Laboratory Manual

Oberlin College Physics 111: Electricity, Magnetism, Thermodynamics

Spring 2023

Physics 111 Lab Schedule; Spring 2023

Week of:	*Experiment:*
January 30	Organizational Meeting (30-45 minutes)
February 6	Electrostatics
February 13	Capacitance
February 20	Mapping Electric Field
February 27	DC Circuits – I (*read the Digital Multimeter Primer and solve the preliminary problem before coming to lab*)
March 6	DC Circuits – II
March 13	Using an Oscilloscope
March 20	*Spring Break*
March 27	Solar Cell
April 3	Measuring Magnetic Field (*solve problem before lab*)
April 10	AC Circuits – I
April 17	AC Circuits – II
April 24	Polarization of Light
May 1	Calorimetry

Notation: When this Lab Manual says "HRW", it means the textbook "Halliday, Resnick, and Walker, *Fundamentals of Physics*, tenth edition (2014)".

Contents

Welcome to the Laboratory

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I am here to help you. Ask questions. I may answer your question with another question to help you think about what you are doing. I like teaching and want to deepen and broaden your understanding, but at the same time I want to grow your capacity for teaching yourself. If you ask me "What is the charge on an electron?" I won't say "1.60×10^{-19} coulomb", I'll say "Google knows better than I do."

The emphasis in lab is always on careful and objective observation and never on getting preconceived "right answers".

Learning Goals: In laboratory you will
- experience first-hand the electric, magnetic, and thermal phenomena that you hear about in lecture and work with through problem assignments;
- construct DC and AC circuits, and use digital multimeters and oscilloscopes;
- use software such as Graphical Analysis or Microsoft Excel to analyze, graph, and interpret data;
- develop laboratory skills including industry-standard documentation habits, collaboration skills, and habitual use of significant figures;
- develop your capacity for teaching yourself.

General Procedures: Laboratory work is generally done in Wright 214 by partners following the instructions in this laboratory manual. Each week, before coming to lab, study the instructions and notes for the experiment to be performed, and review relevant material from your textbook and class notes. At the beginning of the lab period I will go over special techniques and precautions, but I won't review material presented in this manual. Some experiments ask that you do reading or perform calculations before coming to lab.

While carrying out an experiment you might think up a different question, not mentioned in this manual, which could be investigated with the apparatus at hand. Feel free to pursue your own ideas.

Pronouns, Nouns, Adjectives, and the Character of Science: I don't care what pronouns you use in referring to me. Similarly, you may call me "Dan" or "Mr. Styer" or "Dr. Styer" or "Prof. Styer", whichever you find most comfortable. My personal preference, however, is for you to call me "Dan". In this lab we are learning not from books or from people but from nature. I hope you'll accept this learning because it comes from nature, and not because I have earned the right to put a fancy shingle in front of my name.

Grading and Grading Criteria: This course does not use a formal written laboratory report. Instead, when you have completed an experiment, discuss the experiment and your notebook entries with me. Point out anything you've done of which you're especially proud. (Some students feel that pointing to their own accomplishments like this is unseemly boasting, but in fact it's nothing more that the ancient admonishment to not "hide your lamp under a basket".) After the discussion, I will grade your laboratory work as acceptable (C), good (B), or exemplary (A). If your work is unacceptable you must address the concerns raised and then return for re-evaluation.

If you follow this lab manual in a haphazard, intellectually sloppy way, you have earned a C. If you follow this lab manual in a solid, adept way – nothing wrong, nothing to be ashamed of – you have earned a B. To earn an A you must follow this lab manual in a solid, adept way, *plus* do something above and beyond following this lab manual: suggest or, even better, execute a new experiment; ask thoughtful, probing questions; raise issues not brought up in this lab manual. I can't give you explicit instructions for earning an A, because you earn an A by creatively going *beyond* following instructions.

Physics is a science, yes, but it is also an art – the art of teasing nature into revealing its secrets. Like any studio art course – painting, music composition, poetry writing – you are graded not only on your technique – brushstrokes, counterpoint, meter – but also on your creativity.

Laboratory Notebook: Your lab notebook records what you do. Not what you wish you had done, not what you would have done if you had been perfect, not what you think your instructor wants. Below is a list of six "rules for keeping a lab notebook", but all of them really reflect the one rule that the lab notebook records what you do.

Keep the same kind of complete and understandable notebook that a research or development scientist keeps. Do not duplicate the laboratory manual in your notebook. Do not force your notes into a rigid "Procedure, Results, Discussion" format (unless it happens that you executed the lab in a "Procedure, Results, Discussion" format – as I said, the notebook should reflect what you do). The goal is that anyone should be able to tell from the laboratory notebook what experiment was performed, what data were taken, how accurate those data were, what calculations were made, and how the final results compared with theory or with other experiments. A notebook with good layout and neatly entered data and text is far more understandable than one with disorganized scribbles.

Your notebook is a journal of your observations. Record what you observe and interpret what you record, rather than recording something that fits your notion of what ought to be happening. In research and development, you often will not know for weeks or months afterwards whether a particular entry is really significant, so make the meaning of each entry exact, concise, clear, and complete. One aspect of "recording what you observe" is that you must not do mental arithmetic before recording values. For example, suppose a lamp is placed on an optical bench so that its base is at 10.0 cm on the scale and a lens is placed at 30.0 cm. You should record both of these readings and then subtract to get the separation

distance rather than just writing down that the lens is 20.0 cm from the source. This may seem like a trivial point, but having the raw data often helps in tracking down erroneous recordings. Redundant information helps eliminate confusion and correct mistakes.

Your laboratory notebook is a permanent record of your work in this laboratory. Like any research physicist, use a **bound notebook** and tape in graphs and computer printouts. If possible, your notebook should have **pre-numbered pages** so that you can cross-reference your work and insure that no pages have been removed. If you can't find a bound notebook with pre-numbered pages, your first step should be to number the pages. (A spiral-bound notebook or three-ring binder is *not* acceptable because pages might be added or removed.) These are available for purchase at the Campus Bookstore. If you have one already – and it is less than half full – it will be fine to use the empty pages.

Bring this laboratory manual, your laboratory notebook, and a calculator to every laboratory session.

Specific guidelines for keeping your notebook:

1. Leave two or three pages at the beginning for a table of contents, which should be kept up-to-date. Write the date and your name at the beginning of each week's lab write-up.

2. Write down enough explanation of what you are doing, and why, so that your pages of data can be analyzed later without confusion or ambiguity. Do not copy the instructions in this manual instructions into your notebook, instead label sections of data and text to correspond to sections of this laboratory manual (e.g., Part A, C4).

3. Record all work legibly **in ink**. If you make a mistake, **draw a line through it (but do not obliterate).** Note any incorrect readings or comments and write in corrections.

4. Enter directly all data and pertinent information about the equipment and the experimental conditions. **Do not record your observations on scratch paper then copy it later into your notebook.** Enter directly all raw data and information with which to make corrections. Do not try to make corrections in your head while taking data. Whenever possible, use tables or columns for recording measurements.

5. Most data, after being tabulated, should immediately be graphed, both to increase your immediate understanding and for easier recollection and referral. Graphing will be done by computer, **then printed and taped into your laboratory notebook**.

6. Complete the notebook immediately after taking measurements. Do not delay until you've forgotten what you did.

Attendance and Grading: Laboratory work is crucial for this course. At the same time, if you come to lab sick then (1) you *will not* do your best work and (2) you *will* infect others. When illness or emergency prevents you from attending your regular laboratory class, contact me as soon as possible to make arrangements to complete the lab.

Your lab work counts for 25% of your course grade, but if you fail the lab you fail the course, regardless of how well you did in the classroom portion of the course. If you miss one lab (either through failing to correct an unacceptable notebook, or through not informing the instructor of sickness, etc.) then your grade goes down by one letter (A– to B–, for example). Miss two labs, down by two letters. Miss three labs, you fail the labs and hence the course.

Athletes: If your practice/game schedule results in conflicts with laboratory, meet with me in the first week of the semester to resolve the issue.

Error Analysis

What is the pattern of thought most characteristic of science? Is it knowing that "net force causes acceleration rather than velocity"? Is it knowing that "momentum is conserved in the absence of external forces"? Is it knowing that "relativistic mechanics has a classical limit"? No, it is none of these three facts – important though they are. The pattern of thought most characteristic of science is knowing that "every measurement is imperfect and thus every observed number comes with an uncertainty".

As with any facet of science, the proper approach to uncertainty is not "plug into a formula for error propagation" but instead "think about the issues involved". Suppose, for example, that in the "Characteristics of a Solar Cell" lab you measure the distance between a solar cell and a light source to be 27.6 cm. A more accurate measurement would of course provide a more accurate length: perhaps 27.64722031 cm. You don't know the exact distance; you know only an approximate value. In math, 27.6 cm means the same as 27.60000000 cm. But in physics, 27.6 cm means the same as 27.6??????? cm, where the question marks represent not zeros, but digits that you don't know. The digits that you do know are called "significant digits" or "significant figures".

[A more sophisticated treatment of uncertainty is through the "confidence interval". If I think that a length is 27.6 cm, but it could be as large as 27.8 cm or as small as 27.4 cm, I can express the length as 27.6 cm ± 0.2 cm. Estimating and working with confidence intervals is an important scientific skill, which you will learn in Physics 212 or Chemistry 211. For this course we confine ourselves to significant figures.]

Expressing uncertainty

The convention for expressing uncertain quantities is simple: Any digit written down is a significant digit. A distance measured to the nearest millimeter has a length expressed as, say, 103.7 cm or 91.5 cm or 135.0 cm. Note particularly the trailing zero in 135.0 cm: this final digit is significant. The quantity "135.0 cm" differs from "135 cm". The former means "135.0??????? cm", the latter means "135.???????? cm". In the former, the digit in the tenths place is 0; in the latter, the digit in the tenths place is unknown.

This convention gives rise to a problem for representing large numbers. Suppose the distance between two stakes is 45.6 meters. What is this distance expressed in centimeters? The answer 4560 cm is unsatisfactory, because the trailing zero is not significant and so, according to our rule, should not be written down. This quandary is resolved using exponential notation: 45.6 meters is the same as 4.56×10^3 cm. (This is, unfortunately, one of the world's most widely violated rules.)

Working with uncertainty

Addition and subtraction. I measure a plank with a meter stick and find it to be 187.6 cm long. Then I measure a dowel with a micrometer and find it to be 2.3405 cm in diameter. If

I place the dowel next to the plank, how long is the dowel plus plank assembly? You might be tempted to say

```
    187.6
 +    2.3405
    189.9405
```

But no! This is treating the unknown digits in 187.6 cm as if they were zeros, when in fact they're question marks. The proper way to perform the sum is

```
    187.6?????
 +    2.3405??
    189.9?????
```

So the correct answer, with only significant figures written down, is 189.9 cm.

Multiplication and division. The same question mark technique works for multiplication and division, too. For example, a board measuring 124.3 cm by 5.2 cm has an area given through

```
     1243?
 ×     52?
      ?????
     2486?
     6215?
    64?????
```

Adjusting the decimal point gives an answer of 6.4×10^2 cm^2.

While the question mark technique works, it's tedious. (It's even more tedious for division.) Fortunately, the following rule of thumb works as well as the question mark technique and is a lot easier to apply:

When multiplying or dividing two numbers, round the answer to the number of significant digits in the least certain of the two numbers.

For example, when multiplying a number with four significant digits by a number with two significant digits, the result should be rounded to two significant digits (as in the example above). (If you want a justification for this rule of thumb, you'll need to take Physics 212 or Chemistry 211.)

Experiment 1: Electrostatics

Introduction

Atoms are made up of just three types of particles – protons, neutrons, and electrons. Two of these, protons and electrons, have a property called "electric charge". Neutrons have no charge (they are named for their electrical neutrality). While any everyday object contains a vast amount of charge, most objects contain exactly equal numbers of protons and electrons, and therefore have zero net charge. Anything that has an excess of either type of charge is said to be "charged" and will interact with other charged objects according to this rule: *Like charges repel; opposite charges attract*. Electrostatics is the study of charges stationary with respect to one another. (Moving charges interact in a more complicated way to be studied later in the course.) This experiment reproduces some classic observations upon which the theory of electrostatics is based.

Equipment and Discussion

Charge Producers

There are many pairs of materials that separate charge when they are rubbed together. For example, electrons are attracted to silk more than to glass, so when silk is rubbed on glass the silk emerges with a net negative charge and the glass with a net positive charge. Such materials are called "charge producers," although the name "charge separators" would be more accurate. It is impossible to create a net charge. You can, however, separate charges to make two equally and oppositely charged objects. In this lab you will use glass, silk, PVC piping, and paper to separate charges.

Charge Detectors

After charges are produced we need devices to detect them. One of the simplest is a "pith" ball – in our case a light ball of crushed aluminum foil hung on a string. When a charged object touches a pith ball, charge flows to it. Since the pith ball is so light, it is easy to see small electrical forces attracting or repelling it.

A more sophisticated instrument is the electrometer pictured on the next page. This sensitive electronic device measures the voltage produced by small charges. (The concept of *voltage* will be detailed later in the course.) For much of this lab, the magnitude of the voltage is unimportant; only its polarity ($+$ or $-$) is relevant. The electrometer is "zero-centered": it responds to positive charges by swinging to the right; to negative charges by swinging to the left. In this lab, the amount of deflection corresponds to the magnitude of the charge.

**Figure 1: Front Panel Controls of the Electrometer**
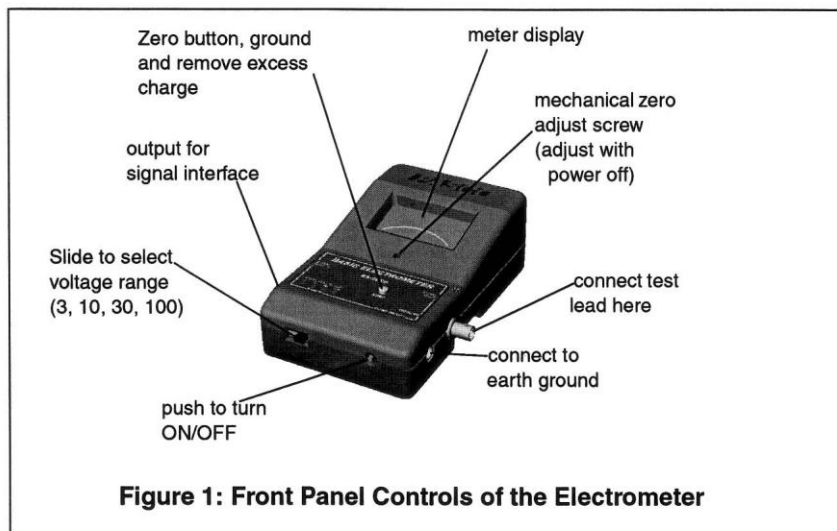
Some important points for general operation of the electrometer:
- The electrometer must be connected to a good earth ground (a water pipe or the ground wire from an electrical socket, which is in turn connected to a water pipe). Only an earth ground provides a sufficient drain for excess charges that may build up during an experiment.
- Before conducting an experiment or even touching the input leads, connect yourself to an earth ground by touching one hand to, for example, the outer shield of the Faraday ice pail in the set up shown on page 11. A person walking across a rug on a cool, dry day can easily acquire several thousand volts.
- Similarly, don't walk around or wave your arms excessively; charge can build up in clothing and affect your results. If you're wearing a sweater, take it off.
- Between measurements, press the **zero** button to discharge the electrometer. Shorting the test leads together is insufficient; there may still remain stray charges within the electrometer itself.

The electrometer is used in conjunction with a double cage arrangement often called a Faraday ice pail, because Michael Faraday did many of the original experiments of electrostatics using a metal pail built to hold ice for refrigeration in 1843 London. The lab apparatus, pictured here, consists of two concentric wire mesh cylinders well insulated from each other.



Figure 8: Faraday Ice Pail

The electrometer is connected to the inner cylinder. When a charge is placed on the inner cylinder, the meter deflects to the left or right, depending on the sign of the charge. In fact, if a charge is even brought near the inner cylinder the meter will deflect, since like charges are repelled from the pail and down the wire to the electrometer.

10
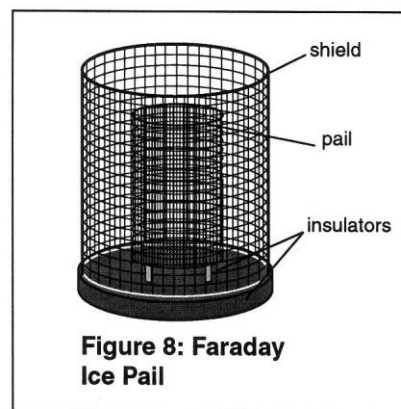
The outer cylinder serves only to shield the inner cylinder from the effects of stray electric fields produced other sources such as fluorescent lamps. In use with the electrometer, the outer pail is connected to ground, as is the ground terminal of the electrometer. Ground is literally the earth, and acts as an infinite reservoir of both positive and negative charges. By connecting the outer pail to ground, the inner pail is shielded from external, unwanted charges such as a wool sweater on a dry winter day. Only the charges that you place inside the inner cylinder should register on the electrometer. To work perfectly the outer pail would have to completely surround the inner one. Though the outer cylinder you will use is imperfect, it remains extremely helpful.

Classic Qualitative Electrostatics Experiments

This laboratory consists of several short qualitative experiments. There are no numbers to report. Instead, record in your lab notebook, for each experiment, what you do (make sketches if that helps), what you observe, and how the observation is explained through the attraction and repulsion of charges.

Figure 1.1: Demonstration Setup
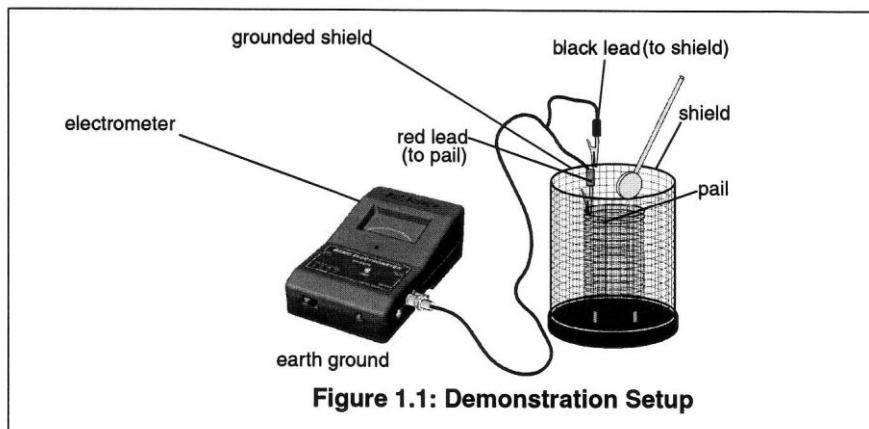
A. *Separation of Charge*

Using the alligator clips, attach the grounded (black) lead of the electrometer to the outer mesh cylinder (shield), and the ungrounded (red) lead to the inner mesh cylinder (pail). Play with the apparatus until you are familiar with it. Always start with the electrometer voltage range in the highest setting (100 V) and adjust down if needed. Analog meters are typically most accurate in the range of 1/3 to 2/3 of full scale.

- Rub the glass rod with the piece of silk. Then insert the rod into the inner cylinder without allowing it to actually touch the cylinder. When you do this you should get a positive deflection on the electrometer. If you don't, try rubbing the silk on the glass again. If you can't get a reading even after several tries, ask your instructor for help.
- Remove the glass rod and again note the electrometer reading. If it never touched the pail, the reading should be zero.

11

Why did the electrometer detect charge when the glass rod was inside the inner cylinder? How is the sign of the charge on the glass rod related to the sign indicated by the electrometer?

This particular experiment, rubbing glass with silk, was originally used by Benjamin Franklin to define positive charge. The choice of the charge on the glass as positive was arbitrary. It turns out that the glass loses electrons, so the charge on an electron is now called "negative".

B. *Conservation of Charge*

The excess electrons on the silk quickly run down your arm and into the ground, so you will probably not be able to detect much charge on the silk. To help you see that there is actually a separation of equal charges, you are provided with two types of plastic mounted on conducting disks that are mounted on rods. The disks are insulated from the rod by white plastic. Do not touch the white insulator with your hands, because oil and dirt will allow charge to leak off. If you have trouble with this experiment, you should try cleaning the insulator with the alcohol kept by the sink. (You have another rod like this with a metal surface on the conducting disk. This so-called "proof plane" will be used in the next section.)
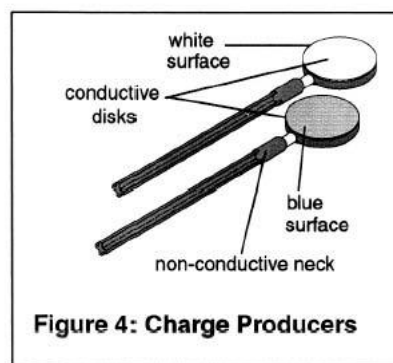

Figure 4: Charge Producers

Residual charge may build up in the plastic insulator between the handle and disk of the proof plane and charge producers. Before any experiment make sure to ground these parts by touching them to the shield on the Faraday ice pail.

- Hold one rod in each hand. Insert the rods one at a time into the inner pail. The rods should be uncharged when you begin, so if you get any reading, ground the disks by touching the back side to the outer pail. Do this until each disk is neutral.
- Now rub the white and blue surfaces together to separate charges. Light rubbing usually works better than hard pressure. Then insert the rods one at a time into the inner pail. Is the deflection caused by one rod equal and opposite to the deflection caused by the other? Try this with several different levels of charge created by more or less rubbing.
- Completely remove all charge from the charge producers by grounding them. Also remove any stray charge from the necks and handles.
- Insert both charge producers into the ice pail and rub them together inside the pail. Note the electrometer reading. Do not let the charge producers touch the pail.
- Remove one charge producer and note the electrometer reading. Replace the first charge producer and remove the other. Note the electrometer readings. Using the magnitude and polarity of the measurements, comment on conservation of charge.

C. *Charging by Contact and Induction*

It is possible, with one charge producer, to deposit either a positive or negative charge on the inner pail!

- Push the **zero** button on the electrometer to remove any residual charge, and make the charge producers neutral. Then rub the charge producers to separate charge, and put one of them aside.
- Insert the other charge producer into the inner pail and note the sign and magnitude of the charge indicated by the electrometer.
- Now let the charge producer paddle (not handle) touch the inside of the ice pail, then remove the charge producer and note the electrometer reading.

Why is there now a permanent charge on the inner pail, as indicated by the electrometer? Where did the charge come from?

- To show that the charge gained by the ice pail was lost by the disk, ground the system by pushing the **zero** button, and then insert the charge producer again into the ice pail. Does any charge remain on it?

Now, can we use the same charge producer to place an opposite charge on the ice pail? Here is a way to try.

- Zero everything. Rub the charge producers to separate charge, and then put the same one aside again.
- Insert the other charge producer into the inner pail and note the sign and magnitude of the charge indicated by the electrometer. *Don't* let it touch the pail!
- With the charge producer still in the pail, touch your finger simultaneously to both inner and outer shields.
- After that, remove the charge producer. What does the electrometer read now? Why? Where did the charge come from? Could we repeat this process without having to recharge the charge producer?

(This is called charging by induction. When the charge producer was first put into the inner pail, it is said to have *induced* a separation of charge on the pail.)

