# Lab Schedule

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Lab Syllabus

Lab Director  Jacob Turner  
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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](https://ocw.mit.edu) as well as [EdX](https://www.edx.org) and [Coursera](https://www.coursera.org).
  - 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 calculus, 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](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](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](mailto:Access.Center@wsu.edu), URL: [http://accesscenter.wsu.edu/](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. 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 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 9.8m/s$^2$. That value is known with an uncertainty of 0.1m/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 \( p_{\text{cart}} \), write down that \( p_{\text{cart}} \) 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 your 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 record 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 ± 0.001 m 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 ± 0.1 m/s².” “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 ± 0.004 m/s².” “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.](image)

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 119 there is a description 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
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.
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 128 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 $9.80\,\text{m/s}^2$. Your result may be $g = 9.75 \pm 0.05\,\text{m/s}^2$. 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 $g_{\text{next}}$ 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 $g_{\text{next}}$ were less than 9.6 or larger than 9.9$m/s^2$ this is a random outlier 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 $[1]$.

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

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.

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.

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 109.

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Lab 1. Electrostatics

Goals

• To understand and verify the behavior of the two kinds of charge, denoted “positive” and “negative”, respectively.
• To understand the response of the electroscope when a charged rod is brought near, so that the electrical charges on the rod interact with charges already present in the electroscope.
• To visualize charge transfer between charged rods, the electroscope, and other objects, and to understand how the electroscope is used to compare the net charges on two objects.

Introduction

Electroscopes are used to detect the presence or absence of electric charge. They come in various forms, but a picture of a typical electroscope is shown in Figure 1.1. Inside the electroscope a metal needle pivots on a wire support shaped something like a paper clip. This structure inside the electroscope is connected to the outside by a metal rod passing through a plastic insulator. The metal disk on top simply allows charge to be detected more efficiently; otherwise its geometry is not too important. The term “electrostatics” refers to charges that are basically stationary, rather than continuously moving as in a wire carrying an electric current. An analogy may be made to water in a bathtub as opposed to a flowing stream of water.

Some important things to remember are:

• Electric charges come in two varieties that are designated positive and negative.
• Charges of the same variety repel one another while charges of the opposite variety attract one another.
• Charges exert greater forces on one another when closer together (Coulomb’s law).
• All materials are composed of positive and negative charges.
• In metal objects, a small fraction of the negative charge is relatively free to move from one place to another within the object. (This is why metals are called conductors.)
• Electric charges in insulators such as rubber and glass are essentially fixed in place.
• The positive charges in solid materials are in the atomic nuclei and are not free to move.
• Electric charges in static equilibrium have no net force acting on them.
• When rubbed with silk, a glass rod acquires a net positive charge on its surface by giving up electrons to the silk, which has a stronger affinity for electrons.
• The plastic (polyvinyl-chloride, or PVC) acquires a net negative surface charge when rubbed with wool by “stealing” electrons from the wool.

Caution: The glass rod is brittle. Return it to the tray when not in use. If placed on the table, the rod can roll off and break. Avoid handling the glass rod, the plastic tube, and the wool and silk fabrics any more than necessary. Their electrostatic properties are degraded by moisture and oil from your hands.

Figure 1.1. “Grounding” the electroscope.

Holding a charged rod close to the electroscope plate

Ground the electroscope as illustrated in Figure 1.1. This works because your body can absorb or give up small amounts of charge without suffering any ill effects. You could use a wire connected to the earth (or ground, hence the term “ground”), but your body is handier in this case. To charge the glass rod, hold the silk cloth by the edge so that it hangs below your hand and stroke the hanging silk with the glass rod. This procedure keeps moisture from your hand from damping the silk. Then position the part of the glass rod that touched the silk just above the circular disk on top of the electroscope without touching the disk with the rod. What do you observe? As the rod is moved away from the disk, what happens? Hypothesize what is happening to the charges. If at any time you suspect that the needle is stuck, gently tap the case of the electroscope with your finger. The case is not connected to the top plate. Tapping the case will not affect the charge on the plate or needle.

Repeat the same sequence with the plastic tube after rubbing it with wool. The wool cloth is thicker than the silk, and is less susceptible to moisture. The best procedure is to put to wool in the palm of

1The effectiveness of the charging procedure depends strongly on the ambient humidity and the cleanliness of the glass rod. On a humid day, it may take some time to properly charge the rod. Cleaning the glass with a glass cleaner helps considerably. On a dry day, the charging procedure can produce much more charge. As you move the rod toward the electroscope, stop when you see the needle move. Sparks between the rod and the electroscope will invalidate this part of the experiment. If the needle moves more than half the distance up the scale, you have probably produced a spark. Sparks transfer charge to the electroscope. The effect of transferred charge will be studied below.
your hand and rub it against the rod. Take care to avoid sparks, as described in the footnote above. Again record your observations.

Now explain your hypothesis with the aid of some simple “cartoons”—a series of pictures with words of explanation; your TA will have some helpful suggestions for making simple drawings. Show what the electric charges on the electroscope are doing as the charged rods are brought close and then moved away. You will need a sequence of several cartoon pictures to show the locations of the charges on the electroscope for different positions of each rod. If you can’t support your hypothesis by your observations and pictures, you may need to make another hypothesis.

**Charging the electroscope by direct contact**

Ground the electroscope again. This time touch the charged glass rod to the disk, and then move the rod away. What happens to the needle of the electroscope? Make a hypothesis about what happened when you touched the disk with the rod using some “cartoons” as visual aids. Without grounding the electroscope, test your hypothesis by bringing the charged glass rod near the disk at the top of the electroscope but without touching it. What happens to the electroscope needle? Explain whether this observation supports your hypothesis or not. If the observation doesn’t support your hypothesis, redo the whole procedure and make sure that the observed behavior is repeatable—an important aspect of the scientific process. Record all your hypotheses, whether they turn out to be correct or incorrect. By using the scientific method we hope to reach the correct explanation in the end. If the behavior is repeatable, then make another hypothesis to explain your observations and test it again. To double check your understanding, bring the plastic tube close to (but not touching) the electroscope that was touched at the outset with the charged glass rod and observe what happens. Is your hypothesis consistent with these additional observations? Explain with the aid of another cartoon sequence.

Repeat the entire process outlined in the previous paragraph, but start this time by touching the initially uncharged electroscope with the charged plastic tube.

Can a net electric charge be left on the electroscope by touching it with the rods? How does the sign of the charge on the electroscope compare to the charge on the rod that touches it? Summarize your findings for this exercise.

**Charging the electroscope by induction**

Ground the electroscope again, as in Figure 1.1. With your finger still touching the edge of the disk and your thumb still touching the body of the electroscope, bring the charged glass rod up close to the other side of the disk (away from your finger) without touching the disk. Now remove your finger from the disk first and then move the glass rod away. What do you observe on the electroscope? Make sure that it is repeatable. Make a hypothesis about what happened to the charge in the electroscope and record it. Then test your hypothesis using what you learned so far. Modify your hypothesis as necessary. Explain your reasoning with another cartoon sequence.

Now beginning with the charged plastic tube repeat the process described in the previous paragraph. Summarize your results for this section.
CHAPTER 1. ELECTROSTATICS

Effect of lit match on electroscope charge

Using your knowledge of the behavior of the electroscope and the charged rods, determine what variety of charge is released when a match is burning. Hold the burning match about 2 cm above the disk. (Hold the match at least 1 cm from the plate.) Try it with the electroscope initially uncharged, positively charged, and negatively charged. Explain in detail your procedure, results, reasoning, and conclusions. More cartoons are needed here.

Summary

Summarize your findings concisely. Provide a brief explanation of your most important observation in each experiment.

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to analyze the experiment and recommend improvements</td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report</td>
<td>Description of experimental procedure leaves it unclear what could be improved upon.</td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed.</td>
<td>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.</td>
</tr>
<tr>
<td>Labs: 1-3, 5, 7, 9, 11, 12</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SL.B.b</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to explain patterns in data with physics principles</td>
<td>No attempt is made to explain the patterns in data</td>
<td>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.</td>
<td>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.</td>
<td>A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit.</td>
</tr>
<tr>
<td>Labs: 1-3, 5, 7, 9-11</td>
<td></td>
<td></td>
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### IL.A
Is able to record data and observations from the experiment

- **Labs:** 1-12

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### WC.A
Is able to create a sketch of important experimental setups

- **Labs:** 1, 2, 4-8

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<td>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.</td>
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Lab 1 Electrostatics

Name: ___________________________    Lab Partner: ___________________________

**EXIT TICKET:**

- Dump matches out in the trash ONLY IF THEY ARE COMPLETELY COOLED. If any match is warm to the touch, wash them in the sink, then dump in the trash.
- Return UNBROKEN glass rod to plastic tray so it cannot roll off table. Place plastic rod in same compartment, as well as matches. Place the wool and silk cloths on the opposite side of the tray.
- Discharge the electroscope
- 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

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Lab 1 Electrostatics

Name: ___________________________    Lab Partner: ___________________________

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- Discharge the electroscope
- 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
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Lab 2. Electric Fields

Goals

- To understand how contour lines of equal voltage, which are easily measured, relate to the electric field produced by electrically charged objects.
- To learn how to identify regions of strong and weak electric fields from maps of electric field lines.
- To quantitatively estimate the magnitude and direction of an electric field using experimental voltage measurements.

Introduction

The concept of the electric field is useful in determining the force on a charged object due to the presence of other charges. The purpose of this laboratory is to quantitatively map, in two dimensions, a set of equipotential lines for two different charge distributions using a voltmeter. An equipotential line connects the set of points for which the potential difference or voltage has a constant value. The two-dimensional charge distributions will be established by applying a potential difference between a pair of conducting electrodes. The electrodes are attached to a board covered with conducting paper. From these equipotential lines the electric field can be determined. Electric field lines always cross equipotential lines at right angles as a consequence of the definition of electric potential. By convention, electric field lines start on positive charges and end on negative charges.

You will use a voltmeter to locate different points on the black conducting paper for which the voltage differences between the points in question and a reference point (say, at zero potential) are the same. These points are recorded on a white sheet of paper with the same grid pattern as the conducting paper. Then connect these points of equal voltage to form an equipotential line. Be sure to connect points with smooth curves, not straight lines with sharp corners. Verify the equipotential line is roughly accurate by testing a point drawn which was not previously measured.

From a set of equipotential lines you can create a map of the vector electric field following the rules stated at the end of the first paragraph of the Introduction section. Since electric field lines start from and end on electrical charges, higher densities of field lines near the electrodes indicate regions of higher charge concentration. From a complete electric field map, the charge densities on the electrodes themselves can be deduced.
Electric field of a long plate parallel to a long rod

Equipment set-up

1. On the white paper grids provided, carefully draw the outlines of the brass electrodes at the same positions as they appear on the black conductive paper.

2. Connect the positive terminal (red jack) of the power supply to the circle-shaped electrode on the conductive paper, as shown in Figure 2.1. This will produce a net positive charge on the circular electrode. Connect the negative terminal (black jack) of the power supply to the bar-shaped electrode on the conductive paper. This will produce a net negative charge on the bar electrode. Use “alligator clips” to connect the wires from the power supply to the electrodes. This configuration simulates the electric field between a positively charged rod and a negatively charged plate.

3. Adjust the current knob on the power supply to the straight-up or 12 o’clock position. Then turn the power supply on and adjust the COARSE voltage control knob to set the voltage to about 5 V as read on the voltmeter on the front of the power supply.

4. Connect the common (COM) terminal of the digital multimeter (DMM) to the bar-shaped electrode. Connect the wire lead with the probe to the V-Ω (volt-ohm) terminal of the DMM, and set the selector knob to measure DC Voltage (V with a solid and dashed straight line). If your multimeter has values listed on the selector knob options, set the range knob to 20 DCV. If no values are listed, then the DMM is auto-ranging.

5. Verify that you have a good electrical connection between the bar-shaped electrode and the power supply by touching the probe to the bar-shaped electrode. The voltage reading should be zero. If this is not the case, ask your TA for assistance.

6. Now fine tune the adjustment of the power supply by: (1) touching the probe to the circle-shaped electrode, and (2) turning the FINE voltage control knob on the power supply until
the voltage reading on the DMM lies between 4.90 and 5.10 V, making sure that the reading is stable. Once set, this voltage should remain constant for the mapping of all the equipotential lines for a given electrode configuration. Check it from time to time as you make your map, and adjust the voltage as necessary to maintain this voltage reading. Be sure to record the actual measured voltage.

7. Touch the probe to the conductive paper at a few random points. The voltage readings on the DMM should lie between zero and the value you measured on the circle-shaped electrode. If this is not the case, ask your TA for assistance.

Caution: Do not mark the conductive paper with pencils or pens, or poke holes in it with the pointed probe.

Data collection

Choose some convenient voltages between 0 and 5 V, say 0.50, 1.00, 1.50, etc.

1. Using the probe find a point on the conducting paper that gives a voltage of $0.50 \pm 0.01$ V. Mark this point on the white grid paper using a symbol of your choice (such as a small x). Now move the probe 1–2 cm away from the point you just located and search for another point on the conducting paper that gives a reading of $0.50 \pm 0.01$ V. Mark this point on the white grid paper using the same symbol. Continue this process until you reach the edge of the conducting paper or you run into points already located. Now connect these points with a smooth line (Don’t just connect the dots with straight line segments!) and label this line “0.50 V”. This is the first equipotential line for this electrode configuration.

2. Repeat the process outlined in (a) above for points with a voltage of $1.00 \pm 0.01$ V, using another symbol to mark these points on (such as a small o). Alternating the plot symbols will clearly distinguish the various lines of equal potential. Repeat this process for the other voltage values.

3. If you have any large blank regions on your map, choose an intermediate value of potential (one that falls between the voltages of previously drawn equipotential lines) and fill in the “blanks.”

4. Each electrode is also an equipotential. Try it by touching the probe to the electrode at various points; you may have to rub the probe on the brass gently to make good electrical contact because of the layer of tarnish that forms on brass. Record the voltage of each electrode on your white grid paper.

Data analysis

First sketch in the electric field lines associated with the equipotential lines measured previously by following the “rules” for field lines as outlined in the Introduction. Since each conducting electrode is an equipotential surface, electric field lines that start or end on a conducting surface must be perpendicular to the surface where they touch it. A suggestion is to start at a point on the positive electrode and draw a smooth continuous line which crosses all equipotential lines at right angles. Extend each line until you either reach the edge of the paper or the negative electrode. Pick other points on the positive electrode and repeat this process.
CHAPTER 2. ELECTRIC FIELDS

From the definition of electric potential, the magnitude of the electric field, $|\mathbf{E}|$, is related approximately to the electric potential (or voltage), $V$, in the following way:

$$|\mathbf{E}| = \frac{\Delta V}{\Delta s}$$  \hspace{1cm} (2.1)

where $\Delta V$ is the difference in voltage between two equipotential lines and $\Delta s$ is the distance between the two equipotential lines measured along an electric field line. This approximation becomes exact in the limit as the distance between the two equipotential lines approaches zero. In our case we must be content with approximate values for the electric field. The electric field is perpendicular to nearby equipotentials, and points from high potential to low. Be sure to indicate the direction of each field line with arrows. Don’t leave any large regions of your map devoid of field lines.

Pick 8–10 points on your electric field map and calculate the approximate values of the electric field using the above equation. Be sure to use adjacent equipotential lines in order to make the approximation better. When you do this, you are finding the average electric field between the two equipotentials, which will closely approximate the actual value of the electric field midway between the two equipotentials. Use a special plot symbol (a different color pen or pencil would be good) to indicate on your map the locations of the points at which you calculate the magnitudes of the electric field. Label the points $P_1$, $P_2$, etc. Show the calculations for each point in your report. Try to locate the places on your map where the electric field is largest and where it is smallest by this process.

Another electrode configuration

Replace your conducting board with another board with a different configuration of electrodes.

Choose the polarity of each electrode and connect the power supply appropriately. Some electrodes may be left neutral or unconnected. Your TA will have special instructions for some electrode configurations.

Repeat the process above to create and analyze another map.

Summary

Based on your electric field maps and calculations of the magnitude of the electric field, make some general observations about where the electric field tends to be largest and smallest. Is it possible to predict from the electric field lines alone where the field will be large or small? Explain your reasoning.
<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>Is able to analyze the experiment and recommend improvements</th>
<th>No Effort</th>
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<td></td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report</td>
<td>Description of experimental procedure leaves it unclear what could be improved upon</td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed</td>
<td>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.</td>
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| SL.B.b | Is able to explain patterns in data with physics principles | 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. |
|        | | | | | |
| Labs: | 1-3, 5, 7, 9-11 | | | | |

| SL.B.c | Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able. | 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. | 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 uncertainties are minimized in an effective way. |
|        | | | | | |
| Labs: | 2, 6 | | | | |

| CT.B.a | Is able to describe physics concepts underlying experiment | 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. |
|        | | | | | |
| Labs: | 1-3, 5, 7, 9-12 | | | | |

| QR.B | Is able to identify a pattern in the data graphically and mathematically | 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. |
| Labs: | 1-3, 5, 7-9, 11 | | | | |

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### QR.C
**Is able to analyze data appropriately**
Labs: 1-4, 6, 7, 9-12

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<td>No attempt is made to analyze the data.</td>
<td>An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate.</td>
<td>The analysis is appropriate for the data gathered, but contains minor errors or omissions</td>
<td>The analysis is appropriate, complete, and correct.</td>
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### IL.A
**Is able to record data and observations from the experiment**
Labs: 1-12

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### WC.A
**Is able to create a sketch of important experimental setups**
Labs: 1, 2, 4-8

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Lab 2 Electric Fields

Name: ____________________________  Lab Partner: ____________________________

EXIT TICKET:

☐ Turn off your multimeter
☐ 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

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Lab 3. Ohm’s Law

Goals

• To understand Ohm’s law, used to describe the behavior of electrical conduction in many materials and circuits.
• To calculate the electrical power dissipated as heat.
• To understand and use a rheostat, or variable resistor, in an electrical circuit.
• To learn how to connect electrical components so that the current can flow around the circuit, and to learn how to use, connect, and read ammeters (current reading instruments) and voltmeters (voltage reading instruments).
• To measure and observe the behavior of the voltage across and the corresponding current through a simple resistor (electronic component) and a tungsten-filament light bulb.

