CALIFORNIA STATE UNIVERSITY, SAN BERNARDINO

DEPARTMENT OF PHYSICS

Physics 222

Physics Laboratory II

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INTRODUCTION

In scientific research, experiments are carried out in order to investigate new phenomena and test the predictions made by theories, which attempt to explain these phenomena. In such cases, it is not known what kind of result to expect when performing the experiment. However, neither your understanding of physics (at least not yet) nor the equipment used in this lab is sufficiently sophisticated to do original research.

In this course we will be performing experiments that have been repeated many times before; we therefore know what kind of results to expect. The main purpose of the lab component of this course is twofold: (1) it will provide concrete examples of some of the concepts from the lecture and make these concepts more clear, i.e., you will learn by doing. (2) You will build up your confidence in your experimental abilities by seeing that, in most cases, you will get a result that agrees closely with the expected result.

Since most of you will be continuing in scientific or technical fields, it is also important for you to be able to keep clear and concise records of your experiments. Therefore, you will fill out a worksheet for each experiment that you perform. You should also be able to work as part of a team; hence you will work with a lab partner on each experiment. You may work together with your lab partner while filling out your worksheet, but each partner must turn in a separate worksheet in your own words. No credit will be given to lab partners who turn in identical worksheets. You will also be required to write two lab reports, one will be written after performing experiment 6; the second will be written after performing experiment 8. You will have one week to write your lab report.

No credit will be given to lab partners who turn in identical lab reports.

Bring a calculator and lab manual to lab each week and read the description of that week's experiment before class.

ATTENDANCE IS REQUIRED. Missing more than two classes results in an automatic F for the lab and lecture. You may not copy your lab partner's data. There are no provisions for making up a missed lab.

Your instructor will explain the grading policies.

Your instructor will begin each lab with a short introduction, including an explanation of what you must include in your lab report.

The treatment of experimental uncertainties, or limits on the accuracy of measurements and their effects on the conclusions you can draw from your experiment, are treated in Taylor and are covered in the previous laboratory class.

EXPERIMENT 1: INTRODUCTION TO ELECTRONICS

OBJECTIVE

The purpose of this experiment is to understand the basic equipment we will be using this quarter, how it works and what it measures.

EQUIPMENT

Power Supply, Digital Voltmeter (DVM), Ammeter, Protective Resistor.

THEORY

Electrical Charge

Macroscopic material objects have certain properties, such as mass and density, by which they are characterized. Another property of material objects is their net amount of electric charge. Electric charges come in two complementary types, which suitably have been named positive and negative. As the names suggest, positive and negative charges are opposites. In fact, positive and negative charges neutralize each other, so an object with equal numbers of positive and negative charges has a total, or net, charge of zero. We call this state of an object “electrically neutral” or “uncharged”.

The constituents of matter that make up atoms are electrons, protons, and neutrons. Protons have a positive charge of one electrostatic unit (esu), electrons have a negative charge of one electrostatic unit, and neutrons have zero charge. Stable atoms have equal numbers of electrons and protons and are electrically neutral. In fact, most objects can be expected to be electrically neutral under ordinary circumstances. In practice, it is relatively easy to ionize some small fraction of the atoms in an object by adding or removing electrons. It is very difficult to add or remove protons in the nucleus, so we give objects nonzero net charges by removing electrons from, or depositing electrons onto, the objects. When objects have nonzero net charges, we will say that they are charged.

Coulomb’s Law

Coulomb's law tells us that charged objects exert forces on each other. Charges of the same sign repel each other, but charges with opposite signs attract each other.

Voltage

Because of this force that two particles exert on each other, when we separate out charges we can produce what is called an electromotive force. The electromotive force (emf) is the external work expended per unit of charge to produce an electric potential difference across two open-circuited terminals. This quarter you will hear the terms emf, potential difference, and voltage interchangeably. Voltage is the emf, it pushes charge through the circuit. The voltage of a circuit is defined as an electromotive force or potential difference expressed in volts; thus the units of voltage is volts (V). Voltage is created with our power supply and measured with a digital voltmeter (DVM). The power supply and DVM we will be using this quarter are pictured below.

Figure 1. Power Supply

Figure 2. DVM

<u>Current</u>

The potential difference/voltage created is what creates current in a circuit by driving charges through the loop. A current is the rate at which electric charges pass through a cross-sectional area of wire. Positive and negative charges in motion are called charge carriers. Charge carriers can be positive, negative, or a combination of the two. For example; in a common conductor, such as copper, current is due to the motion of negatively charged electrons. This is because the atomic structure of solid conductors allows the electrons to be transferred easily from one atom to the next, while protons are relatively fixed inside the nucleus of the atom. In some cases (in gases and dissolved salts, for example) current is the result of positive charges moving in one direction and negative charges moving in the opposite direction. The SI unit for current is the ampere (A). Current is measured with an ammeter. The ammeter we will be using this quarter is pictured below.

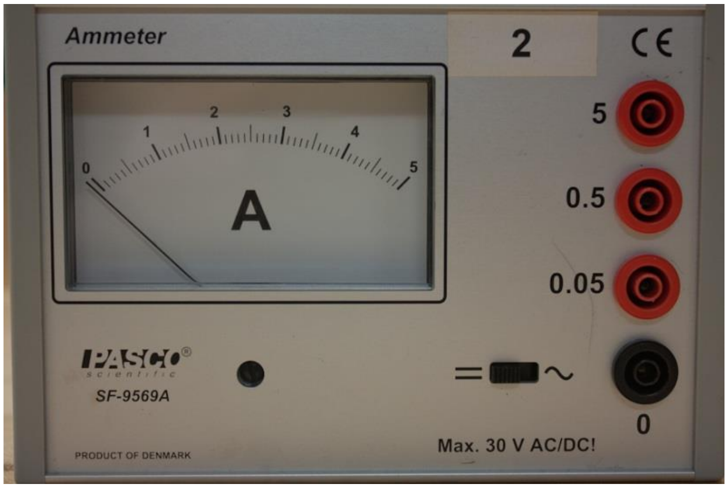


Figure 3. Ammeter

Notice that the ammeter has 3 red ports, each represents a different range. If you plug into the "5", the ammeter will read from 0A to 5A, if you plug into the "0.5" the ammeter will read from 0A to 0.5A, and if you plug into the "0.05" the ammeter will read from 0A to 0.05A.

When you turn on a light it comes on almost instantly. This may make you think that charge carriers are flowing incredibly fast from the socket to the light bulb. In fact, charge carriers move very slowly. What happens, is that as you turn on the switch an electric field is established in the wire. This field (which sets the charges in motion) travels at nearly the speed of light. Electric fields will be discussed more in experiment 5 this quarter.