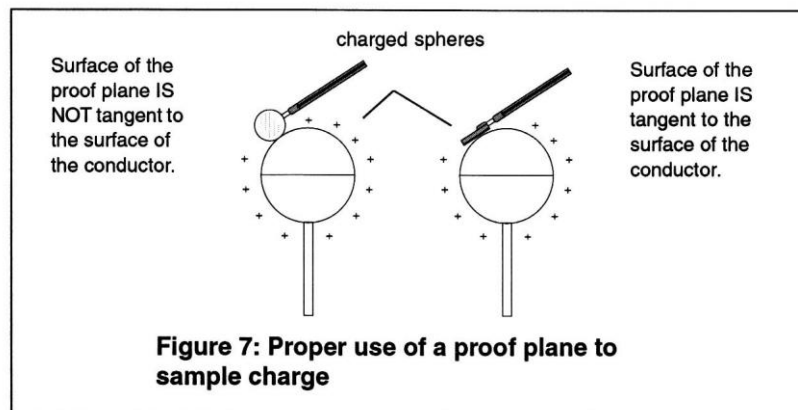**D.** *Charge Distribution on a Sphere*

Charge placed on a conductor will spread over its surface. Exactly how the charges arrange themselves depends on the shape of the conductor. When charges are placed on a sphere, a highly symmetric object, they will distribute themselves evenly over the surface. If another charged object is brought nearby it will *polarize* the first object, repelling like charges to the far side and attracting unlike charges to the near side.

At your station are two metal spheres on insulating stands. One will be connected to a high voltage source and called the charging sphere. The other, called the freestanding sphere, will not be connected to anything.

To detect the distribution of charge on the spheres, you will use a "proof plane", which is simply a conducting disk on an insulated rod. When you touch this disk to the sphere, it picks up a small amount of charge from the sphere. By inserting the proof plane into the ice pail, you can determine the size and type of the charge at that location on the sphere.

An important aspect of measuring charge distributions is charge conservation. The proof plane removes some charge from the surface it samples. If the proof plane is grounded after each measurement, the surface will be depleted of charge with consecutive measurements. However, by not grounding the proof plane (and by not letting it touch the ice pail), the charge on the surface is not depleted. That charge which the proof plane removed for one measurement is always returned to the surface when the next sampling is made.

When the disk of the proof plane touches the surface being sampled, it essentially becomes part of the surface. To minimize distortion of the surface shape when sampling, hold the proof plane flat against the surface, as indicated to the right in the diagram below.

charged spheres

Surface of the proof plane IS NOT tangent to the surface of the conductor.

Surface of the proof plane IS tangent to the surface of the conductor.

Figure 7: Proper use of a proof plane to sample charge

D1. *Uncharged Sphere*

- Switch the electrometer to the 3-volt scale and zero the meter.
- Ground the freestanding (unconnected) sphere by touching one hand to the sphere and one hand to the grounded outer cylinder. Also ground the proof plane and check it with the ice pail. Since the electrometer is now on a much more sensitive setting there may be small movements of the meter which are impossible to get rid of. Just ignore them.
- Now test for charge on the freestanding sphere by touching the proof plane to it at several points and then inserting the plane into the pail. Choose points on all sides to represent an overall sample of the surface. Since the sphere is uncharged, there should be a zero reading.

D2. *Charged Sphere*

- Set the freestanding sphere aside. Connect the other sphere to the 1000 volt output jack of the "electrostatic voltage source" and turn on that source. This voltage source is severely current limited (10 microamps) so it is impossible to get shocked by it even though the voltage is nearly 1000 volts. The voltage source is to be grounded to the same earth ground as the shield and the electrometer.
- Touch the proof plane to the sphere and then test it in the ice pail. If the reading is off the scale, switch the electrometer to a less sensitive range. By touching the plane to the sphere in various places, verify that the charge is evenly distributed over the sphere.
- The wire from the supply is attached to the sphere by a binding post that causes a deviation from the spherical shape. Make it deviate even more by attaching a straightened paperclip. Touch the plane to the tip of the paperclip. Is more or less charge found on this point compared to the rest of the sphere? Can you think of a practical use for this phenomenon?

D3. *Induced Polarity of a Neutral Sphere*

- With the voltage source still on, bring the neutral freestanding sphere close to the charged sphere, about an inch away. (Don't let the spheres touch.) Now test various places on the freestanding sphere with the proof plane. What has happened? Why?

D4. *Charging by Induction (again)*

- With the charged sphere still nearby, ground the freestanding sphere by touching it briefly with one hand while you touch the grounded outer cylinder with the other hand. Turn off the voltage source and move the sphere attached to it. Now study the charge on the freestanding sphere: Is there a net charge on it? Why? Is it positive or negative? How is it distributed?

E. *Pith Balls - Visual Evidence of the Force between Charges*

The electrometer is an extremely sensitive instrument. The pith ball is not. To get a good effect from the pith ball you will produce extremely high voltages that can ruin an electrometer. Therefore *turn off your electrometer before beginning this section of the lab*.

- Bring the glass rod near to the pith ball. Since both are uncharged, nothing should happen.
- Charge the rod by rubbing it vigorously with the silk. Once again bring the rod near the pith ball. The ball should first be attracted to the rod, touch it, and then jump away.

  Why is the uncharged pith ball attracted to the charged rod?
  Why does the ball jump away after touching the rod?

Observe the continued repulsion of the ball by the rod.

- Leave the charge on the ball. Now charge the PVC pipe by rubbing it with paper. Bring it near to the ball, being careful not to let the ball touch it. Why is the ball attracted to the pipe?
- Remove the charge from the ball, the rod, and the pipe by touching them all over. Since the glass rod is an insulator you must run your hand over the entire rod to discharge it. Similarly for the PVC pipe.

Now repeat the first two steps, only this time start using the PVC pipe rubbed with paper.

Then answer this important question: Why is the uncharged ball attracted to *either* the positively-charged rod or the negatively-charged pipe? What does this tell you about the force between charges above-and-beyond the fact that opposite charges attract? Explain all the observations you have made with the pith ball.

Clean-Up

Turn off both the voltage source and the electrometer. Take your lab notebook and discuss your results with the instructor. Straighten up your station before leaving.

Experiment 2: Capacitance

Two conductors, isolated electrically from each other and from their surroundings, are called a *capacitor*. When a capacitor is charged, the conductors, or *plates* as they are called, have equal but opposite charges of magnitude Q. (Capacitors are useful for storing charge and energy.) A capacitor has the property that the amount of charge on each plate is proportional to the voltage, or potential difference, between the plates. (The voltage V, which is indicated on the electrometer, is related to the potential energy of the charges, as you will soon learn in class.) The constant of proportionality is called the *capacitance C* of the capacitor. This constant depends only on the size and geometry of the conductors of a particular capacitor. Thus, the equation describing the electrical behavior of a capacitor is simply $Q = CV$.

The capacitor to be used in this experiment consists of two metal plates, 20 cm in diameter, which can be adjusted to various separations. The movable plate is mounted on a calibrated slide that gives the plate separation directly in centimeters. Binding posts are provided for electrical connection to each plate. Three plastic spacers are attached to the fixed plate so that when the movable plate is made to touch these spacers, the plate separation is 1 mm.

Figure 3: Variable Capacitor
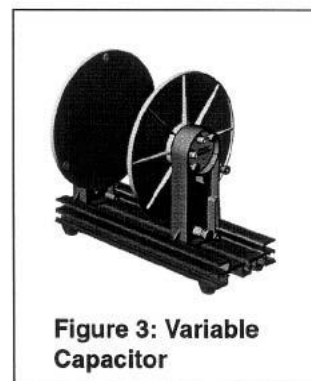
As long as the diameter of the plates is much greater than the distance d between them, and there is nothing between the plates other than air (a vacuum is better), the capacitance of this arrangement is given approximately by $C = \epsilon_0 A/d$, where A is the surface area of the plates and ϵ_0 is the constant you met in Coulomb's law. (This approximation is accurate when the plates are close together, and fails when the plates are far apart.) Thus, as you increase the plate separation d the capacitance decreases, and *vice-versa*.

The purpose of the experiments in this part is to study the relationship between C, V, and Q for the parallel plate capacitor. You will need to keep tables of data.

A. *Dependence of V on Q*

Connect the grounded (black) lead of the electrometer to the fixed capacitor plate, and the other (red) lead to the movable plate. Initially set the electrometer scale to 10 V. The electrometer will directly measure the difference in electrical potential between the two plates, which should be about 2-3 mm apart. **Zero** the electrometer and discharge the capacitor.

Connect the 1000 V jack of the voltage source to the charging sphere, which should be placed far enough away from the capacitor that it does not charge the capacitor by induction. Make sure that both the voltage source and the electrometer are grounded.

- Touch the proof plane to the sphere to pick up some charge, and then touch the proof plane to the top of the movable capacitor plate. Observe the voltage between the plates. Do this several times, noting the electrometer reading at each step. If you always touch the sphere and the capacitor plate at the same place, equal amounts of charge will be transferred each time. Do your observations match your expectations? Why is it sufficient to touch only one plate of the capacitor? Of the three quantities V, Q, and C, what is being held constant in this experiment?
- Repeat this experiment with a doubled plate separation. Compare the readings to the previous case.

B. *Dependence of V on C*

Set the electrometer to the 100 V scale. Put the capacitor plates about 2 mm apart and **zero** the system. Change the wire at the voltage source from the 1000 V jack to the 30 V jack.

- Charge the capacitor to 30 V by briefly touching the voltage source wire to the movable plate. The electrometer should read 30 V.
- While watching the electrometer, slide the movable plate gradually so that the plate separation doubles or triples. What happens? Why? Of the three quantities V, Q, and C, what is being held constant in this experiment?

C. *Dependence of Q on C*

Set the electrometer to the 10 V scale. Connect the electrometer to the ice pail, and separately connect the 1000 V jack of the voltage source to the movable plate of the capacitor. The electrometer, the voltage source, the ice-pail shield, and most especially the fixed plate should all be appropriately grounded. Initially, the plate separation should be about 6 cm. **Zero** the electrometer.

- After grounding the proof plane, sample the charge at different locations on one of the capacitor plates, both on the inner and the outer surfaces. Use the ice pail to measure the charge. How is charge distributed on the plate? Check one or two places on the fixed plate.
- Choose a point near the center of one capacitor plate and measure the charge in this area at different plate separations. How does the charge vary with capacitance? Of the three quantities V, Q, and C, what is being held constant in this experiment?

D. *Dependence of Q on V*

Return the capacitor plate separation to near 6 cm.

- Measure the charge near the center of one capacitor plate when the voltage source is set to 1000 V, to 2000 V, and to 3000 V. How does the charge vary with voltage? Of the three quantities V, Q, and C, what is being held constant in this experiment?

E. *Pith ball*

Move the capacitor plates to surround the hanging pith ball. Ground the pith ball and one plate, set the other plate to 1000 V. Draw the plates close together. Explain what you see. (This experiment suggested by Averly Sheltraw, who took Physics 111 in 2019.)

Experiment 3: Mapping Electric Field

Objective

To find the equipotential lines, and from these the electric field, that exists in a plane perpendicular to two conductors kept at different electric potentials. By the end of this experiment you should have a clear understanding of the relation between electric field and its associated potential field.

Reference: HRW sections 22-1 ("Electric field lines"), 24-2 ("Equipotential surfaces & the electric field"), and 24-6 ("Calculating the field from the potential").

Introduction

On an equipotential surface every point has the same electric potential. Electric field lines are everywhere perpendicular to equipotential surfaces. So if the equipotential surfaces around a charge distribution can be found, the electric field lines can then be mapped by drawing lines perpendicular to the equipotentials. The field lines show the direction of the electric field, and their line density indicates the magnitude of the field.

The method of this laboratory is used to determine the electric field around irregularly shaped conductors, for which a mathematical solution would be very difficult. (Such determinations are routine in the design of integrated circuits.) Although the electric field you will investigate is two-dimensional, it is a good approximation to the field found in three dimensions if the length of the objects in the third dimension (perpendicular to the paper) is very large compared with their sizes within the plane of the paper.

Procedure

There is a theorem (the "mean value theorem") stating that in a region with no charge, the electric potential at a point equals the electric potential averaged over any circle centered on that point. (Remarkably, Coulomb's law is equivalent to the mean value theorem. That is, you can start from Coulomb's law and prove the theorem, or you can start from the theorem and prove Coulomb's law.) This gives rise to a technique called "relaxation": To find the potential in a region, set up a square grid. Fix the potential at parts of the grid. At every other point, set the potential equal to the average of the potential values at the four grid points above, below, left, and right of that interior.
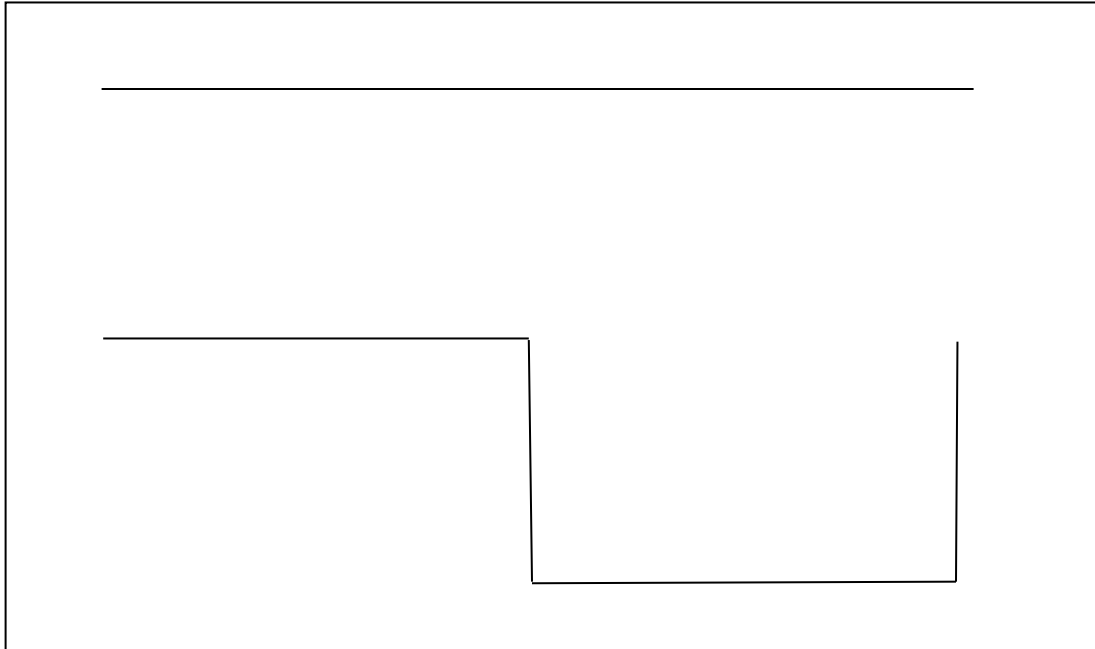
This method can be implemented in Microsoft Excel. First, turn on iterative calculation using

   File | Options | Formulas | Enable iterative calculation

Second, set up the grid: I found it useful to take cells B through AZ and 1 through 30. I narrowed the cells using

Column width | 2   and   Format cells | Number | Decimal places 0

Third, set up the boundary shown here.

I used a potential of 0 for the top line and 99 for the bottom dipper.

Fourth, set up the averaging. For all points not on the line and the dipper, insert the formula

   =AVERAGE(cell above, cell below, cell to right, cell to left)

 Now, to execute the calculation, hit

   Formulas | Calculation | Calculate Sheet

This gives you the potential at every point on the grid.

So now you have the electric potential numbers, but what can you do with a bunch of numbers? I selected all the numbers, then did

   Insert | Recommended Charts | All Charts | Surface | Contour

This gave me a graph upside down from what I wanted. Perhaps you'll be able to figure it out better.

Print the chart and sketch in electric field lines by drawing the field lines perpendicular to the equipotentials. Make the spacing between field lines roughly equal to the spacing between equipotentials in the same region: this will make the field lines close where the field is strong and far apart where the field is weak.

Select one other electrode configuration from the menu on page 23 and repeat.

Questions

Compare your results with those of other lab groups. Use your observations to support your answers to the following questions:

1. Are there any regions where electric field lines cross each other? Can you exclude this possibility theoretically? Explain.
2. Why are the equipotentials perpendicular to the field lines?
3. How would you design an electrode configuration to produce a region in space with a uniform electric field? How would you modify your configuration to obtain the maximum field strength for a given potential difference?
4. How would you design an electrode configuration to produce a region with zero electric field? Describe the electric potential within this region.
5. How do the electric fields near sharply pointed parts of electrodes compare to those near more rounded parts?
6. There are several items in the back of the room for which the shape of the electrodes and their electric field play a role in the function of the device. Comment on how the shape is related to the function of each.

a) Dipole cell membrane bilayer with a dent (injury) on one side.

Lightning rod or building beneath a cloud.

b) Same as (a) but without dent – a parallel plate capacitor.

c) Two parallel nerve fibers with circular cross section, the larger one depolarized by a nerve impulse.

d) Two parallel nerve fibers, both normally polarized.

e) A conducting lump inside a dipole cell membrane layer.

f) A charged linear filament enclosed in a cylindrical sheath.

g) A nerve fiber running parallel to a plane conducting membrane surface. If you can find someone who chose electrode configuration (c), compare results. The similarity leads to the idea of image charges.

h) Electrode structure used to deflect the electron beam in an electron gun.

i) Electrically shielded box (a conducting enclosure).
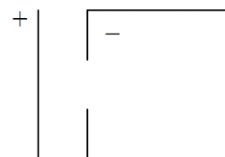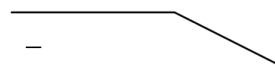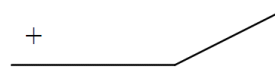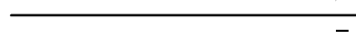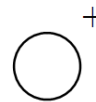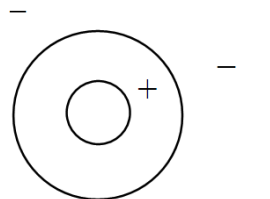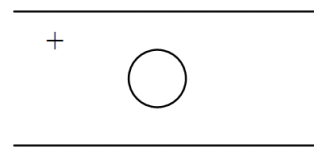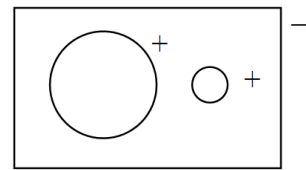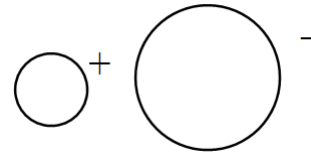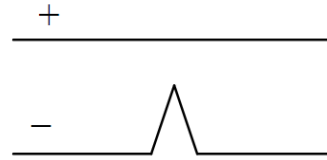
Experiment 4: Direct Current Circuits – I

A. Introduction

In this experiment you design, construct, and understand simple electric circuits. You will become familiar with a power supply, current and voltage meters, various resistors, and capacitors. The basic laws and rules of circuit theory will be studied without attempting to give their full physical justification: theoretical understanding will be attained through lecture, reading, and homework throughout the semester. If you are already an electrical expert, please be patient while the rest of the class catches up. (Sections A through D of these instructions present information – the lab work itself begins with section E.)

B. Before coming to laboratory

Read the *Introduction to the Digital Multimeter* on page 36.

In your lab notebook, solve the preliminary problem presented on page 39 of this manual.

C. Circuit elements

C1. Power source

Technical term: "seat of emf" (electromotive force), "emf device"

Examples: battery, power supply

Circuit symbols:

Algebraic symbols: $\mathcal{E}, V$

Important property: Potential difference between terminals.

Unit: volt (V)

C2. Wires

Technical term: Conductor

Circuit symbol:

Important property: Electrically charged particles can move through conductors; an ideal wire has the same potential everywhere.

C3. Current

Circuit symbol:

Algebraic symbol: i, I

Unit: ampere (A)

Important property: 1 Ampere flowing through a wire corresponds to 6.25×10^{18} electrons/sec (i.e., 1 coulomb/second) crossing any plane through the wire. Current can be measured by an ammeter.
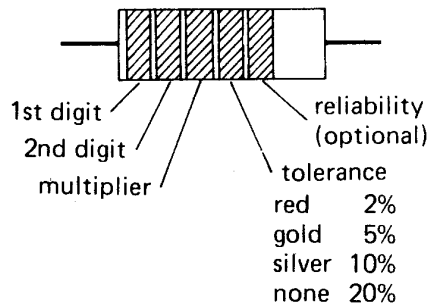
C4. Resistor

Circuit symbol: ─\/\/\/─

Algebraic symbol: R, r

Unit: ohm, symbol: Ω

Important property: For a given power source, resistance determines how large the current is.

Examples: Actual resistors take many different physical forms, which you will meet in laboratory. Often they are little brown cylinders with a wire attached to each end, with colored stripes that denote the numerical value of the resistance according to the following code[1]:

digit	color	multiplier	number of zeros
	silver	0.01	−2
	gold	0.1	−1
0	black	1	0
1	brown	10	1
2	red	100	2
3	orange	1k	3
4	yellow	10k	4
5	green	100k	5
6	blue	1 M	6
7	violet	10 M	7
8	gray		
9	white		

1st digit
2nd digit
multiplier
reliability (optional)
tolerance
red   2%
gold   5%
silver 10%
none   20%

example: red-yellow-orange-gold is a 2, 4, and 3 zeros, or 24k 5%, resistor

Figure 1

(Start reading the code from the band of color closest to the cylinder edge.)

Current flows through a resistor because there is a potential difference ("voltage drop") across the resistor. If you are ever tempted to say "current across a resistor" or "voltage through a resistor" then stop yourself – you're not just making a vocabulary error, you're using an incorrect picture of what goes on in a resistor.

---

[1]Figure from *The Art of Electronics* by P. Horowitz and W. Hill, Cambridge University Press, 1989, p. 1053.

C5. <u>Complete circuit and definition of resistance of resistor</u>

Given the elements introduced above, we may draw a "schematic diagram" of a sample circuit as follows:
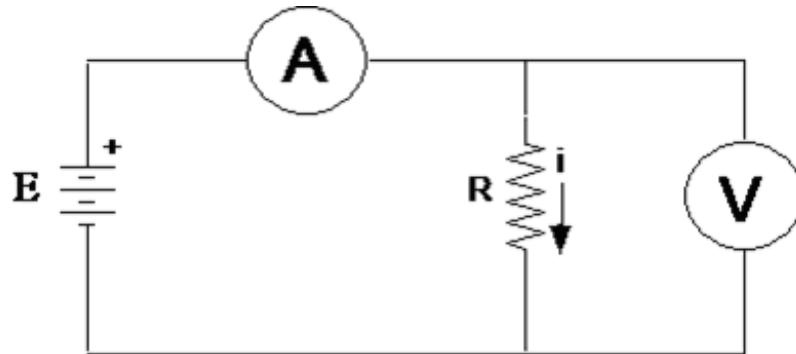

Figure 2

In this circuit, the symbol —(A)— represents a current meter (ammeter), which indicates the magnitude of the current flowing through it. ("A" stands for ampere, the unit of current. An "ideal" ammeter would have no resistance, but all real ammeters have some small resistance and therefore slightly affect the amount of current flowing.)

The symbol —(V)— represents a voltmeter, which indicates the potential difference between its endpoints. ("V" stands for volt, the unit of potential difference. An "ideal" voltmeter would have infinite resistance and therefore no current would pass through it. Real voltmeters have a large but finite resistance and therefore do pass some small amount of current.)

In the circuit of Figure 2, if we know ahead of time that the power source can maintain a particular potential difference $\mathcal{E}$ (it may be a 1.5-Volt battery) and if we read a current i through an ideal ammeter, then by definition the resistance of the resistor is

$$R = \frac{\mathcal{E}}{i}.$$

For many devices, including lightbulbs, this ratio R varies with the current. But for others the ratio is independent of current: in these cases a plot of voltage drop as a function of current is a straight line. Such devices are called "Ohmic" and said to obey "Ohm's Law" (despite the fact that this is not really a law, since it applies to some devices but not others).

D. Apparatus

D1. Digital multimeters (DMM)

This laboratory uses digital multimeters, which employ transistors or integrated circuits to measure voltage or current and display them as numbers on a screen instead of through a moving pointer. (These meters are easier to read and more rugged than the older, mechanical meters based on the d'Arsonval movement.) They are called "multimeters" because they execute for multiple jobs: they measure current, voltage, resistance, or other quantities.

