Physics 102

Lab Manual

Summer 2018

Manual Owner ____________________

Lab Section Number _______________

TA Name _________________________

TA e-mail ________________________

Lab Group Rotation Number ______

Version: Summer ’18, 102, May 29, 2018

Lab Schedule

Note! Lab rooms change frequently. Refer to your schedule below and consult the bulletin boards across the halls from the elevators on the second, third, or fourth floors of Webster Physical Sciences Building for the latest lab room information.

Lab	Week of	Title of laboratory	Open Stax Chapter
0	June 5	Intro to Work in Laboratory	
1	June 7	Electrostatics	18
2	June 12	Electric Fields	18, 19
3	June 14	Ohm's Law	20
4	June 19	Series and Parallel Resistors	21
5	June 21	Magnetic Fields	22
6	June 26	Current Balance	23
7	June 28	Electromagnetic Induction	22
	July 3	**No Labs: Spring Break**	
8	July 5	Reflection and Refraction	25
9	July 10	Interference of Light	27
10	July 12	Images with thin Lenses	25
11	July 17	Optical Instruments	26
12	July 19	Radioactivity	31
	July 24	**Lab Exam** during your regular lab period	
	July 26	**No Labs (Finals)**	

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Contents

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Lab Syllabus

Point of contact:

Lab Director	Dr. Marc Weber
Office	Webster Hall Room 527
Office hours	M,W,F 10:00 am to 11:00 am
	(walk-in are always welcome)
Phone	335-7872
Email	physics.labs@wsu.edu

Prerequisites: MATH 107 or 108 (trigonometry) with a grade of C or better, a minimum ALEKS math placement score 75%, or passing MATH 140, 171, 202, or 206. Algebra/trigonometry-based physics; topics in mechanics, wave phenomena, temperature, and heat; oriented toward non-physical science majors.

Learning goals: To experimentally probe concepts learned from the classroom and related materials; to reduce settings from the natural world to basic testable configurations; to carry out the tests, analyze the observations and conclude by comparing results to initial hypotheses; to document the activities in lab-notes, sketches, and diagrams; to acquire data with various sensors and computer support; to analyze results with Excel and other software and fit them with linear regression tools; to record results and findings; to compose formal reports; to work with a lab partner; to manage limited time allotted for each experiment.

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

Campus Safety: 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” URL: https://oem.wsu.edu/emergency-procedures/active-shooter/ 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 (URL: https://oem.wsu.edu/emergency-procedures/active-shooter/) and visit WSU Safety: URL https://oem.wsu.edu/about-us/.

Academic Integrity: Academic dishonesty, including all forms of cheating, plagiarism, and fabrication, is prohibited as defined in the Standards of Conduce for Students, WAC 504-26-010(3) (URL: http://apps.leg.wa.gov/WAC/default.aspx?cite=504-26-010). The instructor reserves the right to take appropriate action. A failing grade in the class may result. Incidents of academic dishonesty will be referred to the Office of Student Conduct. If you have any questions about what is and is not allowed in this course, you should ask the course instructors before proceeding.

A partial list of prohibited conduct appears in Washington Administrative Code (WAC) Section 504-26 (http://apps.leg.wa.gov/wac/default.aspx?cite=504-26). Of special importance to the laboratories is the false reporting of data, experiment results, information, or procedures. The data and results in your lab notebook and reports must result from your own work in the current semester. Reporting data acquired by others (including your lab partner if you did not contribute) or in previous semesters is academically dishonest. Fabrication of results, information, or procedures, and sabotaging other students' work is also prohibited. Likewise, sharing information about the end-of-semester lab exam with students yet to take the exam is prohibited. Violations of this policy will affect your lab grade and may be reported to the Student Conduct Committee as instances of academic dishonesty.

Attendance, conduct, exams, evaluation, grading

Attendance: Attendance is mandatory. Summer classes are conducted in a very condensed time frame. Missing a lab results in a zero score for that lab. Make-up labs are not granted. In lieu, the two lowest scoring lab grades will be dropped.

Student conduct: Academic integrity is expected of all students (see above). During the experiments students are expected to work in teams of two. The lab partners will jointly carry out all lab activities and at times may even share data among all stations in the room. Data and graphs should be printed out in duplicate or saved for each of the team. However, data analysis and evaluation and reporting in lab-notes or formal reports will be an individual activity. For more information regarding lab notes and reports, refer to the "Lab Work, Notes and Reports" section immediately following the syllabus.

The lab work is conducted in small teams. We expect students to be on time to labs and lab exams and to mute their cell phones for the duration. Being late may drag your lab-partner's grade down. Many physics concepts are subtle, and even the most intelligent students make mistakes. In this environment, it is important that students be willing to ask questions if they don't understand what their lab partners say or do. To this end, we require that students and teaching assistants alike avoid behavior that discourages communication. This includes threats and insults. Students who repeatedly disrupt lab may be directed to leave the room and may receive a zero grade for that week's lab.

Once the lab is complete, students are expected to tidy up and leave the station as they found it.

Submission of work for evaluation: Records (i.e. the lab-notes) of work completed during lab, including tutorials, must be turned in to your teaching assistant before you leave the room. At times students may be permitted to complete assignments after the lab session. Work completed after lab must be turned in to the TA no later than at the start of the next session. Failure to turn in lab-notes will result in low scores.

Exam: An exam is administered during the last week before the lecture final exam within your regularly scheduled laboratory section. Do not skip the exam. This is the time to demonstrate your record keeping skills. The exam may include any experimental techniques, methods of data analysis, and/or concepts covered during the semester. You may need to refer to your graded lab work for the current semester and the lab manual during the exam. You may not refer to the textbooks or other references. Work on the exam is individual (no lab partners). Bring your calculator.

Evaluation: The class grade is composed of 75% from the lecture and 25% laboratory section. See your instructor regarding the lecture component. The experiments include

- 1 introductory tutorial with up to 20 points,
- lab notes from 12 experiments with up to 100 points each with options for bonus points such as homework
- 1 final laboratory exam with up to 100 points.

Each will be scored on a 0 to 100 scale. The lowest two scoring lab notes from experiments will be dropped. Not attending a laboratory experiment or not submitting lab-notes results in a zero score for that lab. Sum up the 10 highest scoring labs and add all bonus points. Cap this at 1000, the maximum lab score. There will be no curving. The teaching TA may not be the person grading your lab.

Grading: The grades are compiled as follows: For each component item (first column) a maximum number of points are given (second column). They contribute to the lab grade according to column 3 (lab only) and the overall grade in the class (column 4).

item	max. points	lab grade%	class grade %	comment
tutorial	50	4	1	1st session
10 of 12 labs	1000	76	19	10 highest scoring labs of 12 plus bonus
tutorial & labs	1050	80	20	
lab exam	100	20	5	
laboratories		100	25	see lab director
lecture	n/a	n/a	75	see instructor
total			100	total grade

By Physics and Astronomy Department policy, should the lab grade fall below 50% lab grade, the student will receive a failing F grade as the class grade independent of lecture performance. In the other end of the scale, should the lab grade be 80% lab grade and higher but the student fails the lecture, he/she may choose to "carry over" the lab grade when the course is retaken. In addition a high laboratory grade in excess of 80% lab grade. To take advantage of this option, the student must notify the lab director no later than the first week of the semester that you are repeating the course. 100-level labs cannot substitute for 200-level labs.

Questions regarding grades on lab assignments need to be discussed with your teaching assistant within two weeks of receiving the graded material (earlier at the end of the semester). Final lab grades will be posted on the bulletin board on the 3rd floor of Webster Hall. To affect the lab grade submitted to your instructor, changes must be made by Friday morning of Final Exam week. Errors that affect your physics course grade will be corrected after final grades are submitted to the Registrar, if necessary.

Safety resources

General information on campus safety is posted at http://safetyplan.wsu.edu—the Campus Safety Plan. Information on how to prepare for potential emergencies is posted on the Office of Emergency Management web site (http://oem.wsu.edu/). Safety alerts and weather warnings are posted promptly at the WSU Alerts site (http://alert.wsu.edu/). 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 in MyWSU. To enter or update this information, click the “Update Now!” link in the “Pullman Emergency Information” box on your MyWSU home page (https://my.wsu.edu/).

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. Students who disobey the safety instructions will be directed to report to the lab director. All accidents and injuries must be reported promptly to your teaching assistant.

An Emergency Guide is posted by one door of each lab room. If faced with an emergency, follow the “Alert, Assess, Act,” protocol: Remain ALERT (through direct observation or emergency notification), ASSESS your specific situation, and ACT to ensure your own safety and the safety of those around you. In case the fire alarm sounds, leave the building promptly in an orderly fashion. If you are not on a ground floor, use the stairs. Do not use the elevators. After exiting the building, gather across from the basketball court behind Waller Hall (down the hill, south of Webster Hall, see Figure 1) with the other members of your lab. A representative of the Department of Physics and Astronomy will tell you when it is safe to re-enter the building. If this does not happen before the end of the lab period, you are free to leave for your next class. If the emergency involves an active shooter, your options are to RUN, HIDE, or FIGHT (https://www.youtube.com/watch?v=5VcSwejU2D0). Each lab room door can be locked from inside in case of a lock down.

Emergency Assembly point.pdf

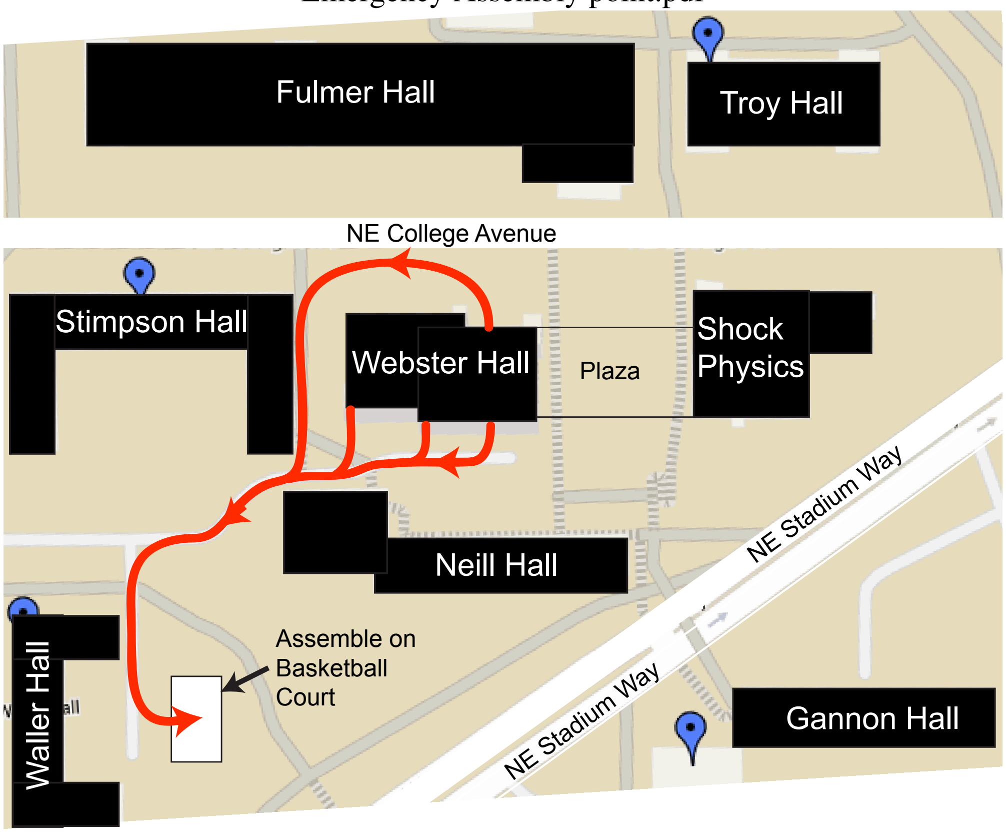

Figure 1. Physics and Astronomy assembly point. In case of a fire alarm, exit the building and gather at the basketball court behind Waller Hall. Use the stairs. Do not use the elevators in case of fire. A department representative will tell us when it is safe to re-enter the building.

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 you are graded according the criteria stated during your lab meeting.

Lab Work, Notes and Reports

> "It is very necessary that those who are trying to learn from books the facts of physical science should be enabled by the help of a few illustrative experiments to recognize these facts when they meet with them out of doors." James Clerk Maxwell "Introductory lecture on experimental physics" in "The Scientific Papers of James Clerk Maxwell", W.D. Niven editor, Volume II, pp 242 to 243, Cambridge University Press (1890).

Just like when learning to drive a car, to perform open heart surgery or to acquire pretty much any skills, book knowledge is insufficient. Hands on practice is makes the driver, surgeon, skier, scientist or engineer. To deepen the understanding of what you learn in the lecture, you will carry out some experiments. "An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer." Max Planck in "The Meaning and Limits of Exact Science", Science (30 Sep 1949), 110, No. 2857, 325. You will develop some skills and concepts of this interaction with Nature. They are best learned in the laboratory. These skills include posing questions, build models and devise experiments, collect and analyze data, and critically comparing results to predictions or theory. Keeping good laboratory and composing formal reports of results helps communicating with peers. You will need some background on statistics to perform quantitative testing of hypothesis. These skills apply to quantitative work in many fields, including health- and life-sciences, mathematics, and engineering and chemistry. Many 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 were. You will often be expected to figure things out on your own in consultation with your lab partner, and will be graded on the quality of those decisions. 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:

- Pose a question to Nature.
- Build simple physical models that incorporate lecture material.
- Design and perform simple experiments to test or improve these models.
- Employ representative software packages to collect and analyze data.

- 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

You should be prepared for the laboratory activities. At times, the laboratory material may not have been covered in class. You should

- 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.
- Before each lab, read the relevant chapter of the lab manual, particularly if the material has not already been covered in lecture. Review related course material
- Arrive at your lab on time. Note that the lab rooms change from week to week. The room schedules are posted on the bulletin boards across from the elevators on the second, third and fourth floors of Webster Hall.
- Bring your lab manual, calculator, pen and pencil, a lab notebook with carbonless copies, and scratch paper to lab each week.
- Come prepared to perform mathematical calculations based on the level of math appropriate for the course. This includes algebra, geometry, and trigonometry. For Physics 201 and 202, calculus is also required.
- Do not bring food, tobacco, or beverages into a lab room.
- If you miss or expect to miss a lab due to sickness or another valid reason, arrange for a make-up laboratory as described in the Requests for Make-Up Laboratories section of this syllabus.

