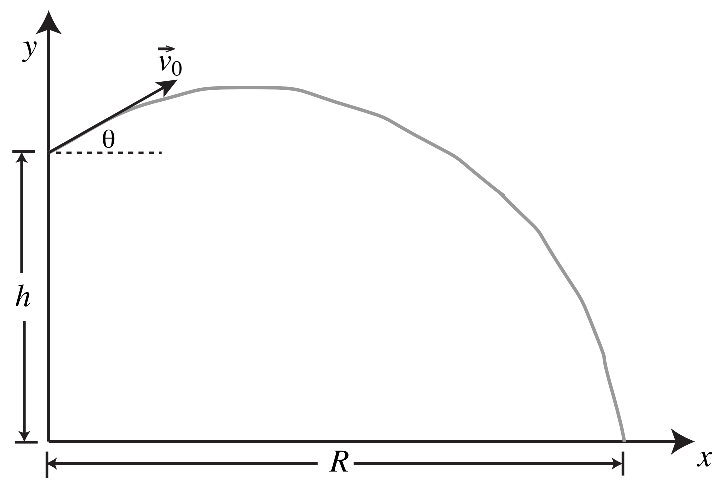



Figure 4.1. Coordinate system for calculating the range, $R$.

## Instructions and precautions for using the ball launcher

**Warning: Never look down the barrel of a launcher. Wear eye protection until all the groups have finished launching projectiles.**

1. Make sure that the launcher is attached securely to the table so it does not move when the launcher is fired. Make sure the launcher is at the proper angle by using the built-in plumb bob on the side of the launcher. Note that the angle measured by this plumb bob is the angle between the "barrel" of the launcher and the horizontal.
2. Since the projectiles will be hitting the floor, use a second plumb bob to locate and mark the position on the floor (blue tape works) directly below the launch point of the projectile. This indicates the initial horizontal position of the ball at floor level so the range (horizontal distance traveled by the ball) can be measured later. You will have to measure the height to get the vertical distance. Clearly indicate in a diagram how you measured the height (from where to where). If you are not sure how the height should be measured, please discuss it with your TA. Note that "Clearly indicate" here means that you should be describing/drawing to within the limit of the accuracy of your measuring instrument (a meter stick, so 0.1mm). Have a justification for why you chose each end of the ruler at which to measure.

3. To launch the projectile, load the ball into the projectile launcher. Use the rod to push the ball into the launch tube to one of the first two out of the three preset launch positions (short, medium, or long range. Do not use Long Range). You will hear a click as you reach each position. Notify others nearby and across the room before firing the ball. Stand out of the way and fire the launcher by pulling on the string attached to its trigger on the top. To minimize the force applied by the string to the launch tube, pull the string at right angles to the launch tube (straight up). You may need to use your other hand to stabilize the launch tube (grip the tube and frame to prevent it from rocking at launch).
4. To record the position where the projectile strikes the floor, tape a white paper target to the thin hard-board sheet (about 0.3 m $\times$ 0.5 m in size) at your lab station. Place the sheet and target at the approximate place where the ball lands. When you are ready to record some landing points, lay a piece of carbon paper (carbon side down) on top of the target. Do not put tape on the carbon paper. The ball will leave a dark smudge on the white paper where it lands. If necessary you can tape the hard-board sheet to the floor to keep it from moving, but avoid the indiscriminate use of tape on the floors. Indicate on your target which marks have already been recorded into your notes to avoid confusion in future measurements.

# Determining the initial speed of the projectile

1. Simplify your general equation for the range for the case when $\theta = 0$ (horizontal launch). Then solve for $v_0$ in terms of $R$, $h$, and $g$.
2. Set the launcher to fire horizontally, that is, to launch at an angle of zero degrees. Care with this angle setting can significantly improve your results later in the lab.
3. Starting with the medium range launch setting, fire the projectile (using the four steps in the previous section) a couple times noting where the projectile lands. Center the paper target as best you can where the ball will land. Now use the carbon paper to record the landing position of four or five launches using the same initial conditions.
4. From your data determine the average range, $R$, of the ball. Use this average distance to calculate the average initial speed of the ball as it was launched.
5. Repeat the same procedure for the short range setting on the launcher.

# Range for nonzero launch angles

1. Choose a launch angle between 30° and 40°. Using the values of the initial speed of the ball measured above and your general equation for the range, calculate the horizontal distance (range) from the launch point to where the ball should land for the short and medium range settings using the initial launch angle that you have chosen. (Do not use the long range setting.)
2. For the short and medium range settings, place a paper target on the floor at the calculated position and fire the projectile. If the projectile misses the target completely, check your calculations and/or discuss it with your TA. If the projectile does hit the target, then repeat several times to get a good average experimental range value and its corresponding standard deviation to compare with your calculated range.
3. Compare your predicted range values with the experimental range values using your ex-

perimental standard deviations. Assume that your predicted range, $R_{predicted}$ has zero uncertainty. Then check if your measurement is consistent with your prediction if $t' = |R_{measured} - R_{predicted}|/\sigma(R_{measured}) < 3$. If you find that $t' > 3$, check your calculations and consider carefully what systematic errors may be present in your experiment.

# Launch angle to achieve a given range

1. Ask your TA to assign a value of horizontal distance (range) for your group.
2. Calculate a suitable angle at one of the range settings for launching the projectile to the target set at the assigned distance. The relationship giving the initial launch angle in terms of the other parameters is:

$$\tan\theta = \frac{v_0^2}{gR} \pm \left[\left(\frac{v_0^2}{gR}\right)^2 - 1 + \frac{2v_0^2 h}{gR^2}\right]^{1/2} \tag{4.1}$$

3. Now set the target and do the experiment with your TA present to observe. Were you able to hit the target? If you have trouble, check your calculations. Is your calculator in radian or degree mode? Get assistance from your TA, if necessary. Again, compare your experimental range value to the range value assigned by your TA. If not, check your calculations and your procedure.

# Conclusion

Summarize all your results, preferably in a table showing the measured and calculated quantities with their uncertainties. Clearly display your comparisons between predicted values and experimental values. Are you convinced that the theoretical predictions made by separating the horizontal and vertical motions agree with experiment, at least within the calculated uncertainties of the experiment? Your answers must be based on your experimental results and the calculated uncertainties of the quantities you are comparing. Do not make vague statements that are not directly supported by your calculations and measurements.

| | **No Effort** | **Progressing** | **Expectation** | **Scientific** |
|---|---|---|---|---|
| **SL.A.b**<br>Is able to identify the hypothesis for the experiment proposed<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified hypothesis is present in the first half page or so of notes | An attempt is made to state a hypothesis, but no clearly defined dependent and independent variable, or lacking a statement of relationship between the two variables | A statement is made as a hypothesis, it contains a dependent and independent variable along with a statement of relationship between the two variables. This statement appears to be testable, but there are some minor omissions or vague details. | The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.c**<br>Is able to determine hypothesis validity<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection. | A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment | A statement about the hypothesis validity is made which is consistent with the data analysis completed in the experiment. Assumptions which informed the hypothesis and assumptions not validated during experimentation are not taken into account. | A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account. |
| **SL.B.c**<br>Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able.<br>Labs: 4, 5, 8, 9, 12 | No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present | No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty. | An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective. | The uncertainties are minimized in an effective way. |
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **CT.A.b**<br>Is able to identify assumptions used to make predictions<br>Labs: 4, 5, 7, 8, 10 | No attempt is made to identify any assumptions necessary for making predictions | An attempt is made to identify assumptions, but the assumptions stated are irrelevant to the specific predicted values or apply to the broader hypothesis instead of the specific prediction | Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction. | Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.c**<br>Is able to make predictions for each trial during experiment<br>Labs: 4, 5, 7, 8, 10 | Multiple experimental trials lack predictions specific to those individual trial runs. | Predictions made are too general and could be taken to apply to more than one trial run. OR Predictions are made without connection to the hypothesis identified for the experiment. OR Predictions are made in a manner inconsistent with the hypothesis being tested. OR Prediction is unrelated to the context of the experiment. | Predictions follow from hypothesis, but are flawed because relevant experimental assumptions are not considered and/or prediction is incomplete or somewhat inconsistent with hypothesis or experiment. | A prediction is made for each trial set in the experiment which follows from the hypothesis but is hyper-specific to the individual trial runs. The prediction accurately describes the expected outcome of the experiment and incorporates relevant assumptions. |
| **CT.A.d**<br>"Is able to identify sources of uncertainty "<br>Labs: 4, 5, 8, 9, 12 No attempt is made to identify experimental uncertainties. | descworst | An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect. | Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty. | All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.A**<br>Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 4 Projectile Motion:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Return the projectile and the carbon paper to the TA Table.
- ☐ Remove all tape from the floor.
- ☐ Wrap the plumb bob string around the cardboard spool.
- ☐ Store the plumb bob and string in its plastic bag.
- ☐ Return the goggles to their plastic bags.
- ☐ Place the plumb bob, tape measure, goggles and rulers in your equipment basket.
- ☐ Loosen the thumbscrew on the launcher so it can move freely.
- ☐ Quit any software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment
  - ☐ Arrive on time
  - ☐ Work well with your partner
  - ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.b | | CT.A.b | | QR.C | |
| SL.A.c | | CT.A.c | | IL.A | |
| SL.B.c | | CT.A.d | | IL.B | |
| CT.A.a | | QR.A | | WC.A | |

---

Lab 4 Projectile Motion:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Return the projectile and the carbon paper to the TA Table.
- ☐ Remove all tape from the floor.
- ☐ Wrap the plumb bob string around the cardboard spool.
- ☐ Store the plumb bob and string in its plastic bag.
- ☐ Return the goggles to their plastic bags.
- ☐ Place the plumb bob, tape measure, goggles and rulers in your equipment basket.
- ☐ Loosen the thumbscrew on the launcher so it can move freely.
- ☐ Quit any software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment
  - ☐ Arrive on time
  - ☐ Work well with your partner
  - ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.b | | CT.A.b | | QR.C | |
| SL.A.c | | CT.A.c | | IL.A | |
| SL.B.c | | CT.A.d | | IL.B | |
| CT.A.a | | QR.A | | WC.A | |

# Lab 5. Newton's Second Law

## Goals

- To determine the acceleration of a mass when acted on by a net force using data acquired via a pulley and a photogate. Two cases are of interest: (a) the mass of the system is fixed and the net force is varied, and (b) the net force is fixed and the mass of the system is varied.
- To make and analyze appropriate graphs of the resulting data that test the validity of your application of Newton's Second Law of Motion to this system.

## Introduction

Newton's First Law states that no change in the motion of an object takes place in the absence of a net force. In other words, the acceleration (change in velocity) of an object is zero unless there is a net force. But how is the acceleration related to the force? Newton's Second Law deals with this relationship. Experimentally we will explore the relationship between the net force on an object, the mass of the object, and the acceleration of the object due to the force. Newton's Second Law of Motion makes some definite predictions that you can test.

**Be sure to level the track carefully before you take any data.**

## Accelerating a fixed mass with a variable force

Behind Newton's Second Law is the assumption that an object (or group of objects) can be modeled as a point with a definite mass and location, that moves along a well defined trajectory through space with a definite velocity and acceleration. A group of objects can often be modeled as a point if it moves together rigidly, without rotation or stretching—and if its mass does not change. When we apply Newton's Second Law to a suitable group of objects, we call the group "the system."

In this experiment, a small mass is connected to the cart by a string that hangs down over a pulley. To apply Newton's Second Law to this situation, the system mass (the $m$ in $F = ma$) and the net force on the object (the $F$ in $F = ma$) must be clearly specified. Draw a free body diagram of the cart, the pulley, and the slotted masses, and use it to express the net force and the system mass in terms of the masses of each part of the system. Ignore friction for now. Check that each part of the system has the same acceleration (the $a$ in $F = ma$). This simplification is possible because both the cart and the hanging mass move as if they were glued together (assuming that the string is not stretchy). Your free body diagram and any text or mathematics needed to support your expressions for $F$ and $m$ must appear in your lab notes.

Using a photogate to measure how fast the pulley rotates, the computer can take the time and displacement measurements required to compute the displacement, velocity, and acceleration of the system as functions of time. The "Photogate with Pulley" section of the Computer Tools Supplement at the back of the lab manual has specific instructions on connecting the pulley to the computer. You will plot all three of these quantities and test to determine the best of two methods for determining the acceleration (two methods explained below).

**Ensure that the string connecting the hanging mass to the cart is resting in the groove of the pulley. This string will often fall out of the groove when the masses impact the ground at velocity.**

If the acceleration is constant, *the slope of the velocity-time graph* will be a straight line whose slope equals the acceleration. The slope of a straight line is easily found along with a useful uncertainty estimate using the "Fit" tool in the toolbar at the top of the graph window. Does the slope of the velocity-time graph yield a more precise acceleration value than simply taking *an average acceleration value* directly from the acceleration-time graph? Compare the two methods for a single data run. Explain your findings in your lab notes.

Although the computer fitting routine gives an uncertainty estimate for the slope of a graph based on one data run, the experimental conditions are not exactly the same each time the cart moves down the track. Therefore, the uncertainty estimate given by the curve fitting routine is a gross underestimate (often by a factor of ten in this exercise). Below you will compare the mass of the cart calculated from your acceleration measurements with the mass of the cart determined by an electronic balance. Incorrect uncertainties can result in false conclusions about the consistency of these two mass values. To measure the uncertainty due to variations in the condition of the cart/track, repeat the acceleration measurement for a least three trips down the track. The average acceleration value is the best estimate for the "true" acceleration, and the standard deviation of the mean is the best estimate for its uncertainty. The Uncertainty-Graphical Analysis supplement at the back of your lab manual defines and discusses the standard deviation of the mean.

You are going to want to vary the force applied to your cart in order to find a trend with respect to force applied. However, adding mass directly to the hanging side of the pulley from an outside supply would mean changing the mass of your defined system. If you change the mass of the system while also changing the force applied, then you would need to graph a three axis plot to track all changes (force, mass, and acceleration).

To avoid this problem, vary the total hanging mass from 60 g to 10 g in 10 g increments keeping the mass of the system as a whole fixed by making sure that any unused hanging masses ride in the cart. It is important that the hanging mass not exceed 60 g. The velocities achieved using larger masses can be sufficient to damage the equipment when the cart strikes the end of the track.

Now make a graph of the force (vertical axis) as a function of the acceleration (horizontal axis). Include error bars on your graph that correspond to the uncertainties in your measured acceleration values.

Newton's Second Law states that the acceleration of a system with constant mass is directly proportional to the net force and that the acceleration of an object under a constant net force is inversely proportional to its mass. If Newton's Second Law is correct, then you should be able to compute the mass of the system from the slope of your graphical analysis (Slope is rise/run, thus force/acceleration). Ask your TA for assistance if it is not clear how to proceed.

Compare the value of the system mass determined from your data, $m_{F/a}$ with the total system mass measured using an electronic balance at the back of the room, $m_{bal}$. To make this comparison quantitative, compute the $t'$-score for the discrepancy (the "error", $\Delta = |m_{F/a} - m_{bal}|$) and the uncertainty of this difference, $u(\Delta)$. The $t'$-score is described in the Uncertainty and Graphical Analysis appendix to the lab manual. If $t' < 3$, it is fair to say that your acceleration data are consistent with Newton's Second Law and your mass measurement. If $t' > 3$, carefully examine your procedures and analysis for sources of systematic error. Include the results of your examination in your notes.

# Accelerating a variable mass with a fixed force

By measuring the acceleration of the system as a function of net force, while holding the system mass constant, we can study the affect of net force on acceleration. Similarly, by keeping a fixed value of mass hanging on the string, while keeping the net force constant, we can also observed the effect of system mass on acceleration. Hang 50 or 60 g on the end of the string for this experiment. Additional rectangular steel bars (two maximum!) can be placed on top of the cart to increase the mass of the whole system. Plot the acceleration (vertical axis) as a function of the system mass (horizontal axis). Qualitatively, what happens to the acceleration when the mass increases?

Newton's Second Law states that the acceleration of a system with constant net force is inversely proportional to its mass. In mathematical form this looks like:

$$F = ma \quad \text{or} \quad a = \frac{F}{m} = F\frac{1}{m} \tag{5.1}$$

The relationship between acceleration and mass with a constant force is trickier than the relationship between acceleration and force, with constant system mass. The mathematical relation between the variables is hard to guess when the graph curves. On the other hand, straight-line graphs are simple to identify and analyze. Is there a way of plotting the accelerations and mass data that is consistent with Newton's second law, but so that the graph is a straight line? (This is called "linearizing" your data) You may need help from your TA. When you have sorted this out, you should be able to compute the value of the net force applied to the system.

Use the $t'$-score to compare the value of applied net force calculated from your graph to the gravitational force acting on the hanging mass.

# Real world effects

Are there reasons that your results might not be totally consistent with the predictions based on Newton's Second Law? Have we included all the forces acting on the system? What effect does the ubiquitous force of friction have? Examine your graph of acceleration versus force carefully.

Newton's Second Law says that the net force and the resulting acceleration are directly proportional, meaning that zero net force produces zero acceleration. Does your graph show this to be the case? Look carefully! Explain how and why the graph might deviate slightly from this ideal. Does the presence of friction invalidate your graphical determination of the system mass? Ask your TA whether your explanation is reasonable.

Your acceleration versus system mass measurements are also affected by friction; however, you do not have enough data to justify pursuing the details.

## Conclusion

Is your data consistent with the predictions of Newton's Second Law? To support your conclusion, you must compare any observed discrepancy with your experimental uncertainty. Now a question to just think about. How was Newton able to formulate the Second Law of motion? Did he have access to equipment comparable to what you used today? Was he compelled to formulate the Second Law based on his experimental results?

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.b**<br>Is able to identify the hypothesis for the experiment proposed<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified hypothesis is present in the first half page or so of notes | An attempt is made to state a hypothesis, but no clearly defined dependent and independent variable, or lacking a statement of relationship between the two variables | A statement is made as a hypothesis, it contains a dependent and independent variable along with a statement of relationship between the two variables. This statement appears to be testable, but there are some minor omissions or vague details. | The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader. |
| **SL.A.c**<br>Is able to determine hypothesis validity<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection. | A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment | A statement about the hypothesis validity is made which is consistent with the data analysis completed in the experiment. Assumptions which informed the hypothesis and assumptions not validated during experimentation are not taken into account. | A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.B.c** Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able. Labs: 4, 5, 8, 9, 12 | No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present | No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty. | An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective. | The uncertainties are minimized in an effective way. |
| **CT.A.a** Is able to compare recorded information and sketches with reality of experiment Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **CT.A.b** Is able to identify assumptions used to make predictions Labs: 4, 5, 7, 8, 10 | No attempt is made to identify any assumptions necessary for making predictions | An attempt is made to identify assumptions, but the assumptions stated are irrelevant to the specific predicted values or apply to the broader hypothesis instead of the specific prediction | Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction. | Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made. |
| **CT.A.c** Is able to make predictions for each trial during experiment Labs: 4, 5, 7, 8, 10 | Multiple experimental trials lack predictions specific to those individual trial runs. | Predictions made are too general and could be taken to apply to more than one trial run. OR Predictions are made without connection to the hypothesis identified for the experiment. OR Predictions are made in a manner inconsistent with the hypothesis being tested. OR Prediction is unrelated to the context of the experiment. | Predictions follow from hypothesis, but are flawed because relevant experimental assumptions are not considered and/or prediction is incomplete or somewhat inconsistent with hypothesis or experiment. | A prediction is made for each trial set in the experiment which follows from the hypothesis but is hyper-specific to the individual trial runs. The prediction accurately describes the expected outcome of the experiment and incorporates relevant assumptions. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.d**<br>"Is able to identify sources of uncertainty "<br>Labs: 4, 5, 8, 9, 12 No attempt is made to identify experimental uncertainties. | descworst | An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect. | Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty. | All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.A** Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |
| **WC.B** Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 5 Newton's Second Law:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

☐ Collect the slotted masses that were hung on the string.
☐ Quit Capstone and any other software you have been using.
☐ Straighten up your lab station. Put all equipment where it was at start of lab.
☐ Required Level of Effort.
  ☐ Complete the pre-lab assignment ☐ Arrive on time
  ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.A.b | |
| SL.A.c | |
| SL.B.c | |
| CT.A.a | |
| | |

| | |
|---|---|
| CT.A.b | |
| CT.A.c | |
| CT.A.d | |
| QR.A | |
| QR.C | |

| | |
|---|---|
| ILA | |
| ILB | |
| WCA | |
| WCB | |
| | |

---

Lab 5 Newton's Second Law:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

☐ Collect the slotted masses that were hung on the string.
☐ Quit Capstone and any other software you have been using.
☐ Straighten up your lab station. Put all equipment where it was at start of lab.
☐ Required Level of Effort.
  ☐ Complete the pre-lab assignment ☐ Arrive on time
  ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.A.b | |
| SL.A.c | |
| SL.B.c | |
| CT.A.a | |
| | |

| | |
|---|---|
| CT.A.b | |
| CT.A.c | |
| CT.A.d | |
| QR.A | |
| QR.C | |

| | |
|---|---|
| ILA | |
| ILB | |
| WCA | |
| WCB | |
| | |

# Lab 6. Simple Pendulum

## Goals

- To understand why we take multiple measures when gathering data
- To understand how to identify and account for systematic error.
- To distinguish between systematic and random error.
- To design and perform experiments that show what factors, or parameters, affect the time required for one oscillation of a compact mass attached to a light string (a simple pendulum).
- To use a simple pendulum in an appropriate manner to determine the local acceleration of gravity.

## Introduction

A simple pendulum consists of a relatively small (in dimension) mass on the end of a string, so the motion may be analyzed as if the mass were a point mass. (For masses with larger dimensions the rotational motion of the mass must also be included in the analysis for good agreement with experiment.) The parameters that potentially affect the period of a simple pendulum are relatively easy to study. Therefore the simple pendulum provides a good "test case" for the application of the scientific method. Although you may ask your TA for help, each lab group is responsible to decide how to take and analyze data for the relevant quantities on their own in the second half of the lab. It is especially important in this lab for you to record how you make these measurements and then analyze the data. Your choice of method also affects how you interpret your results.

## Preliminary observations

Although theory is helpful, it is unwise to design an experiment on the basis of theory alone. A few preliminary observations can dramatically improve your experiment. First, set up Capstone to measure the elapsed time for one complete oscillation, or period, of the pendulum by selecting "Pendulum Timer" as your sensor. Be sure that it is measuring what you think it is. Also remember to increase the precision on any display of digits. Use care in releasing the pendulum at large amplitudes so that the photogate is not damaged. Practice releasing the pendulum so that it swings in a single plane. Then let the pendulum oscillate 40–50 times and display your data in a table. The mean value and the standard deviation of the period can then be determined. Do this for at least two initial amplitudes (initial angles). One amplitude should be about as large as you can reasonably manage. The other should be as small as you can reasonable manage, where the mass swings through a distance of only three or four mass-diameters.

Consider carefully whether the period varies randomly from swing to swing, or whether the period changes in a systematic fashion. If the period varies randomly, the standard deviation of the mean for the data in your table reflects random variations and is a good measure of uncertainty. In this case, averaging the period over ten or more back-and-forth swings can improve the precision of your period measurement. If the period varies systematically, the standard deviation is more related to (possibly unknown) changing conditions than it is to random variations. If at all possible, your experiment should be designed so that any systematic variations are smaller than the random variations.

One way to reduce the systematic error in this case is to make five separate measurements of the period for single back and forth swings; then calculate the average and standard deviation of the mean of these measurements. **It is important to have a reliable value for the uncertainty in your measurements, as they are needed to determine which parameters affect the period in this experiment. Real differences must be larger than these uncertainties.**

Another way to reduce systematic error is to include a correction factor. Doing so does not actually improve your data, nor your resulting theory. Having a correction factor is admitting that there is something you are not accounting for in the experiment, but that you do know in what manner this unknown element influences your data. To build a correction factor, you look for a consistent pattern in the data which can be compensated for with a formula. Finding patterns in data is most easily done via analysis of a graph.