Resistance

As current travels through different elements there is resistance. Resistance reduces the amount of current that flows for a given voltage. Factors that can affect resistance are length (a longer length of copper will have a greater resistance than a shorter length), cross-sectional area (a smaller cross-sectional area will have a greater resistance than a larger cross-sectional area), material (certain materials are better conductors of electricity than others), and temperature (a higher temperature results in a greater resistance than a lower temperature). Any element can cause resistance in a circuit. Some resistance we can measure, such as the resistance contributed to a circuit by a resistor, and some resistance we will not measure, such as the resistance contributed by the wires in our circuit. Resistance is measured in Ohms (Ω).

Circuits

A circuit is a closed loop system, it is a set of electrical components connected so that they provide one or more complete paths for the movement of charges so that a surplus of charge does not collect at any point. A circuit consists of a power supply and at least one element. Without a load (an element) in your circuit you are in danger of creating a short circuit. For example, a short circuit occurs when a wire is connected from one terminal of a battery to the other by a wire with little resistance. Short circuits can be dangerous, wires can overheat and melt their insulation and possibly cause a fire.

Circuits will be represented by circuit diagrams. Different elements will be represented by different figures; some are shown in the table below.

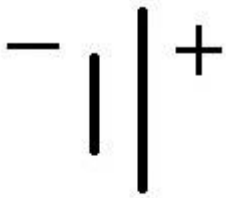
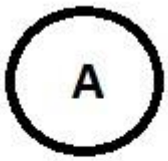
Power Supply	
Wire	
Resistor	
Ammeter	
DVM	

Figure 4.

Other figures for other elements used in circuits will be discussed in future labs.

<u>Equipment</u>

Notice that as you look at the equipment we will be using (power supply, ammeter, and DVM) they all have a red plug and a black plug. When you are building a circuit you must always have a positive and a negative (if we send the current into a piece of equipment it must come out as well).

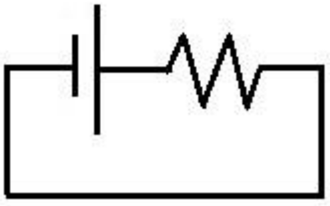
Your Name: ________________________

Lab Partner: ________________________

Experiment 1: Introduction to Electronics Work Sheet

Part I. Building a Basic Circuit

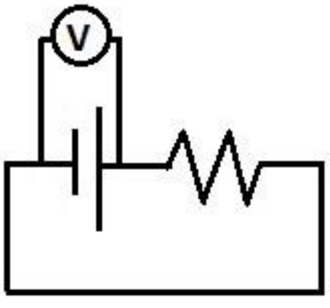
The first thing you will be doing, each week, is building a circuit. As discussed in the theory section a circuit consists of a power supply and at least one element. Our element in our basic circuit will be the protective resistor (which has a value of 630Ω).



Set your power supply to 10V.

Now, we are going to add the voltmeter. You will always build the circuit as depicted in the circuit diagram and then add the voltmeter to the circuit. To do this you will not need to undo any of the circuit that you have built.

Plug the voltmeter across the power supply.



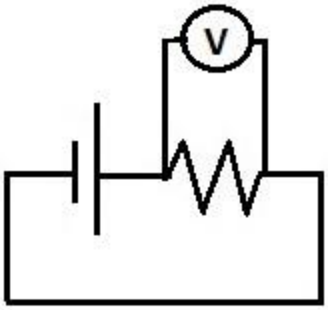
Question 1. What does the voltmeter read?

Next, change the direction that the voltmeter is plugged across the power supply.

Question 2. What does the voltmeter read?

Question 3. What does this tell you about the voltmeter?

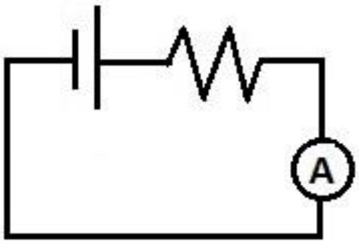
Next, remove the voltmeter from the power supply and plug it across the resistor.



Question 4. What does the voltmeter read?

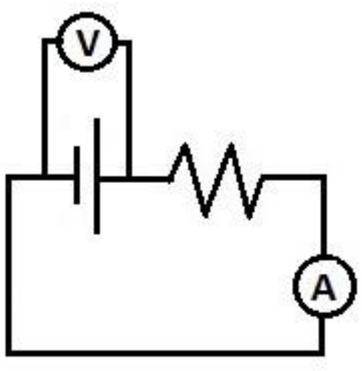
Part II. Reading Current in a Circuit

We are now going to build a circuit with the power supply and two elements. The first element will be our protective resistor (as in Part I), the second element will be the ammeter so we can measure the current in our circuit. Again, we will build our circuit without the voltmeter and then add it to the circuit when we are ready to take a measurement.



Again, set your power supply to 10V.

Plug the voltmeter across the power supply.

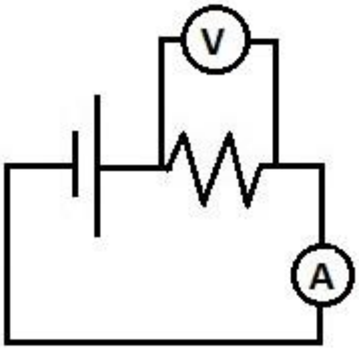


Question 5. What does the voltmeter read?

Question 6. How does this voltage reading differ from the voltage reading across the power supply in Part I?

Question 7. What does the ammeter read?

Next, remove the voltmeter from the power supply and plug it across the resistor.



Question 8. What does the voltmeter read?

Question 9. What does the ammeter read?

Question 10. How does this voltage reading differ from the voltage reading across the resistor in Part I?

Part III. The Many Uses of the Voltmeter

The voltmeter can be used in many different ways. We can use the voltmeter as an Ohmmeter (to measure the resistance of a resistor)

Set your voltmeter to measure Ohms. Plug your voltmeter across the resistor.

Question 11. What does the voltmeter (set as an Ohmmeter) read?

Part IV. Conceptual Questions

These questions can be answered by looking in the theory section of this experiment.

Question 12. Why is it possible for a bird to be perched on a high-voltage wire without being electrocuted? (Hint: Consider the potential difference between the bird's two feet.)

Question 13. If charges travel very slowly through a metal (approximately 10^{-4} $^{m}/_{s}$), why doesn't it take several hours for a light to come on after you flip a switch?

Question 14. What is voltage?

Question 15. What is current?

Question 16. What is a resistor?

