Lab Manual

5B

CALIFORNIA STATE UNIVERSITY, SACRAMENTO

Department of Physics and Astronomy

Physics 5B Laboratory Manual

PHYSICS 5B: LIGHT, ELECTRICITY AND MAGNETISM, MODERN PHYSICS

Laboratory Manual; Fall 2021 ed.

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Fall 2021 Edition Edited by
Laura Legé

Previous Editions Edited by
Barnes (1993), Ashton (1997), Urone (1998), Newcomb (2003), Ndlela (2008, 2013), Hillbrand (2015), Legé (2019, 2020)

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Table of Contents

California State University, Sacramento Department of Physics and Astronomy

Physics 5B Laboratory Safety Policies

This document must be filled out and signed before work can be performed in the laboratory. Signing this document does not guarantee you a seat in the course.

I. Responsibilities

A. Students are responsible for:

1. knowing, understanding, and following the rules of the laboratory.
2. using the information provided by the instructor (including both oral and written instructions) to know and understand the procedures for each experiment.
3. knowing and following instructions for safely using equipment in the laboratory.

B. Instructors are responsible for:

1. communicating hazards unique to an individual experiment.
2. communicating instructions for safely using equipment in the laboratory.
3. communicating emergency procedures, (i.e. evacuations, shelter-in-place).

II. General Laboratory Safety Rules

Failure to comply with the following rules could result in (but is not limited to) (1) reprimand, (2) dismissal from the class, (3) dismissal from the course. If a lab is missed due to dismissal, make-ups will be at the discretion of the instructor, or administration.

A. Students must conduct themselves in a safe, professional manner.

B. Eating and drinking are not allowed in the lab at any time.

C. Students are not allowed to work in the laboratory without an instructor present.

D. You must attend the lab section in which you are enrolled. Make-up labs in an alternate section require *advanced* approval from both instructors.

E. Personal protective equipment must be worn when required.

F. Closed-toed shoes must be worn in the laboratory.

G. Injuries, chemical spills, breakages, and/or malfunctioning equipment should be reported immediately to the instructor.

H. In the event of an emergency, follow the directions of the instructor and/or floor marshal.

I. In the event of an evacuation follow the evacuation procedures.

1. Evacuate building using *exterior* stairwells
2. Meet your instructor in the *Library Quad.*

J. Know the location of emergency information (important phone numbers, safety data sheets) and equipment (e.g. fire extinguisher).

III. Hazards Specific to this Laboratory

The following are a list of hazards you may encounter in the lab. Not every hazard will be present in any given experiment. See lab instructions for hazard instructions for each individual experiment.

A. Mechanical Hazards
    1. Heavy/bulky equipment
B. Electrical Hazards
    1. High voltages
    2. Use caution when plugging and unplugging connections.
C. Thermal Hazards
    1. Use of electric heaters
D. Light Hazards
    1. Use of Helium-Neon Lasers (638 nm, 0.95 mW)
E. Ionizing Radiation Hazards
    1. Use of exempt-level sealed radioactive sources
F. Chemical Hazards
    1. Limited use of flammable solvents

I ACKNOWLEDGE THAT I HAVE BEEN INSTRUCTED IN AND UNDERSTAND ALL OF THE ABOVE POLICIES. I AGREE TO CONFORM TO ITS CONTENTS.

____________________________ Course: ____________

Name (Please Print)

____________________________ Section: ____________

Student ID

____________________________ Date: ____________

Signature

This page to remain in the lab manual for reference

Lab

0

The First Week of the Semester

The first week of classes does not have a standardized lab in place, however it is vital for students to attend lab. Success in the course and lab begins from the first day of class.

0.1 Attendance

Continued enrollment in the course is dependent upon attendance in lab and lecture. In the first week of the course there are many students that are still trying to finalize their class schedules. Maintaining an accurate enrollment enables instructors to allow more students to add who are in need of the course.

Department policy dictates that enrolled students who miss one lab section in the first two weeks of the semester may be administratively dropped without notice. Enrolled students may drop the course on their own for the first two weeks of class. After the second week of class, dropping the course requires, at minimum, instructor permission.

0.2 Safety

Laboratory safety is paramount. All activities in daily life carry some amount of risk. When students are instructed on and follow the proper use of equipment, the risk of injury is greatly diminished. Your instructor will go over the general responsibilities, hazards, rules, and procedures on the first day of lab. The student is to sign the safety policy form, acknowledging the presence of inherent risk and that they were presented the laboratory safety policies. A copy of this safety policy is found on page iii and iv of this manual and posted in the lab room.

More Safety
Every week the instructor will inform students of hazards specific to that lab.

Students will not be permitted to take part in any experiments until they have signed the safety policy form. If a student changes the lab section in which they are enrolled, they must be informed of the policies again by the new instructor and sign a new safety policy form.

0.3 Syllabus and Procedures

Learning how your course is managed is key to progressing to a passing grade. Your instructor will discuss their laboratory routine and policies. Students are expected to read the provided syllabus and ask for clarification when needed.

Laboratory instructors may differ in their course management styles, expectations and rigor. Students should be aware that policies in one section may not be the same in another. It is the student's responsibility to read, ask about, and understand their instructor's policies.

0.4 Other Activities

Your instructor may or may not have other activities planned for the rest of lab time the first week. A discussion and/or activity on uncertainty, a discussion and/or activity on graphing, establishing laboratory groups, a concept inventory, etc. are just a few possibilities.

Lab

1

Electrostatics

"Statics" is a misnomer as the study of electrostatics often involves moving electric charges but not quickly or in a steady current as with electrodynamics.

1.1 Lab Description

In this lab, students will be performing a wide variety of experiments and demonstrations designed to give a better grasp of how to charge and discharge objects, charge interactions, Coulomb's law, and polarization of charge. Students should familiarize themselves with these concepts from their textbook before lab.

1.2 Safety and Hazards

1.2.1 The use of charges produced on the rods and proof plates pose almost no danger to students as they are very small, akin to everyday static build up.

1.2.2 The Van de Graaff generator poses a risk of shock when handled incorrectly. Your instructor will demonstrate its use. Please keep in mind the following:

- Do not touch the metal domes AFTER the generator is activated.
- The grounding dome should be close enough to the generator to allow safe periodic discharge.
- When putting charge on the proof plate, always hold your hand as far away from the metal dome as possible. If your hand is closer than the grounding dome, you can receive a mild shock.
- If you are permitted to do the "hair raising" demonstration, you should stay standing on the wood platform until you have discharged from interactions with the air. Sudden discharges from coming into contact with any conducting materials including, but not limited to, the grounding dome, sink pipes, table legs and frames, and other people can be very painful and potentially hazardous.

- Keep all flammable materials away from the Van de Graaff generator.

1.2.3 Isopropyl alcohol is present and used in small quantities in this laboratory. Isopropyl alcohol is flammable and should be kept away from heat sources and sparks (such as those from the Van de Graaff generator). Isopropyl alcohol is a skin and eye irritant. Students should wear eye protection when using isopropyl alcohol. The amount present in lab and the amounts used by students do not call for gloves. However, it is advised that students do not come into direct skin contact and wash their hands after use.

1.2.4 Fire Hazards are present in these experiments. Keep all flammable objects and liquids away from sparks created by large charge build ups such as those of the Van de Graaff generator.

1.3 Background Information

1.3.1 **Coulomb's law** expresses the magnitude of the force between two charges (q_1 and q_2) separated by a distance r. It is written as $F = k\ \frac{|q_1||q_2|}{r^2}$, where k is the Coulomb force constant $k \cong 8.99 \times 10^9\ \frac{N{\cdot}m^2}{C^2}$. The direction of the force is determined by signs of the charges interacting. If the two charges interacting are of the same sign, they will repel from one another and the force on one will point directly away from the other. If the two charges are of the opposite sign, they will attract and the force on one will point directly toward the other. The Coulomb force on one in the pair of interacting charges will be exactly the same magnitude as the charge experienced by the other. The directions of these forces will point in opposite directions as these are action-reaction pairs.

1.3.2 **Positive and negative charge:** You should assume that excess positive charge has been left on the glass rod rubbed with silk and excess negative charge is left on a rubber rod rubbed with wool. The silk will absorb the glass's electrons and the wool will give up electrons to the rod. With prolonged use, it may become necessary to discharge the silk and/or wool to allow continued charging of the rods used. Your instructor will advise you how to best do this. Do not touch the inside of the silk/wool pockets. Natural oils tend to inhibit the separation of the charges resulting in low or no charge produced on the rods.

Minimize contact between the charged ends of the rod and your hands. Natural oils tend to inhibit the separation of the charges resulting in low or no charge produced on the rods. The rods can be cleaned by putting a small amount of rubbing alcohol onto a paper towel and wiping down the rods. It is also possible to charge the rubber rod using your hair. This works only with dry hair and works best with no hair products in use. If this is done, please clean the rod before attempting to use the wool again. At the end of lab, all rods should be cleaned (regardless of charge method) before returning the tray to the check-out window.

All matter is made up of protons (positive charge), electrons (negative charge), and neutrons (neutral particles). Electrons move easily. Protons do not move readily in most materials. If the number of electrons and protons in an area is roughly equal, the charges cancel out and there is no net charge. By moving electrons into and out of an area without an equivalent number of protons, we induce a net charge, either negative or positive.

You also can picture the charge distribution of a system as the movement of positive and negative charges that move freely in objects. This charge model is not true to life, but can be useful none-the-less in understanding general principles of electrostatics. Your instructor *may* have a preference as to how you should describe the distribution and movement of charges in this lab.

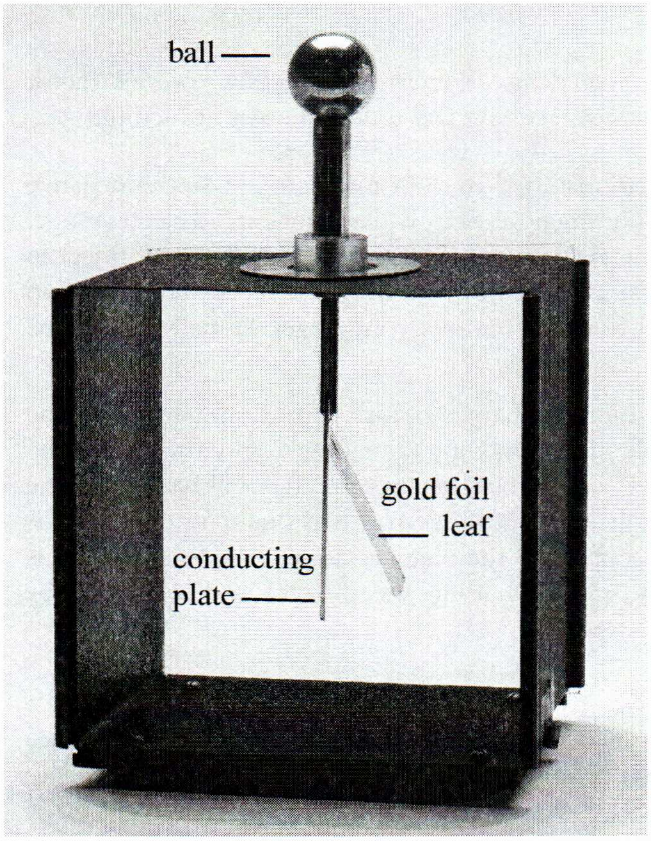


Figure 1.1 The electroscope. Charges should be brought near to and/or touch at the ball.

1.3.3 **The electroscope** is a sealed vessel containing a gold foil leaf and a conducting plate as shown in the diagram on the left. As a charged rod nears the top ball, charges in the ball are either repelled down to, or are attracted from, the plate and the foil. There, Coulomb force will cause the foil leaves to separate. Your instructor will demonstrate the proper use of this instrument.

Caution: The Coulomb force can be stronger than the gold leaf! The gold leaf will tear away if too great a charge is applied to the electroscope. Move the charged rods in slowly at first to avoid damaging the gold leaf. Do not allow the leaf to reach an angle greater than 60°. Never open the glass sides of the electroscope. If there is a problem with the electroscope, please inform the instructor so that they can get it fixed and/or find a replacement.

1.4 Activities

This lab has many short activities. They are numbered for convenience but do not need to be performed in any particular order. Your instructor will inform you of the method in which you will record and examine your findings.

1.4.1 Charging objects

1. Start with an uncharged electroscope by touching the electroscope with a bare finger. Charge the electroscope by direct contact with a negative charge. You may have to rub the rod onto the electroscope ball to transfer enough charge. Describe the movement and position of charges before you begin, while bringing the charged rod closer to the ball, while the rod is in contact with the ball, and after removing the rod again. Where and how does this demonstrate the Coulomb force being inversely proportional to distance?

2. Start with an uncharged electroscope by touching the electroscope with a bare finger. Charge the electroscope by direct contact with a positive charge. You may have to rub the rod onto the electroscope ball to transfer enough charge. Describe the movement and position of charges before you begin, while bringing the charged rod closer to the ball, while the rod is in contact with the ball, and after removing the rod again. Where and how does this demonstrate the Coulomb force being inversely proportional to distance?

3. Using the rods and the hanging cradle, devise, document, and show your instructor simple demonstrations of like charges repelling and unlike charges attracting.

4. Charging by induction will be demonstrated by your instructor. Use the negative rod to charge your electroscope by induction: Start with an uncharged electroscope. Place one finger on the side of the electroscope ball. While keeping your finger in place, bring the negative rod ***close to, but not touching*** the electroscope ball on the other side. Keeping the rod in place, remove your finger. Finally, move the rod away.

   Describe the movement and position of charges before you begin, while bringing the charged rod closer to the ball, after removing your finger, and after removing the rod again. What charge is left on the electroscope? What will happen to the electroscope and the charges on it if the negative rod is brought in close again? What will happen to the electroscope and the charges on it if the positive rod is brought in close? This may be repeated using the positive rod to charge by induction.

1.4.2 Discharging

5. To demonstrate the process called grounding, touch a positively charged electroscope to a sink pipe. Describe and explain what happens. Compare this to using your finger to discharge.

6. Bring a lit match near positively and negatively charged electroscopes. Describe what happens. Hint: What does the heat do to the molecules in the air?

1.4.3 The Van de Graaff Generator

7. Determine whether the charge on the Van de Graaff generator is producing positive or negative charge on the dome. To do this, first charge your electroscope with a known charge (+ or -). Transfer charge from the Van de Graaff to the proof plate. Please use caution and keep your hand as far as possible from the top dome while doing this. Bring the newly charged proof plate ***close to, but not touching*** the ball of your electroscope. Describe and explain the motion of the foil and charges in the electroscope and how this supports your conclusion on the charge sign of the Van de Graaff generator.

1.4.4 Polarization

8. Bring a charged rod near some small bits of paper. Describe and explain what happens. This may be repeated using the oppositely charged rod.

9. Turn on a faucet to produce a slow stream (not a drip). Bring a highly charged positive rod near the stream of water without touching it. Repeat using a highly charged negative rod. Describe and explain what happens. Is there anything about water molecules that may enhance the effects you observe?

1.4.5 Repulsion & Distance

10. Start with an uncharged electroscope. Charge the negative rod. How far away can the charged rod be before you observe the gold leaf moving? Using the charged rods and rulers, estimate the effect of the Coulomb force by estimating the angle the gold leaf makes with the bottom plate at specific distances. Start with the distance you just determined, then at 4 smaller distances. This must be done quickly. Do not recharge your rod between distances. To keep the charged rod stable during this, the suspended cradle can be used and the electroscope slid to be closer and closer. Record your data in a table. Perform the same measurements using a positively charged rod.

    Graph your findings: Plot the angle of the foil repulsion on the y-axis and the distance on the x-axis. Plot the negative rod using ● and the positive rod using ×. What does your plot tell you about the force of repulsion and distance between the charges? What does it tell you about the relative amounts of charge on the rubber vs. glass rods in this set-up? Do the signs of the charged rods change the general behavior of the repulsion?

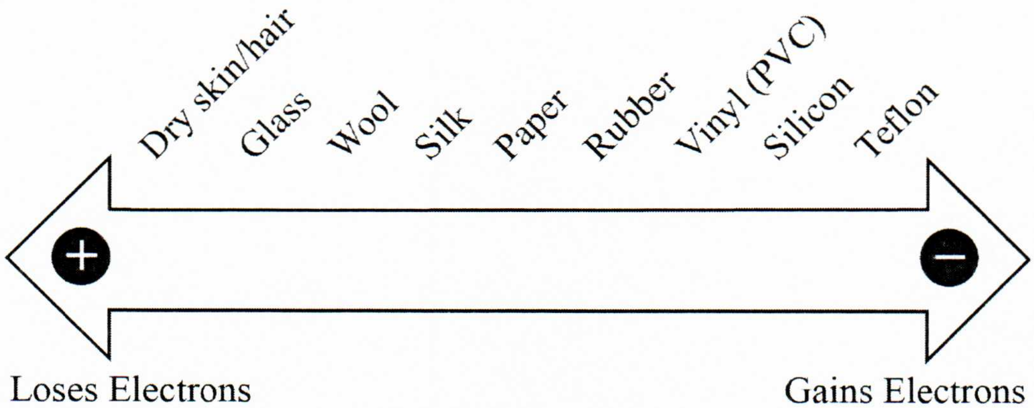


Figure 1.2 Chart of Triboelectricity: When rubbing two materials together, the electrons will tend to migrate from items on the left to items on the right. The electrons in materials on the left are less tightly bound to their nuclei. This is why rubbing glass rod with silk will create a positively charged rod while rubbing a rubber rod with wool will create a negatively charged one.

Lab
2

Electric Fields and Potentials

The presence of an electric charge creates an electric field and potential. This lab discerns differences between these quantities and also how they are related.

2.1 Lab Description

In this lab, students will be using a voltmeter to measure the potential at particular locations around various charge distributions. Equipotential maps will be created then used to map and calculate the electric field for the same charge distributions.

Students should familiarize themselves with the following concepts from their textbook before lab: Electric field, Electric field vectors vs. electric field lines, potential, voltage, equipotential lines, parallel plate capacitor potential and electric field, and dipole potential and electric field.

Students should also read Appendix B covering the use of the digital voltmeter.

2.2 Safety and Hazards

2.2.1 The potentials produced by the voltage source are generally less than 8.0 V. This does not pose a significant risk. However students should act as though the voltage is higher to maintain safe practices. With this in mind please adhere to the following:

- The voltage source should be off unless actively taking data.
- Wiring the circuit should occur while the voltage source is turned off.
- Watch for loose connections and do not allow wires to sit in water.
- When the voltage source is on, do not touch the bars, circular electrodes, neutral conductors, or water surrounding them with anything other than the voltmeter probe.

2.2.2 Isopropyl alcohol is present and used in small quantities in this laboratory. Isopropyl alcohol is flammable and should be kept away from heat sources and sparks. Isopropyl alcohol is a skin and eye irritant. Students should wear eye protection when using isopropyl alcohol. The amount present in lab and the amounts used by students do not call for gloves. However, it is advised that students do not come into direct skin contact and wash their hands after use.

2.3 Background Information

The units for electric field are $\frac{N}{C}$ or $\frac{V}{m}$

2.3.1 An electric field exists in the space around a charge or charged object. It is the electric field that exerts an electric force on any other charges in that field. The strength and direction of the electric field at a given point in space is dependent on the local charge distribution. Electric field lines are a convenient way to visualize the electric field and follow these rules:

- The electric field vector is tangent to the electric field line at all points.
- The number of electric field lines per unit area is proportional to the strength of the electric field in that area.
- The lines must point out of positive charges and go into negative charges. If there is more of one charge polarity than the other, then some lines go out to or come from a point infinitely far away.

"Infinitely far" can just mean far enough so that the value is insignificant.

- The number of lines drawn into or from an object is proportional to the relative magnitudes of charge. i.e. for +q and -2q, there will be twice as many lines going into the -2q as coming from +q.
- The electric field lines are perpendicular to the surface of a conductor or charged object
- Electric field lines cannot cross.
- The electric field inside any conductor, charged or uncharged, will vectorially cancel and be equal to 0 $\frac{N}{C}$.

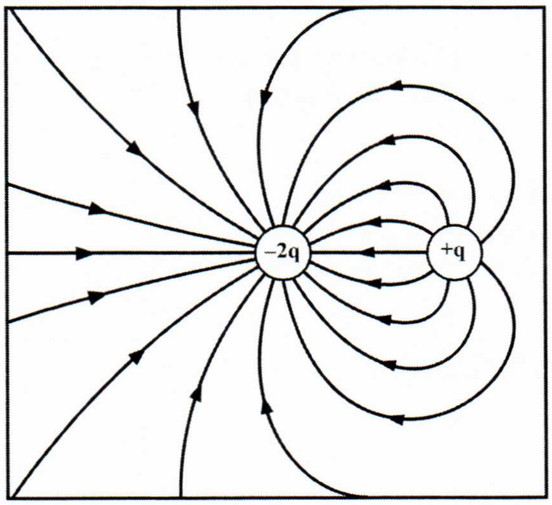


Figure 2.1 The electric field of the region near -2q and +q.

A conducting material in an electric field will become polarized as its electrons move in a direction opposite the direction of the electric field. These separated charges then contribute to the overall charge distribution and electric field of the space.

The units for electric potential are V or $\frac{J}{C}$

2.3.2 The electric potential for a given position in space is the amount of work per unit charge needed to move a positive charge from infinitely far away to that position. The strength of the potential at a given point in space is dependent on the local charge distribution.

- The electric potential near positive charges have positive values. Potential near negative charges is negative.
- The magnitude of the electric potential for a single charge goes as $V \propto \frac{q}{r}$ where q is the charge and r is the distance away.
- As electric potential is a scaler quantity, the potential of many charges is added arithmetically.
- All points on the surface of a conductor are at the same electric potential provided it is in equilibrium.

Equipotential lines are also called equipotential surfaces, equipotential contours or just equipotentials.

In a region of space the locations where the electric potential has the same value is called an equipotential line. Some rules of equipotential lines, electric field lines, and examples follow.

- To move a charge along an equipotential requires no work – that is, the force required to push it along the equipotential will be 0 N.
- The electric field lines are perpendicular to the equipotential lines at every position in space.
- The electric field will always point toward the lower potential value.
- The magnitude of the electric field at the midpoint between two equipotential lines can be calculated from the difference in potentials, ΔV and the distance along the electric field line between those equipotential lines, Δx, as

$$E = \left|\frac{\Delta V}{\Delta x}\right|. \qquad \text{Eq 2.1}$$

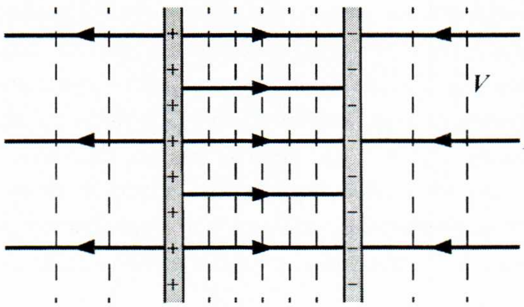


Figure 2.2 The electric field (solid) and equipotential lines (dashed) for an idealized parallel plate setup. As the equipotential lines are equally spaced, the electric field inside the parallel plates is constant. Note that this figure assumes the plates are extended farther than the figure

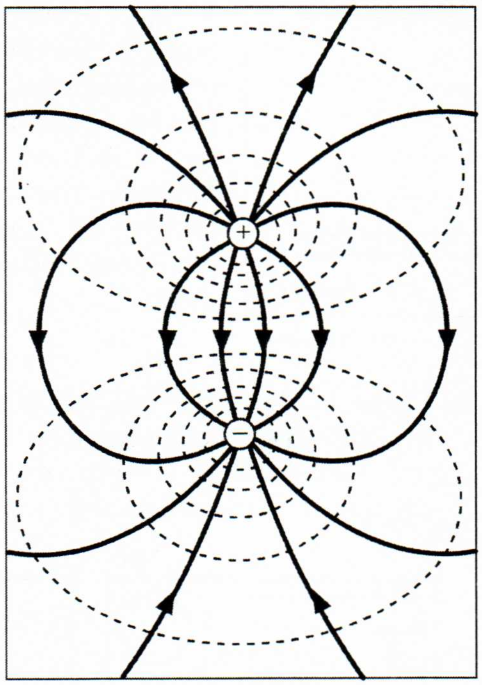


Figure 2.3 The electric field (solid) and equipotential lines (dashed) of an electric dipole configuration. The charges are equal and opposite.

2.3.3 This laboratory exercise *simulates* electrostatic fields produced by static charge distributions. The situations discussed in the text and in class are for static distributions of charge. Despite making the mathematics easier, it turns out to be extremely difficult to measure voltages in truly static situations.

To see why this is the case, imagine applying a constant voltage between two plates and measuring the voltages between them in a tray of water. In this case, positive and negative ions will physically move through the water, distorting your measurement. We will overcome this difficulty by using an alternating current (AC). In this configuration, the electric field and potential oscillate in a controlled manner and your voltmeter measures the amplitude of the oscillation.

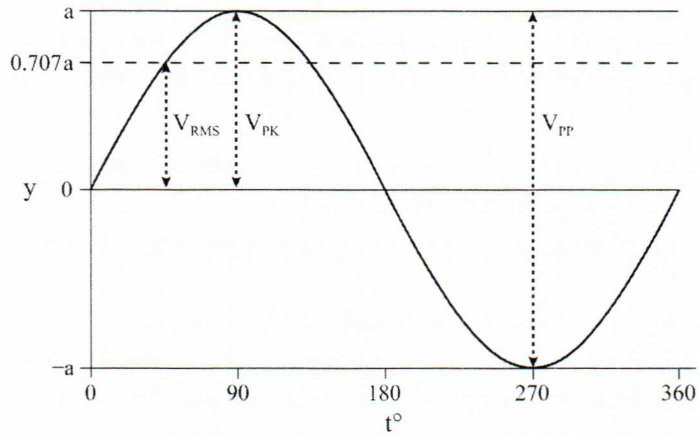


Figure 2.4 The y-axis is the voltage, the x-axis is the phase angle. What we measure in AC voltage is the Root Mean Squared (RMS) level of voltage between two points. The DC voltage level oscillates about 0, peaking slightly higher than the AC level will show. This means that you are measuring an *average* voltage level that will smooth out some of the environmental effects that would be present in a DC measurement

2.4 Activities

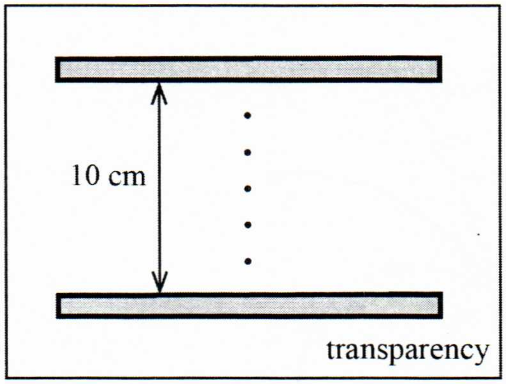


Figure 2.5 The parallel plates with the transparency in the correct landscape orientation.

2.4.1 Set up & Parallel Plates

1. The first charge distribution examined will be **parallel plates**. Stack the provided laminated grid and a clean transparency on top in landscape. Place the bars so that they are 10 cm apart and parallel. Using a permanent marker, trace the positions of the bars. Label one + and the other -. At approximately the middle of the bars, measure out and mark 5 equidistant points as shown in figure 2.5. If you make a mistake, you can use a small amount of isopropyl alcohol or a dry erase marker to erase the permanent marker.

The laminated grid paper should **not** go in the water, be dimpled, or otherwise be marked in any way in these experiments.

2. Figure 2.6 shows the basic set up and wiring. Place the marked transparency into the tray. Place the bars on top of their traced outlines. Fill the provided beaker with water and then pour into the tray so that is about half-full, with no islands of dry tray. Use the plastic putty knife to smooth out the transparency and remove any air bubbles.

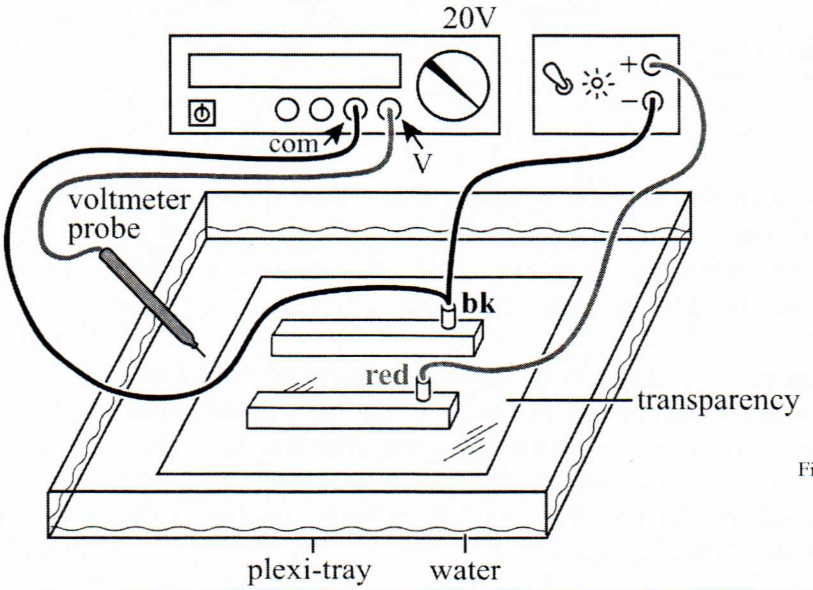


Figure 2.6 The experimental set up for lab 2.

3. The voltage source is a transformer with a **nominal** output of 6.3 VAC, the actual potential value measured will vary. Make sure the voltage source is turned off while connecting your wires. Using two banana-plug wires, connect the bars directly to the voltage source with the "+" bar connected to the red terminal of the voltage source. To add the voltmeter, connect another banana-plug wire to the "negative" bar and the other end to the COM (common ground) input of the multimeter. The voltmeter probe (red) should be plugged into the "V" input. Set the multimeter dial to 20 $\tilde{V}$ (Note the AC symbol) and turn on the meter. Turn on the voltage source, the light on it should illuminate to indicate it is on.

4. Insert the probe straight down into the water, perpendicular to the tray bottom. The voltmeter will display the difference in electric potential between that location and the "negative" bar. Place the probe at one of the equidistant dots between the plates. Note the voltage given to the hundredths place. Move the probe to find other locations that also have that voltage. They should follow a line. Mark these locations by firmly pressing the probe into the transparency. This will make a dimple. Dimples are hard to see while in the water, but when dry you will connect these dimples to make an accurate equipotential map so make as many as needed to be able to do so. These equipotential lines should be dimpled all the way to the edges of the transparency or until it makes a complete loop. Repeat for the next equidistant dot until all 5 have been done.

The locations outside of the plates is called the "fringe." This area is equally important to examine.

5. To estimate the error or uncertainty in the locations of your equipotential lines, perform the following tasks: Place the probe at one of the equidistant dots between the plates. Taking care that the probe is straight up, note the voltage. Without moving the tip, lean the probe so that it is about 45° off, leaning toward the "+" bar and note the new voltage. Pivot the probe to return to the straight up position, move the tip about 1 mm toward the "+" bar and record the new voltage. These errors can be used in a discussion of the equipotential line shapes and their consistency (or lack thereof) with what was expected in part 6.

6. Turn off the voltage supply. Pull the transparency out of the water and dry with paper towel. Using the black marker, connect your dimples for each voltage thereby creating equipotential lines. Compare your drawn pattern with what was expected for this charge configuration. Discuss any abnormalities or surprises.