Take care: these meters are rugged but not bombproof. Look over the *Introduction to the Digital Multimeter* on page 36. Be sure to understand the procedures given there before hooking up circuits in this lab.

Set your DMM to read the property you desire (e.g., current or voltage) *before* inserting it into the circuit. Measure resistance for a component when it is disconnected from a circuit. (If the component were in a circuit, you would not know whether you are measuring its resistance or that of other components within the circuit.)

D2. Power supply

These experiments use a low-voltage DC power supply that converts the 110 V AC line power to DC, with output voltage adjustable up to a maximum of 30 volts and maximum output current of about 1 ampere. The power supply will not deliver more than a certain, adjustable amount of current, called the "preset maximum current". This current-limiting feature prevents damage to parts of the circuit which are incorrectly wired.

The power supply has three output jacks, labeled −, GND, and +:
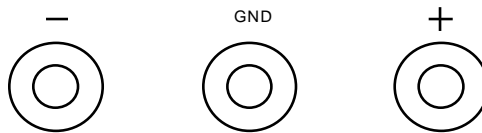

Figure 3

The power supply maintains a set potential difference between the + and − posts, independent of the current through the supply, provided that the current is less than the "preset maximum current". The + post is held at a higher potential than the − post, but it might not be at a positive potential relative to ground.

Remember that electrical potential at a point is always measured relative to some other point. Usually it is measured relative to "ground": the potential of a metal rod driven into the ground. Ground potential is also the potential of one of the three wires in an electrical socket with three holes in it. On these power supplies, the third (green) post is connected to the third prong on the power plug and hence is held at "ground" potential (i.e., the same potential as the building plumbing, steel framework, etc., and the human beings that touch the plumbing, etc.). This

terminal may be connected to any single point in a circuit to prevent a shock hazard which might occur if some of the circuit components were at an elevated voltage with respect to ground. (*Careful! As you will learn on page 46, most electronic instruments – oscilloscopes, function generators, for example – also have one of their terminals connected to ground through the third prong on their power plug. All of these grounds must be connected together in a circuit.*) A small, removable metal bracket is provided to connect the GND terminal to either the + or – terminal, which is often a convenient thing to do. In these experiments, the ground terminal will be connected to the negative terminal.

Typically the power supply generates the voltage difference set by the voltage control knob, and produces as much current as the circuit demands for that set voltage. When working in this fashion, the indicator glows green. But when the circuit demands more current than the "preset maximum current", then the power supply limits the voltage generated so that the current is the "preset" value. When this happens the indicator glows red.

The upper meter on the power supply reads the potential difference between the + and – posts, and the lower meter reads the current being delivered. (If the CURRENT range switch is in the HI position, read the upper scale on the current meter; if in the LO position, read the lower scale.) Digital multimeters read currents and voltages more precisely than these two analog meters permit.

D3. Decade resistance box

A decade resistance box is a metal box with at least two binding post terminals and several knobs. The box contains an assortment of precision resistors, various combinations of which can be connected to the posts by turning the knobs. The total resistance between the terminals is equal to the sum of the readings of the knobs – this resistance is accurate to the nearest ohm.

D4. Other resistors

Several individual resistors mounted on double banana plugs are provided. Refer to the color-code table in Figure 1 to determine their alleged resistances. In contrast to the precise values set on resistance boxes, the resistance values of these fixed resistors may differ from their nominal value by 10% or more. Most (commercial) circuits are designed so that these differences are not significant.

D5. General advice on wiring

It will be much easier for you (and your instructor) to inspect your wiring if it "looks" like the circuit diagram. Physically lay out your circuit so that it matches the circuit diagram. To the extent possible, use red wires for positive potential, black wires for zero potential (ground), and brown or yellow wires for intermediate potentials. A messy circuit behaves the same as a neat circuit – but wiring errors are far easier to find in neat circuits!

As you add components to a circuit, it tends to grow more and more complicated – like tangled strands of spaghetti. Use junction blocks to simplify your wiring.

E. Ohm's law

E0. Setup of power supply

Before doing any experiment, set the "preset maximum current" of you power supply to 50 mA. Before turning on the power, flip the current range switch to LO, turn the current control knob as far as it will go counterclockwise, and the voltage control knob all the way clockwise. Then plug one end of a wire into the + output binding post, and the other end of that same wire into the GND output binding post. Finally, turn the power on and slowly turn up the current until the current meter reads 0.05 A on the bottom scale. You have just set the "preset maximum current" to 0.050 A = 50 mA. Turn the voltage control knob all the way back down (counterclockwise). **Leave the current control knob where you have set it** until you change the "preset maximum current" in section G2. Remove the external wire. Turn the power supply off when you are not using it.

Throughout this laboratory session, begin your measurements on a new circuit with the power supply voltage set to zero (full counterclockwise).

E1. Varying voltage with fixed resistance

For many circuit elements the magnitude of the electric current through the device is proportional to the magnitude of the electric potential difference it. When this is the case we say that the device follows Ohm's Law.

Wire up the circuit shown in Figure 4. Sketch this schematic diagram into your notebook as well. Use the multimeter to measure the potential difference (voltage) across a resistance box adjusted to 2000 ohms. (Set the meter to read DC volts.) Use another multimeter to measure the current through the box. (The highest current you expect to measure is 30 volts/2000 ohms or 15 mA. Therefore set the current meter to the 20-mA scale. If the measured quantity exceeds the scale you choose, the meter will read "1 ." . That is, it will show the digit 1 followed by a several blank spaces and then a period.)
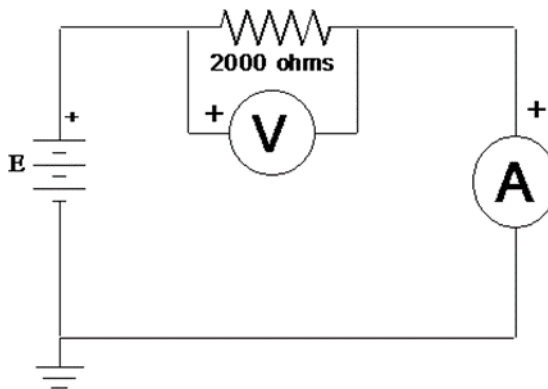

Figure 4

Vary the voltage from the power supply over the entire range from 0 to 30 volts. For at least six values of the voltage across the resistor, read and record the voltage

29

V_R and corresponding current i. Calculate V_R/i. Plot a graph with voltage on the horizontal axis, current on the vertical. Remember that the origin is a data point.

Does your graph show the linear relation expected for a system that obeys Ohm's Law? Draw a best-fitting straight line and from the slope calculate the resistance to which it corresponds. Is it close to 2000 ohms? (If not, something's wrong!)

Tips for graphing in Microsoft Excel: (1) Select the two columns of data to be graphed. (2) Click on "Insert" then "Scatter Chart". (3) Format the graph: at a minimum you will want to label the graphs axes, each with units! (4) To fit to a line, click on "Layout" then "Trendline" and check "Display Equation on chart". (5) That displayed equation will often show too few significant digits. Right-click on the displayed equation, select "Format Trendline Label …" then click on "Number". Now the equation will probably show too many significant digits! You will have to think, and the computer can't do that for you. (Thankfully.)

E2. Varying the resistance with fixed voltage

Now adjust the power supply output so the voltage across the resistor is about 30 volts. Increase the resistance of the decade box in six steps up to about 20,000 ohms. Does the current behave as expected?

F. Resistors in series and parallel

F1. Resistors in series

Connect a second decade box in series with the first one, as shown below. Set the boxes to 2000 and 4000 ohms, respectively.
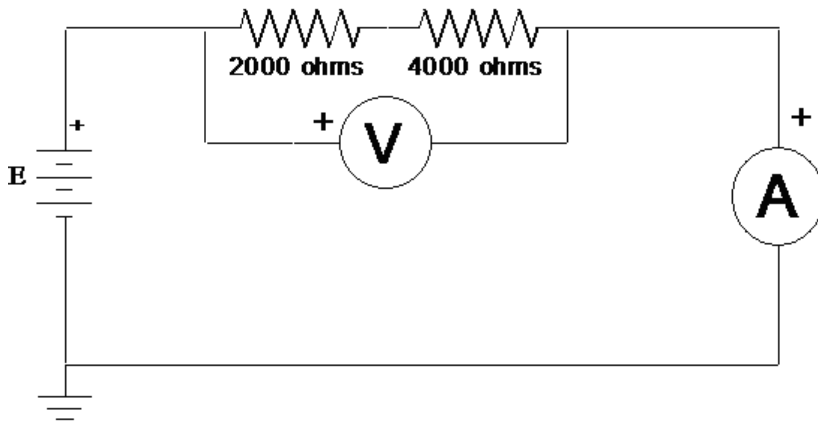

Figure 5

Apply four different voltages across the series combination, measure the current through it for each, and thereby determine the resistance of the combination. Does it agree with what you expect in all cases?

For the last voltage you use, predict the voltage across each resistor individually, using Ohm's Law, and check by measuring them.

You have just seen how two resistors can be used as a <u>voltage</u> <u>divider</u>. You connect them in series with each other, then you connect the series combination across the potential difference which you wish to divide into several smaller potential differences. Voltage dividers are used widely in electronic circuits.

F2. <u>Resistors in parallel</u>

Connect up the <u>parallel</u> combination of resistors shown in Figure 6. Apply four different voltages across the parallel combination, measure the current for each voltage, calculate the effective resistance for the two resistors in parallel for each, and compare with what you expect on the basis of the formula for parallel resistance.

For the last voltage you use, predict the current that should be flowing through each individual resistor and check your predictions.
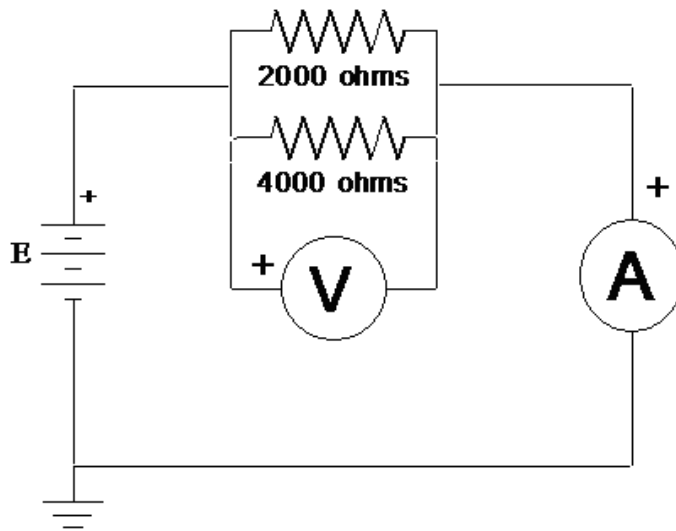

Figure 6

F3. <u>A more complex circuit</u>

Wire the circuit in the figure 7 using the following values:
  R_1 decade resistance box at 400 ohms
  R_2 decade resistance box at 700 ohms
  R_3 decade resistance box at 470 ohms
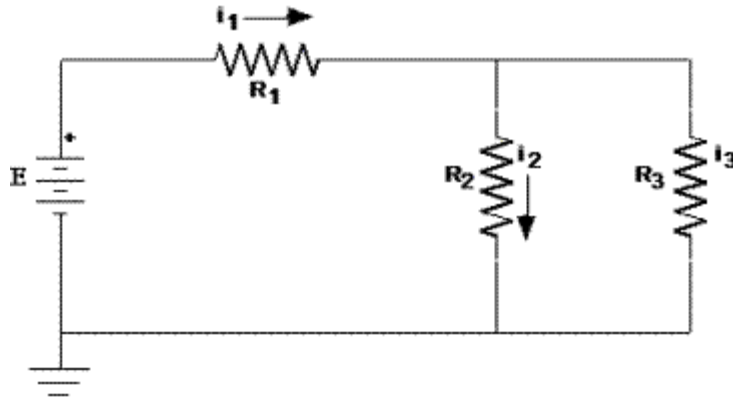 $\mathcal{E}$ power supply set at 10 volts

Figure 7

Set $\mathcal{E} = 10$ V using a digital voltmeter. Insert your ammeter to measure first the current i_1, then i_2, then i_3. Compare your measurements with the predictions on page 39. Explain any significant discrepancies (say, of more than 5%).

G. Measurement of I *vs.* V characteristics of several elements

G1. General procedure

This is the outline of a general procedure to be applied to a study the electrical characteristics of several different devices (or circuit elements) in steps G2, G3, and G4 below. You will put the device of interest, called the "device under test" or DUT into the circuit of Figure 8. Your goal is to simultaneously measure the voltage across and the current through the DUT, determining its so-called I-V characteristics. Use one multimeter to measure voltage and another to measure current. The resistor R protects the DUT by limiting the current that can flow through it. You will measure the current through the element as a function of the voltage across it.
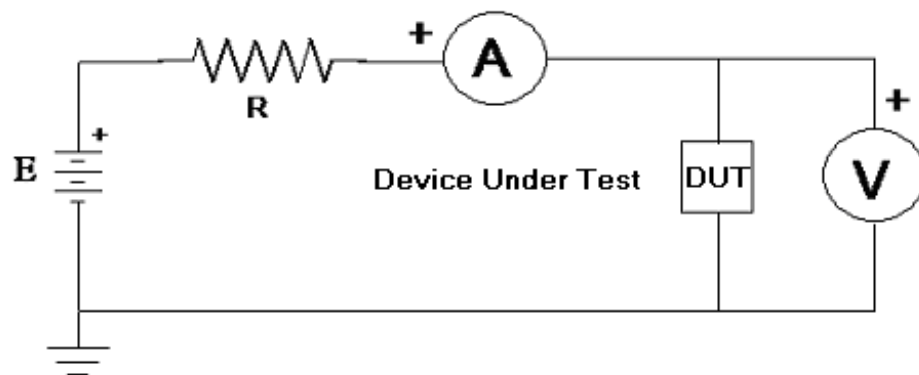

Figure 8

For each element below, start with the applied voltage at a minimum, apply several (say, ten) different voltages to the circuit, and thereby gather data to make a graph of current through the element as a function of voltage across it.

32

G2. Tungsten filament (flashlight bulb)

Using procedure E0 on page 29, reset your power supply for a "preset maximum current" of 300 mA.

Apply procedure G1 to the flashlight bulb (see Figure 9). For the protective resistor, use a total of about 150 ohms. (You have fixed resistors of this size, mounted on a double banana plug, that are capable of dissipating five or ten watts. Do not use your blue-and-white resistance box. It cannot dissipate this much heat!) Do not exceed 6.0 volts across the light bulb.
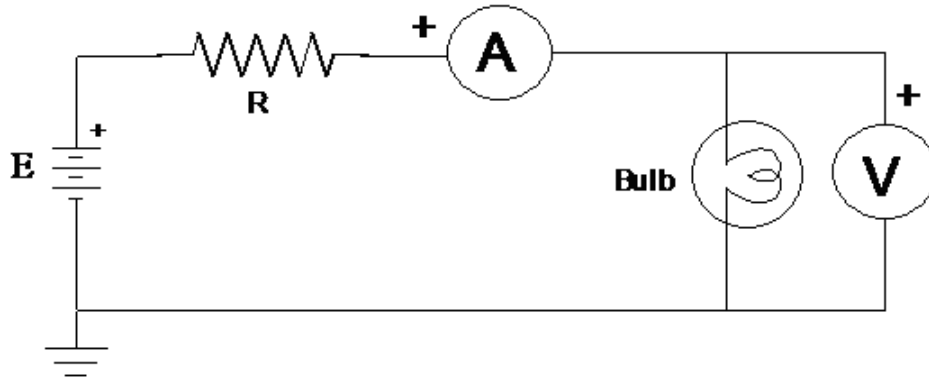
Figure 9

Plot the current through the bulb *vs.* voltage across the bulb (voltage on the horizontal axis), using either a lab computer or graph paper. In either case, tape the graph into your notebook. Does the filament obey Ohm's law? Does the filament have a "resistance"? Speculate on why the filament behaves differently from the resistor you studied earlier.

Does it make any difference which direction the charge flows through the filament? Reverse the connections to the bulb for one value of applied voltage and see how the current changes.

G3. Diode – forward current

You have a small black cylindrical diode mounted on a double banana plug. Unplug the flashlight bulb and insert the diode in its place. (One end of the diode has a grey-silver band. This band should be connected to the negative side of the power supply.) Change the protective resistor to 100 ohms.

Applying the above procedure, determine the current *vs.* voltage response of the diode. Most of the variation in current will occur at low voltages – around 0.6 to 0.8 volts. Take at least ten measurements in this region, and a few at lower voltages.

Plot the current *vs.* voltage (voltage on the horizontal axis) and print.

G4. <u>Diode – reverse current</u>

Does it make any difference which direction the charge flows through the diode?

Reinstall the diode with its leads reversed and measure the current when the voltage is applied to it in the opposite direction. In particular measure the current when 30 volts is applied to the diode. (The current may be in the microampere range so you may have to adjust the scale on the ammeter.)

With this circuit operating and 30 volts applied, unplug the DMM that measures the voltage across the diode. Does the current change? What is going on?

G5. <u>A forward-biased diode (optional)</u>

(This section presents a theoretical calculation. There is no experiment to do.)

Suppose the diode is used in the circuit shown in Figure 10. The "power supply" puts out a voltage $V(t)$ that varies sinusoidally with time, so its output voltage is $V(t) = V_m \sin(\omega t)$. (Don't worry about the meaning of ω at this stage. It just determines how many oscillations there are per second.) Let V_m be 6.0 volts and R be 50 ohms.
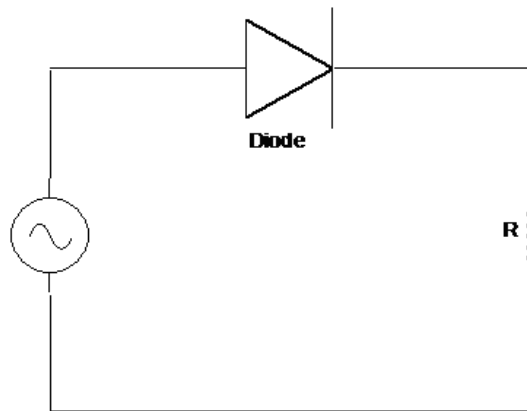

Figure 10

Let's idealize the diode so that its I vs. V curve looks like that in Figure 11.
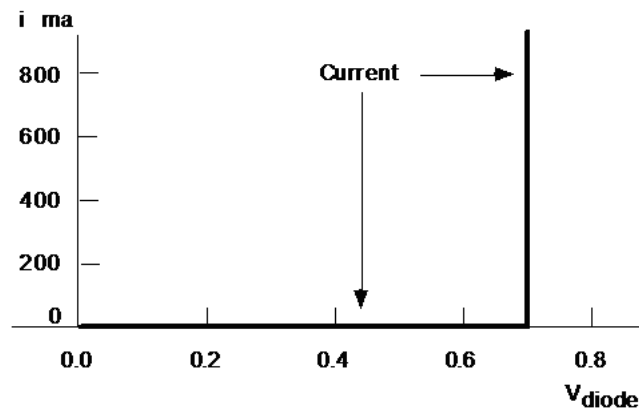

Figure 11

34

Consider two cycles of the input sine wave. Predict how you expect the voltage $V_R(t)$ to depend on time. Sketch on one graph the values of both $V(t)$ and $V_R(t)$ as function of time t. Explain what is going on.

Digital Multimeter Primer

Description of the Multimeter

Many of the electrical measurements in this lab are accomplished using a digital multimeter (DMM). A DMM can measure current, voltage, or resistance. It can test diodes and check an un-powered circuit for continuity.

We use several models of DMMs in the lab, each with slightly different characteristics but with many common features. Each has a **function switch** that lets you choose the kind of measurement to be made (voltage, current, resistance, etc.). The function switch normally has more than one setting for current measurements – depending on the amount of current to be measured. DMMs have an **AC/DC switch** that is used to select alternating (AC) or direct (DC) current or voltage measurements. DMMs also have a **range switch** to determine the meter's sensitivity (e.g., when the readout is 87.3, does that mean 87.3 V or 87.3 mV?). Some DMMs have "auto-ranging" – meaning that the meter will automatically adjust its sensitivity to give the best reading. Usually there is a way for the user to select the range manually, if desired.

<u>Connections</u>. All electrical measurements require two wires – conventionally a red and a black lead (for positive and negative). The DMM usually has three (or four) banana sockets (also called jacks) to choose from in connecting these two leads. One lead (usually black) is <u>always</u> connected to the **common** socket. Which of the two (or three) remaining sockets is used for the second (usually red) wire depends on the kind of measurement to be made. For voltage measurements use the socket labeled "V". For resistance (or continuity) measurements use the socket labeled "Ω". (This is often the same socket that is labeled V.)

Current measurements are more complicated – different sockets are used depending on the magnitude of current to be measured. Usually one socket is used for low currents (say, up to 200 mA) and another is to be used for currents up to 10 A. Sometimes this second socket is also used for very low current measurements (200 μA) but requires that you change the function switch setting.

Voltage Measurements (Figure 1)

1. Set the function switch to V.
2. Connect the red test lead to the V jack and the black lead to the COM jack.
3. The meter is automatically set to DC. To measure AC voltages, press the AC/DC button and "AC" will appear on the display.
4. Connect the test leads to the two points whose potential difference you would like to measure, with the black lead at or near ground potential, if possible.
5. The meter automatically selects the appropriate range, then displays the value of the voltage.
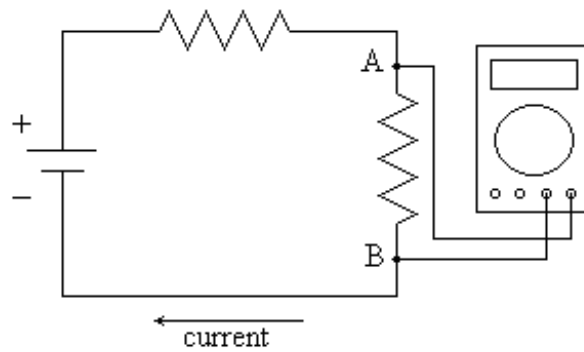
Figure 1. Measuring the potential difference between points A and B

Current Measurements (Figure 2)

To measure current, the meter must be connected in series with the load. When functioning as an ammeter, the multimeter presents a very low resistance. *Incorrectly connecting it in parallel may result in large currents and damage the meter and other parts of the circuit.*

1. Set the function switch to the desired current range. If this is unknown, start with the highest range. Setting the range too low can damage the meter.
2. For current measurements less than 200 mA, connect the red test lead to the mA jack and the black test lead to the COM jack. Otherwise connect the red lead to the 10 A jack.
3. Press the AC/DC button if an AC current is to be measured.
4. Turn off the power to the circuit to be tested. Open the circuit and connect the meter in series by means of the test leads.
5. Turn on the power and read the value of the current from the display. A single "1" on the display indicates the range is set too low.
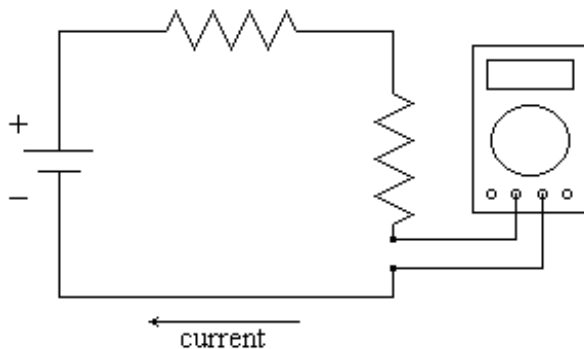

Figure 2. Measuring the current flowing in the circuit

Resistance Measurements

For resistance measurements, it is necessary to remove power from the element to be tested. *(The DMM supplies a tiny amount of current to the circuit, measures V and I, then takes the ratio to calculate R – it will be very confused if some other power source supplies additional current – it might even damage the DMM.)*

1. Set the function switch to the Ω position.
2. Connect the red test lead to the Ω jack and the black test lead to the COM jack.
3. Disconnect from all circuitry the resistance to be measured and connect a test lead to each end.
4. The meter automatically selects the appropriate range and the resistance value is displayed.