EXPERIMENT 2 EQUIPOTENTIAL LINES AND ELECTRIC FIELD LINES

OBJECTIVE

The purpose of this experiment is to determine the equipotential lines and the electric field lines for two oppositely charged point charges, parallel bars, and insulator/conductor circles.

EQUIPMENT

DVM with probes, a battery eliminator (9.0 V), mounting board, conducting board with electrical circuit analogs.

THEORY

Electrodes corresponding to the cross section of two point charges, two parallel bars and insulator/conductor circles are painted on a conducting board using conducting paint. These electrodes are connected to a voltage source establishing a potential difference V_o between them. Choosing a reference potential, a voltmeter and points on the board allows us to map out the equipotential lines on the conducting board. Using the equipotential lines we can determine the electric field lines since the electric field lines are perpendicular to the equipotential lines. The magnitude of the electric field at a point midway between two nearby equipotential lines is given by:

$$|E| = \left|\frac{\Delta V}{\Delta L}\right| = \left|\frac{V_2 - V_1}{\Delta L}\right| \quad (1)$$

where $\Delta V = V_2 - V_1$ is the potential difference between the two equipotential lines and ΔL is the length of the electric field line between the two equipotential lines.

Your Name: ______________________________

Lab Partner: ______________________________

Experiment 2: Equipotential Lines and Electric Field Lines Worksheet

Set up the equipment as shown in Fig. 1. Be careful that the surface of the conducting board does not become damaged when fixing or removing it from the mount. We will first study the equipotential and the electric field lines for two oppositely charged point charges. Mount the conducting board with two silver dots painted on it (the dots approximate two point charges) with the two silver dots visible to you. Attach the leads from the battery to the silver dots and one of the leads of the voltmeter to the reference potential, i.e. the negative terminal of the battery. Using the movable probe, locate the points that correspond to a potential of one half volt higher than the reference voltage. Locate enough points so that you can easily draw the equipotential curve. Obtain as much of the equipotential curve as you can without going too close to the edge of the conducting paper. You can record your data directly on graph paper. Record the position of the "point charges". Repeat for all intermediate equipotential lines in increments of one volt.

Repeat for the configuration for the insulator/conductor circles, as well as two oppositely charged parallel bars. For the configuration of insulator/conductor circles, determine the equipotential lines and electric field lines for points inside each circle and around them. For the equipotential maps obtained above, draw the electric field lines. Find the magnitude of the electric field at several points in each of the charge configurations studied using Eq. (1).

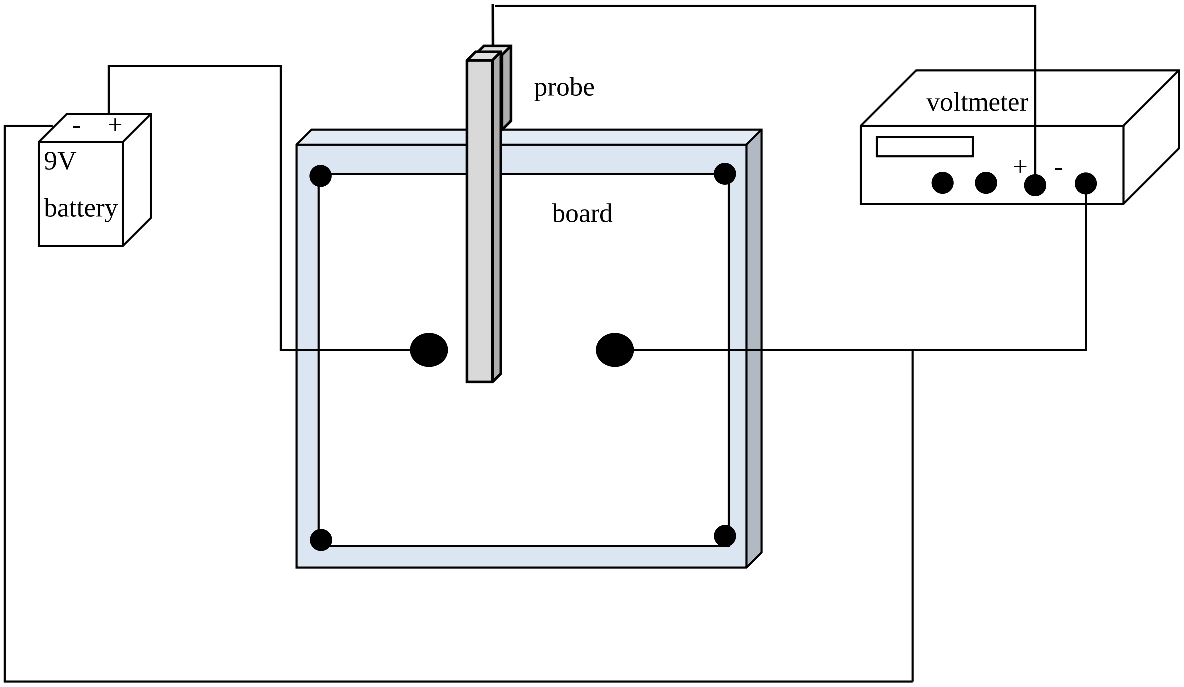


Figure 1. Equipotential and electric field lines board set up.

Plate Type	ΔV_1	ΔL_1	ΔV_2	ΔL_2	ΔV_3	ΔL_3	$\lvert E_1 \rvert$	$\lvert E_2 \rvert$	$\lvert E_3 \rvert$
2 Point Charges									
2 Parallel Bars									
Point Charge w/ ‖ Bar									
Point Charge w/ Horseshoe									
2 Concentric Circles									

Question 1. The component of the electric field $\vec{E}$ in the direction of an equipotential line is zero. Why?

Question 2. Is it possible for two different equipotential lines or two electric field lines to cross? Explain.

Question 3. How much work is done in transferring an electrostatic unit of charge from one electrode to the other?

EXPERIMENT 3 CIRCUITS I: OHM'S LAW

OBJECTIVE

The purpose of this experiment is to find the relationship between the electrical potential difference (or voltage) across a circuit element and the current flowing through it.

EQUIPMENT

Digital Voltmeter (DVM), DC-ammeter, regulated DC-power supply, resistors, protective resistor (630 Ω), light bulb, diode.

THEORY

An electrical resistance may be assigned to any current carrying device in which the electrical energy is dissipated. By definition the resistance R of a dissipative device across which there is an electrical potential difference V and a current I is

$$R = \frac{V}{I}$$

If the potential difference is measured in volts (V) and the current in amperes (A), the resistance is then measured in ohms (Ω).

The resistance of a dissipative device is not in general a constant, but depends on the current or the potential difference. However, there is one important situation in which the resistance of a dissipative element is simple, that is, when the resistance is a constant. The above relation for this special case of constant R is known as ohm's law. It is found that R is constant for a large variety of materials and for an enormous range of currents and potential differences.