During the laboratory session, your TA will provide introductory material. She/he is there to guide and nudge towards sound experimental practice. The TA will not provide plain answers to you but will respond with counter questions. If specific equipment must be set up or malfunctions, your TA will help or call for further assistance. You should

- Note down the date, class and section, the laboratory experiment name, your lab partner.
- Don't panic, be creative, trust your reasoning skills. Interact with your lab partner; bonus credit may lurk around.
- Use only carbonless copy laboratory notebooks with page numbers.
- Complete all labs and the lab exam.
- Computers have crashed. If at all possible, record all measurement data and results in your lab notes! You and your lab partner should each have all data.

- Make sure that all submitted work is your own. Academic dishonesty is not tolerated and is grounds for failing the course.
- Submit the original of your lab notes to your TA. This will be part of your grade. Retain the copy to complete any take home assignments.

After the laboratory session

- Complete all writing assignment and any formal reports as requested.
- Submit your work in the mail slot of your section on the 3rd floor of Webster.
- Do so on time! Do so in the correct mail slot. Failure may result in loss of credit.

Written communication of laboratory work

Records of laboratory work take at least two forms. The lab notebook is a protocol of all activities in the lab. Formal reports communicate key findings and results to a larger audience.

Lab notes: For reference and legal purposes, the primary record of lab work is the lab notebook. In virtually every work environment, be the research lab at universities or in industry or in a medical practice or repair shop, detailed records of activities are maintained. These are the lab notes. They function as memory aides, means to collect thoughts and to lay out upcoming steps in work and research. The notes are used as a workspace for new ideas and the efforts towards their validation, or to prove them wrong. They are a chronological and legal record. We require that you use a commercial notebook with index pages at the front, and numbered carbonless copy pages for notes. Many introductory chemistry laboratories use suitable notebooks. If your chemistry notebook is otherwise suitable and has blank pages left, you are free to use it for this course. At the end of each laboratory, you will submit the copy pages from your notebook to your teaching assistant. You will submit the copies for any work you do outside of class with the rest of the lab assignment. You will retain the original copies for your record and study. When you fill up one notebook, you are expected to obtain another.

Formal report: For communication within a broader technical community, lab work is summarized in technical reports. These reports communicate results and omit many details recorded in your lab notebook. Because the preparation of proper lab reports require considerable time and effort, we will not require a complete report for each laboratory. However, to satisfy UCORE requirements, some formal writing is necessary. For some labs, we will ask that you submit a well written, formal report, where you focus on communication tasks.

These two forms of communication employ different standards that can be only partially implemented in an instructional lab. What we require is described below.

Lab notes—official record of attendance and work performed[1]

In general: The contents of your lab notes are the basis for grading the labs and for you to succeed in the exam. Neatness is not essential, but lab notes must be legible. **If a TA cannot read it, you will not get credit.** Your notes must include a full record of activities in the lab section. The details will be discussed during the first "introductory session" of your lab. Essential components are:

- *Identify yourself* Your name, WSU ID, your partner's name, the date, the class and lab section, the Teaching Assistant's name (TA). Is this a makeup lab?
- *What do you want to know?* The objective of the lab. What concept of physics is up for testing.
- *What do you know?* A collection of knowledge to help with the answer. Key components of the teaching assistant's (TA) introduction belong here.
- *What equations are useful?* Write down equations that are to be tested. These may come from your TA or the classroom lecture or are derived here in the lab.
- *Sketches and free body diagrams* of the experimental setup with definitions. Make **large** drawings. Do not clutter with irrelevant details. Define components (i.e. cart, motion sensor, track, "The track is level). Add physics parameters and define them (i.e. momentum p, initial position xo).
- *Make predictions*: What results do you expect to observe? For example: "The cart will roll along the track with constant speed", or "The cart will accelerate until it hits the end of the track". Illustrate with drawings. Specify, if something is constant, increases linear or "comes to a full stop".
- *Timestamps*: What was done or observed when? Note the time on the right margin! At least once on each page.
- *Write down any activities chronologically*. Note the values of setup parameters. "Tracking the fall of a basketball with a motion sensor". "The track is set horizontally as checked with a level."
- *Data and results*Raw data, analysis results and units must be recorded. Tables are very useful. Values that you enter into Excel spreadsheets **must** appear in your handwritten notes.
- *Error analysis*is as essential to lab work as the measured values and their units. Uncertainties and standard deviations quantify the reliability of a measurement.
- *Graphs* Large format graphs of recorded data (landscape format full page printouts; use zoom and pan). Label them and note where they belong in the lab notes. Clearly mark, which part of the graph is used for any analysis such as curve fitting.

[1] A detailed introduction to the lab notebook is found in: Howard M. Kanare, *Writing the Lab Notebook*, (American Chemical Society, Washington, DC, 1985).

- *Math derivations* Details of mathematical derivations or algebraic steps. The grader should be able to follow your algebraic steps.

- *Comparisons* Experimental findings should be compared to predictions. A quantitative method to do this will be introduced in the labs. If there is disagreement, point that out and explain. Disagreements will not result in loss of grade credit. Failure to point out disagreements or not to discuss them will lead to points subtractions.

Lab notes and exams At the end of the semester, you will take a lab exam in which parts of a few selected experiments are to be reproduced — usually with small changes. Parts of the exam will be impossible to resolve if you did not keep good records in your lab notebook. The exam is much easier if your notes are complete.

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 be lowered due to properly 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.

In case of a dispute over lab attendance or what you did in lab, pages torn from your lab notebook will not be accepted as evidence. Likewise, notes on regular notebook paper will not be accepted as evidence. A computer printout is evidence only if it is permanently attached (taped, not stapled) to an original page in your notebook or shows the signature of the supervising teaching assistant. Missing original pages are evidence for suspicious activity and carry a "presumption of guilt": we will assume you are guilty of something—the only question is what.

If you rewrite or type your notes, understand that your original notes are the official record, not the rewritten notes. Notes made after the fact are not valid records and will not be treated as such. The copy pages with your notes must be submitted in order to receive a grade for laboratory work.

Each entry in your lab notebook should start with the current date and time in the right margin. If you work on your lab notes at home after lab, the entries made at home must also begin with the current date and time (the time of writing, not the time of the lab). 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. You lab notebook should also have an index for this information.

Unlike formal lab reports, texts in lab notes should be brief. These are not novels. Think of headlines and bullet lists. 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 or 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—save time and are easier to understand (i.e. grade). 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.

Lab reports—formal communication with peers

Although lab notebooks are the primary records of lab work, they are poor communication devices. Experimental results are communicated in technical reports. Unlike lab notes, these reports omit most "historical" aspects of the work: false starts are omitted. While one often reports the manufacturer and model number for important pieces of equipment, operational details are usually omitted. (The operational details must be recorded in your lab notes.) While lab notes often include derivations, technical reports normally include only the result. As communication devices, we expect lab reports to conform to the standards of formal written English, with appropriate word choice, grammar, and structure.

Because writing formal lab reports is time consuming, an entire report will not be required for each lab. Some labs will require short writing assignments that focus on one element of an entire report—perhaps an introduction or an experiment section. If the teaching assistant believes a submission is inadequate, the teaching assistant may require that it be rewritten and resubmitted for partial credit. As time permits, we will require complete, formal reports for one or two labs. The deadline for the submission of complete reports will be specified at the time of assignment. Typically a week or two are granted after the lab is performed. Your teaching assistant will inform you of the report requirements.

Lab reports (partial or complete) must be typewritten or printed from a text editor, using the format specified in the "Formal Lab Report Instructions" supplement near the back of the lab manual. You will have the original copies of your lab notes to use in preparing your report. Carbon copies of all relevant lab notes must be submitted to your teaching assistant for credit. The statements and conclusions in your formal report must be supported by the data and analysis in your lab notes. Omissions and gaps in logic, when observed, will lower your grade.

Special requirements for lab assignments

Cover Page

A cover page is required for every submission. It must include:

- The title of the experiment
- Your name and student ID number
- The name of your lab partner
- The date that the lab was performed
- The name of your teaching assistant
- The course and lab section numbers (for example, Physics 101, Lab Section 5)

Nothing else should appear on this page. Lab reports that are submitted in the wrong slot or are otherwise misplaced take much longer to reach your teaching assistant if the information on the cover page is incorrect or incomplete. Work submitted during lab might not require a cover page.

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. 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. 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 the uncertainty methods learned in Physics 101 and 201, respectively, and to use them appropriately.

Lab 0. Intro to Work in Laboratory

Goals

- To understand the purpose of experiments.
- To understand the key ingredients of experiments.
- To learn how to prepare lab-notes.
- To understand data acquisition with Capstone.
- To analyze data with Capstone and Excel.
- To compare results and predictions.

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Important Notes

- Read the lab manual syllabus. The manual is available online at http://www.physics.wsu.edu.
- Read the lab manual experiment section before the actual lab session. Time is not plentiful. You can save a lot of time by preparing.
- There are sections in the back of the lab manual covering the use of Capstone, Excel, Data uncertainties, and the calculation of the t'-score as a means to compare results from different sources.
- If there are questions, concerns, or problems with the lab session, feel free to contact the lab director. His contact information is listed at the beginning of the lab manual. The e-mail contact is physics.labs@wsu.edu.

Experiments in Physics

> “An experiment is a question which science poses to Nature, and a measurement is the recording of Nature’s answer.” Max Planck

Electric circuits are pretty much in every device in use in the modern world. They are part of electric power sources, refrigerators, toasters, computers, cars, motorcycles, bicycles and so on. In these labs a few very basic versions of circuitry will be introduced. All circuits work with electric charges (almost always electrons). The first lab (next session) will bring up static charges. Here, charges and circuits are taken for granted as black boxes. Batteries are frequently used as "storage components" of charge and energy. Another circuit containing a simple resistor and a capacitor is used to learn about basic lab operations. As will be probed in more detail in a later lab, charges are stored on a capacitor and are gradually leaking away across a resistor. This cannot be observed visually but can be detected by using a bias measuring tool called a "digital multimeter" and the computer.

Experiments are a method to check and verify or disqualify these generalizations. They are used to probe the limits of generalization. Experiments are also meant to be reproducible. Given sufficient information, anybody should be able to repeat the experiment and observe the same results.

Returning to the observation of the leaking charges, in this introduction to aspects of lab work the decreasing charge is monitored with the Capstone hardware and software. Some observations can later be generalized and the underlying concepts of an exponential decay is applicable to a broad range of phenomena.

Ingredients of experiments

An experiment is basically a series of answers to a list of questions. In the undergraduate labs a number of them are either covered in the lecture or pre-configured in the laboratory:

- ***What do you want to know?***
- *What do you know about this?*
- *How to simplify the problem as much as possible?*
- ***What will happen?***
- *How much time is available?*
- ***What's the plan?***
- ***Execute the plan***
- textbf*Analyze the data*
- ***Compare to prediction***
- *Draw conclusions*
- *What can/should be done in further experiments?*

"What do you want to know?" in this tutorial and the upcoming first lab, it is the decrease of charge on the capacitor. How rapidly does it decay? No lecture has covered this but the finite usefulness of batteries (another charge storage device) are quite familiar. These ideas are **known** components regarding the function of a capacitor.

To **simplify** the situation, the more complex flow of charges out of a battery is replaced by a simple capacitor.

Predictions regarding it's charge retention can be made. Your TA will discuss this.

Each lab lasts just under 3 hours. The teaching assistant will give some instructions at the onset.

Then, about 2.5 hours are left. It is useful to **manage the available time**. Each lab experiment consists of several mini-experiments or runs. Each run may take a minute. For example, sets of about 5 runs are to be carried out each for a number of different starting parameters. 5 runs of 1 minute each for 5 different parameters result in 25 minutes. After 15 to 20 minutes of an introduction that leaves the experimenters nearly 2 hours to analyze data and record the activities and results.

The **plan for the experiment** is established in the lab manual as well as the introduction by the teaching assistant. However, at times planning may be left to the experimenters. The equipment is installed, sensors are selected and mounted. What remains is to initialize the sensors and data acquisition and to execute the plan.

Typically users are left to **execution of the plan** and to **analyze the data**, i.e. to finalizing the experimental setup, collect data and to extract results from an **analysis**.

Finally, the results are **compared to predictions** or previously existing data. Based on the comparisons conclusions are drawn to either confirm the original hypothesis and predictions. Or, they have to be augmented or even discarded.

Lab-notes

A big component of the power of science in general and physics in particular is the emphasis on reproducibility. One can perform a calculation or an experiment over and over and obtain the same result. For that it is crucial to understand how to compare results, a topic that will be covered further down. The other component are detailed and precise notes.

Lab notes and lab notebooks are legal documents. They are used in patent cases and ownership disputes. Nobel prizes and honors are handed out based on records from lab notes. Important findings are witnessed and countersigned and dated. In undergraduate labs this is practiced to get the hang of it.

While conducting the experiments, the lab-notes are a running log of all activities undertaken in chronological order. They commence with the objective of the experiment at hand. They include the setup of the experiment, the recorded data and the methods of analysis and the results. These notes may be cryptic and a form of short-hand for the experimenter. A more formal report is more like a communication with the community that includes more details and combines data from series of related experiments. The formal notes tend to omit deviations or dead ends in order to streamline the notes. They also include more on the background and motivation for the experiments. Details of a formal lab report are discussed elsewhere.

Providing some structure in lab notes is useful not only for grading but also when it comes to their use as a memory aide. This is tested during the final lab exam. Items that are required for lab notes and make them easy to use include:

- *A cover page*: 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. Note if this is a makeup lab.

- *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.

- *An introduction*: This part should include the objective of the experiment. All relevant physics, such as equations should be included here. They may come from the lecture material and textbooks as well as information from the teaching assistant. A bullet list may be advisable.

- *The setup and sketches*: A description of the experimental setup. Following the proverb “A picture is worth a thousand words.” Sketches, free-body diagrams and drawings are worth more. Sketches are not images or photographs. They leave out all but the essential parts. For example, the position of a sensor is more important than the actual shape. If a line is meant to be straight, add a note. Labels for physics parameters such as "v_{cart}" for velocity of a cart are useful definitions. Make the sketch **big**. Less than 1/2 page sketches lead to lower credit. Add labels like “cart”, “motion sensor”, and “pulley". Arrows that indicate “this way in time and positive direction” are essential. Most of us cannot draw straight lines freehand. If a specific slope is important, note that down. If it is important that certain conditions are met, record them. Examples are “leveling the track" and “the sensor is 21 cm from the cart at start time".

- *Commentary for math*: Don’t just write down equations. Say “p_{cart}” is the momentum of the cart. After all, it could be “power”. “F” may be a force but could denote friction. In algebra, include steps. Basically, imagine you physics book math without any annotation. Would that be comprehensible?

- *Run configuration*: For each mini-experiment or run, one or at times more parameters may be changed. Note the changes. One may want to label the data-set or resulting printout accordingly for easier identification.