Do not proceed in the lab until you have agreed with your partner on a measurement approach (data collection and analysis) which you want to use for all subsequent tasks. Justify your choice in terms of practicality (time taken, difficulty in execution), and final results (uncertainty values)

## What makes a pendulum tick?

For the simple pendulum determine which parameters affect the period (defined as the time for one complete back and forth swing) of the oscillation. Consider such things as the amplitude (the angle of the swing) of the oscillation, the mass of the bob, and the sting length. Vary each parameter over as wide a range as is feasible with the equipment at hand. You will need to support your findings with adequate data in order to be convincing. Explain the effect of each parameter on the period.

## Determine the acceleration of gravity

When a pendulum is displaced from the vertical position, it is the gravitational force that is ultimately responsible for bringing it back to the vertical position. Thus it is not surprising that there is a relationship between the oscillation period and the acceleration of gravity. We can imagine that on the Moon, where the acceleration due to gravity is less than here on Earth, the force bringing the pendulum back to vertical would be smaller; thus the acceleration would be smaller, and the time for an oscillation would be larger. It appears then that the period of the pendulum and the acceleration of gravity are related by an inverse relation; that is, when one parameter gets larger the other gets smaller.

You may need to look in a textbook to find an expression for the relationship between the acceleration of gravity and the period of oscillation. (A PDF copy of the open source *OpenStax College Physics* is available online.) Be sure to note under what conditions the relationship is valid and plan your experiment accordingly. Then take data to determine the acceleration of gravity. Some of the data from the previous exercise may be useful, but you will need to supplement it in order to make a good determination of $g$.

Use a graphical technique to find $g$. (Hint: Find a way to graph the measured parameters in such a fashion that $g$ may be calculated from the slope of a straight-line graph). Use the uncertainty of the slope (the standard error) to determine whether your measurement is consistent with the accepted value of $g$ for Pullman, Washington. Your TA will have some suggestions here, if necessary.)

## General reminders

Carefully describe your measurement procedures in your notes. Be sure that any conclusions you make are justified by your data. When can differences in measured values be attributed to random variations, and when do they represent real differences? How do you decide? Show representative calculations for each step in your analysis.

| | **No Effort** | **Progressing** | **Expectation** | **Scientific** |
|---|---|---|---|---|
| **SL.A.a**<br>Is able to analyze the experiment and recommend improvements<br>Labs: 2, 3, 5, 11, 12 | No deliberately identified reflection on the efficacy of the experiment can be found in the report | Description of experimental procedure leaves it unclear what could be improved upon. | Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none. |
| **SL.B.a**<br>Is able to explain operation and limitations of measurement tools<br>Labs: 2, 3, 6, 11, 12 | At least one of the measuring tools used in lab lacks a clear identification of precision/limitation | All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed | All measuring tools identified with precision/limitation of each tool listed. Description of how to measure using some tools may be incorrect/vague, or precision may not be adequately justified. | All measuring tools are identified with proper precision values and thorough discussion of limitations. Descriptions on how to make measurements are complete and could be understood by readers with no prior familiarity with the measuring tools. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.B.b**<br>Is able to explain patterns in data with physics principles<br>Labs: 2, 3, 6, 8, 11, 12 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **CT.B.a**<br>Is able to describe physics concepts underlying experiment<br>Labs: 2, 3, 6, 9, 11, 12 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |
| **CT.B.b**<br>Is able to identify dependent and independent variables<br>Labs: 2, 3, 6, 12 | No attempt to explicitly identify any variables as dependent or independent | Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified | The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent. | All physical quantities relevant to the experiment are identified as dependent and independent variables correctly, and no irrelevant variables are included in the listing. |
| **QR.B**<br>Is able to identify a pattern in the data graphically and mathematically<br>Labs: 2, 3, 6, 9, 11, 12 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 6 Simple Pendulum:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Return all three pendulums which are not hanging from the bar to their bags, with strings wrapped around the included holders.
- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SL.A.a | | | CT.B.a | | | QR.C | |
| SL.B.a | | | CT.B.b | | | IL.A | |
| SL.B.b | | | QR.B | | | IL.B | |
| CT.A.a | | | | | | WC.B | |

---

Lab 6 Simple Pendulum:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Return all three pendulums which are not hanging from the bar to their bags, with strings wrapped around the included holders.
- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SL.A.a | | | CT.B.a | | | QR.C | |
| SL.B.a | | | CT.B.b | | | IL.A | |
| SL.B.b | | | QR.B | | | IL.B | |
| CT.A.a | | | | | | WC.B | |

# Lab 7. Newton's Third Law and Momentum

## Goals

- To explore the behavior of forces acting between two objects when they touch one another or interact with one another by some other means, such as a light string.
- To compare the magnitudes of the forces exerted by one object on another object and vice versa during collisions.
- To experimentally explore the relationship between an impulse and a change in motion.
- To understand the relationship between impulse and momentum.
- To explore and understand conservation of momentum.

## Introduction

You have already explored how the motion of an object is affected by applied forces, such as gravity. We have not dealt with the idea of what force interactions really are.

The important note made by Newton's Third Law is that forces are not properties of individual objects. What right now is the force of your left hand? What was the force of your body yesterday?

Neither of these questions make enough sense to answer. However, I could ask what force your hand is applying to a book which you are holding up. I could ask what was the force of your body on a chair when sitting down yesterday.

The important change is that I have now asked for a force that is 1) doing something, and 2) involving two objects. Forces are interactions between two objects. There is one force shared by the two objects, and the force is either attractive (direction of force on each objects points toward the other object), or repulsive (direction of force on each object points away from the other object).

Many approaches to Newton's Third Law talk about Force Pairs. Questions testing if you understand Newton's Third Law ask things like "If a motorcycle and an 18-wheeler collide, which one exerts the larger force?" These questions and the idea of pairing forces for "equal and opposite reaction force" can lead to much confusion, as it invites the idea that forces are properties of single objects, and that by some coincidence or mechanism there will be a possibility to find two matched forces.

This is a faulty approach to Newton's Third law. Forces are interactions, there is one force which is acting between two objects. You can consider the effects of the force on each object individually, which is what leads to the idea of "How much force did the Motorcycle apply to the 18-wheeler?" but this choice is one we are making in order to calculate vectors, since the direction of the force on each of the two objects are opposite to one another.

In this experiment we focus on forces acting between two smaller objects.

We also wish to explore the relationship between the impulse, defined as the area under the force-versus-time graph during a brief interaction, to changes in the momentum, $mv$, of an object with mass $m$ and velocity $v$. Finally we will look at the momentum of a two-body system of masses immediately before and after they interact with each other.

# Forces of interaction—Connected objects

Two force sensors are attached individually to the tops of two carts that can roll on an aluminum track. Before beginning any measurements, make sure that both force sensors are “zeroed” by pressing the “tare” button on the side of each sensor while there is nothing pushing or pulling on the hook of that sensor. Check by means of a quick force-time graph that both sensors really read very close to zero. Also make certain that the data sampling rate that you have set is sufficiently high to record the force variations that take place. If the graphs look “jagged,” with straight line segments connecting the data points, then increase the sampling rate until the lines connecting the data points form a smooth curve (even when you expand the time scale). Notice that if you read the supposedly zero force for a longer period of time, it drifts away from zero. To avoid complications from this "zero drift" you will zero your sensors before each data collection today.

Note that the force sensor mounted on Cart 1 measures the force exerted on Cart 1 by Cart 2, and the force sensor mounted on Cart 2 measures the force exerted on Cart 2 by Cart 1. Since the force sensors are oriented “back-to-back,” one sensor will measure positive forces to the right and the other will measure positive forces to the left. This difference is critical because forces are vector quantities. It is possible to change the settings to reverse the readings of one sensor so that both forces measure as positive when the carts are pulling apart, and negative when they are pushing together.

## Carts with equal masses

Place both carts on the track and connect the hooks on the force sensors together using the twisted copper wire. Place one hand on each cart (you can use both hands or work with your lab partner) and push them together or pull them apart (not excessively; getting too violent here can damage the force sensors!) all the while recording both forces as a function of time. Sketch a time segment of your data in your lab notes showing each of the push and the pull.

As you answer the following questions, and do the remaining experiments for the day, remember to zero (tare) the force sensors before each set of measurements.

From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1?

Do your conclusions change if the carts experience a nonzero acceleration? (your initial tests should have been done with the pair of carts relatively stationary, now push the carts together while moving the pair of carts along the track, or pull them apart from one another while also moving the pair of carts along the track)

What can you conclude about the direction of the force on each cart due to the other cart?

### Carts with unequal masses

Add two steel bars (approximately 0.5 kg each) to the cart on the right. With your hand touching only the cart on the left, pull and push the cart on the right while recording a graph displaying both forces as a function of time. (Of course the force sensor hooks must still be connected.) From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? Do your conclusions change if the carts experience a nonzero acceleration? What can you conclude about the direction of the force on each cart due to the other cart?

### Carts connected by string

Now connect the carts with a short length of string. (Only "pulls" are possible with a string, because the string goes slack if you push the carts together.) Do your conclusions change if the carts experience a nonzero acceleration? How does the presence of the string between the carts affect your answers regarding the forces you observed previously?

### Summary of forces of interaction—connected objects

Summarize your conclusions for connected objects clearly and concisely before continuing. Compare your results with what you would predict on the basis of Newton's Third Law. Several common mistakes in homework and on exams relate to the observations you have just made. Ask your teaching assistant if you have any doubts.

## Force of interaction—Colliding objects

### "Bouncy" collisions with equal cart masses

Mount the springs in place of the hooks on the ends of the force sensors. When screwing the springs on, you are not screwing them in until they cannot screw any further, you are just getting them to grip enough that you are unable to pull the springs out with a light tug.

Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Don't push the cart so hard that the springs totally compress during the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision and rescale the graph to show this region clearly. You may also need to adjust the sampling rate of the force sensors to get sufficient data during the collision itself. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer (both carts moving in the same direction compared against both carts moving toward each other)

## "Bouncy" collisions with unequal cart masses

Add two steel bars (approximately 1 kg) to one of the carts. Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Perform two trials, first with the high-mass cart stationary and second with the low-mass cart stationary. Again avoid pushing the cart so hard that the springs totally compress during the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision and rescale the graph to show this region clearly. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer (both carts moving in the same direction compared against both carts moving toward each other)

## 'Sticky" collisions with equal cart masses

Remove the springs from the ends of the force sensors and replace them with small metal "cups" holding pieces of clay. Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Disregard any trial in which the carts don't remain stuck together after the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision and re-scale the graph to show this region clearly. You may also need to adjust the sampling rate of the force sensors to get sufficient data during the collision itself. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer (both carts moving in the same direction compared against both carts moving toward each other)

## "Sticky" collisions with unequal cart masses

Add two steel bars (approximately 1 kg) to one of the carts. Starting with one cart stationary, give the other cart a push so it collides with the stationary cart. Perform two trials, first with the high-mass cart stationary and second with the low-mass stationary. Disregard any trial in which the carts don't remain stuck together after the collision. Display both forces as a function of time in a graph. Focus on the time interval from just before the collision to just after the collision. Rescale the graph to show this region clearly. From your data what can you conclude about the magnitudes of the forces exerted by Cart 1 on Cart 2 and by Cart 2 on Cart 1? What can you conclude about the direction of the force on each cart due to the other cart?

What difference does it make in the force relationships if both carts are moving prior to the collision? Support your answer with additional data. Does the relative direction of motion change your answer (both carts moving in the same direction compared against both carts moving toward each other)

## Summary for forces of interaction—colliding objects

Summarize your conclusions for "bouncy" and "sticky" collisions clearly and concisely before proceeding. Based on your observations how are the results changed by the different collision conditions? You will eventually learn that mechanical energy is lost in sticky collisions but is mostly conserved in bouncy collisions. Something that is true in both kinds of collisions can help you when the concept of conservation of energy is not useful.

# Impulse and momentum during collisions

In this experiment, you will measure the impulse delivered to a cart as it strikes the end of the track. The bracket mounted at one end of the Pasco track has a small hole at just the right height for mounting a spring or clay cup to meet the end of the force sensor on the cart. The impulse is calculated by finding the "area" under the force-time curve during the collision using Capstone. This area has the units of force $\times$ time, or N-s. The impulse will be compared to the change in momentum of your cart. Momentum has units of kg-m/s. Show that units of N-s are equivalent to momentum units in your notes.

The change in momentum experienced by the cart can be calculated from the velocities of the cart just before and after the collision. An ultrasonic motion sensor is used to measure the velocity of the cart. Please refer to the Computer Tools Supplement at the end of your lab manual for more information on using the motion sensor.

## Impulse and momentum in "sticky" collisions

Screw the clay cup from the unused force sensor into the bracket at the end of the track, and set up the motion sensor to measure the velocity of the cart as it moves down the track. The force sensor on the cart you are using should still have the clay cup attached to it. Give the cart a quick push down the leveled track so that it sticks to the clay on the end bracket. Disregard any trial when it doesn't stick securely. Display graphs of the force and the velocity as functions of time as the cart travels down the track and sticks to the end.

To find the impulse (the area under the force-time plot), use the "Highlight range of points in active data" tool (icon with yellow pencil and red points) along the top of the graph to select the force data that correspond to the collision. Then click on the "Display area under active data" icon (red line shaded below in gray). The area under the selected force data will appear in a box on the graph in units of N-s. Now compare the values of the impulse of the contact force during the collision with the change in momentum of the cart. What conclusion can you draw from your data?

Several trials may be necessary to discover a pattern. Remember that impulse and momentum are vector quantities, so the positive $x$-directions for the force sensor and the motion sensor need to be considered carefully.

### Impulse and momentum in "bouncy" collisions

Replace the clay cups with the springs to produce a bouncy collision at the end of the track. Again compare the values of the impulse of the contact force during the collision with the change in momentum of the cart. What conclusion can you draw from your data? Several trials may be necessary.

### Summary for impulse and momentum in collisions

Summarize your conclusions for "sticky" and "bouncy" collisions clearly and concisely before proceeding. Based on your observations, how do the results compare when the collision conditions change?

## Conservation of momentum

Using the motion sensor with clay cups on both carts, explore whether the sum of the momenta of the two carts is the same before and after a "sticky" collision. We investigate only the "sticky" collision, because we can determine the total momentum with only one velocity measurement before the collision and one after. That is all the motion sensor can do.

### Equal cart masses

Push the cart closest to the motion sensor toward the second stationary cart so the carts stick together and move off together after the collision. Compare the momentum of the system of the two carts just prior to the collision with the combined momentum just after the collision. Several trials may be necessary to get a good measurement of the velocity after collision, where the carts stick together.

### Unequal cart masses

Add two steel bars to the cart closest to the motion sensor and repeat the experiment. Compare once again the momentum of the two-cart system before and after the collision. Several trials are in order.

### Summary for conservation of momentum

Summarize your conclusions for equal and unequal cart masses clearly and concisely before going to the Synthesis section. Based on your observations, how are the results changed by varying the cart masses? What predictions can be made regarding the total momentum of both carts just prior to a collision compared to the total momentum of both carts just after the collision? Do your experimental momentum measurements results agree with your predictions about the momentum of the two-cart system before and after the collision?

## Synthesis

Using your observations on forces between interacting objects, discuss how the impulses given to the carts in a two-cart collision are (should be) related. (Refer to Newton's Third Law.) From your observations of impulse and momentum, how do the momenta of the two carts change during a collision if the contact forces during the collision represent for all practical purposes the net forces acting on the carts? Remember that the change in any quantity is defined as the final value minus the initial value. Impulse and momentum are vector quantities, so you need to pay close attention to directions as well as magnitudes.

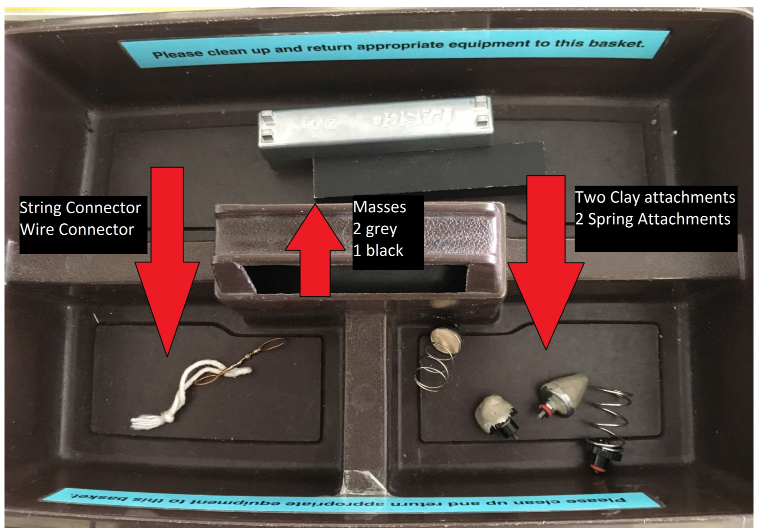



Figure 7.1. Arrange contents as shown, inform the TA if anything is missing or broken.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.b**<br>Is able to identify the hypothesis for the experiment proposed<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified hypothesis is present in the first half page or so of notes | An attempt is made to state a hypothesis, but no clearly defined dependent and independent variable, or lacking a statement of relationship between the two variables | A statement is made as a hypothesis, it contains a dependent and independent variable along with a statement of relationship between the two variables. This statement appears to be testable, but there are some minor omissions or vague details. | The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.c**<br>Is able to determine hypothesis validity<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection. | A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment | A statement about the hypothesis validity is made which is consistent with the data analysis completed in the experiment. Assumptions which informed the hypothesis and assumptions not validated during experimentation are not taken into account. | A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account. |
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **CT.A.b**<br>Is able to identify assumptions used to make predictions<br>Labs: 4, 5, 7, 8, 10 | No attempt is made to identify any assumptions necessary for making predictions | An attempt is made to identify assumptions, but the assumptions stated are irrelevant to the specific predicted values or apply to the broader hypothesis instead of the specific prediction | Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction. | Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made. |
| **CT.A.c**<br>Is able to make predictions for each trial during experiment<br>Labs: 4, 5, 7, 8, 10 | Multiple experimental trials lack predictions specific to those individual trial runs. | Predictions made are too general and could be taken to apply to more than one trial run. OR Predictions are made without connection to the hypothesis identified for the experiment. OR Predictions are made in a manner inconsistent with the hypothesis being tested. OR Prediction is unrelated to the context of the experiment. | Predictions follow from hypothesis, but are flawed because relevant experimental assumptions are not considered and/or prediction is incomplete or somewhat inconsistent with hypothesis or experiment. | A prediction is made for each trial set in the experiment which follows from the hypothesis but is hyper-specific to the individual trial runs. The prediction accurately describes the expected outcome of the experiment and incorporates relevant assumptions. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.A**<br>Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 7 Newton's Third Law and Momentum:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Put the hooks back on the force sensors.
- ☐ Return items to the tray as shown below in Figure 7.1.
- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.A.b | |
| SL.A.c | |
| CT.A.a | |
| CT.A.b | |

| | |
|---|---|
| CT.A.c | |
| QR.A | |
| QR.C | |
| | |

| | |
|---|---|
| IL.A | |
| IL.B | |
| WCA | |
| WCB | |

---

Lab 7 Newton's Third Law and Momentum:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Put the hooks back on the force sensors.
- ☐ Return items to the tray as shown below in Figure 7.1.
- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.A.b | |
| SL.A.c | |
| CT.A.a | |
| CT.A.b | |

| | |
|---|---|
| CT.A.c | |
| QR.A | |
| QR.C | |
| | |

| | |
|---|---|
| IL.A | |
| IL.B | |
| WCA | |
| WCB | |

# Lab 8. Work and Energy

## Goals

- To apply the concept of work to each of the forces acting on an object pulled up an incline at constant speed.
- To compare the total work on an object to the change in its kinetic energy as a first step in the application of the so-called Work-Energy Theorem.
- To relate the work done by conservative forces to the concept of potential energy.
- To apply the concept of conservation of mechanical energy, where mechanical energy is defined as the sum of kinetic and potential energy, to a system where the work done by nonconservative forces is zero or cancelled out, as in this experiment.

## Introduction

The notion of "work" has a special meaning in physics. When the applied force is constant in magnitude and direction, and the motion is along a straight line, the formula for work reduces to:

$$W = Fd\cos\theta = (F\cos\theta)d = F(d\cos\theta) \tag{8.1}$$

where $F$ is the magnitude of the force, $d$ is the magnitude of the displacement, and $\theta$ is the angle between the force vector and the displacement vector. Since magnitudes are always positive, $F$ and $d$ are always positive, and the sign of the work is determined by the factor of $\cos\theta$.

If the force is not constant, then one must sum the work done over each of a series of very small displacements, where the force is approximately constant over each small displacement. In calculus, this process is described in terms of integration.

The concept of work is most useful for point particles in the presence of conservative forces (no friction). Because work is a scalar and forces are vectors, problems that can be solved using the work concept are usually easier to solve by using work than by using Newton's Second Law.

## Work done on a cart moving at constant velocity

Carefully place the wooden block on edge under the end of the track opposite the pulley so that the track is inclined at an angle of 4–5° to the horizontal (About a 4" raise, so your 2x4 block should be set up appropriately). “Hooking” the small rubber feet on the bottom of the track over the edge of the block will keep the track from slipping and changing the angle if the track is bumped. Determine the angle of the ramp to within about one-tenth of a degree. A protractor can’t be read accurately enough; use trigonometry. $\theta = \arctan \frac{rise}{run}$ (Be sure you know if the answer is in degrees or radians, a quick check is to enter $cos(90)$ and check if your answer is 0 or not). Measure the mass of the cart and the mass of one of the black steel bars. A steel bar will be placed in the cart for this experiment.

The final thing to prepare for the lab is to properly zero your spring scale. You will likely need to zero the spring scale multiple times during the lab session. To zero your spring scale, you hold it at the angle which you will be measuring, and then slide the aluminum plate so that the unloaded scale reading is zero grams.

### Work done by you on the cart with spring scale parallel to track

Using the small spring scale held parallel to the ramp, pull the cart with the steel bar on board at a slow *constant* velocity up the ramp a distance of 0.5 m. To know that your velocity is constant, you either go "by feeling" and accept significant error, or you use the velocity readings from Capstone and the "Photogate with Pulley" to keep track of how constant your velocity is Using Capstone like this does add another force to your system, making your calculations more complicated, but your results more accurate. If you area "going by feeling" then your indication that the acceleration is constant is that the spring scale will have a stable reading the entire time you are pulling. The indication that your constant acceleration is zero will be that your velocity has not changed from the start to the finish of the motion (something very hard for people to distinguish clearly with only 1 meter of travel).

From the definition of work in your textbook or the Introduction above, calculate the work done by you on the cart as you pull the cart up the ramp. Be careful of units! The gram readings of the spring scale must be converted to newtons.

Repeat the measurement as you carefully lower the cart down the ramp at constant velocity.

### Work done by you on the cart with spring scale inclined 60° to track

Pull the cart up the track through the 0.5 m distance at constant velocity while holding the spring scale at an angle of 60° with respect to the ramp. If you hold the spring scale along the 30-60-90 plastic triangle provided, you can keep the scale at the required 60° inclination. Again calculate the work done by you on the cart as you pull the cart up the ramp.

Repeat the measurement as you carefully lower the cart down the ramp at constant velocity.

Compare the work with a 60° incline against that parallel to the track and comment on the results.