Ordinary resistors vary in size and shape depending on the energy that they can dissipate and, for most of them, their value is indicated by using a color coded sequence of bands printed on the resistor. Resistors are represented in circuits as a jagged line, as the one shown for the protective resistor in Fig. 1.

Your Name: ______________________

Lab Partner: ______________________

Experiment 3: Circuits I: Ohm's Law Work Sheet

In this experiment you are to measure the voltage across an element as a function of the electrical current flowing through it. The potential difference or voltage across the resistor will be measured using the digital voltmeter or DVM, and the current flowing through the resistor will be measured using a ammeter. Be sure to cover as wide range of voltages and currents while taking data.

<u>Part I. Resistors</u>

Set up the circuit shown in Fig. 1 using a resistor as the element. Notice the way that the voltmeter and the ammeter are connected in the circuit; the voltmeter is always connected across the element for which you want to measure the potential difference between its terminals, and the ammeter is always in line with the element for which you want to measure the current flowing through it.

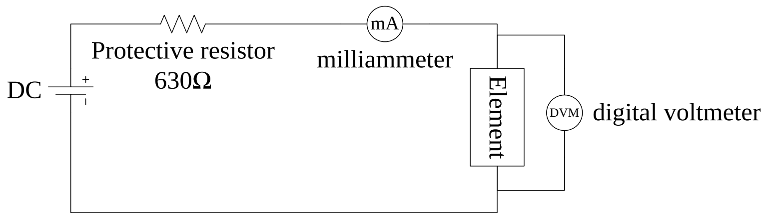


Figure 1.

First, make sure that the knob of the regulated power supply is all to the left before you turn it on and that the DVM is set up as a voltmeter by depressing the "DC" and "VOLTS" buttons. Slowly increase the voltage by turning the knob on the regulated power supply. If the ammeter reads "downscale" (to the left) reverse the leads to that meter.

Increase the voltage. Record the voltage off the DVM and the corresponding current through the element for even intervals of the current. Select your intervals so that you have at least ten measurements. Repeat the procedure for several different resistors and make a graph which clearly shows how the current changes with the voltage for each resistor.

Resistor 1 =____________		**Resistor 2 =____________**		**Resistor 3 =____________**	
V ( )	**I ( )**	**V ( )**	**I ( )**	**V ( )**	**I ( )**

Find the resistance for **one** of the above elements by finding the slope of the best fit straight line.

Question 1. From your graph of voltage vs. current, how do you know if the resistors obey Ohm's Law?

Question 2. Calculate the % Discrepancy between the printed value and measured value of the resistor you graphed.

Part II. Light bulb and diode

Using the same circuit as in Part I, use a small light bulb and then a regular (rectifier) diode as the element. Carefully increase the voltage and record the voltage and current on the element. Next, reverse the direction of the current by reversing the element and repeat the same procedure as before.

Light Bulb		**Light Bulb Reversed**	
V ( )	**I ( )**	**V ( )**	**I ( )**

Create a graph of voltage vs. current for the light bulb and light bulb reversed. Graph both data sets on the same graph.

Question 3. Does the light bulb obey Ohm's Law? Why or why not?

Diode		**Diode Reversed**	
V ( )	**I ( )**	**V ( )**	**I ( )**

Question 4. Does the diode obey Ohm's Law? Why or why not?

EXPERIMENT 4 CIRCUITS II: RESISTORS IN SERIES AND PARALLEL

OBJECTIVE

To study the resistance of various combinations of resistors.

EQUIPMENT

DC power supply, DVM, 3 ammeters, 5-6 different resistors (100-1000 Ω), protective resistor (630 Ω).

THEORY

In this experiment we will examine the resistance of various combinations of resistors. We will consider three types of combinations: series, parallel, and series-parallel.

<u>Series Resistors</u>

If several resistors are connected in sequence end-to-end, they are said to be connected in series. (See Fig. 1 which shows two resistors of resistance R_1 and R_2 in series.) The current through each resistor of a series arrangement is the same. On the other hand, the voltage drop across each resistor depends on the resistance of that resistor. Considering first the case of two resistors in series we can define an overall or effective resistance R_s across the series combination (i.e., between A and B of Fig. 1). This effective resistance satisfies Ohm's law:

$$R = \frac{V}{I} \quad (1)$$

Where V here is the voltage drop across the combination (i.e., from A to B of Fig. 1) and I is the current through each resistor. The combination acts like a single resistor of resistance R_s. It can be shown that the effective resistance is given by:

$$R_s = R_1 + R_2 \quad (2)$$

This can be generalized to the case where there are N resistors R_1, R_2 ... R_N connected in series. The effective resistance of the combination is then:

$$R_s = R_1 + R_2 + \cdots + R_N \quad (series) \quad (3)$$

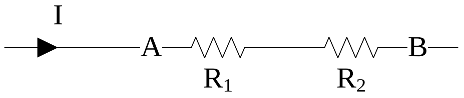


Figure 1. (series)

<u>Parallel Resistors</u>

If several resistors are connected between the same two wire leads; the resistors are said to be in parallel. (See Fig. 2 which shows two resistors in parallel.) In this case the voltage drop across each resistor and across the combination is the same and the current through each resistor depends on the resistance of that resistor. Considering first the case of two resistances R_1 and R_2 in parallel we can define an effective resistance R_p across the combination (i.e. from A and B of Fig. 2). This effective resistance again satisfies Ohm's law with I the total current (see Fig. 2) and with V the voltage across the parallel combination. The combination acts like a single resistance R_p. It can be shown that the combined parallel resistance is given by:

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} \quad (4)$$

$$R_P = \frac{R_1 R_2}{R_1 + R_2} \quad (5)$$

Generalizing to N resistors in parallel it is shown that

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N} \quad (parallel) \quad (6)$$

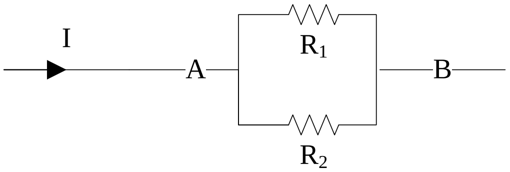


Figure 2. (parallel)

Series-Parallel Resistors

The series-parallel arrangement combines aspects of both series and parallel arrangements. An example is shown in Fig. 3. Here R_1 and R_2 are in parallel. Now R_1 and R_2 can be viewed as a single effective resistance R_p (Eq. (5)). The resistances R_p and R_3 are seen to be in series. Using the series resistance formula Eq. (2) we have for the overall effective resistance R_e (i.e., between A and B of Fig. 3) of this series-parallel combination:

$$R_e = R_P + R_3 = \frac{R_1 R_2}{R_1 + R_2} + R_3 \quad (\text{series} - \text{parallel}) \quad (7)$$

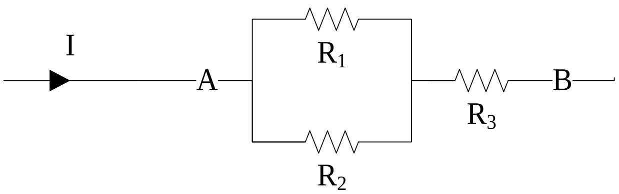


Figure 3. (series-parallel)

Your Name: ________________________________

Lab Partner: ________________________________

Experiment 4: Circuits II: Resistors in Series and Parallel Worksheet

We will experimentally verify the series, parallel and series-parallel combination formulas Eq. (2), Eq. (5), and Eq. (7).