- *Taking data*: When recording the motion of a cart along a track, write in you notes what is done: “First run: give cart a push to let it travel from the right towards the sensor”. If the data are printed, add labels to the printout for easy correlation.

- *The actual experiment*: Not all of the collected data 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**.

- *Taking data*: When recording the motion of a cart along a track, write in you notes what is done: “First run: give cart a push to let it travel from the right towards the sensor”. If the data are printed, add labels to the printout for easy correlation.

- *Printouts*: must be labeled. One may note in the lab notes to refer to printout number 5 at this location. Tables of analyzed results for example from Excel should be printed out.

- *Graphs of data*: Make them **big**. Full page landscape is essential for full credit. Maximize the view of the data such that possibly important trends are in plain sight.

- *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 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*: Fits will be made to find best matches of functions with datasets. Again, highlighting the region that is the basis for a fit. Results should also be in the lab notes and not just on the graph.

- *Results*: Record the results. Draw a box around them, to highlight. Be mindful of significant digits. Digits beyond the uncertainty are irrelevant and add confusion. Every result has a value, an uncertainty and units. You may record the bias reading of the digital multimeter with the precision of 1 milliVolt. Nobody would even think of using micro or nanoVolts. The does not even allow for this. The lower significant digits may fluctuate. Outside sources of "noise" may cause them. One may average over the fluctuations by observing for a while. But each reading may not be known to the lowest displayed digit. There's the uncertainty. "The bias is $1.23 \pm 0.01V$" is an example. The milliVolt readings are not reliable and are meaningless if displayed.

- *Summary and conclusions*: Statements like "we measured a lot" summarize nothing. A summary pulls together key results and findings that answer the initial question. Statements like: "Capacitor discharges in a non-linear fashion. It is an exponential decay. The decay constant $1.2 \pm 0.1V/min^2$." compile the findings of an experiment and provide useful information to a reader. The non-linear exponential behavior may be mysterious right now but it is quite common in nature. Radioactivity, Bio-luminescence or chemical reaction rates are some examples. One could model the speed of a long distance runner over time as he or she tires out with a similar model.

Other practices are useful, help when the notes function as memory aides and make grading easier, i.e. result in higher scores.

- *Be brief*: These are not novels. Lab-note are memory aides for you (and the exam) and recipes and procedures to reproduce the experiment.

- *Do not leave blank space to fill in later*: These are chronological notes.

- *Mistakes* are simply crossed out. Add a reference to where the corrected or updated information is found. There, add why the change was made.

- *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.

To understand data acquisition with Capstone

The program Capstone is used to control a variety of sensors used in the coming labs. It is of great advantage to master essential parts of the program's capabilities. A separate more detailed file will be available online during the labs. An overview of them will be given in order to:

- *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 sub-screens 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.
- *Set up display options*: On the **right** click, hold and drag your choices for display onto the central page. There are graphs, tables, histograms, and more to choose from. Details depend on the requirements of the lab. Up front, simple graphs will do. The axes labels are buttons where you can choose what to display as the x- and y-axis values. Starting with the y-axis automatically sets the x-axis to time in seconds. Buttons at the top of each graph or table appear when clicking on a graph. These let you manipulate the display or add further graphs.
- *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.

To analyze data with Capstone and Excel

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.

- *Math*: Excel lets you do all kinds of math on any worksheet item or column. Each little box has a column character (A, B, C, ...) and row (1, 2, 3, ...). Click on a box where you want a calculation done and then start typing "$= 3 * B5 + D2$" to multiply the value in box "B5" with 3 and add the value of box "D2". Clicking on the box, will give it a fat black outline with a small separate dot in the lower right corner. Clicking on that dot and dragging the mouse down over multiple boxes will apply the same math to all the new boxes. The "B5" and "D2" box addresses will also move along. This can be prevented by changing "B5" to "B5" for example. Now the same value will be used.

- *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.

For many users Capstone as well as Excel are big mysterious programs. They are very powerful and hence the learning curve may be steep. Hang in there. Most tasks in these labs are relatively simple. Learning how to calculate functions in Excel rapidly leads to lots of time saved. Using Excel reduces the chance for errors and makes it possible to find and fix errors that do occur.

To compare results and predictions

In many cases the experiment is to demonstrate that a concept introduced in class is true and applies at least in the lab, if not in the real world where more out of control variables are at play. Coming back to the capacitor, the ideal case in a stand-alone configuration retains the stored charge indefinitely. That is quite untrue, actual devices have a built in material dependent leakage. External influences like heat or UV light may cause changes. The used multimeter has an effect. And so on.

In the end, some of the real life effects can be incorporated in a model by adding a resistor to an ideal capacitor to simulate a real capacitor.

Is a prediction made early on proven wrong? Is the difference to the prediction of zero significant? The comparison or ratio of this difference to the uncertainty offers a clear cut and reproducible method of deciding.

The difference of a measurement m to a prediction p of a theorist or the measurement of a competitor is Δ:

$$\Delta = |m - p| \tag{1}$$

This is then compared to the uncertainty of the measurement m called $u(m)$ combined with the uncertainty of the prediction p called $u(p)$. From mathematics and statistics it is known that the combined uncertainty $u(\Delta)$ is by adding in quadrature:

$$u(\Delta) = \sqrt{u(m)^2 + u(p)^2} \tag{2}$$

The ratio of these is called the t'-score.

$$t' = \frac{\Delta}{u(\Delta)} = \frac{\Delta}{\sqrt{u(m_{F/a})^2 + u(m_{bal})^2}} \tag{3}$$

Nominator and denominator have the same units (from the measurement). Consequently the t'-score has no units. It is also always positive. The higher the t'-score is, the more likely the compared values are not in agreement. In the undergraduate laboratories the cut off value is $t' > 3$ for m and p being different and $t' < 3$ for them to be in agreement. In the latter case, if p is the prediction, then the prediction is confirmed by the experiment.

In modern groundbreaking experiments where standing theories are overturned, a t'-score of more than 5 or even 7 is essential to convince the community of physicists.

The nature of how uncertainties are evaluated based on statistics make it harder and harder to reduce the value of the combined uncertainty in order to drive up t' for a given difference. In general the uncertainty $u(m)$ says that in 68 out of 100 repeats of an experiment the result of any two will agree within $t' < 1$. A $t' > 2$ says that in 5 of 100 cases there is agreement. 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]

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

Let's try this out

#	Task or Activity	Labnotes	Data	Results
1	Start			
		Heading and date/time	Name, TA, class, section	
	What do you want to know?			
		Charge on capacitor (cart) at any time		
	What is known?			
		time $= t$, bias $= U$	capacitance equations	
2	Setup			
		sketch, configuration	set parameters	
3	Predict			
		position and velocity vs time	hand graph	shape of line(s)
4	Finish setup			
		connect resistor connect sensor	Bias	
5	Execute			
		Start record	table of t and U	
6	Analyze			
			Capstone: fit decay	
			τ	$\pm u(\tau)$
		Excel: average		
			from regression	
7	Compare			
		predicted: no decay data $\tau_m \pm u(\tau)$	$t' = \frac{\Delta\tau}{u_{combined}}$	agree or not
8	Conclusions			
				acceleration (?)

You will work through this table with your teaching assistant during this tutorial. In the following labs, you will be left to do more on this by yourself.

Summary

This is not an actual lab but more a tutorial of what to expect to encounter in the lab. Together with the teaching assistant an experiment was carried out. The experiment was preconfigured and set up. Data were acquired and analyzed, the resulting values for acceleration were compared to the prediction of zero acceleration. It was found that the prediction was .... (to be continued).

Keep these instructions and guides in mind for your upcoming labs and note taking activities.

Before you leave the lab please:
    Save what you would like to keep on a thumb drive.
    Quit Capstone and straighten up your lab station.

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.

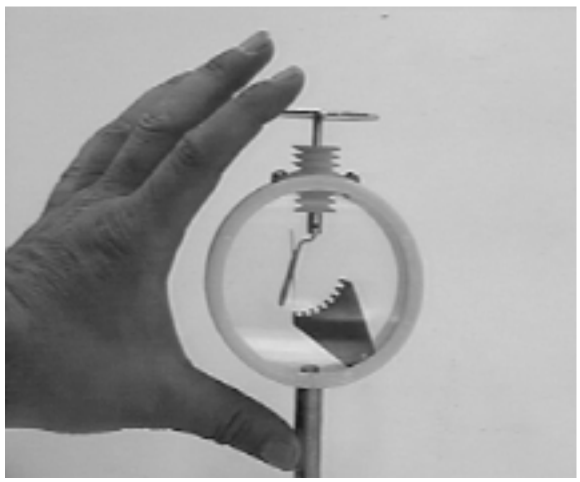


Figure 1.1. “Grounding” the electroscope.

Holding a charged rod close to the electroscope plate

Ground the electroscope as illustrated in Figure 1.1. The newer model has a grounding plug at the base. Either use a cable or both hands for grounding. 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.[1] 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

[1] The 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.

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 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 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.

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.

Before you leave the lab please: Straighten up your lab station. Report any problems or suggest improvements to your TA.

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. From a set of equipotential lines you can create a map of the vector electric field following the rules stated in the previous paragraph. 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

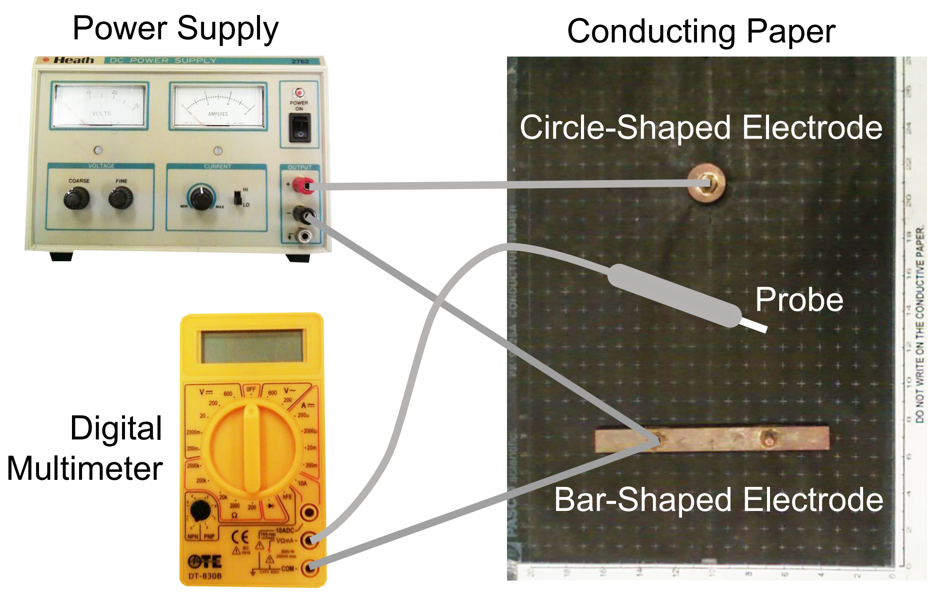


Figure 2.1. Electrical connections.

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 range knob to 20 DCV.

5. 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.

6. 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.

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 ± 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 ± 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 ± 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.

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:

$$|\mathbf{E}| = \frac{\Delta V}{\Delta s} \tag{2.1}$$

where ΔV is the difference in voltage between two equipotential lines and Δs 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.

Before you leave the lab please:

Straighten up your lab station.

Report any problems or suggest improvements to your TA.

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 quantity called the resistance, R, of a component is defined as the ratio of the potential difference, ΔV, across the component to the current, I, flowing through the component, or

$$R = \frac{\Delta V}{I} \tag{3.1}$$

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

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

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".

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.)

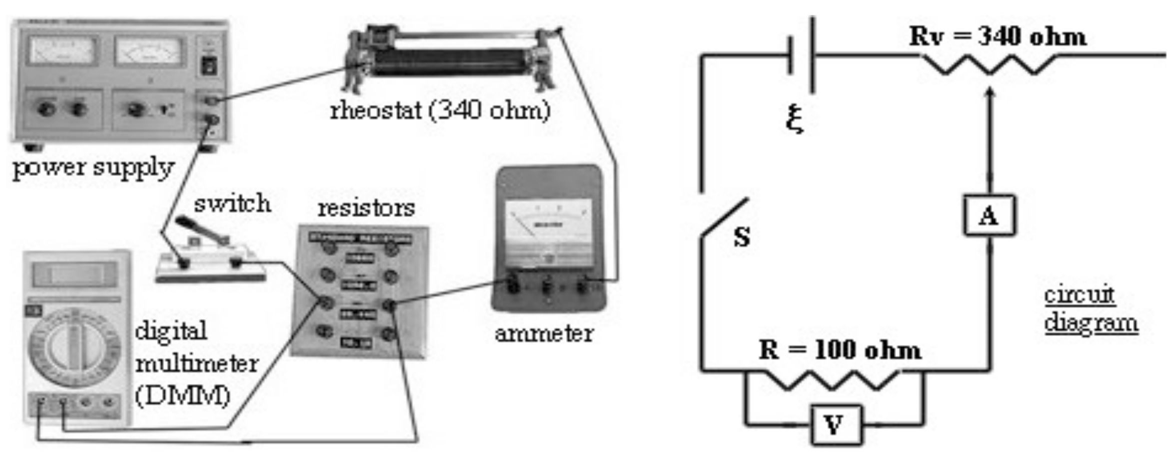


Figure 3.1. Circuit connections.

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 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, 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 ΔV 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.

Before you leave the lab please:
Turn off the power to all the equipment.
Disassemble the circuit and place the small components in the plastic tray.
Straighten up your lab station.
Report any problems or suggest improvements to your TA.

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 resistors 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.

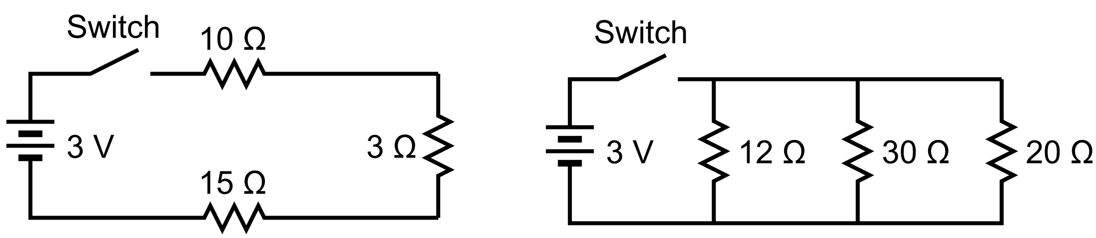
A "series" connection is when Terminal 2 of one resistor is connected to Terminal 1 of the next resistor and so on. This is like adding lengths of garden hose to reach the far corner of the yard. A battery or power supply is connected between Terminal 1 of the first resistor in the chain and Terminal 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

$$R_{total} = R_1 + R_2 + R_3 + R_4 + \ldots \tag{4.1}$$

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 connected 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 straightforward to show that the total resistance of such a parallel combination is

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \ldots \tag{4.2}$$

Simple series and simple parallel resistor configurations



(a) Circuit 1. (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. Be sure to explain your reasoning and show your calculations in your notes! You can summarize your numerical results in the provided table.