Introduction

One of the most basic electrical circuits is a resistor connected to a voltage source, such as a battery or power supply. A heater is exactly this as the entire circuit. A quantity called the resistance, $R$, of a component is defined as the ratio of the potential difference, $\Delta V$, across the component to the current, $I$, flowing through the component, or

$$R = \frac{\Delta V}{I} \quad (3.1)$$

When $\Delta V$ is expressed in volts and $I$ is expressed in amperes (amps), then $R$ is in the SI units of ohms ($\Omega$). The power, $P$ (in the SI unit of watts), dissipated by that component in the form of heat is given by

$$P = I(\Delta V) = I^2R = \frac{(\Delta V)^2}{R} \quad (3.2)$$

The resistance of some materials is constant over a wide range of voltages and currents. When a material behaves in this way, it is called “ohmic.” Electrical components made from ohmic materials are called resistors.

By measuring the current flowing through a component as a function of the voltage across the component, one can determine whether the ratio $\Delta V/I$ is a constant or not. If it is constant, then the
component is ohmic and the constant resistance in ohms can be determined. If the voltage to current ratio is not constant, the device is not ohmic and does not obey Ohm’s law. A voltmeter is used to measure voltage and an ammeter is used to measure current. Ideal voltmeters and ammeters will not affect the currents or voltages in the circuit as the measurements are being made. Real meters only approximate this ideal.

An ammeter measures the electrical current that flows through it. To measure the current flowing through a particular device in a circuit, the ammeter must be connected in such a way that the same current flows through the ammeter as through the device. The ammeter is simply a flow meter for the electrical current, so the wire at one end of the device must be disconnected and the ammeter inserted. The disconnected wire end is now connected to one terminal of the ammeter and a new wire is connected between the second terminal of the ammeter and the device to restore the flow of current through the circuit. This type of connection is called a “series” connection. The ammeter in Figure 3.1 is represented by a box marked with the letter “A”.

Caution: If current flows backwards through the ammeter, the ammeter tries to respond by registering a negative current. Since the meter needle can only show positive values, this can damage the meter. To check that the ammeter is connected with the correct polarity, quickly tap the knife switch (See Figure 3.1) before closing it completely. If the meter does try to deflect in the negative direction, exchange the connections of the two wires connected to the ammeter.

**Current versus voltage for a 100 Ω (nominal) resistor**

In this exercise the voltage across and the current through a known resistor are measured as the current through the circuit is varied. The power supply voltage is kept constant, but the current flowing in the circuit is controlled with a variable resistor, also called a rheostat. (See Figure 3.1)

The rheostat has three terminals. Two terminals are on the ends of the device and are fixed, and the third is connected to a sliding contact that can be moved from one end of the device to the other. The resistance between the end terminals has a fixed value, but the resistance between the

![Figure 3.1. Circuit connections.](image)
one of the end terminals and the sliding contact can be varied from zero to the fixed value of whole device.

**Preliminary calculations**

Assuming that the power supply voltage is fixed at 5.0 V, calculate the following quantities to two significant digits:

1. The current through the nominally 100 Ω resistor when the resistance of the rheostat is a maximum (340 or 360 Ω—your rheostat is marked with the value to use here), and when the resistance of the rheostat is zero.
2. The maximum power dissipated as heat by the 100 Ω resistor. The rated maximum power for this resistor is 0.50 W. If the power you calculate exceeds 0.50 W, please ask your TA for help before proceeding!

**Equipment set-up**

Caution: If current flows backwards through the ammeter, the ammeter tries to respond by registering a negative current. Since the meter needle can show only positive values, this can damage the meter. The ammeter can also be damaged if the magnitude of the current is much larger than the current rating of the chosen scale. To check that the ammeter is connected with the correct polarity and to a safe current scale, quickly tap the knife switch (See Figure 3.1) without closing it completely. If the meter tries to deflect in the negative direction, exchange the connections of the two wires connected to the ammeter. If the meter tries to deflect off-scale in the correct direction, use a current scale with a higher current rating. If the meter passes these two tests, close the knife switch completely and proceed to make measurements.

1. Turn the current knob on the power supply to the straight-up or 12 o’clock position, and set the power supply voltage to 5.0 V.
2. Build the circuit shown in Figure 3.1, leaving the switch open, that is, not making electrical contact. Be sure to use an ammeter scale with a current rating large enough to measure the maximum current you calculated above. By convention ammeters read positive when electrical current flows into the positive terminal (red) of the meter and then flows out of the negative terminal (black) of the meter.
3. Set the rheostat for maximum resistance by moving the slide so that the current must travel through the entire coil.
4. Tap the knife switch to make sure that the ammeter connections are correct. If all is well (refer to bold section above), then close the switch. Both the ammeter and voltmeter should read non-zero values. If the measured current is below the current rating of a more sensitive scale, open the knife switch, move the connection to the more sensitive scale, and tap the knife switch closed to test the new scale. Use the most sensitive current scale that can handle the current safely (reading stays on-scale).
Data collection

1. Make at least ten different measurements of the voltage and corresponding current by adjusting the rheostat between its minimum and maximum resistance. To obtain data points at low currents, you can lower the voltage supplied to the circuit by the power supply to some value less than 5 V. Ask your TA for help as necessary.
2. How does the current measured by the ammeter change if the ammeter is connected between the power supply and the rheostat instead of between the rheostat and the resistor? What if it is connected between the power supply and the switch? Verify your answers experimentally.

Data analysis

1. Draw a graph of the voltage across the nominal 100 Ω resistor as a function of the corresponding current flowing through it.
2. Is the graph linear? Draw a best fit smooth line through your data points, and from your graph find an equation for $\Delta V$ as a function of $I$ in SI units.
3. Does the resistor exhibit ohmic behavior? Explain your reasoning. If so, what is the “real” value of the resistance? How does your value compare to the nominal 100 Ω value indicated by the “color code” painted on it?

Current versus voltage for an incandescent light bulb

Equipment set up

Caution: Be sure to leave the switch open while you construct the new circuit. Before closing the switch, have your TA check your circuit.

1. Build a circuit analogous to the one in Figure 1, but use the 22 Ω rheostat instead of the 340 or 360 Ω one used above and replace the 100 Ω resistor with the small light bulb.
2. Use the highest current scale on the ammeter to begin with. You can always change to a more sensitive scale if the measured current is low enough.
3. Make sure that the power supply is still set to 5 volts.

Data collection

1. Make at least ten different measurements of the voltage and corresponding current by adjusting the rheostat between its minimum and maximum resistance.
2. Does current flow through the light bulb even when the bulb is not glowing? Be sure to take data over the full range of possible values, whether the bulb glows or not.

Data analysis

1. Make a graph of the voltage difference between the light bulb terminals as a function of current. What is the current flowing through the light bulb if the voltage across it is zero? Be sure to plot this point on your graph!
2. Is the light bulb ohmic? Explain your reasoning. If so, what is its resistance? If not, what are the minimum and maximum values of its resistance?

3. What is the maximum power dissipated by the light bulb? (This power is dissipated primarily in the form of heat, but some also appears in the form of visible light.) What is the power dissipated by the bulb when it first begins to glow?

**Summary**

Compare and contrast the electrical behavior of the resistor and the light bulb. Consult a textbook and try learn why the light bulb exhibits a more complicated behavior than the resistor. Explain this in your notes.

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to analyze the experiment and recommend improvements</td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report</td>
<td>Description of experimental procedure leaves it unclear what could be improved upon.</td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed.</td>
<td>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.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SL.B.b</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to explain patterns in data with physics principles</td>
<td>No attempt is made to explain the patterns in data</td>
<td>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.</td>
<td>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.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CT.A.a</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to compare recorded information and sketches with reality of experiment</td>
<td>No sketches present and no descriptive text to explain what was observed in experiment</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>CT.B.a</td>
<td>Is able to describe physics concepts underlying experiment</td>
<td>No explicitly identified attempt to describe the physics concepts involved in the experiment using student’s own words.</td>
<td>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.</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------</td>
<td>------------------------------------------------</td>
<td>-----------------------------------------------------------------</td>
</tr>
<tr>
<td>QR.A</td>
<td>Is able to perform algebraic steps in mathematical work.</td>
<td>No equations are presented in algebraic form with known values isolated on the right and unknown values on the left.</td>
<td>Some equations are recorded in algebraic form, but not all equations needed for the experiment.</td>
</tr>
<tr>
<td>QR.B</td>
<td>Is able to identify a pattern in the data graphically and mathematically</td>
<td>No attempt is made to search for a pattern, graphs may be present but lack fit lines.</td>
<td>The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented.</td>
</tr>
<tr>
<td>IL.A</td>
<td>Is able to record data and observations from the experiment</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes.&quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc.&quot;</td>
</tr>
<tr>
<td>No Effort</td>
<td>Progressing</td>
<td>Expectation</td>
<td>Scientific</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>WC.B</strong></td>
<td>No graph is present.</td>
<td>A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected.</td>
<td>&quot;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. &quot;</td>
</tr>
<tr>
<td>Is able to draw a graph</td>
<td>Labs: 3, 6, 9, 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WC.D</strong></td>
<td>No circuit diagram is drawn.</td>
<td>Components of the circuit are missing, or connected incorrectly. Components are not clearly labelled.</td>
<td>&quot;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. &quot;</td>
</tr>
<tr>
<td>Is able to draw a circuit diagram</td>
<td>Labs: 3, 4, 9, 10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lab 3 Ohm’s Law

Name: ____________________________ Lab Partner: ____________________________

### EXIT TICKET:
- [ ] Turn off the power to all the equipment. ESPECIALLY the multimeter.
- [ ] Disassemble the circuit and place the make sure wires are not tangled.
- [ ] 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

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>CT.B.a</th>
<th>IL.A</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL.B.b</td>
<td>QR.A</td>
<td>WC.B</td>
</tr>
<tr>
<td>CT.A.a</td>
<td>QR.B</td>
<td>WC.D</td>
</tr>
<tr>
<td></td>
<td>QR.C</td>
<td></td>
</tr>
</tbody>
</table>

---

Lab 3 Ohm’s Law

Name: ____________________________ Lab Partner: ____________________________

### EXIT TICKET:
- [ ] Turn off the power to all the equipment. ESPECIALLY the multimeter.
- [ ] Disassemble the circuit and place the make sure wires are not tangled.
- [ ] 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

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>CT.B.a</th>
<th>IL.A</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL.B.b</td>
<td>QR.A</td>
<td>WC.B</td>
</tr>
<tr>
<td>CT.A.a</td>
<td>QR.B</td>
<td>WC.D</td>
</tr>
<tr>
<td></td>
<td>QR.C</td>
<td></td>
</tr>
</tbody>
</table>
Lab 4. Series and Parallel Resistors

Goals

• To understand the fundamental difference between resistors connected in series and in parallel.
• To calculate the voltages and currents in simple circuits involving only resistors using the rules for “adding” series and parallel resistors.
• To learn to connect components correctly according to a circuit diagram and then to make valid current and voltage measurements with ammeters and voltmeters.
• To compare the predicted and measured currents and voltages for three circuits.

Introduction

Circuits are often composed of multiple components connected in various ways. Two general configurations that recur again and again are the so-called “series” and “parallel” combinations. Many resistor networks can be broken down into these simple units. For the sake of the following discussion, assume that the terminals of each resistor are labeled Terminal 1 at one end and Terminal 2 at the other end. (which end is which is unimportant, so long as you remain consistent)

A “series” connection is when Terminal 2 of one resistor is connected to Terminal 1 of the next resistor and so on. This is like adding lengths of garden hose to reach the far corner of the yard. A battery or power supply is connected between Terminal 1 of the first resistor in the chain and Terminal 2 of the last resistor in the chain. Just like the water hose, where water flows into one end of the hose at the same rate as water flows out of the other end, the same electrical current (charge flow) flows through each of the resistors connected in series. It is important to note that in series connections, no other electrical connections can be made anywhere along the chain to add more current or take some away. If extra connections are present, even though the resistors may appear to be in a chain, our assumptions are invalid and the circuit is no longer a simple series combination. It is straightforward to show that resistances connected in series can be summed together to get the total resistance of the whole chain. In other words

\[ R_{total} = R_1 + R_2 + R_3 + R_4 + ... \] (4.1)

A “parallel” connection is when all of the Terminal 1’s of several resistors are connected together. Likewise, all of the Terminal 2’s are connected together. A battery or power supply is then con-
nected between the combined Terminal 1 and the combined Terminal 2. In this case the applied voltage (“pressure” if you will) across each resistor is the same. Using this observation it again is possible to show that the total resistance of such a parallel combination is

\[
\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \ldots
\]  

(4.2)

Simple series and simple parallel resistor configurations

\[
\begin{align*}
\text{Switch} & \quad 3 \text{ V} \\
& \quad 10 \Omega \\
& \quad 3 \Omega
\end{align*}
\]

(a) Circuit 1.

\[
\begin{align*}
\text{Switch} & \quad 3 \text{ V} \\
& \quad 12 \Omega \\
& \quad 30 \Omega \\
& \quad 20 \Omega
\end{align*}
\]

(b) Circuit 2.

Figure 4.1. Diagrams of (a) series and (b) parallel circuits for study.

Analyze Circuits 1 and 2

Answer the following questions for both Circuits 1 and 2. Refer to the Ohm’s Law lab if you cannot remember the equations needed. Be sure to explain your reasoning and show your calculations in your notes! You ought to summarize your numerical results in a table such as that show before the rubrics for this lab.

1. Which circuit contains the series combination and which the parallel combination?
2. What is the value of current through each resistor?
3. What is the voltage across each resistor?
4. What is the total current flowing through the power supply into the entire circuit?
5. What is the power dissipated (as heat) in each resistor? If any value exceeds 2 W, talk with your TA before proceeding to the next step.

Construct and study Circuits 1 and 2

Caution: Set the power supply to 3 V before connecting it to your circuit!

Before you attempt to construct your circuit, draw a copy of the circuit diagram and label terminal 1 and 2 for each resistor. Then draw the board of resistors provided to you, and indicate on that picture how you will make connections. This can help greatly, as once you get a lot of wires crossing one another it can become difficult to compare what is physically happening to the very simple circuit diagrams.
Initially, connect the circuit without any meters present, verify your configuration, then plan where you will connect the ammeter and voltmeter. Be sure you are confident that each meter will measure the component you are interested in only.

1. Measure the current through each resistor, showing on a circuit diagram exactly how and where the ammeter is connected in the circuit for each of the measurements.
2. Measure the voltage across each resistor, showing on a circuit diagram exactly how and where the voltmeter is connected in the circuit for each of the measurements.
3. Measure the total current flowing through the circuit, showing on a circuit diagram exactly how and where the ammeter is connected in the circuit.
4. Measure the total voltage across the whole circuit, showing on a circuit diagram exactly how and where the voltmeter is connected in the circuit.

**Compare measured and predicted potential differences and currents**

Compare your calculated and measured values using table at the end of the lab. (Remove this table from the manual and turn it in with your lab notes.) Percent differences are a good way to compare. Note whether the measured values are larger or smaller than the calculated ones. This is a good way to determine whether the differences are due to a systematic error or to some random process. If all the calculated values are larger than the measured ones, this suggests a systematic error, perhaps due to an non-ideal measuring device. If some values are a little high and others are a little low, the cause of variation is more likely to be random, such as variations in reading the meters.

Use these results to address the following questions. Explain your reasoning and justify your conclusions based on your data.

1. How are the currents through each resistor related to the total current flowing through the power supply in a series circuit? Look for a general rule that will apply to all series circuits.
2. How are the voltages across each resistor related to the total voltage across the power supply in a series circuit? Look for a general rule that will apply to all series circuits.
3. How are the currents through each resistor related to the total current flowing through the power supply in a parallel circuit? Again, look for a general rule that will apply to all parallel circuits.

**Combined series and parallel configuration of resistors**

Calculate, then measure the potential differences across and currents through each component in Circuit 3.
CHAPTER 4. SERIES AND PARALLEL RESISTORS

Resistor Color Code

Figure 4.2. Diagram of Circuit 3.