Part I. Series

Set up a circuit with two arbitrary resistances R_1 and R_2 (in the range 100-1000Ω) in series as in Fig. 4.

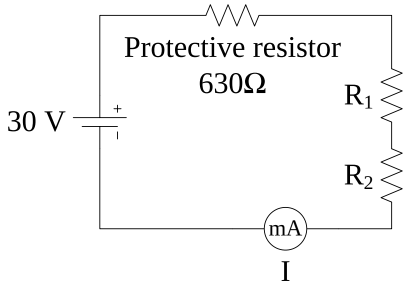


Figure 4.

The flat green protective resistor (630Ω) is used to limit current flow to protect the ammeter. (Note that the internal resistance of the ammeter can be ignored here and in Parts II and III below since this is very small (1Ω) compared to the typical resistances in the circuits involved.) Measure the voltage drops V_1 and V_2 across R_1 and R_2. Measure the current I in the circuit. From the measured V_1, V_2, and I find R_1 and R_2 and their uncertainties (don't use the printed resistance values here). Next measure the overall voltage drop V across the R_1-R_2 combination. From V and I directly, find the (experimental) effective resistance R_S(exp) and its uncertainty from Ohm's Law. Compare R_s(exp) with the theoretical prediction R_S(th) of Eq. (2) using the above R_1 and R_2 values and discuss your results. Perform the above procedure a total of 3 times with different choices for the pair R_1, R_2 each time.

Set #	V_1	V_2	V_{total}	I	R_1	R_2	R_{exp}	R_{theo}	% D
1									
2									

Question 1. Do you confirm the series resistance formula, Eq. (2)?

Part II. Parallel

Set up a circuit with two arbitrary resistances R_1 and R_2 (in the above range) in parallel as in Fig. 5.

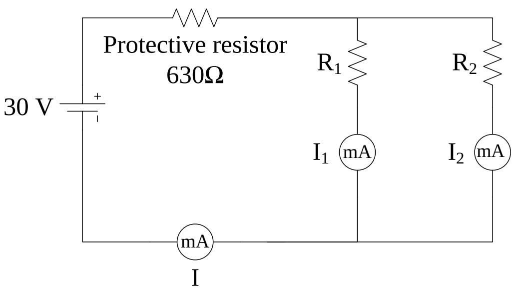


Figure 5.

Measure the voltage drop V across the parallel resistors. Measure the currents I_1 and I_2 through each resistor and the total current I through the parallel combination. From V, I_I and I_2 determine R_1 and R_2 and their uncertainties. From V and I find directly from Ohm's law the (experimental) effective resistance R_p (exp) and its uncertainty. Compare this with the prediction R_p (theo) (Eq.(5)) using the above R_1 and R_2 values and discuss your results. Perform the above procedure a total of 3 times with a different choice for the pair R_1, R_2 each time.

Set #	I_1	I_2	I_{total}	V	R_1	R_2	R_{exp}	R_{theo}	% D
1									
2									

Question 2. Do you confirm the parallel resistance formula, Eq. (5)?

Part III. Series-Parallel

Set up the circuit of Fig. 6. Choose three arbitrary resistors R_1, R_2, R_3 in the above range. By measuring currents and voltage drops as in Parts I and II above determine R_1, R_2, R_3 and their respective uncertainties. Determine the overall voltage drop V across and total current through the series-parallel combination. From V and I find directly from Ohm's law the (experimental) effective resistance R_e(exp) and its uncertainty. Compare with the theoretical prediction R_e (th) of Eq. (7) using the above R_1, R_2, R_3 values and discuss your results. Perform the above procedure for 2 different sets of (R_1, R_2, and R_3).

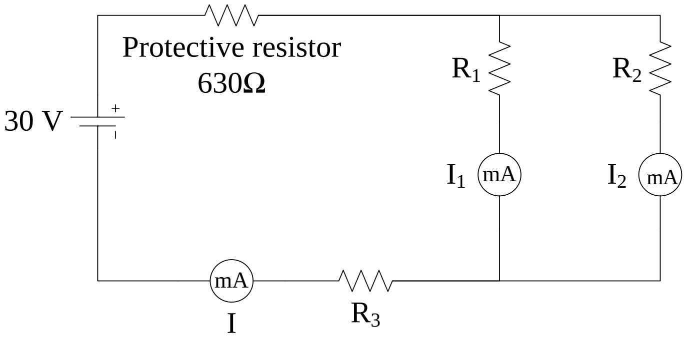


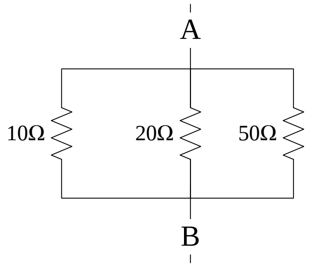
Figure 6.

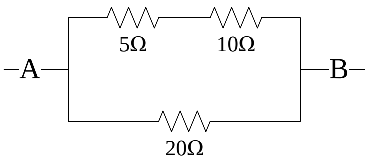
Set #	**I_1**	**I_2**	**I_{total}**	**V_{12}**	**V_3**	**V_{total}**
1						
2						
	R_1	**R_2**	**R_3**	**R_{exp}**	**R_{theo}**	**% D**
1						
2						

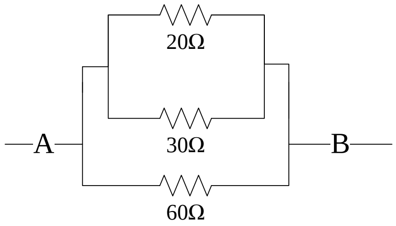
Question 3. Do you confirm Eq. (7)?