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!

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

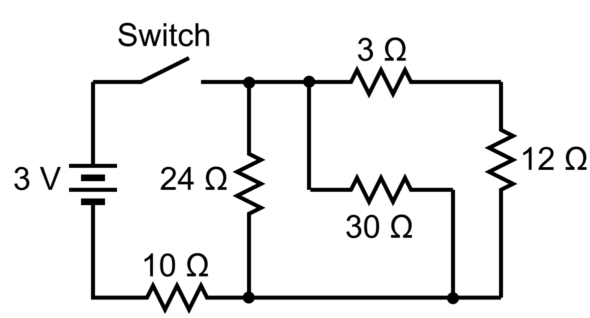


Figure 4.2. Diagram of Circuit 3.

Calculate, then measure the potential differences across and currents through each component in Circuit 3.

Before you leave the lab please:

Turn off the power to all the equipment.

Please put all leads and small components in the plastic tray provided.

Report any problems or suggest improvements to your TA.

Resistor Color Code

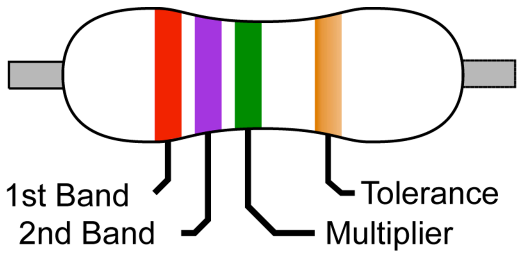


Figure 4.3. Resistor with labeled bands. To read the bands in order, orient the resistor so that the tolerance band (which is all by itself) is on the right. If the first band is red (2), the second violet (7), and the third green (10^5), the resistance is 27×10^5 ohms or 2.7 MΩ. If the tolerance band 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 Blank	Band 1 First Digit	Band 2 Second Digit	Band 3 Third Digit	Band 4 Tolerance
Black	0	0	$10^0 = 1$	
Brown	1	1	10^1	
Red	2	2	10^2	
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Gray	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	±5%
Silver			10^{-2}	±10%
No Color				±20%

Series and Parallel Resistors Data Sheet

Circuit 1 — Series Resistors

		Calculated	Measured	%Difference	Power (W)
$R_{total} =$ ___ Ω	ΔV_{total} (V)				
	I_{total} (A)				
$R_1 = 10\,\Omega$	ΔV_1 (V)				
	I_1 (A)				
$R_2 = 3\,\Omega$	ΔV_2 (V)				
	I_2 (A)				
$R_3 = 15\,\Omega$	ΔV_3 (V)				
	I_3 (A)				

Circuit 2 — Parallel Resistors

		Calculated	Measured	%Difference	Power (W)
$R_{total} =$ ___ Ω	ΔV_{total} (V)				
	I_{total} (A)				
$R_1 = 12\,\Omega$	ΔV_1 (V)				
	I_1 (A)				
$R_2 = 30\,\Omega$	ΔV_2 (V)				
	I_2 (A)				
$R_3 = 20\,\Omega$	ΔV_3 (V)				
	I_3 (A)				

Circuit 3 — Combined Series and Parallel Resistors

		Calculated	Measured	%Difference	Power (W)
$R_{total} =$ ___ Ω	ΔV_{total} (V)				
	I_{total} (A)				
$R_1 = 10\,\Omega$	ΔV_1 (V)				
	I_1 (A)				
$R_2 = 24\,\Omega$	ΔV_2 (V)				
	I_2 (A)				
$R_3 = 30\,\Omega$	ΔV_3 (V)				
	I_3 (A)				
$R_4 = 3\,\Omega$	ΔV_4 (V)				
	I_4 (A)				
$R_5 = 12\,\Omega$	ΔV_5 (V)				
	I_5 (A)				

Lab 5. 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

$$F = ILB \sin\theta \tag{5.1}$$

where θ 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 θ 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.

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 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. 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.

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.

Before you leave the lab please:
Turn off the power to all the equipment.
Disconnect the power supply.
Make sure that all six of the small magnets are accounted for.
Straighten up your lab station.
Report any problems or suggest improvements to your TA.

Lab 6. 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 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 several 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.

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 difference 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.

Mapping a magnetic field with a compass

Equipment set up

1. Tape a large sheet of paper to the hardboard sheet (area about 1 m^2) 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, Φ_{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 6.1.[1] Although the magnetic field is only approximated by the dipole field, the approximation is quite good at positions far from the magnet.

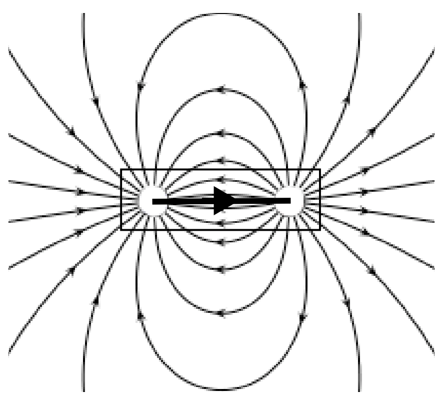


Figure 6.1. Sketch of the magnetic field due to an ideal, infinitely thin permanent magnet. The thick dark line represents the ideal magnet, while the dotted line outlines the corresponding physical magnet.

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, $\mathbf{B_{BAR}}$, as the sum of a vector directed away from the N pole, $\mathbf{B_N}$, and another vector directed into the S pole, $\mathbf{B_S}$.

[1]The image of the field lines, without the magnets, was supplied by the Wikimedia Commons.

$$\mathbf{B_{BAR}} = \mathbf{B_N} + \mathbf{B_S} \quad , \tag{6.1}$$

where $\mathbf{B_N}$ and $\mathbf{B_S}$ 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/ε_0 with Φ_{BAR}. (The total electric flux from a positive point charge is q/ε_0 by Gauss's Law.)

$$\begin{aligned} \mathbf{B_N} &= \frac{\Phi_{BAR}}{4\pi r_N^2} \qquad \{\text{Pointing radially away from the north pole}\}, \text{ and} \\ \mathbf{B_S} &= \frac{\Phi_{BAR}}{4\pi r_S^2} \qquad \{\text{Pointing radially away from the south pole}\}. \end{aligned} \tag{6.2}$$

Figure 6.2 shows a typical null point and the vectors $\mathbf{B_N}$ and $\mathbf{B_S}$ 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.

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,

$$\mathbf{B_N} + \mathbf{B_S} + \mathbf{B_{Earth}} = \mathbf{0} \qquad \{\text{horizontal component only}\} \tag{6.3}$$

at a null point. The magnitude of the horizontal component of Earth's field is 1.9×10^{-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 $\mathbf{B_{Earth}}$ (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 6.2. 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 $\mathbf{B_N}$ and $\mathbf{B_S}$. 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 θ_N and θ_S (shown in Figure 6.2), you can calculate the x-components of the magnetic fields associated with $\mathbf{B_N}$ and $\mathbf{B_S}$ in terms of Φ_{BAR}. Since Φ_{BAR} is the only remaining unknown, you can complete the solution.

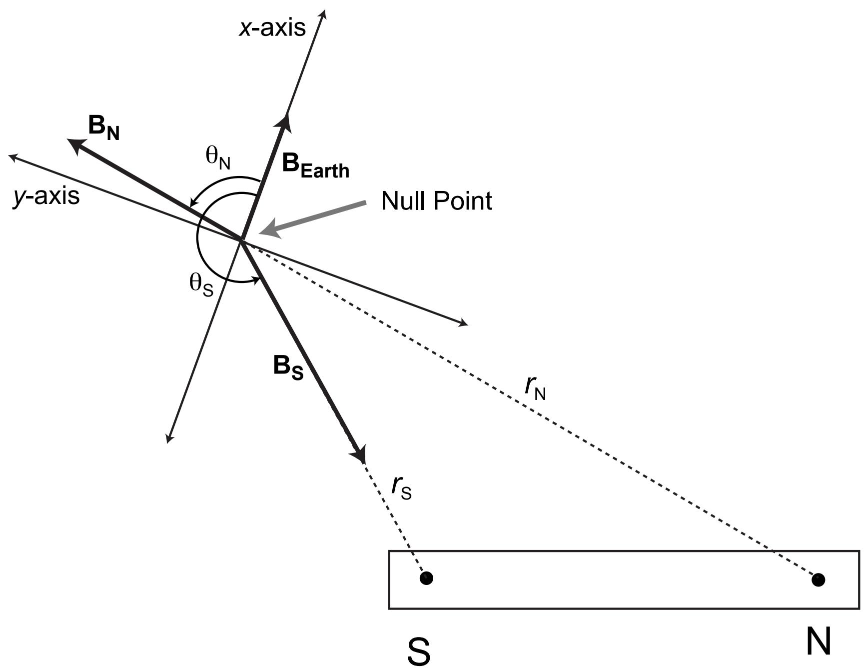


Figure 6.2. Diagram of a coordinate system with its origin at a null point and with its $+x$-axis pointing in the direction of the Earth's magnetic field vector, $\mathbf{B_{Earth}}$. Also shown are $\mathbf{B_N}$ and $\mathbf{B_S}$, vectors that mathematically represent the contribution of the N and S poles of the magnet to the magnetic field at the null point. The distances from null point to the N and S poles of the magnet are labeled r_N and r_S, respectively.

Before you leave the lab please:

- Return the bar magnet(s) to the TA Table.
- Put your rulers, compasses, and iron filings in the basket at your workstation.
- Straighten up your lab station.
- Report any problems or suggest improvements to your TA.

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

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 simply the induction process. Lenz's Law is an abbreviated, text 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.

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.

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.

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.

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. It is not hard to do!

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 cartoons: pictures with words of explanation. Your TA will have some important suggestions for making simple, accurate drawings, particularly of the coil itself. Your cartoons 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 cartoons, 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 cartoons 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.[1] This is true whether our prediction is correct or incorrect. In the end, prediction is much better test of understanding than explanation.

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

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:

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.

[1] Kelly Miller, Nathaniel Lasry, Kelvin Chu, and Eric Mazur, "Role of physics lecture demonstrations in conceptual learning," Phys. Rev. ST Phys. Educ. Res. **9**, 020113 (2013).

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.

Before you leave the lab please:

Straighten up your lab station.

Report any problems or suggest improvements to your TA.

Lab 8. 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. When speaking of peaks and valleys, water waves are a useful example. With sound waves the peaks and valleys correspond to regions of high and low pressure. With electromagnetic waves, such as light, 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 or brightness. Destructive interference produces regions of low intensity or darkness.

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). Laser light is nearly monochromatic (all of the same frequency and wavelength). The diagram in Figure 8.1 shows 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 difference in the distances from the point y to the individual slits, $r_2 - r_1$, must be equal to some integer multiple of the wavelength λ of the light. This can be expressed as

$$r_2 - r_1 = m\lambda \qquad \text{where } m \text{ is an integer } (... - 2, -1, 0, +1, +2, ...) \quad . \tag{8.1}$$

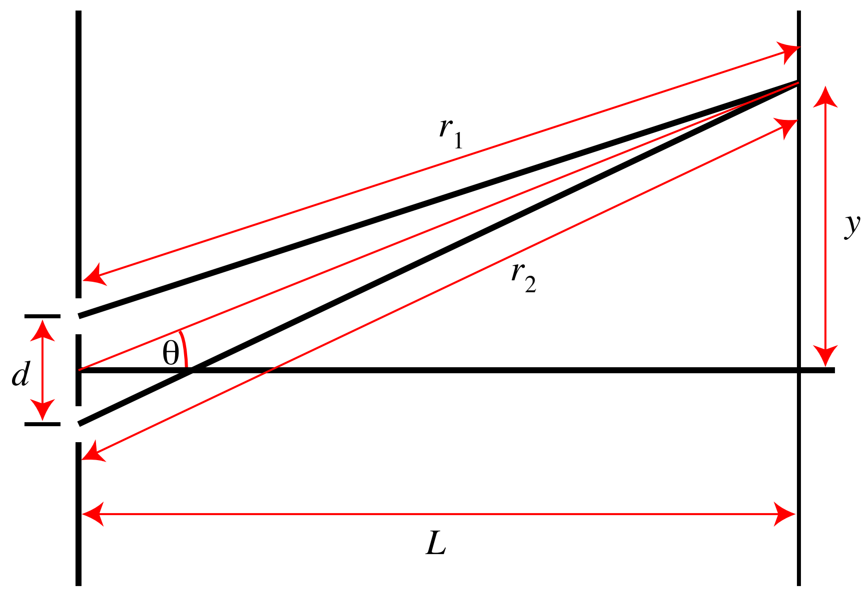


Figure 8.1. Geometry for determining the condition for constructive interference for a double slit.

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

$$d \sin\theta = m\lambda \qquad \text{where } m \text{ is an integer } (... - 2, -1, 0, +1, +2, ...) \quad . \tag{8.2}$$

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

A narrow aperture such as a single slit will interact with a narrow beam of light 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

$$a \sin\theta = n\lambda \tag{8.3}$$

where n is an integer excluding zero, that is, (... –2, –1, +1, +2, ...) Note that zero is missing from the list!

This expression looks a great deal like Equation 8.2, 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 8.2 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 a zero for the lab.

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.

Use the single slit from Column 1, Row (e). (This slit has the same width of each of the double slits on your slide.) Again 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 within the limits of error? From your data, does the slit width have to be less than the laser wavelength in order to produce a diffraction pattern?

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. The glass slide with the green tape on the edges contains the various slit arrangements. 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 compare your calculated wavelength to the accepted value listed for He-Ne lasers in your textbook or a handbook. 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?

Before you leave the lab please: Straighten up your lab station. Report any problems or suggest improvements to your TA.