Important Caveats

A DMM is easy to use and also easy to abuse. It is easy to make mistakes that could damage the DMM. For its own protection the DMM has a small **fuse** that may be accessed through the battery compartment. If excessive current flows into the DMM the fuse will blow. A blown fuse does not affect voltage measurements, but it does make it impossible to measure current. If you measure zero current when you know there must be non-zero current, you should suspect a blown fuse.

The DMM can measure alternating current and voltage, but it is designed only to measure sinusoidal signals, and only those at frequencies less than 500 Hz. A DMM is perfect for measuring voltages or currents associated with 60 Hz AC power available at the wall socket.

Be aware of the limited accuracy of a DMM. Just because it presents many digits of readout doesn't mean they are all significant. The DMM's specification sheet will report its accuracy characteristics, which depend on the particular type of reading and on the scale used. But as a general rule, **the reading is accurate to about 0.5% of the full scale measurement**. That means that if you are on the 200 mV scale, the accuracy is ± 1 mV. So if you measure 4.0 mV on this scale, your measurement is uncertain by ± 25%! Don't be fooled by lots of digits – digits are cheap, calibration is expensive.
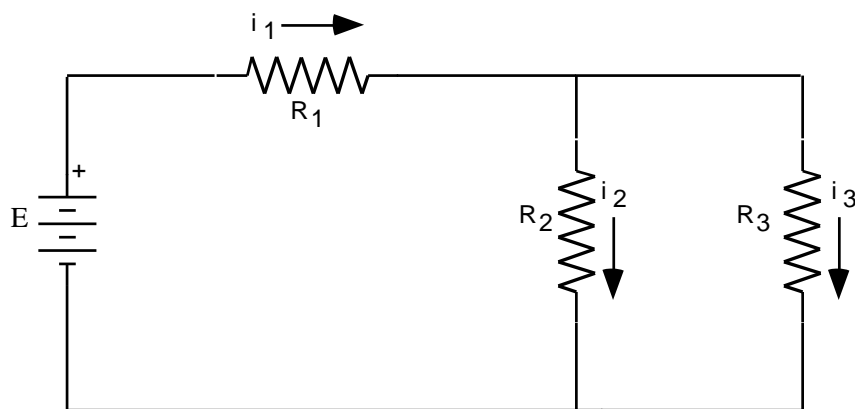
Direct Current Circuit Preliminary Problem

(Please solve this problem in your lab notebook and bring it to the DC circuits I laboratory session.) Three resistors and an emf device (all ideal) are connected as shown:

a. Show that

$$i_1 = \mathcal{E}\frac{R_2 + R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

$$i_2 = \mathcal{E}\frac{R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

$$i_3 = \mathcal{E}\frac{R_2}{R_1 R_2 + R_1 R_3 + R_2 R_3}$$

b. Are these equations dimensionally correct?

c. Do they display the proper symmetry between subscripts 2 and 3?

d. Does it make sense that $i_1 = i_2 + i_3$?

e. The current leaving the top of the battery and passing through R_1 is i_1. What is the current entering the bottom of the battery?

f. If the battery emf $\mathcal{E}$ is tripled, what happens to each of the currents i_1, i_2, and i_3?

g. If every resistance value is doubled, what happens to each of the currents?

h. If $R_3 = 0$, what is i_2?

i. If R_3 is much greater than R_2, what is i_3? Is this what you expect?

j. Does current always take "the path of least resistance"?

Experiment 5: Direct Current Circuits – II

Here we pick up where we left off in the DC Circuits lab.

H.   Capacitors

H1.<u>Charging a Capacitor</u>

Another device used in electrical circuits is a **capacitor**. It stores electric charge and energy. It consists of two conductors (called electrodes) close together. The capacitor in this experiment is contained in a cylinder with two wire leads. If you were to cut it open, you would find inside two long strips of metal foil, separated by a thin layer of insulating material (called a dielectric), tightly rolled up to fit into the cylinder. Each metal strip is connected to a wire. Since the two strips are insulated from each other, charge cannot flow from one to the other as it does in a wire or resistor. However charge can flow into one wire and stop on its electrode, which then repels charge from the other electrode so that the same amount of charge leaves that electrode and departs through the other wire. The net effect is to leave a certain charge on the first electrode and the opposite charge on the second one. To an outside observer, it is just as if charge flows through the capacitor!

Set up the circuit in Figure 12. Let R be 1 megaohm. The switch is like a telegraph key: when you press down on the key, it changes the connection. Use your DMM to determine which jacks are connected when the key is up (not pressed) or down. The switch should be inserted so that when the key is up the voltmeter connects to the capacitor, while pressing the switch down connects the resistor to the capacitor. (In the diagram the jack on the switch connected to the voltmeter is labeled "NC" to indicate "normally connected.") Connect the side of the capacitor labeled GND to ground.

<u>Procedure:</u>

1. Connect a wire temporarily from A to B. Turn on the power supply and adjust the output voltage until a current of 10.0 µA flows. Set this current as accurately as you can.

   Remove the wire from A to B.

   The experiment starts in step 2 below; this paragraph overviews the procedure. You will let a current of 10.0 µA flow into the capacitor for 30 seconds. (The current will tend to fall during this period, and you will have to adjust the FINE voltage control to maintain this current during the measurement period.) Then you will measure and record the voltage across the capacitor (quickly) and again let current flow onto the capacitor for another 30 seconds. You will carry out this charging/measuring process five times, for a total of 150 seconds. You will make sure that the current remains steady at 10.0 µA. Do <u>not</u> discharge the capacitor between these chargings.
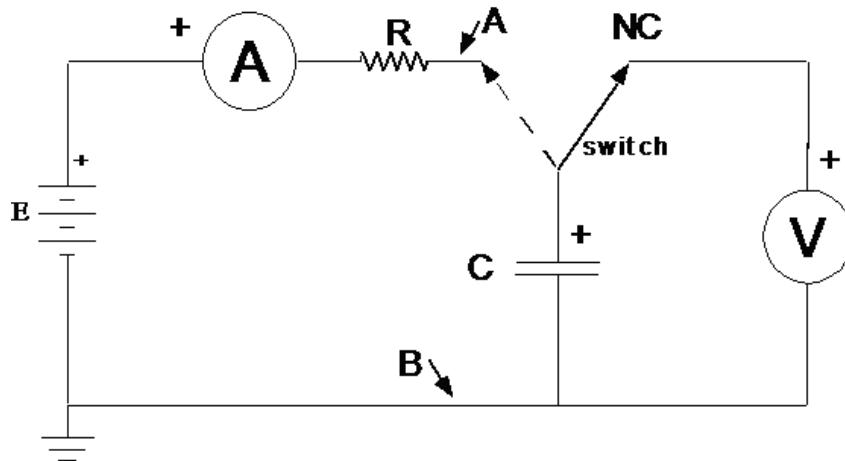
Figure 12

2. Connect a wire across the capacitor for several seconds to completely discharge it. You are ready to begin a series of capacitor chargings and voltage measurements.

3. Follow the procedure above to charge the capacitor for five 30-second intervals, measuring the voltage across it at the end of each period. Use the key switch to charge (press down) and measure (key up). Use a stop watch to measure the 30-second intervals. Keep the voltage-measurement periods as short as possible; otherwise the capacitor will discharge significantly. Remember to keep the current steady!

   If you have to restart your set of charging measurements, begin with step 2.

4. Make a graph of charge stored on the capacitor *vs.* voltage across the capacitor. [In order to plot your data, you will need to calculate how many microcoulombs (μC) of charge are stored by the capacitor during each 30-second charging period. Recall that a current of one ampere represents one coulomb of charge flowing in a one-second period.]

5. What is the relation between the charge stored by the capacitor, Q, and the voltage across it, V? Draw a best-fit straight line that passes through the origin. The observed fact that the ratio Q/V is independent of the magnitude of Q suggests that the ratio be given a name. It is called capacitance:

$$C = \frac{Q}{V}.$$

[The unit of capacitance is called the farad, after the 19th-century British scientist Michael Faraday. If two electrodes have a capacitance of 1 farad, then there will be a potential difference between them of 1 volt (named after the Italian scientist Volta) when they have equal and opposite charges on them of 1 coulomb (named after the French scientist Coulomb). This definition is analogous to the definition of resistance. If the ratio V/I for a conductor is independent of I, then it is useful to define that ratio as the resistance.]

Determine the capacitance from the slope of the line on your graph.

H2. Discharging a Capacitor

1. Connect the circuit in Figure 13. R represents a 68,000 ohm resistor. Set the power supply to about 19 volts, using its own voltmeter. (Do <u>not</u> exceed 25 volts, the rating of the capacitor.)

   You are going to charge the capacitor and then observe its discharge through R, measuring and recording the voltage across it as a function of time.

2. With the power supply at about 19 volts and the key on the switch up, the capacitor is charged to about 19 volts. If you press the key, the charge on the capacitor will gradually leave by means of current through R.

   Press the key and see how the voltage across the capacitor decreases.

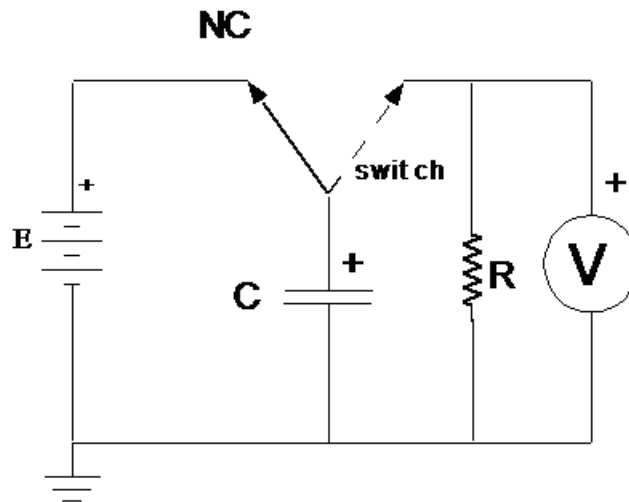   Now it's time to do this quantitatively.

Figure 13

3. Charge the capacitor to 19 volts (key up). Press the key and hold it down. Take your first voltage reading as you start the stop watch.

4. Holding the key down, record the value of the voltage at 10-second intervals (keep the stopwatch running) for a period of 140 seconds. This will require close coordination with your partner.

5. Theory finds, through solving a differential equation, that the voltage across a capacitor C discharging through a resistor R is given by
$$V(t) = V_0 e^{-t/RC},$$
where V_0 is the initial voltage across the capacitor (i.e., the voltage at time $t = 0$). To test this prediction, divide both sides by V_0 (to make both sides dimensionless) then take the natural logarithm of each side to find
$$\ln[V(t)/V_0] = \left[-\frac{1}{RC}\right] t.$$

(You can take the logarithm of only dimensionless quantities, and the logarithm of a dimensionless quantity is of course dimensionless.)

Plot your data with time on the horizontal axis. You can use a linear scale of $\ln[V]$ versus t or you can use a logarithmic scale of V versus t. (If you choose the latter, be aware of the conversion from natural log to base-10 log in calculating the slope.) You should find a straight line. Determine the slope of this line, which should be $-1/RC$. Its units will be s^{-1}.

Measure R with a DMM and find the value of C from this slope. Does it agree with the value you found from your measurements during the charging process?

6. Explain (in writing) what is going on. Why does the voltage drop more and more slowly as time goes on? Don't say, "the differential equation solution tells me so", but describe physically what is happening.

J.   An Unknown Source of emf

A small box labeled UNKNOWN is alleged to contain a source of emf in series with a resistor. You are to design and perform a series of experiments that will determine if the unit acts as alleged, and, if it does, to find the values of emf $\mathcal{E}$ and resistor r.

You may wish to connect a circuit like that shown in Figure 14. R is a decade box. The ammeter and voltmeter are DMMs. Or, you may wish to place the voltmeter and ammeter at other places in the circuit.

The point is, you need to find out whether the UNKNOWN behaves as alleged (that is, like a source of emf with a resistance in series). Graphing an appropriate voltage against an appropriate current may help.
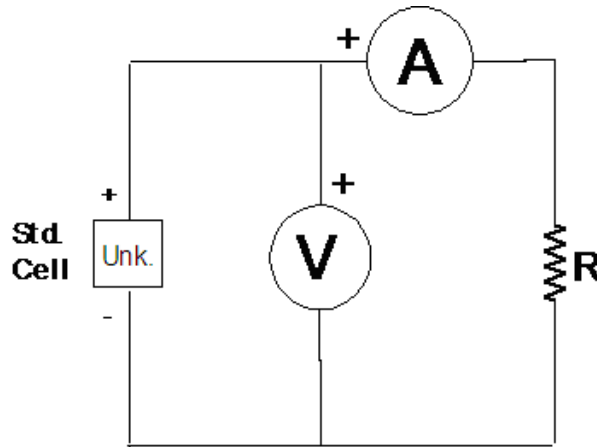

Figure 14

Experiment 6: Using an Oscilloscope

What is an Oscilloscope?

The oscilloscope (or "scope") is a useful and versatile tool. It is used not only by physicists and electrical engineers, but also by chemists, physicians, psychologists, and others. It is to your advantage to learn how to use this important instrument *now*, because you will be using it throughout the rest of this course and, probably, throughout your scientific career.

Fundamentally, an oscilloscope is a voltmeter that displays a graph of voltage against time on a screen.

Today's lab is an exploration, not a race. Play, experiment, and learn how to use this important tool.

Tektronix TBS 1072B-EDU Controls

A high quality digital storage oscilloscope like your Tektronix TBS 1072B-EDU has a number of special features that adapt it to a variety of applications (including video screen repair). Hence the control panel is cluttered with a variety of knobs and push buttons, while the screen is covered with numbers, markers, and icons. Don't panic! Most of the time you will need to adjust only two knobs, the yellow "Vertical Scale" knob and the "Horizontal Scale" knob.

The default settings for the TBS 1072B-EDU are not the best for the experiments we will perform in this course, so you should start off by pressing

> Default Setup
> 1 (yellow) / Probe 10X Voltage / Attenuation 10X / Multipurpose
> 2 (blue)   / Probe 10X Voltage / Attenuation 10X / Multipurpose
> Utility / -more- / Options / Printer Setup / Ink Saver

If your scope misbehaves, carry out this process again.

The Oscilloscope as a Clock

The horizontal axis of the oscilloscope screen measures time. Convince yourself of this by turning the "Horizontal Scale" knob counterclockwise until the middle box near the bottom of the display screen reads "M 1.00 s". The screen will display a yellow squiggle that grows by one horizontal division each second. When it disappears from the right side of the screen, it pops back up on the left. Turn the knob clockwise to speed up the line's growth.

The Oscilloscope as a DC Voltmeter

The vertical axis of the oscilloscope screen measures voltage. Convince yourself of this by connecting the yellow channel 1 inputs of the scope across a 1.5 V battery. (Move the yellow "Vertical Scale" knob counterclockwise if the line jumps off the screen, clockwise if the jump is imperceptibly small.) Measure the battery voltage with a conventional voltmeter to check the oscilloscope's voltage measurement quantitatively.

Vary the yellow "Vertical Scale" knob and observe what happens.

The zero-level of the voltage display is set through the yellow "Vertical Position" knob. Check its operation. The yellow marker on the left of the screen marks the zero-level, and it is ordinarily set to the vertical middle of the screen.

Disconnect the wire from one terminal of the battery to the black (ground) input of the oscilloscope. What happens to the signal on the screen? Describe and explain in your notebook.

The Oscilloscope as a Voltmeter for Time-Varying Signals

The power of an oscilloscope is manifest only when it is used to display time-varying voltages. Devices that produce time-varying voltages are called function generators, and you have one such device before you: a Wavetex 2 MHz Sweep/Function Generator.

This function generator has a lot of knobs and buttons as well. We will not use the sweep, symmetry, or amplitude modulation capabilities of this device. DC offset should be set to zero.

Set up the oscilloscope to display the "MAIN OUT" output voltage of your function generator. As explained in the next section, you must connect the black terminal of the function generator to the black terminal of the oscilloscope, and similarly for the red terminals. Reversing the connection will not harm the equipment, but it won't generate a signal either. (I recommend connecting black wires to the black terminals and red wires to the red terminals. This will help keep your thinking straight.)

Experiment with the FUNCTION toggle of the Wavetex generator, then with the amplitude and frequency controls. Set the output frequency knob to 1000 Hz and measure the period of the sine wave on the oscilloscope screen. Is it what you expect?

Disconnect the wire between the black (ground) terminal of the function generator and the black (ground) input jack of the oscilloscope. What happens to the signal on the screen? This behavior differs from the behavior when you disconnected the battery, for reasons described in the next section.

Grounding

For reasons of safety, one of the two input terminals on your oscilloscope, the black one, is grounded. This means that the black terminal is connected directly by a wire to the metal oscilloscope case and to the third prong of the electrical power plug. The third prong is attached through the building's electrical wiring to the building's plumbing and to a metal stake driven into the dirt (hence the name "ground"). The same applies to the black terminal on your function generator, and indeed to one of the two terminals of almost any electronic device that is plugged into a wall socket. This rather elaborate system helps prevent accidental electrocution. Our immediate concern, however, is not why the grounding system exists but rather its implications for electrical measurements.

Because of the grounding system, the black terminals of the scope and of the function generator are directly connected by wires through the third prong of their power plugs. Think about what this means for the following circuit:

circuit symbol
for ground
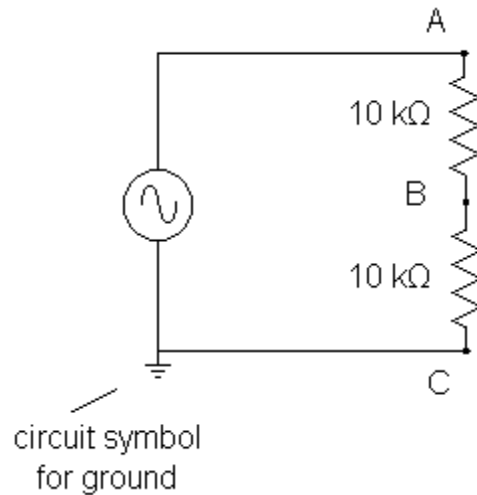
The voltage across both resistors (ΔV_{AC}) will be twice the voltage across either resistor (ΔV_{AB} or ΔV_{BC}). Set up this circuit and measure the voltages ΔV_{AC} and ΔV_{BC} as follows:
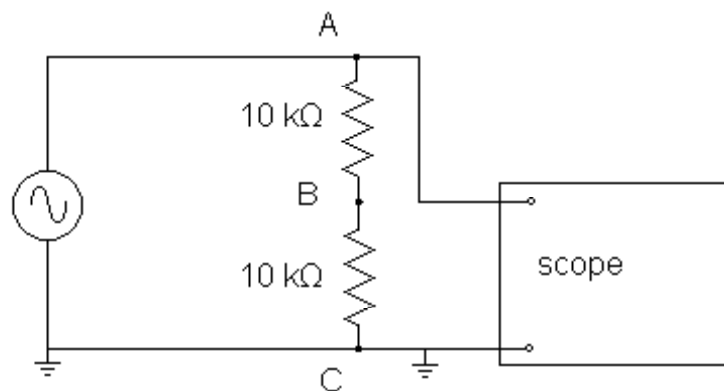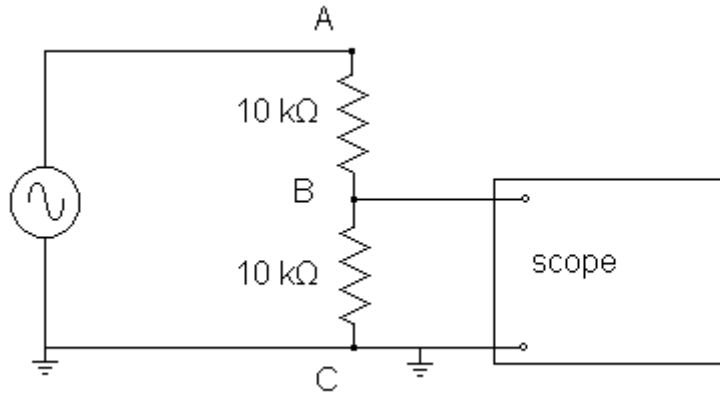
Verify that $\Delta V_{AC} = 2\,\Delta V_{BC}$. Now try to measure ΔV_{AB} with the circuit below:

bad circuit design
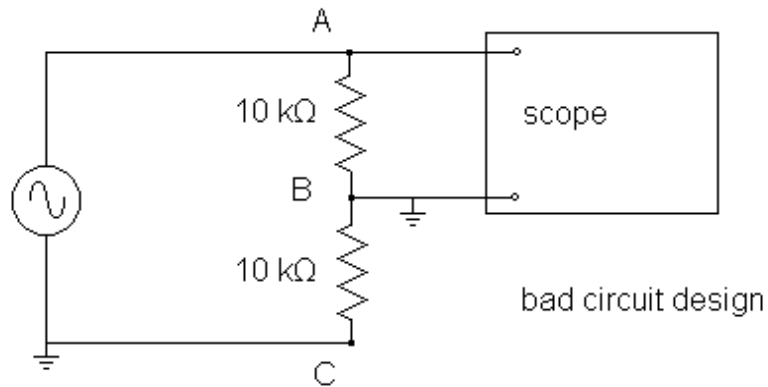
You will measure a voltage that is *not* equal to the previously measured ΔV_{BC}. This is because the function generator's grounded terminal is directly connected to the scope's grounded terminal via the third prong of the power plug. The true circuit diagram for the above situation is:

wire in third prong
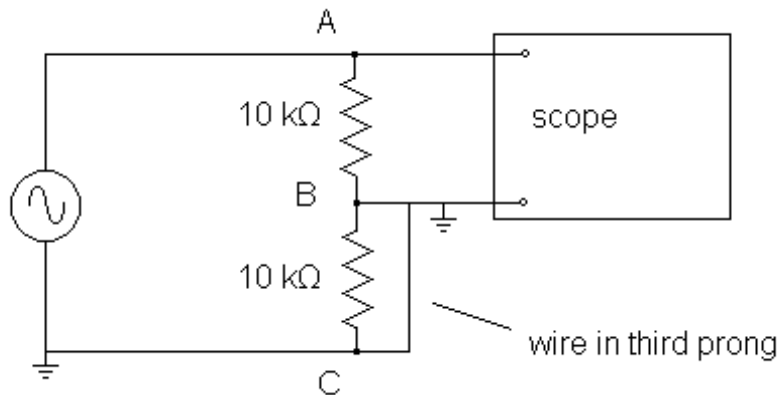
The bottom resistor is connected in parallel with a piece of wire that runs through the grounding system. Naturally more current flows through the low resistance wire than through the 10 kΩ resistor.

To summarize, in a proper circuit design the grounded terminals of the oscilloscope and function generator must be directly connected by wire, because they <u>are</u> connected by wire through the grounding system whether you want the connection or not!

It is extraordinarily easy to set up a circuit incorrectly due to grounding. To prevent this type of error, it is conventional to use black wire for every wire attached directly or indirectly to ground, and to use red, brown, or yellow wires otherwise. Using this convention, any black wire connected to a red wire is an error, so errors are easy to find.

It is merely a social convention, not a law of nature, that black wires represent ground. But it is a useful and sensible convention and I expect you to adhere to it. In the same way, it is "merely a convention" that we call wires "wire" rather than "Draht" (in Germany the convention is the other way around) but your lab partner and your instructor expect you to speak in English and to use black wires for ground. If you ask me for assistance with wiring, the first thing I will do is check to see that you're using the "black only for ground" convention. If you're not, I will provide no more assistance until you correct your wire colors. (I am not willing to provide assistance in German, either. Warum nicht?)