Figure 4.3. Resistor with labeled bands. To read the bands in order, orient the resistor so that the tolerance band (which is all by itself) is on the right. If the first band is red (2), the second violet (7), and the third green (10^5), the resistance is 27 \times 10^5 ohms or 2.7 M\Omega. If the tolerance band is gold, the actual resistance of a new resistor may differ from the indicated value by ±5%. Exceeding the current rating of a resistor can destroy it or change its resistance permanently. Image courtesy of Wikipedia (public domain).
### Color Code Table

<table>
<thead>
<tr>
<th>Color</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>Band 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>0</td>
<td>0</td>
<td>$10^0$</td>
<td>1</td>
</tr>
<tr>
<td>Brown</td>
<td>1</td>
<td>1</td>
<td>$10^1$</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>2</td>
<td>2</td>
<td>$10^2$</td>
<td></td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
<td>3</td>
<td>$10^3$</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
<td>4</td>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
<td>5</td>
<td>$10^5$</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>6</td>
<td>6</td>
<td>$10^6$</td>
<td></td>
</tr>
<tr>
<td>Violet</td>
<td>7</td>
<td>7</td>
<td>$10^7$</td>
<td></td>
</tr>
<tr>
<td>Gray</td>
<td>8</td>
<td>8</td>
<td>$10^8$</td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>9</td>
<td>9</td>
<td>$10^9$</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td></td>
<td></td>
<td>$10^{-1}$</td>
<td>±5%</td>
</tr>
<tr>
<td>Silver</td>
<td></td>
<td></td>
<td>$10^{-2}$</td>
<td>±10%</td>
</tr>
<tr>
<td>No Color</td>
<td></td>
<td></td>
<td></td>
<td>±20%</td>
</tr>
</tbody>
</table>
## Series and Parallel Resistors Data Sheet

### Circuit 1 — Series Resistors

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Measured</th>
<th>%Difference</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{total} = ___ \ \Omega$</td>
<td>$\Delta V_{total} (V)$</td>
<td>$I_{total} (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_1 = 10 \ \Omega$</td>
<td>$\Delta V_1 (V)$</td>
<td>$I_1 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_2 = 3 \ \Omega$</td>
<td>$\Delta V_2 (V)$</td>
<td>$I_2 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_3 = 15 \ \Omega$</td>
<td>$\Delta V_3 (V)$</td>
<td>$I_3 (A)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Circuit 2 — Parallel Resistors

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Measured</th>
<th>%Difference</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{total} = ___ \ \Omega$</td>
<td>$\Delta V_{total} (V)$</td>
<td>$I_{total} (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_1 = 12 \ \Omega$</td>
<td>$\Delta V_1 (V)$</td>
<td>$I_1 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_2 = 30 \ \Omega$</td>
<td>$\Delta V_2 (V)$</td>
<td>$I_2 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_3 = 20 \ \Omega$</td>
<td>$\Delta V_3 (V)$</td>
<td>$I_3 (A)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Circuit 3 — Combined Series and Parallel Resistors

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Measured</th>
<th>%Difference</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{total} = ___ \ \Omega$</td>
<td>$\Delta V_{total} (V)$</td>
<td>$I_{total} (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_1 = 10 \ \Omega$</td>
<td>$\Delta V_1 (V)$</td>
<td>$I_1 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_2 = 24 \ \Omega$</td>
<td>$\Delta V_2 (V)$</td>
<td>$I_2 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_3 = 30 \ \Omega$</td>
<td>$\Delta V_3 (V)$</td>
<td>$I_3 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_4 = 3 \ \Omega$</td>
<td>$\Delta V_4 (V)$</td>
<td>$I_4 (A)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_5 = 12 \ \Omega$</td>
<td>$\Delta V_5 (V)$</td>
<td>$I_5 (A)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### SL.A.b
Is able to identify the hypothesis for the experiment proposed

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No deliberately identified hypothesis is present in the first half page or so of notes.</td>
<td>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.</td>
<td>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.</td>
<td>The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader.</td>
</tr>
</tbody>
</table>

### SL.A.c
Is able to determine hypothesis validity

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection.</td>
<td>A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment.</td>
<td>A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account.</td>
<td>A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account.</td>
</tr>
</tbody>
</table>

### CT.A.a
Is able to compare recorded information and sketches with reality of experiment

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No sketches present and no descriptive text to explain what was observed in experiment.</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
</tr>
</tbody>
</table>

### CT.A.b
Is able to identify assumptions used to make predictions

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No 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.</td>
<td>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.</td>
<td>Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction.</td>
<td>Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made.</td>
</tr>
<tr>
<td>CT.A.c</td>
<td>Is able to make predictions for each trial during experiment</td>
<td>Multiple experimental trials lack predictions specific to those individual trial runs.</td>
<td>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.</td>
</tr>
<tr>
<td>CT.A.d</td>
<td>&quot;Is able to identify sources of uncertainty&quot;</td>
<td>descworst</td>
<td>An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect.</td>
</tr>
<tr>
<td>QR.C</td>
<td>Is able to analyze data appropriately</td>
<td>No attempt is made to analyze the data.</td>
<td>An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate.</td>
</tr>
<tr>
<td>IL.A</td>
<td>Is able to record data and observations from the experiment</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes.&quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc.&quot;</td>
</tr>
<tr>
<td>WC.A</td>
<td>Is able to create a sketch of important experimental setups</td>
<td>No sketch is constructed.</td>
<td>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.</td>
</tr>
<tr>
<td>WC.D</td>
<td>No Effort</td>
<td>Progressing</td>
<td>Expectation</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Is able to draw a circuit diagram</td>
<td>No circuit diagram is drawn.</td>
<td>Components of the circuit are missing, or connected incorrectly. Components are not clearly labelled.</td>
<td>&quot;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.&quot;</td>
</tr>
<tr>
<td>Labs: 3, 4, 9, 10</td>
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</tbody>
</table>
Lab 4 Series and Parallel Resistors

Name: ____________________________  Lab Partner: ____________________________

EXIT TICKET:

☐ 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

<table>
<thead>
<tr>
<th>SL.A.b</th>
<th>CT.A.b</th>
<th>IL.A</th>
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<tbody>
<tr>
<td>SL.A.c</td>
<td>CT.A.c</td>
<td>WC.A</td>
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<td>CT.A.a</td>
<td>CT.A.d</td>
<td>WC.D</td>
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Lab 4 Series and Parallel Resistors

Name: ____________________________  Lab Partner: ____________________________

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Lab 5.  Magnetic Fields

Goals

- To visualize the magnetic fields produced by several different configurations of simple bar magnets using iron filings.
- To use small magnetic compasses to trace out the magnetic field lines of a single bar magnet on a large sheet of paper.
- To calculate the magnetic flux passing through the bar magnet by determining the locations of the points where the magnetic fields of the Earth and the bar magnet sum to zero.

Introduction

A magnetic field exerts forces on a compass needle (a small magnet) such that the needle tends to align itself with the direction of the field. If the magnetic field is strong enough and additional non-magnetic forces (gravity, etc.) are negligible, then the compass needle points for all practical purposes in the direction of the field. In this lab the magnetic fields surrounding bar magnets are mapped out using a compass and iron filings.

The end of your compass needle that points toward the magnetic pole of the Earth in the northern hemisphere (when it is far away from other magnets and magnetic materials) is by definition a N (north-seeking) pole. Therefore Earth’s magnetic pole in northern Canada is actually an S pole, since the N pole of the compass points to it and unlike poles attract. The N pole of the compass needle points toward the S pole of your magnet. The magnetic poles of all magnets can thus be labeled by means of a compass and the definition of an N pole.

Keep cell phones, credit cards, mechanical watches, etc. away from the big magnet on the TA table. Keep compasses at least 20 cm away from big magnet. The big magnet is used to “remagnetize” the bar magnets used in this laboratory. This can become necessary if the bar magnets are dropped or get too close to other magnets. If the poles are reversed on your bar magnet, or it is unusually weak, ask your teaching assistant to remagnetize it.

Mapping magnetic fields with iron filings

In the presence of a magnetic field, iron filings act like many small compass needles. By spreading them out on the paper above the magnet a “picture” of the magnetic field is produced. At your lab station you have a piece of particle board with some grooves in it to hold the bar magnets.
Do not pick up iron filings with the magnet. The filings are difficult to remove from the magnet. Place the jar on a clean piece of paper and open the lid. Filings often will spill out from under the lid. Gently lift the paper with filings off of the magnet. Let the paper sag to make a funnel of sorts, and then pour the filings into the jar. Then replace the jar cover.

Sketch field lines for isolated bar magnet

Draw a full scale outline of the bar magnet on fresh piece of paper and label the N and S poles. Place the bar magnet in the middle groove of the particle board and cover it with a second piece of white paper. Sprinkle iron filings around on the surface of this second sheet of paper. Gently tapping the board will often make the pattern of field lines more clear. Now on the first sheet of paper, with the outline of the bar magnet already drawn, make a careful free hand sketch of the magnetic field lines shown by the iron filings. On your sketch include the direction of the field lines by means of arrows. By convention the field lines outside the magnet itself go from the N pole to the S pole. Each member of your lab group is expected to draw their own sketch.

Sketch field lines for more complex configurations

Now repeat this process for the following configurations of bar magnets. In each case sketch the magnetic field lines and indicate the direction of the field lines everywhere on your sketch.

1. Place two bar magnets end-to-end in the same groove along the middle of the particle board with their N poles 2-3 centimeters apart.
2. Place two bar magnets side by side in parallel grooves with either like poles near or unlike poles near each other.
3. Pick another configuration of your choice. Ensure at least a 2-3 cm gap between any magnets in a common groove.

Analyze your drawings

1. Describe the general characteristics of the fields that you observe.
2. On your sketches label the regions where the magnetic field is especially strong and where it is especially weak for each configuration. Are there any points where the field is essentially zero? Identify these locations clearly as well. Include the reasoning you use to identify these regions of strong and weak fields.
3. Can you find any places where the magnetic field lines cross? If there were a point in space where two field lines crossed, what would the direction of the field be at that point? If magnetic fields from two different sources are present at some point in space—for instance, the magnetic fields of Earth and the bar magnet—will some iron filings feel forces from one field and other filings feel forces from the other field, or will all filings feel forces from both fields simultaneously? Discuss/explain.
CHAPTER 5. MAGNETIC FIELDS

Mapping a magnetic field with a compass

Equipment set up

1. Tape a large sheet of paper to the hardboard sheet (area about 1 m²) located at your lab station. Orient a bar magnet at the center of the sheet as directed by your TA.
2. Carefully outline the bar magnet and mark the orientation of its magnetic poles on the sheet of paper.

Map the field

1. You can start your map anywhere in principle, but let’s start with a point about 10 cm from the center of the magnet. Place the compass on your paper. Use a non-magnetic pencil (Check this carefully!) to put dots on the paper at the tip and tail of the arrow of the compass.
2. Now move the compass (approximately one diameter) so that the tail of the arrow is at the point where the tip was previously. Put a dot at the location of the tip of the arrow. Repeat this procedure until you move off the edge of the paper or run into the magnet itself.
3. To complete the field line in the other direction go back to the initial position, but this time move the compass so that the tip of the arrow is where the tail was previously. This time put a dot at the location of the tail of the arrow and repeat.
4. Connect all the dots with a smooth curve. This now constitutes one magnetic field line. Before proceeding put arrows on the line to indicate which way the magnetic field is pointing.
5. Choose a new starting point and repeat the procedure until you have filled your paper with field lines. Check with your TA to make sure that you have sufficiently mapped the field.

Analyze your map

1. Are there any regions on the map that the field lines seem to avoid? What is the magnetic field at these points? Explain your reasoning. How many such points are there on your map?
2. Look at the magnetic field maps drawn by the other lab groups in your lab section. Each map has been made with the bar magnet in a different orientation. Sketch simple halfpage diagrams of these other map configurations to include with your lab notes. Do these other maps have any features in common with your map? How do they differ from your map? Explain.

Calculating the magnetic flux of the magnet

When a magnet is immersed in the Earth’s magnetic field, the resulting field is the vector sum of the magnet’s field and Earth’s field. In regions where the magnet’s field is larger than Earth’s field, a compass aligns itself more with the magnet’s field. In regions where Earth’s field dominates, a compass aligns more with Earth’s field.

You should be able to see this effect on your magnetic field map. As you move away from the bar magnet and its field gets weaker, Earth’s field, which is essentially constant everywhere on your
map, begins to dominate. Use your knowledge of the magnetic field due to a bar magnet alone to predict the direction of the field due to only the bar magnet at the “special” point(s) that field lines have avoided. Note the direction of Earth’s magnetic field at this same “special” point. This result suggests that the sum of the fields from the bar magnet and the Earth cancel at this point, summing to zero net field. Look at the other map configurations to determine whether this seems to be a general result.

Magnetic field lines exit the N pole of the magnet, circle around, enter the S pole of the magnet, and return through the magnet to the N pole. Since magnetic charges have never been observed, we can safely assume that every field line observed outside the magnet passes through the magnet itself. A useful measure of the strength of a magnet is the magnitude of the magnetic flux, \( \Phi_{\text{bar}} \), passing through the magnet. This flux equals the product of the average magnetic field inside the magnet and its cross sectional area.

The pattern of magnetic field lines outside a magnet looks much like the pattern of electric fields lines from an electric dipole. That is, the vector sum of a radially outward field from a N pole and a radially inward field into a S pole will circle around from the N pole to the S pole outside the magnet, as observed. The critical difference between magnetic and electric dipoles is that the magnetic field lines complete the circuit through the magnet, running from the S pole to the N pole. In addition, the N and S poles are not right at the ends of the physical magnet. A sketch of the relation between a “fat” physical magnet and the ideal, thin magnet used to model it is shown in Figure 5.1. Although the magnetic field is only approximated by the dipole field, the approximation is quite good at positions far from the magnet.

![Figure 5.1. Sketch of the magnetic field due to an ideal, infinitely thin permanent magnet. The thick dark line represents the ideal magnet, while the dotted line outlines the corresponding physical magnet.](image)

We will use this approximation to determine the magnetic flux of the bar magnet. That is, we will treat the magnetic field outside the magnet, \( \mathbf{B}_{\text{bar}} \), as the sum of a vector directed away from the N pole, \( \mathbf{B}_N \), and another vector directed into the S pole, \( \mathbf{B}_S \).

\[
\mathbf{B}_{\text{bar}} = \mathbf{B}_N + \mathbf{B}_S ,
\]

1The image of the field lines, without the magnets, was supplied by the Wikimedia Commons.
where $B_N$ and $B_S$ vary with distance like electric fields (Coulomb’s law). In the case of magnets, however, the source of these fields are the magnetic fluxes leaving the N pole and entering the S pole. At distances far from the poles, the equation for the magnetic field due to one pole can be obtained from Coulomb’s law by replacing $q/\varepsilon_0$ with $\Phi_{BAR}$. (The total electric flux from a positive point charge is $q/\varepsilon_0$ by Gauss’s Law.)

$$
B_N = \frac{\Phi_{BAR}}{4\pi r_N^2} \{\text{Pointing radially away from the north pole}\}, \quad \text{and}
$$

$$
B_S = \frac{\Phi_{BAR}}{4\pi r_S^2} \{\text{Pointing radially away from the south pole}\}.
$$

Figure 5.2 shows a typical null point and the vectors $B_N$ and $B_S$ showing the contribution of the magnet’s N and S poles to the magnetic field at the null point. In the equations and the diagram, $r_N$ is the distance from the N pole of the magnet to the null point and $r_S$ is the distance from the S pole of the magnet to the null point. Since the magnetic field is a vector quantity we must be careful to add the fields associated with the N and S poles as vectors.

![Diagram of a coordinate system with its origin at a null point and with its +x-axis pointing in the direction of the Earth’s magnetic field vector, $B_{Earth}$](image)

On the magnetic field map you made with a compass, choose one of the special “null” points where the magnetic fields of Earth and the bar magnet cancel one another. Earth’s magnetic field actually
points downward at an angle of about 70° relative to the surface of Earth at the latitude of Pullman, but the magnetic field map you have drawn lies only in a horizontal plane. Further, our compasses are constrained to rotate only about a vertical axis, so they respond only to the horizontal (parallel to Earth’s surface) component of Earth’s magnetic field. In other words the magnetic field of the bar magnet cancels only the horizontal component of Earth’s field at a null point. That is,

\[ B_N + B_S + B_{\text{Earth}} = 0 \quad \{ \text{horizontal component only} \} \] (5.3)

at a null point. The magnitude of the horizontal component of Earth’s field is \(1.9 \times 10^{-5}\) T here at Pullman. Show the direction of Earth’s field on your map at your null point. Now you know the horizontal component of \(B_{\text{Earth}}\) (both direction and magnitude) at the null point. Define a coordinate system with its origin at the null point and with the positive \(x\)-axis in the direction of Earth’s magnetic field at the null point, as shown in Figure [5.2]. Draw this coordinate system directly on your field map. This choice of coordinate system simplifies the equations so that we only need to look at the \(x\)-components of \(B_N\) and \(B_S\). Then you can draw radial lines from the N and S poles of the bar magnet to the null point. The lengths of these lines give you \(r_N\) and \(r_S\). After measuring the angles \(\theta_N\) and \(\theta_S\) (shown in Figure [5.2]), you can calculate the \(x\)-components of the magnetic fields associated with \(B_N\) and \(B_S\) in terms of \(\Phi_{\text{BAR}}\). Since \(\Phi_{\text{BAR}}\) is the only remaining unknown, you can complete the solution.

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to analyze the experiment and recommend improvements</td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report</td>
<td>Description of experimental procedure leaves it unclear what could be improved upon.</td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed.</td>
<td>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.</td>
</tr>
<tr>
<td>Labs: 1-3, 5, 7, 9, 11, 12</td>
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</table>

<table>
<thead>
<tr>
<th>SL.A.b</th>
<th>No deliberately identified hypothesis is present in the first half page or so of notes</th>
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<th>No deliberately identified hypothesis is present in the first half page or so of notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to identify the hypothesis for the experiment proposed</td>
<td>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</td>
<td>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.</td>
<td>The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader.</td>
<td>The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader.</td>
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<tr>
<td>Labs: 4-6</td>
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<tr>
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<td>Progressing</td>
<td>Expectation</td>
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<tr>
<td><strong>SL.A.c</strong> Is able to determine hypothesis validity</td>
<td>No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection.</td>
<td>A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment.</td>
<td>A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account.</td>
<td></td>
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<tr>
<td>Labs: 4-6</td>
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</table>

| **SL.B.b** Is able to explain patterns in data with physics principles | 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. | A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit. |
| Labs: 1-3, 5, 7-11 | | | |

| **CT.A.b** Is able to identify assumptions necessary for making predictions | No attempt is made to identify any assumptions necessary for making predictions | 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. |
| Labs: 4-6 | | | |

| **CT.A.c** Is able to make predictions for each trial during experiment | 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. | 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. |
| Labs: 4-6 | | | |

<p>| <strong>CT.B.a</strong> Is able to describe physics concepts underlying experiment | 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 physics concepts underlying the experiment are clearly stated. |
| Labs: 1-3, 5, 7-9, 12 | | | |</p>
<table>
<thead>
<tr>
<th>QR.B</th>
<th>No attempt is made to search for a pattern, graphs may be present but lack fit lines.</th>
<th>The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented.</th>
<th>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.</th>
<th>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.</th>
</tr>
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<tbody>
<tr>
<td>IL.A</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes.&quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc.&quot;</td>
<td>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.</td>
<td>All necessary data has been recorded throughout 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.</td>
</tr>
<tr>
<td>WC.A</td>
<td>No sketch is constructed.</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
</tr>
</tbody>
</table>
Lab 5 Magnetic Fields

Name: ________________________  Lab Partner: ________________________

EXIT TICKET:

☐ Return the bar magnet(s) to the TA Table.
☐ Put your rulers, compasses, and iron filings in the basket at your workstation.
☐ 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.a  SL.B.b  QR.B
SL.A.b  CT.A.b  IL.A
SL.A.c  CT.A.c  WC.A
CT.B.a

Lab 5 Magnetic Fields

Name: ________________________  Lab Partner: ________________________

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

SL.A.a  SL.B.b  QR.B
SL.A.b  CT.A.b  IL.A
SL.A.c  CT.A.c  WC.A
CT.B.a
Lab 6. Current Balance

Goals

• To explore and verify the right-hand rule governing the force on a current-carrying wire immersed in a magnetic field.
• To determine how the force on a current-carrying wire depends on its length, the strength of the magnetic field, and the magnitude of the current flowing in the wire, and to display the relationships graphically.