### Work done by gravity on the cart as it moves up and down the ramp

Draw a free-body force diagram of the cart being pulled up the ramp. (Ignore friction.) You have already computed the work you did as the cart was pulled up the ramp. Now calculate the work done by each of the other forces. Show the steps of your analysis completely and be careful of signs.

Repeat the free-body diagram and work calculations for the cart as it moves down the ramp. Use a table to show the values of the work done by each force acting on the cart for the 0° and 60° orientations of the spring balance. Sum the values of the work to find the total work done by all the forces acting on the cart for each of the two cases.

When a net force begins to act on an object at rest, the object begins to move. One can argue mathematically (see your textbook for the details) that the work done on the object (neglecting friction) is equal to the change in its kinetic energy if we define the kinetic energy to be $mv^2/2$, where $m$ is the mass of the object and $v$ is its speed. Remember that the net force on the cart is zero when it moves with constant velocity.

Based on the Work-Energy Theorem, what total work would you expect for each case? Did your calculated total work values behave in accordance with these expectations? Make quantitative comparisons between your expected and experimental results. Explain.

## Applying the Work-Energy theorem to an accelerating cart

Before beginning this investigation, level the track and take the steel bar out of the cart. Then add or subtract paper clips on the end of the string as necessary to cancel the frictional forces acting on the pulley and cart as the cart moves toward the pulley end of the track. When you have achieved the correct balance between the weight of the paper clips and the friction, the net force on the cart will be very close to zero. Then the acceleration of the cart should also be very close to zero. (What will the velocity-time graph look like if the acceleration is zero?) Give the cart a gentle push toward the pulley and use Capstone with the “Photogate with Pulley” sensor to measure the acceleration. Adjust the number of paper clips as necessary to “fine-tune” the apparatus, so that the average acceleration is as close to zero as possible.

Place a 20-g mass on the end of the string in addition to the paper clips. The net force on the system (cart plus hanging mass) is now the weight of the 20-g mass. As the cart moves and the 20-g hanging mass descends, work is done by the gravitational force on the cart-hanging mass system. Is work done by any other forces acting on the system? Remember that we have “cancelled out” the frictional force with the paper clips, so friction need not be considered here.

Move the cart to the end of the track opposite the pulley and release it from rest. Click the “Start” button in Capstone a couple seconds before releasing the cart. This ensures that you get some data before the cart is released. With the “Photogate with Pulley” sensor, Capstone defines the position of the cart at the beginning of data collection to be zero. This will be helpful below.

Take appropriate data to address the question of whether the total work done on the system is equal to the change in kinetic energy. Note that the computer can calculate the total work done since the system was released from rest and the instantaneous value of the kinetic energy in real time as the cart moves. Use the Capstone "Calculator" tool from the Tools Palette to define expressions for the work done on the system and for the kinetic energy. Your TA can assist if necessary. **Be sure to show the reasoning used to get these expressions in your lab notes.** These defined quantities can then be displayed on a graph just like other measured quantities. Displaying the work and the kinetic energy on the same graph provides the simplest method for comparing the two as a function of time.

Print out the results and discuss your findings. Be sure to address the issue of "change in kinetic energy" versus just "kinetic energy." Are they ever the same?

# Kinetic and potential energy

A slightly more complicated arrangement is produced by raising the end of the track opposite the pulley to make an angle of about 2° with the horizontal. (Laying the block of wood flat on the table under the feet of the track should be adequate.) With the 20-g mass still hanging from the end of the string, the net force on the system of the cart and hanging mass now involves more than one force. (Note: The assumption that the friction force is not changed much by raising the ramp to a small angle should be very good.) Again address the question, does the total work done by the forces equal the change in the kinetic energy of the system? Collect appropriate data to determine the validity of this hypothesis.

## Potential energy and the conservation of energy

Where does the idea of "potential energy" come from? In many ways potential energy is an intuitive concept from everyday experience. For example, if you are hit by a falling apple, you know instinctively (or by experience?) that the damage it does depends on the height from which it falls. We might even be tempted to think about the notion of "conservation of energy." While the apple is falling and losing energy of position (potential energy), is it possible that the energy of motion (kinetic energy) increases so that the sum of the two energies remains constant? One approach to answering this question is to assume that the sum of the kinetic and potential energies remains the same, and then try to discover how the potential energy would have to be defined to obey such a conservation law.

In the previous exercises you have hopefully shown that the work ($W$) done on an object by a net force is equal to the change in kinetic energy ($KE$) of that object. Mathematically we say:

$$W = \Delta KE = KE_{final} - KE_{initial} \tag{8.2}$$

If our energy conservation idea is to be correct, then something like potential energy (denoted $PE$) must exist so that the sum of $KE$ and $PE$ is constant:

$$KE_{final} + PE_{final} = KE_{initial} + PE_{initial} \quad \text{, or} \tag{8.3}$$

$$KE_{final} - KE_{initial} = PE_{initial} - PE_{final} \quad \Rightarrow \quad \Delta KE = -\Delta PE \tag{8.4}$$

The energy conservation idea from Equation 8.4 can be reconciled with the work-energy relationship from Equation 8.2 only if the change in $PE$ is equal to the negative of the work done. That is,

$$\Delta PE = -W \tag{8.5}$$

This relationship cannot be used in the presence of forces like friction since the position of an object in space does not uniquely specify the work done by friction in the process of moving the object to that position; thus the potential energy cannot be uniquely defined either. Fortunately for us, the work done by the gravitational force and the electric force, two of the most common forces in nature, are both defined uniquely as objects move from one place to another. (Refer to your textbook for a discussion of conservative forces, such as gravity and electric forces, and non-conservative forces, such as friction.) Let's apply Equation 8.5 to a simple case of an object of mass, $m$, near the earth's surface falling vertically from a position, $y+h$, to a lower position, $y$. Since the gravitational force is downward, the work done by gravity is positive and equal to $mgh$. Therefore

$$\Delta PE = PE_y - PE_{y+h} = -mgh \quad \text{or} \quad PE_{y+h} - PE_y = mgh \tag{8.6}$$

Interestingly, Equation 8.6 only specifies that the difference in the potential energy from the initial to the final state must be $mgh$. This can be satisfied by setting $PE_{y+h}$ to $mgh$ and setting $PE_y$ to zero. An equally valid solution would be to choose $PE_{y+h}$ = $mg(y+h)$ and $PE_y$ = $mgy$. In this case the zero of potential energy will occur when $y = 0$. There is a certain amount of latitude in choosing the "zero" of potential energy. This is always the case!

If an object moves horizontally near the earth's surface, the gravity force has no component along the direction of the displacement. Thus no work is done, and the potential energy of the object does not change. In cases where both horizontal and vertical displacements occur, only the vertical displacement leads to a change in potential energy of the body.

### Plotting the cart's total mechanical energy as a function of time

Use Capstone's Calculator Tool to calculate and plot the sum of the kinetic and potential energies of the cart/mass system as the cart moves down the track. Is the total mechanical energy of the system is conserved?

## Conclusion

Summarize all your findings carefully and succinctly. Where possible, discuss your results in terms of the measurement uncertainties.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.b**<br>Is able to identify the hypothesis for the experiment proposed<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified hypothesis is present in the first half page or so of notes | An attempt is made to state a hypothesis, but no clearly defined dependent and independent variable, or lacking a statement of relationship between the two variables | A statement is made as a hypothesis, it contains a dependent and independent variable along with a statement of relationship between the two variables. This statement appears to be testable, but there are some minor omissions or vague details. | The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader. |
| **SL.A.c**<br>Is able to determine hypothesis validity<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection. | A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment | A statement about the hypothesis validity is made which is consistent with the data analysis completed in the experiment. Assumptions which informed the hypothesis and assumptions not validated during experimentation are not taken into account. | A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account. |
| **SL.B.c**<br>Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able.<br>Labs: 4, 5, 8, 9, 12 | No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present | No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty. | An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective. | The uncertainties are minimized in an effective way. |
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.b**<br>Is able to identify assumptions used to make predictions<br>Labs: 4, 5, 7, 8, 10 | No attempt is made to identify any assumptions necessary for making predictions | An attempt is made to identify assumptions, but the assumptions stated are irrelevant to the specific predicted values or apply to the broader hypothesis instead of the specific prediction | Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction. | Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made. |
| **CT.A.c**<br>Is able to make predictions for each trial during experiment<br>Labs: 4, 5, 7, 8, 10 | Multiple experimental trials lack predictions specific to those individual trial runs. | Predictions made are too general and could be taken to apply to more than one trial run. OR Predictions are made without connection to the hypothesis identified for the experiment. OR Predictions are made in a manner inconsistent with the hypothesis being tested. OR Prediction is unrelated to the context of the experiment. | Predictions follow from hypothesis, but are flawed because relevant experimental assumptions are not considered and/or prediction is incomplete or somewhat inconsistent with hypothesis or experiment. | A prediction is made for each trial set in the experiment which follows from the hypothesis but is hyper-specific to the individual trial runs. The prediction accurately describes the expected outcome of the experiment and incorporates relevant assumptions. |
| **CT.A.d**<br>"Is able to identify sources of uncertainty "<br>Labs: 4, 5, 8, 9, 12 No attempt is made to identify experimental uncertainties. | descworst | An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect. | Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty. | All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.A**<br>Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 8 Work and Energy:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.b | | CT.A.b | | IL.A | |
| SL.A.c | | CT.A.c | | IL.B | |
| SL.B.c | | CT.A.d | | WC.A | |
| CT.A.a | | QR.A | | WC.B | |
| | | QR.C | | | |

---

Lab 8 Work and Energy:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.b | | CT.A.b | | IL.A | |
| SL.A.c | | CT.A.c | | IL.B | |
| SL.B.c | | CT.A.d | | WC.A | |
| CT.A.a | | QR.A | | WC.B | |
| | | QR.C | | | |

# Lab 9. Buoyancy

## Goals

- To experimentally determine the relationship between the buoyant force on an object and the weight of water that it displaces.
- To compare the buoyant behavior of an object more dense than water with that of an object less dense than water.
- To calculate the densities of aluminum and wood cylinders from your data and to compare these densities to known values.

## Introduction

Buoyancy is the name given to the force that arises when an object displaces a fluid (either a gas or a liquid) in a force field (usually gravity). The buoyant force is responsible for keeping ships from sinking and for keeping hot air balloons in flight. If an object is at rest in or on a fluid, it experiences a net force of zero. The forces acting on a partially or completely submerged object at rest generally include the gravitational force, $F_g$, the buoyant force, $F_{Buoyant}$, and whatever additional force (if any) is required to hold the object in position. In the work below, this holding force is supplied by and measured with a force sensor. When the object is at rest,

$$F_{Sensor} + F_g + F_{Buoyant} = 0 \tag{9.1}$$

In this lab, you will measure the buoyant forces acting on two cylinders as they are submerged in water, and relate these forces to the weight of the water they displace. You will also calculate the average densities of each cylinder. The cylinders are marked at centimeter intervals along their lengths. The cylinders are lowered into a beaker with their long axes perpendicular to the water surface, so the volume submerged, $V_s$, is

$$V_s = \pi R^2 L_s = AL_s \tag{9.2}$$

where $L_s$ is the length of the submerged portion of cylinder, $R$ is the cylinder radius, and $A$ is the cylinder's cross-sectional area. The weight of the water displaced by the object is given by

$$W_{displaced} = \rho_w V_s g \tag{9.3}$$

where $\rho_w$ is the density of water ($1.000 \times 10^3$ kg/m$^3$).

## Buoyant force on an object more dense than water

Before beginning, draw a free-body diagram showing the forces on an object (more dense than water) partially submerged in water.

If you have questions on how to set up the force sensor, refer to the Force Sensor section of the Computer Tools Supplement at the back of the lab manual. The force sensor uses one of the analog input channels (A, B, or C) on the interface unit.

Carefully hang the aluminum cylinder on the force sensor. With the lab jack near its maximum height, adjust the position of the force sensor so that the cylinder sits completely inside the tall beaker without bumping the sides. Then add water to the beaker until the aluminum cylinder is completely submersed. This ensures that the beaker has enough water to cover the cylinder, but is not so full that water will spill when the cylinder is immersed. Use water from the sink at the back of your lab. If your beaker is already filled from a previous lab section, submerge the cylinder to verify that sufficient water remains for full immersion.

To begin the experiment, lower the lab jack so that the aluminum cylinder is completely out of the water. With the aluminum cylinder hanging in the air, tare the force sensor. This sets the force sensor reading to zero with the entire weight of the cylinder applied. The force sensor reading as the cylinder is immersed will then equal the change in force, that is, the upward buoyant force. Since the force sensor in this orientation reads positive for upward forces, the upward buoyant force will be sensed directly as a positive force.

One problem with the force sensors is a phenomenon called "zero drift." This phenomenon is a tendency over time for the sensor to depart the zero point which you defined when you tared the device. To see this in action, you may zero the sensor and record data without allowing anything to change in your setup. Over the course of 10 minutes, the computer will not read a constant zero force.

To minimize the impact of this drift on your data, you must gather the data quickly. Raising your lab jack carefully 1cm, pausing to record the measurements from the software, and then raising carefully another 1cm can take quite a while to do.

One option around this dilemma would be to tare your sensor before each time you raise the lab jack, and to add up the individual force measurements as you submerge more of your cylinder. This relies on an assumption that there is a linear relationship between the force applied and the length submerged. While this seems like a perfectly reasonable assumption, the entire point of this lab is to determine that very relationship. No experiment which makes assumptions about the results to select methods can ever be considered reliable!

So, to avoid constantly zeroing your sensor, but also minimize the impact of zero drift, you are challenged to take your readings quickly. One fast method is to avoid taking the time to transcribe data to your notebook at all during measurement. Starting with the cylinder out of the water, begin measurement, and start to raise the lab jack. Pause in raising the lab jack as you hit each 1cm mark on the cylinder. If you pause for a count of 3, it should be obvious in reviewing the graph of your data where the pause happened (you may need to zoom in on the graph to see this). Any sloped/curved section of the graph is time when you are moving the lab jack, and any flat section of the graph is time when you are pausing for measurement. Take an average of the readings in the flat section of the graph, and record that as your measurement for the relevant 1cm mark.

Make a graph that compares the buoyant force (on the $y$-axis) with the weight of the water displaced (on the $x$-axis) for each value of $L_s$ (so one data point for 1 cm submerged, another for 2 cm submerged...). From the graph, can you deduce a simple mathematical relationship between the two? Discuss/Explain. Look up Archimedes' Principle in a textbook. Do your results support the validity of Archimedes' Principle?

## Buoyant force on an object less dense than water

Before beginning, draw a free-body diagram showing the forces on an object (less dense than water) partially submerged in water. Do the directions of the forces shown depend on the density of the object, or do only the magnitudes depend on the density?

Replace the aluminum cylinder with the wood cylinder, which attaches directly to the force sensor by a screw. **Do not remove the threaded screw in the top of the wood cylinder!** Its mass is negligible relative to the mass of the cylinder itself. **Do not screw the cylinder more than 5 mm (about 1/4 inch) into the force sensor.** The force sensor can be damaged by screwing it in too far. It does not need to screw in until unable to screw in further, only far enough that it will not fall off when released.

Again, measure the buoyant force as the submerged portion of the cylinder is increased in 1-cm increments. Do the buoyant force and the weight of the displaced water obey the same relation in this case? Discuss/explain.

## Relative density of aluminum and wood

In your notebook, show that the density of any solid unknown material $\rho_{Unknown}$ obeys the following relationship:

$$\frac{\rho_{Unknown}}{\rho_w} = \frac{W_{Unknown}}{F_{MaxBuoyant}} \tag{9.4}$$

where $W_{Unknown}$ is the weight of the unknown object, $F_{MaxBuoyant}$ is the maximum buoyant force on the object (that is, the buoyant force when it is totally submerged in water), and $\rho_w$ is the density of water.

Use Equation 9.4 to calculate the density of the aluminum and the wood. Compare your calculated densities with accepted values from a textbook, handbook, or reputable online source. The density of natural wood can vary considerably, and often it is difficult to identify what wood you are working with. Additionally, wood will change in density with environmental conditions and age. A reasonable range of density for wood is that of oak, $0.60 \rightarrow 0.90\frac{g}{cm^3}$. Ultra-light woods like Balsa can go as low as $0.11\frac{g}{cm^3}$, while some hardwoods like ebony may even exceed water with densities as high as $1.33\frac{g}{cm^3}$ List some examples in your notebook. In contrast, the density of aluminum should not vary more than 0.05%. Does your measured density for aluminum agree with the handbook value of $2.7\frac{g}{cm^3}$ within the limits of the expected error for this experiment? If your measurement and the handbook value disagree by more than three standard deviations, carefully examine your calculations and procedures for sources of error.

## Some additional questions

Consider the following questions:

1. How can an aircraft carrier (or a concrete canoe) float when the density of the material used to build it is greater than the density of water?
2. Does air create a buoyant force? If so, how can you estimate the magnitudes of the buoyant forces due to the atmosphere on your wood and aluminum cylinders?
3. Is the direction of the buoyant force always opposite the direction of the gravitational force?
4. Does the buoyant force on a totally submerged object change as the object moves farther and farther below the surface of the fluid?

| | **No Effort** | **Progressing** | **Expectation** | **Scientific** |
|---|---|---|---|---|
| **SL.B.b**<br>Is able to explain patterns in data with physics principles<br>Labs: 2, 3, 6, 8, 11, 12 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |
| **SL.B.c**<br>Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able.<br>Labs: 4, 5, 8, 9, 12 | No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present | No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty. | An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective. | The uncertainties are minimized in an effective way. |
| **CT.A.d**<br>"Is able to identify sources of uncertainty "<br>Labs: 4, 5, 8, 9, 12 No attempt is made to identify experimental uncertainties. | descworst | An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect. | Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty. | All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.B.a**<br>Is able to describe physics concepts underlying experiment<br>Labs: 2, 3, 6, 9, 11, 12 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |
| **QR.B**<br>Is able to identify a pattern in the data graphically and mathematically<br>Labs: 2, 3, 6, 9, 11, 12 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 9 Buoyancy:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Replace the small hook in the force sensor.
- ☐ empty your water pitcher into the sink at the back of the room
- ☐ Verify that the redundant 90°clamps are tightened in place on the rod stand.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.B.b | |
| SL.B.c | |
| CT.A.d | |
| | |

| | |
|---|---|
| CT.B.a | |
| QR.A | |
| QR.B | |
| QR.C | |

| | |
|---|---|
| IL.A | |
| IL.B | |
| WC.B | |
| | |

---

Lab 9 Buoyancy:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Replace the small hook in the force sensor.
- ☐ empty your water pitcher into the sink at the back of the room
- ☐ Verify that the redundant 90°clamps are tightened in place on the rod stand.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | |
|---|---|
| SL.B.b | |
| SL.B.c | |
| CT.A.d | |
| | |

| | |
|---|---|
| CT.B.a | |
| QR.A | |
| QR.B | |
| QR.C | |

| | |
|---|---|
| IL.A | |
| IL.B | |
| WC.B | |
| | |

# Lab 10. Ballistic Pendulum

## Goals

- To determine the launch speed of a steel ball for the short, medium, and long range settings on the projectile launcher apparatus using the equations for projectile motion.
- To use the concepts of gravitational potential energy and conservation of mechanical energy to determine the speed of the ball plus pendulum as it first begins to swing away from the vertical position after the "collision."
- To explore the relationships between the momentum and kinetic energy of the ball as launched and the momentum and kinetic energy of the ball plus pendulum immediately after the ball is caught by the pendulum apparatus.

## Introduction

The "ballistic pendulum" carries this name because it provides a simple method of determining the speed of a bullet shot from a gun. To determine the speed of the bullet, a relatively large block of wood is suspended as a pendulum. The bullet is shot into the wooden block so that it does not penetrate clear through it. This is a type of "sticky" collision, where the two masses (bullet and block) stick to one another and move together after the collision. By noting the angle to which the block and bullet swing after the collision, the initial speed can be determined by using conservation of momentum. This observation incorporates some predictions that we can check. In this experiment, the ballistic pendulum apparatus will be used to compare the momentum of the steel ball before the "collision" to the momentum of the ball and pendulum apparatus, equivalent to the wooden block plus the bullet, after the collision. A comparison of the kinetic energy of the ball before the collision with the kinetic energy of the system afterward will also be made.

Figure 10.1 shows a diagram of the ballistic pendulum apparatus. For the ballistic pendulum experiment, the projectile launcher from the projectile motion laboratory is mounted horizontally so that the pendulum can catch the emerging steel ball. The angle indicator can be used to measure the maximum angle reached by the pendulum as it swings after the collision. The angle indicator should read close to zero when the pendulum is hanging in the vertical position. If the reading is measurably different from zero, then take the difference in the angle readings (maximum angle reading minus initial angle reading).

**Warning: Never look down the launcher barrel. Wear eye protection until everyone is finished launching projectiles.**

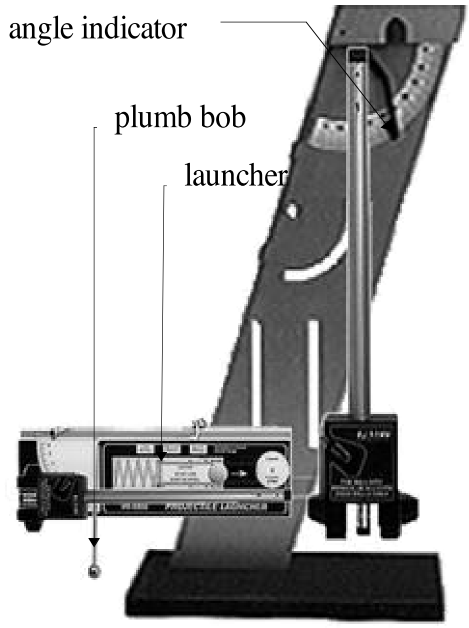



Figure 10.1. Ballistic pendulum apparatus.

## Momentum of steel ball before collision

For this part of the experiment, remove the pendulum by gently unscrewing the rod that supports its upper end. Now determine the muzzle velocity of the steel ball by firing it horizontally and measuring the distance traveled horizontally before striking the ground. Do this for the short, medium, and long range settings of the launcher. Refer back to your notebook pages from Projectile Motion if you need equations and procedures for determining velocity.

The momentum of the ball is found by multiplying its mass times its velocity. Quantitatively estimate the uncertainties in these momentum values based on the uncertainties of the measured horizontal distance traveled and the measured vertical height. The momentum of the ball-pendulum system before the ball collides with the pendulum is now known.

## Momentum of ball and pendulum after collision

The speed (and from it the momentum) of the ball and pendulum just after the collision is computed by assuming that the kinetic energy of the ball and pendulum just after the collision is totally converted into gravitational potential energy at the top of its swing. This requires that the frictional forces on the ball and pendulum system during the swing are small (negligible). The increase in gravitational potential energy is just the weight of the pendulum times the change in height, and the change in height can be computed from the maximum angle of the pendulum swing and some straightforward trigonometry. Since the pendulum is not a point mass, the change in potential energy is given by the change in height of its center of gravity. The center of gravity can be located by removing it from its support screw at the top and then balancing it on a “knife edge”. (A thin ruler works.) While you have the pendulum disassembled, be sure to measure the mass of the pendulum and the distance from the pivot point at the top to the center of gravity. Both of these measurements should be done with the ball bearing inserted into the pendulum.

Mount the pendulum so that it will catch and trap the steel ball before proceeding. Be gentle as you screw in the pendulum support rod; it does not need to be tight, attempting to screw it in "all the way" will break the pendulum. Now launch the ball into the pendulum using the short, medium, and long range settings of the projectile launcher. Repeat each measurement several times and take appropriate averages. (Remember to check the initial angle of the pendulum at rest.)