AC Signals and Transformer Output

Alternating currents (AC) and voltages are rapidly-changing sinusoidal functions of time characterized by three constants – the amplitude, the frequency, and the phase. Expressed as a mathematical function, the voltage is

$$V(t) = V_m \cos(2\pi f t + \phi) = V_m \cos(\omega t + \phi).$$

Here V_m is the amplitude of the voltage, f is the frequency and $\omega = 2\pi f$ the angular frequency, and ϕ is the phase relative to some other AC signal (namely, the one with phase angle equal to 0). In this experiment, phase is not important.

[Do not confuse f and ω. The frequency or "circular frequency" f is measured in cycles per second or Hertz. For example, the frequency of the voltage available at a wall outlet is 60 Hertz. The angular frequency ω is measured in radians per second, and is usually represented as it is here, by the Greek letter "omega". Both f and ω are measured in the same unit, namely s^{-1}, but it is conventional to call the units of f by the name "Hz" and the units of ω by the name "radians/second". A signal with five repetitions in one second has a frequency $f = 5$ cycles/second, a period $T = 1/f = 0.2$ second, and an angular frequency $\omega = 2\pi f = 31.4$ radians/second.]

An AC voltage signal is sketched below.
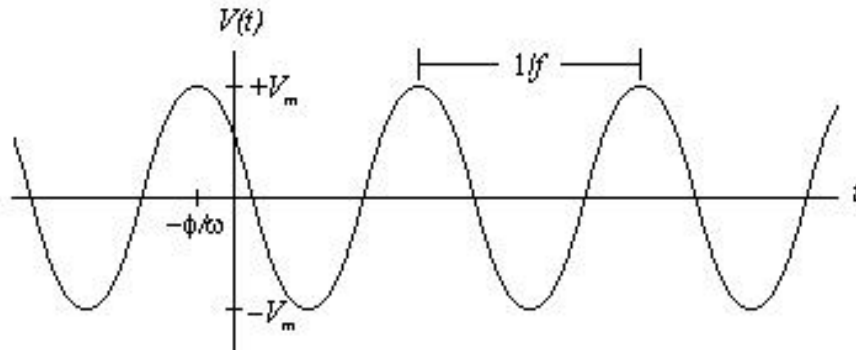
Parameters other than the simple amplitude are often used to indicate the size of an AC current or voltage. For example, the easiest AC voltage measurement to make on a scope is the "peak-to-peak" or "pp" voltage, which is the difference between the maximum and minimum voltages. (This should be called the "peak-to-valley voltage" or the "peak-to-trough voltage" but in fact it is called the "peak-to-peak voltage". Go figure.) The figure demonstrates that

$$V_{pp} = 2V_m.$$

A second parameter is the root mean square amplitude or V_{RMS}, which is in some sense an "average" voltage. The ordinary long-term time-averaged voltage, $\langle V(t) \rangle$, is of course zero, since the voltage is negative as often as positive. To get some sort of average that is not zero, it is customary to use instead

$$V_{\text{RMS}} = \sqrt{\langle V^2(t) \rangle},$$

where the quantity inside the square root is the time-average of $V^2(t)$. To relate V_{RMS} to the amplitude parameter V_m, we calculate

$$V_{\text{RMS}}^2 = \langle V^2(t) \rangle$$
$$= \frac{1}{T} \int_0^T V^2(t)dt$$
$$= \frac{1}{T} \int_0^T [V_m \cos(\omega t)]^2 dt = [V_m]^2 \frac{1}{T} \int_0^T [\cos(\omega t)]^2 dt = \frac{V_m^2}{2}.$$

Thus, $V_{\text{RMS}} = V_m/\sqrt{2}.$

RMS quantities are important because: (1) AC meters (including your digital multimeter) are typically calibrated to read RMS quantities. (2) For DC circuits, the power dissipated in a resistor is given by the formula $P = IV$. For AC circuits, the time-average power dissipated in a resistor is given by the parallel formula $\langle P \rangle = I_{\text{RMS}} V_{\text{RMS}}$.

It's easier to generate and distribute AC voltage than DC voltage, so the electricity available at wall sockets is always AC. The AC used for power distribution in the United States and

Canada has a frequency of 60 Hz and a nominal RMS voltage of 120 volts. This is merely a convention: Western Europe uses 50 Hz and 230 V, Mexico uses 60 Hz and 127 V.

Plug your 6.3-volt transformer into an electrical outlet and look at its output with the oscilloscope. In contrast to the function generator, neither output of the transformer is connected to ground. Measure the difference between the highest voltage and the lowest voltage: the "peak-to-peak voltage". Calculate the amplitude and the RMS voltage.

In addition, measure the output of your transformer with your digital multimeter (DMM). Make sure your DMM is set to measure AC voltages rather than DC. Does the DMM reading agree with one of the values (V_{pp} , V_m, V_{RMS}) you determined using the oscilloscope? Which voltage does the DMM measure?

Use the oscilloscope to determine the period of the observed signal. Set the time scale so that you may measure the time for several complete periods. From the period, calculate the frequency. Is it approximately equal to the value you expect? (Because the transformer has no on/off switch, you should unplug it when you're not actually taking measurements.)

Use your scope's built-in ability to measure amplitude and frequency to confirm these measurements.

Studying a Diode with a Dual Trace Oscilloscope

Think of a diode (crudely) as a valve that allows current to pass in only one direction. Connect the circuit shown in Figure 1. With the ground of the oscilloscope connected to point C, observe the voltage signals between A and C (generator output) and B and C (V_R). You may need to fiddle with the "Trigger Level" knob to get the oscilloscope signal to stand still. Move the oscilloscope ground connection to point B and observe the voltage signal between A and B (V_{diode}).
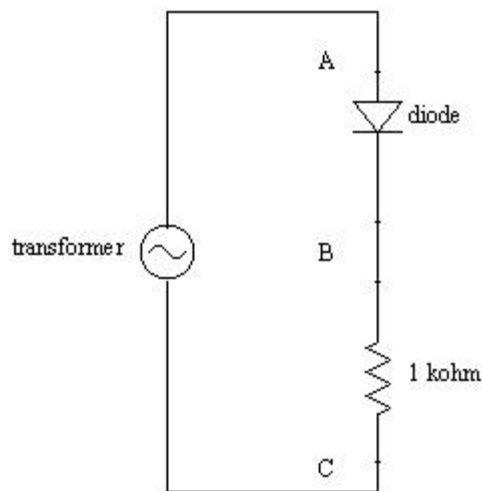
Figure 1

Your oscilloscope's dual trace feature enables you to observe the diode and resistor voltages simultaneously. Your first thought might be to connect the two channels of the scope as shown in Figure 2.
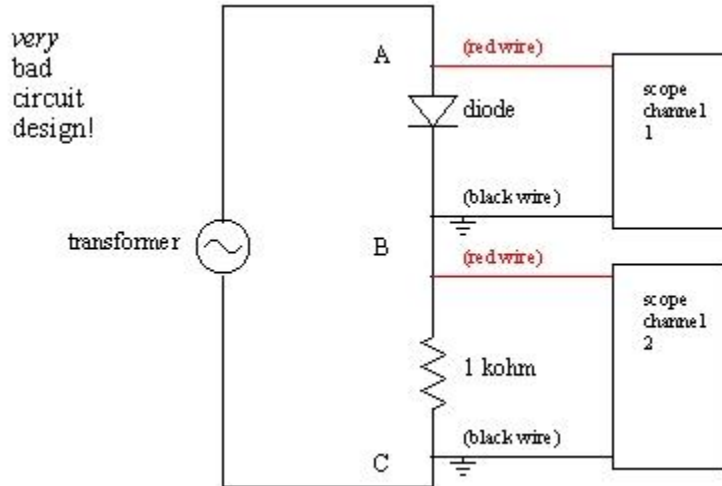
Figure 2

If you try this, you will destroy your diode! That's because the two black ground wires are electrically connected through the third prong of the grounding system (see Figure 3).
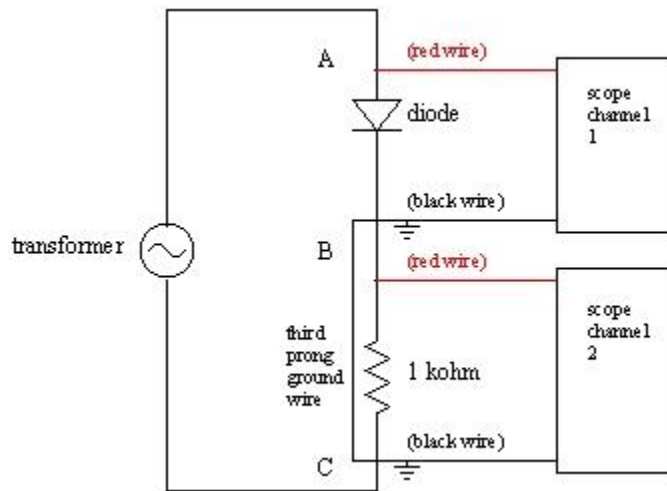
Figure 3

Instead, you must connect your oscilloscope as shown in Figure 4.   In this orientation the two grounds are, as they must be, connected to the same point in the circuit. Turn on channel two (blue). (Assure that both the yellow and blue signals have the same zero-voltage-level,

as described in part D.) Channel two now displays the negative of the resistor voltage. Press the blue menu "2" button then select "Invert On" to show the resistor voltage right-side-up.

Figure 4

(You will face a parallel situation in the experiments 9 and 10 on "Alternating Current Circuits", and you'll probably see it again in your research/development career whether you go into physics, electrical engineering, or neuroscien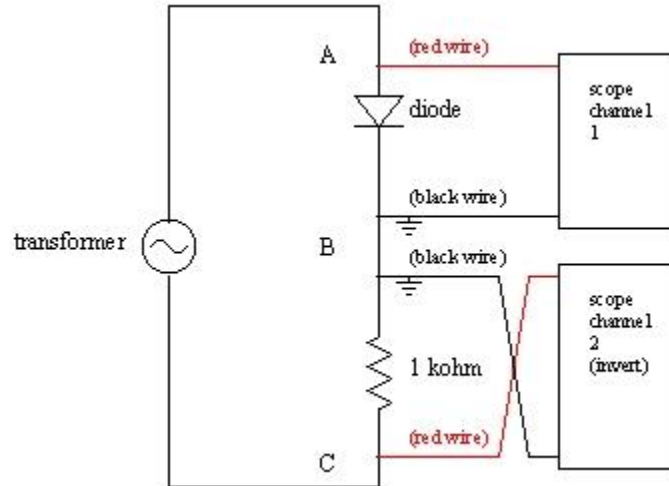ce.) Use the USB drive to print V_{diode} and V_R on a single graph, and tape this graph into your lab notebook.

Connect a 100 μF capacitor in parallel with R. Print out V_R. Explain. (Hint: Calculate RC for these components and compare it with the period of the AC signal you are applying.) You have just constructed a simple DC power supply.

Remove the capacitor.

Usually, as was pointed out at the very beginning of this experiment, the horizontal oscilloscope axis measures time. However, you can make it display channel one voltage on the X axis and channel two voltage on the Y axis by pressing "Utility", then "Display" then changing "Format YT" to "Format XY". In the current set-up channel one displays the voltage across the diode, while the channel two signal is proportional to the current through the diode. Put the oscilloscope into XY mode and see at a glance the I vs. V characteristic curve for your diode! (Recall from "Experiment 4: DC Circuits – I" how much work it was to produce such a characteristic curve by hand.)

Side Benches

On the side benches are four setups that explore various features of an oscilloscope. Look at and take notes on at least one of them:

    a.   Low frequency signals and sound.
    b.   Musical instruments.
    c.   Music on tape.
    d.   Lissajous figures.

Experiment 7: Characteristics of a Solar Cell

Introduction

Before coming to laboratory review the "unknown EMF" experiment on page 43, and your measurements of the I-V characteristics of a diode (pages 34 and 50). You might find this website useful: http://inventors.about.com/library/inventors/blsolar3.htm. If you google "how solar cells work" you'll find many other useful pages.

In this experiment you will determine the electrical properties of a silicon solar cell. These properties (to be defined later in this write-up) are:

1. short-circuit current, I_{SC}
2. open-circuit voltage, V_{OC}
3. maximum power, P_{MAX} (under standard test conditions)
4. fill factor, FF
5. energy conversion efficiency, ε.

A solar cell is a semiconductor diode. A diode is a two-terminal device which allows current to flow more readily in one direction than in the other. The resistors and capacitors we've been working with are said to be "linear" since, when all other conditions are kept fixed, doubling the voltage drop also doubles the current/charge. A diode has a more complicated behavior and is called a "nonlinear" device.

Connecting the Circuit

Our goal is to set up a simple circuit with an ammeter and a voltmeter to measure the I-V curve of a solar cell. Ideally this would look like Figure 1 below, where we have this nice power supply for which we can set the voltage anywhere between −600 mV and +600 mV, and it will supply this voltage no matter how much current is required. The B&K Power Supplies you have used, thus far, are not capable of this. (What we want the power supply to do is "source voltage" so that we can measure the resulting current. The B&K power supply is capable of the opposite – controlling current, then you measure the voltage.)

Figure 1. Ideal circuit for measuring solar cell I-V characteristics. I and V may be measured with digital multimeters. The power supply has special characteristics that are not obtained with the usual models.

54
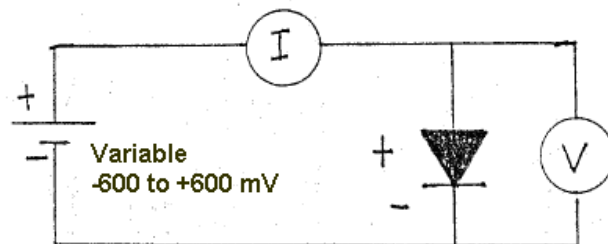
Bill Mohler, the electronics expert here at Oberlin College, has designed and built a voltage controller circuit that works with another DC power supply to accomplish this task. You will have to hook up the power supply, voltage controller circuit, and solar cell as described below.
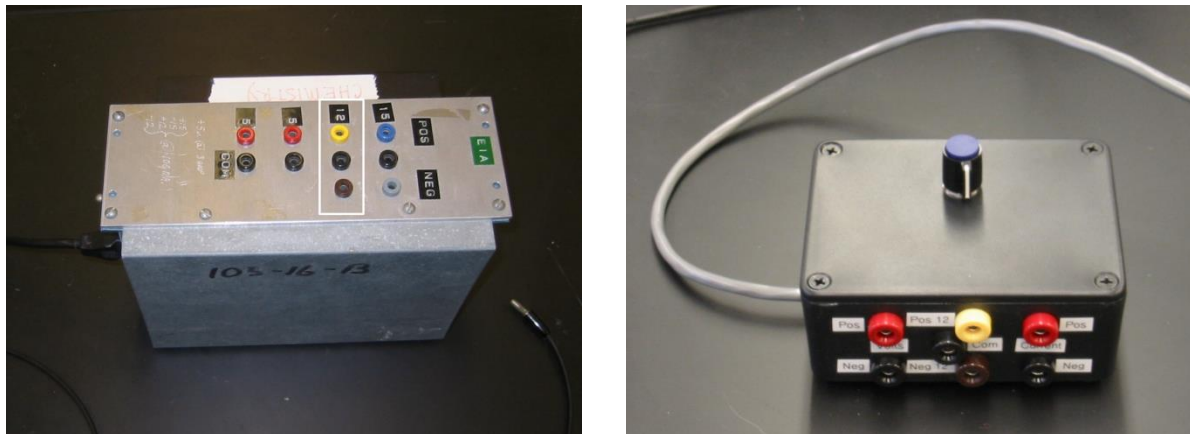
Figure 2. (a) *Gilford Instruments* DC power supply and (b) *Voltage Controller* for the solar cell experiment. The only connections required between yellow, black, and brown banana jacks on both devices (±12 V and ground).

Connect the DC power supply and the voltage controller circuit using three banana wires to join their yellow, black and brown connectors.

Connect the red/black jacks labeled "Volts" on the *Voltage Controller* to a DMM measuring DC voltage (use the 2 V scale). Connect the other pair of red/black jacks (labeled "Current") to a second DMM measuring DC current (start off on the 200 mA scale, and increase sensitivity as needed). Connect the long gray cable from the *Voltage Controller* directly to your solar cell.

The solar cell needs to be mounted on a bracket that will hold it vertically so that light from a slide projector is incident on the cell. To obtain high light intensity the cell should be close to the lens, but to obtain uniform intensity over the entire cell, it should be far from the lens. Obviously a trade-off is necessary! The best compromise is to place the solar cell about a foot away from the light source. A typical arrangement is shown on the next page. Make sure the solar cell is perpendicular to the light rays.

Figure 3. The solar cell is mounted vertically and placed in the light beam of a slide projector as shown.
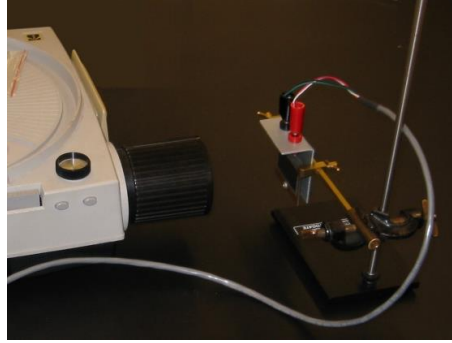
Measurements "In the Dark"

First you will measure the I-V characteristics of the solar cell in the <u>dark</u>. To do this place the cell in the dark (cover it with an opaque cloth). Measure I vs. V, recording your data in a table. Begin with the voltage set to –600 mV and carefully step up to zero then on into forward bias (i.e., positive voltage across the solar cell). Use the most sensitive current range for your ammeter, but don't exceed full scale for any range. Stop increasing the voltage when your current approaches 200 mA. (Otherwise, you'll blow the fuse on your DMM ammeter.) You don't need to take data for equally spaced voltages. Instead, take data so that you are convinced nothing curious is happening in-between adjacent points on your graph.

Plot the data using Excel or another graphing program. (Save your file, as you will add to this graph later.) Choose scales so that voltage is on the horizontal axis (-600 mV to $+600$ mV) and current is on the vertical axis (-200 mA to $+200$ mA). Did you take sufficient data or do you need to go back and get more detailed data for some range of voltage?

At some point take your "opaque shield" off of the cell and see if the measured I or V are affected by background lights.

Measurements Under Illumination

You are now ready to measure the "light" I-V curve for your solar cell. Ideally you would do this under illumination identical to that given by the sun (same intensity and color characteristics). Of course, the sun's light depends on where you observe it: Colorado or Ohio, summer or winter, clear or cloudy, etc. Solar scientists have agreed upon a "standard" sunlight which corresponds (approximately) to the noon-day sun at sea level in Arizona on a clear day in June. This has the intensity

$$J_0 = 1000 \, \text{W/m}^2 = 100 \, \text{mW/cm}^2,$$

which is called **AM1.5** solar illumination.[1] Having such a standard allows for ready comparison of the parameters of different solar cells.

In the Department we have one AM1.5 solar simulator which you might all use – but it would take too long. Instead, you will use the lamp from a slide projector, and the manufacturer's rated short-circuit current to calibrate your light source.

Mount your solar cell in the bracket and place it about a foot in front of the slide projector lens. Repeat the I-V measurements you made in the dark, and plot those measurements on the same graph you used before. You will find an I-V curve that is almost flat followed by a portion that is almost vertical.

For the rest of this experiment it is important that your cell remain fixed relative to the projector – a small change in distance will result in a significant change in light intensity. When you **turn off the slide projector**, slide the switch so that the lamp is off but **the fan continues running**. Cool the bulb in this way for a few minutes before turning the fan off.

Form a table with three columns: voltage across the diode V (mV), current through the diode I (mA), and power dissipated in the diode $P = IV$ (mW). Graph the power dissipated vs. voltage for your illuminated cell. For some values, the power dissipated will be negative. What could this possibly mean? You should find that the power curve shows an extreme (maximum power generated). Take additional I-V measurements in this vicinity to determine P_{MAX}, and the values V_{MAX} and I_{MAX} corresponding to the maximum power point.

Calculate Device Parameters

You are now ready to determine solar cell parameters.

From the graph of your "under illumination" data determine V_{OC} (the voltage for which the current is zero), I_{SC} (the current for which voltage is zero), and P_{MAX}. Calculate the fill factor defined as

$$FF \equiv \frac{P_{MAX}}{I_{SC}V_{OC}}.$$

This fill factor compares the power produced by your real diode to the power that it would have produced if it had been "perfectly flat then perfectly vertical". The fill factor is always less than one; the closer it is to one the better the quality of the solar cell. Refer to your I-V graph and provide (i.e., write out in words and pictures) a geometric interpretation of the fill factor.

Solar cell efficiency is defined to be the ratio of the maximum electric power produced to the incident light power on the cell. The cell efficiency is defined as

---

[1] The AM stands for "air mass." AM0 light has a higher intensity (1380 W/m^2) and corresponds to the intensity of sunlight above the Earth's atmosphere. AM1 light corresponds to sunlight directly overhead on a clear day passing through 1.0 "thickness" of the atmosphere.

$$\varepsilon \equiv \frac{P_{\text{MAX}}}{JA}.$$

where J is the light intensity, A the solar cell area, and P_{MAX} is the maximum power produced. Measure the total area of the solar cell with a ruler.

To find the efficiency you must first determine the light intensity for your experiment. Experience shows that I_{SC} is directly proportional to J. The device manufacturer reports that

$$I_{\text{SC}}^0 = (262 \pm 10) \text{ mA}$$

when illuminated with AM1.5 radiation. If your measured I_{SC} is different because your light intensity differs from J_0. You can then calculate your light intensity from

$$J = J_0 \frac{I_{\text{SC}}}{I_{\text{SC}}^0},$$

along with the uncertainty due to uncertainty in I_{SC}^0. In other words, we are using the known specs of the solar cell to calibrate your light source. (This would fine if the solar cell had exactly the properties reported by the manufacturer. In fact, solar cell properties vary from cell to cell.)

Calculate your light intensity and your corresponding solar cell efficiency. Is this a good efficiency? (What does "good" mean?)

Experiment 8: Measuring Magnetic Field

This experiment demonstrates some properties of magnetic fields, and shows how oscillating magnetic fields can be measured.

Preliminary tasks - **before coming to laboratory**:

    a. Work this problem in your lab notebook: A plane circular coil of 100 turns of wire has an average radius of 14 cm and the current in each turn is 1.0 ampere. Find the numerical value of the magnetic field on the axis of this coil at distances of 0.0 cm, 7.0 cm, and 14 cm above the center of the coil. (See HRW equation 29-26, "Magnetic field due to a coil".)

    b. Review Ampere's law.

A. How to measure magnetic field through Faraday's law (theory)

If the current in a "source" wire – such as the 100 turn coil of the preliminary problem – is constant ("DC"), then the magnetic field at a given point near the wire is proportional to the current. (If, for example, the current were 3.2 amperes, then the field at selected points along the axis of the coil would be 3.2 times what you calculated before coming to laboratory.)

But this lab uses a time-varying ("AC") current where the instantaneous current in the coil is a function of time, namely

$$I(t) = I_m \cos(2\pi f t)$$

where f is the "line" frequency of 60 Hz.

If the current $I(t)$ varies slowly enough (60 Hz qualifies), then the time-varying magnetic field produced is still proportional to the current at each instant. Thus, for our coil the field at point $\vec{r}$ has the form

$$\vec{B}(\vec{r}, t) = \vec{B}_m(\vec{r}) \cos(2\pi f t),$$

where $\vec{B}_m(\vec{r})$ is the field at point $\vec{r}$ that would be produced by a steady current I_m.