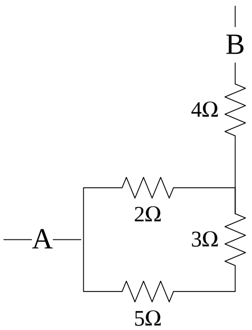
Question 4. Determine the effective resistance between A and B for the following:

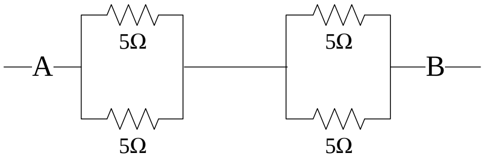
a.) 

b.) 

c.) 

d.) 

e.) 

f.) 

EXPERIMENT 5 THE POTENTIOMETER

OBJECTIVE

To become familiar with the potentiometer, an electrical circuit used for the accurate determination of voltages.

EQUIPMENT

DC power supply, thin wire on a meter stick, galvanometer, batteries, 150 Ω resistor, wires.

THEORY

The potentiometer we will be using is depicted in Fig. 1. The potentiometer is used to measure the cell voltage (also known as the electromotive force or $\mathcal{E}mf$) for several battery combinations. The battery to be measured is placed in the lower "loop" of the circuit (see Fig. 1). The galvanometer is an extremely sensitive ammeter (it can detect currents in the microamp range) and is used to monitor the current through the battery. The thin wire on the meter stick (extending from a to c in Fig. 1) acts as a resistor. The position of the sliding contact (i.e., an alligator clip at the end of a wire) on the thin wire (point b) can be varied. The resistance of the thin wire between points a and b is proportional to the length of wire between a and b: the latter can be read directly off the attached meter stick. The resistor R is used to limit the current into the galvanometer.

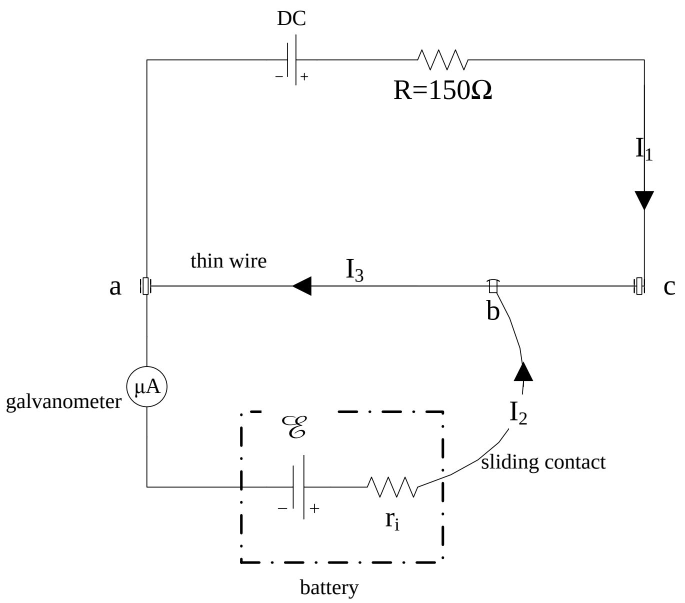


Figure 1.

A variation of the usual operation of the potentiometer which will be used in the present experiment. (We do this as we do not have a "standard" cell, i.e., a cell of standard fixed voltage, which is used in the usual procedure.) With the unknown battery in place the power supply is set to a voltage about 10-20 times greater than what the battery $\mathscr{E}mf$ is roughly expected to be. Then the sliding contact is moved (pressing firmly on the wire) until the current I_2 through the battery is zero. This zero or "null" current condition is very basic to the operation of the device and is accurately established with use of the galvanometer. When $I_2 = 0A$, the $\mathscr{E}mf$ of the battery $\mathscr{E}$ must equal the voltage drop V_{ab} across the portion of the wire from a to b:

$$\mathscr{E} = V_{ab} \quad (\mathrm{I}_2 = 0\mathrm{A}) \quad (1)$$

Eq. (1) follows from the requirement that the sum of the voltage gains equal the sum of the voltage losses (i.e., "IR" losses) going around any closed loop, in this case, the lower loop. Note that the voltage drop across the internal resistance r_i of the battery is zero since $I_2 = 0A$. Now when $I_2 = 0A$ we must have:

$$I_3 = I_1 \quad (\mathrm{I}_2 = 0\mathrm{A}) \quad (2)$$

That is, all the current coming from the power supply into point c must "flow" into the thin wire since otherwise some current would "flow" into the battery contrary to the assumption $I_2 = 0$; this conclusion is a consequence of charge conservation. Denoting the resistance of the wire from a to b by r_b we have using Eq. (2) and Ohm's law in Eq. (1):

$$\mathscr{E} = I_1 r_b \quad (3)$$

Let L_c denote the total length of thin wire (i.e., from a to c, here $L_c = 1.00$ m), L_b the length of thin wire from a to b and r_c the resistance of the entire length of thin wire. Then from the linear proportionality between resistance and length of wire:

$$r_b = \left(\frac{L_b}{L_c}\right) r_c \quad (4)$$

Using Eq. (4) in Eq. (3) and Ohm's Law we find:

$$\mathscr{E} = \left(\frac{L_b}{L_c}\right) V_{ac} \quad (\mathrm{I}_2 = 0\mathrm{A}) \quad (5)$$

where V_{ac} is the voltage drop from a to c:

$$V_{ac} = I_1 r_c \quad (\mathrm{I}_2 = 0\mathrm{A}) \quad (6)$$

Your Name: ________________________________

Lab Partner: ________________________________

Experiment 5: The Potentiometer Worksheet

r_c = ___________________

We will measure the $\mathscr{E}mf$ for the following three "unknown" batteries: (1) one flashlight battery; (2) two flashlight batteries in series (voltages adding); (3) one standard cell battery. Insert the "unknown" battery into the circuit making sure the polarity is as indicated in Fig. 1. Fix V_o initially at 20 V and position the sliding contact so as to register a null current I_2 as described above. When the null condition is achieved measure L_b and V_{ac} (Note that the value of V_{ac} at the null condition is independent of $\mathscr{E}$ and reflects only the choice of V_o (and the fixed values of r_c and R); Next use Eq. (5) to find $\mathscr{E}$. Find the percent discrepancy between the measured and printed values of $\mathscr{E}$ for each battery.

EMF	**L_c ( )**	**L_b ( )**	**V_{ac} ( )**	**ε_{exp} ( )**	**ε_{theo} ( )**	**% D**
1 battery						
2 batteries						
Std. cell					**NA**	**NA**

Question 1. Decrease V_o to 5.0 V and attempt to measure $\mathscr{E}$ for one flashlight battery. Can you find a null current?