Each measurement should be done with two launches if you are able to manage it. Launch the ball into the pendulum, and then (being careful not to lift the pendulum further than the current angle reading) release the bearing and launch once again. The reason for the double launch is that your angle indicator is held in place after the launch by friction. This same friction resists the motion of the pendulum, causing your measured angle to be $1° - 3°$ shorter than the actual angle were we not attempting to measure in this manner. Returning the bearing to the launcher and preparing for a new launch may not be possible with the short range setting.

From your data calculate the speed of the pendulum and ball together just after the collision. Multiply by the appropriate mass to get the momentum. The momentum of the ball-pendulum system just after the collision is now known.

# Is momentum conserved?

Compare the initial momentum of the ball (moving) and pendulum (stationary) system before the collision with the final momentum of the same system just after the collision using your calculated velocities and measured masses just before and just after the collision. Is momentum conserved? You cannot answer this question without comparing the difference between the two momenta with the uncertainty of this same difference. If the difference between the momenta is more than three times the uncertainty of the difference, the odds of the difference being due to random variations is small—your data do not support conservation of momentum in this case. If you expect momentum to be conserved, examine your calculations and procedures for errors.

# Is kinetic energy conserved?

Since you know the masses and speeds of the objects before and after the collision, you can calculate the kinetic energies of the system before and after the collision. Is kinetic energy conserved? To answer this question, you will need to estimate your experimental uncertainties and compare them with any observed differences, as you did to test conservation of momentum.

Assuming that momentum is conserved before and after the collision, find a general symbolic mathematical expression for the ratio of the final kinetic energy over the initial kinetic energy (meaning manipulate equations with variables only, do not enter any values you measured). You may need some help from your TA here.

Using the data from your earlier calculations, compare your experimental kinetic energy ratio to that predicted by assuming momentum is conserved (The ratio found by doing the symbolic mathematical expression). Is it the same ratio?

Is overall energy (all forms of energy, not just KE & PE) conserved in this collision? If so, what forms of energy would need to be included to satisfy the general energy conservation principle?

Note: A simplification has been made by assuming that the pendulum consists of a point mass on the end of a string whose length is equal to the distance from the pivot point to its center of mass. When the pendulum swings, it necessarily rotates about its center of mass. This suggests that some rotational kinetic energy is imparted to the ball and pendulum system along with its translational kinetic energy ($\frac{1}{2}mv^2$). If significant, this would produce a systematic error in the calculated speed of the ball and pendulum system after the collision. Would it make the calculated speed too high or too low? Can you detect any systematic error in your calculated values? Discuss.

# Summary

Mechanical energy and momentum are conserved only when certain conditions are met. Qualitatively summarize your results, explaining why the collision between the ball and the pendulum conserves momentum but not mechanical energy. Similarly, explain why the motion of the pendulum during its swing conserves mechanical energy but (apparently) not momentum.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.b**<br>Is able to identify the hypothesis for the experiment proposed<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified hypothesis is present in the first half page or so of notes | An attempt is made to state a hypothesis, but no clearly defined dependent and independent variable, or lacking a statement of relationship between the two variables | A statement is made as a hypothesis, it contains a dependent and independent variable along with a statement of relationship between the two variables. This statement appears to be testable, but there are some minor omissions or vague details. | The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader. |
| **SL.A.c**<br>Is able to determine hypothesis validity<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection. | A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment | A statement about the hypothesis validity is made which is consistent with the data analysis completed in the experiment. Assumptions which informed the hypothesis and assumptions not validated during experimentation are not taken into account. | A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |
| **CT.A.b**<br>Is able to identify assumptions used to make predictions<br>Labs: 4, 5, 7, 8, 10 | No attempt is made to identify any assumptions necessary for making predictions | An attempt is made to identify assumptions, but the assumptions stated are irrelevant to the specific predicted values or apply to the broader hypothesis instead of the specific prediction | Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction. | Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made. |
| **CT.A.c**<br>Is able to make predictions for each trial during experiment<br>Labs: 4, 5, 7, 8, 10 | Multiple experimental trials lack predictions specific to those individual trial runs. | Predictions made are too general and could be taken to apply to more than one trial run. OR Predictions are made without connection to the hypothesis identified for the experiment. OR Predictions are made in a manner inconsistent with the hypothesis being tested. OR Prediction is unrelated to the context of the experiment. | Predictions follow from hypothesis, but are flawed because relevant experimental assumptions are not considered and/or prediction is incomplete or somewhat inconsistent with hypothesis or experiment. | A prediction is made for each trial set in the experiment which follows from the hypothesis but is hyper-specific to the individual trial runs. The prediction accurately describes the expected outcome of the experiment and incorporates relevant assumptions. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.C** Is able to analyze data appropriately Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A** Is able to record data and observations from the experiment Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B** Is able to construct a force diagram Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.A** Is able to create a sketch of important experimental setups Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 10 Ballistic Pendulum:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Remove any blue tape from equipment and area around lab table.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SL.A.b | | | CT.A.b | | | IL.A | |
| SL.A.c | | | CT.A.c | | | IL.B | |
| CT.A.a | | | QR.A | | | WC.A | |
| | | | QR.C | | | | |

---

Lab 10 Ballistic Pendulum:

Name: ____________________ Lab Partner: ____________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Remove any blue tape from equipment and area around lab table.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SL.A.b | | | CT.A.b | | | IL.A | |
| SL.A.c | | | CT.A.c | | | IL.B | |
| CT.A.a | | | QR.A | | | WC.A | |
| | | | QR.C | | | | |

# Lab 11. Spring-Mass Oscillations

## Goals

- To determine experimentally whether the supplied spring obeys Hooke's law, and if so, to calculate its spring constant.
- To determine the spring constant by another method, namely, by observing how the oscillation frequency changes as the mass hanging on the end of the spring is varied.
- To add additional air resistance to the oscillating system and compare the resulting displacement as a function of time with the theoretical prediction given.

**NOTE: Never pull your mass down to begin oscillations in this lab. Always compress the spring by lifting the mass up from equilibrium. Pulling the mass down can hyper-extend the spring and cause the mass hangar to bounce off the hook completely**

## Introduction

If you hang a mass from the bottom end of a spring, then stretch or compress the spring and release it, the mass will oscillate up and down. In this experiment we explore the nature of the force exerted by a "real" spring when it stretches. We determine if the resulting force oscillation is "simple harmonic" and examine the effect of energy loss on its motion. The term "simple harmonic" is applied to oscillatory motion that can be characterized by a sinusoidal function; that is, the displacement follows a simple sine or cosine function.

This lab makes extensive use of curve fitting routines, where the computer fits a model to your experimental data. Normally a model that omits important features of the experiment will fail to describe the data well. Unfortunately, making a model more complex can give it the ability to fit data for which the theory does not apply. (Some models can "fit an elephant"!) One defense against this is to examine any predictions of the model (or theory) for reasonableness.

## Force exerted by a stretched spring

In this exercise, you are to plot the force exerted by a spring as a function of its "stretch" (e.g. - the change in length, not the overall length). Suspend the spring from a force sensor. Start by adding a 50-g mass to the mass hanger, which also has a mass of 50 g, to make a total of 100 g of mass hanging from the spring. Then increase the hanging mass in 100 g increments up to a total of 1200

g. Devise a method to measure and record the stretch of the spring. Remember to zero the force sensor appropriately and to use SI units.

From your graph determine a mathematical equation relating the spring force to the stretch of the spring. Compare your result to the Hooke's Law model described in your textbook. Can you characterize your real spring with a unique value of the spring constant (sometimes called the force constant) as in Hooke's Law? Based on your data and analysis, how "ideal" is your spring?

# Spring-mass oscillations (neglect damping)

## Experiment set-up

Hopefully your first set of measurements has you convinced that the spring you are using is well described by Hooke's Law due to the spring force being directly proportional to the displacement from equilibrium. The displacement should then be sinusoidal for the oscillating mass. In this case, the spring force itself should vary sinusoidally. That is, the spring force $F_{Spring}$ can be expressed in terms of sine and/or cosine functions of time. In terms of the sine function,

$$F_{Spring}(t) = A\sin(\omega t + \phi) \tag{11.1}$$

where $\omega$ corresponds to the angular frequency of oscillation. The angular frequency has units of $\frac{radians}{s}$ and is just $2\pi$ times the ordinary frequency (Hz). $A$ is the amplitude of the oscillation and $\phi$ is the phase; changing $\phi$ changes the value of the sine function at time $t = 0$.

Hang a 1-kg mass from the spring and set up the force sensor to measure the force oscillations. Verify the sampling rate of the force sensor is 20 Hz. Zero the force sensor when the mass is hanging at equilibrium. Displace the mass about 5 cm from its rest position and release it (Remember to RAISE the mass, not to pull it down). Display the force on a graph. Select 10 or 15 seconds of data showing the oscillation using the "Highlight range of active points" tool in the toolbar across the top of the of the Display Area. Then select the "Sine: $Asin(\omega t + \phi) + C$" function from the "Apply selected curve fits from active data" menu in the tool bar across the top of the Display Area. This tells the software to attempt fitting a function of the form $A\sin(\omega t - \phi) + C$ to your data, the constant $C$ accounts for small errors in taring the force sensor.

After this operation, Capstone should display a curved "best-fit" line which follows the selected data and the values of the constants $A$, $\omega$, $\phi$, and $C$ (and their uncertainties) as determined by a least squares technique. Comment on how accurately the fitted sinusoidal function matches your actual data. (If the curve fit fails, it generally does a very poor job of describing your data. If your curve fit fails, discuss the situation with your TA.) If the uncertainty of $\omega$ is less than the least significant digit of the best fit value, increase the precision of your data in the Data Summary tool from the Tools Palette.

The value of the period of the oscillation is equal to $\frac{2\pi}{\omega}$. Check to make sure that the period value calculated from $\omega$ is reasonable. For instance, you can estimate the period using a watch or the computer clock over several periods and it should be comparable to this calculation. When a curve fitting routine makes an error, it is usually a large one. You do not need a very precise period measurement to perform a useful check on the results of the curve fitting routine.

Perform a simple test of the effect of amplitude on the period of oscillation by displacing the mass about 20 cm from its equilibrium position and releasing it (remember: compress, not stretch). Display the force on a graph and fit the Sine function to this data. Again comment on how accurately the fitted function matches the data and note the value of the period of oscillation. Based on this limited data, how does the oscillation period depend on the amplitude of the oscillation? Compare this behavior with the effect of amplitude on the period of the simple pendulum, which you measured in an earlier lab. The pendulum was a simple harmonic oscillator, do you expect the spring to behave similarly?

## Effect of mass on the oscillation period

Vary the total hanging mass including the mass of the 50-g hanger from 200 g to 1200 g, determining the period of the oscillation for each mass value using the techniques from the previous section. It is a good idea to zero the force sensor with the mass at equilibrium prior to each run. For an ideal spring, the angular frequency, $\omega$, of an oscillating spring-mass system is related to the spring constant, $k$, and the hanging mass, $m$, by the relation:

$$\omega = \sqrt{\frac{k}{m}} \tag{11.2}$$

We hope to determine $k$ by measuring the period $\omega$ as a function of the mass $m$ on the end of the spring. Because the slope of a line can be determined with low uncertainties, we want to modify Equation 11.2 to get the equation of a line with slope $k$. Solve Equation 11.2 for the mass, $m$. Show/explain why making a graph of $m$ (on the vertical axis) as a function of $1/\omega^2$ (on the horizontal axis) should be a straight line with a slope value equal to the spring constant, $k$, and a vertical axis intercept of zero. Make such a graph with your data. Compare the slope value of your graph with the spring constant determined using forces measurements (in the first part of the lab). Do they agree within the uncertainty limits of each? Does your graph have a zero intercept as predicted by the analysis of an ideal spring? What is the intercept value and corresponding uncertainty? What are the units of the intercept value?

Hooke's Law applies to "ideal", that is, massless springs. For ideal springs, the oscillation period goes to zero as the hanging mass is reduced to zero. Thus the oscillation frequency would approach infinity as the hanging mass approaches zero. Remove the hanging mass from your spring, stretch it a small amount (0.5–1.0 cm), and let it go. Is the oscillation frequency of your spring by itself infinite? How does it differ from an ideal spring?

When $m$ (on the vertical axis) is plotted as a function of $1/\omega^2$ (on the horizontal axis), the intercept value will be negative with a magnitude known as the "effective mass of the spring." Using energy considerations and some simplifying assumptions, one can show that the effective mass should be about one-third of the total mass of the spring. How close is the magnitude of your intercept value to one-third of your spring mass?

# Spring-mass oscillations with damping

The term "damping" is just a short way of saying that there are frictional forces which convert the mechanical energy (potential and kinetic) of a system into heat. In our case we will use a thin piece of cardboard moving back and forth through the air to provide damping. The cardboard piece has a small hole punched in the middle allowing it to slide over the top of the mass hanger. Then you can place any additional mass on top of the cardboard piece to hold it firmly in place. For this part of the experiment, put a total of $500 \pm 5$ g (including the mass of the cardboard and the 50-g hanger; record the actual value used) hanging on the spring.

With the hanging mass and cardboard in place compress the spring 8–10 cm from equilibrium and release it. Use Capstone to plot the force as a function of time for 40–60 s. You will notice that the amplitude of the oscillation decreases significantly during the experiment due to the damping effect of air on the piece of cardboard.

As discussed in your textbook, when the damping force is relatively small and proportional to the velocity of the object, the oscillations can be described by a sinusoidal function with an amplitude that decreases exponentially (that is a negative power of $e$). We can check whether this is true for the present system by fitting such a function to our data and determining whether it fits appropriately.

After selecting about 50 s of your data with the "Highlight range of active points" tool (enough to show the decay clearly), choose the "Damped Sine: Ae^(-Bt)(sin($\omega t + \phi$)) + C" option from the "Apply selected curve fits from active data" menu. This tells the software to attempt fitting a function of the form $Ae^{-Bt}\sin(\omega t - \phi) + C$ to your data. The value of "$B$" is the decay constant for the decay. The time $\tau = \frac{1}{B}$ is the time required for the amplitude of the oscillation to decrease from its value of $A$ (at time $t = 0$) to $\frac{A}{e} \approx \frac{A}{3}$ (at time $t = \tau$).

When the fit is done, the actual "best-fit" values of the four constants will be shown in the fit window to the left of your initial guesses and also in a small box within the graph window. Uncertainties (in the form of standard errors) will also be displayed for each value. In the graph window check to make sure that the fitted function actually does a good job of fitting the data. If the amplitude or phase of the fitted function differs significantly from the data (check this carefully!), then you will need to choose some other initial values of the constants and try again.

How closely does the fitted curve match your actual data? You should expand the time scale of a portion of your data so the fitted curve and the actual data can be seen more clearly and print it out to support your conclusions here. Estimate the time required for the oscillation amplitude to reach $\frac{1}{e}$ of its initial amplitude using a watch or the computer clock. Is the value of $B$ reported by the damped sine fit consistent with your estimate? Again, a precise estimate is not required.

Compare the period of the damped pendulum with the period without damping, but with the same total mass ($\pm$ 5 g) on the end of the spring. Use your uncertainties in making this comparison. Explain any differences you see. You may want compare the oscillation frequencies with and without damping using the relationship for damped oscillations given in your textbook. To do this, you will have to covert the $B$ you measured to the equation for the damping constant used in the text.

# Summary

Summarize your findings.

Curve fitting routines are powerful tools in science and engineering. They are simple examples of computer models or simulations. Normally one derives a model from theoretical considerations, then tests it against experiment. If the model is missing important features, it will generally fail to describe the data well. Unfortunately, making a model more complex can give it the ability to fit data for which the theory does not apply. The best defense against this is usually to examine predictions of the model for reasonableness, as you did above when you checked to see if the output parameters $\omega$ and $B$ were reasonable.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.a**<br>Is able to analyze the experiment and recommend improvements<br>Labs: 2, 3, 5, 11, 12 | No deliberately identified reflection on the efficacy of the experiment can be found in the report | Description of experimental procedure leaves it unclear what could be improved upon. | Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none. |
| **SL.B.a**<br>Is able to explain operation and limitations of measurement tools<br>Labs: 2, 3, 6, 11, 12 | At least one of the measuring tools used in lab lacks a clear identification of precision/limitation | All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed | All measuring tools identified with precision/limitation of each tool listed. Description of how to measure using some tools may be incorrect/vague, or precision may not be adequately justified. | All measuring tools are identified with proper precision values and thorough discussion of limitations. Descriptions on how to make measurements are complete and could be understood by readers with no prior familiarity with the measuring tools. |
| **SL.B.b**<br>Is able to explain patterns in data with physics principles<br>Labs: 2, 3, 6, 8, 11, 12 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |
| **CT.B.a**<br>Is able to describe physics concepts underlying experiment<br>Labs: 2, 3, 6, 9, 11, 12 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.A** Is able to perform algebraic steps in mathematical work. Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |
| **QR.B** Is able to identify a pattern in the data graphically and mathematically Labs: 2, 3, 6, 9, 11, 12 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |
| **QR.C** Is able to analyze data appropriately Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |
| **IL.A** Is able to record data and observations from the experiment Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B** Is able to construct a force diagram Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.A**<br>Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 11 Spring-Mass Oscillations:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

☐ Quit Capstone and any other software you have been using.
☐ Straighten up your lab station. Put all equipment where it was at start of lab.
☐ Required Level of Effort.
 ☐ Complete the pre-lab assignment ☐ Arrive on time
 ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.a | | QR.A | | IL.A | |
| SL.B.a | | QR.B | | IL.B | |
| SL.B.b | | QR.C | | WC.A | |
| CT.B.a | | | | WC.B | |

---

Lab 11 Spring-Mass Oscillations:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

☐ Quit Capstone and any other software you have been using.
☐ Straighten up your lab station. Put all equipment where it was at start of lab.
☐ Required Level of Effort.
 ☐ Complete the pre-lab assignment ☐ Arrive on time
 ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.a | | QR.A | | IL.A | |
| SL.B.a | | QR.B | | IL.B | |
| SL.B.b | | QR.C | | WC.A | |
| CT.B.a | | | | WC.B | |

# Lab 12. Vibrating Strings

## Goals

- To experimentally determine the relationships between the fundamental resonant frequency of a vibrating string and its length, its mass per unit length, and the tension in the string.
- To introduce a useful graphical method for testing whether the quantities $x$ and $y$ are related by a "simple power function" of the form $y = ax^n$. If so, the constants $a$ and $n$ can be determined from the graph.
- To experimentally determine the relationship between resonant frequencies and higher order "mode" numbers.
- To develop one general relationship/equation that relates the resonant frequency of a string to the four parameters: length, mass per unit length, tension, and mode number.

## Introduction

Vibrating strings are part of our common experience. Which as you may have learned by now means that you have built up explanations in your subconscious about how they work, and that those explanations are sometimes self-contradictory, and rarely entirely correct.

Musical instruments from all around the world employ vibrating strings to make musical sounds. Anyone who plays such an instrument knows that changing the tension in the string changes the pitch, which in physics terms means changing the resonant frequency of vibration. Similarly, changing the thickness (and thus the mass) of the string also affects its sound (frequency). String length must also have some effect, since a bass violin is much bigger than a normal violin and sounds much different. The interplay between these factors is explored in this laboratory experiment.

You do not need to know physics to understand how instruments work. In fact, in the course of this lab alone you will engage with material which entire PhDs in music theory have been written. Knowing that various waves on a string are harmonic multiples does not make you understand how they sound when played together.

Water waves, sound waves, waves on strings, and even electromagnetic waves (light, radio, TV, microwaves, etc.) have similar behaviors when they encounter boundaries from one type of material (called a medium) to another. In general all waves reflect part of the energy and transmit some into the new medium. In some cases the amount of energy transmitted is very small. For example a water wave set up in your bathtub moves down the length of the tub and hits the end. Very little energy is transmitted into the material of the tub itself and you can observe a wave of essentially the same size as the "incident" wave being reflected. The clamps at the ends of a string provide similar boundaries for string waves such that virtually all the energy of the wave is reflected back and the wave travels from one end to the other. The wave "bounces" back and forth. If waves are sent down a string of some length at a constant frequency, then there will be certain frequencies where the reflected waves and the waves being generated on the string interfere constructively. That is, the peaks of the incident waves and the peaks of the reflected waves coincide spatially and thus add together. When this occurs, the composite wave no longer "travels" along the string but appears to stand still in space and oscillate transversely. This is called a "standing wave." A marching band that is marching "in place" but not moving is a fair analogy. You can demonstrate this phenomenon with a stretched rubber band or jump rope. These standing waves occur only at particular frequencies, known as resonant frequencies, when all the necessary conditions are satisfied. These necessary conditions depend on the factors mentioned above, such as whether the string is clamped tightly at the ends or not (i.e., the boundary conditions), the length of the string, its mass per unit length, and the tension applied to the string.

With this in mind, we will systematically explore how the resonant frequency depends on three of the four factors listed above. In all cases our strings are clamped or held tightly at both ends; we consistently use the same boundary conditions. Finally, we will search for a single equation that describes the effect of length, tension, and mass per unit length on the resonant frequency.

# Equipment set up

A schematic diagram of the set up is shown in Figure 12.1. Connect the speaker unit to the output terminal (marked with a wave symbol) and the ground terminal (marked with the ground symbol) of the Pasco Model 850 interface unit. The interface unit can be configured to produce a voltage that varies sinusoidally at a known frequency. In the Experimental Setup window, click on the image of the output terminal (marked with a wave symbol). In the window that appears, make sure that the waveform pull down menu is set to Sine Wave. Use the frequency and voltage windows to set the frequency and output voltages, respectively. Keep the output voltage below 4.5 V. Select the Current Limit of 0.55 Amps (only available on Channel 1). Click the "Auto" button (which toggles the Auto function off), then click the "On" button to start the voltage generator.

This voltage drives an audio speaker mechanism that lacks the diaphragm that normally produces the sound. You will nevertheless hear some sound from the speaker drive mechanism. This sound can be irritating, so use the minimum voltage required to make a good measurement. This speaker drive oscillates in synchrony with the drive voltage and is connected to the string via an "alligator" clip.

**Caution: Do not apply loads greater than 10 kg to the end of the string!**

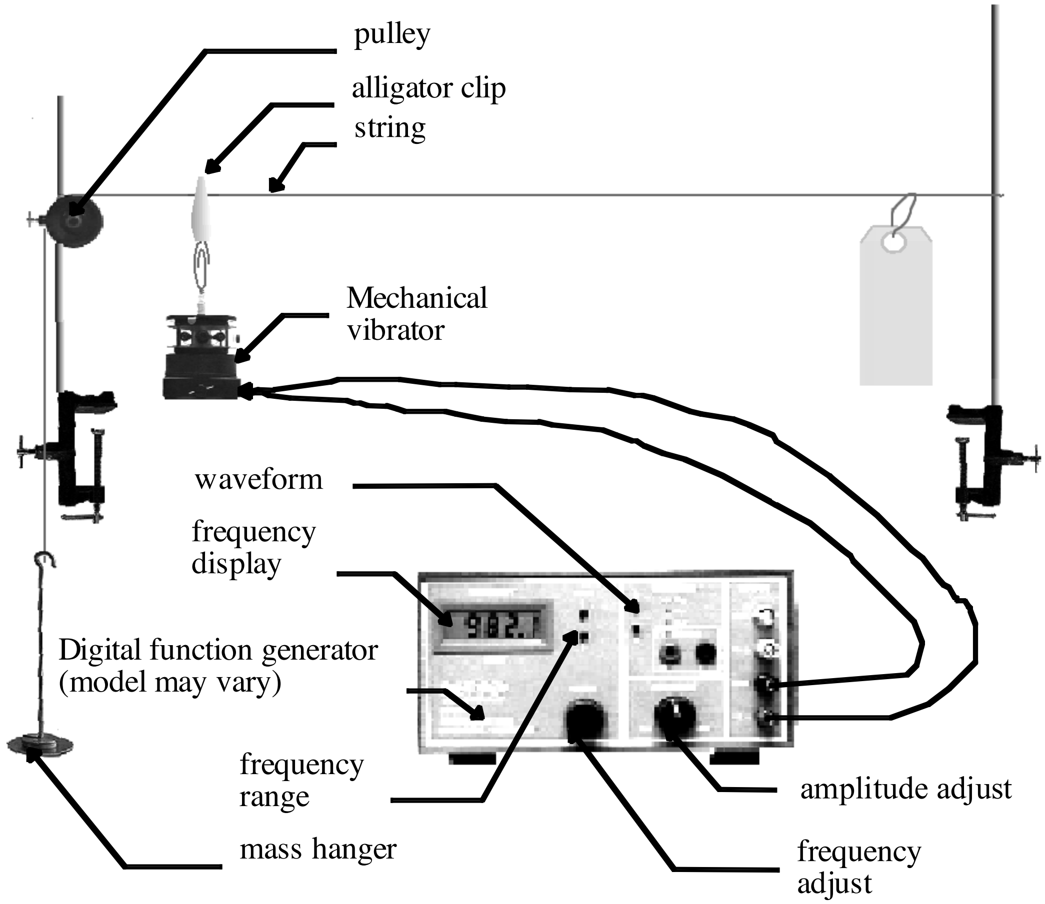



Figure 12.1. Typical apparatus for the vibrating string experiment. The Pasco Model 850 interface unit can be used to control the mechanical vibrator in place of the digital function generator.