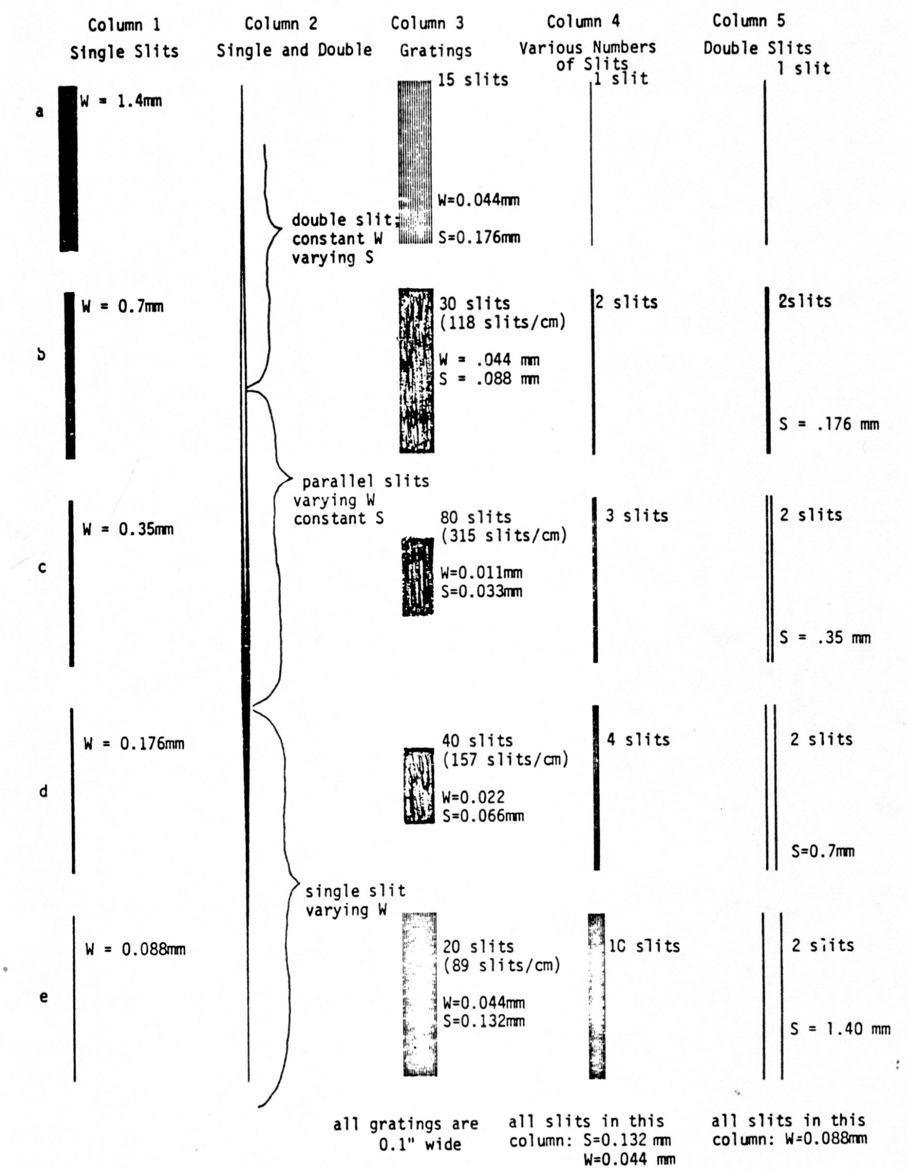


Fig. 2 Arrangement of slits and gratings on the green slide. The dark lines in the figure represent transparent regions on the slide.

W = width of an individual slit

S = spacing between centers of neighboring slits

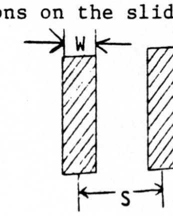


Figure 8.2. Arrangement of slits and gratings on black slide.

Lab 9. Reflection and Refraction

Goals

- To explore the reflection of a light ray from a shiny smooth surface.
- To observe and understand how a curved mirror focuses incoming parallel light rays to a single point.
- To explore the behavior of a light ray as it passes from one transparent medium into another transparent medium.
- To verify Snell's Law of refraction for light rays passing from air to PMMA [a plastic also known as Lucite, Plexiglass, or poly(methyl-methacrylate)] and from PMMA to air.
- To calculate the index of refraction for PMMA from the data.
- To observe the focusing of parallel rays of light by a semi-circular PMMA prism analogous to a simple lens.

Introduction

The basic behavior of light reflecting off mirror surfaces or passing from one medium to another is to be investigated. A "ray box" produces one or more thin beams of light that behave much like the ideal rays used to describe reflection and refraction in the text. Tracing the paths of these rays as they interact with a mirror or an interface shows the behavior of light in these situations.

By convention the angle of incidence is defined as the angle between the incident ray and the surface normal—the direction perpendicular to the surface of the mirror or lens. When dealing with mirrors, the angle of reflection is the angle between the reflected ray and the normal to the surface of the mirror. When dealing with refraction, the angle of transmission is defined as the angle between the transmitted ray and the surface normal at that point.

Caution: Avoid putting fingerprints on the surfaces of the optical elements. Handle them by the edges.

Reflection from a plane mirror

By sliding the plastic mask on the front of the ray box back and forth, single or multiple rays can be obtained. To investigate the reflection of a single ray of light, adjust the box to give a single ray of light. A piece of circular graph paper will be used to measure the angles of incidence and reflection.

Align the plane mirror with the 0°-360° line on a piece of circular graph paper, and direct the ray so that it strikes the mirror at the center of the circular graph paper. Without changing the position of the mirror, measure and record the angles of incidence and reflection as the incident angle of the ray is varied by 10° increments from 10° to 80°. You will have to move the ray box relative to the paper by carefully moving one or the other or both. Make sure that the ray always strikes the mirror at the center of the graph paper. Remember that incident and reflected angles are measured by convention from a line perpendicular to the mirror surface.

Present your results in a table. From your data, can you propose a general relationship between incident and reflected angles? How well is your hypothesis supported by the data?

Reflection from two perpendicular plane mirrors

Place two plane mirrors at right angles to each other in a L-shaped formation near one corner of a piece of engineering paper. The back or non-reflective sides of the mirrors should face toward the edges of the paper.

Using the same ray box configuration as above, place the ray box so that the single ray impinges on the front of one of the mirrors near its middle at an incident angle of about 45°. You should observe a reflected ray from this mirror combination. Use a ruler to draw on your paper the paths of both the incident and reflected rays. Now vary the incident angle of the incoming ray, always making sure that the ray's path includes one reflection from each mirror surface, and again mark the paths of the incident and reflected rays from the mirror combination.

From your observations what general rule might you suggest for the relationship between the incoming and outgoing rays for this configuration? How well does your data support your hypothesis?

Note that radar is a form of electromagnetic radiation, like light, and so exhibits the same properties as light when it comes to reflection. Radar often works by sending out a beam from a point, and then looking to see what, if anything, gets reflected back to that same point. An aircraft has many parts that fit together so that the surfaces make angles with each other. What angles should be avoided when designing "stealthy" aircraft, that is, those hard to "see" with radar?

Focal length of a concave cylindrical mirror

To determine the focal length of a curved mirror, it is useful to adjust the rear box so that it gives several parallel rays. Adjust the ray box to give five rays, and place a piece of engineering paper in front of the ray box. Place the reflective surface of the mirror toward the ray box with the center of the mirror surface perpendicular to the middle one of the five rays. Outline the position of the mirror on the paper. Then trace the path of each incident ray and its reflected ray.

The focal length of a mirror is defined to be the distance from the center of the mirror to the point where parallel incident rays intersect after reflecting from the surface. Determine the focal length for this concave mirror from your ray drawing. If all the rays don't quite meet at the same point, this is called "aberration." Does this mirror exhibit aberration? Does each of the five rays obey the simple rule of reflection from the mirror surface? Discuss and explain in each case.

Refraction at the surface of a semicircular lens

When a ray of light enters a transparent material at any angle except 90°, the ray bends at the interface. To study the bending process, adjust the ray box so that it produces a single ray of light. Use the circular graph paper to measure the angles of the incoming incident ray and the outgoing refracted by. To do this, orient the flat face of the semicircular PMMA lens on the circular graph paper so that it lies along the 0°-360° line. Then position the ray box so that the ray strikes the flat face of the lens at right angles. The point of intersection should lie at the center of the graph paper, so you can measure its angle.

Trace the path of the incoming ray from the ray box and the outgoing ray emanating from the curved side of the lens. Note that when the ray is perpendicular to the interface from air to lens or from lens to air, the ray does not deviate from its original direction. In this case, the incident and refracted angles are both zero. Now vary the angle of incidence from 10° to 80° in 10° increments. In each case trace the incoming and outgoing rays. It is imperative that the incoming ray strikes the PMMA at the center of the straight side of the semicircle each time. After refraction, rays striking the center of the straight edge of the semicircle will pass along a radius of the semicircle and will always strike the curved edge of the lens at right angles. Since the incident angle is 0°, no additional refraction takes place. Care here will ensure the validity of your data.

To determine the relationship between the incident angle and the refracted angle for the air-PMMA interface. Make a graph of the incident angle on the vertical axis versus the refracted angle on the horizontal axis. Based on your graph, can you propose a simple relationship between the two angles?

Historically the relationship between the incident and refracted angles was not fully understood until the wave theory of light was proposed. It is now well understood and experimentally verified that light travels more slowly through materials than through empty space. Air is mostly empty space, so the slowing down of light in air is very small and can be ignored in many cases. The index of refraction of a material is defined as follows:

$$\text{index of refraction, } n = \frac{\text{speed of light in vacuum, } c}{\text{speed of light in material, } c} \tag{9.1}$$

Consequently, the index of refraction for air is essentially 1.00, while the index of refraction of PMMA is greater than one. It has been predicted and verified by careful experiments that the incident angle, θ_i is related to the refracted angle, θ_r, by:

$$n_i \sin\theta_i = n_r \sin\theta_r \qquad \text{(Snell's Law)} \tag{9.2}$$

where n_i is the index of refraction of the material for the incident ray and n_r is the index of refraction of the material for the refracted ray. Now use Snell's Law to determine the index of refraction of the PMMA. A graph is a good way to do this.

The behavior of the light traveling from air into PMMA is characterized by Snell's Law, but is the behavior of light traveling from PMMA into air the same? To test this, put the ray box on the opposite side of the PMMA semicircle. The incoming ray should enter the PMMA through the curved side and pass along a radial line to the center (Important!) of the straight side. Here the ray leaves the PMMA and passes into the air. Again trace rays and measure incident (now in the PMMA) and refracted (now in the air) angles as before. Do you see any differences? For fairly large incident angles, what happens to the refracted ray? The effect that you observe is utilized in optical fiber transmission lines to keep the light from "leaking" out of the fiber. Determine the index of refraction of the PMMA from this data by plotting the angle of refraction versus the angle of incidence. Does the index of refraction agree with the value obtained when the ray was incident on the flat side of the lens?

Determining the focal length of a lens

To determine the focal length of the PMMA lens, adjust the ray box to give five rays once again. Place the lens on a piece of engineering paper and orient the ray box so that the middle rays strike the center of one side of the lens at right angles. Trace the incoming and outgoing rays and determine the focal length of the lens. By convention, the focal length is measured from the center of the lens at its thickest point.

Rotate the lens by 180°. Does this change the focal length? Try rotating the lens, say, 20-30°. Does this change the focal length? Is the focal point as well defined, that is do the rays intersect as closely to a single point? Discuss and explain in each case. Use diagrams liberally.

Block two of the incoming rays on one side of the lens. Does blocking two rays change how the remaining rays focus? If you were given just half a lens, would it focus light properly? Explain.

Summary

Summarize your results and make any final conclusions.

Before you leave the lab please:
Straighten up your lab station.
Report any problems or suggest improvements to your TA.

Lab 10. 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

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \tag{10.1}$$

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. Some ray box light sources are provided with crossed arrows that serve as the object to be imaged. When one has a clear view the light bulb in the light source, the filament of the light bulb can also serve as the object to be imaged. For clearer view of the image, hang a clean sheet of paper over the glass 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.

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. 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. 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 your measurements above, 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. 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. 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 $-s'/s$ 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.

Before you leave the lab please:

- Remove the lenses from the lens holders and place them in the plastic tray provided.
- Straighten up your lab station.
- Report any problems or suggest improvements to your TA.

Lab 11. Optical Instruments

Goals

- To construct a simple telescope with two positive lenses having known focal lengths, and to determine the angular magnification (analogous to the magnifying power of a camera or a pair of binoculars) with the aid of some naked eye observations.
- To construct a simple microscope with two positive lenses having known focal lengths, and to determine the angular magnification with the aid of some naked eye observations.
- To draw a complete, to-scale ray diagram for your microscope configuration.
- To use the thin-lens equation along with the magnification to calculate the angular magnification values for the telescope and microscope that you constructed, and to compare your calculated values of angular magnification with those determined previously by visual techniques.

Introduction

The thin-lens equation relates the object and image distances to the focal length of a lens. Knowing any two of these parameters allows us to calculate the third one. You are provided with an optical bench, three lenses (Handle them only by the edges!), a light source, a viewing screen, and a ruler. Experimentally determine the focal length of the three lenses that you have. Take enough data so that at least one of your focal length measurements is within a few percent of the mean value.

Simple telescope

Telescope construction

Using the longest focal length lens of the three as the objective lens and the shortest focal length lens as the eyepiece, construct a telescope using two lenses. Keep your eye as close to the eyepiece as possible. (Your nose is the limiting factor!) Your lab partner should measure the actual distance from your eye to the center of the eyepiece lens with a ruler or meter stick. Remember that telescopes are used to magnify distant objects. We will compromise a little here and use two parallel vertical lines, 3 cm apart, as the object to be viewed with our telescope. These lines can be drawn on a plain piece of white paper taped to the wall at the end of your lab table and should be at least 2.5 m away from your naked eye. Is the image formed by the telescope real or virtual? How do you know?

Angular magnification from visual image sizes

Although the magnification, m, of a lens system can be calculated if you know all the image and object distances, the angular magnification, M, is of more practical interest, since it tells us how much larger an object will look to us when viewed through the instrument than when viewed directly with our naked eye. The angular magnification is defined as the ratio of the angle subtended by the final optical image in our field of view divided by the angle subtended by the object itself as we look at it with our naked eye. Thus M takes into account not only the sizes of the object and image but also how far the object or image is from our eye. For example, we could devise a lens system that forms a large image located so far from our eye that the image would look small to us. In this case, the magnitude of m would be large, but M would be small, meaning that we were unsuccessful in making the object of interest appear larger.

The angular magnification, M, of the telescope can be determined by visual means. Draw two vertical lines, about 1 inch apart, on a blank piece of paper. Use blue tape to post the paper on the wall (or other surface) in front of the telescope. One lab partner (the viewer) views the lines through the telescope, while the other lab partner (the recorder) stands by the paper with a pencil. The procedure is outlined in Figure 11.1. Note that the image of the lines viewed through the telescope is inverted (upside down).