7. Using the blue marker, draw in the electric field lines. Recall that electric field lines are continuous and perpendicular to equipotential lines at all locations and perpendicular to charged surfaces. Discuss where and how you can tell that the electric field has higher and lower values. Compare your drawn pattern with what was expected for this charge configuration. Discuss any abnormalities or surprises.

8. Calculate value of the electric field in 5 locations: 3 locations between the plates and 2 locations outside the plates in the fringe area. Choose two neighboring equipotential lines connected by an electric field line. Measure the distance *along* the electric field line (note this may be a curved line) using the ruler. Circle this electric field line segment in red marker. Use equation 2.1 to calculate the electric field at the midpoint. The numerical results should be compared to what is expected for the electric field inside a parallel plate configuration.

2.4.2 Other Configurations

Depending upon the instructor, you will perform the experiment again for one or two more charge configurations. Your instructor will let you know which one(s) they expect you to complete. For all, trace the locations of the objects onto a new transparency before placing it into the water.

Parallel Plate with a Metallic Ring: On a new transparency, trace the same bar positions from the parallel plate configuration. Place a neutral conducting circle at approximately the center between the plates. Find the same potentials you had for the parallel plate configuration and note how it changes especially near the neutral conductor. Record the potential value inside the ring at three locations and what the value of the electric field would be at those locations. You do not have to trace the equipotential lines into the fringe for this one.

Circular Electrodes: Use the two round electrodes and place them so that their inside edges are separated by 6.0 cm. They should be placed so that the 6 cm is in the direction of the long direction of the transparency. 5 equidistant locations along that 6 cm should be marked on the transparency. Trace the equipotentials at these locations to the edges of the transparency or until it makes a complete loop.

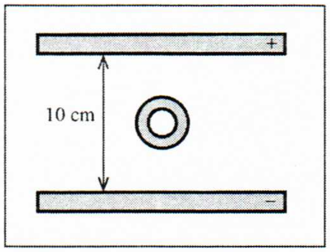
Circular Electrodes with a bar: Use the two circular electrodes and place them so that their inside edges are separated by 6.0 cm. They should be placed so that the 6 cm is in the direction of the long direction of the transparency. Place one of the bars in between the circular electrodes. The bar can be either perpendicular to the 6 cm line or be obviously askew. The bar should not touch either circular electrode. Do not connect the bar to the voltage source. Measure the potential at the positive electrode and divide this value by 6 – you will trace five multiples of this value ($n \times \frac{V_+}{6}$ where n=1, 2, 3, 4, 5). Trace the five equipotential lines to give a good representation of the potential shape, especially near the neutral bar.

The V: Use the two bars again to create a "V" shape. The bars should not touch, leave 0.5-1.0 cm between them. The angle between should be less than 90°. Find the same 5 potentials from the parallel plate experiment.

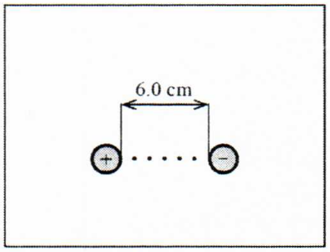
The T: Use the two bars again to create a "T" shape. The bars should not touch, leave 0.5-1.0 cm between them. Find the same 5 potentials from the parallel plate experiment.

The Bar/Circle: Use one bar and one circular electrode. Place the bar so that its long midpoint is 6.0 cm from the inside edge of the circular electrode. Measure and mark 5 equidistant spots along that 6 cm between the circular electrode and bar midpoint. Trace the potentials at these locations to the edges of the transparency or until it makes a complete loop

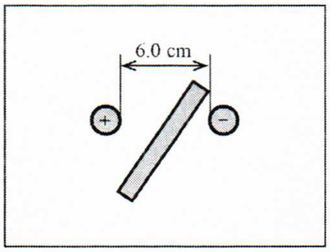
DIY: Come up with a configuration of your own. You should have only one "+" item and one "-" item. Do not allow the + and – to touch. Map the equipotential lines to give a good representation of the behavior everywhere on the transparency.



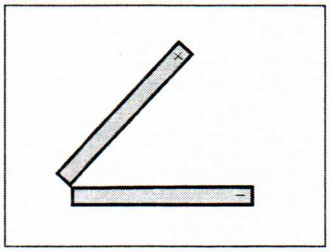
Parallel plates with a metal ring



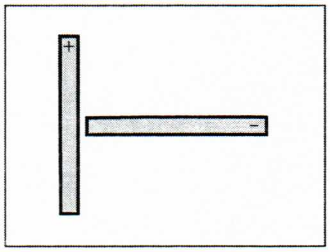
Circular electrodes



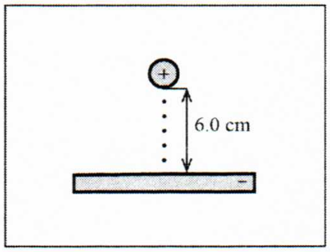
Circular electrodes with bar



The *V*



The *T*



Bar/circle

Figure 2.7 Other configurations.

Lab

3

Resistance and Ohm's Law

An introduction to wiring, using multiple meters, and resistance. Plus a demonstration of Ohm's Law.

3.1 Lab Description

Students will investigate three resistors and compare methods of obtaining their resistance values. One of these resistors will then be used to demonstrate the nature of Ohm's Law. Students will then change out their resistors for a small lightbulb and investigate its ohmic properties.

Students should familiarize themselves with the following concepts from their textbooks before lab: Ohm's law, simple circuits and circuit diagrams.

Students should also read Appendix B covering the use of the digital ammeter, digital ohmmeter, and analog voltmeter.

3.2 Safety and Hazards

3.2.1 The potentials produced by the DC power supply when at the correct settings are up to 12.0 V. This does not pose a significant risk. However, the power supply can produce potentials up to 30.0 V. Students should act with caution as they are initially turning on the power supply and ramping up the potential after. Students should act as though the voltage is higher throughout to maintain safe practices. With this in mind please adhere to the following:

- The power supply should be off unless actively taking data.
- Wiring the circuit should occur while the power supply is turned off.
- Watch for loose connections.
- Dial the power supply to zero (knob turned all the way counter-clockwise) before turning it on.

- When the voltage source is on, do not touch the exposed metallic connectors of the wires, resistor or lightbulb.

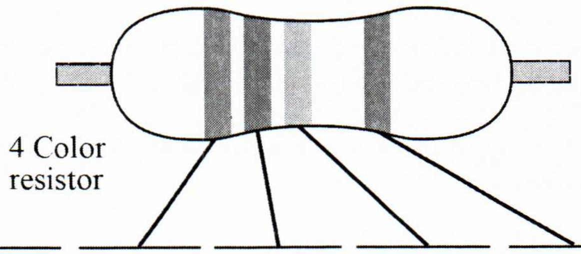
3.2.2 Thermal hazards are present in the exposed wires after the power supply has been turned on. The resistor wires and lightbulb will be at a higher temperature the longer the power supply is on. These are especially dangerous if the power supply is operated at higher potentials, or much longer times than what the lab calls for.

3.3 Background Information

3.3.1 Ohm's law relates the current (I), the potential difference (V) and resistance (R) of a circuit or circuit component as $V = IR$. Eq 3.1

The current is in the direction of higher to lower potential so that the potential difference in Ohm's law (final – initial) can be positive or negative depending on the circuit component and configuration one is investigating.

3.3.2 Resistance in a circuit or that of a resistor, is dependent on its many physical properties such as length of wire and composition. Materials or circuit components that have a constant resistance and obey Ohm's law are said to be "ohmic." "Nonohmic" materials or circuit components have a resistance that varies with potential or current. Resistance cannot be negative.



Color	1st Digit	2nd Digit	Multiplier	Tolerance
Black	0	0	x 1	-
Brown	1	1	x 10	± 1%
Red	2	2	x 100	± 2%
Orange	3	3	x 1K	± 3%
Yellow	4	4	x 10K	± 4%
Green	5	5	x 100K	± 0.5%
Blue	6	6	x 1M	± 0.25%
Purple	7	7	x 10M	± 0.10%
Grey	8	8	x 100M	± 0.05%
White	9	9	x 1G	-
Gold	-	-	x 0.1	± 5%
Silver	-	-	x 0.01	± 10%

Figure 3.1 Resistor color coding. This lab uses 4 color resistors. Note that the colors fade over the years and they are hard to discern if the resistor they are printed on are themselves colored.

3.3.3 The resistance of a professionally manufactured resistor are often marked with colored bands to indicate their resistance and acceptable error at the time of their fabrication. Reading the color code does not constitute a measurement of resistance which may have changed over time by usage. It is useful to see what the *nominal* resistance should be. To read, first look for the metallic band, either gold or silver, and orient the resistor so that this metallic band is towards your right. From the left, the first and second colored bands give the first and second digits of the resistance. The third band gives the multiplier as a power of ten, but can also be thought of as adding this many zeros to the first two digits. The fourth band indicates the precision of the manufactured resistance: 5% for gold and 10% for silver.

For example, if the bands are red, blue, green, and silver, the resistance is then a 2, then 6, then 5 zeros $\pm 10\%$, or 2 6 00000 $\pm 10\%$, or $26 \times 10^5 \Omega \pm 10\%$, or 2.34×10^6 to $2.86 \times 10^6\ \Omega$.

3.4 Activities

3.4.1 The Resistance of Three Resistors

1. Designate the resistors as R_1, R_2, and R_3, respectively.

2. Determine the nominal values of each resistor and tolerance at the time of fabrication by reading the color bands. Express this as a range of values as well.

3. Use the digital ohmmeter to measure the resistance of each resistor. This should be done by having the mounted resistor connected to your breadboard and then connecting the leads of the ohmmeter to the bread board as shown in figure 3.2. **The power supply should not be connected to anything at this time. If a battery or power source is connected while in the ohmmeter mode, you may blow a fuse or damage the meter.** Vary the dial on the ohmmeter to have the maximum number of significant digits possible. Estimate and record your uncertainty. Repeat for all three resistors.

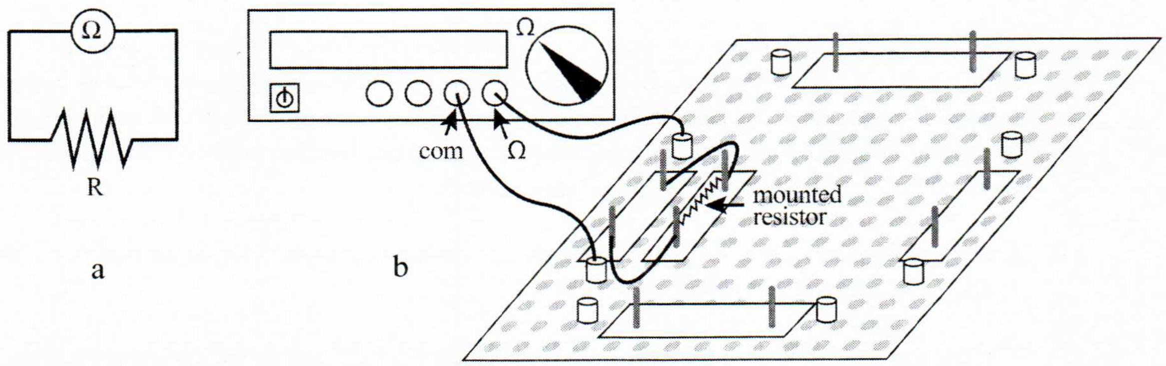


Figure 3.2 Using the digital ohmmeter. 4.2a is the circuit diagram. 4.2b is the real-life schematic. "COM" is Common Ground. The ends of the resistor are interchangeable – it does not matter which end is connected to the "Ω" or "COM" so long as there is one in each.

4. Assemble the simple circuit of the power supply and resistor. Add in the digital ammeter right after the positive terminal of the power supply taking care to set the dial to an appropriate setting. Finally add the analog voltmeter over the resistor using the breadboard connectors. See figure 3.3. If you do not feel confident, you can have your wiring checked by your instructor.

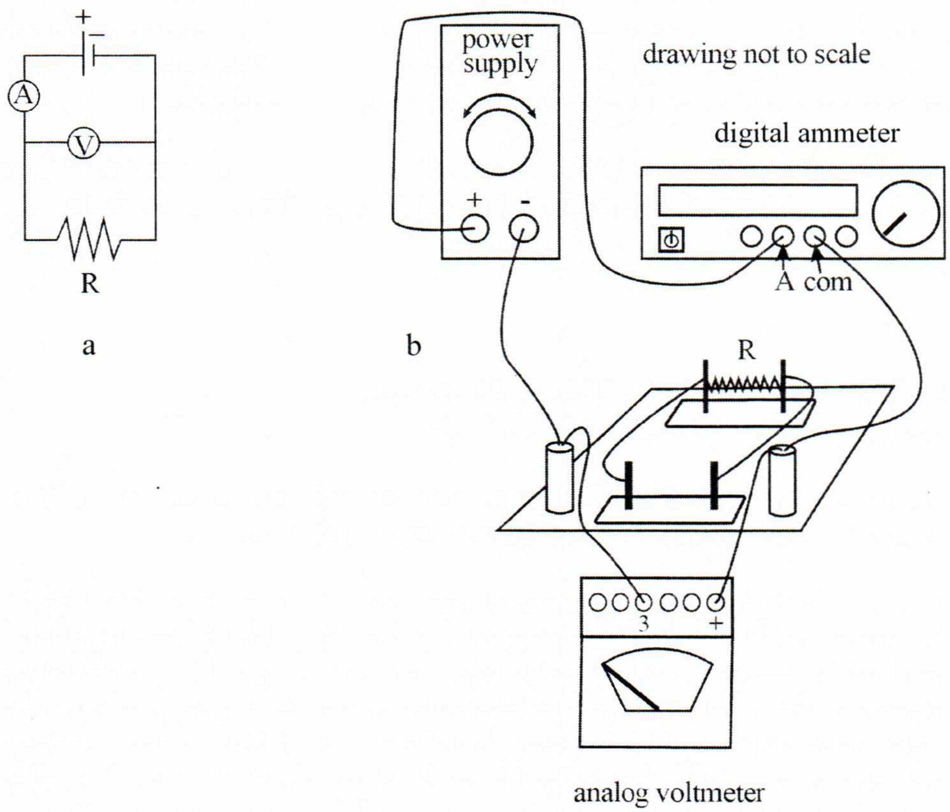


Figure 3.3 This is the set up for simultaneously measuring the voltage and current over a resistor. 4.3a is uses a standard circuit diagram. 4.3b is the real-life schematic.

5. Starting with the power supply at zero, turn on the power supply and ramp up the potential difference over the resistor to 1.50 volts. Record both the applied potential and resulting current in a small data table. Remember to include your uncertainties in measurements and units. Repeat for the other two resistors. You may have to adjust your ammeter dial to maximize your precision as you change resistors.

6. Calculate the resistances of your three resistors using equation 3.1 (pay attention to units used). These are the "Ohm's law" values.

7. Estimating uncertainties in the Ohm's law resistances: calculate the relative error in voltage and for current (see Appendix A). Add these percentages to get the estimated relative error in resistance. Use this to solve for the approximate uncertainty in the calculated resistance. Another way to express this is: $\delta R \approx R\left(\frac{\delta V}{V} + \frac{\delta I}{I}\right)$. Eq 3.2

8. For each resistor, compare the resistance values obtained. Are the values in agreement with each other? Which method is most precise? Which method is least precise?

3.4.2 Testing Ohm's Law for a Resistor

1. Choose a resistor from the previous experiment and keep the same setup (figure 3.3). Make a table of current, voltage and uncertainties in these values. Vary the voltage from 0.00 to 12.0 V by 1.00 V and also include 0.5 V, and 1.5 V (you may use your measurement from the previous section). Remember to change the ammeter dial and voltmeter output terminal to keep values in range and at maximum precision.

2. Plot your data in a full page graph with current on the x-axis, and voltage on the y-axis. Error bars can be included in both directions and are taken directly from your uncertainties.

3. Is your graph linear? Make a best-fit line and determine the value of the slope. What does this slope represent physically? Obtain a value for the resistance of the resistor from this slope and compare to the resistances obtained in the previous section. Is this resistor ohmic or nonohmic?

3.4.3 Testing Ohm's Law for a Lightbulb

1. Keep the same setup (figure 3.3) but replace the resistor from the previous experiment with a lightbulb. Make a table of current, voltage, uncertainties in these values, and V/I. Vary the voltage from 0.00 to 6.00 V. From 0.00 to 2.00 V, use increments of 0.25 V. From 2.00 – 6.00 V use increments of 1.00 V. Remember to change the ammeter dial and voltmeter output to keep values in range and at maximum precision. **Note: The bulb used is a 6V bulb so measurements above 6.0 V will likely melt the filament.**

2. Calculate the resistance of the bulb at each of the voltages and record them in the last column of the table (V/I).

3. Disconnect the power supply and voltmeter from the circuit and connect the ohmmeter to the lightbulb as in figure 3.1. Record the resistance value of the cool lightbulb.

4. Plot your data in a full page graph with current on the x-axis and voltage on the y-axis. Error bars can be included in both directions and are taken directly from your uncertainties.

5. Is your graph linear? What does the instantaneous slope represent physically? Where does the instantaneous slope approximately equal the resistance obtained in step 3? Is this lightbulb ohmic or nonohmic?

Lab

4

Electric Energy

The electric energy lost over a resistor is transformed into thermal energy in the resistor and transferred to a calorimeter filled with water.

4.1 Lab Description

Students will create a simple circuit with the addition of two meters to measure the current and potential difference over a resistor. The resistor is also part of a calorimetric system where the materials are known and the masses and temperature change of the system are measured. The electric energy dissipated over the resistor and the thermal energy gained by the calorimetric system are calculated and compared.

Students should familiarize themselves with the following concepts from their textbooks before lab: Power dissipated by a resistor, simple circuits, circuit diagrams, and calorimetry (no phase changes).

Students should also read Appendix B covering the use of the analog voltmeter and analog ammeter.

4.2 Safety Hazards

4.2.1 The potentials produced by the DC power supply when at the correct settings are generally less than 8.0 V. This does not pose a significant risk. However, the power supply can produce potentials up to 30.0 V. Students should act with caution as they are initially turning on the power supply and setting the correct amount of current for the lab. Students should act as though the voltage is higher throughout to maintain safe practices. With this in mind please adhere to the following:

- The power supply should be off unless actively taking data.
- Wiring the circuit should occur while the power supply is turned off.
- Watch for loose connections.
- When the voltage source is on: the resistor should be in the water, do not touch the exposed metallic connectors of the wires.

4.2.2 Thermal hazards are present in the calorimeter after the power supply has been turned on. The resistor, water and cup will be at a higher temperature the longer the power supply is on. If operated outside the water, the resistor alone can produce skin burns. These are especially dangerous if the power supply is operated at higher currents, or much longer times than what the lab calls for. Please also adhere to the following:

- Handle the aluminum cup and water only when less than 41°C. Measure their masses before the power supply is turned on.
- When a trial is over, and the calorimeter is less than 41°C, remove the temperature probe and wires connecting the resistor. Rinse the resistor with water from the sink to cool and place the resistor into its glass beaker to continue to cool.

4.3 Background Information

There are other ways to express power, this is the most convenient for this experiment

The units for potential are V or $\frac{J}{C}$. The units for current are A or $\frac{C}{s}$. The units for electric energy are J.

4.3.1 The power, P, dissipated by a resistor is given as

$$P = I\,V \qquad \text{Eq 4.1}$$

where I is the current flowing through the resistor and V is the potential drop over that resistor. From Physics 5A we learned that power is the energy expended, E, over a period of time, Δt, or $P = \frac{E}{\Delta t}$. Eq 4.2

This means that the electrical energy expended by the resistor is

$$E = I\,V\,\Delta t. \qquad \text{Eq 4.3}$$

4.3.2 The thermal energy will be measured by the heat transferred into the calorimetric system, Q. Again from Physics 5A, the heat transferred to a substance depends on the amount of that substance, what the substance is, and temperature change within it:

$$Q = m\,c\,\Delta T, \qquad \text{Eq 4.4}$$

where m is the mass of the substance, c is the specific heat of the substance, and ΔT is the change in temperature (T_2 - T_1).

In this experiment, heat will be transferred to the water, aluminum cup, the resistor (wire coil), stirrer, temperature probe, and part of the lid attached to the coil. Fortunately, the last four items have been evaluated by our physics technician and have been determined to have a combined mass and specific heats to the effect of $m_{coil}c_{coil}$. This means we will only need three terms in our expression for the heat gained by the calorimetric system:

$$Q = \left[m_w c_w + m_{Al} c_{Al} + m_{coil} c_{coil}\right](T_2 - T_1) \qquad \text{Eq 4.5}$$

1.000 cal = 4.186 J

c_w	= specific heat of water = 4.186 $\frac{J}{g\cdot°C}$ = 1.000 $\frac{cal}{g\cdot°C}$
c_{Al}	= specific heat of aluminum = 0.900 $\frac{J}{g\cdot°C}$ = 0.215 $\frac{cal}{g\cdot°C}$
$m_{coil}c_{coil}$	= previously determined effect of combined coil = 25.1 $\frac{J}{°C}$ = 6.00 $\frac{cal}{°C}$

4.3.3 Conservation of energy dictates that energy is not created or destroyed but can be transferred and transformed into other forms of energy. This applies to all forms of energy even those arising from non-conservative forces like in the case of thermal energy. For this experiment, the electrical energy lost by the resistor is transformed into thermal energy and transferred into heat within the calorimetric system. A shorter way of putting this:

$$E = Q \qquad \text{Eq 4.6}$$

within experimental uncertainties.

4.4 Activity

4.4.1 Set up

1. Measure and record the mass of the aluminum calorimeter cup (inside only, no ring). The cup should be empty and dry. This measurement will not change when the experiment is repeated.

2. Fill the aluminum cup $\sim\frac{3}{4}$ full with water. Measure and record the mass of the water and cup (inside only, no ring). Determine the mass of just the water.

3. Assemble the calorimeter cup, insulating disk, and metal jacket and insert the resistor / heating coil, stirrer, and temperature probe. Be sure that…
    - the heating coil is completely submerged below the water surface.
    - the thermometer is in the water, but not touching the coil.
    - the stirrer can agitate the water to disperse heat.

4. Plug in and turn on the temperature probe. Note that the plug has one narrow and one wide prong. Set the thermometer to display 0.1 °C precision. Allow the system to come to an equilibrium temperature (about 10 min) and then record this temperature as T_1.

5. Your power supply should be off. The set-up for the experiment is shown in figure 4.1. Build the basic circuit first: power supply and resistor (coil). Take care to connect the wires to the top of the coil so that the lid remains flat against the calorimeter cup. Add in the ammeter between the + side of the power supply and the resistor. Finally, add the voltmeter to measure the potential difference before and after the coil. If you are unsure of your set-up, ask your instructor to check the wiring before turning on the power supply.

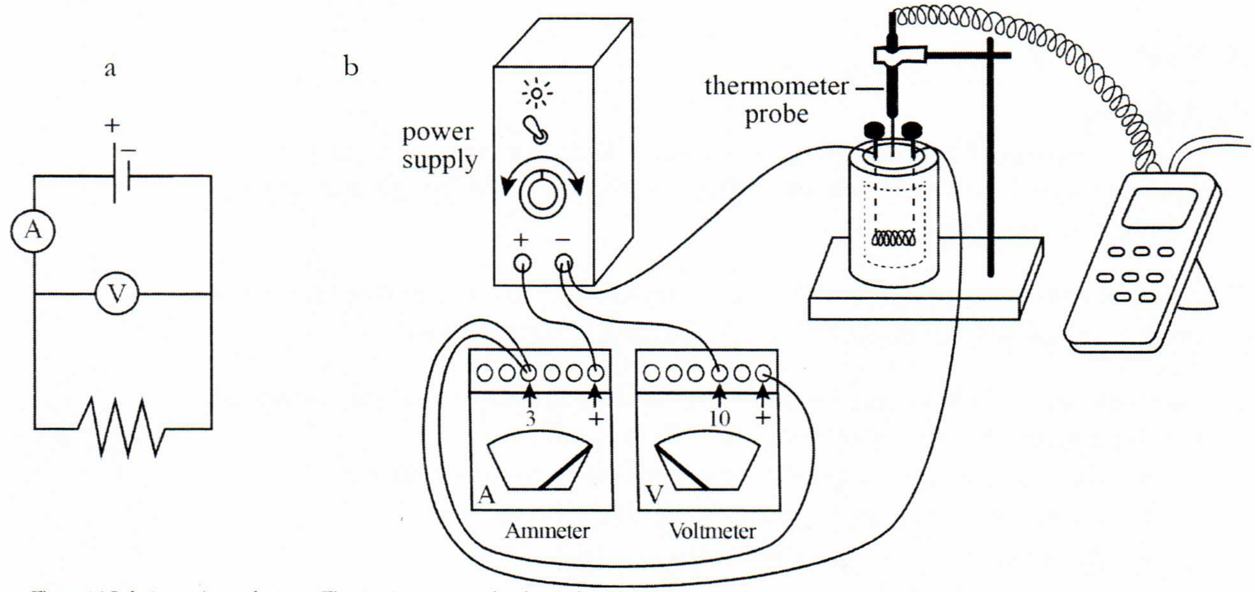


Figure 4.1 Lab 4 experimental set up. Figure 4.1a expresses the electrical portion using a standard circuit diagram. Figure 4.1b shows the entire set up and how the components will connect with the student lab equipment.

Time (min : s)	Time (s)	Temp (°C)	Voltage (V)
0:00	0	$T_1 =$ ___	
0:15			
0:30	30		
0:45			
1:00	60		
⋮	⋮		

6. Prepare to take measurements of the time, temperature, and voltage by making a table similar to that shown to the left. When the current is set correctly, the experiment time should not go past 15 minutes. Assign jobs to everyone in the group (more than one can be done one person). You will need someone to: watch and call out the time, watch and call out the temperature, watch and call out any changes in the voltage or current, and someone to write down all the data.

4.4.2 Taking Data

7. **Before turning on the power supply** know how to read the meters. The power supply needs to be adjusted quickly so that 2.2 A is moving through the circuit. This is done by watching your ammeter while turning the large black knob on the power supply. You should also be ready to start your timer.

8. Start the timer at the same time you turn on the power supply. Quickly adjust the current to 2.2 A. You may need to adjust the power supply occasionally to keep the current constant at 2.2 A.

9. Record the temperature every 15 seconds. The voltage needs to be recorded once the current is at 2.2 A and *if* it changes after that. Stir occasionally to aid in dispersing the heat evenly in the calorimetric system. Take care not to lift the lid when stirring.

10. Allow the experiment to run until the temperature has changed by at least 10.0 °C, and up to 15°C. Record on your data table the **time** at which you turn off the power supply. This is Δt. Keep taking data (including your new voltage) for another 2 minutes. The highest temperature recorded for the trial is T_2.

11. Disconnect the resistor/coil from the circuit and calorimetric system. Rinse and place into the glass beaker. Pour out and rinse the calorimeter cup. Repeat steps 2-10 for a second trial.

4.4.3 Analysis

12. Estimate the uncertainty in each measured value (δI, δV, δt, δm, δT) and record it with the data. Calculate the relative error (see appendix A) for each measured quantity (I, V, m, Δt, ΔT). What contributes the most error to the experiment? Is the electric energy or thermal energy a more precise quantity? Explain your answer.

13. Make a graph of time (x) vs. temperature (y). The range of the y-axis should only include temperatures your group recorded. The graph needs to include data from every 30 seconds, rather than 15 seconds. Indicate the time the power supply is turned off and the maximum temperature. Both trials may be plotted on the same graph. Mark the different trials using different colors or data markers. Is the temperature gain consistent or are there times when it jumps or lags? Please explain why the temperature rise is not constant, if applicable. Is one trial more consistent that the other? After the power supply is turned off, does the temperature go down with a larger or smaller magnitude of the slope than when it was heating? What does this slope after Δt tell you about the calorimeter's ability to trap thermal energy?

14. For both trials, use equation 4.3 to calculate the electric energy lost by the circuit. This should be expressed in joules. If the potential changed frequently and/or significantly while the source was on, the average of the potential should be used.

15. For both trials, use equation 4.5 to calculate the heat gained by the calorimetric system. This should be expressed either in calories or joules depending upon your instructor's preference.

16. Compare your values of electric energy and thermal energy using a percent error:

$$\frac{\left|\frac{Q}{E} - theoretical\right|}{theoretical} \times 100\%$$

Where Q and E are the calculated values found in steps 14 and 15; and the theoretical value is what is expected for $\frac{Q}{E}$. The theoretical value is from equation 4.6 and depends upon the units used in step 15. Discuss your results. Was one type of energy consistently higher? Why would that be? If your percent error was more than 5%, where did the energy go or come from?

Lab

5

Resistors in Series and Parallel

Continuing to build and measure circuits.

5.1 Lab Description

Students will build more complicated circuits and continue to measure their properties. A circuit with resistors in series, a circuit with resistors in parallel, and a circuit with both will be analyzed.

Students should familiarize themselves with the following concepts from their textbooks before lab: Ohm's law, resistors in series and parallel.

Students should also read Appendix B covering the use of the digital ammeter, digital ohmmeter, and analog voltmeter.

5.2 Safety and Hazards

5.2.1 The potentials produced by the batteries when connected are up to 3.0 V. This does not pose a significant risk. Students should act as though the voltage is higher throughout to maintain safe practices. With this in mind please adhere to the following:

- The battery should be disconnected unless actively taking data.
- Wiring the circuit should occur while the battery is disconnected.
- Watch for loose connections.
- When the battery is connected, do not touch the exposed metallic connectors of the wires or resistors.

5.2.2 Thermal hazards are present in the exposed wires after the battery has been connected. The resistor wires will be at a higher temperature the longer the battery is connected.

5.3 Background Information

5.3.1 When resistors are placed in series, there are no junctions for the current to split into. Therefore all resistors in series should have the same current flowing through them. Ohm's law, V=IR, Eq 5.1

still applies to the individual resistors in series so the voltage drop over an individual resistor is directly proportional to the resistance of the resistor. These voltage drops must also add to the potential of the voltage source or battery connected to them. Ohm's law also applies to the entire circuit so if V is the potential of the battery and I is the current drawn from the battery, then R_{ser} is the equivalent resistance of the circuit. The equivalent resistance for resistors in series is calculated by $R_{ser} = R_1 + R_2 + R_3 + \cdots$ Eq 5.2

where R_i is a single resistor's resistance.

This is a good example of Kirchhoff's loop rule at work

5.3.2 When resistors are placed in parallel, the higher potential sides are connected together and the lower potential sides are connected together. This means that all resistors in parallel will have the same potential before and after the resistor making their voltage drops equal. Ohm's law still applies to the individual resistors in parallel making the current flowing through a resistor inversely proportional to their resistances. These individual currents must also add to the current being drawn from the voltage source or battery. Ohm's law also applies to the entire circuit so if V is the potential of the battery and I is the current drawn from the battery, then R_{par} is the equivalent resistance of the circuit. The equivalent resistance for resistors in parallel is calculated by $R_{par} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots\right)^{-1}$ Eq 5.3

where R_i is a single resistor's resistance.

This is a good example of Kirchhoff's junction rule at work

5.4 Activities

As a reminder, the battery can be disconnected between measurements by removing one or both of the wires from the + and - terminals. This prevents draining the battery and unintentional shorts which can harm the battery and meters.