## Effect of string length on resonant frequency

Start with the 1.3 g/m string (see the tag attached to the end of string) and hang a total mass of 5 kg, including the mass of the mass hanger, on the end of the string. Determine the fundamental resonant frequency for five or six different string lengths. Length is measured from the clip of the wave generator to the point where the string touches the pulley.

Plucking the string with your finger near the middle point excites a vibration of the string, primarily in its fundamental resonant mode (also called the first harmonic). Pluck the string and note how the string vibrates. The vibration of the string stops a short time after you pluck it because of energy losses due to air friction. The speaker drive allows you to pump energy into the vibrating system at the same rate that it is lost, so that the vibration can be maintained for as long you wish.

When you pluck the string, only the resonant modes will manifest. This is because all non-resonant modes will tend to self-cancel upon reflection. However, when driving the string vibration with an external force, you can vibrate the string at non-harmonic modes. The string will vibrate strongly only at certain well-defined frequencies which are multiples of the harmonics though. By adjusting the frequency of the speaker drive slowly while watching the string you should be able to find the frequency that makes the string vibrate in its fundamental resonant mode. You can recognize the fundamental resonant frequency easily because the whole middle portion of the string oscillates up and down like a jump rope; the fundamental resonance can be thought of as the “jump rope mode.” For best results you must continue adjusting the speaker drive until you have found the “middle” of the resonance, where the amplitude of the vibration is maximized.

Note that the distance from the alligator clip to the top of the pulley where the string is held tightly determines the length of the vibrating string. The alligator clip does vibrate slightly but the string behaves very nearly as if the clip defines a clamped end. (The motion of the alligator clip cannot be ignored for very heavy strings. For these, you may have to visually locate the point near the alligator clip which appears to be clamped and doesn’t vibrate. This location on the string which stays relatively stationary is called a "node" while the position on the string which vibrates the most each cycle is called an "anti-node.")

Make sure that the string lengths that you test are approximately uniformly spaced between 0.4 m and the maximum string length possible given the length of the table. By graphical means determine a mathematical function for the fundamental resonant frequency, $f$, as a function of $L$, where $L$ is the length of the vibrating string as determined by the placement of the alligator clip. Do you get a linear graph if you plot $f$ on the $y$-axis and $L$ on the $x$-axis? Instead, try plotting $f$ on the $y$-axis and $1/L$ on the $x$-axis. What important property of the wave on the string can be determined from this graphical analysis? The units of the slope of this graph (assuming it is linear) provide information on what this quantity might be. Explain your reasoning!

# Effect of string tension on resonant frequency

Keep using the same string for each of these first three sets of experiments. This will allow you to re-measure any data which seems to warrant closer inspection due to inconsistencies. Determine the fundamental resonant frequency of the string as the total mass on the end of the string is increased from 1.0 to 10.0 kg. The weight of the hanging mass will be equal to the tension in the string, $T$. Graphically determine whether the relationship between the fundamental resonant frequency, $f$, and the string tension, $T$, is a simple power function. Refer to the Uncertainty-Graphical Analysis Supplement in the lab manual.

# Effect of harmonic mode number on resonant frequency

Still using the 1.3 g/m string and now 3 kg hanging mass, set the length of the string to at least 1.5 m. So far you have looked at the fundamental frequency, or first harmonic, of the string vibration. The second harmonic (mode number $n = 2$) will have a “jump rope” mode on each half of the string but they will oscillate in opposite directions. The center of the "jump rope" effect is called an anti-node, and the stationary part of the string between them is called a node. At the fundamental frequency you have one anti-node, and each end of the clamped string is a node, this gives you half of a wave shape. The second harmonic has one full wave shape, so you have two anti-nodes and three nodes (counting the two clamped ends).

Increase the driver frequency until you find this resonance and record it. The third harmonic will have three anti-nodes on the string, etc. At the very least you should collect the data for $n$ = 1, 2, 3, and 4. If time allows, determine frequencies for even higher $n$ values. As you increase your number of anti-nodes, the amplitude will decrease, making it harder to observe the anti-node formation. Placing a contrasting solid color background behind the string can improve visibility. Increasing the voltage of the wave driver can also increase the amplitude. **Do not exceed 6V output.**

Determine the relationship $f(n)$ between the resonant frequency, $f$, and the mode number, $n$, by graphical means.

# Effect of string mass-per-unit-length on resonant frequency

We test string mass last because up until this point you have not had to change the string which is mounted, and are thus able to go back and retest any previous data. Check your data again right now before you change the string to be certain you do not want to run any more trials with the current string density.

For this set of experiments, use the maximum string length employed previously and hang a total of 5 kg on the end of the string. Test the four the strings in the box, noting the mass per unit length ($\mu$) indicated on the attached cards. Find the fundamental oscillation frequency for each of the strings at your station. Remember that you already took one data point while observing the effect of string length. Normally we would determine graphically what the relationship between fundamental frequency, $f$, and the mass per unit length, $\mu$, that is $f(\mu)$, is. But, with only four data points it is not possible to distinguish clearly between the various best fit lines to determine which is the ideal fit to your graph. This relationship should match a power series. Find the equation for frequency as a function of mass/unit length. Refer to the Uncertainty-Graphical Analysis Supplement in this lab manual for details.

Note that by having a relationship between mass per unit length, you are directly showing a second link to frequency and string length. In the first part of this experiment you had determined a relationship between the length and the frequency. The length dependence of this linear density would have influenced your earlier results, causing your best fit line to stray from being a "comfortable" linear fit as a result.

# Summary

Summarize your findings clearly and succinctly. Can you write a single mathematical function that encapsulates all the relationships that you have discovered? That is $f(T,\mu,L,n)$. Note that taking the sum of the four relations you determined above will not work. This is blatantly obvious if you perform a unit analysis on the equation, as you are not allowed to add values together if they have different units.

Compare your experimental results with those theoretically predicted in your textbook. (This is sometimes included in a section on musical instruments.) Show that the textbook formula is dimensionally correct (meaning analyze the units). Be quantitative in your comparisons (meaning analyze the numbers).

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.a**<br>Is able to analyze the experiment and recommend improvements<br>Labs: 2, 3, 5, 11, 12 | No deliberately identified reflection on the efficacy of the experiment can be found in the report | Description of experimental procedure leaves it unclear what could be improved upon. | Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none. |
| **SL.B.a**<br>Is able to explain operation and limitations of measurement tools<br>Labs: 2, 3, 6, 11, 12 | At least one of the measuring tools used in lab lacks a clear identification of precision/limitation | All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed | All measuring tools identified with precision/limitation of each tool listed. Description of how to measure using some tools may be incorrect/vague, or precision may not be adequately justified. | All measuring tools are identified with proper precision values and thorough discussion of limitations. Descriptions on how to make measurements are complete and could be understood by readers with no prior familiarity with the measuring tools. |
| **SL.B.b**<br>Is able to explain patterns in data with physics principles<br>Labs: 2, 3, 6, 8, 11, 12 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |
| **SL.B.c**<br>Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able.<br>Labs: 4, 5, 8, 9, 12 | No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present | No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty. | An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective. | The uncertainties are minimized in an effective way. |
| **CT.A.d**<br>"Is able to identify sources of uncertainty "<br>Labs: 4, 5, 8, 9, 12 No attempt is made to identify experimental uncertainties. | descworst | An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect. | Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty. | All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.B.a**<br>Is able to describe physics concepts underlying experiment<br>Labs: 2, 3, 6, 9, 11, 12 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |
| **CT.B.b**<br>Is able to identify dependent and independent variables<br>Labs: 2, 3, 6, 12 | No attempt to explicitly identify any variables as dependent or independent | Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified | The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent. | All physical quantities relevant to the experiment are identified as dependent and independent variables correctly, and no irrelevant variables are included in the listing. |
| **QR.A**<br>Is able to perform algebraic steps in mathematical work.<br>Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |
| **QR.B**<br>Is able to identify a pattern in the data graphically and mathematically<br>Labs: 2, 3, 6, 9, 11, 12 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |
| **WC.A**<br>Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

Print this page. Tear in half. Each lab partner should submit their half along with the lab report and then retain until the end of semester when returned with evaluations indicated by TA.

---

Lab 12 Vibrating Strings:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Leave only the 1 kg mass hanger on the end of the 1.3 g/m string.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.a | | CT.B.a | | QR.C | |
| SL.B.a | | CT.B.b | | IL.A | |
| SL.B.b | | QR.A | | IL.B | |
| SL.B.c | | QR.B | | WC.A | |
| CT.A.d | | | | WC.B | |

---

Lab 12 Vibrating Strings:

Name: ______________________ Lab Partner: ______________________

**EXIT TICKET:**

- ☐ Quit Capstone and any other software you have been using.
- ☐ Leave only the 1 kg mass hanger on the end of the 1.3 g/m string.
- ☐ Straighten up your lab station. Put all equipment where it was at start of lab.
- ☐ Required Level of Effort.
  - ☐ Complete the pre-lab assignment ☐ Arrive on time
  - ☐ Work well with your partner ☐ Complete the lab or run out of time

| | | | | | |
|---|---|---|---|---|---|
| SL.A.a | | CT.B.a | | QR.C | |
| SL.B.a | | CT.B.b | | IL.A | |
| SL.B.b | | QR.A | | IL.B | |
| SL.B.c | | QR.B | | WC.A | |
| CT.A.d | | | | WC.B | |

# Uncertainty and Graphical Analysis

## Introduction

Two measures of the quality of an experimental result are its accuracy and its precision. An accurate result is consistent with some ideal, "true" value, perhaps a commonly accepted value from the scientific literature. When a literature value is not available, we often perform an additional measurement by other methods. Different methods are usually prone to different errors. We can hope that, if two or three different methods yield consistent results, our errors are small. However, measurements made by different methods never agree exactly. If the discrepancy is small enough, we claim that the results are consistent and accurate. Most of our work with uncertainties will address the question, "How small is small enough?"

Precision refers to the reproducibility of a result made using a particular experimental method. When random variations are large, the precision is low, and vise versa. While we should work hard to reduce the size of random effects, they cannot be entirely eliminated. When we claim that two measurements are consistent, we are claiming that their difference (the discrepancy) is smaller than these random variations. Since many quantities of interest are calculated from measured values, we also need to know how random variations in measured quantities affect the results of these calculations.

## Measurements in the presence of random deviations

### Mean and standard deviation of the mean[1]

In the presence of random variations, the best estimate of a physical quantity is generally given by the average, or mean. The average value of a set of $N$ measurements of $x$, $(x_1, x_2, x_3, \ldots x_N)$, is given by

$$x_{avg} = \frac{x_1 + x_2 + x_3 + \ldots + x_N}{N} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{13.1}$$

[1] A good reference for much of the information in this section is John R. Taylor, *An Introduction to Error Analysis—The Study of Uncertainties in Physical Measurements, 2^nd Edition* (University Science Books, Herndon, Virginia, USA, 1987), especially Chapter 5.

The individual measurements of $x$ will generally deviate from $x_{avg}$ due to random errors. The standard deviation of $x$, denoted $\sigma(x)$, indicates how far a typical measurement deviates from the mean. The value of $\sigma(x)$ reflects the size of random errors.

$$\sigma(x) = \sqrt{\frac{(x_1 - x_{avg})^2 + (x_2 - x_{avg})^2 + (x_3 - x_{avg})^2 + (x_4 - x_{avg})^2 + \ldots (x_N - x_{avg})^2}{N-1}}$$

$$= \frac{1}{\sqrt{(N-1)}} \left[ \sum_{i=1}^{N} (x_1 - x_{avg})^2 \right]^{1/2} \quad (13.2)$$

A small standard deviation indicates that the measurements ($x$-values) are clustered closely around the average value, while a large standard deviation indicates that the measurements scatter widely relative to the average value. Thus a small standard deviation indicates that this particular quantity is very reproducible—that is, the measurement is very precise. Note that the units of the standard deviation are the same as the units of the individual measurements, $x_i$.

The relation between the standard deviation to the deviation of the data from its average value is illustrated in Figure 13.1. Figure 13.1 is a histogram of 100 scores, chosen from a set of over 1000 random scores with an average was 85 and a standard deviation of 7.5. Because of their random distribution, the average of the 100 scores is not exactly 85, and their standard deviation is not exactly 7.5. Because we cannot take an infinite number of measurements, Equations 13.1 and 13.2 are only approximations to the true average and standard deviation. On average, the approximations improve as the number of measurements, $N$, increases.

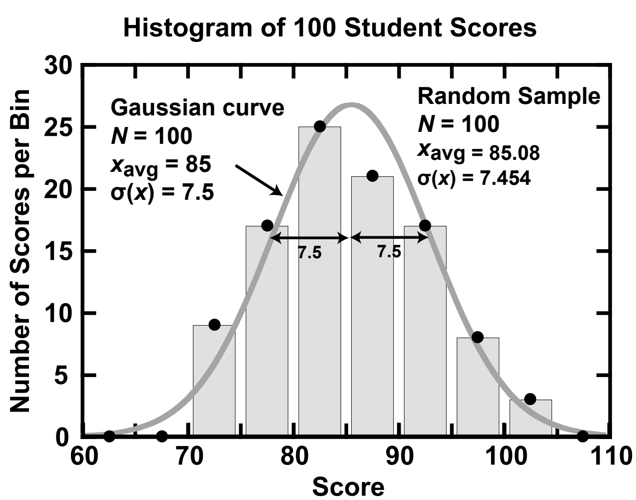



Figure 13.1. Histogram of 100 scores with an average of 85 and a standard deviation of 7.5. The smooth curve is the Gaussian function corresponding to the same number of measurements, average, and standard deviation.

The Gaussian function, $G(x)$, corresponding to 100 scores with an average of exactly 85 and a standard deviation of exactly 7.5 is also shown in Figure 13.1. According to the Central Limit Theorem of statistics, the Gaussian function represents the ideal distribution of scores for a given $N$, $x_{avg}$, and $\sigma(x) = \sigma$ *if* the scores have a finite average and the measurements are statistically independent. These conditions apply to most of the measurements made in lab. (Important exceptions are found in the stock market, among other things.)

$$G(x) = \frac{N}{2\pi\sigma} \exp\left[\frac{-(x - x_{avg})^2}{2\sigma^2}\right] \tag{13.3}$$

The value of the standard deviation in the context of uncertainties is that the probability of finding a score at some distance from the average falls in a predictable way as the distance increases. For an ideal Gaussian distribution, 68% of the measurements lie within one standard deviation of the mean ($x_{avg}$). In Figure 13.1, 63 scores (63% of 100) lie within 7.5 points of 85. Ideally, 95% of the scores lie within two standard deviations (here, $\pm 15$ points) of the average. Ideally, one would expect 99.7% of the points to lie within three standard deviations (here, $\pm 22.5$ points) of the average. No score in Figure 13.1, is more than three standard deviations from the average. (All of the scores lie between $x_{avg} - 3\sigma = 62.5$ and $x_{avg} + 3\sigma = 107.5$.) Unless the total number of scores is very high, the probability of finding a score more than $3\sigma$ from the average is quite low.

Since the standard deviation characterizes random errors, we can pretty much rule out random errors as the source of any difference greater than $3\sigma$. We will make this assumption in the physics labs, although the precise probabilities will usually differ from those given by the ideal Gaussian function. For instance, when the number of measurements is small, our estimates of $x_{avg}$ and $\sigma(x)$ may be poor. In more advanced work, it can be important to correct for this lower precision.[2] When one is attempting to show that one measurement out of a large number differs significantly from the others, a higher threshold for significance ($4\sigma$ or $5\sigma$) may be necessary.

Since the result of an experiment is generally an average value, we need a measure of the precision of the average. This is called the "standard deviation of the mean," $\sigma(x_{avg})$. Although one can repeat the entire set of $N$ measurements several times to compute $\sigma(x_{avg})$, statistics allows us to estimate $\sigma(x_{avg})$ using the original $N$ measurements alone:

$$\sigma(x_{avg}) = \frac{1}{\sqrt{N(N-1)}} \left[\sum_{i=1}^{N} (x_1 - x_{avg})^2\right]^{1/2} = \frac{\sigma(x)}{\sqrt{N}} \tag{13.4}$$

The standard deviation function of most spreadsheet programs (Excel, OpenOffice), Capstone, and calculators gives $\sigma(x)$, from Equation 13.2. To calculate the standard deviation of the mean from this number, you must divide by the square root of $N$, the number of measurements.

On the other hand, spreadsheet Regression functions and Capstone's curve fit function provide the standard deviation of the mean, $\sigma(x_{avg})$ from Equation 13.4.

[2] Student's *t*-test is used to make this adjustment in more advanced work. This is described at the end of Chapter 5 in John R. Taylor, *op. cit.*, and in many statistics books.

## Other methods for estimating the effect of random errors

When several measured quantities are used in a calculation, a relatively crude measurement of one quantity may contribute little to the overall uncertainty. If so, there is little point in improving the measurement. To demonstrate that the uncertainty is small, we must provide an upper bound on the uncertainty and show that the effect of this uncertainty is indeed relatively small.

### Smallest division

Most measuring devises have a a smallest division that can be read. In this case, one can use the size of the smallest division as an upper bound on the uncertainty. In some cases, it is appropriate to to use one-half of this smallest division. For instance the smallest division displayed on a meter stick is usually 1 mm. The distance $d$ is read to the nearest mark. Suppose, for example, you look at the meter stick a few times and read $d$ = 85 mm each time. Because you never measured 84 or 86 mm, you are confident that $84.5 \leq d \leq 85.5$. That is, the magnitude of the uncertainty in $d$ is less than 0.5 mm. This is a useful upper bound. You must use your judgement in cases where the measurement cannot be practically made with this precision. For instance, your precision can be much worse if you don't have a clear view of the ruler.

### Interpolation

If the uncertainty in such a measurement is not small relative to the other uncertainties in an experiment, a better estimate of the uncertainty is needed. In this case, taking the standard deviation of the mean of multiple measurements is necessary. For instance, you can estimate $d$ to one-tenth of a mm using a meter stick. (Estimating values between the marks is called interpolation.) In this case, repeated estimates, made with care, will disagree, and you can calculate the standard deviation of their mean.

### Manufacturer's specification

The user manuals for many instruments (electronic ones in particular) often include the manufacturer's specification as to the "guaranteed" reliability of the readings. For example, the last digit on the right of digital voltmeters and ammeters is notoriously inaccurate. In this case, it makes sense to use the manufacturer's specification as a simple upper bound.

### Terminology—Uncertainty and significant digits

Because the standard deviation is not the only measure of random variation, it helps to have another name and symbol for this quantity. We will call the the expected effect of random variation on $x_{avg}$ its uncertainty, and represented it by the symbol $u(x_{avg})$. If the average and standard deviation of $x$ are available, the best estimate of $x$ is $x_{avg}$, and the best estimate of the uncertainty of $x_{avg}$ is the standard deviation of its mean, $\sigma(x_{avg})$. Then $u(x_{avg}) = \sigma(x_{avg})$. The uncertainty is often indicated by a $\pm$ sign after the average value. For instance, you might specify a length measurement as "1.05 $\pm$ 0.02 mm. Because there is more than one way to estimate the uncertainty, you must also specify how your estimate was made. For instance, the result of a length measurement may be reported as "1.05 $\pm$ 0.02 mm, where the uncertainty is the standard deviation of the mean of five length readings;" or "24 ± 1 mm, where the uncertainty is the distance between marks on the meter stick."

With or without a formal uncertainty estimate, you are expected to have a general idea of the uncertainties of the numbers you use. These uncertainties are communicated by the number of significant digits you provide with the number. For instance, a length written as 3.14 mm has an implied uncertainty of less than 0.1 mm; the inclusion of a digit in the second decimal place means that you have some knowledge of it. In your lab notebook and reports, you should not use more significant digits than are justified by your knowledge. Since rounding operations slightly increase the uncertainty in the last decimal place, it is appropriate to keep one extra significant digit in each step of a calculation. However, the final result must be rounded to an appropriate number of significant digits. Most physics texts include a discussion of significant figures.

# Uncertainties in calculated quantities

Uncertain measured values are often used to calculate other quantities. These calculated quantities will be uncertain as well, and the degree of uncertainty will depend on the uncertainty of our measurements. We will the Minimum-Maximum method to estimate uncertainties in calculated quantities.

Let us start with a simple example. Assume that we have measured the quantity, $x$, and we need to calculate a value for the function $f(x) = 1/x$. Say that several measurements of $x$ have yielded $x_{avg} = 2.0$, with an uncertainty $u(x_{avg}) = \sigma(x_{avg}) = 0.1$. As long as there is no confusion, this can be reported as $x = 2.0 \pm 0.1$.

The value of $f(x)$ when evaluated at $x = 2.0$ is 0.50, but how does the uncertainty in $x$ (the ± 0.1) affect our value for $f(x)$ (the 0.50)? For simple functions, the change in $f(x)$ due to a change in $x$, $\Delta x$, can be evaluated directly by calculating $f(x+\Delta x)$ and $f(x-\Delta x)$. Here $\Delta x = u(x_{avg})$ and we have $f(x+\Delta x) = 1/(2.0+0.1) = 0.476$. Similarly $f(x-\Delta x) = 1/(2.0-0.1) = 0.526$. [Note that for $f(x) = 1/x$, $f(x)$ increases as $x$ decreases and vise versa.]

The Minimum-Maximum method gives two uncertainties, $u_+[f(x)] = |0.526 - 0.500| = 0.026$ for the upper error and $u_-[f(x)] = |0.476 - 0.500| = 0.024$ for the lower error. This can be summarized by saying that $f(x) = 0.50 + 0.026, -0.024$. Since the uncertainty is in the second place to the right of the decimal it would be legitimate to round the uncertainty in $f(x)$ to 0.50 +0.03, –0.02. Notice that the plus and minus uncertainties are not equal even after rounding.

In many cases, our goal is to use our uncertainty to compare our measured $f(x)$ with another measurement or prediction. In this case, it is not necessary to calculate both $u_-[f(x)]$ and $u_+[f(x)]$. If the prediction is greater than $f(x)$, then $u_+[f(x)]$ (the upper error) is the important quantity. Similar, if the prediction is smaller than $f(x), u_-[f(x)]$ (the lower error) is the important quantity. Your knowledge of how $f(x)$ varies with $x$ will usually allow you to guess whether $(x+\Delta x)$ or $(x-\Delta x)$ is needed. If you guess wrong, you just use the other.