Introduction

Electric charges can experience a force when they move through a region of nonzero magnetic field. Stationary charges experience no force. Since currents are just electric charges in motion, current carrying wires can also experience forces when immersed in magnetic fields. The magnitude of the force $F$ on a straight wire of length $L$ carrying a current $I$ in the presence of a uniform magnetic field of strength $B$ is given by

$$F = ILB \sin \theta$$

(6.1)

where $\theta$ is the angle between the direction of positive current flow and the magnetic field. The direction of the resulting force is determined by applying the “right-hand rule” as shown in your textbook. In this experiment the angle $\theta$ between the wire and the magnetic field is always 90° so that $\sin \theta = 1$.

The purpose of this experiment is to measure the force on a current carrying wire in the presence of a magnetic field and to determine how this force depends on magnetic field strength, current, and wire length. You should also be able to apply the right hand rule to predict the direction of the force on a current carrying wire in a magnetic field.

Caution: The load limit for these electronic balances is 200 grams. Use appropriate care to make sure that this limit is not exceeded.
Right Hand Rule

For the right hand rule, it is vital to use the appropriate hand. Or to remember that your result is reversed if you must use your left. There are two versions of the right hand rule which are useful in electromagnetic interactions. (Descriptions and images via Buffalo State)

**Right Hand Rule 1**

Right-Hand Rule 1 determines the directions of magnetic force, conventional current and the magnetic field. Given any two of these, the third can be found.

Using your right-hand: point your index finger in the direction of the charge’s velocity, v, (recall conventional current).

Point your middle finger in the direction of the magnetic field, B.

Your thumb now points in the direction of the magnetic force, \( F_{\text{magnetic}} \).

You can change which vector is represented by each finger, so long as you keep them in the same order (So it can be F->I->B, or I->B->F, or B->F->I).

**Right Hand Rule 2**

Right-Hand Rule 2 determines the direction of the magnetic field around a current-carrying wire and vice-versa.

Using your right hand: Curl your fingers into a half-circle around the wire, they point in the direction of the magnetic field, B.

Point your thumb in the direction of the conventional current.

Application this week

For each charge flowing through your wire, the Right Hand Rule applies as shown (Image via Khan Academy)

**Force versus wire length**

**Equipment set up**

1. Using all six of the small magnets, place the magnets and magnet holder on the electronic balance and tare the balance. The “red ends” of the small magnets are N poles. The “white ends” are S poles. It is a good idea to check the direction of the magnetic field just above the
CHAPTER 6. CURRENT BALANCE

gap with a compass. Make certain that all the magnets are oriented with the same polarity so that the magnetic field is maximized.

2. Plug circuit sf37 into the ends of the shiny metal bars of the current balance apparatus mounted on the stand. (sf37 is the manufacturer’s designation and has no other purpose than to identify it.)

3. With the power supply off, connect the red and black jacks on the front of the power supply to the current balance apparatus using the holes provided on the tops of the metal bars of the apparatus.

4. Before turning on the power supply, adjust the “Coarse” voltage knob and the “Current” knob to their full counter-clockwise positions.
   • If your power supply does not have a digital display: Adjust the “Fine” voltage knob to the middle of its range, with the white mark pointing vertically upward. Set the current switch to the “Hi” position. In this position, the ammeter on the front of the power supply reads on the 0–3 A scale.

Analysis of forces on wire and balance

1. Draw a free-body diagram of the magnets and magnet holder in equilibrium on the balance with no current flowing through the circuit.

2. Draw another free-body diagram of the magnets and magnet holder in equilibrium when current is present in the wire that is between the poles of the magnet. You must apply the right-hand rule in conjunction with the magnetic force equation given earlier to determine the direction of the magnetic force on the wire. Make sure that your diagram and explanation are very clear here. Remember that, by convention, the magnetic field outside the magnet itself points from the N pole to the S pole. Also recall that current flows out of the red (+) terminal of the power supply and into the black (–) terminal.

3. On the basis of your free-body diagrams predict whether the electronic balance will read a positive value or a negative value.

Force measurements

1. Position the bottom of the U-shaped “wire” on sf37 so that it is centered between the poles of the magnet sitting on the electronic balance. Align sf37 carefully so that it is not touching the magnet holder anywhere. You may need to tare the balance again at this point before turning on the power supply.

2. Turn on the power supply and adjust the current knob clockwise until the ammeter reads 2 A. Check this from time to time during the rest of this exercise since the current sometimes can drift small amounts as the power supply warms up.

3. Compare and comment on the sign of the reading on the balance. If you didn’t get it right the first time, go back and rethink it. Explain in your report how you went wrong and give a corrected explanation.

4. Record the balance readings for sf37, sf38, sf41, and sf42 keeping the current set at 2 A.

5. For sf42 only, reverse the direction of the current by switching the connections to the black and red terminals on the power supply. What happens to the reading given by the electronic balance? What did you expect to happen? Explain.
Data analysis

Convert all the balance readings from mass units to forces in newtons. For each of the circuits, sf37, sf38, sf41, and sf42, measure the effective length of the wire that was immersed in the magnetic field and produced a net force on the magnet. Plot the force on the magnet as a function of the length of the wire immersed in the magnetic field. If appropriate, fit a straight line to the data and calculate the magnetic field in tesla (T) for all six magnets. Refer back to the force law described above for help here.

Force versus strength of magnetic field

Equipment set up

1. Plug circuit sf41 into the ends of the current balance apparatus.
2. The manufacturer assures us that the magnetic field between the poles of the magnet is directly proportional to the number of small magnets used. You have already made a measurement with sf41 and six small magnets. Now remove one of the small magnets, leaving five. Center the five magnets relative to the magnet poles.
3. Align the wire of sf41 relative to the magnet poles as done previously.

Force measurements

1. Set the power supply current to 2 A.
2. Record the balance reading when current is passed through the wire. Be sure to tare the electronic balance appropriately.
3. Remove one magnet at a time and repeat the measurement. You should have six data points counting your measurement with sf41 during your study of force versus wire length.

Data analysis

Make a graph of the magnetic force as a function of the number of magnets. Based on your graph what can you say about the relationship between the force and the value of the magnetic field? If it is linear, find the slope of the graph and calculate the magnetic field of all six magnets again. Remember that the field of all six magnets is simply six times greater than the field of a single magnet.

Force versus current

Equipment set up

1. Replace all the magnets, making sure that all the red poles and white poles are aligned correctly.
2. Plug sf42 into the ends of the current balance apparatus.
3. Set the current from the power supply at 3 A.
CHAPTER 6. CURRENT BALANCE

Force measurements

1. Record the balance reading when current is passed through the wire between the poles of the magnet.
2. Lower the current to 2.5 A and repeat the measurement.
3. Continue reducing the current in 0.5 A increments until you reach 0.5 A. Record the balance reading in each case.

Data Analysis

Plot the magnetic force on sf42 as a function of the current. What can you say about the relationship between force and current? From this analysis you should be able to calculate the magnetic field with all the small magnets present. This calculated magnetic field should agree with the magnetic field value calculated from your measurements of force versus wire length and force versus magnetic field strength. Does it? Compare, discuss, and explain.

Conclusion

The fundamental magnetic force law for current carrying wires in magnetic fields given in the Introduction makes certain predictions about the dependence of the force on the current, wire length, and the magnetic field. Are your findings in harmony with the force law as formulated? Be very specific here and speak to the results of each set of measurements. If not in harmony, explain specifically in what way your results differ.

It is important to remember that the force law as formulated actually was induced from experiments like those you have done today. Thus the law as stated just characterizes how nature behaves; it doesn’t prescribe beforehand how nature must behave. Nature behaves however she wishes, and we can only hope to characterize that behavior in simple ways from time to time. Of course, we often express these characterizations in mathematical terms, the shorthand of science.
<table>
<thead>
<tr>
<th>SL.A.c</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to determine hypothesis validity</strong></td>
<td>No deliberately identified attempt to use experimental results to validate hypothesis is present in the sections following data collection.</td>
<td>A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment.</td>
<td>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.</td>
<td>A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account.</td>
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</table>

<table>
<thead>
<tr>
<th>SL.B.c</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able.</strong></td>
<td>No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present</td>
<td>No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty.</td>
<td>An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective.</td>
<td>The uncertainties are minimized in an effective way.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CT.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to compare recorded information and sketches with reality of experiment</strong></td>
<td>No sketches present and no descriptive text to explain what was observed in experiment</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
</tr>
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</table>

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<tr>
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<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to identify any assumptions necessary for making predictions</strong></td>
<td>No 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</td>
<td>An attempt is made to identify assumptions, but the assumptions stated are not properly evaluated for significance in making the prediction.</td>
<td>Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction.</td>
<td>Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made.</td>
</tr>
<tr>
<td>No Effort</td>
<td>Progressing</td>
<td>Expectation</td>
<td>Scientific</td>
<td></td>
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<td>--------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>CT.A.c</td>
<td>Multiple experimental trials lack predictions specific to those individual trial runs.</td>
<td>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.</td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>CT.A.d</td>
<td>descworst</td>
<td>An attempt is made to identify experimental uncertainties, but many sources of uncertainty are not addressed, described vaguely, or incorrect.</td>
<td>All experimental uncertainties are correctly identified. There is a distinction between experimental uncertainty and random uncertainty.</td>
<td></td>
</tr>
<tr>
<td>QR.A</td>
<td>No equations are presented in algebraic form with known values isolated on the right and unknown values on the left.</td>
<td>Some equations are recorded in algebraic form, but not all equations needed for the experiment.</td>
<td>All equations required for the experiment are presented in standard form and all 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.</td>
<td></td>
</tr>
<tr>
<td>QR.C</td>
<td>No attempt is made to analyze the data.</td>
<td>The analysis is appropriate for the data gathered, but contains minor errors or omissions</td>
<td>The analysis is appropriate, complete, and correct.</td>
<td></td>
</tr>
<tr>
<td>IL.A</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes.&quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. &quot;</td>
<td>All necessary data has been recorded throughout 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.</td>
<td></td>
</tr>
<tr>
<td>WC.A</td>
<td>Is able to create a sketch of important experimental setups</td>
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<tr>
<td>Labs:</td>
<td>1, 2, 4-8</td>
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</tbody>
</table>

- No Effort: No sketch is constructed.
- Progressing: 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.
- Expectation: 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.
- Scientific: 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.

<table>
<thead>
<tr>
<th>WC.B</th>
<th>Is able to draw a graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labs:</td>
<td>3, 6, 9, 11</td>
</tr>
</tbody>
</table>

- No Effort: No graph is present.
- Progressing: A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected.
- Expectation: "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."
- Scientific: 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.
Lab 6 Current Balance

Name: ________________________  Lab Partner: ________________________

EXIT TICKET:

☐ Turn off the power to all the equipment.
☐ Disconnect the power supply.
☐ Make sure that all six of the small magnets are accounted for.
☐ Return all circuits to the box.
☐ 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  WC.A
CT.A.a  QR.A   WC.B
Lab 7. Electromagnetic Induction

Goals

- To understand what it means to have magnetic flux through a loop or coil in a circuit.
- To understand and apply Lenz’s law and the right hand rule for magnetic fields produced by currents to correctly predict the direction of currents produced by changing magnetic fields.
- To explain the steps in the induction process precisely through words and pictures for several different cases.

Introduction

A major portion of the learning activity for this week’s lab is precision of language. Students often write things like "the coil wants to..." in the course of this lab. This is false, no matter how you finish the sentence. The coil wants nothing. The coil can do nothing. Please be careful in your word choices as you describe what you expect and what you observe. Refer to physical principles and established laws/theories. Do not anthropomorphize your equipment.

Magnetic flux can be thought of as the number of magnetic field lines passing through a given area. According to Faraday’s Law a change of the magnetic flux through an area bounded by closed circuit induces a voltage that drives the flow of current around the circuit. This is the induction process. Lenz’s Law is an abbreviated version of Faraday’s Law that gives the direction of the emf (potential change) as one moves around the circuit loop:

The polarity of the induced emf (or voltage) is such that it tends to produce a current that will create a magnetic flux to oppose the change in magnetic flux which is causing the emf.

In this experiment you are supplied with a coil of wire, a bar magnet, and a sensitive ammeter—also called a galvanometer. Remember that the ammeter reads a positive value of current when the current enters the positive (+) input terminal and leaves through the negative (−) or common terminal. Students often record results in this lab as "We moved the magnet this way, so the needle moved left" which is a useless recording, as you can swap your connections to the galvanometer and the needle will now deflect in the opposite direction.

Essentially the only way to record any observations in this lab is through careful use of diagrams supplemented with text. In prior labs this was ideal, but in this lab it is mandatory. Look at Figure 7.1 for an example. Refer to Lab 6 Current Balance writeup for the two options you may use for Right Hand Rules to include in your drawing.
Figure 7.1. One approach to drawing a single observation during this week. You may draw the RHR in other manners, but must include it in some style.

Move the bar magnet in to, out of, or through the coil of wire. Using the galvanometer, you can demonstrate that an electrical current flows when you do this. Your goal for the end of the laboratory is to be able to explain how the needle will react if you move the bar magnet from one end of the coil completely through the other end without stopping (explain prior to performing, and then perform to verify explanation accuracy).

Remember that, by convention, the magnetic field lines external to a bar magnet go from the N pole to the S pole. Since magnetic field lines are continuous, that is, they do not start or end anywhere, the field lines inside the bar magnet must necessarily go from the S pole to the N pole. All the field lines outside the magnet must be squeezed together as they pass through inside, going the opposite direction. If this is confusing, draw a simple diagram of a bar magnet, and add field lines to your drawing both inside and outside the magnet, indicating the directions of the fields with arrows. You may still have your drawings from the Magnetic Fields lab previously which you can simply supplement with the internal field lines.

Just a reminder that electric and magnetic fields differ significantly in this regard. Electric fields do begin and end somewhere, namely on electric charges. At this point scientists have yet to discover a single magnetic “charge” existing by itself, with magnetic field lines emanating from it radially analogous to the electric field of a point electric charge. The current understanding of the source of magnetism is the motion of electrons. This explanation makes a magnetic monopole impossible to exist, so if one were ever discovered it would cause significant changes in fundamental physics, and thus all more complicated physics as well.
CHAPTER 7. ELECTROMAGNETIC INDUCTION

Be sure to check the pole designation of your bar magnet with a compass using the Earth’s magnetic field as a reference before beginning this experiment. Bar magnets can be remagnetized in strange ways by bringing them close to another magnet, so this check is important.

Prediction

Imagine pushing the bar magnet N-pole first into the right-hand end of the wire coil. Predict which way the galvanometer needle will deflect based on your knowledge of the magnetic fields of bar magnets, the magnetic fields due to currents in wires, the configuration of the wire windings of the coil, the right-hand rule, and the connection of the ammeter. Illustrate your method of prediction with a series of simple, annotated drawings: pictures with words of explanation. Refer to Figure 7.1. Your depiction must clearly show:

- The position of the ammeter and coil in your circuit. Clearly label the positive terminal of the ammeter.
- How the direction of the current (clockwise or counterclockwise) around the solenoid is related to the direction of its flow (from left-to-right or from right-to-left) along the coil.
- The initial position of the magnet relative to the coil and the direction of magnet motion. Clearly label the N and S poles of the magnet.
- The dominant direction of the magnetic field of the magnet at points inside the coil.

In notes below these depictions, draw arrows and additional annotated sketches to show:

- The direction of increasing magnetic field inside the coil.
- The direction of the induced magnetic field required by Lenz’s Law. Refer to Lenz’s Law in this step.
- The direction of current in the coil required to produce this induced magnetic field. Specify both direction (left-to-right) and sense (clockwise or counterclockwise).
- You will need the right-hand rule. Draw a simple right hand. The direction of the current at the positive terminal of the ammeter. Clearly indicate the direction of the initial motion of the needle.

The required drawings and notes will occupy most of a page in your lab notebook.

The process of prediction is important for two reasons. First, prediction is the true test of whether we understand a phenomenon. When we know the answer ahead of time, we often settle for a partial explanation with missing or incorrect steps. Second, we remember what we observe better if we make a prediction before observing it. This is true whether our prediction is correct or incorrect. In the end, prediction is much better test of understanding than explanation.

Additionally, when you fail to set your prediction down in permanent form, so long as the observation makes sense to you as it happens, your mind will decide that whatever you believed before the experiment was correct. Even when the observation is directly contrary to what you believed before the experiment. By having a prediction written down in permanent form, you are

---

forced to acknowledge any flaw in your understanding, and can then work on learning the proper approach.

**Experiment**

Now perform the experiment. Did the ammeter deflect in the predicted direction? Do not erase or throw away your cartoons in any case. Go over them carefully and identify any mistakes. Make a note in the margin near the mistaken text or drawings, then redraw or rewrite the mistaken material below your original prediction or on a subsequent page. **This is the only acceptable way of correcting lab notes when an error has been made.**

**Predictions and experiments for other geometries**

The manual will not remind you in each experiment to predict, then experiment. You are expected to do so for your own improvement/understanding. Always draw and explain precisely what you expect to see, then observe and look carefully for chances to prove your prediction wrong.

**Magnet starting at rest in coil with N pole to right—move to right**

Position the bar magnet inside the wire coil with the N pole on the right and S pole on the left. Predict the direction of the current when you pull the magnet out the right-hand end of the coil—drawing another set of annotated cartoons. Then do the experiment and draw corrected cartoons as required. Make sure that your explanation above is consistent with your explanation here.

**Magnet starting left of the coil with S pole to right—move into coil**

Push the bar magnet S-pole first into the left-hand end of the coil. Predict/observe.

**Magnet starting at rest in coil with N pole to right—move to left**

Starting with the bar magnet at rest inside the wire coil, with the N pole on the right and S pole on the left, pull the magnet out the left-hand end of the coil. Predict/observe.

**What does it take to induce a current in an ammeter?**

Perform additional experiments to answer the following questions (Remember to predict first):

What effect does varying the speed with which you insert or remove the magnet from the coil have? Explain your observations using Faraday’s Law.

Under what conditions does a current flow in response to a magnetic field? For instance, how about when the magnet is at rest in the coil? Explain.

Can you cause a current to flow in the coil by moving the bar magnet along the outside of the the coil rather than inside the coil? If so, are certain orientations of the magnet more effective than
others for inducing this current? Observe and explain.