5.4.1 Individual Resistances

1. Use the digital ohmmeter to measure the resistance of each resistor. This should be done by having the mounted resistor connected to your breadboard and then connecting the leads of the ohmmeter to the bread board as shown in figure 4.2. **The batteries should not be connected to anything at this time. If a battery or power source is connected while in the ohmmeter mode, you may blow a fuse or damage the meter.** Vary the dial on the ohmmeter to have the maximum number of significant digits possible. Estimate and record your uncertainty. Repeat for all three resistors.

2. Label each resistor R_1, R_2, and R_3 in order of increasing resistance.

5.4.2 Resistors in Series

1. Construct the resistor portion of the circuit as shown in Figure 5.1. Connect the ohmmeter to measure the total resistance, R_{E1ser}. This is the first experimental value of the equivalent resistance.

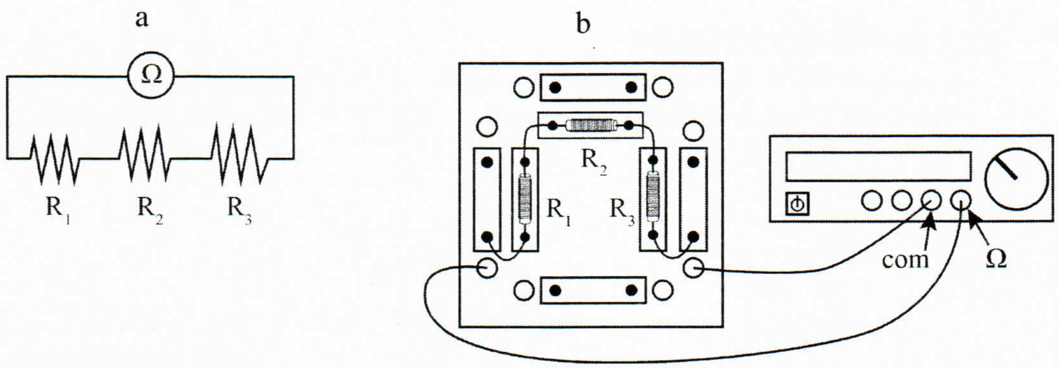


Figure 5.1 The ohmmeter and resistors in series. Figure 5.1a uses a circuit diagram. Figure 5.1b is the real-life schematic. . "COM" is Common Ground. The ends of the resistor are interchangeable – it does not matter which end is connected to the next component.

2. Calculate the equivalent resistance using equation 5.2. This is the theoretical value of the equivalent resistance. Compare the two equivalent resistances and give a percent error.

3. Add the battery and ammeter to the resistors in series as shown in Figure 5.2. Make sure the ammeter is dialed into an appropriate setting before turning on. Connect the second battery lead only when ready to take data. Finally add the voltmeter last by connecting the leads (wires connected to the meter) to the battery terminals. Record the current drawn from the battery and the battery potential while connected to the circuit. The settings for both the ammeter and voltmeter should be altered so that the maximum precision is obtained.

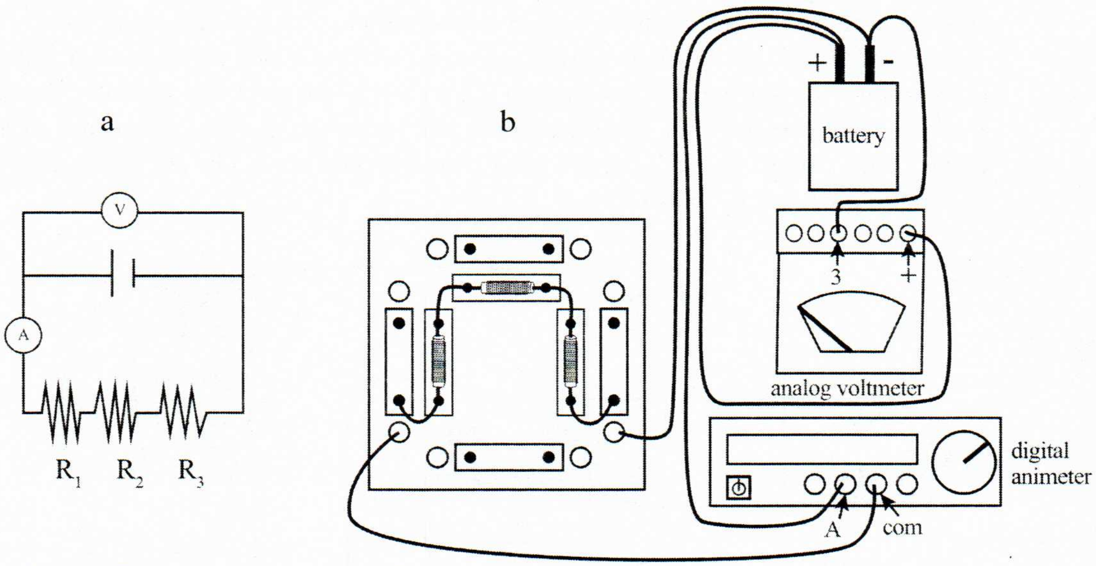


Figure 5.2 The resistors in series circuit. Figure 5.2a uses a circuit diagram. Figure 5.2b is the real-life schematic.

4. Using these values and equation 5.1, calculate the second experimental value for the equivalent resistance, R_{E2ser}. Compare to the theoretical value and give a percent error.

5. Remove the voltmeter leads from the battery terminals. With the battery connected and your fingers touching only the rubberized portion of the voltmeter leads, place the voltmeter leads across the posts of R_1, and record the voltage drop. Repeat for each resistor in series. Are the potential changes consistent with theory?

5.4.3 Resistors in Parallel

1. Construct the resistor portion of the circuit as shown in Figure 5.3. Connect the ohmmeter to get the total resistance, R_{E1par}. This is the first experimental value of the equivalent resistance.

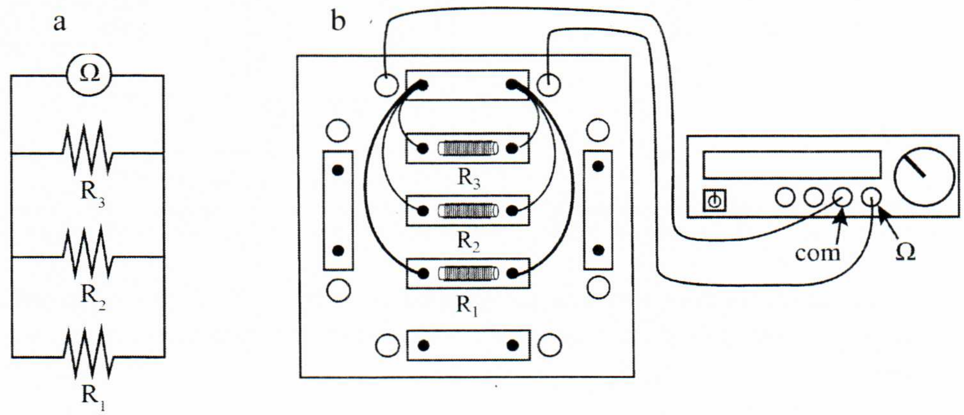


Figure 5.3 Measuring the resistance in parallel. Figure 5.3a uses a standard circuit diagram. Figure 5.3b is the real-life schematic.

2. Calculate the equivalent resistance using equation 5.3. This is the theoretical value of the equivalent resistance. Compare the two equivalent resistances and give a percent error.

3. Add the battery and ammeter to the resistors in series as shown in Figure 5.4. Make sure the ammeter is dialed into an appropriate setting before turning on. Connect the second battery lead only when ready to take data. Finally add the voltmeter last by connecting the leads (wires connected to the meter) to the battery terminals. Record the current drawn from the battery and the battery potential while connected to the circuit. The settings for both the ammeter and voltmeter should be altered so that the maximum precision is obtained.

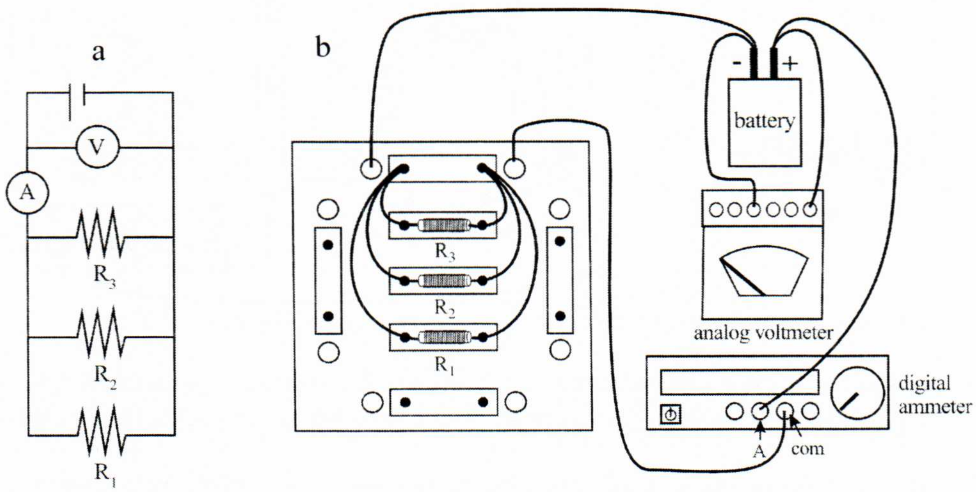


Figure 5.4 The resistors in parallel circuit with ammeter at positive terminal of battery and voltmeter over battery. 5.4a circuit diagram. 5.4b real-life diagram

4. Using these values and equation 5.1, calculate the second experimental value for the equivalent resistance, R_{E2par}. Compare to the theoretical value and give a percent error.

5. Disconnect one of the battery terminals. Remove the voltmeter and ammeter. Move the ammeter to measure the current flowing through R_1 as shown in figure 5.5. Repeat for each resistor in parallel. Are the currents measured consistent with theory?

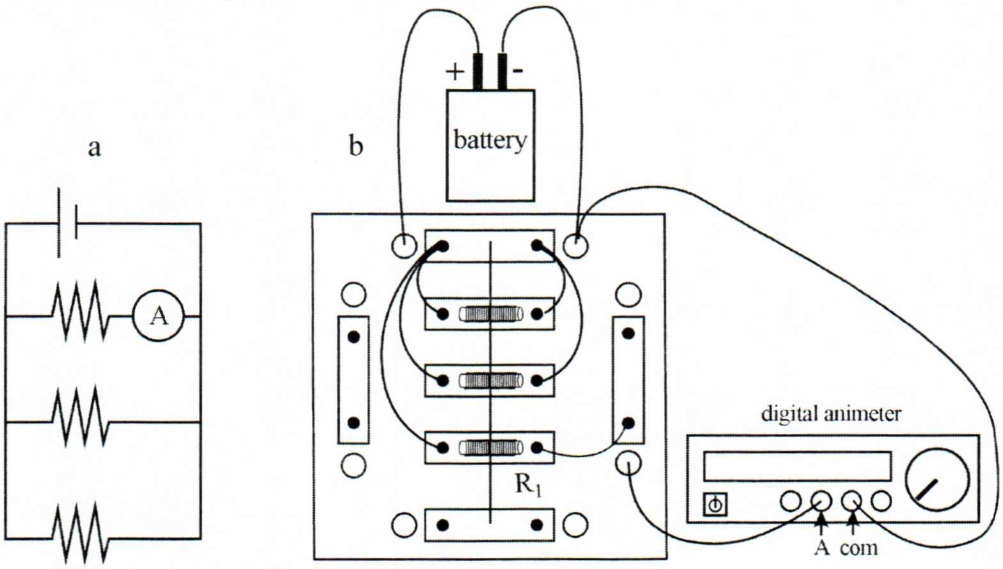


Figure 5.5 Measuring the currents over resistors in parallel. Figure 5.5a uses a standard circuit diagram. Figure 5.5b is the real-life schematic.

5.4.4 Resistors in Series and Parallel

1. Construct the circuit shown in figure 5.6. Leave one lead of the battery unconnected for now.

2. Determine the equation for the equivalent resistance of this resistor configuration. This will be Eq. 5.4. This could have been assigned as a pre-lab assignment, worked out by your lab group, worked out as a class or just given to you. Your instructor will determine which is appropriate for your lab.

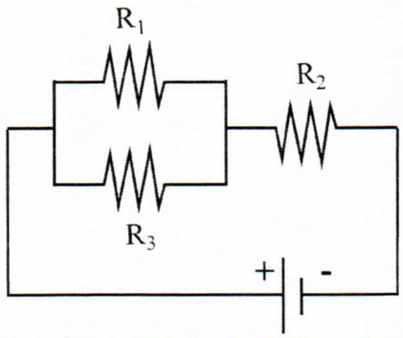


Figure 5.6 A circuit diagram with three resistors connected in series and parallel.

3. Use your individual resistance values and equation 5.4 to calculate the equivalent resistance. This is your theoretical value.

4. Connect the battery to the circuit and record the voltage provided by the battery and the current drawn from it.

5. Use the current and voltage values and equation 5.1 to obtain the equivalent resistance. This is your experimental value. Compare the experimental and theoretical equivalent resistances and give a percent error.

Lab

6

Kirchhoff's Rules

Building and measuring more complex circuits then applying Kirchhoff's rules to them.

6.1 Lab Description

Students will build multi-junction circuits and continue to measure their properties. Kirchhoff's junction rule and Kirchhoff's loop rule will be tested.

Students should familiarize themselves with the following concepts from their textbooks before lab: Ohm's law, Kirchhoff's rules, circuit diagrams.

Students should also read Appendix B covering the use of the digital ammeter, digital voltmeter, and digital ohmmeter.

6.2 Safety and Hazards

6.2.1 The potentials produced by the batteries when connected are up to 3.0 V. This does not pose a significant risk. Students should act as though the voltage is higher throughout to maintain safe practices. With this in mind please adhere to the following:

- The battery should be disconnected unless actively taking data.
- Wiring the circuit should occur while the battery is disconnected.
- Watch for loose connections.
- When the battery is connected, do not touch the exposed metallic connectors of the wires or resistors.

6.2.2 Thermal hazards are present in the exposed wires after the battery has been connected. The resistor wires will be at a higher temperature the longer the battery is connected.

6.3 Background Information

6.3.1 Current is the result of charges moving due to potential differences. Because charge is a conserved quantity, any charge put into a system must come from and go somewhere as it cannot be created or destroyed. Kirchhoff's junction rule is the logical expression of this at circuit junctions. A junction is where three or more wires meet and current is able to flow on those wires. The amount of current flowing into a junction must equal the amount of current flowing out of the same junction, or $\sum I_{in} = \sum I_{out}$. Eq 6.1

6.3.2 The amount of potential energy for a test charge in a circuit will change depending upon its position within the circuit. The electric potential is an expression of that potential energy for a hypothetical positive charge. Because energy is a conserved quantity, the same location in a circuit will have the same potential no matter how a charge moved to get there. Kirchhoff's loop rule is the logical expression of this idea. If one starts anywhere on a circuit, travels along the wires and circuit components in any route to end at the same location, then the potential differences (final – initial) over all components on that route will add to zero, or $\sum(V_f - V_i) = 0$ Eq 6.2

All Kirchhoff loops within a circuit will yield consistent results with each other though the loop directions over the same components may vary. Each term represents the change in voltage following the loop direction and the sign of the term should reflect that direction. For a loop that goes over a battery from the negative terminal to the positive, $(V_f - V_i)$ will be positive. For a loop that goes over a battery from the positive terminal to the negative, the negative terminal has a lower potential than the positive one so $(V_f - V_i)$ will be negative. For a loop that goes over a resistor in the same direction as the current, $(V_f - V_i)$ will be negative because the current flows from high to low potential. For a loop that goes over a resistor in the opposite direction as the current, $(V_f - V_i)$ will be positive.

6.4 Activities

6.4.1 Individual Resistances

1. Use the digital ohmmeter to measure the resistance of each resistor. This should be done by having the mounted resistor connected to your breadboard and then connecting the leads of the ohmmeter to the bread board as shown in figure 4.2. **The batteries should not be connected to anything at this time. If a battery or power source is connected while in the ohmmeter mode, you may blow a fuse or damage the meter.** Choose the most sensitive scale on the ohmmeter to have the maximum number of significant digits possible. Estimate and record your uncertainty. Repeat for all three resistors.

2. Label each resistor R_1, R_2, and R_3 in order of increasing resistance.

6.4.2 Kirchhoff's Rules

1. Assemble the first circuit as shown in figure 6.1. Do not connect the battery terminals until you are ready to make measurements. If you need to pause while making measurements, the batteries should also be disconnected to avoid shorts and draining the batteries.

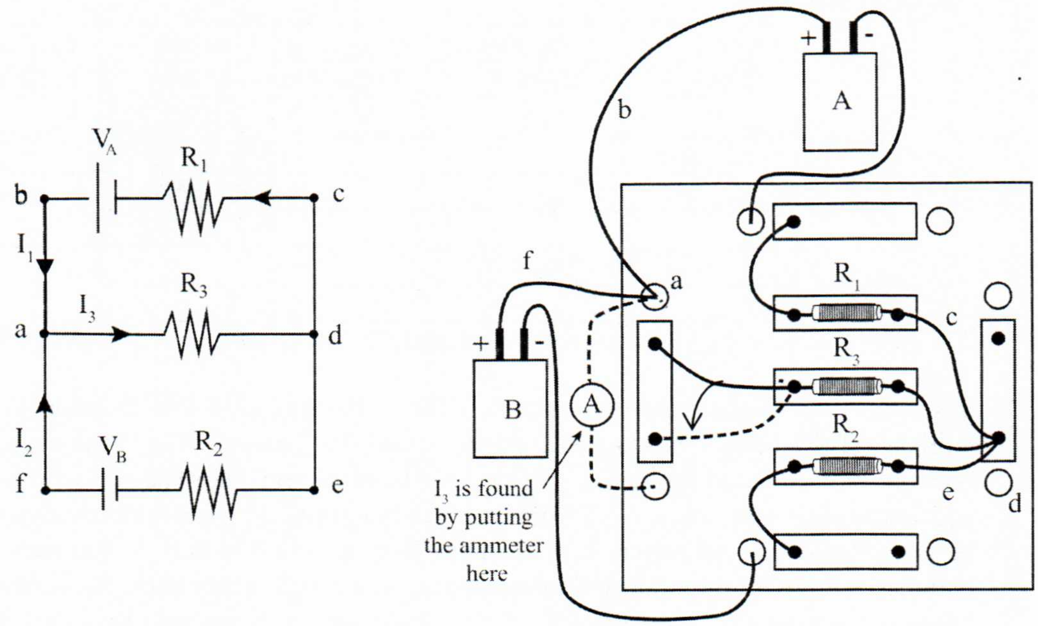


Figure 6.1 Multi-loop circuit 1. 6.1a is the circuit diagram. 6.1b is the real-life schematic. Note that in figure 6.1b the wire connecting point a to R_3 must be moved to the dashed position to accommodate an ammeter put in in part 7 to measure I_3.

2. Prepare the digital voltmeter by turning on, inputting banana-banana leads, and setting the dial appropriately.

3. Connect the batteries to the circuit. Connect the voltmeter leads into Battery A's two terminals to measure the voltage. **Important: you must have both batteries connected to get an accurate measurement.** Remove the voltmeter leads and repeat for Battery B. Remove the voltmeter leads.

4. With the batteries still connected and your fingers touching only the rubberized portion of the voltmeter leads, place the voltmeter leads across the posts of Resistor 1, and record the voltage as V_1. Repeat for each resistor. Disconnect the batteries but do not take apart the circuit.

5. Use Ohm's law and the measured values of resistance and voltage over each of the resistors to calculate the currents flowing through each of the resistors (this does not go into data as is it not measured). Use the junction rule and the circuit diagram in figure 6.1 to make an expression relating the three currents. Are your calculated currents consistent with Kirchhoff's junction rule within the uncertainty?

6. Create the following table so that the voltage over each circuit component in a Kirchhoff loop can be easily viewed. Remember that positive and negative values can depend on the loop direction and direction of the current. You can also re-read the voltmeter readings, this time going in the direction of the loop with the "com" lead positioned at the start of the component and the "V" lead at the other end to know the sign of each voltage.

loop	Component Voltage	Component Voltage	Component Voltage	Component Voltage	Sum of Voltages
adcba	R_3	R_1	V_A		
efade					
bfecb					

Are the measured voltages consistent with Kirchhoff's loop rule within the uncertainty?

7. Disconnect the batteries and voltmeter. Change the multimeter to function as an ammeter. The lead locations as well as the dial should be changed. Wire in the ammeter between Battery A and Resistor 1. Connect the batteries and record (as data) the value and uncertainty in Current 1. Disconnect the batteries. Move the ammeter to be between Resistor 2 and Battery B. Reconnect Resistor 1 and Battery A. Connect the batteries and record the value and uncertainty in Current 2. Disconnect the batteries. Move the ammeter to be between Resistor 3 and point a. Reconnect Resistor 2 and Battery B. Connect the batteries and record the value and uncertainty in Current 3. Disconnect the batteries.

8. Compare the calculated currents from step 6 to the measured values in step 7. Are they the same within the error or are they different? If they are different, why is there a difference?

9. Are the measured values of current consistent with Kirchhoff's junction rule?

10. Kirchhoff's rules can be combined to solve for the currents in terms of the battery terminal voltages and resistances:

$$I_1 = \frac{V_A(R_2 + R_3) - V_B R_3}{R_1R_2 + R_1R_3 + R_2R_3} \quad \text{Eq 6.4}$$

$$I_2 = \frac{V_B(R_1 + R_3) - V_A R_3}{R_1R_2 + R_1R_3 + R_2R_3} \quad \text{Eq 6.5}$$

$$I_3 = \frac{V_A R_2 + V_B R_1}{R_1R_2 + R_1R_3 + R_2R_3} \quad \text{Eq 6.6}$$

Use your measured values for battery voltages and resistances to calculate the currents with these equations. These are your theoretical values. Compare the calculated values from step 6 and the theoretical values and give three percent errors. Discuss your results.

6.4.3 Another Three Loop Circuit

1. Create the circuit in figure 6.2 without the help of a real-life schematic. **Do not connect you batteries until your circuit has been checked as incorrect wiring may cause current to run the wrong direction over a battery and drain it in seconds.**

2. Repeat the experiment for the new circuit.

3. In what direction does the current I_2 flow? How did you determine this?

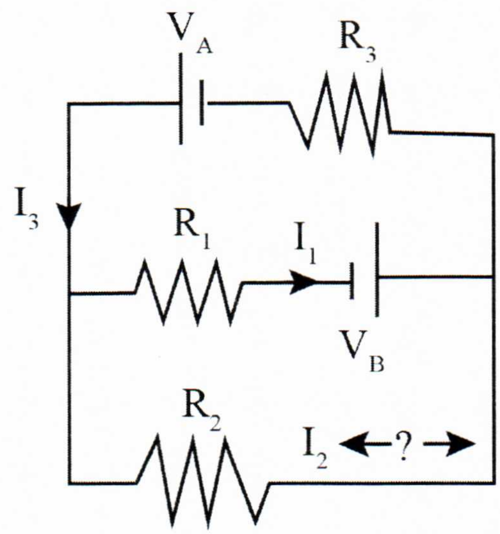


Figure 6.2 Multi-loop circuit #2.

4. Kirchhoff's rules can be combined to solve for the currents in terms of the battery terminal voltages and resistances:

$$I_1 = \frac{V_B(R_2 + R_3) + V_A R_2}{R_1R_2 + R_1R_3 + R_2R_3} \quad \text{Eq. 6.7}$$

$$I_2 = \frac{V_B R_3 - V_A R_1}{R_1R_2 + R_1R_3 + R_2R_3} \quad \text{Eq. 6.8}$$

$$I_3 = \frac{V_A(R_1 + R_2) + V_B R_2}{R_1R_2 + R_1R_3 + R_2R_3} \quad \text{Eq. 6.9}$$

Lab

7

Electromagnetic Induction

More and more, electromagnetic induction is becoming part of our everyday life: traffic light sensors, wireless cell phone chargers, cooking tops and rail travel to name a few examples.

7.1 Lab Description

Faraday's law and Lenz's law are investigated qualitatively so that students can develop an instinctive understanding of induced current and induced magnetic field directions.

Students should familiarize themselves with the following concepts from their textbooks before lab: Magnetic fields of coils and bar magnets, Faraday's law of induction, Lenz's law, magnetic flux, induced emfs and induced currents.

7.2 Safety and Hazards

7.2.1 The potential produced by the battery is 1.5 V. This does not pose a significant risk. Students should act as though the voltage is higher throughout to maintain safe practices. With this in mind please adhere to the following:

- Use the switches to keep the circuit disconnected unless actively taking data. .
- Watch for loose connections.
- When the battery is connected, do not touch the exposed wires of the coils or connectors.

7.3 Background Information

7.3.1 Magnetic fields are the means by which the magnetic force can act on other objects with magnetic fields such as moving charges or permanent magnets in that field. Magnetic field lines make closed loops and the directions are dependent on the object creating the field. A bar magnet will have the magnetic field lines pointing out of the north end and going into the south end. A current-carrying wire will have magnetic field lines that make

Compasses will align to and point the direction of a magnetic field

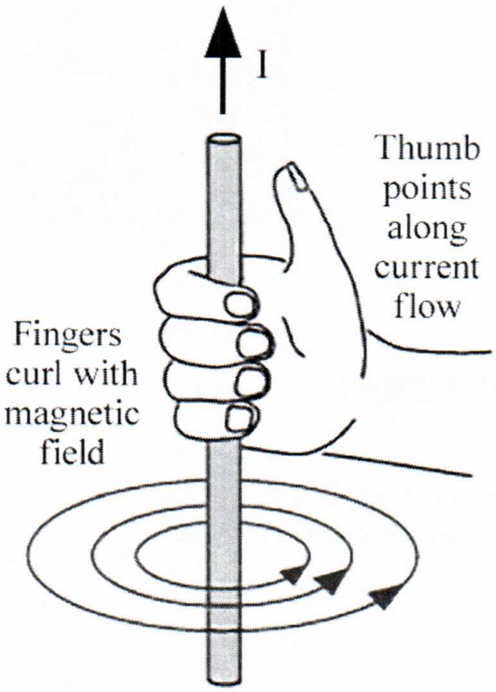


Figure 7.1 The Right Hand Rule for magnetic fields. Align your right thumb with the direction of current. Your fingers will curl in the direction of the magnetic field.

concentric circles about the wire as shown in figure 7.1, the direction depends upon Ampère's right hand rule.

Following Ampère's right hand rule, the magnetic field of a coil can be deduced (and will be in the activities). The coil is an especially useful current configuration as the strength of the magnetic field is proportional to the number of loops, making the effects easy to detect with smaller currents. The coil also has the distinction of having a magnetic field very similar to a short bar magnet.

7.3.2 Magnetic flux, Φ, can be thought of as the amount of magnetic field that goes through a cross-sectional area, A, usually bounded by a wire. The magnetic flux depends on the direction of the magnetic field in reference to the cross-sectional area as the maximum amount of flux occurs when the magnetic field lines are perpendicular to the cross-sectional area and zero when they are in the same plane.

Often this is expressed as $\Phi = B\,A\cos\theta$. Eq 7.1

Where θ is the angle between the magnetic field and the vector normal to the cross-sectional area. Alternately, one can use $\Phi = B \perp A$, Eq 7.2

where one can find the amount of the magnetic field, B, that is perpendicular to the cross-sectional area.

Faraday's law states that when there is any change in that flux bounded by a wire over time, there will be an emf, and therefore a current, induced in that wire as

$\varepsilon \propto \frac{\Delta\Phi}{\Delta t}$ Eq 7.3

Utilizing Lenz's law, one can determine the direction of that induced current. The current induced in the wire will have a magnetic field point in a direction such that it will **oppose the change in the magnetic flux**.

7.3.3 The galvanometer is a type of ammeter that measures current direction and strength with its deflecting needle. As an ammeter, the galvanometer is wired in series with the component to be measured. In general, the needle will point or deflect toward the wire where the current came from. This can be tested by connecting it to the battery and one of your coils. The amount of deflection indicates the relative current strength.

7.4 Activities

In all of the following activities, the metal support rod should run through the coils being used. Use the hooks attached to the coils to move them when called for.

7.4.1 Testing the Equipment

Occasionally, the compasses and/or bar magnets in the trays can change polarization due to prior mishandling or how they were stored. For this reason we test our equipment first.

1. Place your compasses out on the lab table away from any magnets and allow them to align with the Earth's magnetic field. Determine if your compasses have the correct polarity: the colored end should point (geographic) northward. Your instructor can aid you in repolarizing if needed.

2. Test your bar magnets with your functioning compasses. Toward what end should the compass needle point? Your instructor can aid you in repolarizing if needed.

3. Connect the battery, coil, switch, and galvanometer in series as shown in figure 7.2. Briefly close the switch. In what direction does the current run? In what direction does the needle deflect?

4. Disassemble the coil, battery, galvanometer, and switch.

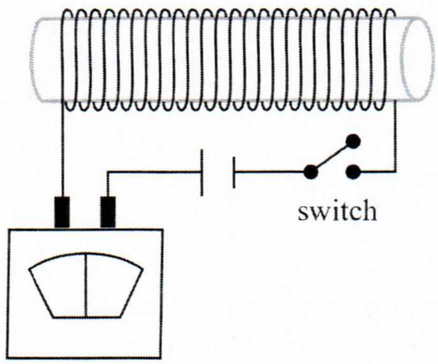


Figure 7.2 A battery, coil, switch and galvanometer in series.

7.4.2 The Magnetic Field of a Coil

1. Connect a coil to the battery. Determine the direction of current in the coil. Using the right hand rule, work out the shape and directions of the magnetic field lines. Test this by using the compass. Be sure to include both the inside and outside of the coil.

2. Make drawings that indicate the direction of current and magnetic field. Explain how the direction of the field is consistent with the right hand rule.

3. Disconnect the battery and reconnect with the reverse polarity. Repeat steps 1 and 2.

4. How does the strength of the magnetic field from the current through the coil compare with the errant magnetic fields present in the room? At what distance from the coil center, along the coil axis, can you no longer get an accurate reading on the coil's magnetic field direction?

7.4.3 Induced Current by a Coil

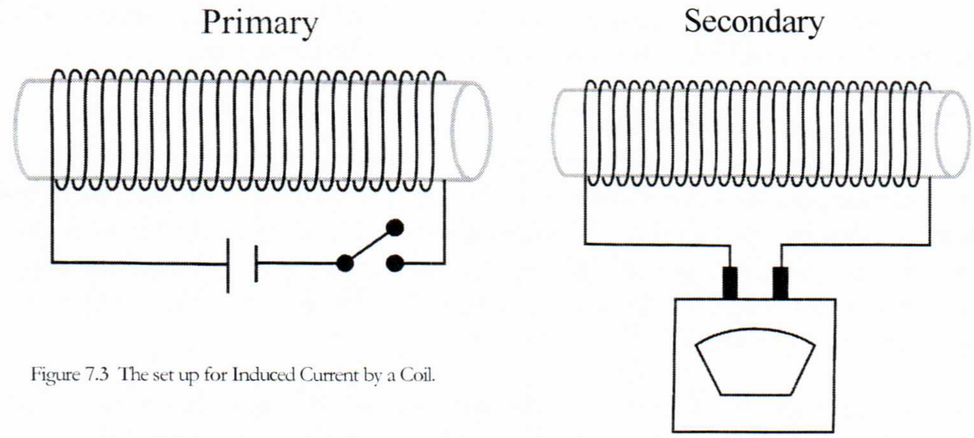


Figure 7.3 The set up for Induced Current by a Coil.