For more complicated functions, say $f(x,y)$, one calculates $u_+[f(x,y)]$ by choosing the signs of $\pm\Delta x$ and $\pm\Delta y$ that together maximize the value of the function $f(x,y)$. For instance, if $f(x,y) = x^2/y$, then $f(x,y)$ is maximized by choosing a high value of $x$ and a low value of $y$. Similarly, the function is minimized by choosing a low value of $x$ and a high value of $y$. Therefore,

$$u_+[f(x,y)] = \frac{(x_{avg}+\Delta x)^2}{(y-\Delta y)} \qquad \text{and} \qquad u_-[f(x,y)] = \frac{(x_{avg}-\Delta x)^2}{(y+\Delta y)} \tag{13.5}$$

Again, you do not need to compute both $u_+[f(x)]$ and $u_-[f(x)]$ if your only goal is to compare your measurement with a prediction or another measured value.

The Minimum-Maximum method is relatively easy to use, but it has some drawbacks that are beyond the scope of this introduction. The problems are usually minor as long as the uncertainties are small and $u_+[f(x)] \approx u_-[f(x)]$.

# Using uncertainties to compare measurements or calculations

Suppose you have measured a cart's mass, $m_{F/a}$, from force and acceleration measurements and Newton's Second Law, $F = ma$. To check for systematic errors, you have also measured the cart's mass using an electronic balance, with the result $m_{bal}$.

A straightforward way to determine whether these two measurements is to compare the discrepancy between the two measurements, say $\Delta = \left|m_{F/a} - m_{bal}\right|$, with the expected uncertainty of $\Delta$, that is $u(\Delta)$. As illustrated in Figure 13.1, the probability of $\Delta$ being more than three standard deviations from the mean because of random errors alone is quite small. Therefore, if $\Delta > 3u(\Delta)$ most of the discrepancy is almost definitely due to systematic problems. In this case, we say that the measurements of $m_{F/a}$ and $m_{bal}$ are not consistent.

The ratio between the discrepancy and its combined standard uncertainty is a useful measure of the seriousness of a discrepancy. Because this ratio is similar to the $t$-statistic of classical statistics, we call it the $t'$-score.[3] In this example,

$$t' = \frac{\Delta}{u(\Delta)} = \frac{\Delta}{\sqrt{u(m_{F/a})^2 + u(m_{bal})^2}} \tag{13.6}$$

When you compare experimental results and find $t' > 3$, you should carefully review your calculations and measurement procedures for errors. If systematic errors appear to be significant, and you know what they might be, you should describe them in your lab notes. If time permits, repeating a portion of the experiment is in order. Whatever your conclusion, your lab notes must indicate how you estimated your uncertainties.

In the United States, the general authority on the reporting of uncertainties is the National Institute of Standards and Technology.[4] These standards have been developed in consultation with international standards bodies. When the potential consequences of a decision are critical or when the data are unusual in some way, one should consult a statistician.[5]

---

[3] N. T. Holmes and D. A. Bonn, "Quantitative comparisons to promote inquiry in the introductory physics lab," Phys. Teach. **53**(7), 352 (2015). DOI: 10.1119/1.4928350

[4] Ibid, Barry N. Taylor and Chris E. Kuyatt.

[5] W. Edwards Deming, *Out of the Crisis* (MIT Press, Cambridge, Massachusetts, 1982). Some authors attribute the

# Determining functional relationships from graphs

Linear relations are simple to identify visually after graphing and are easy to analyze because straight lines are described by simple mathematical functions. It is often instructive to plot quantities with unknown relationships on a graph to determine how they relate to one another. Since data points have not only measurement uncertainties but also plotting uncertainties (especially when drawn by hand), slopes and such should not be determined by using individual data points but by using a "best-fit line" that appears to fit the data most closely as determined visually. If graphing software is used, then the slope of the line can usually be determined by a computer using a "least squares" technique. We won't go into detail about these methods here.

## Linear functions $(y = mx + b)$

If $x$ and $y$ are related by a simple linear function such as $y = mx + b$ (where $m$ and $b$ are constants), then a graph of $y$ (on the vertical axis) and $x$ (on the horizontal axis) will be a straight line whose slope ("rise" over "run") is equal to $m$ and whose $y$-axis intercept is $b$. Both $m$ and $b$ can be determined once the graph is made and the "best-fit" line through the data is drawn. if $x = 0$ does not appear on your graph, $b$ can be found by determining $m$ and finding a point $(x, y)$ lying on the "best-fit" line; then equation $y = mx + b$ can be solved for $b$.

## Simple power functions $(y = ax^n)$

In nature we often find that quantities are related by simple power functions with $n = \pm 0.5, \pm 1, \pm 1.5, \pm 2$, etc., where $a$ is a constant. Except for $n = +1$, making a simple graph of $y$ (vertical axis) versus $x$ (horizontal axis) for simple power functions will yield a curved line rather than a straight line. From the curve it is difficult to determine what the actual functional dependence is. Fortunately it is possible to plot simple power functions in such a way that they become linear.

Starting with the equation $y = ax^n$, we take the natural logarithm of each side to show

$$\ln(y) = \ln(ax^n) = \ln(a) + \ln(x^n) = \ln(a) + n\ln(x) \tag{13.7}$$

If $\ln(y)$ is plotted on the vertical axis of a graph with $\ln(x)$ plotted on the horizontal axis (This is often called a doubly logarithmic, or log-log graph.), then Equation 13.7 leads us to expect that the result is a straight line with a slope equal to $n$ and a vertical axis intercept equal to $\ln(a)$. If the relationship between $y$ and $x$ is a simple power law function, then a graph of $\ln(y)$ as a function of $\ln(x)$ will be linear, where the slope is $n$, the power of $x$, and the intercept is the natural logarithm of the coefficient $a$. This is quite useful, because it is easy to determine whether a graph is linear. If we suspect a simple power function relationship between two quantities, we can make a log-log graph. If the graph turns out to be linear, then we are correct in thinking that it should be a simple power function and can characterize the relationship by finding values for $n$ and $a$.

---

ability of Japanese automakers to break into the U.S. market to their skillful application of the principles of statistical quality control popularized by W. Edwards Deming and Joseph Juran.

### Exponential functions $(y = ae^{bx})$

Radioactive decay, the temperature of a hot object as it cools, and chemical reaction rates are often exponential in character. However, plotting a simple graph of $y$ (on the vertical axis) and $x$ (on the horizontal axis) does not generate a straight line and therefore will not be readily recognizable. A simple graphical method remedies this problem. Starting with an equation for the exponential function, $(y = ae^{bx})$. We can take the natural logarithm of each side to show

$$\ln(y) = \ln(ae^{bx}) = \ln(a) + \ln(e^{bx}) = \ln(a) + bx \tag{13.8}$$

If $\ln(y)$ is plotted on the vertical axis and $x$ is plotted on the horizontal axis (This is called a semi-log graph.), Equation 13.8 takes the form of a straight line with a slope equal to $b$ and a vertical axis intercept equal to $\ln(a)$. Thus any relationship between two variables of this simple exponential form will appear as a straight line on a semi-log graph. We can test functions to check whether they are exponential by making a semi-log graph and seeing whether it is a straight line when plotted this way. If so, the values of $a$ and $b$ that characterize the relationship can be found.

## Using error bars to indicate uncertainties on a graph

When plotting points $(x, y)$ with known uncertainties on a graph, we plot the average, or mean, value of each point and indicate its uncertainty by means of "error bars." If, for example, the uncertainty is primarily in the $y$ quantity, we indicate the upper limit of expected values by drawing a bar at a position $y_{max}$ above $y_{avg}$, that is, at position $y_{max} = y_{avg} + u(y_{avg})$. Similarly, we we indicate the lower limit of expected values by drawing a bar at position $y_{min} = y_{avg} - u(y_{avg})$. Figure 13.2 shows how the upper error bar at $y_{max}$ and the lower error bar at $y_{min}$ are plotted. If the quantity $x$ also has significant uncertainty, one adds horizontal error bars (a vertical error bar rotated 90°) with the rightmost error bar at position $x_{max}$ and the leftmost error bar at position $x_{min}$.

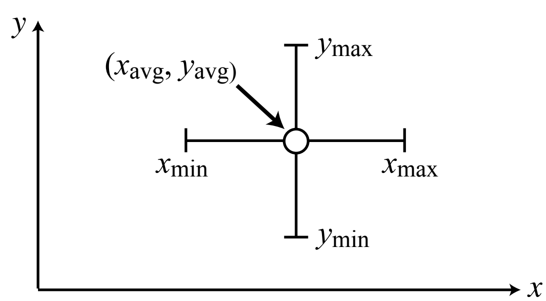



Figure 13.2. Diagram of error bars showing uncertainties in the value of the $x$- and $y$-coordinates at point $(x_{avg}, y_{avg})$.

Occasionally one encounters systems where the upper and lower error bars have different lengths. In this case, the upper uncertainty, $u_+(y_{avg})$ does not equal the lower uncertainty, $u_-(y_{avg})$. This often happens when the Minimum-Maximum method is used to estimate uncertainties.

# Computer Tools for Data Acquisition

## Introduction to Capstone

You will be using a computer to assist in taking and analyzing data throughout this course. The software, called Capstone, is made specifically to work with the interface unit connected to your computer. This may be either the black PASCO Scientific Science Workshop 750 Interface, or the blue and gray PASCO 850 Universal Interface. These interface units can accept up to four digital inputs (the four receptacles on the front left, numbered 1–4), and at least three analog inputs (the three receptacles on the front right (labeled A, B, and C).

A digital input essentially detects either a "1" or "0". In other words it can detect whether something is "on" or "off." For compatibility with the integrated circuits inside the box, an electrical voltage of zero volts represents the "off" state and a voltage of 5 volts represents the "on" state. For example, a photogate consists of an infrared light source in one arm and an infrared light detector in the other arm, and sends a zero volt signal to the computer when something blocks the beam and sends a 5 volt signal when the beam is unblocked. This allows the computer to time objects as they pass through the gate. For the study of motion, timing is an important tool, so most of the sensors that we plug into the interface will be of this digital nature.

The analog inputs detect electrical voltages between +10 volts and –10 volts. Thus electrical circuits can be monitored directly since the signals are already electrical in nature. Other sensors can be constructed to convert forces, pressures, temperatures, etc., into electrical voltages. These kinds of sensors also use the analog inputs. If the computer software knows the relationship between the quantity of interest, say pressure, and the electrical voltage produced by the sensor, then the computer can display the pressure directly rather than simply displaying the voltage.

The Capstone software assumes that you are working in SI units (meters, kilograms, seconds, and coulombs). Any numbers that you enter are assumed to be in these units, so convert any values to SI units before entering them into the program.

### Setting up a new experiment

Make sure that the interface unit connected to your computer is turned on. The on-off switch is located on the right rear of the ScienceWorkshop 750 (SW 750) units and on the left front of the 850 Universal Interface (850 UI) units. When the power is on, a small green light should be glowing on the far left side of the front panel. (Note: SW 750 interface units connected to the computer with USB adaptors are not recognized by the computer if the interface is turned on after the computer has booted up. Restarting the computer will solve this problem. Interface units that do not need special USB adaptors don't have this idiosyncrasy.)

The icon for the Capstone software should be present on the left side of the desktop (the default screen when the computer is first turned on) when the log-in process is complete. Start the Capstone software by finding and clicking on the Capstone icon on the desktop of the computer. When Capstone loads, the display screen appears. Use the Tools Palette on the left hand side of the Display Area to set up the sensors for your experiment and the Display Palette on the right hand side of the Display Area to set up your data display. Both palettes can hidden or rendered visible using the Workbook menu at the top of the screen.

Click on the uppermost icon in the Tools Palette is a picture of a 850 UI unit, labeled “Hardware Setup". If for some reason the software did not find the interface, a yellow warning triangle will appear along with a message to that effect. If you get this message, check the USB connection and make sure the interface unit is powered up. Then have the software scan again for the interface. Interface units with USB adaptors will also require you to restart the computer. The Hardware Setup screen should appear with a picture of your interface unit when the interface is recognized and all is well.

## Choosing a sensor or sensors

Now you must choose the appropriate sensor(s) to use for your particular experiment. Usually the required sensors are provided along with the apparatus for the day's exercises. Sensors come in two varieties, digital and analog. By looking at the connector on a sensor and comparing it to the digital and analog input receptacles on the front of the interface, one can easily determine whether it is an analog or digital sensor. Most sensors have only one connecting cable to the interface, but the rotary motion sensor and the ultrasonic motion sensor (described below) have two cables to be connected to adjacent digital inputs on the interface. Multiple sensors are also used in some experiments. Plug the connecting cable(s) from the sensor(s) into the interface. If you are using multiple sensors, this must be done in a thoughtful way so that you know what each sensor will be measuring.

## Setting up Capstone for your sensor

After connecting the hardware, you must tell Capstone software which sensor(s) you have connected. On the computer monitor make sure that you see the “Hardware Setup” screen with a picture of your interface unit. Yellow circles will mark the position of each input and output jack. If, for example, you have connected a digital sensor to digital Channel 1, move the cursor within the yellow circle surrounding the Channel 1 input and click it. This reveals an alphabetical list of all currently compatible digital sensors. Some of them have special names. The more complex sensors are labeled with their names. Move the cursor to the name of the sensor of choice, highlight it, and click OK. The software should now display the chosen sensor connected to Channel 1 along with a setup window specifically for that sensor. You may have to edit settings that are specific to your sensor using the Properties window, which can be opened by clicking on the word “Properties" to the right and below the picture of your interface unit. For instance, the resolution of some sensors can be changed in the Properties window.

Analog sensors are set up in a similar fashion. You will often need to adjust the sampling rate—how often to take a reading. The sampling rate can be adjusted using the Controls Palette below the Display Area.

To exit the Hardware Setup screen, click again on the 850 UI icon. You can return to the Hardware Setup screen at any time to make changes.

## Displaying data

The two most commonly used displays are Graph and Table. For instance, if you wish to graph you data, drag the Graph icon from the Display Palette into the Display Area. A graph will appear that fills the entire Display Area.

Below the horizontal axis is a <Select Measurement> button. Clicking on this will bring up a list of quantities that can be plotted on the horizontal axis. A similar button on the vertical axis allows you to choose the quantity to be plotted on the vertical axis. Only the quantities available for the sensors you have set up are shown. (Some of the options are calculated from the data reported by your sensor. For instance, velocity and acceleration values can be calculated from position measurements from a motion sensor.) Capstone will provide the appropriate axis labels, showing the quantity followed by the SI abbreviation for its units in parentheses. These labels are required for all graphs, whether they are drawn from Capstone or not. If you use other software or draw a graph by hand, you will have to manually provide these labels.

To plot more than one graph in the same Display Area, click on the "Add new plot area to the Graph display" icon along the top of the graph. These graphs will have the same horizontal axes, but different vertical axes. To plot a second quantity with the same units using the same horizontal axis, but with the $y$-axis values listed on the right hand side of the graph, click on the "Add new $y$-axis to the active plot area" icon along the top of the graph. Finally, to plot a second quantity using the same horizontal and vertical axis, click on the vertical axis label button and choose "Add similar measurement" from the menu that appears. A list of the available similar measurements (for instance, potential energy in a graph of kinetic energy versus time) will appear. Choose the quantity to be plotted from the list. Each of these formats will prove useful.

All graphs should have titles. In Capstone, the title can be typed into the lower left hand corner of the Display Area, to replace the text "[Graph title here]". If you forget to type the title in, you can print the title across the top of your graph by hand. Similarly, horizontal and vertical axes labels may be printed by hand if they are not provided by the software.

## Preparing graphs for printing

Graphs can be extremely useful device for displaying the results of an experiment. However, much of their value is lost if certain mistakes are made. Without titles or axes labels, the reader will not know what is plotted. Graphs that are too small, or are dominated by data that is irrelevant to the goal of the experiment, are almost useless. For lab notes, certain information must be recorded directly on the graph. For instance, the results of curve fitting procedures should be noted on the graph along with their uncertainties; you should also indicate on the graph which data were included in the curve fitting process. Observations about the plotted data—especially comments about relationships between plotted quantities, are much more clear if they are written on the graph itself. For instance, a vertical line can show that the minimum of one quantity coincides with the the maximum of another quantity. To make room for these notes, the important parts of your data must be plotted in as large a format as possible.

Before printing a graph, make sure that the horizontal and vertical scales are adjusted to show the data of interest in as large a format as possible. Capstone allows you to adjust both scales arbitrarily. When the cursor is moved over one of the numbers along the horizontal scale, it morphs into "a spring with an arrow on each end." Click and drag the cursor and the scale expands or contracts. The vertical axis can be adjusted in a similar fashion. You can move the whole $x$ and $y$ axes horizontally or vertically by moving the cursor over one of the axis lines until it morphs into a small hand. Clicking and dragging now allows you to adjust the position of the axes horizontally and vertically to give the best presentation of the desired data.

The data in most graphs occupies a larger portion of the page if printed in the "landscape" format, as opposed to the "portrait" format, since the long edge of the graph is printed along the long dimension of the paper. This fills the sheet more efficiently and makes the graph bigger. Unfortunately "portrait" is the default setting. The "Print" command is in the drop-down menu under "File" on the very top left hand corner of the main Capstone window. "Print Page Setup" on the same drop-down menu can be used to specify the "landscape" format. It will be there somewhere, but the exact location is printer dependent. If it is not readily apparent, choose the printer "properties" tab and you should be able to find it under the options available in that window.

## Uncertainty analysis with Capstone

The mean, $x_{avg}$, and standard deviation, $\sigma(x)$, of a set of data are easily computed from tables and graphs. (On graphs, you can highlight the data you want to average with the cursor.) Click on the down arrow just to the right of the $\Sigma$ on the toolbars at the tops of the graph and table windows to calculate means and standard deviations. In Capstone and Excel, it is important to distinguish between the standard deviation of your data, $\sigma(x)$, and the standard deviation of the mean, $\sigma(x_{avg})$, which represents the uncertainty in $x_{avg}$. These are defined in the Uncertainty/Graphical Analysis Supplement to the lab manual. The standard deviation function in Capstone and Excel returns $\sigma(x)$, the standard deviation of the selected data. To calculate the uncertainty in $x_{avg}$, you must divide $\sigma(x)$ by the $\sqrt{N}$, where $N$ is the number of selected data points.

"Least squares fits" to graphical data are easily done. If you wish to fit only part of the data, first select the data you want to fit using the "Highlight range of points in active data" tool (icon with yellow pencil and blue dots) above the Display Area. For a linear fit, select "Linear: y = mt+b" from the "Apply selected curve fits to active data" tool (icon with red line and blue points) above the Display Area. The software displays a box showing the slope and intercept of the linear equation along with standard errors of the slope and the intercept values. The standard error corresponds to $\sigma(x_{avg})$.

### Changing data precision in Capstone

Although Caption acquires and stores data at the maximum precision provided by the sensor, the precision of values in tables and graphs is often lower. When the least significant figure of the displayed data (or the least significant figure of a value determined from a curve fit) is larger than the indicated uncertainty, you need more precise data in the display. To increase the precision, select the graph or table with the data and click on the “Data Summary” icon in the Tools Palette on the left side of the screen. The Data Summary window displays a list of your data. Select the data you wish to modify, then click on the gear icon to its right. From the Properties window that opens, click on the “Numerical Format” tab and adjust the number of decimal places in the text entry box.

## More details for specific sensors

### Motion sensor (ultrasonic, digital)

Plug the leads from the motion sensor into the digital Channels 1 and 2 of the interface unit. Any two adjacent digital channels will work for the motion sensor, but the yellow plug must be to the left of the black plug. In the Hardware Setup window, assign the motion sensor to the input channel with the yellow-banded plug. The motion sensor sends out a short high-frequency pulse of sound waves at about the limit of human hearing and measures the time for the echo to return. Thus position, velocity, and acceleration can be computed with that information. The sampling rate for the motion sensor is limited to 50 Hz or to 50 readings per second. You may need to adjust this rate from the default setting of 20 Hz to optimize the data collected for your particular experiment. The sampling rate is set in the Control Palette along the bottom of the Display Area. Don’t hesitate to experiment a little to determine the best setting. Position, velocity, and acceleration are the default data quantities. Graphs are by far the most common display for this sensor. Objects less than 0.4 m (0.25 m for the newer model) or more than 4 m from the motion sensor are not reliably detected. At small distances the echo returns too quickly to be measured reliably while at large distances the echo is too weak. Relatively smooth, flat surfaces make better reflectors of sound. Beware of stationary objects close to your experiment that may reflect the sound waves and give you spurious results.

### Rotary motion sensor (digital)

Plug the leads from the rotary motion sensor (RMS) into Channels 1 and 2 (digital) of the interface unit. Any two adjacent digital channels will work for the RMS, but the yellow plug must be to the left of the black plug. Internally this sensor consists of two photogates. You can get a brief explanation of how it works at http:// www.sxlist.com/techref/io/sensor/pos/enc/quadrature.htm. You need to tell Capstone that the rotary motion sensor is connected to the interface unit, what quantity is to be measured with the sensor, and how you want the resulting data displayed.

On the image of the interface unit in the Hardware Setup window, click on the digital input channel with the yellow plug. A list of digital sensors will be displayed. Find the RMS in the sensor list. Highlight it by clicking on it with the cursor and hit OK. The RMS should now be displayed in the

Hardware Setup window as connected to the interface. Click on the Properties button along the bottom half of the window. To measure position, velocity, and acceleration the software assumes that you are passing a string over a pulley on the shaft of the rotary motion sensor, and that the position, velocity, and acceleration will be the speed of the string. For a particular rotation rate, the string will move much faster if it passes over a large-radius pulley than over a small-radius pulley. Thus the circumference of the pulley must be indicated. If the standard black PASCO pulley is used, then you can choose “Large Pulley (groove),” “Med Pulley (groove),” or “Small Pulley (groove),” and the correct circumference will automatically be inserted in the “Linear Conversion Value” box. For some experiments, the lab manual will also direct you to change the “Resolution” setting.

When setting up a graph or a table, you will select the measurement you wish to display using the <Select Measurement> button. Note that all the angle measurements are in radians. The kinematic equations for angular motion conventionally use radians and not degrees. This makes it simple to convert angular displacements, velocities, and accelerations to their corresponding linear displacements, velocities, and accelerations. If you display a linear quantity, it is important to have the correct pulley selected in the Hardware Setup Properties window of the RMS.

Click on the “Record” button and spin the shaft of the rotary motion sensor. After a few seconds click the “Stop” button. Since the computer arbitrarily set the scales of the graphs, the displayed data may be too small or too large. Once the data is taken, Capstone can change the scale of the graphs to have the data fill the available space. The “Scale to Fit” feature must be applied to each graph separately. Click anywhere on the graph to highlight it with a line box around it. Then click on the “Scale to fit” icon on the far left in the toolbar at the top of the graph window or adjust the horizontal axis and vertical axis scales separately as discussed above. When the scaling is complete, you can print out the graphs. Be sure that the graph window is active so that’s what gets printed. If you reverse the direction of rotation of the sensor shaft, the signs (+, –) of the angular position and angular velocity change. Interchanging the input leads that are plugged into Channels 1 and 2 also changes the signs of these measured quantities. This feature allows you to choose the positive vertical axis for any experiment that you do.

## Photogate (infrared so you won’t see the light!)—digital

Plug the ‘photogate” into one of the four digital channel receptacles, say Channel 1. Make sure that the plug is inserted all the way into the receptacle. The photogate consists of an infrared light source in one arm and an infrared light detector in the other arm. It outputs zero volts to the computer when something blocks the beam and 5 volts when the beam is unblocked. Now that the hardware is connected, you need to inform the software what is connected to the interface. If the Hardware Setup window is already displayed, click on Channel 1 on the image of the interface unit to display a list of digital sensors. (The Hardware Setup window can be opened by clicking on the interface unit icon in the Tools Pallete.) After clicking on Channel 1, select “Photogate” from the pull-down menu that appears. If done successfully, you should see a picture of the photogate connected to the chosen digital channel. Note that there are other sensor choices for specialized applications of the photogate.