Does the position of the bar magnet within the coil change your results at all? Not just direction of deflection, but even magnitude of deflection (how far from zero the indicator swings)? Test with the magnet sliding on the bottom, on each side, on the top, or going perfectly in the center.

**Summary**

Be as precise as possible in presenting your experimental results. Don’t make such broad sweeping statements that they are meaningless. State all your conclusions clearly in a summary (maybe even a table) at the end of the report.

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to analyze the experiment and recommend improvements</strong></td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report</td>
<td>Description of experimental procedure leaves it unclear what could be improved upon.</td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed.</td>
<td>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.</td>
</tr>
<tr>
<td>Labs: 1-3, 5, 7, 9, 11, 12</td>
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<tr>
<th>SL.B.b</th>
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<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to explain patterns in data with physics principles</strong></td>
<td>No attempt is made to explain the patterns in data</td>
<td>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.</td>
<td>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.</td>
<td>A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit.</td>
</tr>
<tr>
<td>Labs: 1-3, 5, 7-11</td>
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<tr>
<th>CT.A.a</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to compare recorded information and sketches with reality of experiment</strong></td>
<td>No sketches present and no descriptive text to explain what was observed in experiment</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
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<tr>
<td>Labs: 3, 4, 6, 8</td>
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<td>Expectation</td>
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</tr>
<tr>
<td><strong>CT.B.a</strong>&lt;br&gt;Is able to describe physics concepts underlying experiment&lt;br&gt;Labs: 1-3, 5, 7, 9-12</td>
<td>No explicitly identified attempt to describe the physics concepts involved in the experiment using student’s own words.</td>
<td>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.</td>
<td>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.</td>
<td>The physics concepts underlying the experiment are clearly stated.</td>
</tr>
<tr>
<td><strong>QR.B</strong>&lt;br&gt;Is able to identify a pattern in the data graphically and mathematically&lt;br&gt;Labs: 1-3, 5, 7, 9-11</td>
<td>No attempt is made to search for a pattern, graphs may be present but lack fit lines</td>
<td>The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented.</td>
<td>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</td>
<td>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.</td>
</tr>
<tr>
<td><strong>IL.A</strong>&lt;br&gt;Is able to record data and observations from the experiment&lt;br&gt;Labs: 1-12</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. &quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. &quot;</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>WC.A</strong>&lt;br&gt;Is able to create a sketch of important experimental setups&lt;br&gt;Labs: 1, 2, 4-8</td>
<td>No sketch is constructed.</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
</tr>
</tbody>
</table>
Lab 7 Electromagnetic Induction

Name: ___________________________  Lab Partner: ___________________________

**EXIT TICKET:**
- [ ] 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

<table>
<thead>
<tr>
<th>SL.A.a</th>
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<th>IL.A</th>
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<tbody>
<tr>
<td>SL.B.b</td>
<td>CT.B.a</td>
<td>WC.A</td>
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<td>QR.B</td>
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</table>

Lab 7 Electromagnetic Induction

Name: ___________________________  Lab Partner: ___________________________

**EXIT TICKET:**
- [ ] 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

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<tbody>
<tr>
<td>SL.B.b</td>
<td>CT.B.a</td>
<td>WC.A</td>
</tr>
<tr>
<td></td>
<td>QR.B</td>
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</tbody>
</table>
Lab 8. Transformers

Goals

- To understand and explain mathematically the relationship between coils in a transformer.
- To predict and then verify a specified voltage transformation.
- To explain physical observations in electromagnetic induction and magnetic fields.

Introduction

In Lab 7: Electromagnetic Induction you learned that a change in magnetic flux caused an electromotive force (a voltage). To generate the change in magnetic flux you used a moving magnet. For this lab you will use a coil with an alternating current to create the changing magnetic flux. A secondary coil will be used to detect the change in magnetic flux and the resulting voltage.

Setup

Variable Coil

Follow figure 8.1 for an example of what your wire wound coil should resemble. Take a wire. Run it down the length of the rod. Bend it at the end. Take the end that was just bent and begin winding it around the rod. The wound part should go around the rod and a straight portion of the wire. Running the wire beneath your windings is important so that both exposed ends of the wire are on the same side of your coil.

![Figure 8.1. A wire wound coil.](image)

The coil that you just made will be referred to as the variable coil. The provided copper coil with numerous windings will be referred to as the fixed coil.
Data Gathering

You will be using two analog sensors to detect voltage. Attach one to each coil. Follow fig 8.2 to setup your sensors in Capstone. Use voltage sensor for the analog inputs.

For displaying the data collected, use the fourth option on the right bar: Scope. Use it to display both wave forms. You will be using high frequencies, so change your data gathering mode to "Fast Monitor Mode" and set the sample rate to 10.00MHz. Fast Monitor mode is required to display the measurements at the frequencies used in this lab, but the trade off at going at the faster rate is that only the visible data is recorded by the computer.

![Sensor Setup](a)
(a) Sensor Setup.

![Scope Graph](b)
(b) Scope Graph.

![Fast data gathering](c)
(c) Fast data gathering.

![Sample Rate](d)
(d) Sample Rate.

Figure 8.2. Setup of the sensors. Use the scope for displaying voltages. Set data gathering to fast, and the Sample rate to 10MHz.

Use output 1 for creating your AC signal. Operate it by using the signal generator as shown in fig 8.3. The highest output frequency possible from the signal generator is 100 kHz. To start, set your output to 100 kHz. Choose the maximum output current. Adjust the amplitude as necessary such that the wave form is clearly visible and not clipped.
Problem 1

Before beginning any useful measurements you must test for variables that you may need to take care to keep fixed. The clearest results come about when only one variable is changing.

Check which coil should be used as the field generator (have the output attached to it) and which one should be used to detect the change in flux (Be connected only to the voltage monitor). Which configuration is better? Explain in your words why it’s the better option.

Check for edge effects. Where can you get the maximum voltage? Move the coils relative to each other. Does it matter how far the smaller coil is inserted in to the larger? Why? Explain in your words. Is there an optimum position or range? Justify and keep fixed for the rest of the lab.

Problem 2

Does it matter which direction the small coil is inserted in to the large coil? How does it change? Describe in your own words a possible explanation.

Problem 3

There are two kinds of transformers. Step-up transformers increase the voltage while step-down transformers decrease the voltage. Given the equipment that you have figure out which variables change the voltage. Take date and plot graphs to prove or disprove the relationship between the variable and amplification(β). Use eq (8.1) to define the amplification. The generator is the coil connected to the signal generator to generate the magnetic field.
\[ \beta = \frac{V_{\text{sensor}}}{V_{\text{generator}}} \]  

(8.1)

**Problem 4**

Given the relationships between variables and \( \beta \), setup your equipment to get \( \beta = 1, 20, 0.1 \). Describe in your own words how you are doing this. Get scope graphs for each case and print them out.

**Problem 5**

Take the winding end of the wire from the small rod. Run it back up and create a secondary winding. Wind the wire from top to bottom as before. Check if there is any difference for winding in the same direction as the inner coil and the opposite direction as the inner coil. Describe in your own words a possible explanation.
<table>
<thead>
<tr>
<th>SL.B.a</th>
<th>Is able to explain operation and limitations of measurement tools</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At least one of the measuring tools used in lab lacks a clear identification of precision/limitation</td>
<td></td>
<td>All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>Labs:</td>
<td>Not used</td>
<td></td>
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</table>

| SL.B.c | Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able. | 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. |
|        | | | | | |
| Labs:  | 2, 6 | | | | |

| CT.A.b | Is able to identify assumptions used to make predictions | 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. |
|        | | | | | |
| Labs:  | 4-6 | | | | |

<p>| CT.A.c | Is able to make predictions for each trial during experiment | 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. |
|        | | | | | |
| Labs:  | 4-6 | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th>CT.B.b</th>
<th></th>
<th>QR.B</th>
<th></th>
<th>IL.A</th>
<th></th>
</tr>
</thead>
</table>
|                      | Is able to identify dependent and independent variables | No attempt to explicitly identify any variables as dependent or independent | Is able to identify a pattern in the data graphically and mathematically | No attempt is made to search for a pattern, graphs may be present but lack fit lines | Is able to record data and observations from the experiment | "Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes."
|                      | Labs: Not used | Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified | 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 | "Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc."
|                      |                      | The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent. | 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. |                      |
Lab 8 Transformers:

Name: ___________________________  Lab Partner: ___________________________

EXIT TICKET:
- ☐ Quit any software you have been using.
- ☐ Unroll the wire from the small rod. Wrap it in to a small roll and place in equipment tray.
- ☐ 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

<table>
<thead>
<tr>
<th>SL.A.b</th>
<th>SL.B.c</th>
<th>CT.B.b</th>
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<td>SL.A.c</td>
<td>CT.A.b</td>
<td>QR.B</td>
</tr>
<tr>
<td>SL.B.a</td>
<td>CT.A.c</td>
<td>IL.A</td>
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</tbody>
</table>

Lab 8 Transformers:

Name: ___________________________  Lab Partner: ___________________________

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- ☐ 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

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<th>SL.B.c</th>
<th>CT.B.b</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL.A.c</td>
<td>CT.A.b</td>
<td>QR.B</td>
</tr>
<tr>
<td>SL.B.a</td>
<td>CT.A.c</td>
<td>IL.A</td>
</tr>
</tbody>
</table>
Lab 9. RC Circuits

Goals

- To appreciate the capacitor as a charge storage device.
- To measure the voltage across a capacitor as it discharges through a resistor, and to compare the result with the expected, theoretical behavior.
- To use a semilogarithmic graph to verify that experimental data is well described by an exponential decay and to determine the decay parameters.
- To determine the apparent internal resistance of a digital multimeter.

Introduction

A diagram of a simple resistor-capacitor (RC) circuit appears in Figure 9.1. A power supply is used to charge the capacitor. During this process, electrons accumulate on one side of the capacitor and repel electrons from the other. This gives the appearance of continuous charge flow through the capacitor, but "flow" will stop when the power supply is incapable of forcing any additional electrons onto the negative side of the capacitor.

A digital multimeter set to measure voltage behaves in a circuit like a large (in ohms) resistor (Represented here as a resistor and ideal meter in parallel). When the power supply is disconnected from the capacitor, charge “leaks” from one side of the capacitor, through this resistor, back to the other side of the capacitor, until no voltage appears across the terminals of the capacitor. This leakage is the repulsion of all the electrons on one side of the capacitor, and the attraction of the electron deprived opposite side.

Figure 9.1. Diagram of RC circuit and power supply.
The power supply in Figure 9.1 is represented by a battery. Note that the positive output of the power supply is connected to the plate of the capacitor marked with a plus sign. The capacitors used in this experiment are polarized, meaning charge accumulation only works properly in one direction. Electrolytic capacitors (the polarized type we are using) can be made inexpensively and are widely used in power supplies. As you may remember from chemistry, the sign of the voltage is critical in electrolytic reactions. Make sure that the positive end of the capacitor is connected to the positive output of the power supply in your circuit.

The voltmeter in Figure 9.1 is enclosed by a dashed line. The voltage sensing circuit is represented by a circle with a “V” inside. All voltmeters have resistance, and this resistance is represented by the resistor symbol inside the box. Our goal is to measure the value of this resistance, $R$.

**Theory**

We plan to monitor the voltage across the capacitor as a function of time after the switch is opened. The functional form of this dependence can be derived by circuit analysis using Kirchhoff’s loop law. A simplified diagram of the circuit after the switch is opened is shown in Figure 9.2. For the purposes of analysis, we indicate the positive direction of current by an arrow. This choice defines the sign of positive charge, $Q$ on the capacitor. ($Q$ is positive when the arrow points toward the plate with positive charge.) It also defines the positive direction of $\Delta V$. ($\Delta V$ is positive when the arrow points in the direction of increasing potential.)

![Figure 9.2. Diagram of RC circuit and power supply.](image)

Because our circuit contains no source of emf, the only potential differences in the circuit appear across the capacitor and across the resistor. By Kirchhoff’s loop rule, the total potential change as you go all the way around the loop ($\Delta V_{loop}$) must be zero. Let the potential difference across the capacitor be $\Delta V_C$ and the potential difference across the resistor be $\Delta V_R$. Then

$$\Delta V_{loop} = \Delta V_C + \Delta V_R = 0 \quad .$$

In the presence of a positive charge $Q$ on the capacitor, $\Delta V_C$ must be negative, as the potential drops as one moves from a positively charged plate to a negatively charged plate. The capacitance, $C$, of a capacitor is defined so that the magnitude of $\Delta V_C$ is $Q/C$. Therefore $\Delta V_C = -Q/C$. Likewise, potential drops as charge passes through a resistor in the direction of positive current, $I$. The magnitude of this drop is given by Ohm’s law, so that $\Delta V_R = -IR$. Substituting these relations into Kirchhoff’s loop rule yields
\[ \Delta V_C + \Delta V_R = -\frac{Q}{C} - IR = 0 \quad \text{or} \quad I = -\frac{Q}{RC} \quad (9.2) \]

When the switch in Figure 9.1 is closed, a positive charge \( Q = \Delta V \times C \), where \( \Delta V = 5 \text{ V} \), is on the top plate of the capacitor. According to our choice of positive direction, both \( Q \) and \( \Delta V_C \) are initially negative. While negative charges and potential differences may appear to be inconvenient, they make no difference as far as the math is concerned. It is safe to choose the direction of positive current arbitrarily and work from there, if you wind up with a negative current in the end, it indicates that flow is actually in the opposite direction to what you selected. With a negative charge on the top plate of the capacitor, a positive current \( I \) will flow through the resistor. In this case, a positive current will decrease the magnitude of \( Q \), but since \( Q \) is initially negative, the corresponding \( dQ/dt \) is positive. Therefore \( I = dQ/dt \). One of the handy features of Kirchhoff’s loop rule is that \( I \) always equals \( dQ/dt \) if you set it up correctly. This is not always true for other approaches to circuit analysis. This relation allows us to reduce Kirchhoff’s loop rule to a simple equation with one derivative.

\[ \frac{Q}{C} = -R \frac{dQ}{dt} \quad \text{or} \quad \frac{1}{Q} \frac{dQ}{dt} = -\frac{1}{RC} \quad (9.3) \]

Equation (9.3) is a simple differential equation. The expression on the right hand side of Equation (9.3) is easily integrated, but its solution depends on the initial charge across the capacitor. If we start with an initial charge \( Q_0 \) on the capacitor, the charge as a function of time, \( Q(t) \) is given by

\[ Q(t) = Q_0 \exp \left( -\frac{t}{RC} \right) \quad (9.4) \]

Since the voltage across the capacitor is directly proportional to the charge stored on it at any instant of time, the voltage difference \( \Delta V_C \) can be written as

\[ \Delta V_C(t) = \frac{Q_0}{C} \exp \left( -\frac{t}{RC} \right) = \Delta V_0 \exp \left( -\frac{t}{RC} \right) \quad (9.5) \]

where \( \Delta V_0 \) is the initial voltage across the capacitor. The voltmeter measures this voltage directly. When \( t/RC \) equals one (that is, when \( t = RC \)), the voltage has decayed to \( 1/e \) of its original value. The quantity \( RC \) is called the time constant of the decay process. When \( R \) and \( C \) are expressed in the SI units of ohms and farads, respectively, the \( RC \) time constant has units of seconds.

Before proceeding, verify that the expression for \( Q(t) \) given above is really a solution to the differential equation preceding it. Include this verification in your lab notes.

**Experiment**

Set up the circuit shown in Figure 9.1 using the Fluke voltmeter (larger yellow one). Have your TA check it before continuing. With the power supply set to 5.0 V, close the switch and charge the capacitor. When the switch is opened, the voltage begins to decrease. Try it! Now read the initial
voltage, then open the switch and read the voltmeter at 10-second intervals until the voltage is less than 10% of its original value. Repeat this process two more times, making sure that the initial voltage is the same for all three trials.

**Analysis**

To determine the resistance of the voltmeter, make a table in Excel listing the observed voltages and times for your three data sets. (Enter the time data only once.) Add an additional column in the spreadsheet to average the three voltage readings corresponding to each time. Then calculate the standard deviation of the mean of these three values for each time. (Refer to the Uncertainty/Graphical Analysis Supplement at the back of the lab manual for additional details.) The standard deviation of the mean gives an estimate of the uncertainty in the individual voltage measurements.

Plot the average voltage values as a function of time with error bars. Your error bars should look like the one in Figure 9.3. The circle in Figure 9.3 marks the calculated average value for one data point, $y_{avg}$. The top and bottom bars mark the maximum and minimum values ($y_{max}$ and $y_{min}$) on either end of the range of $y$-values within one standard deviation ($\sigma$) of $y_{avg}$. Thus the top bar is located at $y_{max} = y_{avg} + \sigma$, while the bottom bar is located at $y_{min} = y_{avg} - \sigma$. Get help from your TA if you aren’t sure how to plot error bars in Excel.

![Figure 9.3. Diagram of a data point with upper and lower error bars.](image)

Clearly this is not a linear graph. To determine the value of $RC$, one could perform an exponential curve fit using Excel. However, Excel’s curve fit function does not provide the uncertainty estimate we need. Excel’s Regression function will provide an uncertainty, but it requires a linear function. Taking the natural logarithm of both sides of Equation 9.5 will produce the linear equation we need.

\[
\ln(\Delta V_C(t)) = \ln(\Delta V_0) - \frac{t}{RC}
\]

A plot of $\ln[\Delta V_C(t)]$ vs $t$ should produce a line of slope $-t/RC$ and that equals $\ln(\Delta V_0)$ at time $t = 0$. The intercept is not very useful this case, except to confirm our knowledge of $\Delta V_0$. The slope, however, gives us $1/RC$. Assuming that the value of $C$ marked on the capacitor is reasonably accurate, we can calculate $R$, the internal resistance of the meter. In practice, the uncertainty in the marked value of $C$ is $\pm 20\%$. With this and the uncertainty (standard error) in the slope given by Excel’s Regression feature, we can estimate the uncertainty in $R$. 