1. The metal support rod should run through the coils being used. Use the hooks attached to the coils to move them when called for. Add a switch in series with the coil and battery from activity 7.4.2 as shown. The coil connected to the battery is the primary coil. The coil set next to it connected to the galvanometer will be the secondary coil. See figure 7.3. The coils should have their windings go in the same direction and be no more than 2 cm apart on the support rod. The secondary coil will have the induced current and induced magnetic field due to the changing magnetic flux with in it.

For steps 2-6, draw out and explain the following:

- Before and after the moment the action is executed, in what direction will the current flow in the primary?
- In what direction will the magnetic field from the primary at the location inside of the secondary coil point?
- Is the flux enclosed by the secondary coil getting larger, smaller, or remaining the same when the action is executed?
- Using Lenz's law, in which direction should the induced magnetic field point?
- Using the right hand rule, in what direction does the induced current point? Is this consistent with what the galvanometer displays?

2. The switch is already open, then it is closed.

3. The switch is already closed, then opened.

4. The switch is already closed, the secondary is moved away from the primary. Note what happens if the motion is faster.

5. The switch is already closed, the secondary is moved toward the primary.

6. The switch is already closed, the primary is moved away from the secondary.

7.4.4 Induced Current by a Magnet

1. Remove the primary coil and keep the secondary coil connected to the galvanometer.

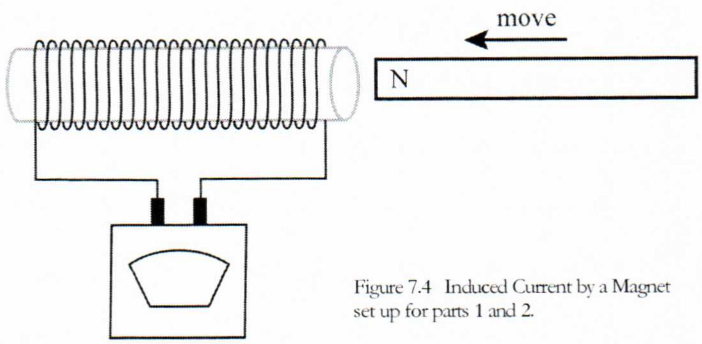


Figure 7.4 Induced Current by a Magnet set up for parts 1 and 2.

For steps 2-6, draw out and explain the following:

- At the moment the action is executed, in what direction will the magnetic field from the magnet at the location inside of the secondary coil point?
- Is the flux enclosed by the secondary coil getting larger, smaller, or remaining the same when the action is executed?
- Using Lenz's law, in which direction should the induced magnetic field point?
- Using the right hand rule, in what direction does the induced current point? Is this consistent with what the galvanometer displays?

2. Move the north end of the bar magnet into the core of the secondary coil. Examine the effect of the speed of the motion.

3. Pull the north end of the magnet out and away from the secondary.

4. Move the south end of the bar magnet into the core of the secondary coil.

5. Pull the south end of the magnet out and away from the secondary

7.4.5 Some Questions about Induced Current

1. Since energy is conserved, where does the current in the coil come from?

2. If you wanted to induce continuous current in one of the coils (so that the galvanometer stays on one side or the other), can you think of a way to do that with the magnet and coils from today's experiment? What types of energy (potential energy, thermal energy, etc.) could you use in this manner to generate electricity?

Lab

8

Reflection and Refraction

An introduction to ray optics.

8.1 Lab Description

This lab consists of multiple short exercises on ray optics. Students will be introduced to using a helium-neon laser in order to observe and become familiar with simple reflection and refraction topics.

Students should familiarize themselves with the following concepts from their textbooks before lab: the law of reflection, index of refraction, Snell's law, and critical angle.

8.2 Safety and Hazards

8.2.1 This lab uses helium-neon lasers which are a light hazard. These helium-neon lasers have a wavelength of 632.8nm, and operating power of 0.95 mW. Although indirect exposure to the eye is considered safe, please observe the following safety procedures throughout the lab session:

- Do not point the laser in or near your, or anyone else's eyes.
- Either turn off or close the aperture of the laser when not in use.
- When turning on or opening the aperture, warn others that may be in the light's path.
- When using mirrors or lenses, do your best to block reflected or refracted light.

8.2.2 This lab uses desk lamps which are a thermal hazard. The light bulb and surrounding metal can get very hot after a short time of use. Students should avoid touching these parts of the lamp and manipulate the neck of the lamp if the light must be adjusted.

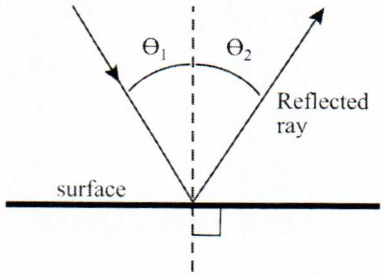


Figure 8.1 The law of reflection. θ_1 is the incident ray. The dashed line is perpendicular to the surface.

Material	n
Air	1.00
Water	1.33
Acrylic/ Plexiglas	1.49
Crown Glass	1.48 – 1.62
Flint Glass	1.52 – 1.92

Table 8.1

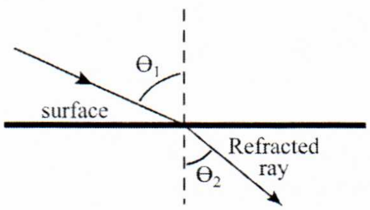


Figure 8.2 Here the speed of light is greater for the incident ray than the refracted ray.

8.3 Background Information

8.3.1 When a ray interacts with a mirror, the law of reflection states that the angle of the incident ray is equal to that of the reflected ray as in figure 8.1. The mirror is at the plane of incidence. The angle of the incident ray is defined to be between the ray and a line perpendicular to the surface of the mirror where the ray makes contact. The angle of the reflected ray is defined to be between the ray and a line perpendicular to the surface of the mirror where the ray made contact. For all mirrors, the incident angle will be equal to the reflected ray or $\theta_1 = \theta_2$. Eq 8.1

8.3.2 When in vacuum, light travels at the speed of light, $c = 3.00 \times 10^8 \frac{m}{s}$. When light crosses into any medium, it will move at a different speed as $v = \frac{c}{n}$ Eq 8.2

where n is the index of refraction. Some values for the index of refraction useful for today's lab are found in table 8.1. As light moves from one medium to another, the change in speed leads to a change in the trajectory of the light. This change is expressed as Snell's law:

$n_1 \sin\theta_1 = n_2 \sin\theta_2$ Eq 8.3

where, once again, the angles are defined as between the ray and the line perpendicular to the plane of incidence where the ray made contact. See figure 8.2. When the speed is greater for the incident ray ($n_1 < n_2$) then the refracted ray seems to bend toward the perpendicular (away from the plane of incidence). When the speed is smaller for the incident ray ($n_1 > n_2$) then the refracted ray seems to bend away from the perpendicular (toward the plane of incidence).

In the case of $n_1 > n_2$, as θ_1 is increased, θ_2 also increases but there is a limit: θ_2 can only get up to 90°. Snell's law can be used to find what θ_1 would be for this special case of $\theta_2 = 90°$:

$$\theta_1 = \sin^{-1}\left(\frac{n_2 \sin 90°}{n_1}\right) = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \theta_C \qquad \text{Eq 8.4}$$

For this special case, θ_1 is referred to as the critical angle, θ_C. When $\theta_1 \le \theta_C$, the incident ray refracts. When $\theta_1 > \theta_C$, there is total internal reflection.

8.4 Activities

Initial Set-Up

See figure 8.3. The optical carriages clamp to the optical bench. These should be placed far enough apart so that the platform and laser will not touch. The short rods screw into the bottoms of the laser and platform and then fit into the two optical carriages.

The height of both the laser and platform should be adjusted during the experiments so that the laser beam hits the object. The laser should be at least 2 mm

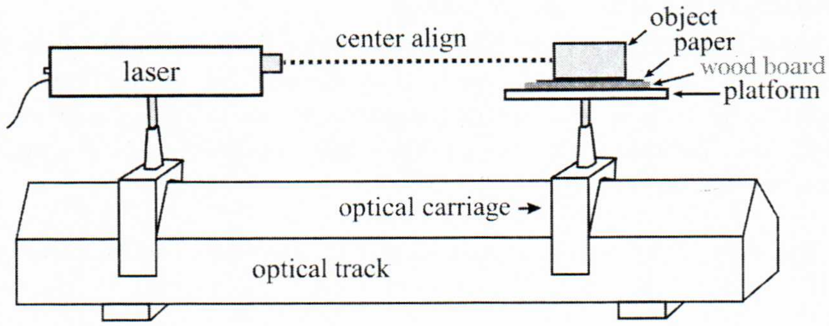


Figure 8.3 The apparatus set-up.

above the paper. The platform will wobble if turned so place the other wood board on top **and move that rather than the platform**. Place your paper on the board to mark positions and rays.

During the experiment, the object should be outlined carefully so that the plane of incidence will be accurate.

There are two ways to trace the laser beam:

1) Use the provided pins to mark the path by making small holes in the paper. This has the advantage of having a small cross-sectional area so that if the laser is hitting the pin, it is also likely to be hitting the middle of the pin

2) Use a pencil to mark the path by making small dots on the paper. This has the advantage of being able to erase if an error is made.

The locations of where at the plane of incidence the ray hits the object, enters, exits, or reflects at the change in mediums should also be marked.

In all of the following activities rulers are to be used to make straight lines and protractors to measure angles to the nearest 0.5°.

8.4.1 The Law of Reflection

1. Draw a straight line on a paper with a ruler and align the plane mirror to it. Angle the cork so that the laser's incident angle is greater than 10°.

2. Without moving anything, mark on the paper where the laser hits the mirror. Mark the incident and reflected rays.

3. Repeat for 2 different angles - there should be at least a 10° difference. You can keep the same mirror line but you should not hit the same point of reflection. If needed, make notes as to what marks go with what trial.

4. Remove the paper from the cork. Using the ruler, connect the marks to their corresponding reflection point.

5. Use the protractor and ruler to make a dotted line perpendicular to the mirror surface where the ray made contact for each reflection. Use the protractor to measure the angles of incidence and reflection. Do your results reasonably match theory? The differences in the incident and reflected ray angles can be used as an estimate for error in reading your angles for the rest of the experiment.

8.4.2 The Index of Refraction of Glass

1. On a new sheet of paper, trace the glass block. Point the laser at the glass block and rotate the cork board so that the angle of incidence is between 20° and 70°. A rough check can be done by placing the protractor on the paper against the glass block. Mark the incoming ray and where it hits the prism. Mark where the refracted internal ray terminates.

2. Repeat for the triangular prism starting with tracing the prism (on the same paper if possible).

3. Remove the paper from the cork. Using the ruler, connect the marks to recreate the light ray. You may have to extend the refracted ray so that it will be long enough to measure the angle accurately. Using the protractor and ruler, make a dotted line normal to the plane of incidence. Use the protractor to measure the incident and refracted angles.

4. Assume that the index of refraction for air is 1.00. Use Eq. 8.3 to determine the index of refraction for the glass block and the triangular prism. Compare these to each other. Compare these values to the value of ideal crown glass, 1.52, and give the percent errors. Use your errors stated in Activity 8.4.1 to aide your discussion.

8.4.3 Critical Angle for Glass-Air Interface

1. On a new sheet of paper, trace the triangular prism. Point the laser at the prism and move the cork board so that it looks like figure 8.4a.

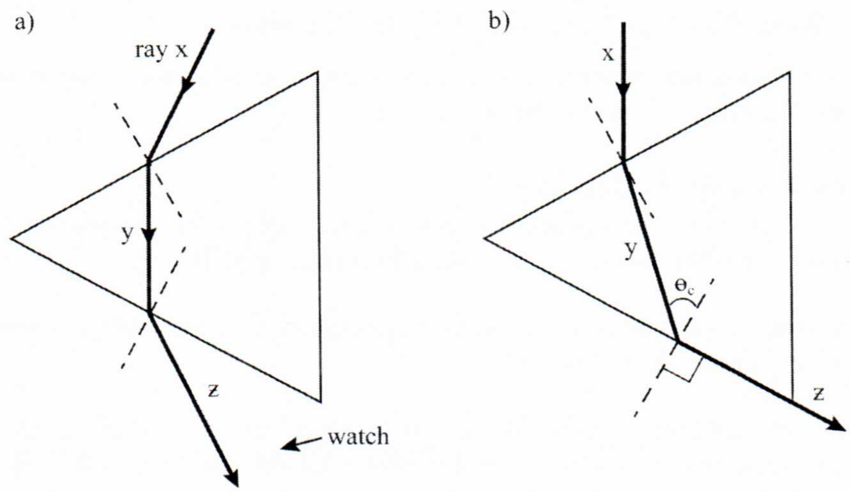


Figure 8.4 Ray x is the incoming beam. Ray y is the first refracted ray. Ray z is the 2nd refracted ray and will go to 90° when the critical angle is found in figure b

2. Slowly and carefully, rotate the cork board while watching ray z to have a larger angle of refraction. At the position where the refracted angle is 90° and ray z disappears (figure 8.4b), mark the locations denoting the start and end points of ray y. Mark the location of ray z as well.

3. Remove the paper from the cork. Using the ruler, connect the marks to recreate ray y. You may have to extend ray y where it began so that it will be long enough to measure the angle accurately. Using the protractor and ruler, make a dotted line normal to the plane of incidence where ray y ended. Use the protractor to measure the critical angle.

4. Calculate the critical angle using Eq. 8.4 and the value of ideal crown glass, 1.52. Compare the two values of the critical angle and give a percent error. Use your errors stated in Activity 8.4.1 to aide your discussion.

8.4.4 Multiple Refractions

1 On a new sheet of paper, trace the plexiglass pie tray. Partially fill the pie tray with water and a pinch of powdered milk. Gently stir and the laser light will be much more noticeable inside the water.

2 Move and rotate the corkboard so that you have at least 5 cm of incoming ray on the paper, the ray goes into the acrylic glass, traverses the water, exits the acrylic glass on the next interaction and then have at least 5 cm of outgoing ray. Mark on the paper where the laser enters and exits at the two air/ plexiglass interfaces. Study the internal rays carefully. Does the ray at the plexiglass /water interface occur at the same spot as the air/ plexiglass interface? If not, how will you account for this?

3 Remove the paper from the cork. Using the ruler, connect the marks showing the ray's full path. Using the ruler and protractor, make dotted lines normal to the plane of incidences – there will be four this time due to the tray thickness. Again using the protractor measure and label the incident and refracted rays in air and water – there will be four.

4 Take the index of refraction for air to be 1.00. Solve Snell's law twice to obtain two experimental indexes of refraction for water. Average these values and compare to the known value for the index of refraction for water. Calculate the percent error.

Lab
9

Thin Lenses and Their Images

Virtual and real images are formed using converging and diverging lenses.

9.1 Lab Description

This lab introduces students to the use of thin lenses and further enforces the ideas of real and virtual images and their locations. Measurements of objects, images and focal lengths will be used to test the lens equations.

Students should familiarize themselves with the following concepts from their textbooks before lab: The lens equations, converging vs. diverging lenses, magnification, real vs. virtual images, and ray tracing.

9.2 Safety and Hazards

9.2.1 This lab uses desk lamps and optical image lights which are a thermal hazard. The light bulb and surrounding metal can get very hot after a short time of use. Students should avoid touching these parts of the lamp and manipulate the neck of the lamp if the light must be adjusted.

9.3 Background Information

9.3.1 When parallel rays are projected on to a converging lens, the rays will converge to a single location called the principle focus, a distance f away from the center of the lens. The reverse is also true: rays from a light source at the principle focus will emerge from the converging lens parallel to each other. When parallel rays are projected on to a diverging lens, as the name suggests, the rays will diverge or spread apart and appear to come from the principle focus. Rays bound for the principle focus on one side of the lens will bend to be parallel to each other on the other side.

Rays bound for the exact center of the lens will maintain their original trajectory after emerging from lens for both converging and diverging lenses.

9.3.2 Ray tracing takes these fundamental ideas about how light behaves when moving through these thin lenses and shows where the light emitted by any object at any location will be focused or *appear* to be focused. Figures 9.1a and b demonstrate the following rays:

- Draw a ray from the top of the object parallel to the optical axis to the center of the lens. Bend the ray to move through (or appear to have come from) the principle focus.
- Draw a ray from the top of the object so that it moves toward (or moves away from) the secondary focus to the middle of the lens. Bend the ray so that it emerges parallel to the optical axis.
- Draw a ray from the top of the object through the exact center of the lens and do not change the trajectory.

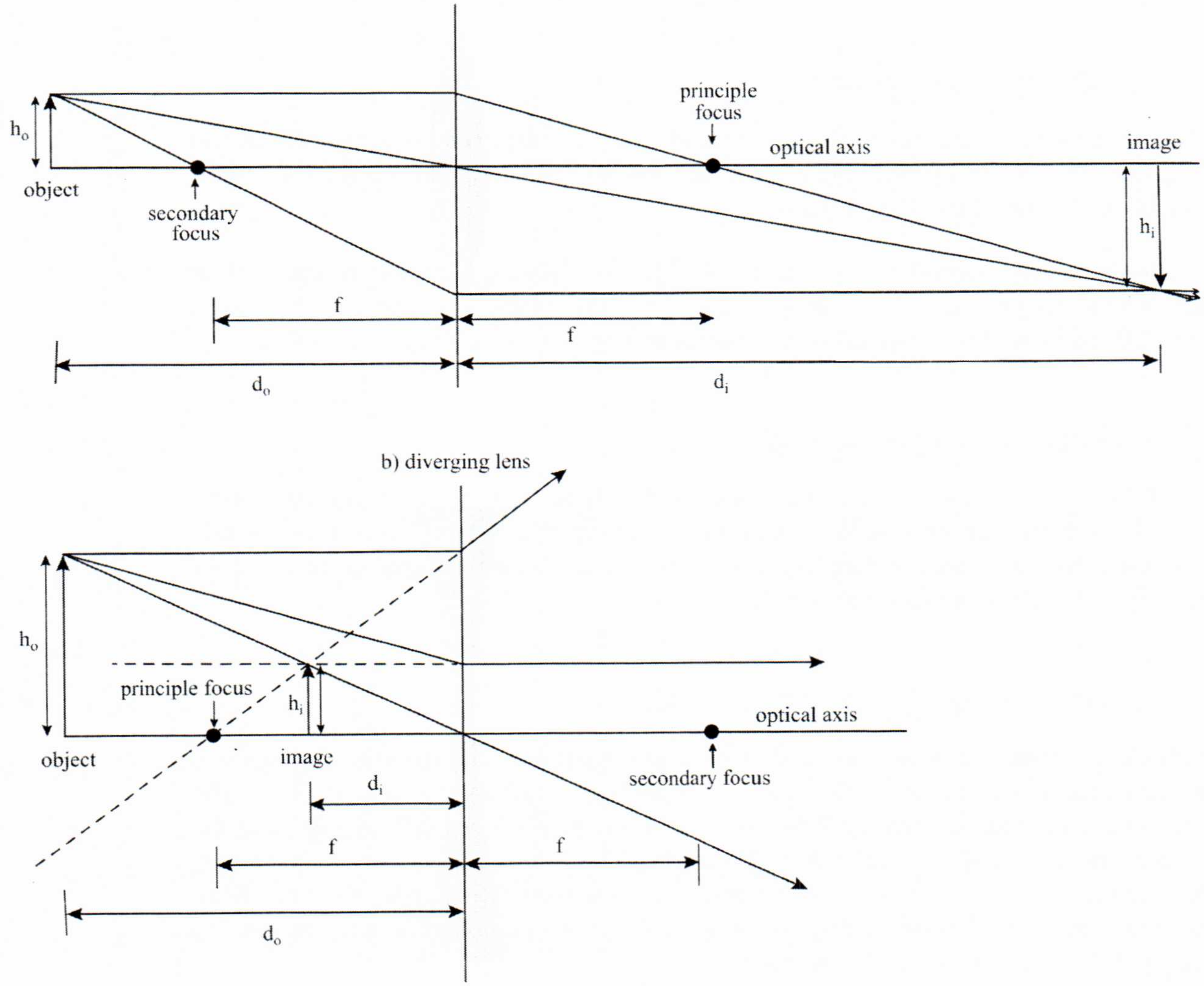


Figure 9.1 a is a converging lens, b is a diverging lens.

9.3.3 Using geometry we can express the same ideas about these thin lenses and relate their focal length, f, the distance of the object from the center of the lens, d_o, and the distance of the image from the center of the lens d_i with the lens equation: $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$ Eq 9.1

The sign of the focal length indicates which type of lens is in use. Converging lenses use a positive f, while diverging lenses have a negative value. The sign for the distance to the image conveys whether the image is real or virtual. Real images have all three rays that converge in a location. This makes it so that the image can be seen at that location if a screen were placed there. Virtual images are those where the rays would be traced back by an observer to find where they appear to have come from. The virtual rays converge at the location of the virtual image. Virtual images cannot be seen at their location unless the observer is perceiving the bent rays though the lens.

Going back to the parallel rays of 9.3.1, the rays actually converge at the principle focus of a converging lens, which would make that a real image and a positive value for f. The diverging rays bent by a diverging lens are traced back by the observer to be at the principle focus. The light does not actually come from that location, so it is a virtual image and so f is negative. The value of the object distance is always positive in the case of single lenses.

The ratio of object height, h_o, to the image height, h_i are also related to the ratio of the object and image positions as $\frac{h_i}{h_o} = m = \frac{-d_i}{d_o}$. Eq 9.2
where m is the magnification of the image. When m and h_i are negative, this indicates that the image is inverted or flipped from the original object orientaiton.

9.4 Activities

Initial Set-Up

See figure 9.2. The object for today is the arrow printed on a small lamp. The lamp fits in the optical carriage and should be at one end of the optical track. The two lenses should be fit into the holders and lightly secured. These in turn also fit into an optical carriage. The frosted glass in the screen holder fit into another carriage at the other end of the track from the lamp. The relative heights should be adjusted so that the arrow, lens, and frosted glass follow a line parallel to the track.

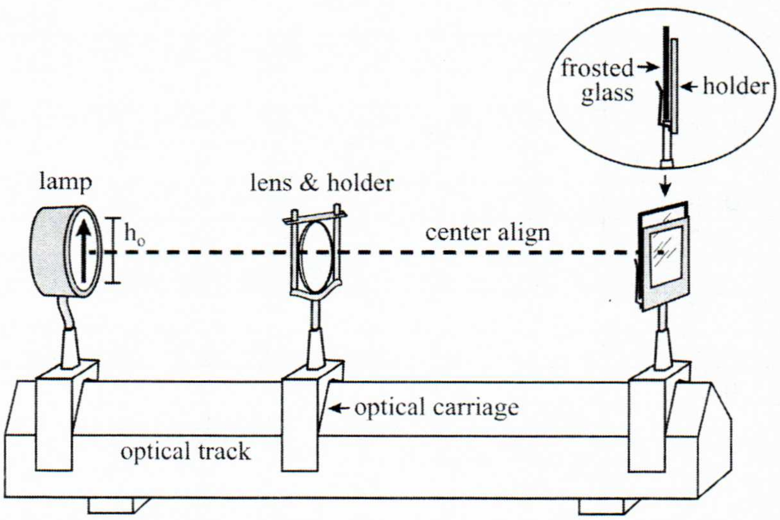


Figure 9.2 The optical bench set up.

9.4.1 The Focal Length of a Converging lens

1. Place the converging lens into its holder. Identify your "very distant" object. The very distant object will either be something out the window or a light bulb at the front of the classroom (weather, time, and instructor preference may determine).

2. Go to the lab wall opposite the very distant object and hold the lens up. Adjust the distance between the lens and lab wall until you have the sharpest (smallest) image projected.

3. While one person holds the lens in position, another member of the group then measures the distance between the middle of the lens and the wall. This is a measurement of the focal length. Estimate your uncertainty.

9.4.2 Images from Thin Lenses and Testing the Lens Equations

1. Use the ruler to measure the height of the object / arrow on the lamp.

2. Start with the converging lens in the holder on the optical bench. Place the lens so that $d_o > 2f$. Take uncertainty into account and make d_o at least 5 cm greater than $2f$. Move the screen to find the location where the image is sharply focused.

3. Using a ruler or meter stick, measure the distance from the object/lamp face to the middle of the lens, the distance from the middle of the lens to the image/frosted glass, and the height of the image on the frosted glass. Estimate your uncertainties. Do not use the markings on the optical bench.

4. Note the qualities of the image: is it real or virtual, upright or inverted, and if the image is larger or smaller than the object. Fill in the data table for the configurations noted including those with the diverging lens.

Configuration	d_o (cm)	d_i (cm)	h_i (cm)	Real or Virtual	Upright or Inverted	Larger or Smaller
Converging Lens						
$d_o > 2f$						
$d_o = 2f$						
$2f > d_o > f$						
$d_o = f$						
$d_o < f$						
Diverging Lens (f=20 cm)						
$2f > d_o > f$						
$d_o = f$						
$d_o < f$						

What changes must be made to observe a virtual image? Where are the virtual images located?

5. It is possible to measure the location and height of a virtual image. This can be done either qualitatively or quantitatively: Place the wire hook into an unused optical carriage and place it on the track between the lamp and lens. Arrange

yourself so that you can see both the image though the lens and the hook. While focusing on the image through the lens, move the hook toward and away from the lens until it is also in focus. The hook should be looked at in your peripheral vision, as looking right at it will snap it into focus no matter its location.

a) Qualitatively: The viewer or a lab partner should hold the hook. The general location of the image, between the lens and object or beyond the object, can be determined. The size of the image is only compared to the object, bigger or smaller, upright or inverted.

b) Quantitatively: The distance of the hook from the middle of the lens is d_i. To get the height, keep the carriage in place but lower the hook to sit on the top of the image while looking through the lens. Take the pointer and place it at the same distance as the hook and point to the bottom of the image though the lens. Have another group member measure the distance between the hook and the pointer to get h_i. Estimate your uncertainties.

6. To verify the focal length of the diverging lens, start by placing the object at 20 cm from the diverging lens. Using equations 9.1 and 9.2, one can find that if $d_o = f$, then $h_i = \frac{1}{2} h_o$. Adjust your viewing angle so that the bottom of the image of the arrow is on the cross-bar as seen in figure 9.3. Adjust the object distance until the image height is exactly one half the object height. Measure this object distance. Does this match the 20 cm you were given as the focal length? Give a percent error.

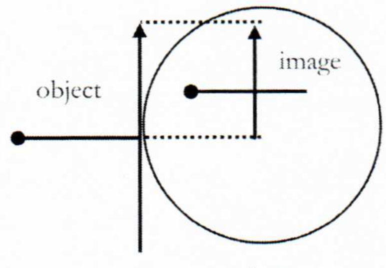


Figure 9.3 $2h_i = h_o$ when $d_o = f$.

7. Verifying the focal length for the converging lens: Using your measured d_o and d_i for the real images, use equation 9.1 to calculate the focal length. Average these for each lens. Compare the averaged focal length for the converging lens to the result from activity 9.4.1. Give a percent error.

8. Using your focal lengths which you either measured (9.4.1) or were given (for diverging) and the measured d_o values, use equation 9.1 to calculate the image locations and compare to those measured and qualitatively assessed. Discuss any trends or abnormalities.

9. Using your measured d_o, d_i, and h_o for each case, use equation 9.2 to calculate the image heights. Compare these to the measured image heights. Discuss any trends or abnormalities.

9.4.3 Ray Tracing

1. Draw ray diagrams for the five cases of the converging lens and the first case of the diverging lens. Use blank or light graph paper, a sharp pencil, and rulers for the best results.

2. Use the measured value for f for the converging lens, the given value for f for the diverging lens, and your measured d_o. Do not assume the image location or image height. Establish and write down the horizontal scale to be used (i.e. IRL 3cm = 1 cm on paper). The vertical scale will be 1:1 with what was measured. Trace

three rays for each of the cases (except for $d_o = f$, which can only have two). There should be a maximum of three diagrams per page turned in.

3. Do your image locations and heights agree with what was found in activity 9.4.2? Discuss any trends observed.

Lab

10

Optical Instruments

Some applications for thin converging lenses.

10.1 Lab Description

This lab continues the use of thin converging lenses, alone or in pairs, to create and understand three basic but functional common optical instruments.

Students should familiarize themselves with the following concepts from their textbooks before lab: The lens equations, simple magnifiers, telescopes, and microscopes. Students should also be aware that often textbooks and lab manuals do not agree on notation, ideal image location, etc. for these tools. It is the student's responsibility to discern what is used in their lecture versus what is used in this lab manual.

10.2 Safety and Hazards

10.2.1 This lab uses desk lamps which are a thermal hazard. The light bulb and surrounding metal can get very hot after a short time of use. Students should avoid touching these parts of the lamp and manipulate the neck of the lamp if the light must be adjusted.

10.3 Background Information

10.3.1 The simple magnifier is a single converging lens used to create an upright virtual image so that it appears larger for the observer. As seen at the bottom of figure 10.1, unaided, the object's angular size, θ, is larger the closer it is placed to the observer. However, the eye can only focus objects farther than the near point so the object's angular size is at a maximum when at the near point of 25 cm. When aided by a simple magnifier, the object can be moved closer than the near point and inside the focal length of the lens. This produces a virtual image larger than the object and at a location where the observer can view it in focus.

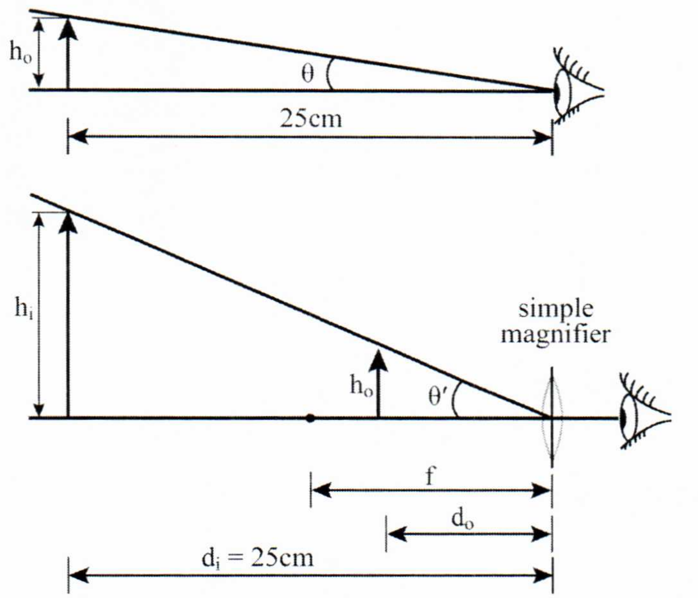


Figure 10.1 (top) The unaided eye is limited to view objects at least 25 cm away which limits the angular size. (Bottom) An aided eye sees a larger image and larger angular size.