If now a second small coil of wire – called a "pick-up" coil – is placed somewhere in this varying magnetic field, an EMF will be induced in the pick-up coil. According to Faraday's law, the EMF induced is

$$\mathcal{E}(t) = -N_p \frac{d\Phi}{dt},$$

where N_p is the number of turns in the pick-up coil and $\Phi(t)$ is the magnetic flux linked by a single turn of the coil. That flux is

$$\Phi(t) = \iint \vec{B}(t) \cdot d\vec{A} \equiv \overline{B_n(t)} \, A,$$

where A is the area of one turn of the pick-up coil, and $\overline{B_n(t)}$ is the space average of the magnetic field component *normal* to the plane of the pick-up coil. In our case

$$\overline{B_n(t)} = \overline{B_{m,n}}\cos(2\pi f t),$$

(that is, $\overline{B_{m,n}}$ is the amplitude of $\overline{B_n(t)}$), so

$$\mathcal{E}(t) = \mathcal{E}_m \sin(2\pi f t) = N_p A \overline{B_{m,n}} 2\pi f \sin(2\pi f t).$$

Thus, we can calculate the component of magnetic field normal to the pick-up coil by measuring the EMF within the pick-up coil!

In this lab the small pick-up coil has 3000 turns and an average radius of 2.0 cm. (Confirm this radius with your own measurements.) Find an equation relating the amplitude of the normal component of magnetic field (in tesla) to the pick-up coil EMF amplitude $\mathcal{E}_m$ (in volts). Your equation should be one of the three listed below:

$$\overline{B_{m,n}} = (4.2 \times 10^{+3} \text{ s/m}^2)\,\mathcal{E}_m.$$

$$\overline{B_{m,n}} = (3.0 \times 10^{-2} \text{ s/m}^2)\,\mathcal{E}_m.$$

$$\overline{B_{m,n}} = (7.0 \times 10^{-4} \text{ s/m}^2)\,\mathcal{E}_m.$$

B. Measurement of the magnetic field near the center of a coil

Your lab bench has a large "source" coil wound with 100 turns of wire on an average radius of about 14 cm (measure this radius, keeping in mind that that the inner wire loops have smaller radius than do the outer loops). It also has a transformer and a DMM which should be assembled as shown below. Use the DMM as an AC ammeter – **plug into the 10 A jack**.
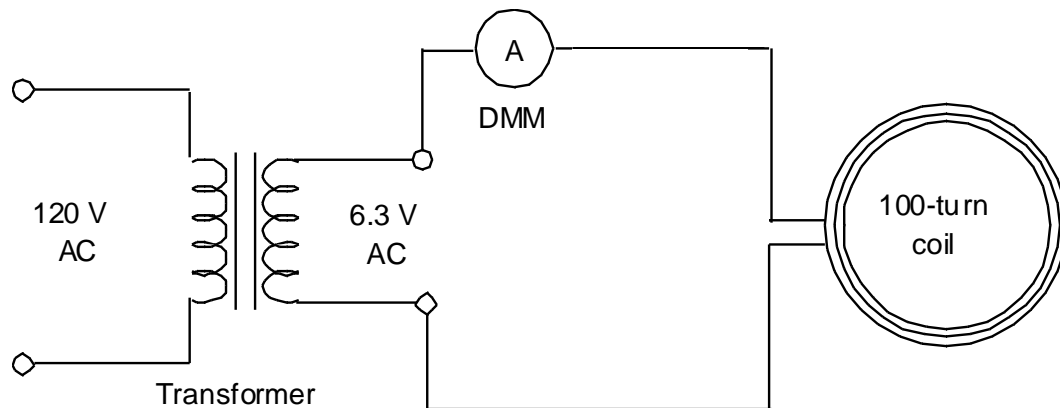
Plug in the transformer and use the DMM to read the RMS current. Calculate the current amplitude using $I_{\text{RMS}} = I_m/\sqrt{2}$.

Rotate the pick-up coil so it is within the plane of the large coil and near its center. Use the scope to observe the voltage induced (clue: press the "Measure" button, select "Ch1" and then "Maximum") and then calculate the amplitude of the magnetic field at the pick-up coil.

Compare your measured field value (pick-up coil) with the one you calculated for the 100-turn coil before coming to laboratory. (Remember that the current in the source coil is not exactly 1 ampere.)

C. Ampere's Law

Review with your partner the meaning of Ampere's law,

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I.$$

Although this is a law of magnetostatics, it holds to high accuracy at every instant if the current changes slowly enough (and 60 Hz is certainly slowly enough). For an AC current, a convenient instant is when $I(t)$ and $|\vec{B}(t)|$ take on their maximum values.

The pick-up coil may be moved on its arm in a closed circular path of radius about 12.1 cm (measure it) around the side of the large coil; reference marks are placed on the bearing every 20° around the circle. Measure the normal component of magnetic field every 20°, and graph this field as a function of angle. Estimate the area under this curve and relate that area to the line integral

$$\oint \vec{B} \cdot d\vec{s}$$

for this path. How does its value compare with the prediction of Ampere's law?

What effect does the earth's magnetic field have on this result?

Experiment 9: Alternating Current Circuits – I

Introduction

The experiments for this week and next investigate circuits where the driving voltage changes with time, and that include capacitors and inductors as well as resistors. The input (driving) voltage will be either a square-wave or a sinusoidal signal, with an adjustable frequency. Voltages are measured using an oscilloscope.

The mathematical treatment of alternating current ("AC") circuits found in your text is elegant, impressive, and, let's face it, intimidating. These formulas are so long and intricate that they seem to preclude qualitative understanding. This lab should convince you that a good qualitative understanding can come from a few simple concepts: capacitor takes a lot of slowly changing voltage, inductor takes a lot of rapidly changing voltage, etc.

The three parts of this two-week experiment are:

> Series RC circuit, capacitive impedance, high- and low-pass filters, phase relations between voltage and current.

> Series RL circuit, inductive impedance, phase relations between voltage and current.

> Series RLC resonant circuit, frequency dependence of current, phase relations.

The repetition rate of an AC signal may be denoted by either of two frequencies. Ordinary (or circular) frequency f has units of cycles/second or Hertz, while angular frequency ω has units of radians/second. These two frequencies are related through $\omega = 2\pi f$. In the United States and Canada, line voltage (from the electrical sockets in the wall) has a frequency of $f = 60$ Hz.

The function generator has an output impedance of about 50 Ω. That is, it behaves like a pure source of emf in series with a resistance of 50 Ω. This can seriously affect your results when the generator is connected directly into a circuit (i.e., not through a transformer). We have tried to avoid those difficulties by the design of the experiments below, but you may notice an effect near resonance in the series RLC circuit of part D.

A. Series RC Circuit – Square-Wave Applied Voltage

A1: Low-pass filter. Begin by investigating the behavior of a voltage divider circuit in which one of the elements is a capacitor instead of a resistor. Set your function generator to produce a **square wave** output with a frequency of about 200 Hz and an amplitude of 3.0 volts (peak-to-peak amplitude of 6.0 V). Observe with your oscilloscope.

Wire the circuit shown in figure 1, a so-called "low-pass filter." Let $R = 10,000$ Ω (a black box) and $C = 0.047\ \mu F$ (microfarad – an orange capacitor on a double banana plug).

Remember that the oscilloscope ground and the function generator ground are electrically connected through the third prong in their power cords. Thus you must connect point B (not point A) in the circuit to the oscilloscope ground.

Display the voltage across the function generator on one channel of your oscilloscope, and the voltage across the capacitor on the other channel. Using the USB drive, print this display. You may understand what you see by thinking of the process as repetitive chargings of the capacitor, first in one direction and then the opposite. Sweep the frequency from 200 Hz up to 2000 Hz. Record your general impressions.

Figure 1

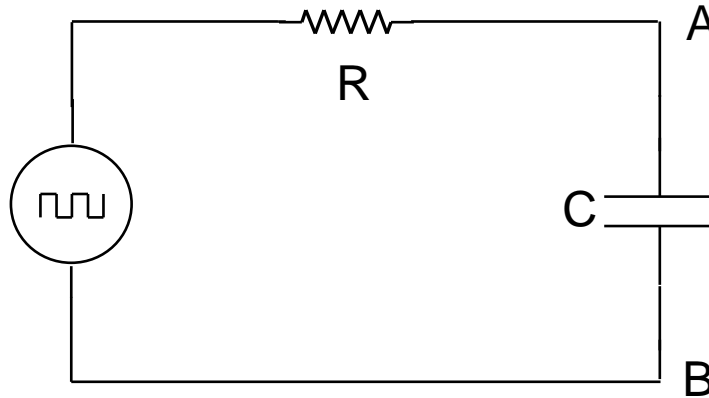**A2: High-pass filter.** Replace the low-pass filter by a "high-pass filter," shown in figure 2. Again sweep the frequency from 200 Hz to 2000 Hz. Record your general impressions.
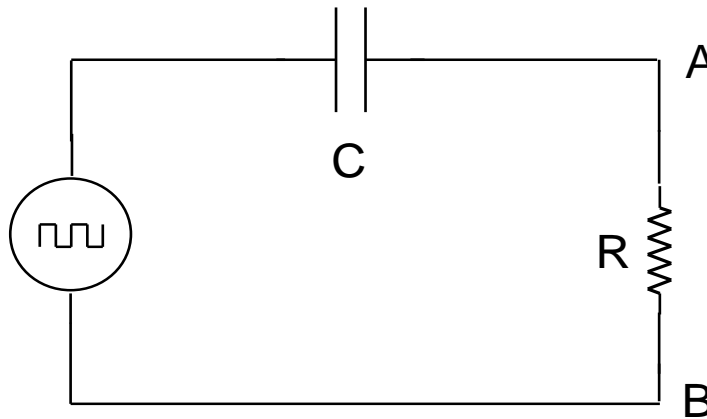

Figure 2

Adjust the period of the function generator so that in one-half period, the voltage across the resistor falls to $1/e$ (or approximately $1/3$) of its initial value. Compare this measured time to the "time constant" RC.

The voltage drop across R is proportional to the current in the circuit. Starting from the fact that

$$i(t) = \frac{dq(t)}{dt},$$

show that, for either of these circuits,

$$V_R(t) = RC \frac{dV_C(t)}{dt}.$$

Verify that this equation is dimensionally acceptable.

I like to **summarize** the results of this section as follows:

AC input slow, long period, low frequency, $V_{in}(t) \cong V_C(t)$, lots of charge, little current
AC input fast, short period, high frequency, $V_{in}(t) \cong V_R(t)$, little charge, lots of current

B. Series RC Circuit - Sinusoidal Applied Voltage

B1: Amplitudes. Assemble the circuit in figure 3. The circle with part of a sine wave in it represents a function generator set to produce sinusoidal voltages.
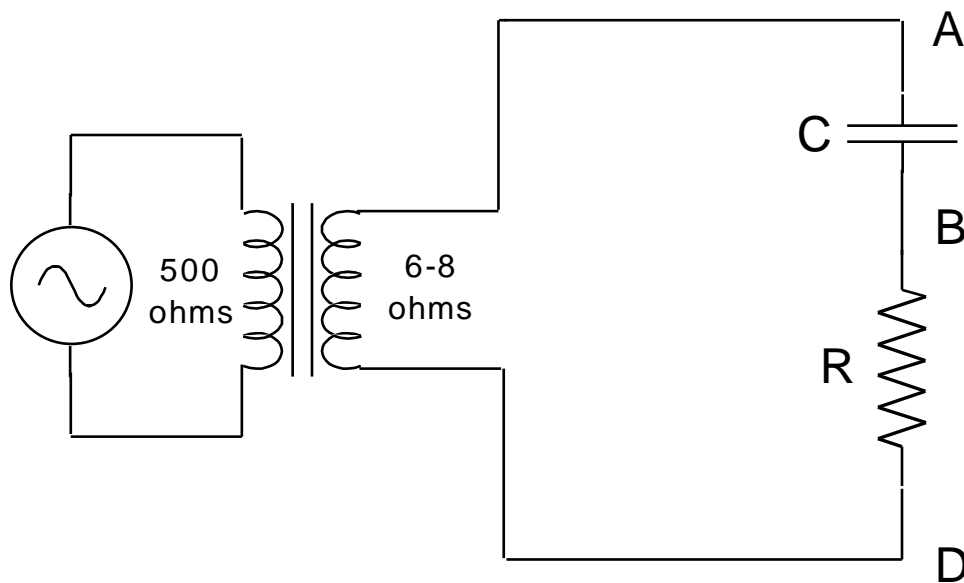
Figure 3

In this circuit a transformer has been added. The function generator and transformer together apply a **sinusoidal** oscillating voltage

$$\mathcal{E}(t) = \mathcal{E}_m \cos(\omega t)$$

to the RC circuit.

The transformer has the effect of reducing the effective output resistance of the voltage source (function generator plus transformer) from about 50 Ω to 6-8 Ω. The side of the transformer labeled 500 Ω should be connected to the function generator. The side of the

transformer labeled 6-8 Ω is <u>not</u> grounded. Therefore any of points A, B, or D may be put at ground potential when making measurements with the oscilloscope.

When a sinusoidal voltage is applied to the RC circuit by the function generator plus transformer, the voltages across the resistor and capacitor also vary sinusoidally with time. We study the amplitudes of the capacitor and resistor voltages as a function of the frequency of the applied voltage, for a fixed amplitude of applied voltage.

Begin your study at a frequency of about 400 Hz. Measure the applied voltage (i.e., the voltage between points A and D) and adjust the generator output level so that the amplitude of the applied voltage is 0.3 V.

Use the dual trace feature of your oscilloscope to observe both $V_C(t)$ on channel 1 and $V_R(t)$ on channel 2. Because both oscilloscope inputs have the same ground, point B in figure 3 must be connected to the grounded (black) terminal. (You faced the same situation in experiment 6, "Using an Oscilloscope", part H, "Studying a Diode with a Dual Trace Oscilloscope", on page 50.) This leads to the mildly distressing fact that although channel 1 displays $V_{AB}(t) = V_C(t)$, as desired, channel 2 displays $V_{DB}(t) = -V_R(t)$, the <u>negative</u> of the voltage across R. You can (and should) eliminate this distress by depressing Menu "2" then "Invert On".

Notice a relationship between the zeros of $V_R(t)$ and the maxima of $V_C(t)$. Can you derive this relationship? Does it hold at different frequencies? Does it hold for any waveform or only for sinusoidal signals?

Measure the amplitude of the voltage across the capacitor, $V_{C,m}$, and across the resistor, $V_{R,m}$, at frequencies from about 100 Hz to 800 Hz in steps of 100 Hz. Plot both $V_{C,m}$ and $V_{R,m}$ as a function of frequency f. Notice that there is a "crossover frequency" f_x near 350 Hz where $V_{C,m} = V_{R,m}$. Find and measure f_x with your oscilloscope.

At this crossover frequency the impedances ("impedance" is a generalization of resistance) of these two elements are equal. The impedance of a capacitor is given by $1/\omega C$. Using the nominal value of your capacitor and the frequency f_x you have determined, calculate the impedance of the capacitor at f_x and compare the result with the resistance R.

Does the summary on page 64 apply to sinusoidal signals?

At frequencies lower than f_x the capacitor has a greater impedance than the resistor, so most of the applied voltage appears across the capacitor. If the signal applied to the RC circuit is not sinusoidal but something else (such as a square wave, or a voice signal), then (Fourier theorem) it can be regarded as the sum of sinusoidal signals with various frequencies. Most of the low-frequency components of the sum appear across the capacitor, while the high-frequency components appear across the resistor. The pattern you saw when you applied a square wave to an RC circuit, and then examined the voltage across the capacitor, was a square wave with its high-frequency components removed.

For this reason, an RC circuit is called a "low pass filter" (meaning "low *frequency* pass filter") when $V_C(t)$ is observed; a "high pass filter" when $V_R(t)$ is observed.

B2: Phases. Look again at your data. Note that at every frequency $V_{R,m} + V_{C,m} > V_{transf,m}$!
Is this a violation of Kirchhoff's voltage loop theorem?

This conundrum is resolved by remembering that the voltages depend upon time. If we consider the time-dependent voltages (not peak values) across R, C, and the source, then at any instant of time, $V_R(t) + V_C(t) = V_{transf}(t)$. But these signals do not attain their peak values at the same time. Therefore it is not surprising that for the voltage amplitudes alone we have $V_{R,m} + V_{C,m} > V_{transf,m}$.

To observe the total voltage drop $V_{transf}(t)$ press "M", then "Operation +". Make sure that all three voltage traces use the same vertical scale. Study and print out the display at frequency f_x, at one frequency below f_x, and at one frequency above f_x.

B3: Theory. A theoretical expression for the current in this RC circuit is obtained by setting $L = 0$ in the equations 31-63 and 31-65 of HRW. So doing, we see that if the emf imposed on this circuit is

$$\mathcal{E}(t) = \mathcal{E}_m \sin(\omega_d t),$$

then the steady-state current in the circuit will be

$$i(t) = I_m \sin(\omega_d t - \phi)$$

where

$$I_m = \frac{\mathcal{E}_m}{\sqrt{R^2 + (1/\omega_d C)^2}}$$

and

$$\tan \phi = \frac{-1/\omega_d C}{R}.$$

Amplitude dependence on f. These equations relate the imposed emf to the resulting current. This is not directly helpful, because you don't have an ammeter to measure current. What you do have, however, is a voltmeter (namely an oscilloscope). The voltage across the resistor is related to the current through

$$V_R(t) = i(t)R = I_m R \sin(\omega_d t - \phi),$$

so the amplitude of the voltage across the resistor is

$$V_{R,m} = I_m R = \frac{\mathcal{E}_m R}{\sqrt{R^2 + (1/\omega_d C)^2}} = \frac{\mathcal{E}_m}{\sqrt{1 + (1/f(2\pi RC))^2}}.$$

You have already taken (and plotted) data for $V_{R,m}$ as a function of f, and now you have a theoretical expression for how $V_{R,m}$ ought to depend upon f. You might think you could immediately use Microsoft Excel's "Trendline" fitting feature to fit this curve. The trouble is, Excel has no fit for a function $y(x)$ of the form

$$y = \frac{1}{\sqrt{a + b/x^2}}.$$

Show, however, that the equation for $V_{R,m}$ as a function of f is equivalent to

$$\frac{1}{V_{R,m}^2} = \frac{1}{\mathcal{E}_m^2} + \frac{1}{(2\pi\mathcal{E}_m RC)^2} \frac{1}{f^2}.$$

Use Excel to calculate columns of $1/V_{R,m}^2$ and of $1/f^2$, make a graph and calculate the value of RC from the slope of your curve.

Phase relations. The last paragraph gave a very neat test of the theory concerning amplitude, but said nothing about phase. The summary on page 64 tells us what we need to know: at low frequencies, $V_C(t)$ is in phase with $V_{\text{transf}}(t)$. At high frequencies, $V_R(t)$ is in phase with $V_{\text{transf}}(t)$. What happens at the crossover frequency f_x?

Experiment 10: Alternating Current Circuits – II

Part C concerning RL circuits parallels experiment 9, part B, concerning RC circuits. Go through it quickly and focus on the new material in part D concerning RLC circuits.

C. Series RL Circuit - Sinusoidal Applied Voltage

C1: Amplitudes. A theoretical inductor is implemented by a physical coil of wire. Because it has many turns of wire, the coil will have resistance r_L as well as inductance L. Measure the resistance of your coil with a DMM.

Assemble the circuit in figure 4, using an R of 1000 ohms. The dashed box represents the coil of wire with inductance L and also resistance r_L. Begin your study at a frequency of 200 Hz. Measure the applied voltage (i.e., the voltage between points A and D) and adjust the generator output level so that the amplitude of the applied voltage is 0.3 V.

Use your oscilloscope to measure the amplitude of the voltage across the inductor, $V_{L,m}$, and across the resistor, $V_{R,m}$, at this frequency. (Connecting point B to the ground of the oscilloscope will facilitate this measurement.) Repeat this process for frequencies of about 400 Hz, 800 Hz, 1.2 kHz, 2 kHz, 4 kHz, 8 kHz, 12 kHz and 20 kHz. Plot both $V_{L,m}$ and $V_{R,m}$, as a function of frequency f on the horizontal scale.
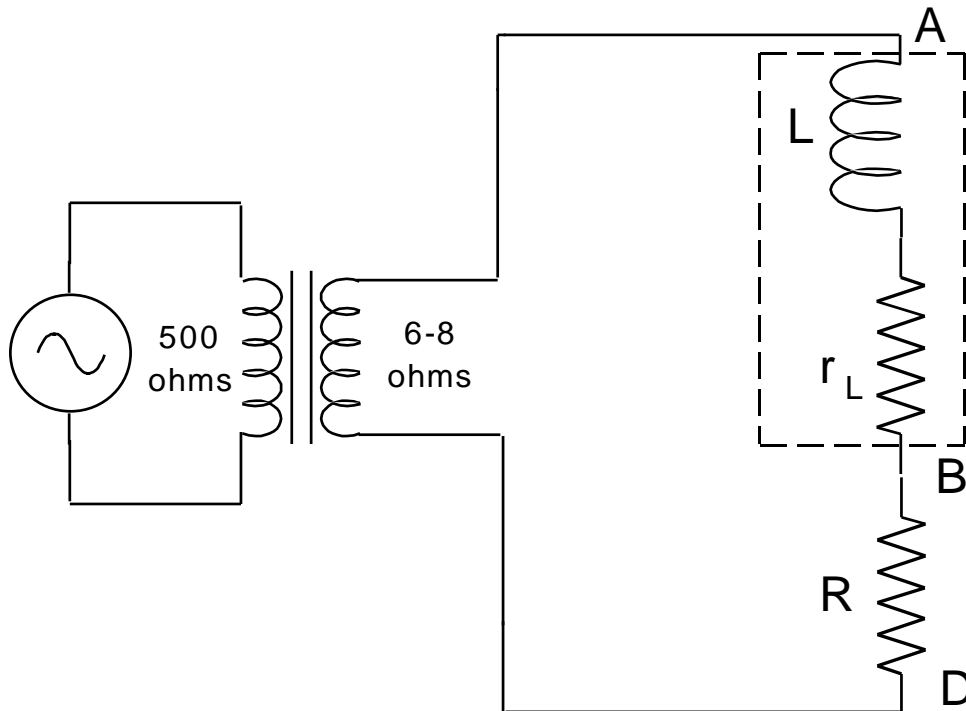

Figure 4

Determine the "crossover frequency" at which the amplitude of the potential differences across the inductor and resistor are equal. At this frequency, the inductor has an impedance of 1,000 Ω. From the relation

$$\omega_x L = 1000 \ \Omega,$$

calculate the inductance of the coil. Summarize the results of your RL investigations with a pithy two-part conclusion paralleling the summary of RC investigations on page 64.

C2: Phases. At the crossover frequency, measure the amplitude of the voltage output from the transformer. How does it compare with the sum of the voltage amplitudes across the inductor and resistor? Why don't they agree?

Observe the relative phases of the voltages across the resistor and inductor using the dual trace technique described in section "B2: Phases" on page 66. Print the oscilloscope display and tape it into your notebook.

C3: Theory. Once again using equations 31-63 and 31-65 of HRW, only this time setting $C = \infty$ ($X_C = 0$), we find that if the emf imposed on this circuit is

$$\mathcal{E}(t) = \mathcal{E}_m \sin(\omega_d t),$$

then the steady-state current in the circuit will be

$$i(t) = I_m \sin(\omega_d t - \phi)$$

where

$$I_m = \frac{\mathcal{E}_m}{\sqrt{R^2 + (\omega_d L)^2}}$$

and

$$\tan \phi = \frac{\omega_d L}{R}.$$

At the crossover frequency, do the observed current amplitude and phase agree with these predictions? Check them also at one frequency high above crossover.