Taking the natural logarithm of both sides of Equation 9.5 will produce the linear equation we need.

\[
\ln(\Delta V_C(t)) = \ln(\Delta V_0) - \frac{t}{RC}
\]
A graph with the logarithm of one quantity on one axis versus a non-logarithmic quantity on the other axis is called a semilog graph. (The logarithm appears on only one of the two axes.) Plot a semilog graph of your data. Again include the error bars with each plotted point. Does your graph support the hypothesis that the relationship between the voltage and time is an exponential function? Using the value of \( C \) marked on your capacitor, compute the value of the \( R \) of the voltmeter and compare it to the value from the manufacturer’s specification.

**Internal resistance of an inexpensive voltmeter**

Repeat your measurements of \( \Delta V_C(t) \) versus time using the relatively inexpensive (smaller, red or black) digital voltmeter at your lab station. Repeat the analysis above to determine its internal resistance. How does it compare with the internal resistance of the relatively expensive Fluke digital voltmeter?

The internal resistance of a voltmeter is one measure of its quality. To measure the potential difference across a component with a high resistance, the internal resistance of your voltmeter should be much higher than the resistance of the component. A voltmeter with a high internal resistance can be used in applications where the measurement error of a meter with a low internal resistance would be unacceptably high.

**Summary**

Begin by “filling in the blanks” of the argument for a simple exponential function being a straight line when plotted semi-logarithmically. Then state your findings clearly, succinctly, and completely.
<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CT.B.a</strong>&lt;br&gt;Is able to describe physics concepts underlying experiment&lt;br&gt;Labs: 1-3, 5, 7-12</td>
<td>No explicitly identified attempt to describe the physics concepts involved in the experiment using student’s own words.</td>
<td>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.</td>
<td>The physics concepts underlying the experiment are clearly stated.</td>
</tr>
<tr>
<td><strong>QR.A</strong>&lt;br&gt;Is able to perform algebraic steps in mathematical work.&lt;br&gt;Labs: 3, 6, 9-12</td>
<td>No equations are presented in algebraic form with known values isolated on the right and unknown values on the left.</td>
<td>Some equations are recorded in algebraic form, but not all equations needed for the experiment.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>QR.B</strong>&lt;br&gt;Is able to identify a pattern in the data graphically and mathematically&lt;br&gt;Labs: 1-3, 5, 7-11</td>
<td>No attempt is made to search for a pattern, graphs may be present but lack fit lines</td>
<td>The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented.</td>
<td>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.</td>
</tr>
<tr>
<td><strong>QR.C</strong>&lt;br&gt;Is able to analyze the data appropriately&lt;br&gt;Labs: 1-4, 6, 7-12</td>
<td>No attempt is made to analyze the data.</td>
<td>An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate.</td>
<td>The analysis is appropriate for the data gathered, but contains minor errors or omissions</td>
</tr>
<tr>
<td><strong>ILA</strong>&lt;br&gt;Is able to record data and observations from the experiment&lt;br&gt;Labs: 1-12</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes.&quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc.&quot;</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>All necessary data has been recorded throughout 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.</td>
</tr>
<tr>
<td></td>
<td>No Effort</td>
<td>Progressing</td>
<td>Expectation</td>
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</tr>
<tr>
<td><strong>WC.B</strong></td>
<td>Is able to draw a graph</td>
<td>A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected.</td>
<td>&quot;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.&quot;</td>
</tr>
<tr>
<td><strong>Labs:</strong></td>
<td>3, 6, 9, 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WC.D</strong></td>
<td>Is able to draw a circuit diagram</td>
<td>Components of the circuit are missing, or connected incorrectly. Components are not clearly labelled.</td>
<td>&quot;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.&quot;</td>
</tr>
<tr>
<td><strong>Labs:</strong></td>
<td>3, 4, 9, 10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lab 9 RC Circuits

Name: ___________________________  Lab Partner: ___________________________

EXIT TICKET:

□ Turn off the power to all the equipment, including the battery-powered digital voltmeters.
□ Please put all leads and small components in the plastic tray provided.
□ 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

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>QR.A</th>
<th>IL.A</th>
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</thead>
<tbody>
<tr>
<td>SL.B.b</td>
<td>QR.B</td>
<td>WC.B</td>
</tr>
<tr>
<td>CT.B.a</td>
<td>QR.C</td>
<td>WC.D</td>
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Lab 9 RC Circuits

Name: ___________________________  Lab Partner: ___________________________

EXIT TICKET:

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<tr>
<td>CT.B.a</td>
<td>QR.C</td>
<td>WC.D</td>
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</table>
Lab 10. AC Circuits

Goals

• To show that AC voltages cannot generally be added without accounting for their phase relationships. That is, one must account for how they vary in time with respect to one another.
• To understand the use of “root mean square” (rms) voltages and currents.
• To learn how to view and interpret AC voltage and current waveforms using a scope display.
• To learn how to measure the phase between sinusoidal voltage waves using a scope display.
• To understand how to use phasor diagrams (analogous to diagrams of vector addition) as a technique for adding AC voltages or currents with various phases.
• To observe electrical resonance (analogous to mechanical resonance in a vibrating string) in an RLC circuit.

Introduction

While DC (direct current) circuits employ constant voltages and currents, AC (alternating current) circuits employ sinusoidally varying voltages and currents. It may seem strange that sinusoidal quantities should be so common, but rotating devices generate most of the electrical power in the world. In a natural way, this produces voltages and currents that vary in a sinusoidal fashion.

A complicating factor in AC circuits is that inductors and capacitors introduce phase shifts. That is, the voltages across some components can peak well before or after the currents flowing through them. At any one instant in time, the voltage across each component in a series circuit will indeed sum to zero—but the voltage peak for each component (proportional to the amplitude) will be reached at different times. Under these conditions, the sum of the voltage amplitudes in a circuit containing inductors and capacitors will not in general be zero—in apparent violation of Kirchhoff’s loop rule. In this experiment you will explore the relationships between voltages and currents for inductors, capacitors, and resistors. This will include determining their phase relationships and how they depend on frequency. For this study, we consider a simple circuit consisting of a resistor, a capacitor, and an inductor connected in series with a sinusoidal voltage source.
A brief review of theory

A diagram of a typical RLC circuit is shown in Figure 10.1. Normally the current (which must be equal at all points along a series circuit) is used as a reference signal in AC circuits. Although the current flows back and forth, one direction is designated the positive direction. This defines the direction of positive voltage differences when Kirchhoff’s loop rule is applied to the circuit. The positive end of each component in Figure 10.1 is marked.

![Figure 10.1. Diagram of a resistor, inductor, and capacitor connected in series.](image)

Potential differences for RLC circuit

With a DC power supply, the voltages across the inductor $V_L$, the resistor, $V_R$, the capacitor, $V_C$ and the power supply output, $V_{Out}$, in Figure 10.1 sum to zero. That is,

$$V_L + V_R + V_C + V_{Out} = 0. \quad (10.1)$$

When the voltages are changing in time, Equation 10.1 must hold at each instant of time. If the output of the power supply is sinusoidal, the steady state voltages across each of the components will also be sinusoidal. However, each voltage in the circuit will have its own phase. That is

$$V_{L(0-p)} \cos(\omega t + \phi_L) + V_{R(0-p)} \cos(\omega t + \phi_R) + V_{C(0-p)} \cos(\omega t + \phi_C) + V_{Out(0-p)} \cos(\omega t + \phi_{Out}) = 0 \quad (10.2)$$

where the $(0-p)$ subscript in $V_{L(0-p)}$ and the other voltage amplitudes refers to their “zero-to-peak” values. When multiplied by the proper sine or cosine function, the zero-to-peak amplitude gives the actual measured potential difference across the component as a function of time. The non-zero phase angles, denoted by $\phi$ in Equation 10.2, complicate the analysis of AC circuits.
The phase of the potential difference across an ideal capacitor

Capacitors are essentially two conducting sheets or plates separated by some insulating material that may include air or a vacuum. When a voltage is applied between the two plates of the capacitor, charge is accumulates on one plate and repels from the other. Thus a current flows through the voltage source and the connecting wires. As the voltage increases and more charge collects on the plates, adding more charge becomes increasingly more difficult, because like charges repel. Therefore the current flowing into the capacitor is greatest when the plates begin to charge. The current drops to zero when the charge build-up reaches a maximum.

If a sinusoidally varying voltage source (one that oscillates positively and negatively in time with the shape of a sine function), is connected across the capacitor, the voltage across the capacitor “lags” the current by 90° in phase, meaning that the voltage peak occurs one-fourth of an oscillation period after the current peak. This relationship is illustrated in Figure 10.2, where the voltage across the resistor (\( V_R \)) shows the variation of current during a single cycle. Voltage is a measure of the charge present on the capacitor, and as described when there is more charge on one plate of the capacitor that causes a reduction in current flow. The oscillation period of the signal in Figure 10.2 is 1 s, and the voltage across the capacitor (\( V_C \)) peaks 0.25 s (one-fourth of a cycle) after the peak in \( V_R \). We say that the phase of the voltage across an ideal capacitor is shifted 90° (360°/4) with respect to the current. The sign is chosen so that if \( I \) and \( V_R \) are proportion to \( \cos(\omega t) \), \( V_C \) is proportional to \( \cos(\omega t + \phi) \); this requires a negative phase. For an ideal capacitor, \( \phi = -90° \).

![Figure 10.2. Voltages across an ideal induction, an ideal resistor, and an ideal capacitor in an RLC circuit. The times as which the three voltages cross zero (during the falling portion of the cycle) are labeled \( t(V_L = 0-) \), \( t(V_R = 0-) \), and \( t(V_C = 0-) \), respectively. The components in your experiment are not ideal, so the phases will be different.](image-url)
The phase of the potential difference across an ideal inductor

An inductor usually takes the form of a coil of wire with many loops. When a time-varying electrical current passes through the loops, the resulting time-varying magnetic field induces a voltage in the coil. According to Lenz’s law (and energy conservation) this induced voltage opposes the source voltage, making the current small. When sinusoidally driven, the voltage across and ideal inductor peaks one-fourth of an oscillation period before the current peaks. That is, the voltage “leads” the current by 90° in an ideal inductor. We say that the voltage experiences a +90° phase shift relative to the current in an ideal inductor. This relationship is illustrated in Figure 10.2, where the voltage across the inductor, \( V_L \), peaks 0.25 s (one-fourth of a cycle) before the peak in \( V_R \). Again, the sign is chosen so that if \( I \) and \( V_R \) are proportion to \( \cos(\omega t) \), \( V_L \) is proportional to \( \cos(\omega t + \phi) \), where \( \phi = +90^\circ \).

Recall that in the conductor accumulation of charge means that current flow is initially unimpeded, but resistance to current increases as charge accumulates. For an Inductor, there is initially no magnetic field and so no induced potential, but as the current increases, so does the magnetic field. This results in an increasing emf generation, reducing the potential on the line for other components in the circuit.

In practice, it is difficult to determine the position of the peak in a sinusoidal signal precisely, because voltage changes slowly near the peak. Measuring the time at which the voltage crosses zero, where the voltage changes rapidly, gives more precise results. Because the voltage crosses zero twice per cycle, it is important to be consistent about which zero crossing is used. The arrows in Figure 10.2 show the zero crossings for \( V_L \), \( V_R \), and \( V_C \) where the voltage is falling, that is, where the voltage crosses zero from above.

To derive an equation for the phase angle \( \phi \) for a given voltage signal, one observed that 360° of phase corresponds to one oscillation period \( T \),

\[
\phi = \frac{[t(V_R = 0) - t(V = 0)]}{T} \times 360^\circ
\]

(10.3)

The order of terms in Equation 10.3 is chosen so that a voltage signal that lags \( V_R \) has a negative phase, as required by the sine and cosine functions.

Using phasors to represent AC voltages

The AC voltages across an AC power supply, an inductor, a capacitor, and a resistor, all connected in series, can be added much like vectors. The length of each vector, or phasor, represents the measured voltage amplitude of the corresponding circuit element. Similarly, the angle between the resistor phasor (which points in the same direction as the current phasor) and each of the other phasors equals the phase difference between the current and the AC voltage across the corresponding circuit element. These relationships are illustrated in Figure 10.3. To represent the time-varying voltages in an AC circuit, all four phasors are rotated at angular velocity of \( \omega t \). The measured voltage across each circuit element at time \( t \) is equal to the horizontal component of that element’s phasor at that time.
Phasors are used to represent the various time-varying voltages in more complex AC circuits. They are also used to represent the addition of other quantities that vary sinusoidally in time. For instance, the electric fields in monochromatic electromagnetic waves (laser beams) vary sinusoidally in time. Phasors are often used to account for phase differences in single-slit diffraction.

Figure 10.3. Phasor diagram of the voltages across an inductor, a resistor, a capacitor, and the output in a series $RLC$ circuit. The current phasor is not shown, but is proportional to the resistor’s phasor. The dotted phasors show that the sum of all four voltage phasors is zero, as required by Kirchhoff’s loop rule. The phases $\Phi_L$, $\Phi_C$, and $\Phi_{E0}$ are measured with respect to the phase of the voltage across the resistor (or equivalently, the phase of the current signal). The measured voltage across each component is equal to the projection of its phasor onto the $x-$axis. As a function of time, each vector rotates about the origin with angular velocity $\omega t$.

**Expressing AC voltages in terms of their root-mean-square (rms) values**

AC voltages are often expressed in terms of their root mean square (abbreviated rms) values. In DC circuits the product of the current and voltage gives the power. It is convenient to use a similar formula for the average power dissipated in AC circuits when the current and voltage are in phase. However, the product of the raw voltage and current amplitudes (the zero-to-peak voltages and zero-to-peak currents), is twice the actual average power. To correct for this, we use rms voltages and currents. The rms voltage is the zero-to-peak voltage divided by $\sqrt{2}$, and the rms current is the zero-to-peak current divided by $\sqrt{2}$. When these are multiplied, the factor of 2 in the denominator yields the correct average power. (This procedure yields the average power only when the voltage and current have the same phase.) Most AC voltmeters and ammeters display rms volts and rms amps, respectively. The voltage at a wall plug in the United States is 120 V rms. The corresponding zero-to-peak voltage is about 170 V.
CHAPTER 10. AC CIRCUITS

Equipment set up

The Pasco Scientific RLC Circuit (Model CI-6512) is already configured with a series combination of resistor, inductor, and capacitor. Choose the 10 \( \Omega \) resistor, the 8.2 mH inductor, and the 100 \( \mu \)F capacitor. They are already connected in series. (You can see the connections on the bottom of the circuit board.) The analog inputs of the interface unit (Channels A, B and C) can be employed to measure the voltage difference across each of the three components using the three patch cords supplied with the circuit board.

Since switching the red and black leads across a component reverses the sign of the detected voltage difference, it is important to connect the red and black ends of each patch cord to the three components in a consistent fashion. This requires that you define one current direction to be positive, and use this direction to identify the positive end of each component. The positive end of each component is labeled (+) in Figure 10.1 for the choice of positive direction shown in the figure. Attach the red lead of the patch cord for the resistor, for instance, to the positive end of the resistor, and the black lead to the negative end of the resistor. Attach the patch cords used to measure the voltage differences across the inductor and the capacitor in the same fashion, being careful of sign.

To take the data, you will need to tell Capstone that you want to connect voltage sensors to Channels A, B, and C, and that you wish to use the output from the interface unit as the voltage source for the circuit. The output jacks are to the right of Channel D. You will need to add a “scope” display (instead of a graph) so all of this can be viewed. Then you can add the voltages for Channels A, B, and C, and \( V_{Out} \) to the vertical axis using the “Select Measurement” button, then choosing “Add Similar Measurement” function for the subsequent readings. You want to show all four signals on the same display. Your TA can be helpful here.

To collect data, use the “Fast Monitor Mode”. If a waveform appears choppy, like a series of connected straight lines, you probably need to increase the data sampling rate. For best results, the sampling rate should be about 50 times the frequency of the wave that you want to observe. Adjusting the time per division on the horizontal scale of the scope display will automatically change the sampling rate and may solve this problem. Otherwise, you can manually change the sampling rate on the Control Palette along the bottom of Capstone’s Display Area.

Phase and voltage measurements

Set the sinusoidal output voltage amplitude to 4.0 V at a frequency of 10 Hz (so you will want to be measuring at 500 Hz now). Now individually measure the zero-to-peak voltages across the resistor, inductor, and capacitor and the zero-to- peak output voltage. A table is a good way to record all this information. Convert all the peak voltages and currents to rms values. Record the zero-crossing times for all four voltages and and the current, and compute their phases with respect to the phase of the voltage across the resistor.

Repeat the voltage and phase measurements for each component at 100 Hz and 1000 Hz.
Adding AC voltages

From Figure [10.1], we expect that the sum of the voltage drops across the three components $V_L + V_R + V_C$ and the output voltage $V_{out}$ equals zero at each instant of time. In the absence of time variation, the voltages would add like DC voltages. We would expect:

$$V_L + V_R + V_C + V_{out} = 0$$  \hspace{1cm} (10.4)

However, each voltage in the circuit varies in time with its own phase. As seen in Figure [10.2], when $V_R$ peaks, both $V_L$ and $V_C$ are zero (A clear non-zero sum), yet when $V_R$ is zero, then $V_L$ and $V_C$ are opposite (A clear zero sum). Expressing Equation (10.2) in terms of rms voltages yields

$$V_{Lrms} \cos(\omega t + \phi_L) + V_{Rrms} \cos(\omega t + \phi_R) + V_{Crms} \cos(\omega t + \phi_C) + V_{Outrms} \cos(\omega t + \phi_{Out}) = 0$$  \hspace{1cm} (10.5)

To verify that the voltages do add this way, it is sufficient to show that the equation holds at two times. Two times are needed to resolve the ambiguity associated with the phases of the voltage signals in Figure [10.2]. At most times, it is not enough to know the voltage reading alone. (One must also know whether the voltage is rising or falling.) The times $\omega t = 0$ and $\omega t = -90^\circ$ make for simple expressions. Then

$$V_{Lrms} \cos(\phi_L) + V_{Rrms} \cos(\phi_R) + V_{Crms} \cos(\phi_C) + V_{Outrms} \cos(\phi_{Out}) = 0$$
$$V_{Lrms} \sin(\phi_L) + V_{Rrms} \sin(\phi_R) + V_{Crms} \sin(\phi_C) + V_{Outrms} \sin(\phi_{Out}) = 0$$  \hspace{1cm} (10.6)

Ideal components constitute an important special case. For ideal components, $\phi_L = +90^\circ$ and $\phi_C = -90^\circ$. By convention, $\phi_R = 0^\circ$. For ideal components, these relations reduce to

$$\sqrt{(V_{Crms} - V_{Lrms})^2 + V_{Rrms}^2} = V_{Outrms}$$  \hspace{1cm} (10.7)

At each frequency check to see whether the voltages across the resistor, inductor, and capacitor obey Equations (10.1), (10.6), and (10.7). Tabulate all these results clearly. Is ignoring the phase a good idea?