Question 2. For a given choice of V_o is it possible that the unknown $\mathscr{E}mf$ may be such that a null current may not be found for any contact position?

Question 3. Referring to the figure and thinking about the "competing" $\mathscr{E}mf$'s of the power supply and battery, how should V_o be changed so as to allow a null current reading? Explain.

Question 4. Show that when $I_2 = 0A$, V_{ac} is given by:

$$V_{ac} = \left(\frac{r_c}{R + r_c}\right) V_0 \quad (7)$$

Hint: Use the fact that: the sum of voltage gains is equal to the sum of voltage losses around any closed loop (see above) and Eq. (2).

Question 5. Show using the result from Question 2 that at the null condition L_b/L_c is given by (when $I_2=0A$):

$$\frac{L_b}{L_c} = \left(\frac{R + r_c}{r_c}\right)\frac{\mathscr{E}}{V_0} \quad (8)$$

Question 6. For fixed R, r_c, and $\mathscr{E}$, explain from Eq. (8) why a null current cannot be registered for sufficiently small V_o.

EXPERIMENT 6 THE OSCILLOSCOPE

OBJECTIVE

To become familiar with the digital oscilloscope and to measure the speed of sound.

EQUIPMENT

Digital oscilloscope, tuning forks, signal generator, speaker, microphone, meter stick.

THEORY

SEE APPENDIX C FOR FULL INSTRUCTION ON THE OSCILLOSCOPE.

The digital oscilloscope is a complex, delicate electronic device. However, you will NOT damage the oscilloscope by pushing the buttons, turning the knobs, or plugging in the wires as long as you exercise a little caution. If a knob is hard to turn, do not turn it any farther. If a connecter does not fit together easily, do not force it. The voltages available in our laboratory will not harm the oscilloscope, and will not shock you. At first, the oscilloscope will probably seem impossibly complicated, but that is mostly because it is unfamiliar. With a little practice, you will learn how to perform simple tests with it very easily. The best advice is to be fearless experimenters!

When we measure voltages with the usual digital meters, we get an average voltage over time. This makes a digital voltmeter a good tool for measuring signals that are constant, or slowly changing. But many processes in nature change so quickly that we cannot get meaningful data from average values. We need a voltmeter that can react very quickly to changes, and can record the changes over a long enough time period to discern patterns in a signal. This is the purpose of the oscilloscope.

The oscilloscope takes advantage of the fact that there are many devices (microphones, strain gages, motion sensors) that can translate physical phenomena (a pressure pulse, a bending piece of metal, a light beam being blocked) into electrical signals. The voltage pattern of these electrical signals is displayed by the oscilloscope which enables us to study the physical phenomena represented by the signals.

The oscilloscope display is a cathode ray tube (CRT), like the picture tube in an old television or a computer monitor. A CRT contains an electron gun that accelerates a beam of electrons toward the viewing screen. In a color display, there is an electron gun for each color: red, green, and blue. Vertical and horizontal deflecting plates steer the beam allowing the beam to make changing patterns on the screen. In our oscilloscope CRT, the vertical deflection plates are controlled by the input signal, and the horizontal deflection plates are set to sweep steadily across the screen at a selected rate.

PROCEDURE AND ANALYSIS

Part I. Measuring period and frequency

With the LINE POWER on, set the TRIGGER SOURCE control to LINE, the SWEEP RATE to 1.00s/div (see onscreen status line display), and the oscilloscope TRACE, a single dot, travels across the screen. Adjust INTENSITY to give a trace that is clear and easily visible, but not too bright. Adjust the vertical POSITION of the trace so it travels along the horizontal axis of the screen. Increase the sweep rate (reduce the time value of each division), and the dot moves across the screen faster. Press the MAIN/DELAYED button above the SWEEP RATE control to enable the softkeys, and switch the time reference from center to left and see how that changes the pattern.

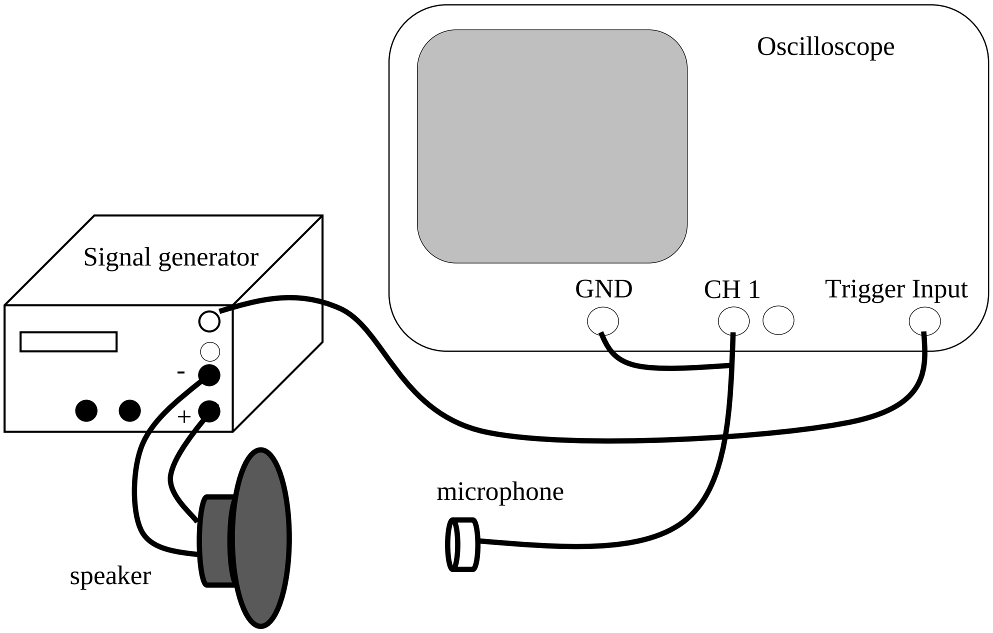
Use the SETUP key and the softkey to return to the default setup. Select CHANNEL 1. Connect the microphone to CHANNEL 1 by connecting one microphone wire to the CHANNEL 1 input, and one wire to the COMMON GROUND (rake symbol). The microphone wires are not interchangeable, so try the wires both ways to see which works. With the microphone switch ON, hum, whistle, and sing a long, steady note into the microphone, which should produce a fairly regular pattern on the screen. Adjust the SENSITIVITY and SWEEP RATE controls until you see a few periods of the wave pattern, about half as tall as the screen. With a little practice, you should be able to generate a reasonably uniform pattern. Each person should try this exercise.