D. Series RLC Resonant Circuit

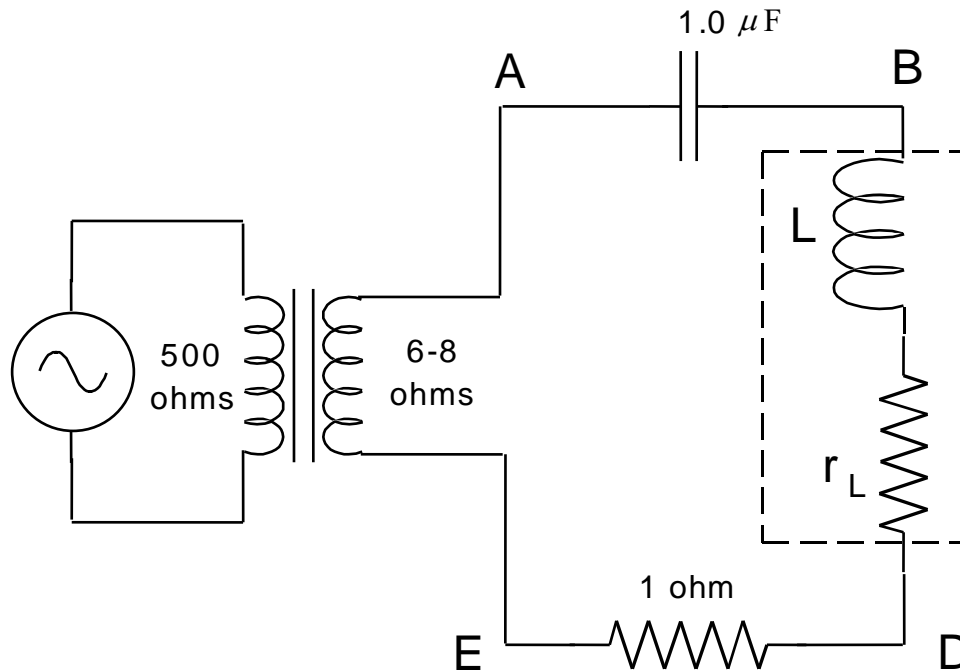**D1: Location of resonance.** Assemble the circuit in figure 5.

Figure 5

We will study the current in this circuit as a function of generator frequency f. First, quickly sweep through the frequency range while observing $V_R(t)$ on the oscilloscope to determine approximately the frequency at which the current amplitude is a maximum. This quick sweep indicates what frequency ranges are interesting, but it is only approximate because the applied voltage $V_{\text{transf}}(t)$ varies somewhat in amplitude as the frequency changes. To correct for this variation you must reset the generator amplitude each time you change the frequency. This is most easily done by displaying $V_{\text{transf}}(t)$ on channel 1 of your scope and $V_R(t)$ on channel 2. (Point E must then be grounded.) Set the amplitude of the transformer voltage equal to 0.3 V for every frequency, then record the amplitude of the voltage across the resistor.

Carry out this procedure for a range of frequencies, spending little time on the uninteresting frequencies far from resonance. (In parts B and C, I specified which frequencies to use. Now I'm trusting you to find appropriate frequencies yourself.) Plot the amplitude $V_{R,m}$ as a function of frequency, and find the one frequency that leads to maximum current ("resonance"). The resonance (angular) frequency is denoted ω_0, and theory says that $\omega_0 = 1/\sqrt{LC}$. How does this check out?

D2: Character of resonance. Investigate the character of resonance using your scope in dual trace mode. There are now four voltages of interest: $V_{\text{transf}}(t)$, $V_R(t)$, $V_L(t)$, and $V_C(t)$,

but only two can be displayed at any one time. My recommendation (but you may of course carry out this investigation in a different way) that you start by investigating $V_{\text{transf}}(t)$ and $V_R(t)$ because your circuit is already set up for this. Then swap the resistor and inductor to investigate $V_{\text{transf}}(t)$ and $V_L(t)$. (Do not simply move the oscilloscope leads from the resistor to the inductor … to do so would mess up your carefully planned grounding arrangement.) Next swap the inductor and capacitor to investigate $V_{\text{transf}}(t)$ and $V_C(t)$. In the first part of my investigation I recorded these data (my resonance frequency was 608 Hz):

frequency	$V_{\text{transf},m}$	$V_{R,m}$	$V_{R,m}/V_{\text{transf},m}$	phase of $V_R(t)$ relative to $V_{\text{transf}}(t)$
250 Hz	304 mV	4.01 mV	0.0132	leads
608 Hz	268 mV	28.4 mV	0.106	in phase
2000 Hz	300 mV	3.96 mV	0.0132	lags

When you've made similar investigations for the inductor and capacitor voltages, see if any questions arise and, if they do, think of experiments to answer them.

The current in the circuit depends on the frequency of the applied voltage. Once again using equations 31-63 and 31-65 of HRW, we find that an applied emf of $\mathcal{E}(t) = \mathcal{E}_m \sin(\omega_d t)$ results in a steady-state current of

$$i(t) = \frac{\mathcal{E}_m}{\sqrt{R^2 + \left(\omega_d L - \dfrac{1}{\omega_d C}\right)^2}} \sin(\omega_d t - \phi)$$

where

$$\tan \phi = \frac{\omega_d L - \dfrac{1}{\omega_d C}}{R}$$

(In these expressions R includes the resistance of the resistor, plus that of the coil, plus the effective resistance of the voltage source.) These expressions should agree with your observations so far. In particular, $\phi = 0$ at the resonance frequency. At frequencies below resonance, the capacitor presents a higher impedance than the inductor, and the current leads the applied emf (phase ϕ is negative). Above resonance, the impedance is predominantly inductive, and current lags applied emf (phase ϕ is positive).

D3: The quantity Q. Several properties of a resonant circuit can be expressed in terms of a quantity called "Q", which stands for *quality*. The higher the Q of a resonant circuit, the sharper (i.e., higher quality) is the resonance peak in the graph of $V_{R,m}$ as a function of frequency f. This quantity is defined as $Q = \omega_0 L/R$. (Here R represents the *total* resistance in the circuit: take the effective resistance of the transformer to be 3.0 Ω.) If you're ambitious, you can show theoretically that the fractional width of the resonance curve at half-

71

height, $\Delta f/f_0 = \Delta\omega/\omega_0$, is $\sqrt{3}/Q$. By measuring the width at half-height of your experimental resonance curve, estimate the Q of your resonant circuit and compare it with the Q calculated from the definition.

[Why is a narrow resonance curve considered "high quality"? To answer this question we must consider how RLC resonance circuits are used. A radio antenna picks up signals from all the local radio stations at the same time. If you were to amplify the signal direct from a radio antenna, you would hear all the local radio stations at once … an unpleasant experience! So instead the antenna signal is fed into an RLC circuit. The signals from high frequency stations appear across the inductor. The signals from low frequency stations appear across the capacitor. And the signal from the station you want appears across the resistor. This signal across the resistor is then amplified and sent to a loudspeaker. If the resonance curve is wide (this is, of low quality Q), then you will hear two or three stations at once.]

D4: The quantity Q, again. The quantity Q turns up in another context. At resonance, the source voltage equals the voltage across the resistance R. The voltages across the capacitor and inductor might be quite large, but they exactly cancel out. Use equations from the previous page to show that the amplitude of the voltage across the inductor is $Q\mathcal{E}_m$, and that the amplitude of the voltage across the capacitor is the same. Show also that, at resonance, $V_{L.m} = QV_{R,m}$.

You have already measured the voltage amplitudes discussed. Use them to calculate a value of Q. How does it compare with the value found in procedure D3? Which method of finding Q do you expect is more accurate?

Experiment 11: Polarization of Light

Introduction

Any light beam is characterized by three properties: its intensity, its color, and its polarization. Nearly all visual art is based on varying the intensity and color of light. Polarization is a phenomenon just as important at intensity or color, but our eyes cannot detect polarization so most people don't even realize that it exists. Some people are color blind, but all of us are polarization blind. In this laboratory we use our brains and our hands to perceive what our eyes cannot.

Polarization is important in physics, chemistry, astronomy, biology, engineering, and other fields. It can be understood mostly through observation and applied by non-experts. No special knowledge or theoretical background is required.

Polarized light has many interesting and practical applications. Radio waves are polarized, laser beams are often polarized, and even some seismic waves (from earthquakes) are polarized. Engineers use polarized light to measure stresses. The liquid crystal displays (LCDs) of calculators, watches, cell phones, computers, and televisions work by controlling light polarization. Bees navigate using the polarization of skylight. (The eyes of bees, unlike those of humans, *can* detect polarization.) Perhaps the Vikings did too, through their use of *sólarsteinn* ("sunstones"). Artists[1] use polarized light to project a dazzling display of changing color patterns. Polarization is used in compact disc players, sunglasses, photography, and 3-D movies.

Apparatus

three linear polarizers (Polaroids)	bottle of karo syrup
sun and sky (if not cloudy)	cellophane
lamp, angle table, glass setup	saran wrap
scattering solution	cellophane tape

A. Making and detecting polarized light

The light emitted by a hot material (incandescent bulb or the sun) is unpolarized – demonstrate this to yourself by looking at the lamp through the polarizer and rotating the polarizer. However, there are many physical processes which modify the light so that afterwards the light is polarized. Such a process may be used either to produce polarized light or to analyze light to find out whether it is polarized.

When we say light is "unpolarized" this doesn't mean that the electric field points in no direction. It means that the electric field doesn't point in any particular direction: sometimes

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[1] Austine Wood Comarow, for example, creates all her artwork using polarized light. Her large installation "Human Connections" is on continuous display at the Boston Museum of Science.

it points north, sometimes east, sometimes southwest, etc. If this random direction fluctuates quickly enough, we should call the light "randomly polarized" or "polarized in rapidly fluctuating direction" but in fact we call it "unpolarized".

A1. Polarization by emission

Control of polarization is easiest when you control the process that produces the light. Maxwell's equations imply that when charged particles accelerate, they set up electric and magnetic fields that propagate with finite speed away from the charges. This process is called "radiation" and the fields produced are called "electromagnetic radiation" or "light".

Suppose a charge oscillates up and down along the x axis of some coordinate system. It accelerates and thus radiates. If one makes measurements at point P, many wavelengths away from the charge, the radiation is linearly polarized, with where the electric field $\vec{E}$ in the wave always within the plane containing the x axis and the line from P to the origin.
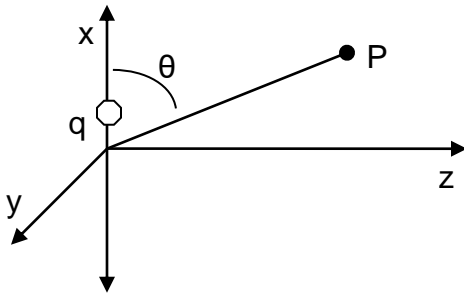
The intensity of the radiation varies with θ and, in particular, no radiation is emitted along the direction of oscillation ($\theta = 0°$ or $\theta = 180°$).

This so-called "dipole radiation" explains why commercial radio emissions are polarized: the radio waves come from huge vertical antennas and hence are vertically polarized. Light emission comes from atoms rather than man-made antennas, and we can't reach in and orient the atoms. Nevertheless the concept of "polarization by emission" will be the key to explaining several polarization processes.

A2. Polarization by selective absorption

If we begin with unpolarized (or "randomly polarized") light and absorb the electric field that points in one direction, we will end up with light polarized in the perpendicular direction. How can we accomplish this? By fixing things so that one component can do work and the other cannot.

For example, we could pass the light through a skein of wires all parallel to the y axis. The electric field in the y direction will push electrons in the wires, so this component of the field loses energy (as the wires grow slightly warmer) and eventually dies out altogether. No electric field parallel to y makes it through the skein.

The electric field in the x direction also pushes electrons, but the electrons don't move very far because they can't jump out of their wires. This component of the electric field doesn't do work, so it doesn't die out. The light that makes it through the skein is thus polarized in the x direction.
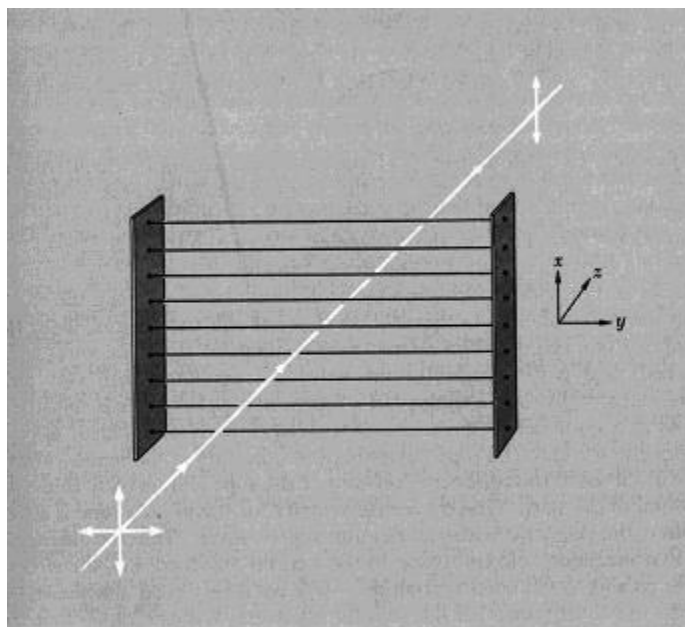
The "skein of wires" technique works well for microwaves, but it's not effective at optical frequencies because it's impossible to manufacture wires spaced about a wavelength of light apart. But in 1938 Edwin H. Land figured out how to make the equivalent of such closely-spaced wires. The process starts with a sheet of plastic made up of long hydrocarbon chains. The sheet is stretched in one direction so that most of the chains are parallel. Then the sheet is dipped into a solution containing iodine, which attaches to the chains and makes them conducting. Land called his invention "Polaroid" and founded a company to manufacture it. That company eventually branched into other directions, but other companies took up the manufacture of Polaroid sheets. Mr. Land retired a very wealthy man, but he loved to dabble in his laboratory even in retirement. (Today any kind of polarizer is often called "Polaroid", just as any kind of facial tissue is often called "Kleenex".)

A sheet of Polaroid passes only light polarized in one direction, the direction perpendicular to the hydrocarbon chains. This is called the "easy axis" of a sheet of Polaroid.

Hold two Polaroids sandwiched in front of your eye. Slowly rotate one while keeping the other fixed. Record what you see. (The filter near the light source is often called the polarizer, while the one near your eye is called the analyzer.)

Hold two Polaroids in front of your eye, in such a way that the light intensity is at a minimum. This position is called *crossed Polaroids.* Then, insert the third Polaroid between the two crossed Polaroids and rotate it. Record what you see.

A3. Polarization by a single scattering

On the Moon, the sky is dark. But on Earth, the sky is bright because the atmosphere scatters sunlight. For example, if the light from the Sun were polarized in-and-out of the page (top of figure), then it would make the dipole of a nitrogen molecule oscillate in-and-out of the page. In turn, that oscillating dipole would radiate, and send some of the resulting radiation in the direction of the person shown.
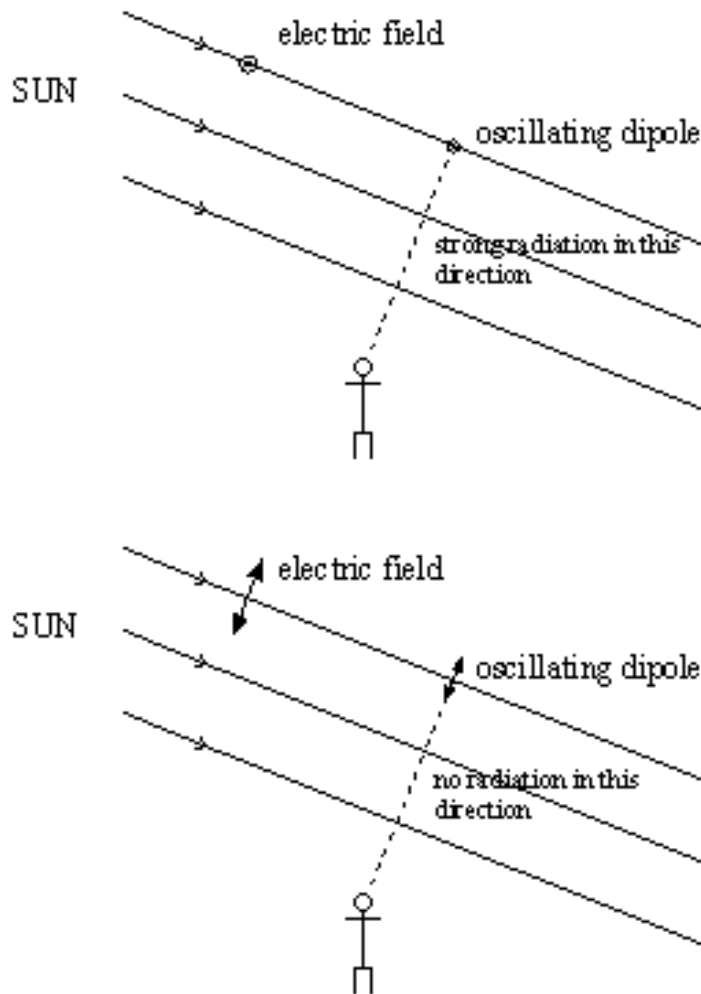
However, suppose the light from the Sun were polarized within the page (bottom of figure). Then the dipole of the nitrogen molecule would oscillate within the page. That oscillating dipole would radiate, but it would send none of the resulting radiation in the direction of the person shown.

Look at the blue sky through a Polaroid. (For safety's sake, don't look directly at the sun.) You will find that the sky is unpolarized near the sun, but highly polarized 90° from the sun. Because the blue sky provides a source of light with a known polarization direction, you should use it to identify the easy axis of transmission for one of your Polaroids. Compare the direction of the polarization at different points in the sky with the direction toward the sun. (At sunset on a clear evening, this 90° belt is noticeable directly above your head if you look up while wearing Polaroid sunglasses.)

Incidentally, the sky is blue because the short wavelengths (blue) of light from the sun are scattered more effectively than the long wavelengths (red). The polarization of sky light means that when you look at the sky through a polarizer the blue sky looks dark and the unpolarized light from a white cloud stands out beautifully. Photographers use polarizing filters for this purpose.

If it's a cloudy day, you can simulate the blue sky effect using a projector lamp instead of the sun and water with a few drops of milk instead of the sky.

A4. Polarization by specular reflection – Brewster's angle

With your apparatus is a pane of glass. (The back side is painted black to minimize reflection from that surface.) Mount this in the center slot of the wooden block on the angle table, and observe the reflection of the light bulb in the glass.
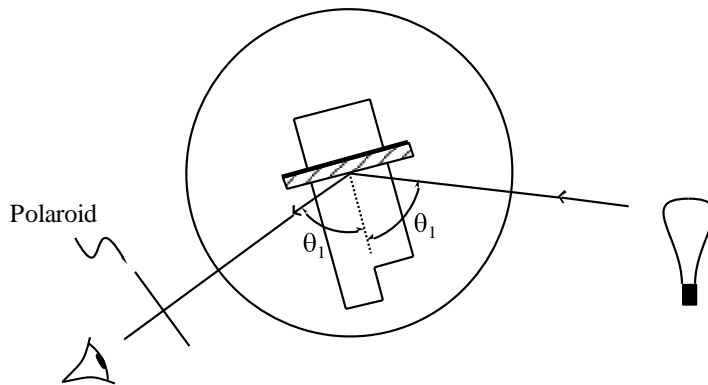
Test the polarization of the reflected light with a piece of Polaroid. Even though the light from the bulb is unpolarized, there is a particular angle of incidence for which the reflected light is 100% linearly polarized, and hence may be extinguished by the Polaroid. This angle is called Brewster's angle—measure it for glass.

To understand this phenomenon, we investigate what's going on in reflection of light from a glass surface. You know that one light ray comes in (the "incident ray") and two go out (the "reflected ray" and the "refracted ray"). What is the physical source of the reflected and refracted rays? The incident ray causes electrons on the glass surface to oscillate, and (as we've seen) this oscillation causes them to radiate.

The figure below shows the special case when the reflected ray is perpendicular to the refracted ray. Suppose the incident ray is polarized perpendicular to the plane of the figure (i.e. in-and-out of the page). Then the surface dipoles oscillate perpendicular to the plane of the figure, and they radiate both in the direction of the reflected ray and in the direction of the refracted ray. But suppose the incident ray is polarized parallel to the plane of the figure. Then the surface dipoles oscillate within the plane of the figure. Remember that oscillating dipoles *don't* radiate parallel to the direction in which they oscillate. The fact that these dipoles *are* radiating in the direction of the refracted ray means that they're *not* radiating in the direction of the reflected ray.

On the other hand, suppose the incident ray is unpolarized (that is, sometimes polarized perpendicular and sometimes polarized parallel). The outgoing refracted ray is also unpolarized. But because the reflected ray comes out only when the incident ray is perpendicular polarized, the reflected ray is polarized perpendicular. In short, for this particular condition the reflected ray is polarized perpendicular to the plane of the figure.
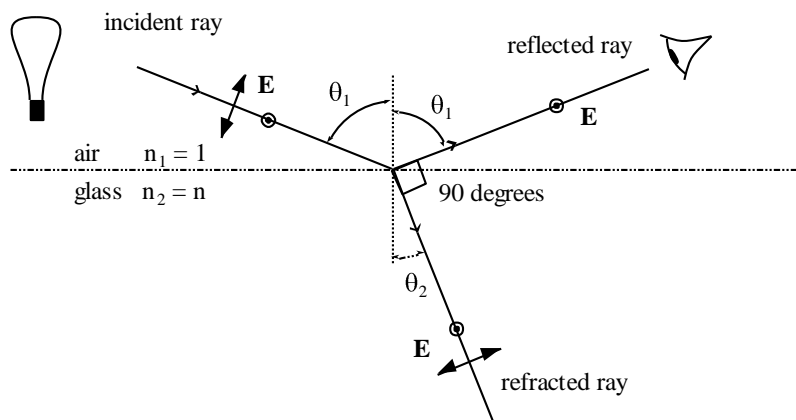
We can calculate a condition for Brewster's angle. The angles of incidence and refraction, namely θ_1 and θ_2, are related through Snell's law,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2.$$

Brewster's angle is θ_1 when $\theta_1 + \theta_2 = 90°$. Using $n_1 = 1$, $n_2 = n$, and $\sin \theta_2$ equal to $\sin(90° - \theta_1)$, which is $\cos \theta_1$, show that

$$\tan \theta_1 = n, \qquad \theta_1 = \text{Brewster's angle.}$$

From your measurement of Brewster's angle for glass, calculate its index of refraction.

Advertisements say that polarizing sunglasses pass most sorts of light but eliminate glare, where "glare" means the sunlight reflected from a horizontal surface, such as a puddle. In polarizing sunglasses, should the easy axis be oriented horizontally or vertically?

Go out into the hallway and notice that the light coming in through the window is unpolarized, but the light reflected from the linoleum floor *is* polarized. In this way, test your prediction about polarizing sunglasses.

A5. Haidinger's brush

I said earlier that human eyes cannot detect polarization, and that is almost always correct. Set a white sheet of paper on your lab bench and illuminate it with your lamp. Now view the white paper through a Polaroid. You might see a faint blue and yellow pattern like this:
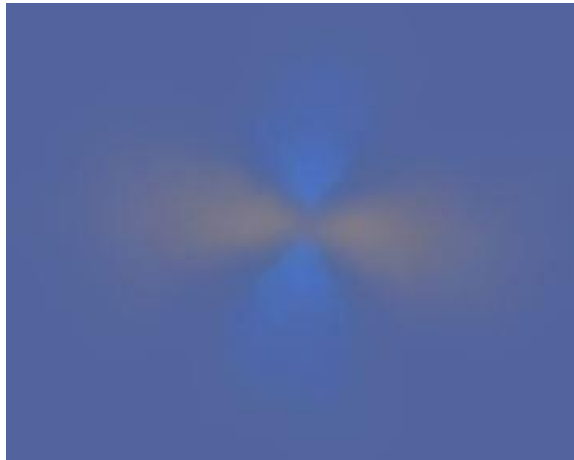
Rotate your Polaroid, and if the pattern moves along with the Polaroid then you've seen Haidinger's brush. (The pattern subtends an angle of about 3°, and the blue pieces are parallel to the direction of polarization.) Some people can see the brushes without using a polarizer (for example in the polarized blue sky), some need a polarizer to see them, and some people can never see them. (I'm particularly apt to see them if I've just done some intense physical exercise, such as sprinting.) They are probably caused by selective absorption of light with one direction of polarization by the pigment in your eye's retina.