For future reference, it is worth comparing the measured phases for $V_L$ and $V_C$ to their ideal values. Capacitors are usually pretty close to ideal.

RLC circuit at resonance

By trial and error, adjust the frequency of the sine wave output of the interface unit until the output voltage and current, which drive the circuit, are in phase. Do this carefully. When the current and voltage are in phase as required, look at the inductor voltage and the capacitor voltage. What relationship do they now have with respect to one another? Since real inductors have both
resistance and inductance, the phase shift for the real inductor does not equal the +90° phase shift for an ideal inductor. If the resistor phasor is plotted along the x—axis, you will need to compare the y—component of the voltage across the inductor with the y—component of the voltage across the capacitor. This particular state of the system is called “resonance.” What is the overall effect on the circuit of the inductance and capacitance at resonance? Resonant circuits are useful in filtering out certain frequencies. Radio tuning dials work on this principle.

<table>
<thead>
<tr>
<th>SL.B.b</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Is able to explain patterns in data with physics principles.</strong></td>
<td>No attempt is made to explain the patterns in data.</td>
<td>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.</td>
<td>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.</td>
<td>A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit.</td>
</tr>
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</table>

| CT.B.a | 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 | 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. |

<p>| QR.B | 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. |</p>
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<thead>
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<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
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<td>Is able to analyze data appropriately</td>
<td>No attempt is made to analyze the data.</td>
<td>An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate.</td>
<td>The analysis is appropriate for the data gathered, but contains minor errors or omissions</td>
<td>The analysis is appropriate, complete, and correct.</td>
</tr>
<tr>
<td>Labs: 1-4, 6, 7, 9-12</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. &quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. &quot;</td>
<td>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.</td>
<td>All necessary data has been recorded throughout 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.</td>
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<th>Scientific</th>
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<tr>
<td>Is able to record data and observations from the experiment</td>
<td>No attempt is made to analyze the data.</td>
<td>An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate.</td>
<td>The analysis is appropriate for the data gathered, but contains minor errors or omissions</td>
<td>The analysis is appropriate, complete, and correct.</td>
</tr>
<tr>
<td>Labs: 1-12</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. &quot;</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. &quot;</td>
<td>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.</td>
<td>All necessary data has been recorded throughout 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.</td>
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<th>Expectation</th>
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<tbody>
<tr>
<td>Is able to draw a circuit diagram</td>
<td>No circuit diagram is drawn.</td>
<td>Components of the circuit are missing, or connected incorrectly. Components are not clearly labelled.</td>
<td>&quot;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. &quot;</td>
<td>Circuit diagram contains minimal connecting lines, components are neatly arranged to ensure labels are readily identified to appropriate components.</td>
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</tbody>
</table>
Lab 10: AC Circuits

Name: ____________________    Lab Partner: ____________________

EXIT TICKET:
- Disconnect the Pasco interface and the RLC Circuit.
- Put all the connecting wires neatly in the tray provided at your lab table.
- Quit Capstone and any other software you have been using.
- Straighten up your lab station.
- 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  QR.A  IL.A
CT.B.a   QR.B  WC.D
QR.C     

Lab 10: AC Circuits

Name: ____________________    Lab Partner: ____________________

EXIT TICKET:
- Disconnect the Pasco interface and the RLC Circuit.
- Put all the connecting wires neatly in the tray provided at your lab table.
- Quit Capstone and any other software you have been using.
- Straighten up your lab station.
- 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  QR.A  IL.A
CT.B.a   QR.B  WC.D
QR.C     

Lab 11. Interference of Light

Goals

- To observe the interference patterns for laser light passing through a single narrow slit, through two closely spaced slits, and through multiple closely spaced slits, noting the similarities and differences.
- To determine by graphical techniques the wavelength of the laser light based on the observed interference patterns for single, double, and multiple slits.
- To compare the calculated values of wavelength with the accepted value for a red helium-neon laser.
- To “measure” the diameter of a human hair by observing and analyzing the interference pattern created when it is placed in the center of laser beam.

Introduction

Two waves that have the same frequency can “interfere” constructively when the peaks coincide or destructively when a peak of one wave coincides with a valley of the other. With water and sound waves, waves which travel through a medium, interference manifests as larger positive and negative displacements of the medium (water or air, respectively). Electromagnetic waves, such as visible light, do not travel through any medium. The peaks and valleys correspond to regions of positive and negative electric and magnetic field vectors. Constructive interference of light rays produces regions of high intensity, thus adding greater illumination to a surface. Destructive interference produces regions of low intensity, thus adding little or no additional illumination to a surface.

While it is possible to view interference patterns in waves of water which are in many ways similar to those you will observe with light today, it should be noted that light and water waves work through very different mechanisms. Light is able to interfere with itself, even a single photon fired at a time to perform the same experiments we are doing today would result in the same data. While it helps to form a mental model to understand what is happening, and a mental model of a wave tank is certainly useful, be warned that the model produced through such analogy is not nearly accurate to what is really happening.
Double slit interference

The simplest example of interference takes place when monochromatic light passes through two nearby, parallel slits (narrow openings for the light to come through). Normal light through the double slit will not produce an interference pattern because there are multiple wavelengths (different energy levels and wave patterns), and the light is travelling in many divergent directions. However, laser light is nearly monochromatic (all of the same frequency and wavelength). Laser light is also highly columnated (all waves are travelling in nearly a straight line, with all paths parallel to one another).

The diagram in Figure 11.1 shows a single interference peak along the path of a laser beam, traveling from left to right, incident on two slits at an incident angle of 0°. This configuration assures that the phase of the waves at each of the slits is the same. In other words the peak of the wave in one slit is synchronized with the peak of the wave in the other slit. Let $d$ be the center-to-center spacing between the slits. The light intensity is observed at a distance $y$ from the center of the slit pattern. For constructive interference to take place at the point $y$, the distance from the point $y$ to each individual slit is $r_2$ & $r_1$. The difference in these two distances ($r_2 - r_1$) must be equal to some integer multiple of the wavelength $\lambda$ of the light. This can be expressed as

$$r_2 - r_1 = m\lambda$$

where $m$ is an integer ($\ldots, -2, -1, 0, +1, +2, \ldots$).

(11.1)

![Diagram of double slit interference](image)

Figure 11.1. Geometry for determining the condition for constructive interference for a double slit.

What difference in distance to the slits would result in destructive interference (a dark spot)?

When the distance $L$ from the viewing screen to the slits is much larger than the distance between the slits $d$, the lines denoting the distances $r_2$ and $r_1$ are essentially parallel, like the edges of a very tall skinny triangle. For this limiting case the difference in the distances can be written to a good approximation as $d \sin \theta$. Then condition for constructive interference then becomes
$d \sin \theta = m\lambda \quad \text{where} \ m \ \text{is an integer } (-2, -1, 0, 1, 2, \ldots) \quad (11.2)$

This equation defines the angles for maximum intensity on the screen.

Interference patterns from double slits can be used to find the spacing between the two sources of light if the wavelength of the light being used is known. In other words, from the measured positions of the intensity maxima on the viewing screen, one can calculate the angles corresponding to the various values of $m$ and determine the unknown $d$. On the other hand, if $d$ is known, then the wavelength can be determined. Historically the wavelengths of light were difficult to measure until good quality slits became available about 100 years ago.

**Single slit diffraction**

![Figure 11.2. Geometry for determining the condition for destructive diffraction for a single slit.](image)

A narrow aperture such as a single slit will interact with a narrow beam of light in such a way that some of the light appears to be “bent” from its original direction of travel. The term diffraction refers to this apparent change of direction. This behavior is due to interference between parts of the light wave that pass through the slit at different points within the slit. Thus diffraction can be thought of—not as some new phenomenon—but as another manifestation of the interference of waves. For a single slit of width $a$ the relationship that describes the locations of the minima of intensity on the viewing screen is given by

$$a \sin \theta = n\lambda \quad (11.3)$$

where $n$ is an integer excluding zero, that is, $(-2, -1, 1, 2, \ldots)$ Note that zero is missing from the list! Also remember that with the double slit we measured to the maxima instead.

This expression looks a great deal like Equation 11.1, which describes intensity maxima for a double slit arrangement. Remember the important differences!
Multiple slit (more than two slits) interference

When more than two equally spaced slits are present, the explanation proceeds in exactly the same way as it does for the double slit arrangement. In fact the condition for making light from adjacent slits interfere constructively on the viewing screen is sufficient to ensure that the light from all of the slits will interfere constructively on the screen. Thus Equation 11.2 also prescribes the conditions to be met for intensity maxima when more than two equally spaced slits are present.

Determining the wavelength of light from a helium-neon laser

Never look directly into the beam or at reflections of the beam. Don’t point the laser at anything other than the screen. Failure to follow these instructions may lead to being expelled from the lab (will count as an absence).

If you need to locate the laser beam, insert a piece of paper into the beam path.

Minimize reflections by positioning the slide with the slits close to the exit aperture of the laser, which directs the reflected beam back toward the laser. If a laser is powered up but the beam is not visible, make sure the aperture at the front of the laser is open.

Using single slit diffraction

While the physics of double slit interference is relatively simple, the resulting diffraction patterns are relatively complicated. This is because each member of a double slit pair is also a source of single slit diffraction; in the double slit geometry, both patterns are observed together. The two effects are easier to disentangle after you have characterized the simpler, single slit pattern.

The glass slide with the green tape on the edges contains the various slit arrangements. Refer to Figure 11.3 for identification of slits on the slide. Use the single slit from Column 1, Row (e). (This slit has the same width of each of the double slits on your slide.) Mark maxima or minima as appropriate and calculate the wavelength of the light from this data. Does your calculated value agree with the accepted value for He-Ne lasers of 632.8 nm within the limits of error? How does the slit width compare to the laser wavelength? Does this comparison have any significance? (If so, test to verify)

Using double slit interference

On the viewing screen observe and mark the locations of the maxima or minima of intensity, as appropriate, for a double slit. Use one of the double slits from Column 5, either (b) or (c). From this information calculate the wavelength of the laser light. Consider an appropriate graph. Most students will find Excel helpful. You should again compare your calculated wavelength to the accepted value listed for He-Ne lasers. Does your calculated value agree with the accepted value within the limits of the expected uncertainties?
Using multiple slits

Choose a multiple slit from Column 3, either (b), (c), or (d), and calculate the wavelength from the resulting data. Does your calculated value agree with the accepted value within the limits of the expected uncertainties?

Measuring the diameter of a human hair with laser light

Mount a human hair so that it can be placed in front of the laser beam and look at the resulting light pattern. Does it most closely resemble the pattern of a single slit, a double slit, or multiple slits? Look at it carefully and note the pattern of bright and dark regions, particularly their spacing with respect to the center of the pattern. Then mark intensity maxima or minima as appropriate on the viewing screen. Using the textbook value for the wavelength of the laser light, calculate the diameter of the hair. Compare this value of the diameter to that obtained with a micrometer. Machinists use micrometers to make precise length measurements. Do the measurements agree within their expected uncertainties?

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
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<td><strong>Is able to analyze the experiment and recommend improvements</strong></td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report.</td>
<td>Description of experimental procedure leaves it unclear what could be improved upon.</td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed.</td>
<td>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.</td>
</tr>
<tr>
<td>Labs: 1-3, 5, 7-11</td>
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<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
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<tbody>
<tr>
<td><strong>Is able to explain patterns in data with physics principles</strong></td>
<td>No attempt is made to explain the patterns in data.</td>
<td>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.</td>
<td>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.</td>
<td>A reasonable explanation is made for the pattern in the data. The explanation is testable, and accounts for any significant deviations or poor fit.</td>
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<tr>
<td>Labs: 1-3, 5, 7-11</td>
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<td>Is able to perform algebraic steps in mathematical work.</td>
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<td>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.</td>
<td>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.</td>
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| **QR.B**  |             |             |            |
| Is able to identify a pattern in the data graphically and mathematically | 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. |
| Labs: 1-3, 5, 7, 9-11 |             |             |            |

| **IL.A**  |             |             |            |
| Is able to record data and observations from the experiment | "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. |
| Labs: 1-12 |             |             |            |

| **WC.B**  |             |             |            |
| Is able to draw a graph | 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. |
| Labs: 3, 6, 9, 11 |             |             |            |
Figure 11.3. Arrangement of slits and gratings on black slide.
Lab 11 Interference of Light

Name: ___________________________  Lab Partner: ___________________________

EXIT TICKET:

☐ Quit any software you have been using.
☐ Remove your hair sample from any mounting and dispose of it.
☐ 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

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<td>WC.B</td>
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Lab 11 Interference of Light

Name: ___________________________  Lab Partner: ___________________________

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Lab 12. Images with Thin Lenses

Goals

• To learn experimental techniques for determining the focal lengths of positive (converging) and negative (diverging) lenses in conjunction with the thin-lens equation.
• To learn how to make a scale “ray diagram” for a combination of a positive and negative lens using three principle rays for each lens and interpret it.
• To understand the specific meaning of the term “magnification” as applied to optical systems and to determine its value by three methods: (a) direct measurement, (b) calculation using the thin lens equation, and (c) using a ray diagram.

Introduction

For a simple focusing element with focal length $f$, it can be shown that

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

(12.1)

where $s$ and $s'$ are the object and image distances respectively. This is called the thin-lens equation. The object distance is measured from the light source to the center of the lens, and the image distance is measured from the viewing screen, where the real image is displayed, to the center of the lens.

An optical bench with a metric length scale attached to it, two lenses and holders, a light source, and a viewing screen are provided. The ray box light source is provided with crossed arrows that serve as the object to be imaged. For clearer view of the image, hang a clean sheet of paper over the viewing screen on the side facing toward the ray box.

Caution: Always secure (but not too tightly) the optical mounts on the optics bench so that the optical elements do not fall and break. Handle the lenses using the edges only. Your TA will demonstrate how to put a lens in the lens holder. Also be cautious not to let the optical bench near the table edges, the bench must remain perfectly level for the optics to align and measure properly, additionally the older benches are solid steel and will easily lead to injury.
Determining the focal length of a converging lens

Use the optical bench with the light source and the viewing screen to determine the focal lengths of the two lenses provided, one a converging lens (positive focal length) and the other a diverging lens (negative focal length). You should be able to tell which is which by looking at their cross-sections, a converging lens is thicker in the middle than along the edges. The focal length of the converging lens should be determined first. This can be done experimentally by finding pairs of object and image distances that give clear real images of the light source on the viewing screen. (A “real” image can be projected onto a screen.) Then use the thin lens equation to calculate the focal length. Repeat this several times using significantly different values of $s$ and $s'$. Find the mean value of the focal length and compute its standard deviation. If you do not know the how to compute a standard deviation, consult the Uncertainty/Graphical Analysis supplement to the lab manual.

What happens when you try the same procedure for the negative (diverging) lens?

Determining the focal length of a diverging lens

A diverging lens forms a real image only when used in conjunction with a converging lens. This is because the diverging lens forms the image on the same side that of the lens as the object being imaged. But if you place a screen between the object and lens, then you prevent image formation.

So, in order to view the image of the diverging lens, you must have an object which is not blocked by your screen. If we use the image which would be formed by a converging lens as the object of our diverging lens, then we can place the viewing screen on the opposite side of both lenses from the light source.

Using both lenses (place the converging lens nearest the light source), find lens and screen positions that yield clear images. In this configuration we can measure only the object distance of the converging lens and the image distance of the diverging lens. Knowing the focal length of the converging lens from previous measurements, the thin lens equation can be used to find the location of the image formed by the converging lens. Then treat the image of the converging lens as an object (be careful of the sign of the object distance) for the diverging lens. Apply the thin lens equation again to find the focal length of the diverging lens. Note that the sign conventions used in the thin lens equation demand that the focal length for a diverging lens be a negative number. Repeat this process for several significantly different lens and viewing screen positions. Calculate the mean focal length and the corresponding standard deviation.

Drawing a ray diagram for a two-lens system

Pick one configuration of lenses and viewing screen from your measurements on the diverging lens and draw a complete ray diagram to scale showing the formation of the intermediate image from the converging lens and the final image of the diverging lens. Ray diagrams for single converging and diverging lenses are shown in your textbook.
A simple ray diagram treats the object as a single point at the tip of an arrow drawn extending from the perpendicular line through the center of the lens. From the tip of this arrow you draw three lines:

1. A line perpendicular to the lens, which bends at the middle of the lens to pass through the focal point on the image side of the lens
2. A line through the focal point on the object side of the lens, which bends at the middle of the lens to run perpendicular to the lens
3. A line through the center of the lens, which continues straight through without bending to the image side of the lens.

While these three lines are sufficient to find the image formation, they are a simplification of how lenses work. Light from every point on the surface of the actual image used in real life is emitted in every direction at all times, and each light ray bends through the lens wherever it strikes the lens to wind up at the appropriate location on the final image.

Trace the rays for the lens closest to the light source first; then use the resulting image as the object for the second lens. Use your experimental values of focal lengths as given values on your diagram (This drawing needs to be done to scale so you can measure results from it). Does your ray diagram predict the correct location for the final image? Compare the result to your experimental value using the diverging lens.