The distance from the object to the lens, d_o, would be inside the focal length of the lens to create a virtual image, but where exactly is determined by where we want the virtual image located, d_i. From equation 9.1, $d_o = \left(\frac{1}{f} - \frac{1}{d_i}\right)^{-1}$, Eq 10.1

where f is the focal length of the magnifier. If we require the virtual image to be 25 cm away from the lens and therefore viewable by the observer, the distance from the object to the lens would be $d_o = \frac{25\ cm \times f}{25\ cm + f}$. Eq 10.2

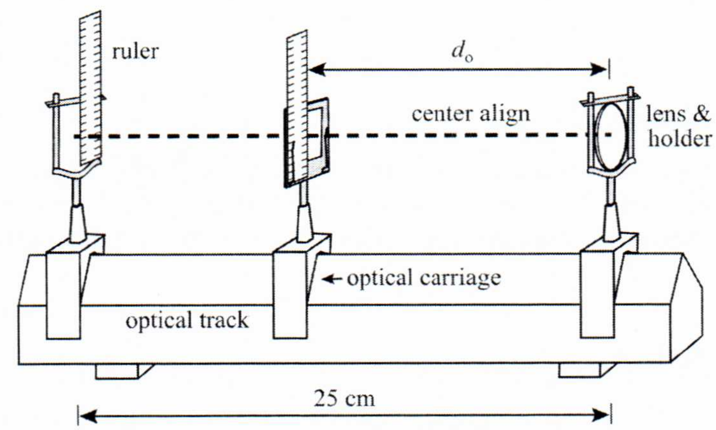


Figure 10.2 The Simple Magnifier set up

To get the magnification, m, of the configuration, we can use both definitions from equation 9.2. The first is the ratio of the image and object heights, $m = \frac{h_i}{h_o}$. Eq 10.3

The other definition of magnification uses the ratio of the object and image distances.

$m = \frac{-d_i}{d_o}$ Eq 10.4

Inserting our requirements for d_i and d_o, $m = \frac{25\ cm + f}{f}$. Eq 10.5

10.3.2 A refracting telescope also creates a larger virtual image, however it uses two converging lenses to view an object at a very large distance. A diagram of its basic function is found in figure 10.3.

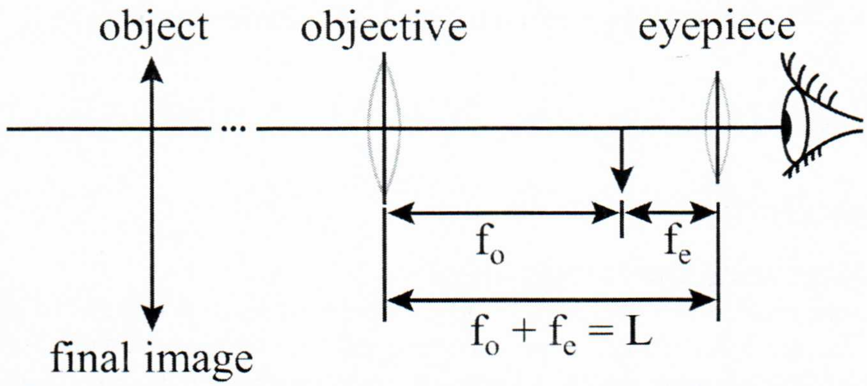


Figure 10.3 The refracting telescope with the object and image at a long distance on the left. The objective lens has a focal length of f_o while the eyepiece has a focal length of f_e.

The virtual image formed is inverted as a result of the objective lens. The eyepiece should be positioned to view the image with a relaxed eye / seen at a very far distance. If the object and final image are both sufficiently far, the distance between the lenses becomes the sum of the two focal lengths and the total magnification is $m = \frac{-f_o}{f_e}$. Eq 10.6

This magnification is an angular magnification: it is the ratio of the angles the image (aided) and object (unaided) subtended.

10.3.3 The compound microscope as seen in figure 10.4 also uses two converging lenses to create a larger, inverted, virtual image seen with a relaxed eye. The object for a microscope is close to the objective lens, placed so that $2f_o > d_o > f_o$, where f_o is the focal length of the objective lens. The closer to f_o, the greater the magnification from the objective lens.

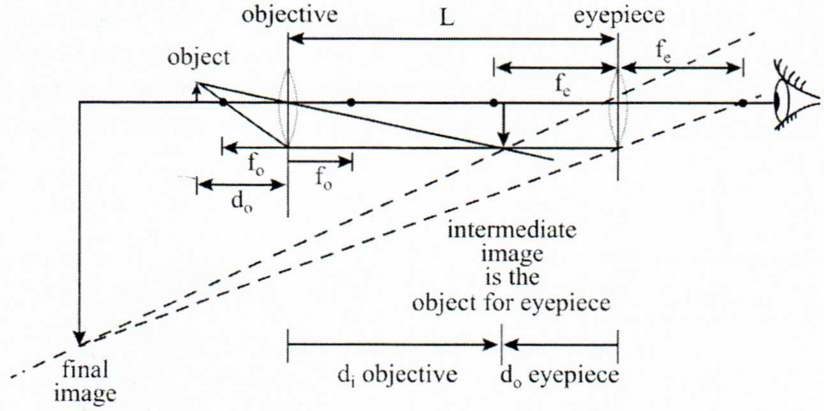


Figure 10.4 The compound microscope has the object distance farther than the objective focal length to the objective lens.

The distance between the two lenses, L, can be altered to create the final image at different distances for the observer. If the distance between the two lenses is made so that the intermediate object is at the focal point of the eye piece, f_e, then the final image will be at infinity.

If the object is made to be just outside the objective focal length so that $d_o \approx f_o$ and the length made so that the final image is very far away $L \approx d_i + f_e$, then the magnification from the objective is approximately $m_o = \frac{-d_{i\ objective}}{d_{o\ objective}} \approx \frac{-(L-f_e)}{f_o}$ and that of the eyepiece is $m_e = \frac{25\ cm}{f_e}$. Combined, the total magnification of a microscope is then

$$m \approx \frac{-(L-f_e)}{f_o}\frac{25\ cm}{f_e}. \qquad \text{Eq 10.7}$$

This magnification is also an angular magnification.

10.4 Activities

10.4.1 Measuring the Focal Lengths

1. Place one converging lens into its holder. Identify your "very distant" object. The very distant object will either be something out the window or a light bulb at the front of the classroom (weather, time, and instructor preference may determine).

2. Go to the lab wall opposite the very distant object and hold the lens up. Adjust the distance between the lens and lab wall until you have the sharpest (smallest) image projected.

3. While one person holds the lens in position, another member of the group then measures the distance between the middle of the lens and the wall. This is a measurement of the focal length. Estimate your uncertainty.

4. Repeat for the other two lenses.

10.4.2 The Simple Magnifier

1. Use either of the two lenses with larger focal lengths as your magnifier. See figure 10.2. Place the lens in the holder and then into the optical carriage. Use equation 10.2 to determine where the object – in our case, a vertical ruler should be placed with respect to the lens. The ruler will be placed on and lightly taped to the screen holder in the optical carriage. The image should then be 25.0 cm from the lens. To measure the height of the object at the image location another ruler will be placed on, and lightly taped to another lens holder in an optical carriage, 25.0 cm from the lens.

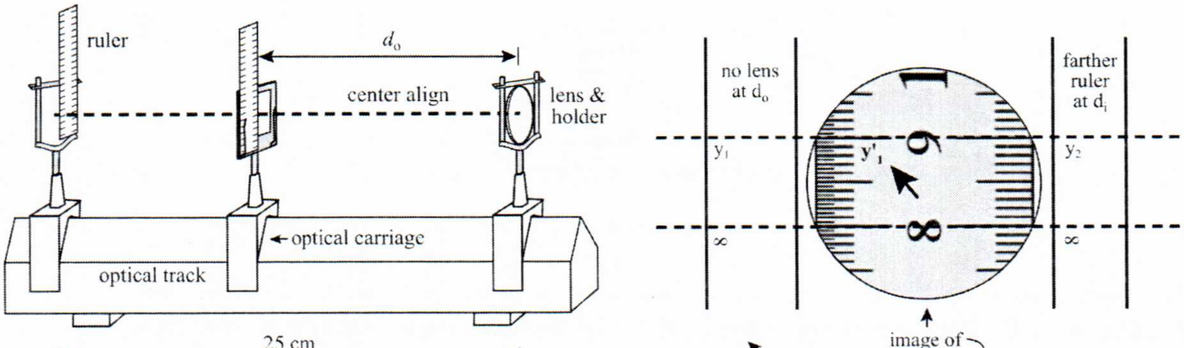


Figure 10.5 The simple Magnifier set-up and explanation of how to measure hi and ho with the two rulers.

2. When looking at the ruler at d_o through the lens, you are seeing the larger virtual image. See Figure 10.5. Move your head slightly left or right to view the ruler at d_o without the lens. This is your object, unaided. Move your head slightly left or right to view the ruler at d_i without the lens. This is to measure the image at the image location.

3. When looking at the lens, have your eye close to the lens. Find a way to keep the observer's head at a consistent height. The rulers must be aligned with respect to the observer. Use the straight edge of a piece of paper folded in half and hold it at the center of the lens. When looking at the ruler at d_o through the lens, the number on the ruler aligned with the paper should align with that of the ruler at the image distance. Raise and lower your holders in their optical carriages to achieve this. Record this number as y_0.

4. Move the folded paper up so that while looking at the image (through the lens) the paper marks the highest whole number. Record this number as y_1'. Keeping the paper in place and level, move your head slightly left or right to view the ruler at d_o without the lens (object, unaided). Record the measurement that aligns with the paper as y_1. Move your head slightly left or right to view the ruler at d_i without the lens. Record the measurement that aligns with the paper as y_2.

5. To calculate the magnification, use your measurements in steps 3 and 4 and equation 10.3. $h_i = |y_0 - y_2|$ and $h_o = |y_0 - y_1|$

6. Use equation 10.5 to calculate the theoretical magnification and compare with that found using the heights. Give a percent error. Discuss your results

10.4.3 The Refracting Telescope

1. Using section 10.3.2 and equation 10.6 as a guide, build your telescope to maximize the magnification. You can point it out the window to view trees or other buildings. If location or time of day prevents this, you can point the telescopes at the large measuring boards next to the lightbulbs on the other side of the classroom. You may need to raise one end of your optical bench by placing a textbook under it in order to point the telescope to the appropriate object. Adjust the length between the lenses to view the image in focus with a relaxed eye.

2. Draw out the design of your telescope including the focal lengths of the lenses used and a measurement of the distance between the objective and eyepiece lenses. Is this distance different from theory? If yes, why is your design different?

3. Identify an object you can see with both your unaided eye and with the telescope. Describe the image: is it upright or inverted? Is it larger or smaller than the object?

4. Estimate the magnification observed. This can be done by estimation or by sighting the object aided and unaided with a protractor used as an inclinometer. Use equation 10.6 to calculate the theoretical magnification. Discuss your results.

10.4.4 The Compound Microscope

1. Using section 10.3.3 as a guide, build a compound microscope. The focal length of the eyepiece should be larger than that of the objective (why?). Use the included card with millimeter markings as your object. Make sure your object is reflecting plenty of light from the desk lamp. Adjust the distance between the eyepiece and objective to view the image in focus with a relaxed eye. If you are having trouble, you may try the following: put the desk lamp in the place of the notecard, just outside the focal length of the objective. Place a piece of paper between the objective and eyepiece to locate where the light bulb is in focus. Place the eyepiece f_e farther than this location. Replace the notecard as the object and look through the eyepiece, lightly adjusting the eyepiece location to find where the image is in focus.

2. Draw out the design of your microscope including the focal lengths of the lenses used and a measurement the distance between the objective and eyepiece lenses.

3. Describe the image: is it upright or inverted? Is it larger or smaller than the object?

4. Estimate the magnification observed. This can be done by estimation or by sighting the object aided and unaided with a protractor used as an inclinometer. Use equation 10.7 to calculate the theoretical magnification. Discuss your results.

Lab

11

Interference and Diffraction

Calculating the wavelength of light in nanometers by measuring distances in the lab apparatuses and resulting interference patterns.

11.1 Lab Description

Students will observe the interference patterns of in-phase, monochromatic light through one and two slits. Students will also be able to see the difference in the pattern when the distance between the slits is altered.

Students should familiarize themselves with the following concepts from their textbooks before lab: constructive versus destructive interference, Young's double slit experiment, and order

11.2 Safety and Hazards

11.2.1 This lab uses helium-neon lasers which are a light hazard. These helium-neon lasers have a wavelength of 632.8 nm, and operating power of 0.95 mW. Although indirect exposure to the eye is considered safe, please observe the following safety procedures throughout the lab session:

- Do not point the laser in or near your, or anyone else's eyes.
- Either turn off or close the aperture of the laser when not in use.
- When turning on or opening the aperture, warn others that may be in the light's path.

11.2.2 This lab uses desk lamps which are a thermal hazard. The light bulb and surrounding metal can get very hot after a short time of use. Students should avoid touching these parts of the lamp and manipulate the neck of the lamp if the light must be adjusted.

11.3 Background Information

11.3.1 Double-slit interference occurs when coherent, monochromatic (same wavelength, λ, and in-phase) light is emitted from two locations a distance d apart. The wave nature of light makes it such that the light from each location will interfere with the other, adding wave amplitudes at all locations. If a screen is placed a distance L away from the slits, the light will interfere at the screen producing light and dark fringes. How the light interferes at a particular spot on the screen will depend upon to the difference in distance from each of the sources compared to the wavelength used. As shown in figure 11.1, there is a central bright spot at the location across from the midpoint between the slits. This is order m = 0 and defines the origin from which to measure the fringe distance to the other orders, y_m.

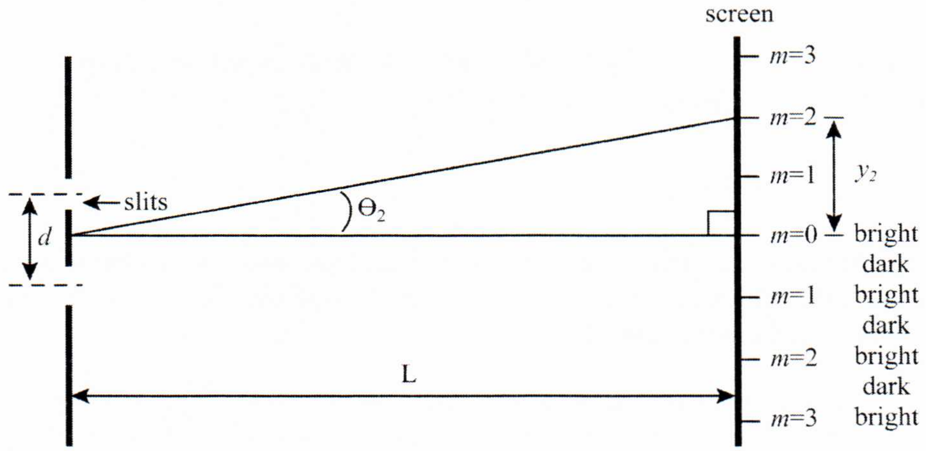


Figure 11.1 The double-slit experiment and an explanation of physical variables.

The path difference from each slit is $d \sin\theta$. For the light from each slit to add constructively at the screen, the pathlength must differ by a whole mutliple of the wavelength $m\lambda$. Together, $d \sin\theta = m\lambda$ Eq 11.1

where $m = 0, 1, 2, 3, \ldots$ for bright finges.

Dark fringes are found at $m = 0.5, 1.5, 2.5, \ldots$.

The distance y_m is easily found with geometry $y_m = L \tan\theta$. Eq 11.2

Combining equations 11.1 and 11.2 rigorously, we get $d \sin\left[\tan^{-1}\left(\frac{y_m}{L}\right)\right] = m\lambda$. However, $L \gg y_m$ as the orders we will be using are low so θ will be small. This allows us to use the small angle approximation of $\sin\theta \approx \tan\theta$. Using the small angle approximaiton and equations 11.1 and 11.2, we get $d\frac{y_m}{L} \approx m\lambda$. Eq 11.3

This small angle approximation also allows for the bright fringes to be approximately uniformly spaced near the central bright fringe and $y_1 \approx \frac{y_m}{m}$. Eq 11.4

Using this in equation 11.3 then yeilds $\lambda \approx d\frac{y_1}{L}$ Eq 11.5

11.3.2 Single-slit interfernece occurs when monochromatic light is emitted from a single source of width D. Each location within the slit acts as a source light and interferes with the light from all the other sources at all locaitons accroding to the path differences and wavelength of light. If a screen is placed a distance L away from the slit, the light will interfere to produce light and dark fringes on the screen again. The central bright fringe is wide compared to the bright fringes that surround it.

When two waves come from parts of the slit separated by $\frac{1}{2}D$, they will be out of phase by 180°. So as the path lengths differ by $D\sin\theta$ at the screen location, there will be destructive interference when

$$D\sin\theta = m\lambda, \quad \text{Eq 11.6}$$

where $m = 1, 2, 3, \ldots$.

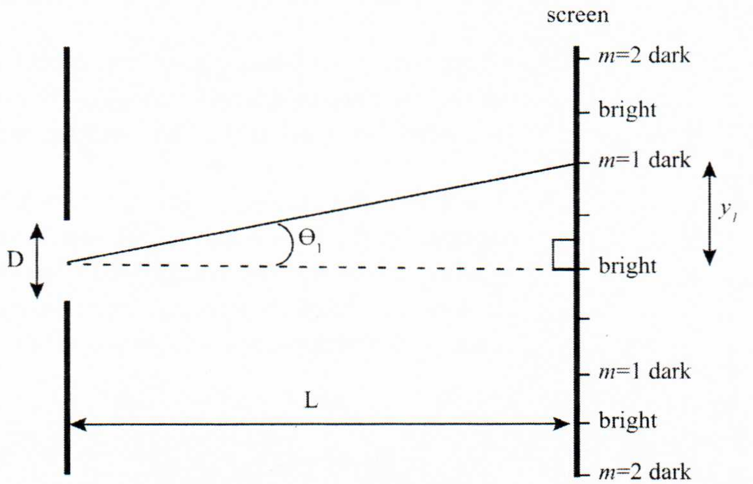


Figure 11.2 The single-slit with screen.

11.4 Activities

11.4.1 Obtaining the Distance Between the Slits

1. When the dial on the traveling microscope is rotated, the eyepiece moves left or right. To read the position of the object in the microscope, you must look at two locations on the top as shown in figure 11.3. The first two digits of the position to the tenths place are read from the location marked with an X. The marker location is the smaller number it has past. For example, if the marker is between 3.1 cm and 3.2 cm, 3.1 cm is certain and the next two digits, or down to the thousandths place, will be obtained from the dial position marked Y.

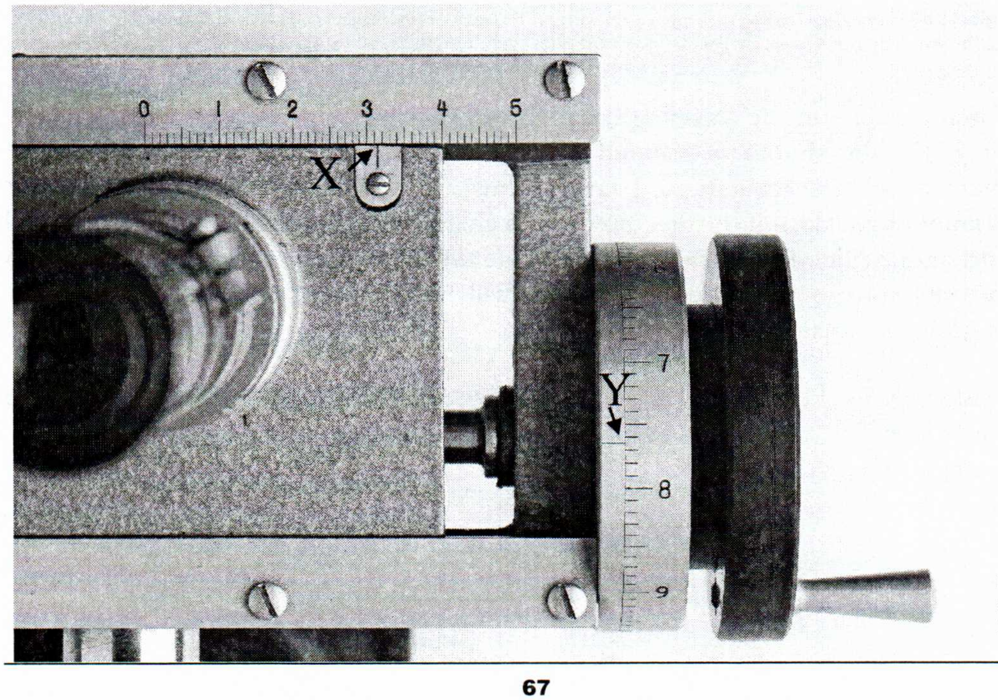


Figure 11.3 The top of the traveling microscope. This position is read as 3.176 cm

2. Hold your slide up to the desk lamp. Notice there are four sets of double slits on the slide. We are interested in the set the set with the second largest separation – this will be double slit A, and the set with the smallest separation – double slit B.

3. Place a piece of white paper, followed by the petridish, and topped with the slide in the viewing area of the traveling microscope. Crane the desk lamp to shine at the petri dish so that the slide will be back-lit when the overhead lights are off.

4. Look into the eyepiece. Move your slide by hand to both get a feel for how the optics flip the image and locate one set of the double slits. Focus your image by slightly loosening the thumbscrew on the eyepiece and moving the eyepiece up and down. **Lightly** tighten once in focus. Rotate the top part of the eyepiece to change the orrientation of the crosshairs as needed.

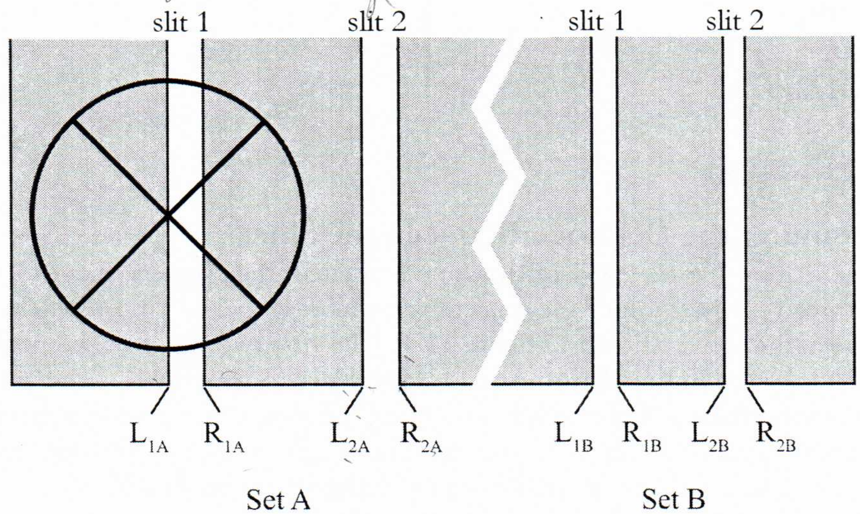


Figure 11.4 The slits as seen through the traveling microscope. The shaded portion is the opaque part of the slide and the white is the part the light can pass through. The labels on the bottom edge of the slits are in reference to equations 11.5 and 11.6. For example R_{1A} means that it is the right side of slit 1 in set A.

5. When the dial on the traveling microscope is rotated, the eyepiece moves left or right. The slits should be oriented to be perpendicular to that motion. While these microscopes are accurate and fairly robust, their age has created a significant amount of backlash if the dial direction is changed. To avoid all backlash, you will start at one side of the slide and only rotate the dial in a single direction. If you go too fast and go past your target, you will have to start again to measure the positions for that set.

6. Using figures 11.3 and 11.4 as your guide, meaure the positions of slit/slide boundaries.

(cm)	Set A	Set B
L_1		
R_1		
L_2		
R_2		

7. The distance between the slits can be found by calculating the distance from left side to left side or right side to right side. To get more accurate results, we find both and then average them so that $d_A = \frac{|L_{2A}-L_{1A}|+|R_{2A}-R_{1A}|}{2}$. Eq 11.7
   And the error in the slit difference is conservatively half the difference between the right and left side distance values: $\delta d_A = \left|\frac{|L_{2A}-L_{1A}|-|R_{2A}-R_{1A}|}{2}\right|$. Eq 11.8
   If this error is equal to zero, use an estimate of the instrument resolution error instead.

11.4.2 Measuring the Bright Fringes

1. Place the slit slide in its holder, and then into the adjustable optical carriage on one side of the optical bench. Place the laser in fixed optical carriage and on the other end of the optical bench. The laser should point toward the slit slide. Identify a wall at least 4.00 m from your lab bench. Move your optical bench so that the laser will hit that wall at a right angle with the wall. A protractor may be used to check your alignment.

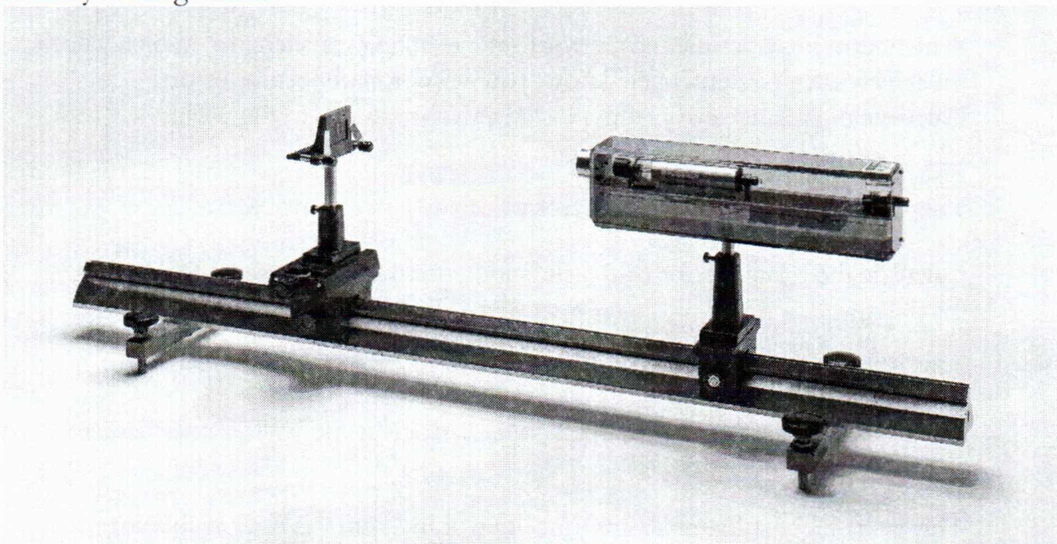


Figure 11.5 Set up to put the laser light through the double slits.

2. Turn on your laser and point it at the double slits – the slit slide may be adjusted up, down, left and right to get the laser to pass through both slits. For the wider slits set, often the slits and laser must be far apart on the optical bench so that the beam is large enough to go through both.

3. Use the tape measure to measure the distance from the slit slide to the wall. Be aware of sag, but do not pull so tight that you break, rip or otherwise destroy the tape measure. Estimate your uncertainty in the distance from the slits to the wall.

4. Tape a piece of paper to the wall where the interference pattern is brightest. Note on the paper where m = 0 is located. Trace and lable the locations of the bright fringes from m = 1 to m = 5 on both sides of the central bright fringe.

5. Measure the distance from m = 5 on one side of the central bright fringe to m = 5 on the other side. This is $2y_5$. Estimate you error in $2y_5$ taking intop account how you marked the locations.

6. Repeat steps 4 and 5 for the wider slit set.

7. For the wider slit set, what sort of pattern are you seeing before you have the correct alignment? Is it an interference pattern? What type? For both sets of slits, you may notice that there is a pattern within the pattern even when properly aligned. What is this larger pattern from?

11.4.3 Calculating the Wavelength of the Laser

1. A helium-neon laser emits light at a wavelength of 632.8 nm.

2. For each slit set, use equation 11.4 to calculate y_1 for each pattern. Use equation 11.5, your value for L, your value for d for that slit set, and y_1 to calculate the wavelength. You will end up with 2 values for wavelength. Give two percent errors.

3. Which term provides the most error to the resulting wavelength? Which value are you most leery of? To definitively know, you will compare relative errors:
Calculate the relative error of the distance from the slits to the wall:
$$\frac{\delta L}{L} \times 100\%. \qquad \text{Eq 11.9}$$
This is the (percent) amount of error in λ that L is responsible for.

   Calculate the relative error of the slit width, use the smaller value for d:
$$\frac{\delta d}{d} \times 100\%. \qquad \text{Eq 11.10}$$
This is the highest (percent) amount of error in λ that d is responsible for.

   Calculate the relative error of the fringe distance at the wall, use the larger slit width:
$$\frac{\delta 2y_5}{10 \cdot y_1} \times 100\%. \qquad \text{Eq 11.11}$$
This is the highest (percent) amount of error in λ that y is responsible for.

   What term is the least precise and therefore responsible for the most error in the wavelength? The value for y_1 for the smaller slit set should contribute a smaller amount of error for the y_1 terms – do your calculated values for λ support this?

Lab

12

The Hydrogen Spectrum

Gratings, multiple wavelengths, and the electron transitions of hydrogen atoms.

12.1 Lab Description

Students will continue their investigation into the wave nature of light using a grating and viewing the interference pattern of a multiple wavelengths at once. This light will be provided by a spectral lamp containing hydrogen allowing students to also analyze the Bohr model of hydrogen at the same time.

Students should familiarize themselves with the following concepts from their textbooks before lab: diffraction gratings, spectroscopes, the Bohr model of hydrogen, energy level diagrams, emission versus absorption of light by an atom.

12.2 Safety and Hazards

12.2.1 This lab uses desk lamps and spectral lamps which are a thermal hazard. The light bulb, surrounding metal and elemental tubes can get very hot after a short time of use. Students should avoid touching these parts of the lamp and manipulate the neck of the lamp if the light must be adjusted. Please do not touch the elemental tubes. Turn off and allow the spectral lamps to cool when not in use.

12.2.2 This lab uses hydrogen spectral lamps which can emit low levels of UV radiation. Do not stare at the spectral tube without the spectroscope or glasses for long periods of time as glass is able to block a significant portion of UV light.

12.3 Background Information

12.3.1 The functionality of a diffraction grating is very similar to that of a double-slit as discussed in Lab 11, section 11.3.1. The grating consists of many slits, uniformly spaced a distance d apart. Light from each slit will interfere at every location by adding wave amplitudes. How the light interferes at a particular location will depend on the difference in distance from each of the slits compared to the wavelength of light in

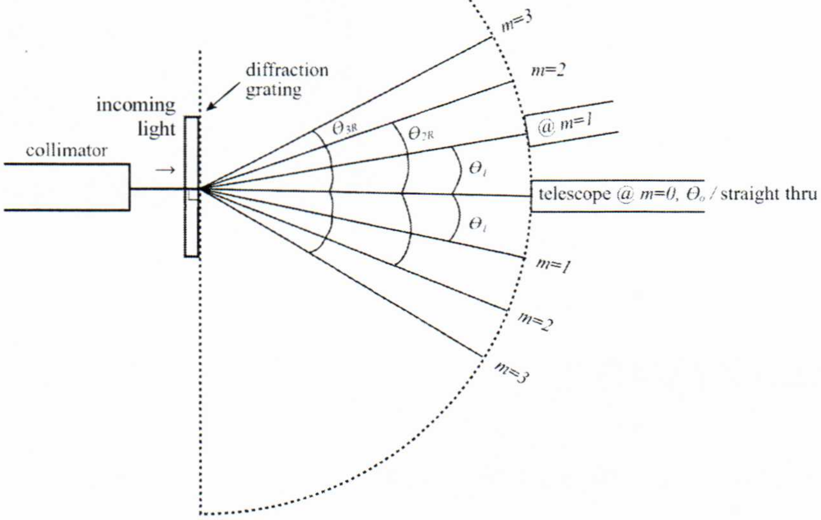


Figure 12..1 How the grating fits into the spectroscope and the definitions of the angles and orders. This schematic only shows the constructive interference for a single wavelength.

question. As shown in figure 12.1, there is a central bright spot where all the wavelengths in use will add constructively. This location is perpendicular to the grating, corresponds to order m = 0, and defines the origin (θ_0) from which to measure the angles to the other orders for all wavelengths, $\theta_{m\lambda}$.