B. Double Refraction

B1. Physics

Take two pieces of Polaroid and cross them so that no light gets through. Then slip a piece of cellophane (say from a candy wrapper or a bread wrapper — almost any kind of clear plastic will do) between the crossed Polaroids. Now light gets through! Since the cellophane is perfectly transparent, with none of the "dark" appearance of Polaroid, we know that the cellophane is not absorbing light. So this is not the phenomena we noticed before with a Polaroid between two crossed Polaroids. The cellophane is not *making* polarized light, but *changing the character* of already-polarized light.

Rotate the piece of cellophane between the Polaroids, keeping the Polaroids crossed. You should find two angles at 90° from one another where the cellophane has its greatest effect and two angles at 90° from one another where the cellophane has no effect. Thus cellophane has two special directions, oriented at 90° to one another and lying within the plane of the cellophane, which are related to the rotation of polarization.

Not all transparent plastic has this peculiar property. Find a piece of household plastic wrap (such as Saran Wrap) or a piece of the stretchy polyethylene used by dry cleaners to protect clothes. Try this between crossed Polaroids. You will find that it has little effect — not much light gets through. The cellophane had two special directions, but for the Saran Wrap all the directions are the same.

However, with Saran Wrap you can make special directions. Take a piece of this stretchy plastic and stretch it. Check it between crossed polarizers again. There should now be a huge effect! Furthermore, the greatest transmission comes when the stretched direction is oriented 45º relative to the polarizers.

Here is the explanation for the behavior of stretched Saran Wrap. Before stretching, the long organic molecules of the plastic are coiled in a spaghetti-like mess going in all directions. No direction is special. However, during stretching the molecules straighten out and align. Now when an electric field is applied parallel to the chains, the electrons in the molecules can respond dramatically, whereas when an electric field is applied perpendicular to the chains, there is little response. The material is highly polarizable parallel to the chains and weakly polarizable perpendicular to the chains. (Here the word "polarizable" refers to electrostatic polarization, not polarization of light.) The electric susceptibility is different in these two directions, thus the dielectric constant is different in these two directions, thus the *index of refraction is different for light polarized in these two directions*.
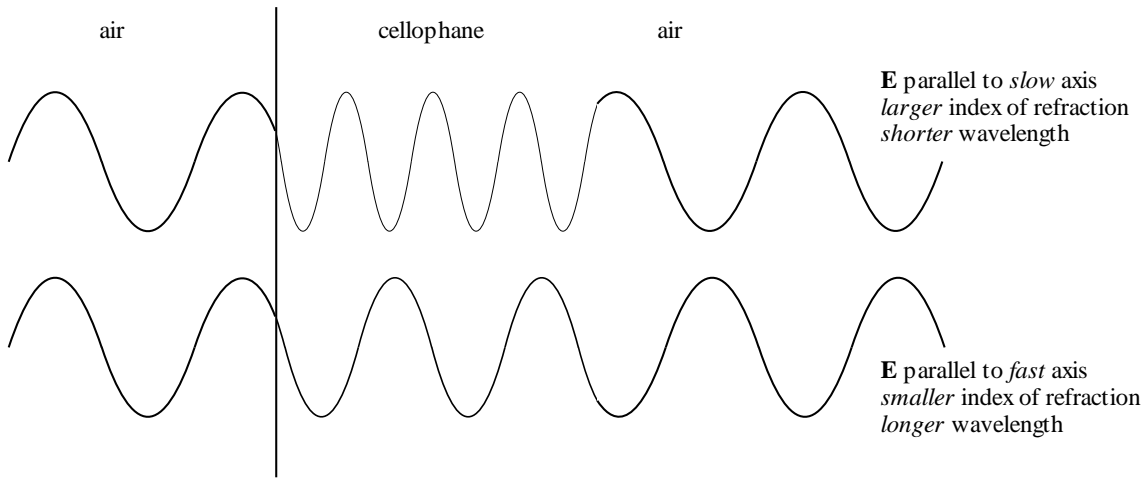
These two directions, the stretch direction and the direction perpendicular to it, are called the optic axes. The optic axis with the larger index of refraction (for electric field $\vec{E}$ directed along it) is called the slow axis. (Large index of refraction means slow phase velocity.) The other optic axis is called the fast axis. The two corresponding indices of refraction are called

n_s and n_f. (A sheet of cellophane or stretched Saran Wrap or any other material having these properties is called a "retardation plate," and is said to exhibit "double refraction".)

So far so good, but how does this anisotropy change the character of polarization?

Suppose the incoming light is polarized parallel to the slow axis. Then it emerges polarized parallel to the slow axis, as in the top half of the figure below. If the incoming light is polarized parallel to the fast axis, it emerges polarized parallel to the fast axis, as in the bottom half of the figure.

But what if the incoming light is polarized parallel to some other axis? In that case resolve the incoming light into two components: one component parallel to the slow axis and one component parallel to the fast axis. Each component will emerge with its same polarization, but the figure shows that *the two components will no longer be in phase*.

air   cellophane   air

E parallel to *slow* axis
larger index of refraction
shorter wavelength

E parallel to *fast* axis
smaller index of refraction
longer wavelength

At a given point in space, the tip of the total $\vec{E}$ vector does not simply vibrate up and down, it precesses around in an elliptical path in a plane transverse to the direction of propagation — the light is said to be "elliptically polarized". When such light arrives at the analyzing Polaroid, the $\vec{E}$ field now has a component parallel to the easy axis of the Polaroid, and that component is transmitted. Thus light passes through the two crossed Polaroids.

The phase difference may in fact be calculated. Suppose the cellophane has thickness t. The wavelength λ_n of the wave in cellophane is related to its vacuum wavelength λ by

$$\lambda_n = \frac{\lambda}{n}.$$

In the figure, there are within the cellophane $t/\lambda_f = n_f t/\lambda$ wavelengths of the fast component and $n_s t/\lambda$ wavelengths of the slow component. Thus there are $(n_s - n_f)t/\lambda$

more slow wavelengths than fast ones, and since each wavelength occupies 2π radians of phase, the phase difference between the two components leaving the cellophane is

$$\delta = 2\pi(n_s - n_f)\frac{t}{\lambda}.$$

If the phase difference δ happens to be an integer multiple of 2π, the light emerging from the cellophane will be linearly polarized just as it went in, and it will be completely blocked by the crossed analyzing Polaroid.

B2. Colors

The equation for δ says that the phase difference depends on the wavelength of the light. The phase difference will be considerably different for violet light ($\lambda = 400$ nm) than for red ($\lambda = 650$ nm). Suppose that three sheets of cellophane produce a phase change of 2π for yellow light ($\lambda = 590$ nm). Then yellow light will not pass through a sandwich of crossed Polaroids with three sheets of cellophane in the middle. But red light will undergo a phase change of less than 2π, so it will pass through. Similarly blue light will undergo a phase change of more than 2π, so it also will pass through. If the system is illuminated with white light, all components but yellow light will pass through. The name of white with yellow removed is "purple".

Mount two Polaroids in a crossed position at the two ends of the wooden block, fold the cellophane several times in a random manner, and hold it between the Polaroids. Shine white light through the system, and observe the view from behind the analyzer while slowly rotating the cellophane. If you rotate one of the two Polaroids through 90°, each color should change into its complementary color.

Insert transparent objects between two crossed Polaroids and record your observations. Suggested items: plastic rulers, eyeglasses, cellophane tape, flexed plastic protractor.

Use the index card or a piece of glass to hold cellophane tape to insert between your Polaroids. Try using layers of tape. Produce a work of art.

B3. Applications

The fact that stresses in transparent objects become visible between two polarizers can be used in many different ways, for example:

(a) Engineers use plastic models of parts such as those used in airplanes to make visible the stresses under certain loads and to measure the stresses quantitatively. (The essay by Robert Mark, "The Structural Analysis of Gothic Cathedrals," in the November 1972 issue of *Scientific American,* shows how to measure wind stresses on models of Gothic cathedrals using this technique.)

(b) Chemists, biologists, geologists, and crime scene investigators: The stresses in chemical compounds, biological samples, and rocks can be viewed using polarized light, e.g., with a

microscope equipped with a polarizer and polarization analyzer. This can provide valuable information about the composition and history of the sample.

(c) Glassblowers: When glass cools down after a glassblower removes the torch, stresses develop that can eventually lead to spontaneous breakage. In order to relieve stresses, glassblowers anneal their product by heating the finished glass object and then cooling it very slowly (often overnight). Then glassblowers sometimes examine their products between polarizers to see if any stresses remain.

(d) Opticians: So-called safety eyeglasses can be hardened *(tempered)* by heating them and then cooling them quickly. This makes glass harder (exactly as rapid cooling makes steel harder) and less likely to break. It also leaves stresses in the glass, which can be seen between polarizers.

Some safety glasses are chemically hardened rather than heat-treated and these look like untempered glass when put between polarizers. You may still be able to see some stress near the edges. (Federal regulations require that only safety glasses may be sold. The side windows in many American cars are tempered glass. Windshield glass is laminated glass, not tempered glass. You may notice this difference when you're wearing polarizing sunglasses inside a car.)

C. Liquid Crystal Displays

One important application of polarization is the *liquid crystal display (LCD),* used in most digital watches, cell phones, calculators, computers, and televisions. The simplest such displays are those in watches and calculators. The digits on these displays are black on a white background as seen by reflected light. You can convince yourself that polarization matters by putting a polarizer on top of your watch or calculator. You can similarly check out a cell phone or computer display. (When I bought a flat screen TV, I played with it and a sheet of Polaroid for a long time. This was a lot more interesting than the TV shows.)

Liquid crystals are special liquids which have many of the properties of solids. The type commonly used for LCDs contains rod-like molecules which tend to align themselves in one direction. In an LCD, the liquid crystal is contained in a thin layer between thin glass plates. Outside these plates are crossed linear polarizers, so if the liquid is removed, no light passes through the display. The inner surfaces of the glass plates are treated so that the molecules in the liquid align along the direction of the polarizer on that plate (see figure on next page).

Thus the direction of alignment of the molecules gradually changes by 90° in going from one surface to the other. As the polarized light passes through the liquid, the plane of polarization is rotated 90° by the molecules, and the light passes through the crossed polarizers with little loss.

VOLTAGE OFF   **VOLTAGE ON**

P

Molecules

P

Mirror
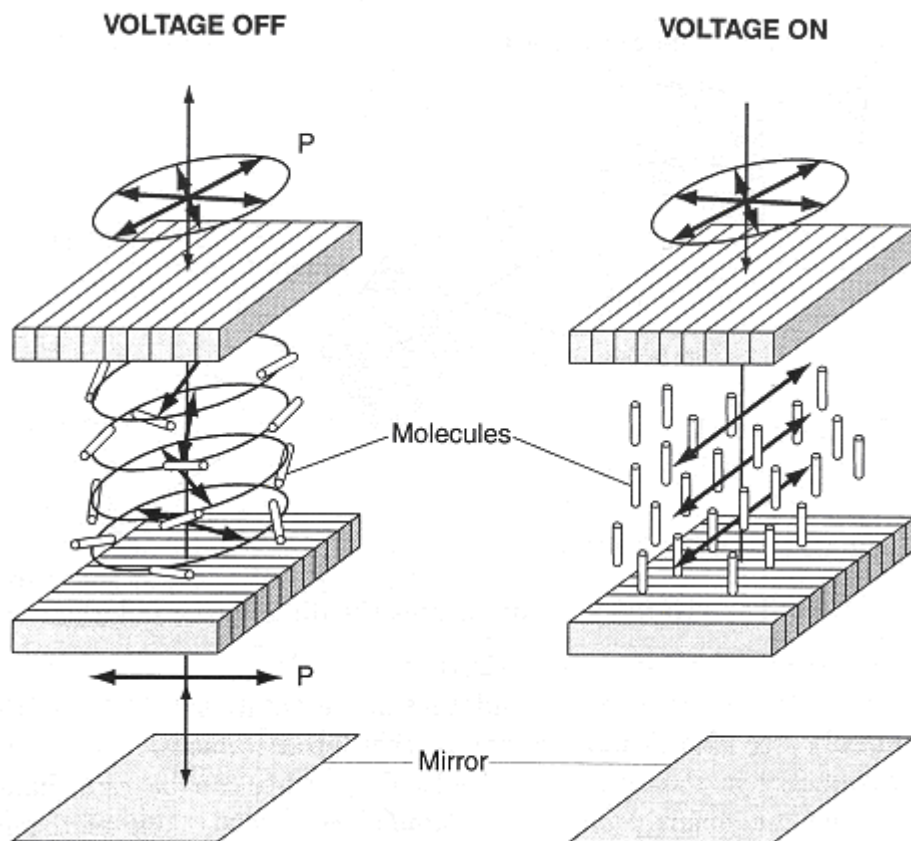
The other important property of liquid crystals used for displays is that the molecules are electric dipoles which tend to align with an electric field. If you look carefully at the dissected display you can faintly see the segments of the display. These are electrodes on the inner surface of one glass plate. If a voltage is applied to one or more segments, the molecules in that area align normally to the plates, and the plane of polarization of the light is no longer rotated. That segment thus appears dark.

The electronic circuits in the watch or calculator can turn the individual segments of each digit on separately. With the right combinations of segments, any number can be displayed.

D. Optical Activity

Hold a linear polarizer under the beaker of corn syrup and another linear polarizer on top. Let light shine through both polarizers and through the solution; turn the top polarizer and record what you see.

Without the solution between the polarizers or with plain water, no light would pass through the crossed polarizers. You will notice that this is no longer true with the corn syrup between. The corn syrup rotates the direction of polarization; it is called "optically active".

Does the angle of rotation depend on wavelength? How do you know? Does the angle of rotation depend on the thickness of the optically active material? How do you know?
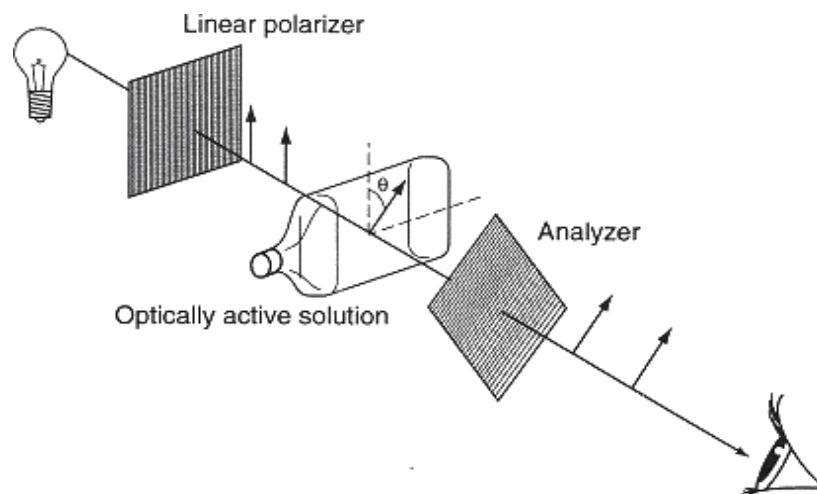
This rotation is due to asymmetry in the corn syrup molecules, which can be "right-handed" or "left-handed". (Fruit sugar and turpentine rotate polarized light in opposite directions.) Most such asymmetrical molecules are produced by living organisms — this is one of the mysteries of life. (See Stuart Clark, "Polarized starlight and the handedness of life," *American Scientist* **87**(4) (Jul/Aug 1999) 336-343.) Almost all amino acids produced by living organisms here on Earth have a *left-handed* optical activity. Amino acids found in certain meteorites are equal mixtures of right- and left-handed molecules, and this is evidence of their extraterrestrial origin.

Chemists use devices called *polarimeters* to examine and measure the optical activity of chemical compounds. This can be used to identify compounds. Also, since optical activity changes when a *magnetic field* is applied (this is called the *Faraday effect),* optical and radio astronomers study polarized light and radio waves to deduce the magnetic fields in stars and galaxies.

Conclusion: When I was an undergraduate, I go the impression that optics was nothing more than setting up lenses along a line in order to make devices like microscopes, telescopes, and cameras. I hope you realize now that this is only a fraction of optics. If you wish to investigate optical phenomena in more detail, I recommend *Light and Colour in the Open Air* by M.G.J. Minnaert and *Rainbows, Halos, and Glories* by Robert Greenler. (Bob Greenler's daughter graduated from Oberlin College.)

Experiment 12: Calorimetry

Objectives

This experiment uses computerized data acquisition to determine the latent heat of vaporization of liquid nitrogen and the specific heat of a metal. These quantities are discussed in HRW section 18-4 ("Absorption of heat by solids and liquids"). Also useful is C.W. Thompson and H.W. White, "Latent heat and low-temperature heat capacity experiment for the general physics laboratory," *Am. J. Phys.* **51** (4), 362-364 (1983).
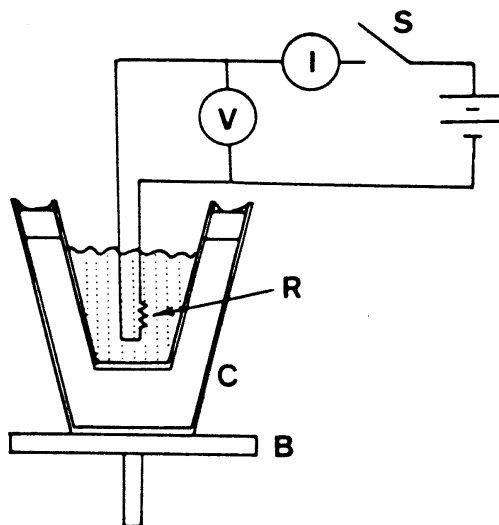
Apparatus

> stainless steel dewar
>
> supply of liquid nitrogen
>
> ohmic heater with 30 VDC power supply
>
> multimeters (2 per group)
>
> thermometer (room temperature)
>
> digital balance modified for computerized data-taking
>
> computer with interface card
>
> assortment of metal samples
>
> tongs & safety goggles

A: Latent Heat of Vaporization of Liquid Nitrogen

Overview: You will place a thermally insulated container (dewar) of liquid nitrogen on a digital balance. Immersed in this will be a resistor attached to a power supply and an ammeter and voltmeter. Initially there will be no current through the resistor and you will measure the background mass loss rate of the liquid nitrogen as it vaporizes due to thermal contact with air at room temperature. Once you have established this background mass loss rate you will turn on the current through the resistor, noting the current through the resistor and the voltage across it. After this resistive heating you will turn off the current and again monitor the mass loss rate. By analyzing a plot of the mass of the system versus time and calculating the energy dissipated in the resistor you will determine the heat of vaporization of liquid nitrogen.

     1. Set up the apparatus as shown in Figure 1. You will use two multimeters: one as an ammeter and one as a voltmeter. What is the rated power dissipation of the resistors? If you turn on the power supply to test the circuit, be careful not to exceed the power rating of the resistors. Otherwise you will get some smoke and melt the solder connections!

<u>Figure 1</u>: Schematic of the apparatus. The letters refer to: B, balance pan; C, stainless steel dewar; I, ammeter; V, voltmeter; S, switch; R, resistor.

2. During this experiment you need to coordinate your computerized data-taking with the use of the ohmic heater. You will use the Logger Pro "Calorimetry" program that records a mass reading once a second. Make a plan with your partner. Think about what your mass vs. time plot will look like and discuss which features of the plot you will use to calculate the latent heat. Do you need to keep track of exactly how long the heater is on?

3. Take your dewar to the instructor to get some liquid nitrogen. **Wear goggles during this process and whenever you work closely with liquid nitrogen!** Place the dewar on the balance and insert the resistive heater, without turning it on. Make sure the heater is completely immersed and does not touch the side of the dewar. When the liquid nitrogen reaches a steady boiling rate, begin taking data.

4. Take mass data for about 200 seconds to establish the background mass loss rate, then turn on the heater. Record the reading on the ammeter and voltmeter. Take mass data for about 200 more seconds, then turn off the heater. Finally take mass data for about 200 more seconds to determine the background loss rate after heating.

5. Plot your mass vs. time data using Logger Pro. Break the data up into a pre-heating, heating, and post-heating phases. Analyze them separately to determine (a) background mass loss rate before heating, (b) background mass loss rate after heating, and (c) the mass loss rate due to ohmic heating.

6. Using the current and voltage readings for the heater, determine the power input into the system. From this determine the heat of vaporization of liquid nitrogen. Compare this with the accepted value of 197.7 J/g and with the values obtained by your classmates.
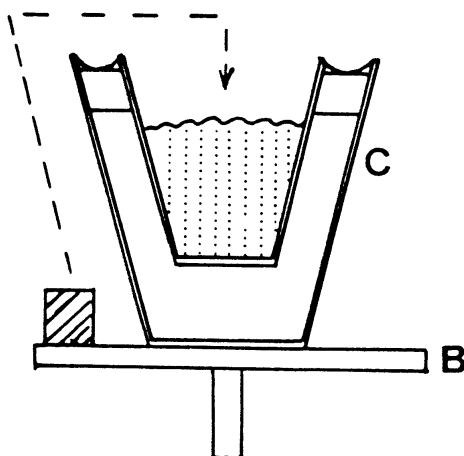
B: Specific Heat of a Metal

Overview: The specific heat of a metal sample is obtained by immersing the sample, initially at room temperature, into a dewar of liquid nitrogen. The mass loss due to this heat input is used to calculate the **average** specific heat of the metal, where the averaging is over the temperature range from room temperature to the liquid nitrogen boiling point (77.3 K).

    1. This experiment will determine the mass loss ΔM due to immersing the metal sample in liquid nitrogen. Derive an equation using ΔM to find the average specific heat of the metal over this temperature range.

    2. Using the setup shown in Figure 2, and your experience in part A, devise an experimental procedure to find ΔM for one of your metal samples.

Figure 2: Schematic of the apparatus illustrating that the metal sample is transferred from the balance pan into the liquid nitrogen during the specific heat measurement. B is the balance pan and C is the stainless steel dewar.

    3. Using the accepted value of $L_V = 197.7$ J/g, convert this mass loss into a Q due to the heat content of the metal sample. From this Q, find the average specific heat of the metal over this temperature range.

    4. Compare your measured average specific heat with the tabulated specific heats in the table on the next page. (If you're ambitious, you might determine the temperature average of these tabulated specific heats.)

	Cu	Pb	Al	C (graphite)	Si
average atomic mass [g/mol]	63.55	207.2	26.98	12.01	28.09
T [K]	molar specific heat [J/mol K]				
70	11.0	23.2	7.7	0.9	4.3
80	13.0	23.6	9.7	1.2	5.2
90	14.7	24.0	11.4	1.4	6.2
100	16.2	24.4	13.0	1.7	7.2
120	18.3	24.9		2.3	9.1
140	19.9	25.1		2.9	10.8
150			18.5		
160	21.1	25.5		3.6	12.5
180	22.0	25.7		4.3	14.1
200	22.6	25.9	21.5	5.0	15.4
220	23.1	26.1		5.7	16.5
240	23.6	26.3		6.4	17.4
250			23.2		
260	23.9	26.5		7.2	18.1
280	24.2	26.7		7.9	18.8
300	24.5	27.0	24.4	8.6	19.5

Table 1: Tabulated molar specific heats at constant pressure.

5. You may want to measure the specific heat of another metal. Alternatively, you may want to repeat this experiment, trying to improve your procedure.