**Magnification**

Magnification is defined as the ratio of the size of the image to the size of the object being imaged. When the image is upside down, the magnification is negative. If the image is upright, having the same orientation as the object, the magnification is positive. Using ray diagrams, one can show that the magnification (sometimes called the transverse magnification), \( m \), is equal to \( \frac{-d'}{d} \) for both positive and negative lenses. Compare the heights of the object and image in your ray diagram to determine magnification of the two-lens combination. Compare this value with the magnification calculated using the thin-lens equation for the same lens configuration, knowing the focal lengths and positions of the lenses relative to the object and the final image.
### Chapter 12. Images with Thin Lenses

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<tr>
<th>SL.A.a</th>
<th>Is able to analyze the experiment and recommend improvements</th>
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<tr>
<td><strong>No Effort</strong></td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report</td>
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<tr>
<td><strong>Progressing</strong></td>
<td>Description of experimental procedure leaves it unclear what could be improved upon.</td>
</tr>
<tr>
<td><strong>Expectation</strong></td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed.</td>
</tr>
<tr>
<td><strong>Scientific</strong></td>
<td>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.</td>
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<tr>
<td>WC.C</td>
<td>No Effort</td>
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<tr>
<td>Is able to construct a ray diagram</td>
<td>No Ray Diagram is constructed.</td>
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Lab 12 Images with Thin Lenses

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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 vice 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

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 $x$, $(x_1,x_2,x_3,...,x_N)$, is given by

$$x_{\text{avg}} = \frac{x_1 + x_2 + x_3 + ... + x_N}{N} = \frac{1}{N} \sum_{i=1}^{N} x_i$$  \hspace{1cm} (13.1)

The individual measurements of $x$ will generally deviate from $x_{\text{avg}}$ 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.

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

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

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 $N$, $x_{\text{avg}}$, 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.)

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

(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 ($x_{\text{avg}}$). 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, ±15 points) of the average. Ideally, one would expect 99.7% of the points to lie within three standard deviations (here, ±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 $x_{\text{avg}} - 3\sigma = 62.5$ and $x_{\text{avg}} + 3\sigma = 107.5$.) 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 $x_{\text{avg}}$ and $\sigma(x)$ may be poor. In more advanced work, it can be important to correct for this lower precision.

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,” $\sigma(x_{\text{avg}})$. Although one can repeat the entire set of $N$ measurements several times to compute $\sigma(x_{\text{avg}})$, statistics allows us to estimate $\sigma(x_{\text{avg}})$ using the original $N$ measurements alone:

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

(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, $\sigma(x_{\text{avg}})$ 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 devices have 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 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 \( x_{\text{avg}} \) its uncertainty, and represented it by the symbol \( u(x_{\text{avg}}) \). If the average and standard deviation of \( x \) are available, the best estimate of \( x \) is \( x_{\text{avg}} \), and the best estimate of the uncertainty of \( x_{\text{avg}} \) is the standard deviation of its mean, \( \sigma(x_{\text{avg}}) \). Then \( u(x_{\text{avg}}) = \sigma(x_{\text{avg}}) \). 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—the Derivative Method**

Derivatives can be used to estimate the uncertainty associated with a function of the measured quantity, \( f(x) \), due to uncertainty in the measured variable, \( x \). We normally have an experimental value of \( x_{\text{avg}} \). To see how the uncertainty in \( x \) affects \( f(x_{\text{avg}}) \), we can plot \( f(x) \) as shown in Figure 13.2. The change due to small variation in \( x \) is given by \( \Delta f \approx f'(x) \Delta x \), where \( f'(x) \) is the slope (and the derivative) of \( f(x) \) at \( x_{\text{avg}} \).

For the simple function \( f(x) = 1/x \), with \( x_{\text{avg}} = 2.0 \) and \( u(x_{\text{avg}}) = 0.1 \), the uncertainty in \( f(x) \), \( u[f(x)] \), is

\[
u[f(x)] = \sqrt{\left[ \frac{df}{dx} u(x_{\text{avg}}) \right]^2} = \sqrt{\left[ -\frac{1}{x^2} u(x_{\text{avg}}) \right]^2} = \sqrt{\left( \frac{1}{4.0^2} \right)^2 (0.1)^2} = 0.25 \quad (13.5)
\]

---

If $f$ is a function of more than one variable, say $(x,y,z)$, where $x$, $y$, and $z$ represent three measured quantities, the uncertainty in $f(x,y,z)$ is found by computing uncertainties for each variable alone and adding them in quadrature, as explained below. The uncertainty due to $x$ is computed by treating $f(x,y,z)$ as a function of $x$ only. Then from Equation 13.5

$$u[f(x)] = \sqrt{\left(\frac{\partial f}{\partial x} u(x_{\text{avg}})\right)^2}$$

where we introduce the $\partial$ symbol to indicate that the $y$ and $z$ variables are being treated as constants when the derivative is taken. This is equivalent to assuming that the variables are independent; that is, none of the variables are completely determined by any subset of the others. Likewise:

$$u[f(y)] = \sqrt{\left(\frac{\partial f}{\partial y} u(y_{\text{avg}})\right)^2}$$
$$u[f(z)] = \sqrt{\left(\frac{\partial f}{\partial z} u(z_{\text{avg}})\right)^2}$$

(13.7)

where $u[f(x,y,z)]$ is the estimated uncertainty in $f(x,y,z)$; $u(x_{\text{avg}})$, $u(y_{\text{avg}})$, and $u(z_{\text{avg}})$ are the uncertainties in the measured values of $x_{\text{avg}}$, $y_{\text{avg}}$, and $z_{\text{avg}}$, respectively, all evaluated at $(x_{\text{avg}}, y_{\text{avg}}, z_{\text{avg}})$. Again, the $\partial$ symbols indicate that $x$ and $z$ are treated as constants when the derivative with respect to $y$ is taken; likewise $x$ and $y$ are treated as constants when the derivative with respect to $z$ is taken.

If you draw a two dimensional version of Figure 13.2, the Pythagorean theorem can be used to show that the uncertainties add like the edges of a right triangle, that is, in “quadrature.” (This is how individual deviations add when a standard deviation is calculated.) For a function of three variables, the uncertainties add in the same way:

$$u[f(x,y,z)] = \sqrt{\left(\frac{\partial f}{\partial x} u(x_{\text{avg}})^2 + \left(\frac{\partial f}{\partial y} u(y_{\text{avg}})^2 + \left(\frac{\partial f}{\partial z} u(z_{\text{avg}})^2\right)\right)^2}$$

(13.8)

This technique can be generalized to account for as many measured parameters as necessary. When uncertainties from difference sources are added in this way, the result is called the “combined standard uncertainty,”\(^4\) or the “standard uncertainty.”\(^5\)

Consider the function $f(x,y,z) = x^{1/2}y^2\sin(z)$. To illustrate the difference between the derivatives used to calculate uncertainties, consider the regular (or total) derivative of $f(x,y,z)$ with respect to $x$, calculated using the product rule for derivatives.

$$\frac{df}{dx} = \frac{y^2 \sin(z)}{2x^{1/2}} + x^{1/2}y \sin(z) \frac{dy}{dx} + x^{1/2}y^2 \cos(z) \frac{dz}{dx}$$

(13.9)


However, in an experiment, \( x, y, \) and \( z \) are independent variables. Therefore we expect \( dy/dx = dz/dx = 0 \). For the purposes of calculating the contribution of \( u(x_{\text{avg}}) \) to the uncertainty of \( f, y \) and \( z \) might as well be constants. The three required derivatives of \( f(x,y,z) \) from Equation 13.8 are:

\[
\frac{\partial f}{\partial x} = \frac{y^2 \sin(z)}{2x^{1/2}} \quad \frac{\partial f}{\partial y} = 2x^{1/2}y \sin(z) \quad \frac{\partial f}{\partial z} = x^{1/2}y^2 \cos(z) \tag{13.10}
\]

In practice, taking derivatives can be a lot of work. However, many calculations involve products, which are simplified by starting with the natural logarithm of the calculated quantity. Since

\[
\frac{\partial}{\partial x} \ln(f) = \frac{1}{f} \frac{df}{dx},
\]

we can calculate the derivatives we need from the derivatives of the logarithm. Since the logarithm function splits our function into terms with simple (partial) derivatives, they are easy to compute. In our example, \( \ln(f) = (1/2) \ln(x) + 2 \ln(y) + \ln(\sin(z)) \), so

\[
\frac{\partial}{\partial x} [\ln(f)] = \frac{\partial}{\partial x} \left[ \frac{\ln(x)}{2} \right] = \frac{1}{2x} \quad \frac{\partial}{\partial y} [\ln(f)] = \frac{\partial}{\partial y} [2 \ln(y)] = \frac{2}{y} \quad \frac{\partial}{\partial z} [\ln(f)] = \frac{\partial}{\partial y} [2 \ln(\sin(z))] = \frac{\cos z}{\sin z} = \cot(z) \tag{13.12}
\]

Substituting these partial derivatives into Equation 13.8 yields

\[
u[f(x,y,z)]_f = \sqrt{\left[\frac{u(x_{\text{avg}})}{2x_{\text{avg}}}\right]^2 + \left[\frac{2u(y_{\text{avg}})}{y_{\text{avg}}}\right]^2 + [\cot(z_{\text{avg}})u(z_{\text{avg}})]^2} \tag{13.13}
\]

While this expression is not pretty, it is much simpler than the one obtained by substituting the derivatives of Equation 13.10 directly into Equation 13.8. For simplicity, the uncertainty is in Equation 13.13 is expressed as a fraction of the value of \( f(x,y,z) \). This is called the “relative uncertainty,” or more completely, the “relative combined standard uncertainty.”

**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 \( m_{\text{bal}} \).

A straightforward way to determine whether these two measurements is to compare the discrepancy between the two measurements, say \( \Delta = |m_{F/a} - m_{\text{bal}}| \), 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 certainly 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. In this example,

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

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. 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.

### 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) versus \( x \) (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

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7Ibid, Barry N. Taylor and Chris E. Kuyatt.

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) and \( x \) (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

\[
\ln(y) = \ln(ax^n) = \ln(a) + n\ln(x) = \ln(a) + n\ln(x)
\]  

(13.15)

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 \[(13.15)\] 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 \( a \).

**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

\[
\ln(y) = \ln(ae^{bx}) = \ln(a) + \ln(e^{bx}) = \ln(a) + bx
\]  

(13.16)

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 \[(13.16)\] 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 \(y_{\text{max}}\) above \(y_{\text{avg}}\), that is, at position \(y_{\text{max}} = y_{\text{avg}} + u(y_{\text{avg}})\). Similarly, we indicate the lower limit of expected values by drawing a bar at position \(y_{\text{min}} = y_{\text{avg}} - u(y_{\text{avg}})\). Figure 13.3 shows how the upper error bar at \(y_{\text{max}}\) and the lower error bar at \(y_{\text{min}}\) 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 \(x_{\text{max}}\) and the leftmost error bar at position \(x_{\text{min}}\).

Occasionally one encounters systems where the upper and lower error bars have different lengths. In this case, the upper uncertainty, \(u_+(y_{\text{avg}})\) does not equal the lower uncertainty, \(u_-(y_{\text{avg}})\).

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**Figure 13.3.** Diagram of error bars showing uncertainties in the value of the \(x\)- and \(y\)-coordinates for point \((x_{\text{avg}}, y_{\text{avg}})\). When you print a graph in lab, the labels are omitted.
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 your 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 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, $x_{\text{avg}}$, 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, $\sigma(x_{\text{avg}})$, which represents the uncertainty in $x_{\text{avg}}$. 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 $x_{\text{avg}}$, 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: $y = mx+b$” 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 $\sigma(x_{\text{avg}})$. 
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 Σ. This Capstone’s “statistics” icon. Clicking on the down arrow just to the right of the Σ 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 Σ 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 → 0.00” icon along the top of your table. (To increase the precision, click on the “0.00 → 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 Σ 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:
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:

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

<table>
<thead>
<tr>
<th>SL.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to analyze the experiment and recommend improvements</td>
<td>No deliberately identified reflection on the efficacy of the experiment can be found in the report</td>
<td>Description of experimental procedure leaves it unclear what could be improved upon.</td>
<td>Some aspects of the experiment may not have been considered in terms of shortcomings or improvements, but some are identified and discussed.</td>
<td>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.</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>SL.A.b</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No deliberately identified hypothesis is present in the first half page or so of notes</td>
<td>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</td>
<td>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.</td>
<td>The hypothesis is clearly stated and the direct link to the experiment at hand is apparent to any reasonably informed reader.</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL.A.c Is able to determine hypothesis validity</td>
<td>A statement about the hypothesis validity is made, but it is not consistent with the data analysis completed in the experiment.</td>
<td>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.</td>
<td>A statement about the hypothesis validity is made which is consistent with the data analysis and all assumptions are taken into account.</td>
</tr>
<tr>
<td>Labs: 4-6</td>
<td></td>
<td></td>
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</table>

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.

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SL.B.a</strong></td>
<td>At least one of the measuring tools used in lab lacks a clear identification of precision/limitation</td>
<td>All measuring tools are identified with mention of the precision/limitation of each tool, but no details on how measurements are performed</td>
<td>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.</td>
</tr>
<tr>
<td>Labs: Not used</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL.B.b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to explain patterns in data with physics principles</td>
<td>No attempt is made to explain the patterns in data</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>Labs: 1-3, 5, 7, 9-11</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL.B.c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Is able to explain steps taken to minimize uncertainties and demonstrate understanding through performance where able.</td>
<td>No explicitly identified attempt to minimize uncertainties and no attempt to describe how to minimize uncertainties present</td>
<td>No explicitly identified attempt to minimize uncertainties is present, but there is a description of how to minimize experimental uncertainty.</td>
<td>An attempt is made and explicitly identified for minimizing uncertainty in the final lab results, but the method is not the most effective.</td>
</tr>
<tr>
<td>Labs: 2, 6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>CT.A.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to compare recorded information and sketches with reality of experiment</td>
<td>No sketches present and no descriptive text to explain what was observed in experiment</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
</tr>
</tbody>
</table>

| Labs: 3, 4, 6-8 |

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.

<table>
<thead>
<tr>
<th>CT.A.b</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to identify assumptions used to make predictions</td>
<td>No attempt is made to identify any assumptions necessary for making predictions</td>
<td>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</td>
<td>Relevant assumptions are identified regarding the specific predictions, but are not properly evaluated for significance in making the prediction.</td>
<td>Sufficient assumptions are correctly identified, and are noted to indicate significance to the prediction that is made.</td>
</tr>
</tbody>
</table>

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.
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.

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.

<table>
<thead>
<tr>
<th>CT.B.a</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to describe physics concepts underlying experiment</td>
<td>No explicitly identified attempt to describe the physics concepts involved in the experiment using student’s own words.</td>
<td>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.</td>
<td>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.</td>
<td>The physics concepts underlying the experiment are clearly stated.</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No attempt to explicitly identify any variables as dependent or independent</td>
<td>Some variables identified as dependent or independent are irrelevant to the hypothesis/experiment, or some variables relevant to the experiment are not identified</td>
<td>The variables relevant to the experiment are all identified. A small fraction of the variables are improperly identified as dependent or independent.</td>
<td>All physical quantities relevant to the experiment are identified as dependent and independent variables correctly, and no irrelevant variables are included in the listing.</td>
</tr>
</tbody>
</table>

This rubric also should be completed 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.
**LIST OF ALL RUBRICS**

<table>
<thead>
<tr>
<th>QR.A</th>
<th>Is able to perform algebraic steps in mathematical work.</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No equations are presented in algebraic form with known values isolated on the right and unknown values on the left.</td>
<td>Some equations are recorded in algebraic form, but not all equations needed for the experiment.</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>Labs</td>
<td>3, 6, 9-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 completed 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.

<table>
<thead>
<tr>
<th>QR.B</th>
<th>Is able to identify a pattern in the data graphically and mathematically</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No attempt is made to search for a pattern, graphs may be present but lack fit lines</td>
<td>The pattern described is irrelevant or inconsistent with the data. Graphs are present, but fit lines are inappropriate for the data presented.</td>
<td>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</td>
<td>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.</td>
</tr>
<tr>
<td>Labs</td>
<td>1-3, 5, 7, 9-11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>QR.C</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to analyze data appropriately</td>
<td>No attempt is made to analyze the data.</td>
<td>An attempt is made to analyze the data, but it is either seriously flawed, or inappropriate.</td>
<td>The analysis is appropriate for the data gathered, but contains minor errors or omissions</td>
<td>The analysis is appropriate, complete, and correct.</td>
</tr>
<tr>
<td>Labs: 1-4, 6, 7, 9-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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](https://openstax.org), [MIT OpenCourseWare](https://ocw.mit.edu), [EdX](https://www.edx.org) and [Coursera](https://www.coursera.org). 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.

<table>
<thead>
<tr>
<th>IL.A</th>
<th>Is able to record data and observations from the experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labs:</td>
<td>1-12</td>
</tr>
<tr>
<td>No Effort</td>
<td>&quot;Some data required for the lab is not present at all, or cannot be found easily due to poor organization of notes. &quot;</td>
</tr>
<tr>
<td>Progressing</td>
<td>&quot;Data recorded contains errors such as labeling quantities incorrectly, mixing up initial and final states, units are not mentioned, etc. &quot;</td>
</tr>
<tr>
<td>Expectation</td>
<td>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.</td>
</tr>
<tr>
<td>Scientific</td>
<td>All necessary data has been recorded throughout 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.</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>IL.B</th>
<th>Is able to construct a force diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labs:</td>
<td>Not used</td>
</tr>
<tr>
<td>No Effort</td>
<td>No force diagrams are present.</td>
</tr>
<tr>
<td>Progressing</td>
<td>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.</td>
</tr>
<tr>
<td>Expectation</td>
<td>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.</td>
</tr>
<tr>
<td>Scientific</td>
<td>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.</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No sketch is constructed.</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
</tr>
</tbody>
</table>

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.
**WC.B**

Is able to draw a graph

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No graph is present.</td>
<td>A graph is present, but the axes are not labeled. OR there is no scale on the axes. OR the data points are connected.</td>
<td>&quot;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.&quot;</td>
<td>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.</td>
</tr>
</tbody>
</table>

Labs: 3, 6, 9, 11

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.

**WC.C**

Is able to construct a ray diagram

<table>
<thead>
<tr>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Ray Diagram is constructed.</td>
<td>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.</td>
<td>&quot;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.&quot;</td>
<td>&quot;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.&quot;</td>
</tr>
</tbody>
</table>

Labs: 12

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.

<table>
<thead>
<tr>
<th>WC.D</th>
<th>No Effort</th>
<th>Progressing</th>
<th>Expectation</th>
<th>Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is able to draw a circuit diagram</td>
<td>No circuit diagram is drawn.</td>
<td>Components of the circuit are missing, or connected incorrectly. Components are not clearly labelled.</td>
<td>&quot;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.&quot;</td>
<td>Circuit diagram contains minimal connecting lines, components are neatly arranged to ensure labels are readily identified to appropriate components.</td>
</tr>
<tr>
<td>Labs: 3, 4, 9, 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

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