The viewer points the telescope so that the leftmost line of the image (viewed through the lens with one eye) lines up with the leftmost line of the object (viewed by looking around the lens with the other eye). This is easier if the viewers eyes are a few inches behind the eyepiece (not very close to the lens). The viewer then directs the recorder to move the pencil until it lies directly over the rightmost line of the image. When the viewer is satisfied with the position of the pencil, the recorder marks the position of the pencil on the paper.

The angular magnification of the telescope is L_i/L_o, where L_i is the distance between the lines as viewed through the lens (the image), and L_o is the distance between the lines as viewed around the lens (the object).

Note: The viewer needs both eyes to determine the angular magnification. If for any reason you do not have the use of both eyes, your lab partner should be the viewer. Wearing glasses or contacts does not usually pose a problem.

Angular magnification from the thin-lens equation

Before moving the lenses or the optical bench, measure (a) the distance from the sheet of paper with the vertical lines to the objective lens, (b) the distance between the two lenses, and (c) the distance from the eyepiece lens to your eye. With the thin-lens equation and some trigonometry, calculate the locations and sizes of the final images using the thin lens equation. Then calculate the angle that each final image subtends from the position of the eye. Remember that M is just the image angle divided by the corresponding object angle. Don't hesitate to ask for some help! Do not use the equation given in your textbook for the angular magnification of a telescope. Your

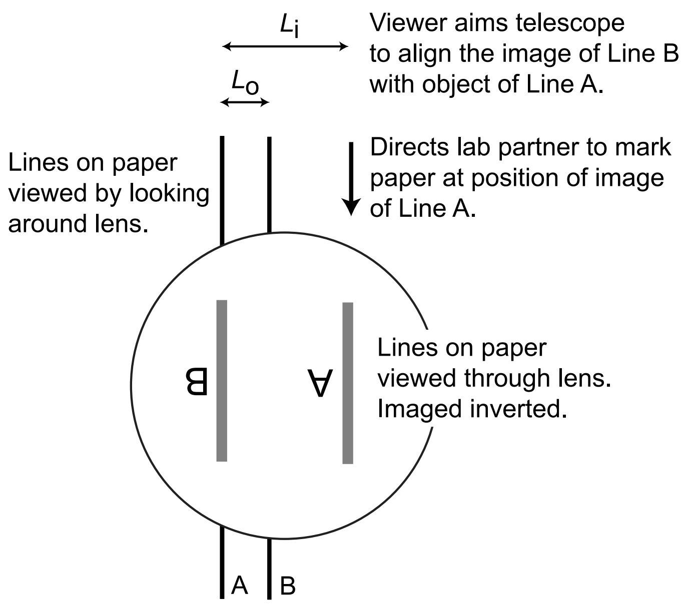


Figure 11.1. Sketch of the procedure for visually determining the angular magnification of a two-lens microscope. The angular magnification is the ratio L_i/L_o.

textbook assumes that the object is located at infinity, which is not true for the object here. Estimate the uncertainties in your visual determination of M and your calculated value. Do the two results agree within the expected uncertainties? Discuss.

Simple microscope

Microscope construction

Using the shortest focal length lens of the three as the objective lens (i.e., the lens closest to the object to be observed) and the intermediate focal length lens for the eyepiece (i.e., the lens closest to your eye), build a simple microscope using just the two lenses. Use blue tape to attach a piece of graph paper to the back of the viewing screen to serve as the object to be observed with your microscope. Remember that microscopes are used to magnify things that are relatively close to us.

Microscopes are used with your eye in a fixed location, close to the eyepiece. It can help to put your eye as close to the eyepiece as possible; touching the eyepiece lens holder with your nose will provide a reproducible location for your eye. Have your lab partner measure the actual distance from your eye to the center of the eyepiece lens for use in your calculations. Make sure that the final image seen when looking through the eyepiece is in clear focus. Continue adjusting the positions of the lenses until this is achieved. When you have achieved a configuration giving a clear magnified image, move just the eyepiece lens (and your eye!) as close to the objective lens as possible while still maintaining the clear image. The adjustability of the lens of your eye makes this range of positions possible. Is the image formed by the microscope real or virtual? How do you know?

Angular magnification from visual image sizes

It is convenient to use an object 1 or 2 mm long, that is, one or two of the smallest divisions on the graph paper. The magnification can be determined visually by viewing the graph paper through the lenses with one eye and directly (not through the lenses) using the other eye. Alternatively, one can take a picture of the graph paper centered on the edge of the lens, so that the graph paper is viewed through both lenses in part of the image and viewed directly (not through the lenses) in another part, as shown in Figure 11.2. A wide range of angular magnification values is achievable. Choose a single configuration that yields an angular magnification between 6 and 12.

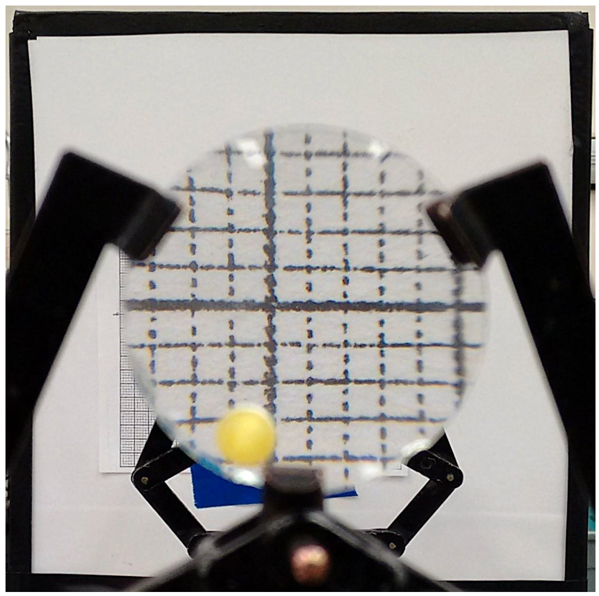


Figure 11.2. Magnified image of square grid viewed trough a two lens microscope. An unmagnified image of a corner of the grid is visible in the lower left. The angular magnification M of the microscope can be estimated by comparing the size of squares in the magnified image to the the size of the squares in the unmagnified image. The angular magnification of this microscope is about 13. Image provide by Kamrul Ome.

Angular magnification from the thin-lens equation

When you have achieved an angular magnification within the acceptable range, record the positions of all the lenses as well as the position of the ruler and your eye. To get a better number for the distance from the ruler (object) to the center of the objective lens, measure this distance directly with a meter stick rather than using the readings on the optical bench itself. The reading on the optical bench actually marks the position of the center, thickness-wise, of the plastic viewing screen. The ruler (object) has been placed “off-center” on the surface of the viewing screen. It is usually a small difference, but it can be significant in your calculations!

With the thin-lens equation and some trigonometry, calculate the locations and sizes of the final image using the thin lens equation. Then calculate the angle that the object and the final image subtends from the position of the eye. Remember that M is just the image angle divided by the corresponding object angle.

Ray diagram for the simple microscope

Draw a complete ray diagram for the chosen configuration of your microscope. Include all three principal rays for each lens. This diagram must be drawn to-scale on a page in your lab notebook. Be sure to indicate the distance represented by each division on the paper. (We have not asked for a scale diagram of the telescope because the object is so far away from the telescope objective lens. With any reasonable choice of scale distance, the distance between the objective lens and the eyepiece lens is too small for useful measurements.)

Quantitatively compare the experimental (visual determination) of M, the theoretical (calculated) value of M, and the value of M determined from the appropriate angles on your ray diagram. Do the angular magnification values agree within the expected errors of the methods used? Address this issue quantitatively.

Summary

Briefly summarize your results.

Before you leave the lab please:

- Remove the lenses from the lens holders and return them to the plastic bags.
- Remove rulers taped to viewing screens, paper sheets taped to walls, etc.
- Place the light source and viewing screen at opposite ends of the optical bench.
- Straighten up your lab station.
- Report any problems or suggest improvements to your TA.

Lab 12. Radioactivity

Goals

- To gain a better understanding of naturally-occurring and man-made radiation sources.
- To use a Geiger-Müller tube to detect both beta and gamma radiation.
- To measure the amount of background radiation from natural sources.
- To test whether the radiation intensity from a physically small radiation source decreases as one over the distance squared. (The light intensity from a single incandescent light bulb decreases according to this same inverse-squared law as one moves away from it.)
- To compare our ability to shield beta and gamma radiation.
- To understand the meaning of the term "half-life" by simulating the decay process and calculating the half-life in arbitrary time units.

Introduction

The nucleus of an atom consists of protons and neutrons. Since the protons are positively charged and confined to a very small space, they exert strong repulsive electrical forces on each other. Another force of nature, called the strong nuclear force, binds all the components of the nucleus together. Neutrons also help keep the nucleus together by increasing the distance between protons. As with electrons in atoms, however, the nucleus wants to be in its lowest energy state. If it is in an excited state, having too many protons or neutrons, it will spontaneously rearrange itself, giving off particles and/or energy in the process. This process is called radioactive decay or, simply, radioactivity. The three most common types of radiation resulting from this decay process are alpha, beta, and gamma radiation. These names are just the first three letters of the Greek alphabet—not very imaginative.

Alpha particles are just nuclei of helium-4 atoms. Because they are relatively large particles and electrically charged, they interact easily with matter. Most alpha particles are blocked by human skin, but they can be dangerous if the radioactive material is ingested into the body. Beta particles are simply electrons. Gamma particles, commonly called gamma rays, are high-energy photons, the same particles as visible light but of a much higher energy. They penetrate matter most easily.

Safety

Radiation sources

The radiation sources used in this lab are "exempt" sources, meaning that anybody can purchase them and use them without a special license. Although the radiation from exempt sources is not particularly hazardous, the basic principles of minimizing radiation dose should be followed:

- Do not eat, drink, or apply cosmetics while handling the sources.
- Do not hold sources longer than necessary; do not put sources in pockets.
- Hold the disks by their edges. Avoid touching the unlabeled flat sides of the disks.
- Place sources away from living organisms with the printed label facing up when not in use.
- Wash hands after handling sources (after the laboratory).

In keeping with campus radiation safety policies, we require you to view a short presentation on radiation safety prior to working with any radioactive sources.

Geiger-Müller tube

A Geiger-Müller tube (also called a Geiger tube or a Geiger counter) is used to measure beta and gamma radioactivity. The tube is filled with a low-pressure gas and contains two electrodes with a potential difference of typically 500–1000 V between them. An incoming particle ionizes some of the gas, freeing electrons from the gas atoms, and initiates a gaseous discharge, or "spark." The potential difference across the electrodes drops precipitously during the discharge and is detected by external circuitry as a "count."

Caution: The "end window" on the bottom end of the Geiger-Müller tube, where the particles actually enter the tube, is thin and fragile. Do not touch it or poke anything at it! If the window is broken, the tube becomes inoperable.

Background radiation

Nuclei are disintegrating around us all the time. This includes nuclei in our own bodies. To make quantitative measurements of radioactivity from a source, the ever-present, randomly occurring background radiation must be independently determined and then subtracted from the radiation measured with the source present. The difference gives the intensity of the radiation from the source alone. With the radioactive sources removed far from the Geiger-Müller tube, count the background radiation in the laboratory room for at least 100 seconds and display it in a table using Captstone. Record the mean value of the counts/second and the standard deviation. Increase the precision of the data in the table to display more digits. (Ask your TA how to do this if you don't remember!) Also display the data in the form of a histogram. This shows the number of times one gets zero counts in a one-second time interval, the number of times one gets one count in a one-second time interval, and so on. Note the random variation about the average value. Comment on the range of counts/second displayed on the histogram or shown on the table of data.

On the last page of this lab is a radiation dose worksheet published by the US Nuclear Regulatory Commission. You can use it to estimate your annual radiation exposure in millirems. You can download a copy for yourself at:

http://www.nrc.gov/reading-rm/basic-ref/teachers/average-dose-worksheet.pdf

More information, including an interactive radiation dose calculator, can be found at:

http://www.nrc.gov/about-nrc/radiation/around-us/doses-daily-lives.html

Beta radiation—Effect of distance and shielding

Place the thallium-204 (thallium with mass number 204, or ^{204}Tl) source directly under the Geiger-Müller tube. This source only emits beta particles with energies of 0.7634 MeV (1eV $= 1.602 \times 10^{-19}$J). Set the initial distance from the top of the active source to the end window of the Geiger tube to 2 cm. Record the mean and standard deviation of the count rate (counts/s) for this geometry. Keep the histogram of the data stored in the computer. Now increase the distance from the source to the end of the Geiger tube to 2.5 cm and repeat the data collection. Repeat for larger distances; 3, 4, 6, and 10 cm. As the count rate changes how are the shapes of the histograms altered?

If all the emitted beta particles come from a single point, then we should expect the number of detected particles to drop as the detector is moved away from the source. The magnitude of the electric field due to a point charge drops in a similar fashion as you move away, falling as $1/r^2$, where r is the distance to the charge. Similarly the intensity (brightness) of a light bulb decreases as $1/r^2$ as you move farther away. Use your data to test the hypothesis that the count rate decreases in proportion to one over the square of the distance from the source to the detector. Explain your method, justify why it is a valid method, and discuss your findings. Suggestion: expressing the distances in centimeters gives easier numbers to graph.

Another way to reduce the intensity of radiation from radioactive sources is shielding. Cobalt-60 emits beta and gamma radiation while thallium-204 is strictly a beta emitter. Different types of radiation are affected by different types of shielding, so that one material may be useful as a shield for certain types of radiation, while not as useful for other types. In a few specialized applications, the wrong kind of shielding can be worse than no shielding at all.

Carefully place a lead sheet on top of the thallium-204 source with the end of the Geiger tube mounted about 4 cm above the lead. Record the mean and standard deviation of the count rate. Compare this count rate with your measured background count rate. How good is the lead sheet in shielding the detector from the beta radiation?

Place a thin white plastic square on top of the source and repeat the measurement? How well do beta particles penetrate through the plastic?

Beta radiation with gamma radiation—Effect of shielding

Place the Co-60 (^{60}Co) source about 2 cm from the end of the Geiger-Müller tube. Each radioactive decay of the cobalt nucleus yields one 0.3179 MeV beta particle, one 1.1732 MeV gamma ray, and a 1.3325 MeV gamma ray. Count the source for 100 seconds and record the mean and standard deviation of the count rate.

Now place the thin white plastic square on top of the source and repeat the measurement and record the results. Remove the plastic sheet and place one lead sheet on top of the source and repeat the measurement process. Add another lead sheet and repeat. What thickness of lead will block half of the gamma radiation produced by this source? Justify your method and explain your results.