The locations of constructive interference occur where,

$$d \sin \theta_m = m\lambda \qquad \text{Eq 12.1}$$

and $m = 0, 1, 2, 3, \ldots$.

Gratings typically have the number of slits per unit length printed on them. This is not the distance between the slits d, but rather d^{-1}.

To view the interference pattern for this experiment, students will utilize a spectrometer. The spectrometer schematic is shown in figure 12.2. The various wavelengths of light are emitted by the spectral lamp. The light then goes into the single slit at the end of the collimator. This adjusts the amount of light and the width of the light columns seen by the observer. The light then reaches the many slits of the diffraction grating. Some of the light diffracted by the grating then goes through the telescope to the eye of the observer.

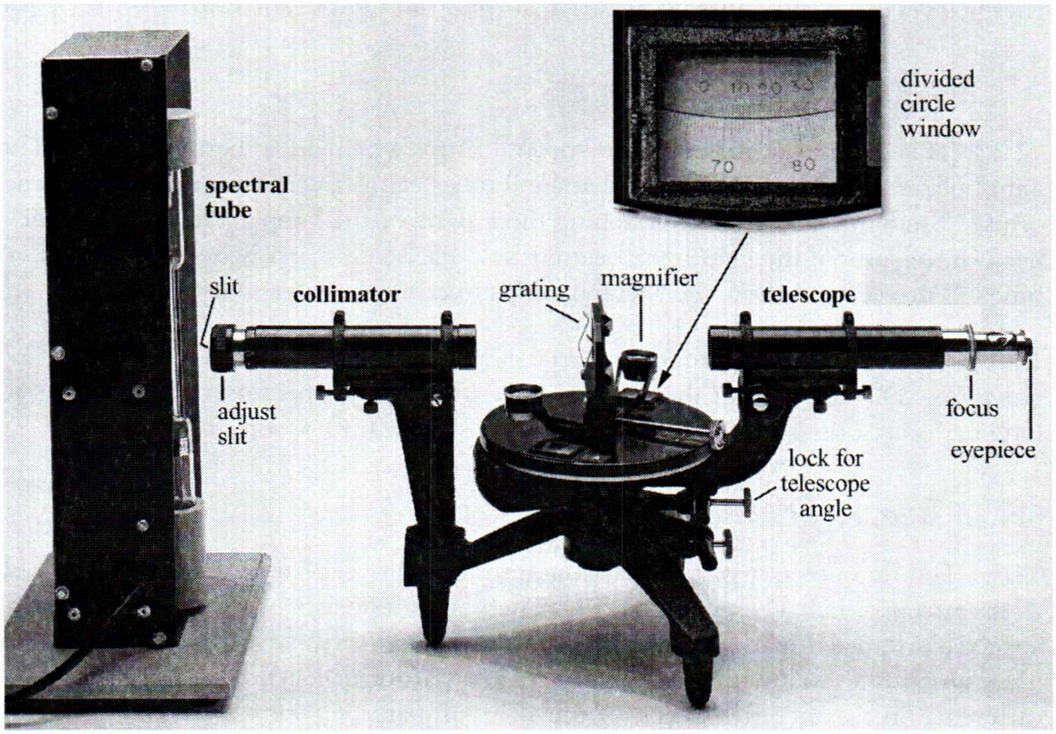


Figure 12.2 Spectrometer schematic.

Depending on θ, the angle of telescope with respect to the straight-through position θ_0, the observer will see either darkness (destructive interference for all wavelengths) or a vertical line of color (constructive interference for that/those wavelength/s).

12.3.2 Reading the Vernier scale displayed on the spectrometer requires patience and decent near-vision. Use and move the magnifier attached to aid your readings. Figure 12.3 displays one of the divided circle windows on the spectrometer. The bottom of the scale is in degrees and the top is in minutes of arc. The first step allows the reader to get to 0.5° precision: locate the "0" mark on the top scale and read off the numbers it falls between on the bottom scale. In figure 12.3, the 0 mark falls between 66.5° and 67.0°. The lower of the two marks is noted. In the next step, the reader looks at the divisions on the top and bottom scales and finds the location where they most closely align. The minute marking where this alignment occurs is the amount of minutes to be added to the degrees noted in the first step. In figure 12.3, the divisions align at the 14' mark so the angle is 66.5° + 14' or $66.5° + 14'\left(\frac{1°}{60'}\right) = 66.5° + 0.23° = 66.73°$.

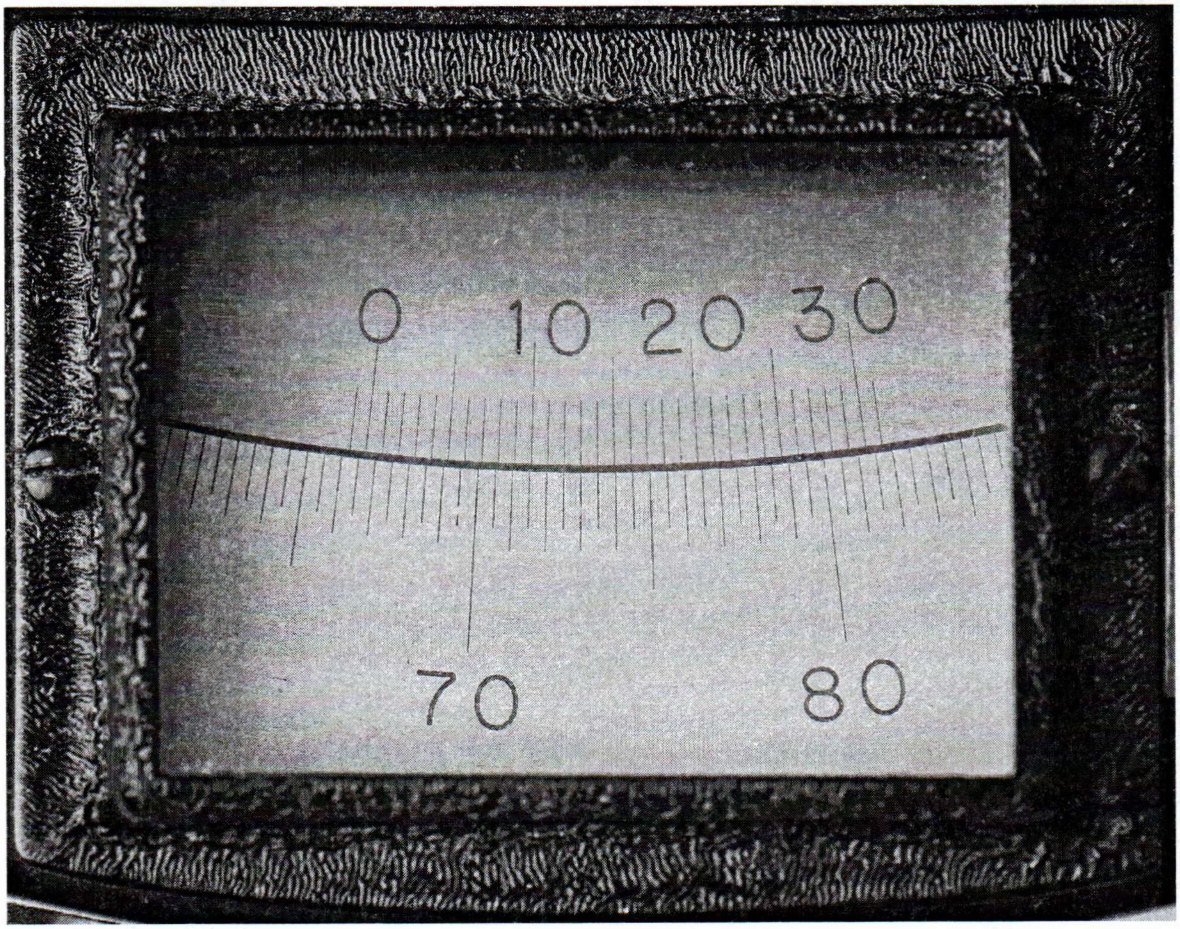


Figure 12.3 The Vernier scale of the Divided Circle on the spectrometer. This reads 66.5° + 14′ or 66.73°.

12.3.3 The light emitted will be from a spectral lamp. The glass tube contains hydrogen gas which will be in its lowest energy state/ ground state /n = 1 when not turned on. When the atoms are given the right amount of energy, the electron can move away from the nucleus to an excited / higher energy state. This energy for excitation can be transferred in many ways but the amount of energy is quantized so that it can only transition to established energy levels. Once excited, an atom can spontaneously emit energy via a photon to transition to a lower energy level. This photon will have the exact amount of energy that separates those two energy levels.

$1.000\ eV = 1.062 \times 10^{-19}\ J$

$E = \frac{hc}{\lambda}$

$hc = 1240\ eV \cdot nm$

For neutral hydrogen, the energy for each orbital level n, was worked out by Niels Bohr to be $E_n = \frac{-E_1}{n^2}$, Eq 12.2

where E_1 is equal to 13.6 eV. Knowing the relationship between wavelength and energy of a photon, the wavelength required to either excite from a lower orbit, n_l, to a higher one, n_h or the wavelength emitted when transitioning from a higher orbit level to a lower orbit is then $\frac{1}{\lambda} = R\left(\frac{1}{n_l^2} - \frac{1}{n_h^2}\right)$ Eq 12.3

where R is the Rydberg constant equal to $1.097 \times 10^7 \frac{1}{m}$. Another form inverts the Rydberg constant and converts to nanometers: $\lambda = \frac{91.15nm}{\left(\frac{1}{n_l^2} - \frac{1}{n_h^2}\right)}$. Eq 12.4

In the de-excitation of the neutral hydrogen atom, the four lowest energy transitions of the Balmer series ($n_l = 2$) have wavelengths that fall within the visible spectrum (400 – 700 nm).

12.4 Activities

These spectral lamps and tubes are more fragile than incandescent bulbs so you are asked to not touch the tubes at all, even when turned off, as the oils from your hands can damage them.

When on for too long, the seals on the spectral tubes can degrade and allow for escape and contamination of the remaining gas. **The lamps should only be left on for 30 minutes at a time and then given 10 minutes to cool** before continuing to use. In these cool off periods, you can skip to 12.4.3 step 6, obtaining theoretical values of wavelength.

12.4.1 Set-up of Spectroscope

1. Place the spectroscope so that a person may comfortably look into the eyepiece for long periods and be able to read one of the divided circle windows. Start with the collimator and telescope aligned with one another.

2. Insert the grating holder into the spectroscope and align it with the collimator so that the light coming from the collimator intersects the grating at a 90° angle. Gently tighten the grating clamping screw. A protractor can be used to aid in this alignment. Note the lines per unit length printed on the grating. Insert the grating into its holder (landscape).

3. Place the spectral lamp so that the spectral tube is ~2 cm from the slit at the end of the collimator. Open the slit to its widest position and make sure the slit is oriented vertically. Turn on the lamp and look through the telescope eyepiece. Slowly and gently move the telescope side to side and position the spectrometer feet until you can see the bright light going straight through the spectrometer (it will be the same color as the lamp).

4. Focus the light by twisting the focusing ring near the eyepiece and identify the crosshairs. The crosshairs are focused by pulling the eyepiece in and out of the telescope.

5. Adjust the slit width so that it simultaneously is wide enough to allow enough light in to easily see the dimmer wavelengths but thin enough to make finding the center with the crosshairs easy.

12.4.2 Observing and Measuring Angles

1. Center the crosshairs on the m = 0 position. This is the same as the light going straight through the spectrometer. The spectroscope should not be moved along the table after this point. Center the crosshairs on the column of light. Note that moving your head slightly left or right will change their relative positioning so you should also make sure that the column is centered in your field of view. Once the column is centered on the crosshairs, inspect the divided circle windows at the top of the spectrometer. Decide on a window to measure from for the entirety of the experiment. The reading on the Vernier scale will be θ_0 and $30° < \theta_0 < 330°$ to avoid later confusion. You may have the angle reading verified by your instructor to ensure that you are reading the scale correctly.

2. Move the telescope gently to the left of the m = 0 line. The observer should see 3 to 4 colors as they go left: One or two violet lines, then a teal-blue line, finally a red line. These are the first order visible hydrogen Balmer lines. For each of these four lines, you will center the crosshairs on the line and read the angle from the divided circle window. The second and dimmer violet line is close to the brighter violet line, between the brighter violet and the m = 0 line. If you are having trouble identifying the second violet line, your instructor may be able to help with tips like using an averted gaze or getting it close to the cross hairs for you. Some people may not be able to see this deep violet line at all.

3. If you keep moving the telescope left of the first order lines, you may see the second order or higher lines. What do you notice about the color order as you move away from m = 0? What do you notice about the intensity of the light and sharpness of the line?

4. Move the telescope back to m = 0 and continue to the right to view the first order visible hydrogen Balmer lines on the other side. For each of these four lines, you will center the crosshairs on the line and read the angle from the divided circle window.

12.4.3 Analysis

1. Use the following table and section 12.3.2 to guide you in getting the angle from m = 0 for all eight first order spectral lines.

	left, m = 1				m = 0	right, m= 1			
angle label	θ_{3L}	θ_{4L}	θ_{5L}	θ_{6L}	θ_0	θ_{6R}	θ_{5R}	θ_{4R}	θ_{3R}
raw data: xx.x°, xx'									
convert data: xx.xx°									
from θ_0 $\lvert \theta_0$ - xx.xx° $\rvert$									
color	red	teal	violet 1	violet 2	center	violet 2	violet 1	teal	red

2. The colors should have similar angles from m = 0 on the right and left sides. If you find they vary greatly, you should return to the spectroscope and double check your readings and alignment. Average the angles from θ_0 for each color in the first order. i.e.: $\theta_3 = \frac{\theta_{3L}+\theta_{3R}}{2}$. Eq 12.5
   You should have averages for 4 angles with four significant digits (to the hundredths place).

3. Calculate the spacing between the slits based on the printed lines per unit length and convert to nanometers.

4. Use equation 12.1 and your results from steps 2 and 3 to calculate the wavelength of each color in the first order for hydrogen to four significant figures (to tenths of nm).

5. The error in your angle reading for a particular color is conservatively half the difference between the two angle values, in radians. i.e.:
   $\delta\theta_3 = \frac{|\theta_{3L}-\theta_{3R}|}{2} \times \frac{\pi}{180°}$. Eq 12.6
   If this happens to be equal to zero, use an estimation of your instrument resolution error in radians. The error in the wavelength for each color can be calculated by using $\delta\lambda_3 = d \times \delta\theta_3 \times \cos\theta_3$. Eq 12.7
   This should be to tenths of a nm.

6. Calculate the theoretical values for the visible hydrogen wavelengths using either equation 12.3 or 12.4 to four significant figures (to tenths of nm). Your instructor may ask for you to include a correction factor to the sin of the angle values obtained in step 2 to accommodate the collimator and the grating not being perfectly perpendicular.

7. Compare the theoretical and experimental values for each color. Calculate the percent errors, these should be <0.5% for this experiment. Does the theoretical value fall within the range of $\lambda_n \pm \delta\lambda_n$? Which color was most accurate, which color was the least accurate? Which color was most precise, which color was the least precise?

Lab

13

Nuclear Decay and Half-Life

Shielding and the exponential decay of radioactivity demonstrated.

13.1 Lab Description

Students will measure the rates of decay or activity of three radioactive sources with different decay modes and compare them to the everyday background radiation levels present in the laboratory. Students will test different means of shielding or blocking the emissions of these decay processes. The exponential decay of the radioactivity of a source and its half-life will also be investigated.

Students should familiarize themselves with the following concepts from their textbooks before lab: Radioactive decay law, decay rate or activity, decay constant, mean lifetime, half-life, the three main decay modalities and their emissions.

13.2 Safety and Hazards

13.2.1 . This lab uses exempt-level sealed radioactive sources. This means they are very low level and are both exempt from regulation by the California Department of Health Services and the U. S. Nuclear Regulatory Commission or the regulatory requirements for possession and use of the sources are minimal. These sources are still an ionizing radiation hazard so we will be following protocol. You are to adhere to the following safety measures:

- There is no food or drinks allowed in the lab at all. Packaged and unopened food or drinks, water, mints, gum, etc. must all be left outside the laboratory. They may not be kept in your backpack in the laboratory.
- Anything that is applied to your mouth should be left outside such as an inhaler, CPR mask, lip balm, etc. should also be left outside the laboratory
- Do not apply make-up, put in contact lenses, or apply anything that makes contact with your mucus membranes in the laboratory.
- Do not touch the radioactive sources directly. You should use either the tweezers or a nitrile glove provided. In the case of a seal being broken on the

sources, only the tweezers and glove will be contaminated. For this reason you should not play with the tweezers or use them on anything but the sources. The glove should only be used to touch the sources and not your pencil, papers, face, etc..

- Tomfoolery is not permitted around the radioactive sources. Any horseplay, malarkey, or general mischief will be grounds to ask you to leave the laboratory.
- If at any time you leave the laboratory room, wash your hands before you do anything including use the restroom or get a drink of water.
- The instructor will go over this safety information with you. If you have any questions on safety procedures, ask the instructor. You are required to sign an acknowledgement that you have been briefed on safety and have had your safety questions answered before your group is given their radioactive sources.

13.2.2 This lab uses lead radiation absorbing disks. Lead is known to be toxic to humans when ingested, inhaled, or absorbed by the skin in large amounts. The lead disks in use have a plastic ring allowing students to not touch the lead disks. The lead is in a solid form and so cannot be inhaled. All food and drink is banned from the laboratory so lead will not be ingested. Please wash your hands when you leave the laboratory to avoid any trace lead contamination.

13.3 Background Information

13.3.1 The Exponential Decay of Radioactivity
An unstable parent nucleus X will decay into a daughter nucleus Y. For the particular isotope of X there is a probability that the nucleus will decay into Y in one second. We call this probability the transition rate or ω. With large numbers of nuclei, the number of X nuclei decays exponentially over time as $N_t = N_0 e^{-\omega t}$ Eq 13.1
where N_t is the number of X nuclei at time t and N_0 is the number of X nuclei at time t = 0. The rate of decay is also known as the activity of the sample of X nuclei. This is dependent on the number of X nuclei at that time and how likely they are to decay as $R_t = \omega\, N_t$. Eq 13.2
It then follows that the rate of decay also follows equation 13.1 as $R_t = R_0 e^{-\omega t}$. Eq 13.3

Useful mathematics		
$e = 2.718\ldots$, Euler's constant	$\log_e x = \ln x$, the natural log of x	
If $\ln x = N$, then $e^N = x$.	$\ln e = 1$	$e^{\ln x} = x$
$\ln\left(\frac{1}{x}\right) = -\ln x$	$\ln x^p = p \ln x$	

Another way to describe the decay of a particular parent isotope is in terms of the half-life, $t_{1/2}$. The half-life is the time required for a sample of a particular parent isotope to decay to half its original number of nuclei as $N_t = \frac{1}{2}N_0 = N_0 e^{-\omega t_{1/2}}$. It is also the time when the activity of a sample is at half its original level. $t_{1/2}$ is related to ω as

$$t_{1/2} = \frac{\ln 2}{\omega}. \qquad \text{Eq 13.4}$$

Another way to describe the exponential decay is then $\frac{N_t}{N_0} = \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} = \frac{R_t}{R_0}$ Eq 13.5

and $\ln\left(\frac{R_t}{R_0}\right) = \frac{-\ln 2}{t_{1/2}}\, t.$ Eq 13.6

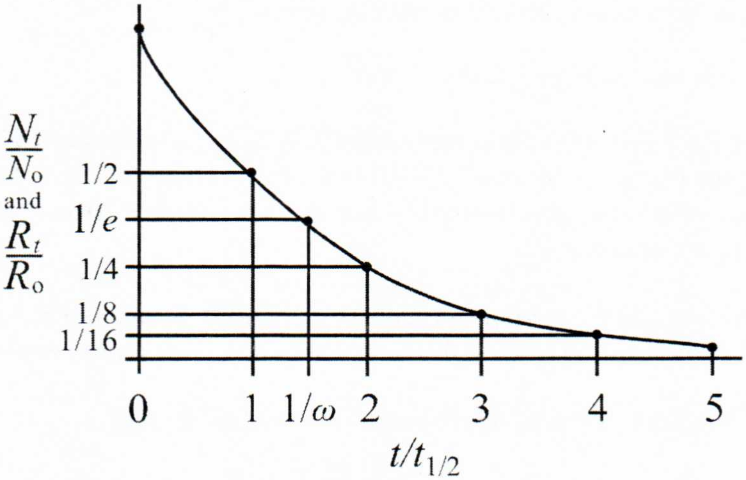


Figure 13.1 The radioactive decay law for large samples. Note that the y-axis can be either the fraction of the parent nuclei left or the fraction of the activity observed.

13.3.2 In this lab we will be measuring discrete events: either the nucleus decays and we detect it or it does not. The chance of the decay occurring is probabilistic in a uniform time interval. The probability of observing a number of events in a given amount of time is shaped like a Poisson distribution (or a bell-curve, shown in figure 13.2) for large numbers of counts that is centered on $\boldsymbol{N}$ the most probable value. Here, $\boldsymbol{N}$ is the number of counts detected

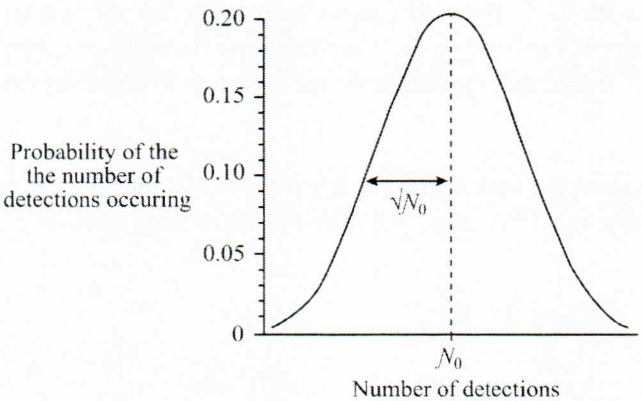


Figure 13.2 The Poisson distribution for large numbers detected. The probability of observing a value $\boldsymbol{N}$, if the true value is $\boldsymbol{N_0}$.

The distribution has a standard deviation of $\sqrt{\mathcal{N}}$. So, if you observe $\mathcal{N}$ decay events in a time t, the best estimate of your uncertainty on that measurement is $\delta\mathcal{N} = \sqrt{\mathcal{N}}$.

Each of these measurements of counts is performed over a uniform time interval in the experiments today. If the Geiger counter used was able to detect all events (all directions, all energies), then $R = \frac{\mathcal{N}}{t}$. Since our Geiger counter is directional, not all events will be detected. However, if we keep the location of the source constant then the ratio of the current counts versus an earlier time will be the same as the ratio of the current activity versus an earlier time or $\frac{\mathcal{N}/t}{\mathcal{N}_0/t} = \frac{\mathcal{N}}{\mathcal{N}_0} = \frac{R}{R_0}$. Eq 13.7

Thus, the error in R will also be $\delta\mathrm{R} \approx \sqrt{\mathcal{N}}$ Eq 13.8

It should be clear that if you observe a small number of counts, say 16 in a two minute period, the uncertainty is 4 or a 25% relative error. If you observe 1600 counts in a two minute period, the uncertainty is 40 or a 2.5 % relative error. More counts will give you a lower uncertainty.

13.3.3 There are three common modalities of natural decay: alpha, beta and gamma decay. The samples used in this lab are alpha, beta -, and gamma emitters.

In alpha decay, an alpha particle (helium-4 nucleus) is ejected:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He.$$

The alpha particles can be effectively blocked by your epidermis and even paper.

In beta decay, either a neutron or a proton within the parent nucleus is changed depending upon which type of beta decay occurs:

$$^{A}_{Z}X \rightarrow {}_{Z-1}^{\ \ A}Y + e^{+} + \upsilon, \ \beta\text{+ decay}$$

$$^{A}_{Z}X \rightarrow {}_{Z+1}^{\ \ A}Y + e^{-} + \bar{\upsilon}, \ \beta\text{- decay}$$

There are other variations of beta decay. Beta emissions require more substantial shielding than alpha. Depending upon the energy and decay rate of the beta particles, a few centimeters of plastic, a few millimeters of aluminum, to a few centimeters of lead may be required.

In gamma decay, a decay precedes the event leaving a nucleus that is at a higher energy state. The nucleus then rearranges itself to have a lower energy state, releasing a gamma-ray.

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$$

Gamma-rays can deeply penetrate lead so a few centimeters of lead will greatly reduce the amount of gamma rays but not completely absorb all of them. Very thick concrete is a cost-effective absorber additionally used in many industrial settings including fission power plants.

13.4 Activities

13.4.1 Background Activity

1. The detection tube has its optimal operating voltage printed on it. On the counter, make sure the voltage knobs on the left are both set to 0 V. Push the power on. Start with the course voltage knob and click to the highest value without going over the optimal operating voltage. Next adjust the fine voltage knob to bring it up to the optimal operating voltage. Do not exceed the recommended value. To turn off the counter, reverse this procedure: knobs to 0 volts then power off button.

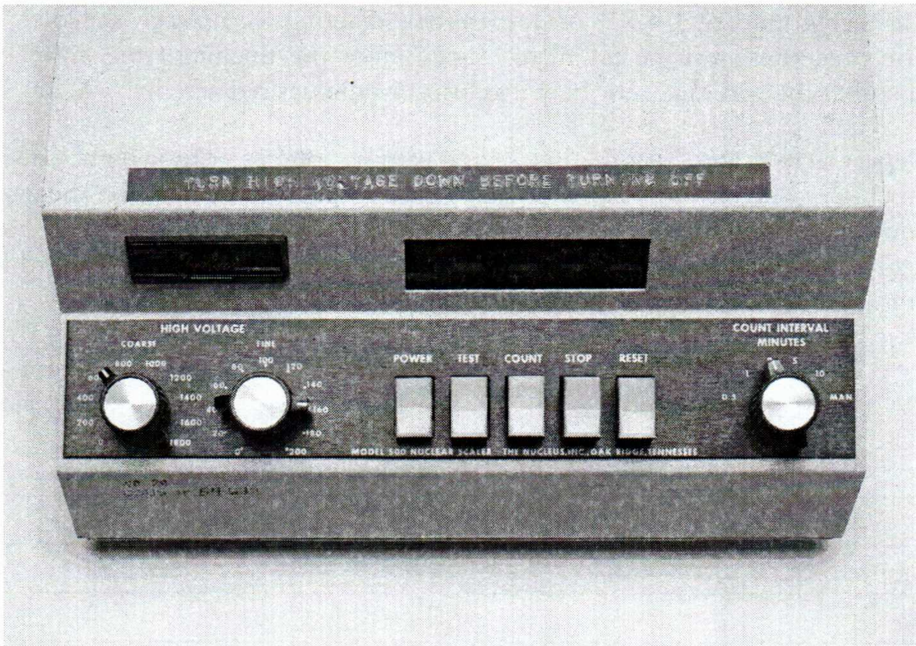


Figure 13.3 The counter.

Set the Count Interval knob on the far right to 2 minutes. With your radioactive sources on your work bench but as far as you can get them from your detection tube, press STOP, then RESET, then COUNT. The counter will count the number of detections over a two minute interval and stop on its own. You may want to set a timer yourself so that you know when it has actually stopped and not just paused. Write down the count and work out its uncertainty. Again, press STOP, then RESET, then COUNT to get a second and third measurement and uncertainty.

2. Average the three counts of the background and take the square root to determine its uncertainty – this range is your background activity. $B \pm \delta B$

13.4.2 Penetration of Alpha, Beta and Gamma Particles

Older alpha sources may require placement in the first slot to detect higher than background activity.

1. Place the alpha decay source, label down, on the source tray. Place the source tray in the third slot down from the detection tube. Measure and write down the activity of the alpha source over a two minute interval. This is your R_0 for this source.

2. To study the effective shielding for this sample, start with the thinnest plastic absorbing disk placed in the slot just above the alpha source. Measure the activity detected over a two minute interval. If the activity level is greater than half the original activity, $R > \frac{1}{2}R_0$, then replace the absorber with a thicker absorber and try again. Repeat to find the material and thickness for $R \sim \frac{1}{4}R_0$ and $R \sim \frac{1}{8}R_0$. Finally, find the material and thickness for when the activity level is at or below the background, $R \leq (B + \delta B)$, then the radiation is completely shielded. Please note that these will be far from exact. Note the thickness and count for the absorber that produces the activity closest to the desired activity.

3. Repeat steps 1 and 2 for the Beta – and gamma sources. These do not need to be label side down like the alpha decay. These sources (depending on the age of the sources) *may* require thicker lead than thickest absorber in your kit. You may stack lead disks and add their thickness to determine the effective shielding thickness. It is possible that background not be achieved with more active sources.

	alpha			beta			gamma		
	material	thickness (in)	count	material	thickness (in)	count	material	thickness (in)	count
R_0									
$\frac{1}{2}R_0$									
$\frac{1}{4}R_0$									
$\frac{1}{8}R_0$									
$\leq B + \delta B$									

4. Do your effective shielding materials and/or thicknesses coincide with the known properties of the emitted radiation for each type of decay? Explain. Do you see a mathematical connection between the fraction of the initial activity and the thickness?

13.4.3 The half-life of Indium-116

Foil samples of ^{115}In (half-life of ~10^{14} yrs) are bombarded with a neutron howitzer in the basement of Sequoia Hall by our technician. This produces foils enriched with ^{116}In which then experiences a beta-decay to tin-116. There are not enough foils or technicians to enrich enough samples for every group so data collection will be a class effort and displayed at the front of the room.

1. Obtain the average background activity for this device as in activity 13.4.1.

2. Place the indium-116 foils in the source tray, in the top slot of the detection tube.

3. Take counts at two minute intervals for at least 64 minutes by one of the following processes:

   a. Set the count interval to 2 minutes and press STOP, RESET, COUNT to begin. Start a timer at the same time so that you are prepared when it stops to **quickly** memorize the count, and press STOP, RESET, COUNT again. Record the count. Repeat for the 32 intervals.

   b. Set the interval count to manual. Start a timer and STOP, RESET, COUNT to begin at the same time. At every 2 minutes exactly, write down the current count. For each time, subtract the count at that time from the count at the time previous to get the activity over that 2 minute interval.

   c. Set the count interval to 2 minutes and press STOP, RESET, COUNT to begin. Start a timer at the same time so that you know when the subsequent counts are done. Over the next **90 minutes** someone from your group will be responsible for going up at least 3 times to get another count and share with the class. When the timer gets to a whole, even number of minutes, press STOP, RESET, COUNT. This is the count at the time you started. Your group should write down the data for t=0, your three times, and at least two other times.

All three methods have common mistakes and/or lags that can affect the precision and/or accuracy of the data collected. Discuss these with your group and be sure to include them in your discussion of your results.

time (min)	Raw Activity Count	Count-B	$\ln\left(\frac{R_t}{R_0}\right)$
0		(=R_0)	0
⋮			

4. Graph $\ln\left(\frac{R_t}{R_0}\right)$ on the y-axis and time on the x-axis. This should take up a full page, with a range and scale that make sense for the data. The axes should be labeled and include appropriate units. The data should be marked and left as a scatter plot. Using a ruler or a trendline function, create a best-fit line and determine its slope (either using two points that are not data points or by displaying the trendline equation) with the appropriate units.

5. Use equation 13.6 and your slope to determine the half-life of ^{116}In. Compare this with the known value of 54.3 min. Give a percent error and discuss your results. Do you see evidence that the half-life does not depend on when you start counting?