The software now understands that a photogate is connected to Channel 1, but does not know what you want to measure. To continue, click on the "Photogate Timer" icon just below the Hardware Setup icon in the Tools Palette. Capstone will guide you through the steps to set up your time. Photogates are often used to measure the speed of small objects that pass through the infrared beam. For this application, select the default "Choose a Pre-Configured Timer" option and click on the <Next> button to complete the first step of the setup. In Step 2, make sure the box next to your photogate "Photogate, Ch 1", is checked and click on the <Next> button. To measure speed, choose "One Photogate (Single Flag)" option from the list in Step 3. In Step 4, make sure that the "Speed" option is checked. You may also want to check the "Time in Gate" option. Capstone will calculate the speed of your object by dividing the width of the object (the Flag Length) by the time the beam is blocked as the object passes through. Enter the width of the object (in meters) whose speed you wish to measure into the Flag Length block in Step 5. Finally, you can give your timer a name in Step 6. Exit the Photogate Timer setup window by clicking once on the Photogate Timer icon in the Tools Palette.

To display your speed measurement(s) in a table, drag the Table icon from the Display Palette on the right into the Display area. A table with two columns will appear. Select the measurements to display from the menus that appears when you click on the <Select Measurement> buttons. Putting the time in seconds in one column and the speed in m/s in the other will work for now. If you plan to print your Table for inclusion in your lab notes, describe of your data briefly on the [Table Title Here] line.

To take some test data find a pen or pencil, click on the "Record" button along the bottom left of the Display Area, and pass the pen or pencil back and forth through the photogate a few times; then click the "Stop" button that appears where the "Record" button had been. The table now displays some times along with the measured speeds. When you activate the "Record" button, an internal clock is started. When the light beam is blocked or unblocked, the time when it is blocked or unblocked is recorded relative to the arbitrary "zero time" when you hit the "Record" button. If necessary, repeat the data collection process to clarify the details. Notice that the second set of data is simply named "Run #2."

You can connect a photogate to any of the four digital channels of the interface unit and they will work just the same.

## Photogate with pulley (digital)

A photogate can be used to measure displacement and velocity of objects connected to a string that runs over a pulley. The photogate must be plugged into a digital Channel on the interface unit. Choose the "Photogate with Pulley" option when you set up the interface unit. As the pulley turns, the spokes of the pulley successively block and unblock the light beam from the photogate. With the pulley, the photogate works much like the Rotary Motion Sensor, but with one serious limitation. The photogate has no way of determining which direction the pulley is rotating, so distances are always considered to be positive. If the object that we are studying moves in only one direction, this limitation poses no problems. The software knows the circumference of the pulley and can compute position, velocity, and acceleration as a string passes over the pulley and turns it. Angular quantities can also be measured. These quantities can be graphed, displayed in a table, or whatever.

## Force sensor (analog)

The Force Sensor must be plugged into one of the analog Channels, A, B, or C. In the "Hardware Setup" window click on the analog channel with your sensor and choose the "Force Sensor" option [not "Force Sensor (student)"]. The default measurement of the sensor is force in newtons. The data from the sensor is usually most useful when shown in a table. You can change the "sampling rate," that is, how often the computer reads the output of the force sensor. The default sampling rate is 10 Hz, or 10 times a second. For some applications, this can be reduced to 1 Hz, or one reading each second. The sampling rate is set in the Control Palette along the bottom of the Display Area. It is necessary to "zero" the sensor by pushing the small tare button located on the side of the sensor. This is exactly analogous to zeroing an electronic balance before weighing something. It is good practice to make sure that the force sensor really reads zero after pushing the tare button by clicking the "Record" button and checking the resulting data table. You will notice that the force value is not exactly zero, but varies a bit. This is normal. These variations will also be present if a mass is suspended from the sensor. So, what is the "real" value of the force? Answering this question will introduce you to some of the data analysis options available with the Capstone software.

If we measure something multiple times but get slightly different answers each time, then the average value or "mean" value is often the "best value." When using a mean value, it is important that each time the measurement is made nothing significantly changes. In other words the conditions under which the measurements are made must remain essentially unchanged. As long as the hanging mass is not swinging or something, the conditions are unchanged. One question remains: how large are the variations from the mean value? Statistically speaking, the standard deviation is a measure of this variation. You can read more about how these quantities are defined and used in the "Uncertainty Analysis Using Capstone" section earlier in this document.

The standard deviation of the mean is a useful estimate of the uncertainty of the average value of $x$. Throughout this course the standard deviation of the mean will play this role, and you will have occasion to use it again and again. On the toolbar along the top of the Table window, look for the Greek symbol $\Sigma$. This Capstone's "statistics" icon. Clicking on the down arrow just to the right of the $\Sigma$ opens a drop-down menu that includes the mean and standard deviation. Make sure a check mark appears by each function you want to display. Then clicking on the $\Sigma$ causes these numbers to appear at the bottom of your table. If you want increase the number of significant figures in the display (say, to minimize round-off error), you can increase the number of displayed digits by clicking on the "0.0 $\rightarrow$ 0.00" icon along the top of your table. (To decrease the precision, click on the "0.00 $\rightarrow$ 0.0" icon.) To calculate the standard deviation of the mean from the standard deviation, divide the standard deviation by the square root of $N$, the number of measurements. Capstone will display $N$ if you also check the "Count" function in the $\Sigma$ menu.

## Voltage sensor (analog)

The Voltage Sensor is simply two wires with a special plug that connects from the circuit of interest to one of the analog Channels A, B, or C of the interface unit. The interface then serves as a voltmeter. The voltage can then be observed using various displays. If the voltage remains constant with time, using the "Meter," "Digits," or "Table" display may serve you well. For voltages that vary with time the “Graph” or “Scope” display may be more useful. The “Graph” display is often best for a one-time event where the voltage varies with time. For repetitive voltage signals, that is, those that repeat in time, the “Scope” display is extremely useful.

## Geiger counter (digital)

The Geiger counter is used to detect certain types of radiation, including beta particles and gamma rays. Our older Geiger counters have an AC power cord must be connected to a regular electrical outlet. The signal cable is inserted into one of the digital input channels. Our newer Geiger counters are powered by the cable that connects to the interface unit.

The device can be controlled to count for a specified length of time, then record the number of counts, then repeat the process for as many times as you like, before stopping. The sampling rate is the length of time for each individual counting period. The default is 1 Hz (counts per second), but it can be changed in the Control Palette along the bottom of the Display Area. To set the duration of data collection, click on the “Recording Conditions” icon in the Control Palette along the bottom of the Display Area; then set the “Stop Conditions” option for “Condition Type” to “Time Based” and the “Record Time” to 100 s.

When the resulting data is displayed in a table, you can use the statistics options to compute the average count rate, its standard deviation, and the standard deviation of the mean. The procedure is described above in the Force Sensor section. Geiger counter data is often plotted in a histogram, with the count rate (counts per second) along the horizontal axis, and the number of samples with each specified count rate along the vertical axis. To display a histogram, drag the “Histogram” icon from the Display Palette on the right into the Display Area. The table and histogram views fit nicely side by side.

# Excel Spreadsheets and Graphs

Spreadsheets are useful for making tables and graphs and for doing repeated calculations on a set of data. A blank spreadsheet consists of a number of cells (just blank spaces surrounded by lines to make a little "box"). The cell rows are labeled with numbers while the columns are labeled with letters of the alphabet. Thus Cell A6 is the "box" in Row 6 of Column A, which is the first column. Text, numbers, and formulas of various kinds can be entered in each cell.

## Tables

Making a table of, say, the force exerted by a spring as its length is changed requires entering the force values in the cells of one column and the length values in the corresponding rows of an adjacent column. Adding some explanatory text in the cells above each column can complete the table. It is sometimes useful or necessary to adjust row heights and/or column widths to accommodate more or less "stuff" in the cells. Clicking on "Help" in the main toolbar at the top of the screen opens a small window where you can type in your question. In this case type in the words "column width" (without the quotation marks) and click on "Search." Several options will be displayed, including "Changing column width and row height." Click on it and get detailed instructions how to make the desired changes. Don't be afraid to use the help screens in Excel. Most of the time you can find answers to your questions fairly quickly.

## Graphs

To make a graph in Excel, first select the data to be graphed by clicking on the upper-left cell of the $x$-data and dragging the cursor down to the lower-right cell of the $y$-data. A box should appear around your data and the selected cells will change color. Then select the Insert tab on the main toolbar, click on the Scatter icon, and select the "Scatter with Only Markers" icon from the pull down menu that appears. This icon appears first in the list and shows dots for data points, with no lines joining them. This choice is almost always the best choice for the graphs we make in lab. A graph of the data should appear on the worksheet. In addition, the "Chart Tools" ribbon should appear in the main toolbar. (If your $x$-values are not adjacent to your $y$-values, you will need to use the "Select Data" option to add data points to your blank graph. This option appears in the "Chart Tools" ribbon after clicking on the graph.)

If you do something unwanted, immediately stop the operation and click on "Undo" icon near the top-left corner of the Excel window. This icon is a blue arrow that curves to the left. Usually you can escape your predicament and try again.

Now you can add a descriptive title ("Graph 1" or "Exercise 1" is not sufficiently descriptive) to the graph and label the quantities (with their units!) plotted on the horizontal and vertical axes. Clicking on the "Layout" tab in the Chart Tools ribbon at the top of the Excel window will bring up icons labeled "Chart Title" and "Axis Labels", among others. For the chart title, select the "Above Chart" option. A text box for the title will appear. Move your cursor to the text box and type your title. To label the horizontal axis, move your cursor to the "Axis Labels" icon and choose the "Title Below Axis" option for the "Primary Horizontal Axis Title". To label the vertical axis, choose the "Rotated Title" option for the "Primary Vertical Axis Title." In each case, a text box will appear in which you can type the axis label with units. For instance, if a cart velocity is plotted along the $y$-axis, you would want a label like "Velocity (m/s)". The velocity units should be indicated parentheses after the main label.

You may wish to add other features to your graph, such as legends, gridlines, best-fit curves to match the plotted data, different axis labels, etc. Even the size and aspect ratio of the graph can be changed. Some of these options appear when you right-click on an axis. Others can be accessed from icons under the Design, Layout, and Format tabs in the Chart Tools ribbon. Your best approach is to do some exploring. Only a few of the options will likely be useful to you on a regular basis, but you need to find where they are.

When you print a graph, don't print the whole spreadsheet. Move the cursor over the graph and click it to highlight the graph. Then using the "Print" command in the drop-down menu under the "File" tab on the main toolbar will print just the graph. Selecting "Landscape Orientation" under "Settings" will make the graph as large as possible while still fitting on one page. Graphs printed for you lab notes should be printed in the landscape orientation. Excel will display a preview that shows exactly how the graph will appear on the paper when it is printed. Make any necessary adjustments, then print the graph by clicking on the printer icon in the top-left hand corner of the print window.

# Making calculations on a set of data

For example let us say that you have data values in Cells A1 and B1 and you wish to take the product of these two numbers and put the result in Cell C1. In Cell C1 type =A1*B1 (the * symbol indicates multiplication). The "equal" sign tells Excel that a formula is to follow. When you hit "enter," the calculation will be performed and the product displayed in Cell C1. The formula for calculating the number in the cell is still present but hidden behind the number in a sense. If you now change the number in Cell A1, as soon as you enter it, the number in Cell C1 will also change as it re-computes the product with the new number. Suppose that we have one set of numbers in Column A, Rows 1–10, another set of numbers in Column B, Rows 1–10, and that we want to calculate the following products, A1*B1, A2*B2, ..., A10*B10. After typing the product formula into Cell C1, we can click on Cell C1, making a dark outline appear around it. Move the cursor to the bottom right corner of Cell C1 until the cursor morphs into a little + sign. Click and drag down to Cell C10 copying the product formula to successive cells along the way. When you release the click button, the desired products should be displayed in Column C, Rows 1–10.

The symbols used for various mathematical functions are:

* = multiplication / = divide
+ = addition
- = subtraction
ˆ = powers (need not be integer values)

Use parentheses to make it perfectly clear to Excel what you want to do. The formula =A1+B1/C1 is computed as =A1+(B1/C1). If you wish to sum A1 and B1, then divide by C1, you need to write it as =(A1+B1)/C1. The operations of multiplying, dividing, and taking powers are done first before adding and subtracting.

Some other useful functions in Excel are:

SUM(A1:A9) = sums the numbers in Cells A1–A9.
AVERAGE(A1:A9) = calculates the average (mean) of the numbers in Cells A1–A9.
STDEV(A1:A9) = calculates the standard deviation, $\sigma(x)$, of the numbers in Cells A1–A9.
SIN(A3) = assumes that A3 is in radians and calculates the sine of the angle.
COS(A3) = assumes that A3 is in radians and calculates the cosine of the angle.
TAN(A3) = assumes that A3 is in radians and calculates the tangent of the angle.
ASIN(A6) = calculates the angle in radians whose sine is the number in Cell A6.
ACOS(A6) = calculates the angle in radians whose cosine is the number in Cell A6.
ATAN(A6) = calculates the angle in radians whose tangent is the number in Cell A6.
SQRT(A11) = square root of the number in A11.
LN(A7) = natural logarithm of the number in A7.

Note: These functions must be preceded by the “equal” sign in order to be treated as a formula and do a calculation. For example, =SQRT(B9) typed into Cell C12 will calculate the square root of the number in cell B9 and record it in Cell C12. If the functions are part of a more complicated formula, then only the leading “equal” sign is required. For example, =A2+SIN(A4) typed in Cell B8 will add the number in Cell A2 and the sine of the number in Cell A4 and record it in Cell B8.

## Fitting data with straight lines–only if the data are linear!

Often in physics the dependence of one variable on another is characterized by a linear relationship, meaning that the variables are related to one another through the equation of a straight line of the form $y = mx + b$, with $m$ being the slope and $b$ the $y$-intercept of the graph. The slope and intercept often can be quantities of interest. When several data points, $(x, y)$, are related linearly, how can we calculate the best values of the slope and intercept of the relationship? “Least squares” methods minimize the sum of the squares of the deviations of the fitted line from each of the data points and thus give the “best” values for the slope and intercept of the line.

Excel is capable of doing these kinds of fits quite easily. If you have a graph that appears to be quite linear and thus suitable for fitting with a straight line, you can add a “Trendline” to the graph by moving the cursor over the symbol for one data point on the graph and right clicking on it. A drop-down menu should appear with “Add Trendline” as one of the options. Click on it and choose “Linear”. In the same small window click on the “Options” tab near the top and mark the little box for “Display equation on chart.” Clicking on “OK” will display the “best-fit” line on the graph and give the equation of the line as well on the graph. You can move the equation with your cursor by clicking and dragging if it obscures some of the data points. You can also add or subtract digits of precision to the numbers given for the slope and intercept by right clicking on the equation after highlighting it with the cursor. In spite of its applications in other disciplines, the *R* or *R*-squared value is seldom useful in the physical sciences and should not be displayed on the graph.

Finding the “standard error” (basically the standard deviation of the mean) for the slope and intercept values, respectively, is also important, because it gives information regarding how precisely we know the slope and intercept values. Excel can do this using the more advanced Regression feature of least-squares fitting. (In OpenOffice and LibreOffice, the LINEST function performs the same regression.) In Excel, the following steps are required:

1. Click on the “Data” tab in the Chart Tools ribbon and click on the “Data Analysis” icon in the “Analysis” group on the right.
2. In the pull-down menu that appears, scroll down to the “Regression” option and click on it to highlight it. After choosing OK, the Regression window should appear.
3. To input the *y*-values in the first blank text box, move the cursor to the box and click in it. Now move the cursor to the top of the *y*-data column in your spreadsheet and click and drag down to select the whole set of *y*-values. The corresponding cell numbers should appear in the *y*-value box in the Regression window. Now move the cursor to the box for inputting the *x*-values in the Regression window. Click and drag over the column of *x*-values in your spreadsheet and these cell numbers should appear in the *x*-value box in the Regression window.
4. In the Regression window under “Output options” mark the circle for “Output range.” Move the cursor into the blank space just to the right of “Output range” and click it.
5. Now move the cursor to an empty cell in the leftmost column of your spreadsheet near the bottom and click it. The corresponding cell number will appear in the box. This tells Excel where to put the results of the regression analysis.
6. Now you are ready to click OK in the Regression window. Excel will do the appropriate calculations and display them below and to the right of the cell that you chose for the Output range. The values of interest are displayed in the lower-left corner of the stuff displayed, just to the right of labels, “Intercept” and “X Variable.” The first column to the right of the word “Intercept” shows the value of the *y*-intercept. This value should equal the value in the trendline equation on the graph—a nice check! The next column to the right shows the “standard error”, or uncertainty of the intercept value. In other words, the intercept will have a plus/minus uncertainty given by this standard error. Similarly the first column to the right of “X Variable” shows the value of the slope (which should equal the slope in the trendline equation) and the next column shows the plus/minus uncertainty of the slope value. How does Excel get from X Variable to slope? If you look carefully at the regression output, Excel is calling “slope” the coefficient of the X Variable, which is true in the equation of a straight line. A little awkward, but it works.

It is important to avoid fitting a straight line to data that is definitely curved. In this case, your eye is telling you that your model does not fit the data. Such fits are misleading at best. It is often acceptable to select part of your data that does appear to lie on a straight line and fit those points to a straight line.

# List of All Rubrics

## Scientific Literacy

Students will have a basic understanding of major scientific concepts and processes required for personal decision-making, participation in civic affairs, economic productivity, and global stewardship.

### Students use evidence-based reasoning to form testable hypotheses about the natural world

At an introductory level, students are not yet prepared to fully design and execute effective experiments. But having simple steps to follow with machine-like obedience will do nothing to develop a sense of the investigation and discovery so vital to scientific advancement. These three rubrics aim to have students think about the reasons for each action taken during lab.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.a**<br>Is able to analyze the experiment and recommend improvements<br>Labs: 2, 3, 5, 11, 12 | No deliberately identified reflection on the efficacy of the experiment can be found in the report | Description of experimental procedure leaves it unclear what could be improved upon. | Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed. | All major shortcomings of the experiment are identified and reasonable suggestions for improvement are made. Justification is provided for certainty of no shortcomings in the rare case there are none. |

This task is to be completed at the end of a lab, but taking notes throughout the lab when you have thoughts on how something is inadequate to your needs will certainly help. If you were performing an experiment of your own design to investigate a matter of interest to you, then all of your time and energy would be devoted to making certain you are getting the best results possible with appropriate equipment and methods.

No experiment ever provides flawless knowledge. What we believe to have measured accurately can be found to be seriously flawed when the same measurement is performed with better tools or with a different approach. The idea is to think about the experiment you performed and all the tools you used, and determine any way in which your data could have been more accurate or the experiment could have better reflected the phenomena of interest.

It is always possible to find minor improvements, but the true objective is to identify those things which are most easily changed for the greatest impact. Each piece of equipment should be considered for the role in the experiment and how it could perform better (for example, a ruler could instead have been a caliper, allowing sub-millimeter accuracy). Then those potentials for improvement should be considered for how large of an impact they could have on the experiment. Finally, some mention should be made of how to improve, or an explicit statement of having attempted to think of a better approach and failing. It is also acceptable to discuss personal shortcomings for this rubric: If the group failed to understand instructions or had problems performing the tasks required for the experiment.

Progressing is assigned when a student is unable to explain what shortcomings there are in a manner the reader can comprehend or when no discussion of how to improve on the shortcomings is presented. Scientific is assigned when a student identifies all shortcomings which have a significant impact on the experimental outcomes and has a reasonable discussion on how to improve the experiment in a realistic manner.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.b**<br>Is able to identify the hypothesis for the experiment proposed<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified hypothesis is present in the first half page or so of notes | An attempt is made to state a hypothesis, but no clearly defined dependent and independent variable, or lacking a statement of relationship between the two variables | A statement is made as a hypothesis, it contains a dependent and independent variable along with a statement of relationship between the two variables. This statement appears to be testable, but there are some minor omissions or vague details. | The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader. |

A hypothesis is a proposed statement of a relationship between two variables. One variable is the independent variable – a value which we can control through choices in setting up each experimental trial – and the other one is the dependent variable – a value which we will measure as a result of each experimental trial.

Forming this hypothesis absolutely must be done prior to running any experimental trials, as your hypothesis informs you what to change between trials (the independent variable), and what to measure during them (the dependent). Knowing how the two values are related is not an important part of the hypothesis. You make a speculation based on your prior knowledge if they are proportionally or inversely related (both increase in tandem, or as one increases the other decreases), or even if there is no relationship at all (changing the independent won't have any reliable impact on the value of the dependent). Then through experimentation you will determine what the relationship truly is.

As we often deal with far more than two variables in a given lab, you will often have more than a single hypothesis during a lab.

Typically in science you seek to use your experiment to prove that your hypothesis is not correct, as even if you show something to be true a dozen times you cannot say if it is always true, but if you show it to be false just one time you know for certain that it is not true.

Progressing is assigned when it is unclear which two variables are being discussed, or even just unclear which variable is controlled and which is measured, and when there is no attempt to make an initial statement as to the relationship between the variables. Scientific is assigned when the hypothesis makes it clear which variables are being considered, how they will come in to play in the experiment, and what results are anticipated.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.A.c**<br>Is able to determine hypothesis validity<br>Labs: 4, 5, 7, 8, 10 | No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection. | A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment | A statement about the hypothesis validity is made which is consistent with the data analysis completed in the experiment. Assumptions which informed the hypothesis and assumptions not validated during experimentation are not taken into account. | A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account. |

You form your hypothesis before the experiment ever begins, but you make a statement about the validity of the hypothesis after the experiment has concluded. When formed, the hypothesis included a statement of the relationship between the independent and dependent variables. The experiment tested that relationship. And so when the experiment is done you go back and reflect on your hypothesis with your new knowledge.

No experiment can ever *prove* any hypothesis. Your experiment can disprove the hypothesis (shows a case where the relationship absolutely is not what you stated it would be), or it can *support* the hypothesis (you did your best to disprove the hypothesis and failed). Disproving your hypothesis does not prove the opposite of your hypothesis any more than failing to disprove your hypothesis would prove that initial statement. But when you do disprove your hypothesis you should consider the experiment from that point out as an attempt to now disprove the inverse of your hypothesis (so if you said when an object is dropped it flies up to the ceiling, and then found one case where it instead fell to the floor, you would know that the hypothesis that objects fall up is not true, and would now seek to check if the inverse hypothesis that things fall down can be disproven as well. If you managed to disprove both cases, then your experiment would be one which supports the *null hypothesis*, a statement that there is no relationship between these two variables.

Of course, it is always possible that other factors were important besides those which we paid attention to. In mechanics friction is unavoidable, but often ignored. This is an assumption that friction has only a minor contribution to the outcome of the experiment. Unless the actual impact of friction is measured, any statement about the impact from it is just an assumption. We also assume things like a table being flat, or an experiment being unaffected by the amount of light in a room.

A large part of science is learning how to determine what assumptions are being made, and which ones may be relevant to the experiment.

Progressing is assigned when a student fails to understand their own data and makes an incorrect statement about the validity of the hypothesis. Scientific is assigned when a student correctly interprets their data and considers the assumptions which informed the design and outcome of the experiment.