Now it is easy to understand how shielding radiation workers from alpha and beta particles is relatively simple, but that shielding from gamma rays is much more difficult.

Half-life simulation

Since the radioactive decay of a nucleus occurs spontaneously and the probability of any one kind of nucleus decaying is the same for all of them, the decay rate (number per unit time) is directly proportional to the total number of radioactive nuclei present at any given time. In other words, if you have ten million radioactive nuclei, the decay rate is twice as great as when you have five million nuclei. In this experiment we are going to simulate the decay process using white beans to represent undecayed nuclei and colored beans to represent decayed nuclei. We will assume that approximately 10% of the nuclei radioactively decay during a time interval of one bn. (We will measure time in arbitrary bn units, where bn is an abbreviation for bean.) The simulation is constructed so that if we start out with 100% of our sample, we will have $0.9 \times 100\% = 90\%$ of our sample left undecayed after a time of 1 bn. After a time of two bns has elapsed we will have $0.9 \times 90\% = 81\%$. Note that $81\% = 0.9^2 \times 100\%$. Following this pattern it is easy to see that after a time of n bns has passed, the remaining undecayed sample will be $(0.9)^n \times 100\%$. The term "half-life" refers to the elapsed time at which half of the original sample of undecayed nuclei is present.

Note that the decay rate, R, the number of nuclei decaying in a time interval of one bn, follows the same pattern as the total number of undecayed nuclei. In other words we expect that the decay rate after n one-bn time intervals will be $(0.9)^n \times R_0$, where R_0 is the initial decay rate. Similarly when the decay rate drops to half of its original value, a time interval of one "half-life" has elapsed. At your laboratory station you will find a container with 200–240 g of beans in it. Ten percent of the beans are colored indicating that they are "decayed" nuclei. An electronic balance is also present at each station.

Data acquisition

1. Find the initial decay rate, R_0, by pouring all of the beans into a flat pan and counting the number of colored beans. Count carefully!
2. Pour all of the beans back in the original container and make sure that the colored beans are

mixed as randomly as possible. (A pencil or pen can serve as a suitable stirring rod.) The decay rate, R_1, after a one-bn time interval is found by transferring 10% of the beans to a second container. Then count the colored beans in the remaining 90%. A shallow pan is provided to make the counting process easier.

3. Pour all of the beans back in the original container and make sure that the colored beans are mixed as randomly as possible. The decay rate, R_2, after a two-bn time interval is found by dumping out 19% of the beans into a second container and counting the colored beans in the remaining 81% ($0.9^2 \times 100\%$). Failure to follow this procedure can bias your data significantly, because random variations in your first choice of beans affect all your other measurements. In radioactive materials, the decayed atoms are not replaced—but the number of radioactive nuclei is enormous; over human time scales, the effect of this bias is quite small.

4. Repeat the procedure of Step 3 to find $R_3, R_4, \ldots R_{15}$. You should have sixteen data points in all, counting R_0.

Data analysis

1. Use Excel to plot a graph of the decay rate as a function of time in bn units. Plot the rate, R_0, at the time $t = 0$

2. Assuming that the uncertainty of the decay rate value is simply the square root of the value, add vertical error bars to the graph in Step 1 using Excel. (While the square root assumption is good for most radioactivity counting experiments, not all of the necessary criteria are met in our simulation; it is only a reasonable approximation. Ask your TA for help if you are unfamiliar with adding "custom" error bars in Excel.)

3. To determine whether or not the graph made in the previous two steps is actually an exponential function of the form $y = ae^{bx}$, you must use the technique found near the end of the "Uncertainty/Graphical Analysis Supplement" at the back of your lab manual. If the function is an exponential of the form given, plotting the natural logarithm of y, $\ln y$, on the vertical axis and x on the horizontal axis as usual will result in a straight line. For this experiment, y is the radioactive decay rate, R, and x is the time in bn units. Such a graph is called a "semi-log" graph. If the graph is reasonably linear, then we can be quite certain that the decay rate and time are related by an exponential mathematical function of the simple form given with a slope $= b$ ($b < 0$ in our case) and a vertical axis intercept $= \ln a$. Calculate the natural logarithms of your sixteen rate values and plot them on another graph as a function of time in bn units using Excel. The syntax in Excel for calculating natural logarithms is $\ln(\text{number})$.

4. Add a "trend line" by right clicking on one of the data point symbols on the graph. A linear trend line is the default. Under the "Options" tab, check the box for "Display equation on graph." The trend line is a so-called "least squares fit" calculated by minimizing the square of the vertical differences between points on the line and the actual data points corresponding to the same value of x.

5. To give a better idea of whether a straight line fit is justifiable, appropriate vertical error bars

need to be added to the semi-log graph. It is tempting but incorrect to use the $\ln(R^{1/2})$ as the uncertainty estimate. The reason is that $\ln(R+R^{1/2}) \neq \ln(R)+\ln(R^{1/2})$. Consequently, to calculate the "positive" part of the error bar one must use $[\ln(R+R^{1/2})-\ln(R)]$. The "negative" part of the error bar is calculated similarly using $[\ln(R)-\ln(R-R^{1/2})]$. Use Excel to do these calculations. Then add the vertical error bars to the graph.

Half-life calculation

After the time of one half-life has elapsed, the decay rate, $R = R_0/2$, by definition, where R_0 is the initial decay rate. As you have hopefully demonstrated with your graphs, the decay rate can be written in the following mathematical form (see your textbook):

$$R = R_0 \exp(-\lambda t) \tag{12.1}$$

where t is the elapsed time and λ (the "decay constant") is a positive constant. The half-life is often denoted symbolically as $T_{1/2}$. When $t = T_{1/2}$, $R = R_0/2$. Therefore Equation 12.1 may be rewritten as:

$$\frac{R_0}{2} = R_0 \exp(-\lambda T_{1/2}) \qquad \text{or simply} \qquad \frac{1}{2} = \exp(-\lambda T_{1/2}) \tag{12.2}$$

Remember that the decay constant λ is determined by the negative of the slope of the straight-line fit to the semi-log graph. Refer to the lab manual appendix referenced earlier for the details. Now all that remains is to solve for the half-life, $T_{1/2}$. The simplest way to remove the exponential in Equation 12.2 is to take the natural logarithm of both sides of the equation. This maintains the equality. So:

$$\ln(0.5) = -\lambda T_{1/2} \tag{12.3}$$

Equation 12.3 can easily be solved for $T_{1/2}$. Remember that your calculated half-life value is in time units of "bns."

Summary

Comment on your findings about the behavior of beta and gamma particles with regards to shielding and the source-detector distance.

How "good" is your value of half-life? In other words how precise is it? The Regression function of Excel can provide an error estimate rather simply. Follow the instructions given on the last two pages of the "Computer Tools Supplement" near the end of your lab manual. The Regression function can give you the uncertainty (called the "standard error" in Excel) of the slope of your semi-log graph. This is the uncertainty in λ. Then the maximum and minimum values of the half-life can be calculated using the "maximum-minimum method" of propagating the uncertainty. (See the "Uncertainty/Graphical Analysis Supplement" toward the end of the lab manual for the details if you have forgotten.) Now summarize these results and clearly state the conclusions that you can draw.

Before you leave the lab please:
        Straighten up your lab station.
        Report any problems or suggest improvements to your TA.

Uncertainty and Graphical Analysis

Introduction

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

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

Measurements in the presence of random deviations

Mean and standard deviation of the mean[1]

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

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

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

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

$$\sigma(x) = \sqrt{\frac{(x_1 - x_{avg})^2 + (x_2 - x_{avg})^2 + (x_3 - x_{avg})^2 + (x_4 - x_{avg})^2 + \ldots (x_N - x_{avg})^2}{N-1}}$$
$$= \frac{1}{\sqrt{(N-1)}} \left[\sum_{i=1}^{N} (x_1 - x_{avg})^2 \right]^{1/2} \tag{13.2}$$

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

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

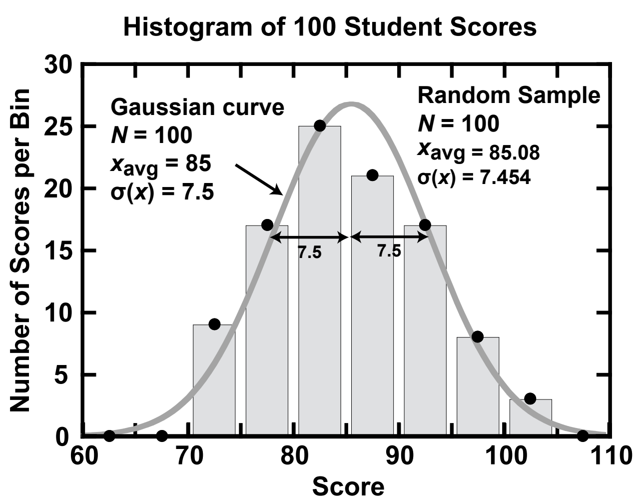


Figure 13.1. Histogram of 100 scores with an average of 85 and a standard deviation of 7.5. The smooth curve is the Gaussian function corresponding to the same number of measurements, average, and standard deviation.

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

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

The value of the standard deviation in the context of uncertainties is that the probability of finding a score at some distance from the average falls in a predictable way as the distance increases. For an ideal Gaussian distribution, 68% of the measurements lie within one standard deviation of the mean (x_{avg}). In Figure 13.1, 63 scores (63% of 100) lie within 7.5 points of 85. Ideally, 95% of the scores lie within two standard deviations (here, ± 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 $x_{avg} - 3\sigma = 62.5$ and $x_{avg} + 3\sigma = 107.5$.) Unless the total number of scores is very high, the probability of finding a score more than 3σ 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 3σ. We will make this assumption in the physics labs, although the precise probabilities will usually differ from those given by the ideal Gaussian function. For instance, when the number of measurements is small, our estimates of x_{avg} and $\sigma(x)$ may be poor. In more advanced work, it can be important to correct for this lower precision.[2] When one is attempting to show that one measurement out of a large number differs significantly from the others, a higher threshold for significance (4σ or 5σ) may be necessary.

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

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

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

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

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

Other methods for estimating the effect of random errors

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

Smallest division

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

Interpolation

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

Manufacturer's specification

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

Terminology—Uncertainty and significant digits

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

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

Uncertainties in calculated quantities

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

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

The value of $f(x)$ when evaluated at $x = 2.0$ is 0.50, but how does the uncertainty in x (the $\pm$ 0.1) affect our value for $f(x)$ (the 0.50)? For simple functions, the change in $f(x)$ due to a change in x, Δx, can be evaluated directly by calculating $f(x+\Delta x)$ and $f(x-\Delta x)$. Here $\Delta x = u(x_{avg})$ and we have $f(x+\Delta x) = 1/(2.0+0.1) = 0.476$. Similarly $f(x-\Delta x) = 1/(2.00.1) = 0.526$. [Note that for $f(x) = 1/x$, $f(x)$ increases as x decreases and vise versa.]

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

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

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

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

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

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

Using uncertainties to compare measurements or calculations

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

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

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

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

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

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

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

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

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

Determining functional relationships from graphs

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

Linear functions $(y = mx + b)$

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

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

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

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

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

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

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

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

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

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

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

Using error bars to indicate uncertainties on a graph

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

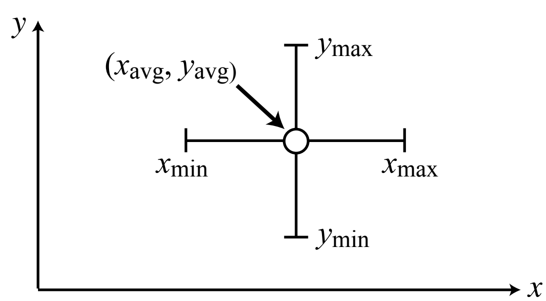


Figure 13.2. Diagram of error bars showing uncertainties in the value of the x- and y-coordinates at point (x_{avg}, y_{avg}).

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

Excel Spreadsheets and Graphs

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

Tables

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

Graphs

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

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

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

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

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

Making calculations on a set of data

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

The symbols used for various mathematical functions are:

* = multiplication / = divide

+ = addition

- = subtraction

ˆ = powers (need not be integer values)

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

Some other useful functions in Excel are:

SUM(A1:A9) = sums the numbers in Cells A1–A9.

AVERAGE(A1:A9) = calculates the average (mean) of the numbers in Cells A1–A9.

STDEV(A1:A9) = calculates the standard deviation, $\sigma(x)$, of the numbers in Cells A1–A9.

SIN(A3) = assumes that A3 is in radians and calculates the sine of the angle.

COS(A3) = assumes that A3 is in radians and calculates the cosine of the angle.

TAN(A3) = assumes that A3 is in radians and calculates the tangent of the angle.

ASIN(A6) = calculates the angle in radians whose sine is the number in Cell A6.

ACOS(A6) = calculates the angle in radians whose cosine is the number in Cell A6.

ATAN(A6) = calculates the angle in radians whose tangent is the number in Cell A6.

SQRT(A11) = square root of the number in A11.

LN(A7) = natural logarithm of the number in A7.

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

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

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

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

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

1. Click on the "Data" tab in the Chart Tools ribbon and click on the "Data Analysis" icon in the "Analysis" group on the right.

2. In the pull-down menu that appears, scroll down to the "Regression" option and click on it to highlight it. After choosing OK, the Regression window should appear.

3. To input the y-values in the first blank text box, move the cursor to the box and click in it. Now move the cursor to the top of the y-data column in your spreadsheet and click and drag down to select the whole set of y-values. The corresponding cell numbers should appear in the y-value box in the Regression window. Now move the cursor to the box for inputting the x-values in the Regression window. Click and drag over the column of x-values in your spreadsheet and these cell numbers should appear in the x-value box in the Regression window.

4. In the Regression window under "Output options" mark the circle for "Output range." Move the cursor into the blank space just to the right of "Output range" and click it.

5. Now move the cursor to an empty cell in the leftmost column of your spreadsheet near the bottom and click it. The corresponding cell number will appear in the box. This tells Excel where to put the results of the regression analysis.

6. Now you are ready to click OK in the Regression window. Excel will do the appropriate calculations and display them below and to the right of the cell that you chose for the Output range. The values of interest are displayed in the lower-left corner of the stuff displayed, just to the right of labels, "Intercept" and "X Variable." The first column to the right of the word "Intercept" shows the value of the y-intercept. This value should equal the value in the trendline equation on the graph—a nice check! The next column to the right shows the "standard error", or uncertainty of the intercept value. In other words, the intercept will have a plus/minus uncertainty given by this standard error. Similarly the first column to the right of "X Variable" shows the value of the slope (which should equal the slope in the trendline

equation) and the next column shows the plus/minus uncertainty of the slope value. How does Excel get from X Variable to slope? If you look carefully at the regression output, Excel is calling "slope" the coefficient of the X Variable, which is true in the equation of a straight line. A little awkward, but it works.