6. There are roughly 10^{22} ^{116}In nuclei in the foil sample. Approximately how long would it take to be left with only one ^{116}In nucleus?

Appendix

Appendix

A

Error and Uncertainty

Different instructors may require different levels of understanding and use of uncertainty in labs. This is meant as a broad overview of the subject at a non-calculus level.

Types of Error

There are generally two types of error or uncertainty that we utilize with in this course: random and instrument resolution error. Here, error or uncertainty in a measurement of x is denoted as δx.

Random Error and the 2/3 Estimate

For some experiments, you may have many trials measured under identical conditions. In these cases, repeating the experiment can give you a method of determining both the expected value and the uncertainty on that expectation.

When errors are random, which is typically a valid assumption provided your experiment is properly calibrated, the values you record will tend to cluster around a mean and have a distribution that is "normal" or Gaussian.

For a normal distribution, roughly $\frac{2}{3}$ of total number of measurements will lie within the uncertainty on your average value.

For example, here are six values of t from one experiment: 9.0, 9.8, 10.1, 10.2, 10.3, 11.0 s

The average value is 10.1 s. We want to include $\frac{2}{3}$ of the values closest to the mean from this measurement set. Since we have 6 measurements, we will include 4. They will be the 4 values closest to the average of 10.1 s. Thus the group from 9.8-10.3 s has the smallest range of a set of 4 measurements.

The estimate uncertainty is the difference between the average value and the measurement furthest from the average. So our uncertainty is $\delta t = |10.1 \text{ s} - 9.8 \text{ s}| = 0.3$ s. The measurement with uncertainty is $t \pm \delta t = 10.1 \pm 0.3$ s.

This estimate of the uncertainty is approximate but is sufficiently accurate to provide you with insights that will allow you to compare the accuracy of different measurement techniques used in this laboratory.

Instrument Resolution Error

Instrument resolution errors come from the inability of any measuring device and the person using it to give infinitely accurate answers. Generally, the instrument resolution error is the maximum precision to which the device can be read. It is common to take the instrument resolution to be half the finest scale division that may be read or *estimated*. For example, a meter-stick has marks to 0.001 m (1 mm) so the error in distances d, measured with it is $\delta d = 0.0005$ m. When the reading is fluctuating, there are **parallax** effects, or other difficulties in measuring; the user must make an honest estimation of how far off their reading could be.

Parallax
When the user's point of view can change the apparent position of an object.

Propagating Errors

If the measurement(s) is used to calculate another quantity, that calculated quantity also has an error. One way to figure out the error in the calculated quantity is to use the maximum and minimum values of the measurements to deduce the maximum and minimum calculated values possible.

For example, the measured quantity is 13.0 ± 0.1 and it multiplied by a whole number 6; the result is then $12.9 \times 6 = 77.4$ to $13.1 \times 6 = 78.6$ or 78.0 ± 0.6.

When using two or more measured quantities, each with an error, the chances of both quantities being at their extreme is low. The error in the calculated value should also reflect a margin that would contain $\frac{2}{3}$ of any repeated results. For these reasons you may be asked to use a more specialized equation for the error in a calculated quantity to propagate the errors.

Relative Error and Precision

When the values obtained from multiple trials are consistently very close in value, we say that they are precise. We should quantify this precision by calculating the relative error by $\left|\frac{\delta x}{x}\right| \times 100\%$. The lower the value, the more precise the measurement is.

What is good precision?
If relative error is $\leq 5\%$, then it is considered precise.

If you have a calculated value using two or more measured quantities with errors you can use the relative error calculation to note how much each of those measurements contribute to the error in the calculated quantity.

Comparing Values

If there is a theoretical or accepted value to compare your experimental result to, you can do this in a few ways depending on what error information you have on that result.

What is good percent error?

If percent error is ≤5%, then it is considered in good agreement for most of the 5B labs.

The most basic way to compare the two values is by a **percent error**. This does not require any information on the error in the experimental value. $\left|\frac{x_{theo}-x_{exper}}{x_{theo}}\right| \times 100\%$ The lower the value, the better the agreement.

If the error in the experimental value is obtained then you can make a statement on whether the experimental value is **consistent** or **discrepant** with the theoretical value. If the theoretical value falls within the error of the experimental value, then it is consistent. If it falls outside the error (it does not matter by how much), then it is discrepant.

If you are comparing two experimental values, x_1 and x_2 you can calculate the **percent difference**: $\frac{|x_1-x_2|}{\left(\frac{x_1+x_2}{2}\right)} \times 100\%$. This does not require any information about the error in the experimental values.

If you are comparing two or more experimental values with error to each other, you can have **agreement** or **disagreement**. If the range of possible values for two experimental values overlap at any point, then they agree. If their errors do not have an overlapping value anywhere, then they disagree.

Appendix

B

Measuring Circuits

The use of a voltmeter, ammeter, and/or ohmmeter is needed for labs 2-6.

The Digital Multimeter

The digital multimeter can be used to measure the difference in electrical potential / voltage (as a voltmeter), the current (as an ammeter), or the resistance (as an ohmmeter) of a circuit component depending on the settings and wiring.

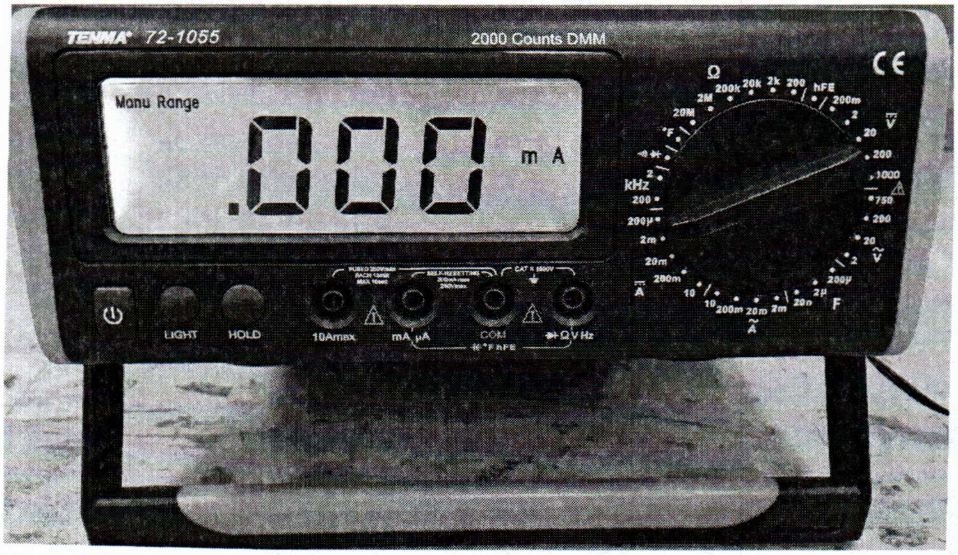


Figure B.1 The digital multimeter, no connections to the circuit.

The power button is on the lower left. The dial on the right is used to select the meter function and the effective range. The inputs on the lower middle are determined by the meter function and the configuration of the circuit component.

As a Voltmeter

The leads should be in terminals COM (common ground, 3rd from left) and V (far right). The other ends of these should be put in parallel to the component being measured. The higher potential (if known) should be input to the V terminal. A positive value displayed means that the lead from the V terminal is at a higher potential than the position of the lead from the COM. If the value displayed is negative, the lead from the COM terminal is at a higher potential.

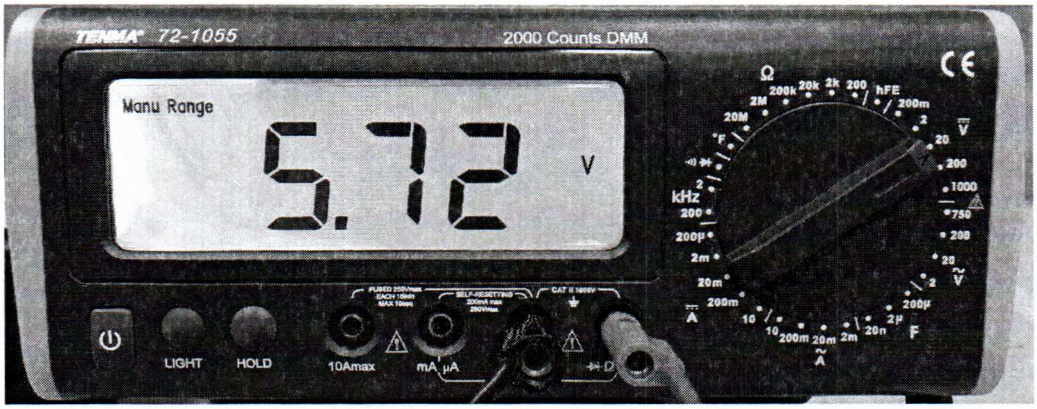


Figure B.2: Voltmeter with optimal precision.

The experiments in this manual use predominantly DC measurements. For DC the dial should be at some value under $\overline{\overline{V}}$. For AC the dial should be at some value under $\tilde{V}$. A "V" should be displayed on the screen to the right of the measurement. The number on the dial indicates the maximum value that it can read. In Figure B.2 the voltage displayed is 5.72 V when the value "20" is selected. If "2" is instead chosen, this makes the meter give an overflow (error) message shown in Figure B.3. If the dial is set to "200" then the voltage displayed loses precision and displays a value of 5.7 V. It is good practice to set the dial to get the best precision (maximum number of significant digits) possible.

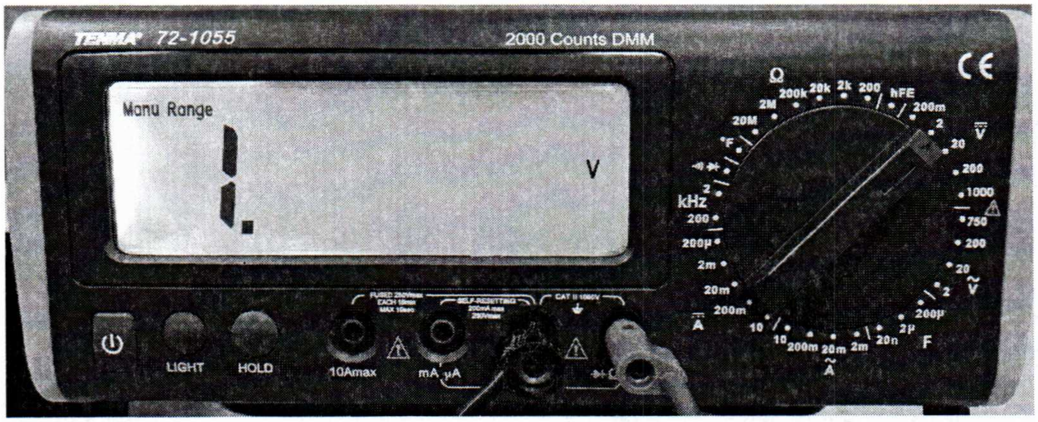


Figure B.3: Error message, the dial is set at too low a value.

As an Ammeter

The leads should be in terminals COM (common ground, 3rd from left) and mA μA (2nd from left). The other ends of these should be put in series with the component being measured. The higher potential (if known) should be input to the mA μA terminal. A positive value displayed means that the lead from the mA μA terminal is at a higher potential and the current is going into the meter from that position. The current is then coming out of the lead from the COM and continuing in the circuit. If the value displayed is negative, the lead from the COM terminal is at a higher potential.

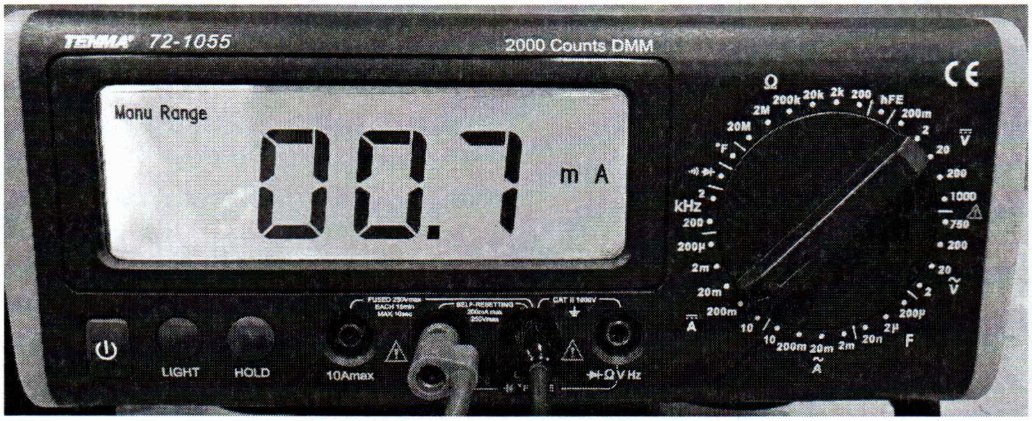


Figure B.3: Initial configuration as an ammeter

The experiments in this manual have DC current measurements only. The dial should be at some value under $\overline{\overline{A}}$. The number on the dial indicates the maximum value that it can read. Fuses are most often blown when the user has overloaded the ammeter. For this reason, it is good practice to start your readings with the dial at 200m. If there is only 0 or less than three significant digits displayed, then the user should dial down until three significant digits are displayed. If the dial is too low an error message similar to Figure B.3 will be displayed. If the dial is set even lower, there is a chance of blowing a fuse.

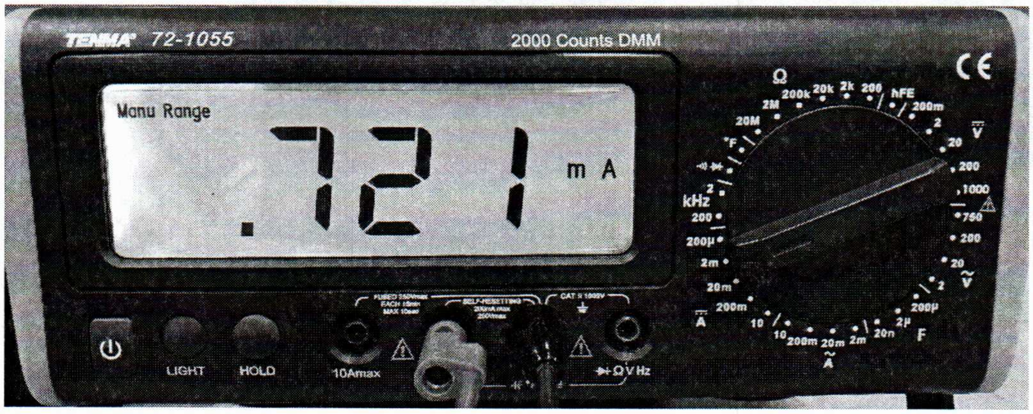


Figure B.4: Ammeter with optimal precision

As an Ohmmeter

To measure the resistance of a component, that **component must not be connected to anything else**. If a battery or other potential source is connected while in the ohmmeter setting, you can blow a fuse or otherwise damage the meter. The leads should be in terminals COM (common ground, 3rd from left) and Ω (far right). The other ends of these should be connected to the ends of the component to be measured. The dial should be set to **Ω**. A "MΩ" or a "kΩ" should be displayed on the screen to the right of the measurement. The number on the dial indicates the maximum value that it can read. It is good practice to set the dial to get the best precision (maximum number of significant digits) possible.

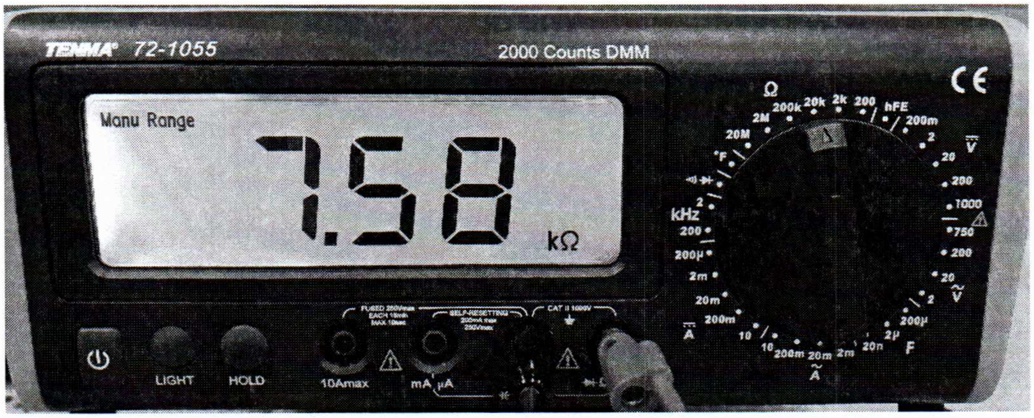


Figure B.5: Ohmmeter with optimal precision

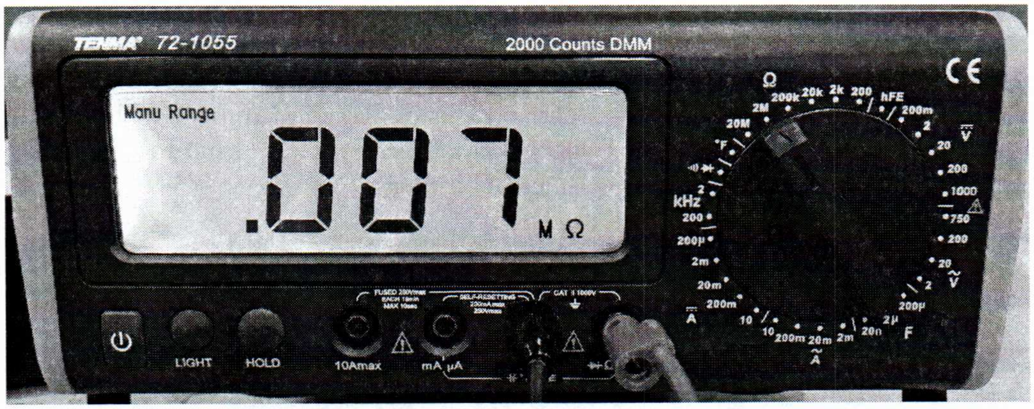


Figure B.6: Ohmmeter with very low precision

The Analog Voltmeter

The analog voltmeter will yield at least two significant figures when used properly. The voltmeter should be laying down on the table with the face pointing to the ceiling. The face has a mirror strip so that the user can align themselves to eliminate parallax error: the user should move their head so that the needle and its reflection are aligned. One lead should be in the red "+" terminal and the other in one of the black terminals which also sets the scale to be read. The other ends of these should be put in parallel to the component being measured. The higher potential should be input to the "+" terminal.

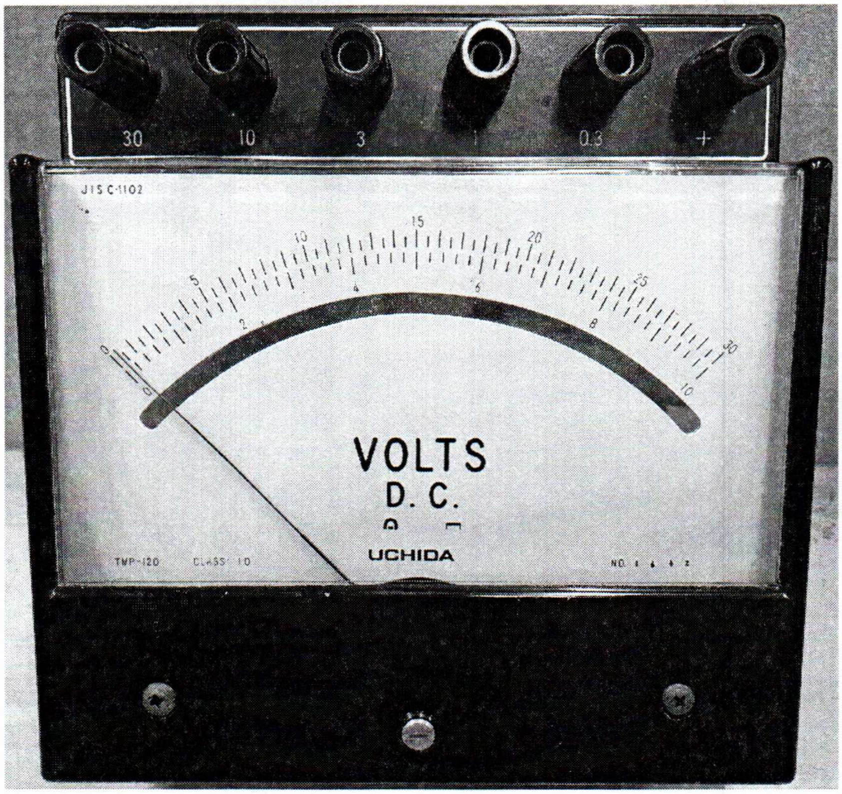


Figure B.7: The Analog Voltmeter

The black terminals are the maximum values (in V) that can be read when connected. By inspecting your source(s) you should be able to estimate the maximum voltage possible for the element being investigated; start there. The voltmeters are most precise when the needle is mid-range. You can change the black terminal used to optimize your reading.

Black terminal	Scale to read	Min (V)	Max (V)	Finest Scale (V)
30	Top	0	30	0.5
10	Bottom	0	10	0.2
3	Top	0	3	0.05
1	Bottom	0	1	0.02
0.3	Top	0	0.3	0.005

There are two scales to read on the meter. Which one to use and what magnitude they represent is dependent upon which black terminal is in use.

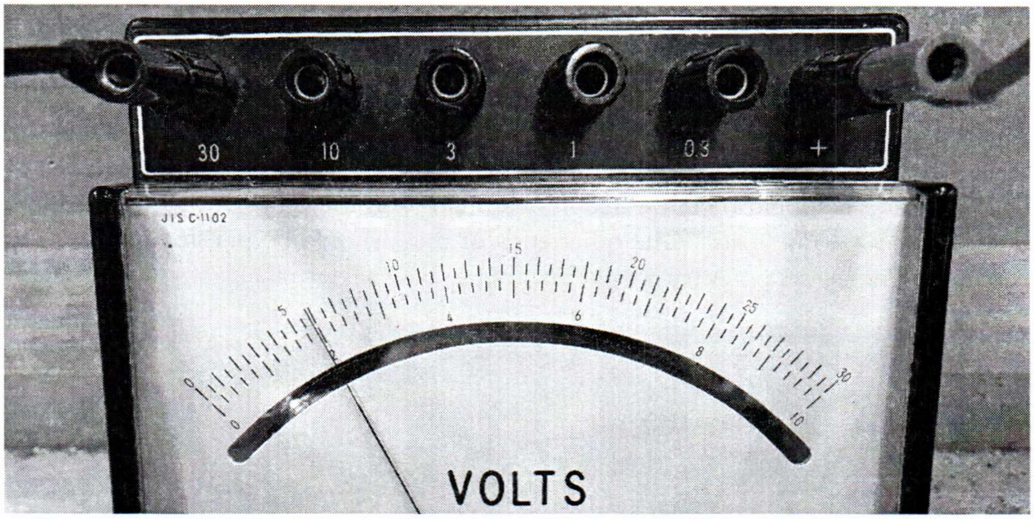


Figure B.8: This reads ~5.8 V

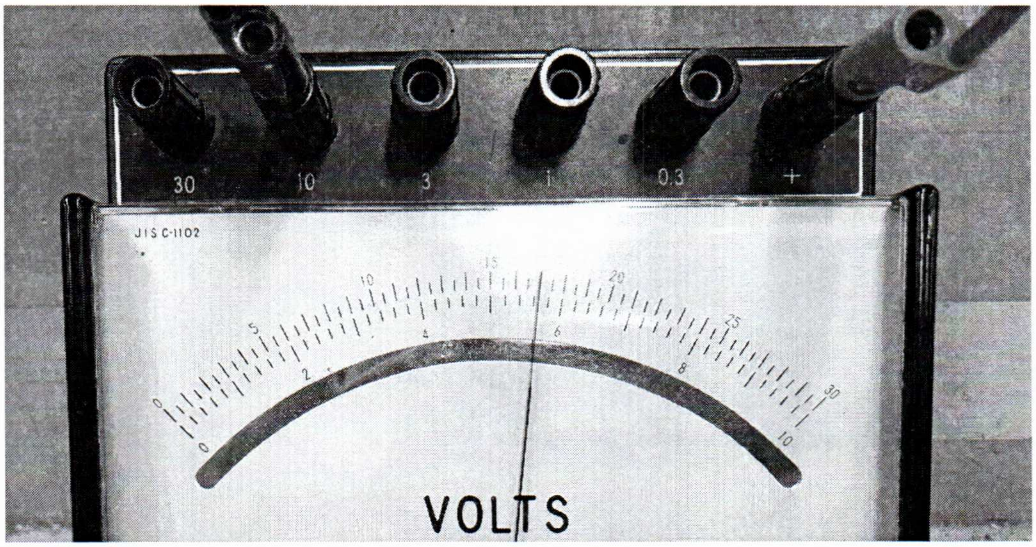


Figure B.9: This is the same circuit but the output terminal has changed. This reads ~5.65 V and is more precise than the previous figure.

If a terminal is chosen so that the actual voltage over the component is larger than the value indicated on the terminal, the needle will point off the scale and if kept there too long or done too often, can damage the meter

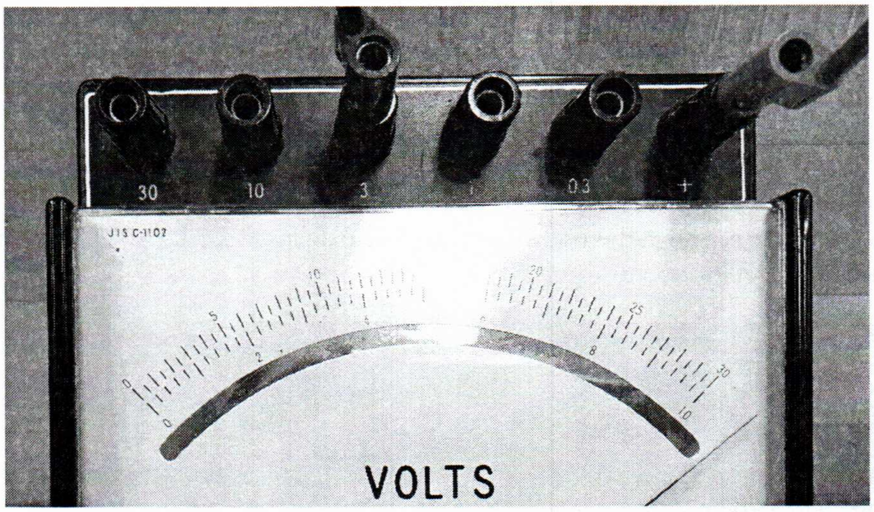


Figure B.10: This scale is too small for the voltage being evaluated. Disconnect immediately.

If the terminals are mistakenly switched, then the voltage would be negative. This meter has no way to show a negative and will instead push the needle well to the left of 0.0 V. This can also damage the meter if left too long or done too often.

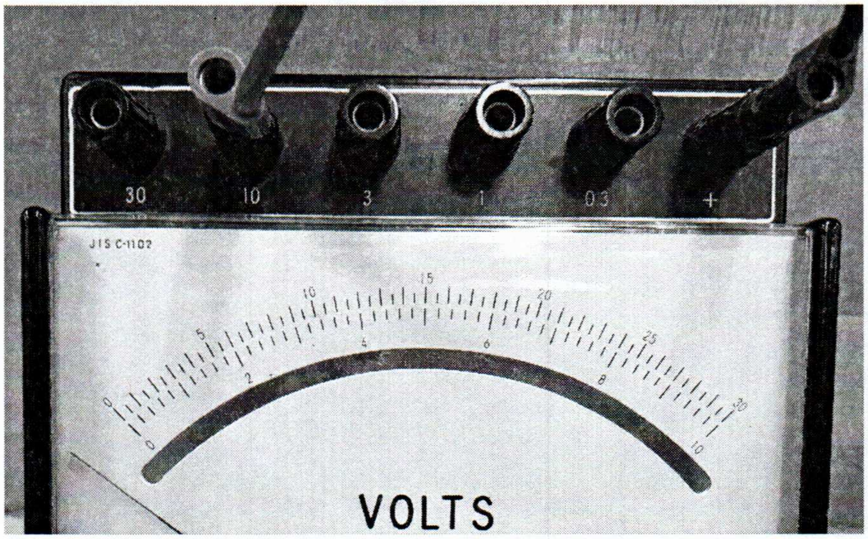


Figure B.11: This is connected backwards. Disconnect immediately. Switch the terminals and try again.

The Analog Ammeter

The analog ammeter is better for measuring larger currents than the digital ammeter (I >.1 A) and can yield at least two significant figures when used correctly.

The ammeter should be laying down on the table with the face pointing to the ceiling. The face has a mirror strip so that the user can align themselves to eliminate parallax error: the user should move their head so that the needle and its reflection are aligned.

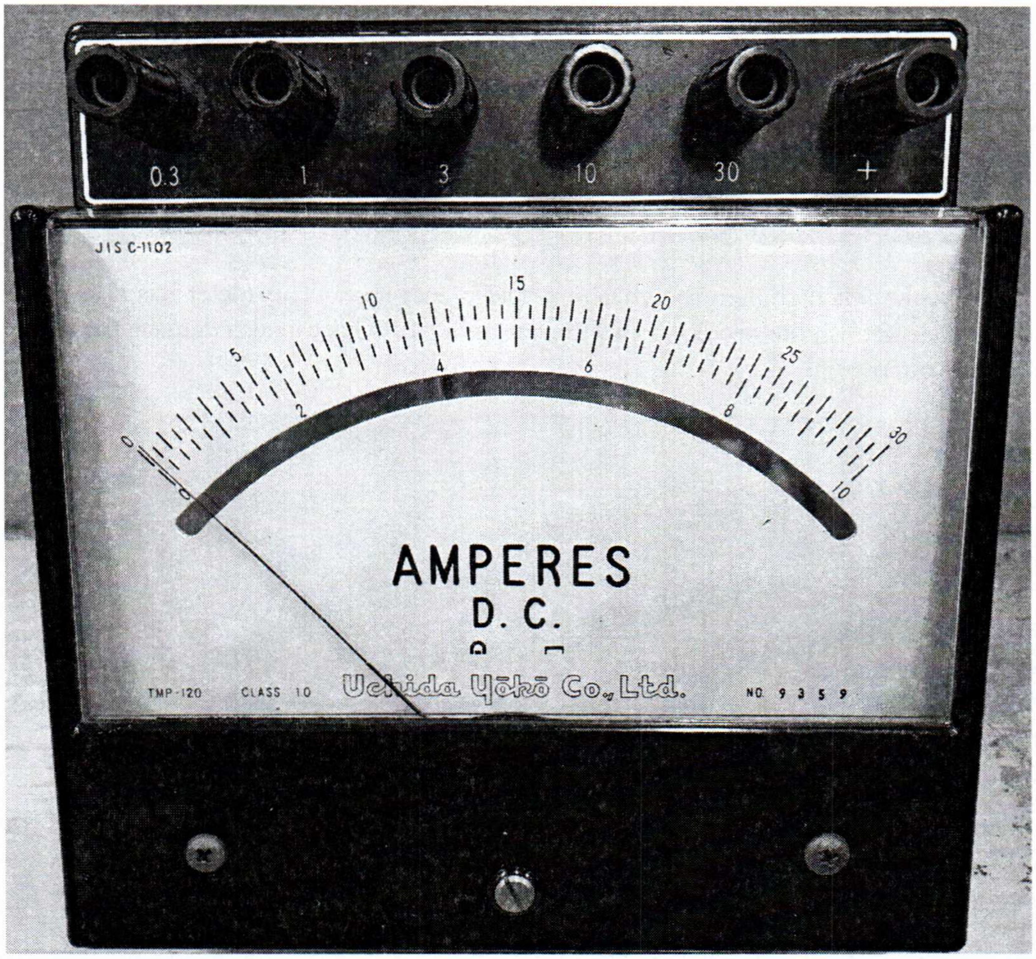


Figure B.12: The analog ammeter

One lead should be in the red "+" terminal and the other in one of the black terminals which also sets the scale to be read. The other ends of these should be put in series with the component being measured. The higher potential should be input to the "+" terminal. This means the current will be going into the meter at "+" and out of the black terminal.