## Students demonstrate understanding of key concepts or basic principles in the discipline

Physics explains that natural world through discovery and explanation of patterns. We discover these patterns with careful observation and precise measurement via appropriate tools. These three rubrics ask you to consider how we measure the world, to understand the patterns observed in the world, and to acknowledge the differences between measured values and real values.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.B.a**<br>Is able to explain operation and limitations of measurement tools<br>Labs: 2, 3, 6, 11, 12 | At least one of the measuring tools used in lab lacks a clear identification of precision/limitation | All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed | All measuring tools identified with precision/limitation of each tool listed. Description of how to measure using some tools may be incorrect/vague, or precision may not be adequately justified. | All measuring tools are identified with proper precision values and thorough discussion of limitations. Descriptions on how to make measurements are complete and could be understood by readers with no prior familiarity with the measuring tools. |

Measuring things reduces the complexity of the object to a simple number. This is phenomenal for allowing us to handle a lot of information quickly, but can lead to blind spots. It is vital to understand precisely what you are measuring and how accurately you are doing so. If I use a ruler to measure the length of a book, but I place the ruler across the book at an angle, then calling the resulting number the length of the book is incorrect. If I ask a dozen people to use a 12 inch ruler to measure the width of a hair or the length of a football field, I will find that the answers do not agree with one another at all. Each tool used to make measurements has limitations in what it can measure, and must be used in specific ways for the measurement to be valid. In many cases your lab manual will ask you to find values without mentioning what tools to use for measurement. You must select the appropriate tool and use it properly, while keeping in mind the limitations of the tool. Even when told what instrument to use and how to use it, taking the time to describe the measurement can help focus the mind on proper procedures.

Discussions of how to perform measurements included in your lab notebook should assume that the reader does not have access to the lab manual, and so cannot benefit from instructions provided in the manual for how to set up equipment. Much of the descriptions which satisfy this rubric can be prepared in advance of attending lab.

Progressing is assigned when students make no mention of the details for how they will perform measurements (ie - "we will use a meter stick to find the height." instead of "We will measure from the floor straight up to the bottom most point of the object"), scientific is assigned when students are completely clear on details involved in measurement and limitations of the tool precision.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.B.b**<br>Is able to explain patterns in data with physics principles<br>Labs: 2, 3, 6, 8, 11, 12 | No attempt is made to explain the patterns in data | An explanation for a pattern is vague, OR the explanation cannot be verified through testing, OR the explanation contradicts the actual pattern in the data. | An explanation is made which aligns with the pattern observed in the data, but the link to physics principles is flawed through reasoning or failure to understand the physics principles. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |

Physics relies heavily on observing patterns to describe the world around us. But finding a pattern alone is not sufficient to improve your understanding of physics. Being able to link patterns you observe to formula you work with in the lecture course is the aim of this rubric item.

Progressing is assigned when students are unable to understand their data or attempt to provide blanket proposals. Scientific is assigned when students demonstrate a clear understanding of the connection between physics formulas and experimental results.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **SL.B.c**<br>Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able.<br>Labs: 4, 5, 8, 9, 12 | No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present | No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty. | An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective. | The uncertainties are minimized in an effective way. |

Any measurement we make includes some degree of interpretation by the observer. If you are using a ruler to measure a length and the object falls between two markings on the ruler, you have to decide what value to use for your final decimal place in the recorded measurement. When an object is not a true rectangle, but you are asked to find the surface area through measuring length and width you must decide which length and width to measure and how to handle the abnormal shape. Many other cases like these will come up regularly in your experiments. At other times there are practical limitations, like if you use a stopwatch to time something, then your reaction speed will dictate how long after the event actual ends you manage to stop the timer.

Progressing is assigned when students mention possible approaches to reduce uncertainties but do not make it clear to the reader that they have done so during the experiment. Scientific is assigned when students clearly explain how to reduce uncertainties and demonstrate that they have followed their own procedures throughout the experiment.

# Critical Thinking Rubrics

Students will use reason, evidence, and context to increase knowledge, to reason ethically, and to innovate in imaginative ways.

## Students identify and evaluate the key evidence underlying scientific theories

In these four rubrics, students carefully record their observations and evidence gathered in each experiment, and pay attention to why they record specific information and why they do not record the rest of what is observed. All science starts and ends with observations of either the physical reality before us or of the possibilities left open by combining various established explanations of that reality.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.a**<br>Is able to compare recorded information and sketches with reality of experiment<br>Labs: 3-8, 10 | No sketches present and no descriptive text to explain what was observed in experiment | Sketch or descriptive text is present to inform reader what was observed in the experiment, but there is no attempt to explain what details of the experiment are not accurately delivered through either representation. | Sketch and descriptive text are both present. The sketch and description supplement one another to attempt to make up for the failures of each to convey all observations from the experiment. There are minor inconsistencies between the two representations and the known reality of the experiment from the week, but no major details are absent. | Sketch and description address the shortcomings of one another to convey an accurate and detailed record of experimental observations adequate to permit a reader to place all data in context. |

A significant requirement of your lab notebook is to give the reader the sense that they know what happened during your experiment to a degree that they would be able to repeat what you have done, but would not feel the need to do so. This means providing a clear picture in both words and literal pictures to the reader to capture as many details as you can without causing undue distraction. Carefully recording your observations and being honest about the limitations of your records is important here. Often times a quick drawing will not have items in the proper locations or will fail to maintain proper scale. This is only a problem if the reader is left to believe that the drawings are more accurate than they really are. And written descriptions can be incredibly detailed, but leave readers completely confused due to excessive details or poor writing practices. Analogies are frequently used in discussing science concepts, but without a discussion of how the analogy begins to fail, such discussions can cause more harm than good. Thus having both a written description and a sketch is the ideal approach.

Progressing is assigned when students provide a description and/or sketch with flaws in it and make no attempt to figure out those flaws on their own. Scientific is assigned when a sketch is present along with a description of finer details not captured accurately through the sketch alone.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.b**<br>Is able to identify assumptions used to make predictions<br>Labs: 4, 5, 7, 8, 10 | No attempt is made to identify any assumptions necessary for making predictions | An attempt is made to identify assumptions, but the assumptions stated are irrelevant to the specific predicted values or apply to the broader hypothesis instead of the specific prediction | Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction. | Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made. |

There is a very important distinction between a prediction and a hypothesis. A hypothesis states two variables and a relationship between them which will be tested in the course of experimentation, but a prediction states as accurately as possible an exact outcome of a specific trial set. Thus a prediction starts from the hypothesis and any data already acquired in earlier trial runs, and then through a few assumptions you decide on a numerical range as small as possible in which you anticipate the measurements in your trial to land. As you perform more experimental trials, your predictions for each one should become more accurate, as you will begin to refine the assumption used in each prediction. These assumptions can be formal things like assuming that the Conservation of Energy applies, or informal things like the magnitude of impact from air resistance. Stating precisely what assumptions you are making is important, as well as stating exactly how these assumptions will influence your predicted value range.

Progressing is assigned here when students fail to identify assumptions which have an actual impact on the value being measured. Scientific is assigned when students identify relevant assumptions and accurately state the nature of their impact on the measurement.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.c**<br>Is able to make predictions for each trial during experiment<br>Labs: 4, 5, 7, 8, 10 | Multiple experimental trials lack predictions specific to those individual trial runs. | Predictions made are too general and could be taken to apply to more than one trial run. OR Predictions are made without connection to the hypothesis identified for the experiment. OR Predictions are made in a manner inconsistent with the hypothesis being tested. OR Prediction is unrelated to the context of the experiment. | Predictions follow from hypothesis, but are flawed because relevant experimental assumptions are not considered and/or prediction is incomplete or somewhat inconsistent with hypothesis or experiment. | A prediction is made for each trial set in the experiment which follows from the hypothesis but is hyper-specific to the individual trial runs. The prediction accurately describes the expected outcome of the experiment and incorporates relevant assumptions. |

After figuring out what assumptions need to be made in order to predict an accurate range in which you anticipate your measurements to occur, you must then state what that predicted range is. This should be done every time that the equipment is adjusted since those adjustments should result in different measurement ranges, or those adjustments are being made to test that they are not relevant, in which case you must explicitly state that you predict no change from your previous measured ranges. As stated in CT.A.b, the predictions should be informed by the hypothesis, but should be specific values which are only relevant for this precise set up of your experiment.

Progressing is assigned here when predictions are too broad or have no justification. Scientific is assigned when predictions are made for every trial run with narrow ranges that accurately encompass the actual measured values.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.A.d**<br>"Is able to identify sources of uncertainty "<br>Labs: 4, 5, 8, 9, 12 No attempt is made to identify experimental uncertainties. | descworst | An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect. | Most experimental uncertainties are correctly identified. But there is no distinction between random and experimental uncertainty. | All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty. |

As discussed in SL.B.a out measurement tools have limitations in how accurately they can make measurements. When we use measurements which are not absolutely accurate (and none are), then the values we find by using those measurements in equations are also not absolutely accurate. In addition to that, we are measuring real world values, and there are numerous factors which can influence the results of our experiment beyond those which we have control over. These factors should be addressed in our assumptions, and include things like friction, wind, and variations in material quality. These sort of uncertainties contribute to the fact that we get different measurements even when we believe that two trial runs were set up the same. This is why our predictions must be ranges and not single values.

In this rubric, you are meant to describe what contributes to the uncertainty in your measurements. Ideally you can make a distinction between random uncertainties (things you cannot control nor predict) and experimental uncertainties (things which could be less uncertain with better procedures or tools).

Progressing is assigned when students are unable to identify relevant uncertainties with any precision. Scientific is assigned when a student makes it clear precisely what contributes to the uncertainty in their experiment and properly identifies those uncertainties as random or experimental.

## Students demonstrate understanding of the role of controlled experiments in the scientific process OR Students test hypotheses using appropriate methods involving data collection and analysis, and make valid inferences from results

This rubric category is at the heart of experimentation, and many of the rubrics could be assigned here as well as in the categories where they exist now. The two rubrics included in this category look for students to distill the experiment to the purpose and the most important data.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.B.a** Is able to describe physics concepts underlying experiment<br>Labs: 2, 3, 6, 9, 11, 12 | No explicitly identified attempt to describe the physics concepts involved in the experiment using student's own words. | The description of the physics concepts underlying the experiment is confusing, or the physics concepts described are not pertinent to the experiment for this week. | The description of the physics concepts in play for the week is vague or incomplete, but can be understood in the broader context of the lab. | The physics concepts underlying the experiment are clearly stated. |

This should be completed before coming to lab each week. Through research in your text book or various online sources, you should arrive at lab understanding the physics involved in the experiment for the week with a solid idea of what will be happening during lab.

Knowing what you expect to do and what results should be observed will inform your development of a hypothesis and of individual predictions. It will help you to decide what assumptions are being made, and determine what limitations the equipment force upon your experiment. The title of the lab alone should give students a clear indication of what to focus their preparation on, and the manual will illustrate how lab will proceed.

Search YouTube for "The Monkey Business Illusion" for a clear example of why you cannot properly observe an event without knowing what to expect in advance. This is another reason why coming to lab fully prepared for the material is important, because you can easily be distracted by irrelevant details if not properly prepared.

Be especially mindful of plagiarism in this rubric, as copying directly from your sources does not show you understand the material, and is a violation of the WSU Academic Honesty policy.

Progressing is assigned here when students show that they are still uncomfortable with the physics concepts for the week, and hopefully students will realize this problem and ask questions at the start of lab to supplement their understanding. Scientific is assigned when students demonstrate a clear understanding of physics concepts involved in the lab by stating them in their own words.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **CT.B.b** Is able to identify dependent and independent variables Labs: 2, 3, 6, 12 | No attempt to explicitly identify any variables as dependent or independent | Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified | The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent. | All physical quantities relevant to the experiment are identified as dependent and independent variables correctly, and no irrelevant variables are included in the listing. |

This rubric also should be compelted before you arrive at lab for the week. Knowing what values you can control in an experiment and which ones you need to measure is critical to performing any experiment. It is also relevant to how you present your data to a reader. In most of our labs we explicitly inform you which variables are important, and the procedures make it clear which ones you have control over. But the lab notebook is intended to be recorded for a reader to understand without access to the lab manual. Building the habit of explicitly identifying your controlled and measured variables will improve your presentation of information in the future.

Progressing is assigned when students are unable to clearly state all values involved in the experiment. Scientific is assigned when students identify appropriate which variables are independent and which are dependent.

# Quantitative Reasoning Rubrics

Students will solve quantitative problems from a wide variety of authentic contexts and everyday life situations.

Without the data experimentation doesn't exist. Knowing how to work with your data is vital to being able to understand what the data is telling you.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.A** Is able to perform algebraic steps in mathematical work. Labs: 3-5, 7-12 | No equations are presented in algebraic form with known values isolated on the right and unknown values on the left. | Some equations are recorded in algebraic form, but not all equations needed for the experiment. | All the required equations for the experiment are written in algebraic form with unknown values on the left and known values on the right. Some algebraic manipulation is not recorded, but most is. | All equations required for the experiment are presented in standard form and full steps are shown to derive final form with unknown values on the left and known values on the right. Substitutions are made to place all unknown values in terms of measured values and constants. |

We deal with quite a few formula throughout physics, and seeing letters in an equation doesn't always mean you are looking at variables since we also deal with units to identify which values measure what variables. In addition, many times we need to apply the same formula to multiple sources of information, and will denote this through subscript notation, which adds even more letters which are not actually variables to equations. As with CT.B.a and CT.B.b, this should be compelted before you come to lab each week.

It is absolutely vital to form a habit of manipulating your equations without inserting any known values until you have a final form of the equation ready.

Progressing is assigned here if students fail to identify all equations required for the experiment. Scientific is assigned when students identify all equations required in their standard form, and show all algebra and substitutions involved in setting up final forms of the equations for use in the experiment.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.B** Is able to identify a pattern in the data graphically and mathematically Labs: 2, 3, 6, 9, 11, 12 | No attempt is made to search for a pattern, graphs may be present but lack fit lines | The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented. | The pattern has minor errors or omissions. OR Terms labelled as proportional lack clarity - is the proportionality linear, quadratic, etc. Graphs shown have appropriate fit lines, but no equations or analysis of fit quality | The patterns represent the relevant trend in the data. When possible, the trend is described in words. Graphs have appropriate fit lines with equations and discussion of any data significantly off fit. |

If you want to show a relationship between two variables, you need to use a graph. Tables are great for showing a large list of single value variables and discussing how they all interact, but to get a pattern to show or to establish a relationship you want to use a graph and focus on two variables at a time. Once you have a graph of your data, you need to be able to identify the pattern displayed as accurately as possible. This is done with finding a fit line, and including the equation for that line.

In the event your data contradicts known physics principles, you still need to explain the pattern which does show up in your data. You will likely want to also discuss why you believe that your data conflicts with known physics. This explanation would be needed by rubrics CT.B.a and CT.A.d anyway. Failing to find a pattern which aligns with physics principles will make your discussion for rubric SL.B.b quite a bit more interesting as well, and should lead to many ideas for SL.A.a

Due to uncertainties and data measurements happening in ranges, finding these patterns can be difficult, especially if the data taken was not taken well. This rubric focuses on how well you work with the data you have, while other rubrics have dealt with how good of data you acquire. Remember whenever you present a graph to place the independent variable (the one you control) on the X axis (horizontal) and the dependent variable on the Y axis. Also do not leave lines connecting your data points, as a line implies that anywhere you add a point along that line is as valid as data which was collected. This is not the case in our labs, as we did not gather data for those specific values of our independent variable, and our uncertainties mean we cannot say what the actual data point would be. The fit line accounts for the uncertainties in each reading and includes a term to explain how far off of the line new data is expected to be.

Progressing is assigned when an improper fit line is used in a graph or a written description of a pattern is incorrect. Scientific is assigned when both a written description and a graph are present with a proper fit line and equation for the fit line.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **QR.C**<br>Is able to analyze data appropriately<br>Labs: 2-12 | No attempt is made to analyze the data. | An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate. | The analysis is appropriate for the data gathered, but contains minor errors or omissions | The analysis is appropriate, complete, and correct. |

In QR.A you were asked to perform all algebraic manipulation before inserting any known values. Now you are being instructed to insert the units of your values without the numbers so that you can focus on making sure that your units make sense. Unit analysis can show you when a unit conversion is needed (like converting millimeters to meters) and it can show you when terms are missing from your equation (it is not possible to add two variable sets with different units, and units should be the same on both sides of an equal sign). Attempting to evaluate units and numbers at the same time can cause quite a mess in larger equations, so even in simple equations it is good to work on developing good habits of treating the units apart from the numerals.

Progressing is assigned when units are not placed in SI form or appropriately converted from SI form to the scale appropriate to the lab work, or when there are clear conflicts in the treatment of units in the equations. Scientific is assigned when students use unit analysis to verify equations are accurate throughout the lab.

## Information Literacy Rubrics

Students will effectively identify, locate, evaluate, use responsibly, and share information for the problem at hand.

Your existing information literacy skills are going to be vital for arriving at lab prepared for the experiment each week. I advise you to check out OpenStax, MIT OpenCourseWare, EdX, and Coursera. Other resources exist, such as Khan Academy and Hyper Physics. Just be sure to validate any information you find by checking it against at least one other known reliable source.

But in this category the information literacy we are focusing on developing purposefully during lab are about pulling information from the real world and recording it to share with others.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **IL.A**<br>Is able to record data and observations from the experiment<br>Labs: 1-12 | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. " | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. " | Most of the data is recorded, but not all of it. For example measurements are recorded as numbers without units. Or data is not assigned an identifying variable for ease of reference. | All necessary data has been recorded throughout the the lab and recorded in a comprehensible way. Initial and final states are identified correctly. Units are indicated throughout the recording of data. All quantities are identified with standard variable identification and identifying subscripts where needed. |

This rubric is all about recording information to share with others. If your reader cannot make sense of the information you have recorded, then that information is useless. That means numbers written on the page need to be linked to a variable and a unit. Variables should be identified through subscripts to keep initial and final states or different objects distinct from one another.

Progressing is assigned when some data is recorded poorly or the reader is unable to figure out how it is intended to be understood, but it appears that data was being recorded throughout the lab. Scientific is assigned when all data from the lab is presented clearly and legibly.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **IL.B**<br>Is able to construct a force diagram<br>Labs: 1-12 | No force diagrams are present. | Force diagrams are constructed, but not in all appropriate cases. OR force diagrams are missing labels, have incorrectly sized vectors, have vectors in the wrong direction, or have missing or extra vectors. | Force diagram contains no errors in vectors, but lacks a key feature such as labels of forces with two subscripts, vectors are not drawn from the center of mass, or axes are missing. | The force diagram contains no errors, and each force is labelled so that it is clearly understood what each force represents. Vectors are scaled precisely and drawn from the center of mass. |

Force diagrams are a phenomenal tool for understanding how to properly assemble equations in mechanics. Every time an object moves in a new direction it is worth your time to draw up a force diagram for that object. This can help you identify assumptions as well. These simplified diagrams of forces also lend an understanding of motion to any other sketches of your experiment for a reader who understands Newton's Laws.

Progressing is assigned when force diagrams are present but so poorly completed that the reader cannot make sense of them. Scientific is assigned when it is possible to understand the outcome of an experiment through the force diagrams alone.

## Writing and Communication Rubrics

Students will communicate successfully with audiences through written, oral, and other media as appropriate for the audience and purpose.

This final set of rubrics includes more specific guidance in various elements of your lab manual which are required to fulfill other rubrics.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.A** Is able to create a sketch of important experimental setups<br>Labs: 2, 4, 5, 7, 8, 10-12 | No sketch is constructed. | Sketch is drawn, but it is incomplete with no physical quantities labeled, OR important information is missing, OR it contains wrong information, OR coordinate axes are missing. | Sketch has no incorrect information but has either a few missing labels of given quantities, or subscripts are missing/inconsistent. Majority of key items are drawn with indication of important measurements/locations. | Sketch contains all key items with correct labeling of all physical quantities and has consistent subscripts. Axes are drawn and labeled correctly. Further drawings are made where needed to indicate precise details not possible in the scale of initial sketch. |

As mentioned in CT.A.a, a sketch is important for providing clarity to written descriptions. While it is hard to convey all information through sketches alone, developing good practices in designing your sketches will help inform the reader of important details and let them know how the sketch links to the written descriptions provided along with them.

Progressing is assigned here when the sketch lacks vital information about what is being shown or vital details which help connect the image to the written description. Scientific is assigned when sketches show great attention to detail and help guide the reader's attention to important aspects of the experiment.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.B**<br>Is able to draw a graph<br>Labs: 2, 3, 5-9, 11, 12 | No graph is present. | A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected. | "A graph is present and the axes are labeled, but the axes do not correspond to the independent (X-axis) and dependent (Y-axis) variables or the scale is not accurate. The data points are not connected, but there is no trend-line. " | The graph has correctly labeled axes, independent variable is along the horizontal axis and the scale is accurate. The trend-line is correct, with formula clearly indicated. |

As discussed in QR.B, a graph is used to show a pattern in your data. Failing to provide graphs when they are needed will penalize you in QR.B, but short of including no graphs at all for the entire lab, you are evaluated in WC.B only on the graphs you do provide to see how well you construct those graphs. Graphs should be drawn to scale so that straight lines really do indicate linear relationships, and the graph should be labelled so that all values are understood and units are known. As stated in WC.B, make sure that any line on your graph can be properly interpreted to mean that all points on the line are expected to be appropriate values as if measurements were made for those specific values.

Progressing is assigned when critical information is missing from the graph, but the data is present. Scientific is assigned when the graph conveys all information acquired in the lab including the trendline and equation.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.C**<br>Is able to construct a ray diagram<br>Labs: Not used | No Ray Diagram is constructed. | Some Ray Diagrams are constructed, but not for all cases considered during the experiments. OR Rays drawn in the Ray Diagram do not follow the correct paths. Object or image may be located at the wrong position. | "Ray diagram is missing key features, but contains no errors. One example could be the object is drawn with the correct lens/mirror, but rays are not drawn to show image. Or the rays are too far from the main axis to have a small-angle approximation. Or the diagram was drawn without the aid of a straight-edge. " | "Ray diagram has object and image located in the correct spot with the proper labels. Rays are correctly drawn with arrows and contains at least two rays per object/image pair. A ruler was used to draw the images. " |

Ray diagrams are useful tools to simplify geometric optics. In our simplified lab arrangements they do not offer much extra insight, but you are being presented simple arrangements now so that if you continue to work with optics you understand how to use ray diagrams to figure out more complicated optical arrangements.

Progressing is assigned when some ray diagrams are omitted or when the ones present are poorly rendered. Scientific is assigned when the ray diagram appropriately locates the image and is sharply presented.

| | No Effort | Progressing | Expectation | Scientific |
|---|---|---|---|---|
| **WC.D** Is able to draw a circuit diagram<br>Labs: Not used | No circuit diagram is drawn. | Components of the circuit are missing, or connected incorrectly. Components are not clearly labelled. | "Circuit diagram is missing key features, but contains no errors. It may be difficult to follow electrical pathways, but it can be determined which components are connected with sufficient scrutiny. " | Circuit diagram contains minimal connecting lines, components are neatly arranged to ensure labels are readily identified to appropriate components. |

Circuit diagrams rarely look like the physical circuit we create with components and wires in real life. The reason for a circuit diagram is to make it trivial to figure out how the components connect to one another, and to establish labels for identification of each component. To assist with clarity, the number of connecting lines in a circuit diagram should be kept to a minimum, and lines should only cross one another when connected if at all possible. Even if the diagram for your circuit is provided in the manual for the experiment, you should always include a circuit diagram in your journal to ensure the reader understands the circuit being used.

Progressing is assigned when some details of the circuit diagram itself are incorrect. Scientific is assigned when the circuit diagram is completely legible and provides valuable information to the reader.

Rubrics adopted from Scientific Abilities Rubrics produced by Rutgers for the ISLE labs. Adopted and modified with permission by Eugenia Etkina.