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

Formal Lab Report Instructions

The following eight pages of instructions are formatted like your formal lab report. The format is deliberately plain to the point of being ugly. Reports generally undergo substantial revision after submission and before approval no matter where you work. The double spaced text allows room for edits. A uniform, plain look encourages the editor to focus on the presented information and logic. It is also designed to fit smoothly into the institution's publishing workflow.

If you intend to include your report in your Junior Writing Portfolio, please follow the instructions with care. Avoid copying fragments of text from the lab manual or other sources—especially material from the goals and introduction sections. Those who evaluate the physics submissions often have experience as physics teaching assistants, and are likely to identify the material as plagiarized.

Formal Lab Report Instructions—Title of Lab Here

Authors names here. You will be the first author, with your lab partner's name following.
Author address(es) here. Write your Course and Lab Section Numbers here in lieu of an address.

Put your abstract on the first page. Do not label it "Abstract." It will be obvious that it is an abstract. The abstract is a brief summary of your report, including your results and conclusions. Normally, the length of your abstract should be about 5% the length of your report. Your abstract should make it implicitly clear what your report includes and what it omits. By implicit, I mean that you don't say, "This report includes *x* and omits *y*." You don't even say that it is a report. A good summary of your results and conclusions will do the job implicitly. Readers use these summaries to decide whether to read your report. If they notice discrepancies between your abstract and what actually appears in your report, they feel cheated.

1. Introduction

What to include in the introduction. Like the abstract, your introduction should describe the subject of your paper. An introduction is longer than an abstract, so the subject is described in more detail. One includes the purpose of the experiment and describes its scope. For instance, you will often specify which parameters were explored and how much they were varied. Any background information that the reader needs to understand the rest of your introduction is also included. For the purposes of this exercise, assume that your reader is an introductory physics student like yourself who has not performed this particular experiment.

The introduction is usually written after the main body of your report is complete. Paradoxically, it is seldom clear exactly what you are going to write until you actually write it.

Characteristics of good technical writing.[1] Good technical English is unified, coherent, clear and concise. Unity is achieved by enforcing a theme to the paper as a whole. Subjects that are not encompassed by the theme should be left out. The *choice* of theme is critical to the success of the writing operation. The theme is not stated explicitly. (Don't write, "The theme of this paper is…") The abstract of the work should make it clear what belongs in the report and what does not. A good abstract helps the author maintain unity. Ideally, your theme should include everything you intend to write and exclude everything else. After writing the abstract, you may decide to add or delete material as appropriate to make the report a unified whole.

Coherence is achieved by providing logical transitions between the parts of your paper. The order of topics in your paper has a major effect on coherence. If you find yourself repeating ideas in different parts of the paper, you may have failed to order your topics appropriately. Cause and effect is a major part of technical writing. Be sure you state cause and effect relationships clearly.

Clarity is achieved by removing potential sources of ambiguity. Avoid text that can be interpreted inappropriately. In general, your statements should be as specific as possible. The goal is to communicate as much information as possible. Do not hide information that should be available to the reader.

Conciseness is generally achieved by good editing. All other things being equal, you should use as few words as necessary to communicate what you have to say. Sentences that start with “There are” or “It is” can often be shortened by making an appropriate noun the subject of the sentence. This often resolves unintended ambiguities as to what “it” refers to. Verbs and adjectives with more specific meanings can shorten sentences and improve readability. Active verbs are better than passive verbs unless they shift your focus inappropriately. Your report is not about you. Similarly, do not write about your report in your report. Focus on your subject.

Formatting technical reports is mostly a matter of achieving conformity. Creative formats are not rewarded. (The nail that sticks up gets beaten down.) Your reader must focus on the content of your work, not the details of presentation. Any deviation from standard formatting must be well justified as an improvement (more clear, more concise, etc.). Although these standards are to a large degree arbitrary, many are related to the need for good-looking copy when reproduced. For the purposes of this assignment, the formatting requirements will follow those of the American Institute of Physics.[2]

With the exception of figures and equations, this assignment must be printed from a word processor. Use a 12 point serif font, preferably Times. (A point is about 1/72 of an inch. In this context, the font size refers to the intended spacing between single-spaced lines, not the size of the letters themselves.) Set the line spacing to exactly 24 points (not double-spaced), with no extra space before or after paragraphs. (Exceptions include lines with equations or figures, which often need more room. These usually need to be single-spaced, that is, with a line space of “at least 12 points”. Lines with equations and figures should be the only lines in your paper that are single-spaced.) Use one-inch margins on all four sides of the paper. For regular paragraphs, justify the text along both left and right margins. The first line of every paragraph should be indented 0.5 inches. Disable automatic formatting options like “format the next paragraph like the one before it." They often cause formatting faults and complicate inserting equations and figures.

Use a spell checker, but keep a dictionary at hand for unusual words.

2. Experiment

Title this section Experiment, not Experimental. Titles normally function as nouns, and "Experimental" is not appropriate in this role. Put an extra line break (24 point) before and after numbered headings (as well as figures and equations).

What to include in the experiment section. The experiment section should not include all the procedures that appear in your lab notes. Assume that your reader is familiar with the equipment. Omit most of the information that would normally be found in equipment manuals. Do include the manufacturer's name and model numbers of any equipment with special features that might not be easily duplicated. Also include any details that might be necessary to the replication of the experiment but would not be clear from reading the manuals. For instance, it is often important to include sample rates for data collection, but not important to specify the units employed when acquiring data.

The experiment section is not the best place to describe some experimental details. Details that apply to only one section of the results can (and usually should) be included in the appropriate part of the results section. This reduces the strain on the reader's memory and eliminates the temptation to repeat these details unnecessarily. Details that apply to more than one section of the results are generally included in an experiment section. The goal is to avoid repetition, not to collect all the experimental details in one place.

Equations and math. Any equations in your paper should be numbered in sequence on the right hand margin. The number should be in parentheses. Position the equation itself near the middle of the page (left and right). In a word processor, this is achieved by right-justifying the line to position the equation number [(1), (2), etc.] on the right hand margin, then inserting tabs to center the equation. Equations are normally type-set using an equation editor. If necessary, hand-write your equations. Computer type-set equations must generally be inserted into lines that are single-spaced. For instance, the magnitude of the gravitational force of the earth on the moon, $|F_{EonM}|$, can be calculated using the equation:[3]

$$|F_{EonM}| = \frac{Gm_E m_M}{R_{EM}^2} \quad , \qquad (1)$$

where G is the Universal Gravitational Constant (6.67×10^{-11} N-m^2/kg^2), m_E is the mass of the earth (5.97×10^{24} kg), m_M is the mass of the moon (7.35×10^{22} kg), and R_{EM} is the distance between the earth and the moon (average 3.84×10^8 m).[4] In text, symbols for variables and constants are italicized. If experimental uncertainties are available, specify them as well (for example, 1.01 ± 0.01 g).

All mathematical variables must be defined in the text immediately before or after the first time they are used, except for numbers like π and e. (Similarly, acronyms must be defined the first time they are used.) If you define a variable in Equation (1), and the same variable is used in Equation (2), use the same symbol in both equations and define this variable only once, with Equation (1). In the text that follows an equation, refer to it as Equation (1) or Equation (2), etc. Equation can be abbreviated “Eq.”, except at the beginning of a sentence. Do not abbreviate the first word of a sentence. The first word of each sentence should be completely spelled out.

3. Results and Discussion

Descriptive titles. Papers of modest length do not need numbered subsections. Subheadings are useful. Mark a new subsection by placing a bold title at the beginning of the first paragraph of that section. Do not include the exercise number. Readers quickly loose count.

Short *descriptive* titles are a great help. When sections become longer than a few double-spaced pages, numbered subsections are appropriate.

For emphasis, use *italic*, not **bold** or underlined characters.

What to include in the Results and Discussion section. The general principle is to include all the data needed to support your conclusions, with enough discussion to convince the reader of the truth of your conclusions. If some of your data can be interpreted in more than one way, for instance, you will want to present data and/or explanations that support your interpretation. Although we must structure the labs so that they make maximum use of your data to teach physics, your report should be more focused. Everything needed to support your conclusions must be included, and everything that is not related to those conclusions must be excluded. A great deal depends upon what you choose to conclude. Conclusions that are overly broad or too narrow can ruin your entire report. Consider your conclusions carefully.

Unless each data point is of special interest to the reader, tables of data are generally inappropriate. (Data tables are important in your lab notes.) If you need to display your data, use a format that communicates not only the data, but any important relationships. In most cases, figures are the best way to display data. If a table is necessary, they should be numbered with Roman numerals (Table I, Table II, etc.) and provided with descriptive titles. Double lines run across the top and bottom, and a single line separates the column headings from the data. No other lines should appear. A properly formatted example appears below as Table I.

Table I. Power loss versus frequency.

Frequency (Hz)	Power Loss (W)
10	0.24
100	1.75
1000	0.68

Figure formats. In your lab notes, your figures generally should be as large as possible. You may, for instance, want to add handwritten notes or slope calculations. In a formal report, you want them to fit comfortably with the text. Figures are normally less than 3.2 inches across, including all labels. If a figure has many parts that can be arranged in two columns, you can double the width. Large figures must fit on a single page with their captions while maintaining the normal one-inch margins. In reports, titles are optional, but captions are mandatory. Figure labels should normally use the same font as the text or a sans serif font like Arial. The figure and caption must contain sufficient information so that the reader does not need to refer to the text to understand what is being presented. Figure captions start with a phrase that serves as a title. This introductory phrase is not a complete sentence. The text that follows consists of complete sentences. Captions should not normally include a discussion of the data. The implications of your data should appear in the text.

All figures must be described in the text. Figures must appear as soon as possible *after* they are mentioned in the text. The word Figure may be abbreviated (Fig.) in the middle of a sentence, but never at the beginning.

If possible, embed your figures as high resolution bitmap files—at least 300 dots per inch (dpi). TIF files (Tagged Image Files) are compatible with many word processes. To ensure that your graphics files are readable, all lines should be at least 1 point (about 0.014 inch) thick. The smallest letter (including superscripts and subscripts) should be at least 1 mm high. This rules out most superscript and subscript fonts unless you can manually control the size. Do not use open symbols (○) for data points; always use closed symbols (●). Remove all grids and backgrounds. (The background should be transparent.) Center your figure left and right on the page on a single-spaced line. Not long ago, figures were traced by hand for publication. You may trace your figures and label them neatly by hand, if the size requirements are met.

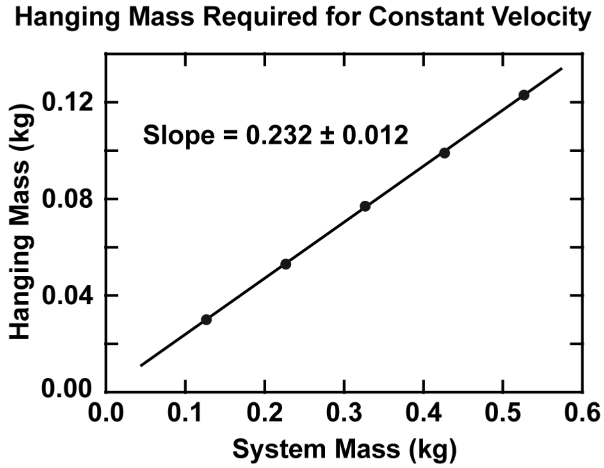


Fig. 1. Hanging mass required to move a pine block across a clean aluminum surface at a constant velocity of 0.2–0.3 m/s as a function system mass (the sum of the mass of the block and any added masses). The slope of the graph corresponds to the kinetic coefficient of friction.[5]

Discussion Section. Relatively short papers do not need a separate discussion section. (Section 3 is then a "Results and Discussion" section, as above.) Otherwise, the third section is titled "**3. Results**" and the fourth section is titled "**4. Discussion**." In your report, a separate discussion section is probably not warranted. Discuss your results as they are presented in the results section.

Generally, it is inappropriate to answer questions for further discussion in a formal lab report. Although these questions are designed to help you learn, your report must be more focused. You should include everything necessary to support your conclusions and nothing more. If the answers form a logical part of your report, and you have data to back them up, they are probably appropriate. If this is true, it would be superfluous to have a subsection entitled, "Questions for further discussion." You would need to provide other, more descriptive, titles.

Traceability. As a rule, formal reports do not contain the details needed to fully verify whether your conclusions are valid. The reader will assume a reasonable level of competence on the part of the authors. If questions arise, the reader will need access to your lab notes. Do not put anything in your report that is not supported in your lab notes. Your lab notes must in general be recorded at the same time the work was performed. That is, notes about experiment details must be made during the course of the experiment. Notes about data analysis must be made when you analyze the data. Notes about conclusions should be made when you are prepared to conclude. Notes made after the fact are not reliable records. Turn in your lab notes along with your lab report. You teaching assistant should be able to support your conclusions from your report's Results and Discussion section, which in turn must be supported by the data in your lab notes. This is called traceability.

4. Conclusion

Never conclude anything you don't discuss. Do not discuss anything that does not relate to your results. Raising new issues in the conclusion is a bad idea. Conclusions must be supported by your work, not merely be related to it. Medical misinformation, for instance, is often presented in conclusions that are not supported in the rest of the report.[6] As noted above, your conclusions determine what you choose to put in the rest of your report.

Acknowledgments

Acknowledgments are optional. If someone or some organization has supported your work financially or provided significant assistance, say so here. Example:

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[5] Charles A. Maney, "Experimental study of sliding friction," Am. J. Phys. **20**(4), 203-210 (1952).

[6] J. P. A. Ioannidis, "Why most published research findings are false," PLoS Med **2**(8), e124. (2005) doi:10.1371/journal.pmed.0020124.

[7] Some publications permit paragraph-length notes in the references section. Few publications require article titles in their citation lists, but they help the reader. Please include them. If you do not know the official abbreviation of a journal title, write out the entire journal title. Article and section titles are enclosed in quotes. Book titles are italic. Journal volume numbers are bold. Journal issue numbers, if provided, should be in parentheses. Page numbers follow, with the year of publication in parentheses. Normally one does not cite URL's (Uniform Resource Locators for web-based material) unless the links are permanent. To address this problem, many publishers provide each article with a Digital Object Identifier (DOI). One can often locate an article on the web by searching on its DOI at http://www.doi.org. If you know the DOI, provide it. Do not cite unpublished work unless absolutely necessary.