The black terminals are the maximum values (in A) that can be read when connected. By inspecting your source(s) you should be able to estimate the maximum current possible for the element being investigated; start there. The ammeters are most precise when the needle is mid- range. You can change the black terminal used to optimize your reading.

Black terminal	Scale to read	Min (A)	Max (A)	Finest Scale (A)
0.3	Top	0	0.3	0.005
1	Bottom	0	1	0.02
3	Top	0	3	0.05
10	Bottom	0	10	0.2
30	Top	0	30	.05

There are two scales to read on the meter. Which one to use and what magnitude they represent is dependent upon which black terminal is in use.

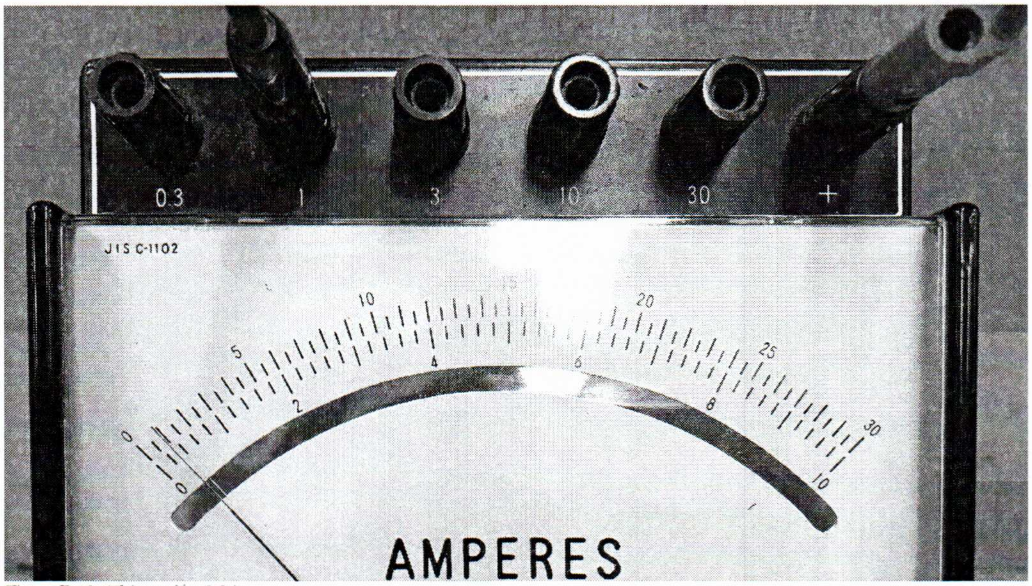


Figure B.13: This reads ~0.3A

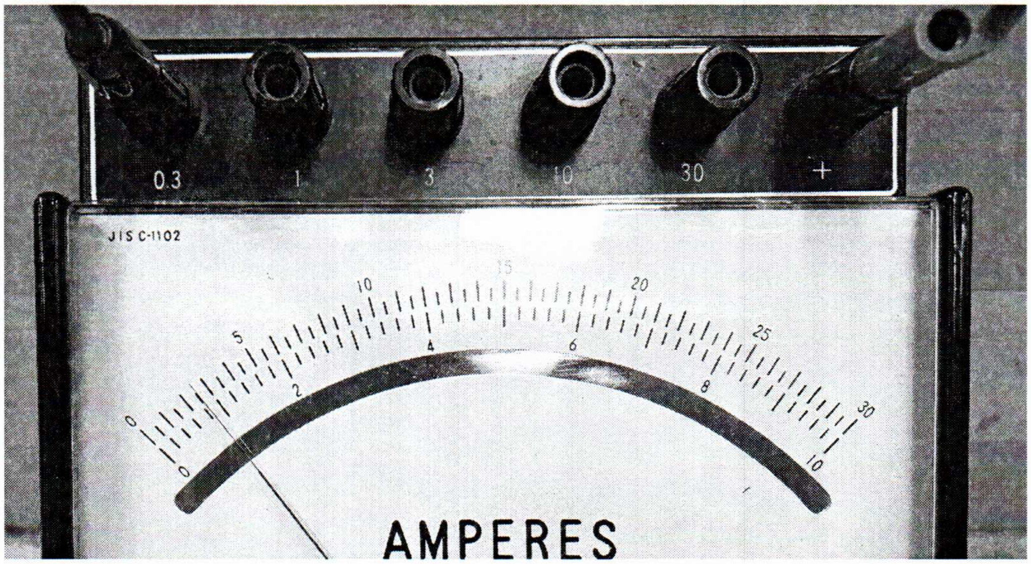


Figure B.14: This is the same circuit with a different output terminal in use. This reads ~0.252 A and is more precise.

If a terminal is chosen so that the actual current through is larger than the value indicated on the terminal, the needle will point off the scale, similar to figure B.10 and if kept there too long or done too often, can damage the meter

If the terminals are mistakenly switched, then the current would be negative. This meter has no way to show a negative and will instead push the needle well to the left of 0.0 A, similar to Figure B.11. This can also damage the meter if left too long or done too often.

Appendix

C

Graphing

Plotting data can be the best way to show mathematical relationships between measurable quantities and compare your real-world experience to established physics.

What to Plot

You have data and want to compare that to an established physical concept that has a mathematical relationship. An example would be measuring the velocity of a cart was at various times. From Physics 5A, we know $v = v_0 + at$, Eq C.1

where v is the velocity at time t, v_0 is the velocity at t = 0, and a is the acceleration. In this course, we will stick to linear graphs so the relationship we will seek to plot will have the form

y = mx + b, Eq C.2

where y and x are the variables plotted on the y- and x-axis respectively, m is the slope of the line, and b is the y-intercept. Rearranging equation C.1 to be in the form of C.2 we see that

$$v = at + v_0$$
$$y = mx + b$$

the velocity at time t should be on the y-axis. We have measurements for time, not acceleration so t will be on the x-axis and the slope will be the acceleration. The y-intercept will represent the initial velocity v_0.

What if the established relationship is not linear? In an experiment you are measuring the potential of a capacitor as it begins to discharge at t = 0, the current going over a resistor in the process. The established mathematical relationship is $V_c = V_0\, e^{-t/RC}$, where V_C is the potential difference over the capacitor at time t after beginning the discharge, V_0 is the fully charged potential difference, R is the resistance of the resistor in the circuit and C is the capacitance of the capacitor. This is not linear but you can manipulate it so that has the form of equation C.2:

$$\ln\left(\frac{V_c}{V_0}\right) = \frac{-1}{RC}\, t$$
$$y = mx + b$$

By plotting the natural log of the ratio of the potentials on the y-axis and the time on the x-axis, the resulting plot will be linear with the slope of the line equal to $\frac{-1}{RC}$. The intercept should be zero.

Always strive to create a linear plot and know what the resulting slope and intercept should be compared to.

Scale and Range

The plot should have both axes labeled and have the appropriate units in parenthesis where applicable. The scale of the axes should allow for all the data to fit with minimal area empty of data. In general 30% or more of either the horizontal or vertical scale that contains no data is a waste of paper and is detrimental to the precision of your results stemming from the plot. To continue our discussion, let us return to the idea of a cart with the velocity measured at various times and have some actual data to work with:

time (s)	velocity (m/s)	δ v (m/s)
1.0	0.85	0.08
2.0	1.21	0.08
3.0	1.31	0.08
4.0	1.41	0.08
5.0	1.76	0.08
6.0	1.96	0.08
7.0	2.05	0.08
8.0	2.25	0.08
9.0	2.57	0.08

If working in Excel, the range and scale of the data can be continuously refined as you go. Select the data to be included (do not include cells with labels or units). Under the *Insert* tab go to *charts* and select "scatter" from the menu. See Figure C.1. If a column is plotted on the wrong axis, the easiest thing to do is to first click on a data point which will then display a blue and purple outline of the data in the spreadsheet. Move the cursor to the outline of the blue and move it down, then move the purple over, then move the blue to where the purple was.

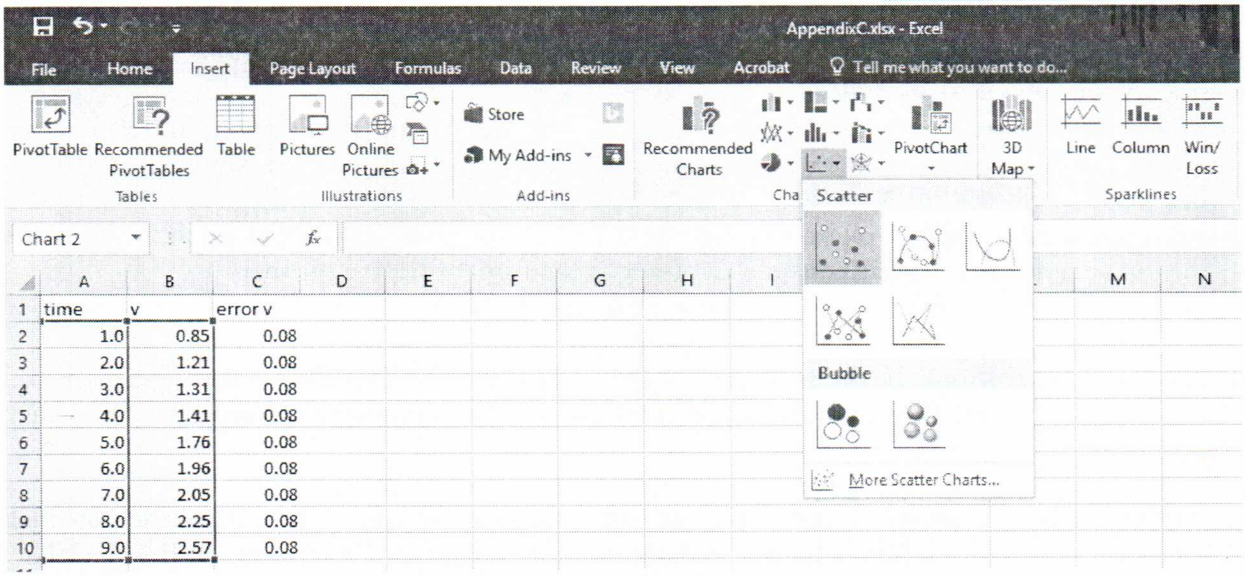


Figure C.1 Select the data by highlighting with the cursor. The purple will be on the x-axis, the blue on the y-axis.

Click on the green plus sign next to the chart for *chart elements*. Select *axis titles* and then edit the titles to have labels and units. Click on the numbers on the axis to format the axis. Under *Axis Options*, change the scales to have minimal empty plot area. See Figure C.2. Select to view the major and minor gridlines. You may have to adjust these yourself to get good values that will work well when seen on a full page.

When working on paper, you must plan your range and scale ahead. For this set of data, the x-axis will plot the time. There is no error in time mentioned so this range must minimally go from 1.0 to 9.0. If we include 0 in the range displayed, this will mean that minimally, 1/9 (11%) of the horizontal space will be devoid of data. This would be an acceptable amount. If the range went from 0 to 10.0, this will mean that 2/10 (20%) of the horizontal space will be devoid of data. This would

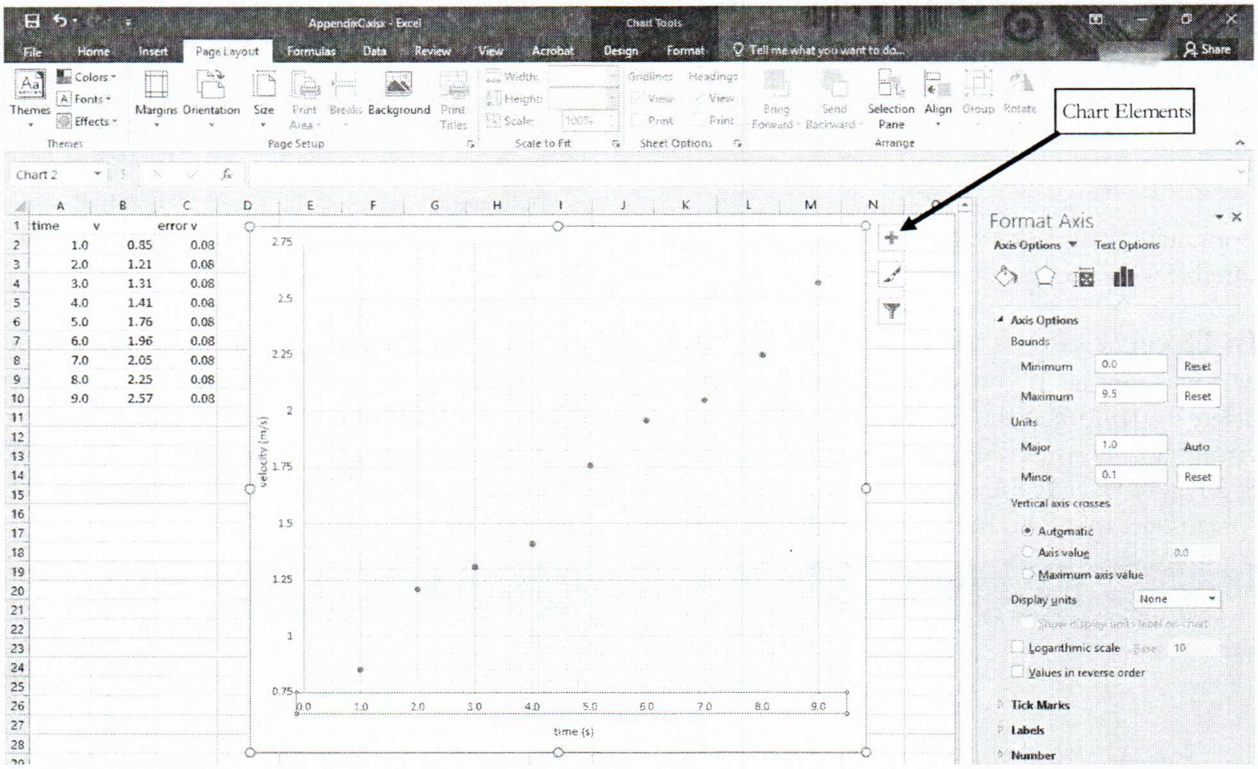


Figure C.2 Formatting the axes should be done to minimize data-free zones and make an easily readable data points when printed – this means having minor gridlines visible and on a convenient scale.

be about the maximum amount of wasted plotting area that should be allowed. Draw your axis allowing room for labels and numbers. Count the number of squares along the x-axis available to you. If there are 48 squares available. 8.0 s / 48 squares = 0.167 s per square. This is not a good scale, but it is the minimum for the data to all fit. Choose a larger, nicer scale like 0.20 s per square. 0.20 s/square × 48 squares = 9.6 s will fit across. So start with 0, every square is 0.2 s and you can get up to t = 9.6 s on the horizontal. This will mean that 1.6 s / 9.6 s (17%) of the horizontal space will be devoid of data, and that is acceptable.

The velocity data has error so the range of must cover 0.77 (0.85 - 0.08) to 2.65 (2.57 + 0.08). If we include 0 in the range displayed, this will mean that minimally, 0.77/2.65 (29%) of the vertical space will be devoid of data. This would NOT be an acceptable amount. If the range went from 0.75 to 2.75, this will mean that only 0.12/2 (6%) of the vertical space will be devoid of data. Count the number of squares along the y-axis available to you. If there are 65 squares available. 1.88 m/s / 65 squares = 0.0289 m/s per square. This is not a good scale, but it is the minimum for the data to all fit. Choose a larger, nicer scale like 0.03 m/s per square. 0.03 m/s/square × 65 squares = 1.95 m/s will fit. So start with 0.76, every square is 0.03 m/s, 8 squares up is 1.00 m/s and you can get up to v =2.71 m/s on the horizontal. This will mean that 0.07 / 1.88 m/s (4%) of the vertical space will be devoid of data, and that is acceptable. If you instead chose 0.05 m/s per square you would have 42% of the vertical space will be devoid of data, and that is not acceptable.

Error Bars

If uncertainty is present in the data to be plotted, it should be represented by error bars if those bars can be seen in the scale used. Uncertainty may be the same for all of one variable or it may be unique to each data point. It may be present in the variable plotted on the x- and/or the y-axis.

Continuing with our example data set, only vertical error bars should be present as velocity is the only variable with error accounted for.

In Excel, return to *Chart Elements* and click on the *Error Bars* option. Both vertical and horizontal error bars will appear. If you do not want one of these, click on one in the chart area and press backspace to delete it. To format the vertical error bars in our chart, click on a vertical bar in the chart area and click on error bar options in the format menu. You can select and enter a *Fixed value* if all the error are the same. See Figure C.3. If they are different, choose *Custom* and then click *Specify Value*. Select the error in the spreadsheet to use on both sides of the data point.

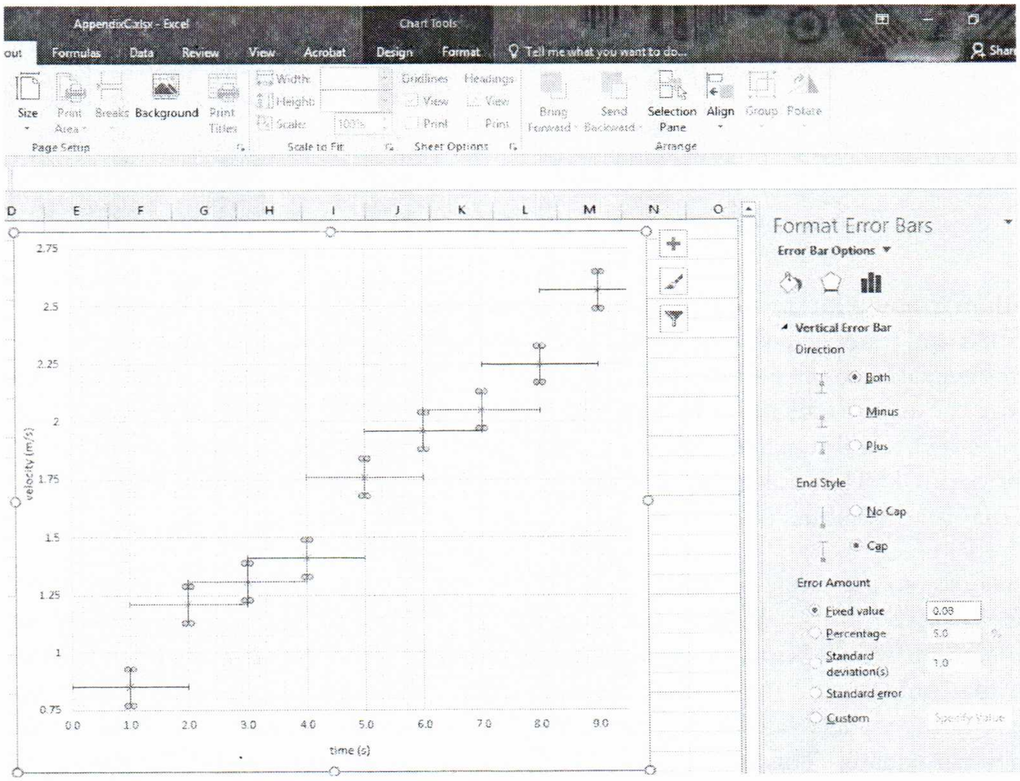


Figure C.3 Both horizontal and vertical error bars are created by default. This shows the fixed value option for the vertical error bars. The horizontal error bars will be deleted. The data markers have been changed by clicking a marker, going to *Format Data Series*, selecting *Marker*, *Marker Options*, select *Built-in* and change *Type*.

On paper, the same scale should be used on the vertical error bars as the rest of the vertical data. The error is ± 0.08 m/s for all points with the scale at 0.03 m/s per square, the error bar should then be 2.67 squares up and 2.67 squares down from the data point.

The Best-Fit Line

The best-fit line is the line that best represents the relationship between the x- and y-variables taking into account all data present. The best fit line should not just go from the first to the last data point – this only takes two data points into account. The line should be straight, do not just connect the dots. See Figure C.4.

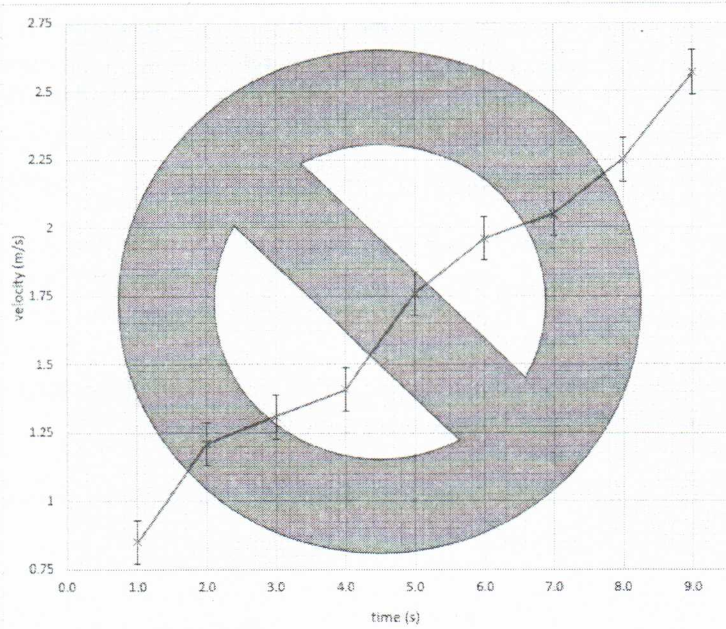


Figure C.4 Do not play connect the dots with your data.

In Excel, return to *Chart Elements* and click on the *Trendline* option. Select a linear trendline and format. The line should be solid. The equation should be displayed along with the R-squared value. Move and resize this label as needed to be easily visible and not obscure the data or axes. See Figure C.5. When you go to use this equation, remember that the slope will have units of [(y-axis units)/(x-axis units)] and the intercept will have the same units as the y-axis. From our example, the final equation relating v to t would be
$v\left(\frac{m}{s}\right) = 0.2005\,\frac{m}{s^2} \cdot t(s) + 0.7053\,\frac{m}{s}$.

The R-squared value is a measure of the variance of the y-value plotted from the trendline value at the same x-coordinate. It can have a value from 0 to 1, 1 being the best (trendline and all data are exactly the same). If your trendline has an obvious outlier, you can move the data point to the end of the data table within the spread sheet and exclude it from the series that the trendline is covering. You should still display this data point by adding that point as another series on the same plot. This outlier should also be discussed in your lab report.

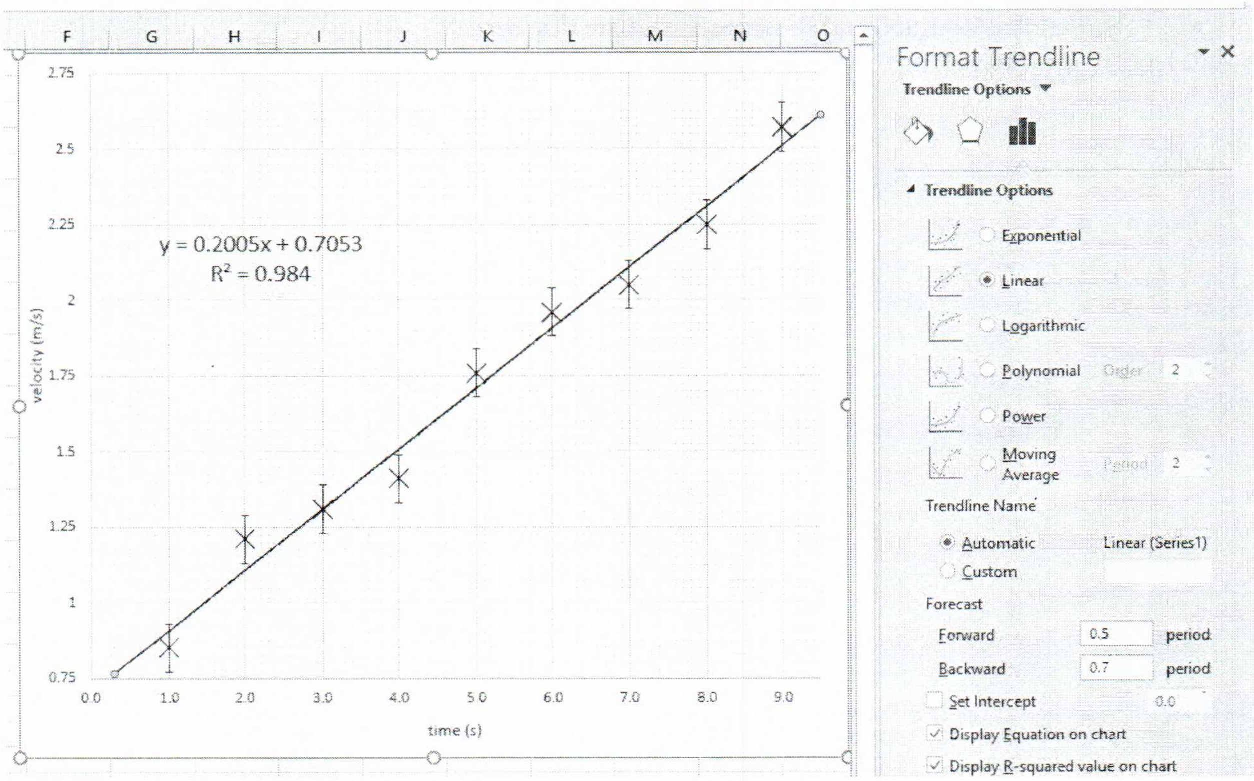


Figure C.5 Formatting the trendline. Forecast has been used to extend the line to the edges of the plot area.

On paper, use a ruler placed on edge to find a straight line that goes through the most number of error bars or, if lacking error bars, roughly the same number of data points above and below the line on the right and left side of the plot. Mark this line across the entire plot area. Locate two locations where the best-fit line crosses a grid vertex, these should not be data points. Find the coordinates of these two locations using the scale already created. Find the slope of the best-fit line by using $m = \frac{(y_2 - y_1)}{(x_2 - x_1)}$. Eq C.3

The units of the x- and y-axes should be present in the numbers input. Continuing our example, the slope of the line obtained would be in units of m/s/s or m/s^2, which is appropriate for the slope being representational of the acceleration experienced by the cart. To get the y-intercept, solve equation C.3 for b: $b = y_1 - m\,x_1$, Eq C.4
input the slope just obtained along with (x_1, y_1) used in the slope calculation. This too will need consistent units. In our example the y-intercept will be in units of m/s and represents the velocity at time t = 0.

For the Excel graph, select the chart area and click the *File* tab to either *print* in the classroom or *export* as a pdf for later printing and/or emailing.

The final checklist for your graphs:

- The graph takes the full page
- The range has a minimal amount of plot area that is devoid of data
- The scale is easy to follow (i.e. has one digit like 0.1 or 30; or an easy fraction like .25 or .333)
- *Minor gridlines in the horizontal and vertical directions are present
- Error bars when applicable, on the same scale as the axis
- Best-fit line
- *The trendline equation and R-squared value are displayed

*Denotes for Excel graphs only, see Figure C.6.

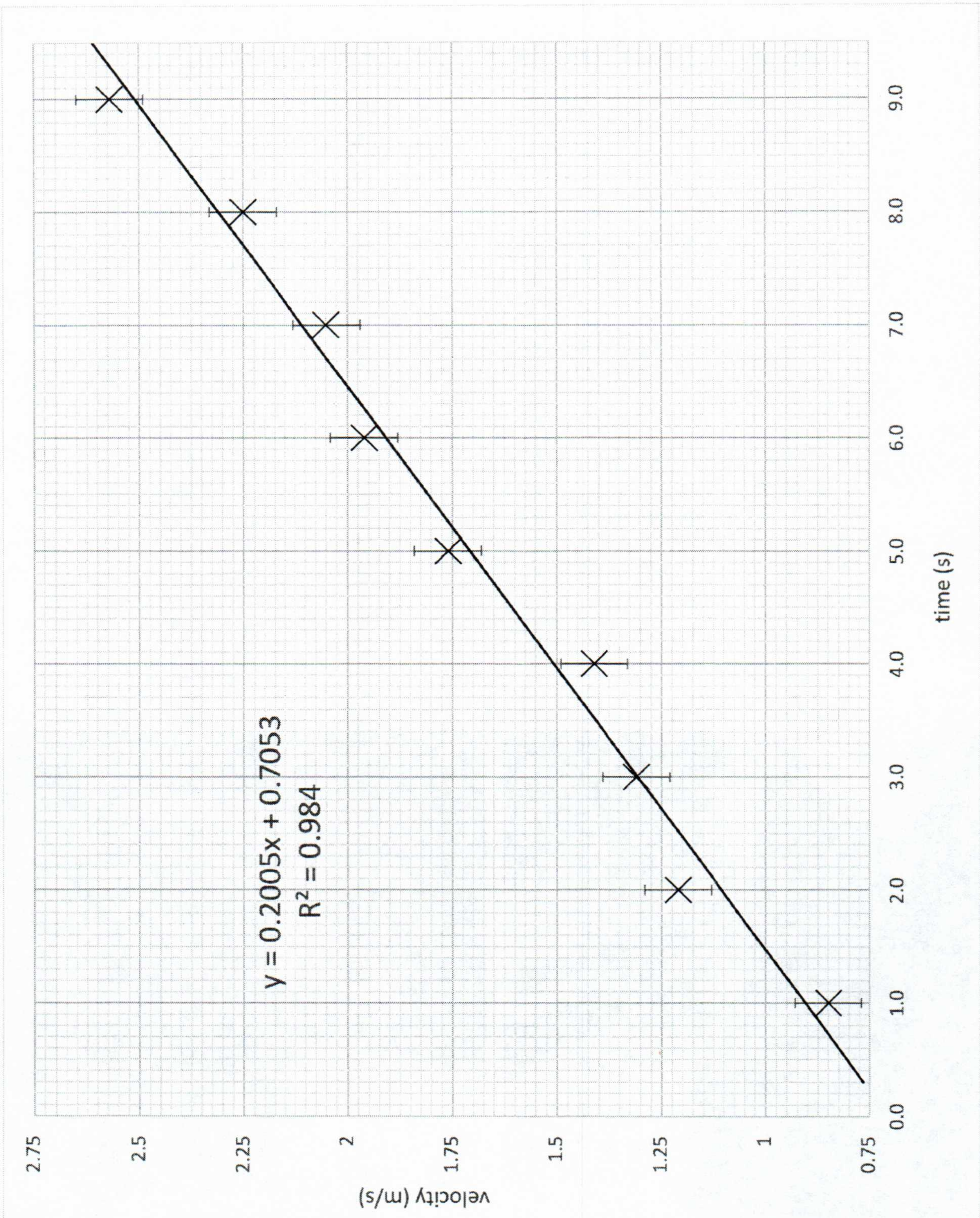


Figure C.6 The final, properly formatted graph to be turned in.

Notes & Lab Partner Email Addresses

Figure C.7: Flerken and Nick Furry wish you an enlightening lab experience. May you use the correct units, write thoughtful analyses, and have functioning equipment

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