A. Find and record the period of each pattern. The period is the time represented by the distance on the screen between two identical points on consecutive waves. To calculate the period, multiply the SWEEP RATE and the distance of one wave. Show that the calculation of the period done in this manner gives the correct units. Alternately, you can use the CURSOR key and the softkeys to position the time cursors (T_1 and T_2) to the correct distance and thus, Δt is the period. Recall that frequency is the inverse of period. Calculate the frequency from the period.

B. Using the TIME menu commands, find and record the period and frequency of the note. Compare these values to the values found in Section A. Using the VOLTAGE menu, select V_{rms} using the softkey to find the root mean square voltage of the note.

C. Using two of the tuning forks and the microphone setup, find and record the period and frequency of each tuning fork using the TIME menu commands.

Part II. Speed of sound



Select the default setup. Keep the microphone connected to the oscilloscope and connect the signal generator trigger output to the TRIGGER input of the oscilloscope. Using the SOURCE softkey menu, select EXTERNAL. This will synchronize the beginning of each waveform output from the signal generator with the beginning of each sweep across the oscilloscope screen. Connect the signal generator output to one terminal of the speaker, and the ground from the signal generator to the other terminal of the speaker. Test the setup by turning the signal generator on, with the amplitude at about half of maximum, and the waveform set to produce square waves at about 50Hz. Remember that Hertz (Hz) is the unit of frequency, which is "inverse seconds". A periodic signal with frequency of 2.5Hz means that the signal's pattern repeats itself 2.5 times per second, often described as 2.5 cycles per second. You should hear a steady low-pitch sound coming from the speaker.

Turn on the microphone and position it about 50cm from the speaker. You will measure the distance from the speaker to the microphone by placing the speaker at one end of a meter stick on the bench, and the microphone at various points along the meter stick. Look at the wave pattern on the oscilloscope screen, which should be irregular. Adjust the SENSITIVITY control so the pattern is as large as possible, and set the SWEEP RATE to 1 milliseconds/div. The irregular pattern on the screen is synchronized with the signal from the signal generator by the TRIGGER function, so when you change the distance from the speaker to the microphone, the whole pattern should shift across the screen. Move the microphone closer to the speaker, and the pattern should shift to the left. Try this now, and see that the pattern grows vertically as well, since the microphone is transmitting a stronger signal. As you move the microphone even closer, you can keep the pattern small enough to fit on the screen by adjusting the

SENSITIVITY or the signal generator amplitude, or both.

Position the microphone as close to the speaker as you can, which we will call a distance of d=0cm from the speaker. Adjust the oscilloscope and signal generator controls to give a pattern on the screen that is as large as possible and shift the largest spike to the left of the screen. Align the CURSOR for T_1 to the spike of the pattern. This pattern will look different from the patterns we have seen so far. As you move the microphone away from the speaker, the time delay for the signal to travel the greater distance will be seen as the pattern spike shifts to the right across the oscilloscope screen. Align the CURSOR for T_2 to the spike as it shift across the screen. The value of the time delay is Δt.

A. Measure the time delay for distances from 0 to 100cm, in 10cm increments. Include uncertainty values for the distances and the delay times. Make a graph showing the speaker-to-microphone distance as a function of the delay time, with error bars. Fit a straight line to the graph. Physics 222 students, compute the least-squares best-fit line to your data (see Ch. 8 in Taylor). Find the speed of sound in the laboratory from the slope of your graph. Compare your result to 34000cm/s, which is the standard value for the speed of sound in air at standard temperature and pressure.

Question 1. What is the speed of sound from your graph? What is the percent discrepancy?

Question 2. Why does your value for speed of sound differ from the known value of speed of sound?

B. Using the VOLTAGE menu, find and record the signal strength at 20cm, 40cm, and 60cm with the signal generator amplitude setting fixed.

Question 3. How do you expect the V_{rms} values to be related?

Your Name: ______________________________

Lab Partner: ______________________________

Instructor Signature: ______

Experiment 6: The Oscilliscope

A. Period and Frequency

	Sweep Rate SW (unit of time/div)	Divisions (div)	Period_{theo} ( )	Period_{exp} ( )	Frequency ( )	V_{rms} ( )	%D of Period
Hum							
Whistle							
Note							
Tuning Fork 1	**Frequency 1 =**						
	Period 1 =						
Tuning Fork 2	**Frequency 2 =**						
	Period 2 =						

B. Speed of Sound

Sweep Rate: ____________(units of time/div)

Microphone Distance (cm)	Time Delay ( )	V_{rms} ( )
0		**N/A**
10		**N/A**
20		
30		**N/A**
40		
50		**N/A**
60		
70		**N/A**
80		
90		**N/A**
100		**N/A**

EXPERIMENT 7 RC CIRCUITS

OBJECTIVE

The purpose of this experiment is to study the properties of the capacitor by studying the way it charges and discharges in a simple circuit.

EQUIPMENT

Signal generator, oscilloscope, 4μF capacitor, two 0.1 μF capacitors, 1000Ω resistor, computer with interface and voltmeter attachment, and various banana wires.

THEORY

Capacitors are devices in which electric charges are stored. In fact, any object on which charges are deposited acts as a capacitor. The capacitance (C) is defined as the ratio of the charge Q stored in the capacitor to the electrical potential V_c across its terminals, that is

$$C = \frac{Q}{V_c}$$

If Q is measured in coulombs (C) and V_c in volts (V) then the capacitance is given in farads (F). The farad is a large unit and most capacitors are labeled in microfarads (μF), nanofarads (nF) or picofarads (pF). The symbols used to represent them in schematics reflects their physical construction (see Fig. 1.), and in some cases they also indicate their polarity, such as with electrolytic capacitors which require a definite polarity for proper operation (improper polarity can result in an explosion).

Figure 1.

Referring to the circuit in Fig. 2, consider the case where the capacitor is initially uncharged and that the switch S closes at time t=0s. It is found that the voltage across the capacitor does not rise instantly when the switch is closed, but instead it increases according to the following equation:

$$V_c(t) = V_s\left(1 - e^{-\left(t/_{RC}\right)}\right) \quad (1)$$

As the voltage across the capacitor rises, the voltage across the resistor decreases, and thus the current charging the capacitor decreases according to

$$I_c(t) = I_0 e^{-\left(t/_{RC}\right)} \quad (2)$$

Where $I_o=V/R$ is the current at t=0s. The product RC has the units of time, and determines how fast the capacitor charges; this product is known as the time constant of the circuit, τ.

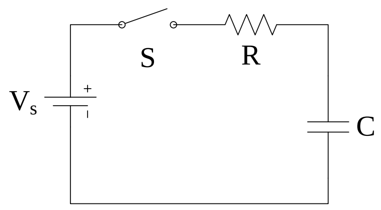


Figure 2.

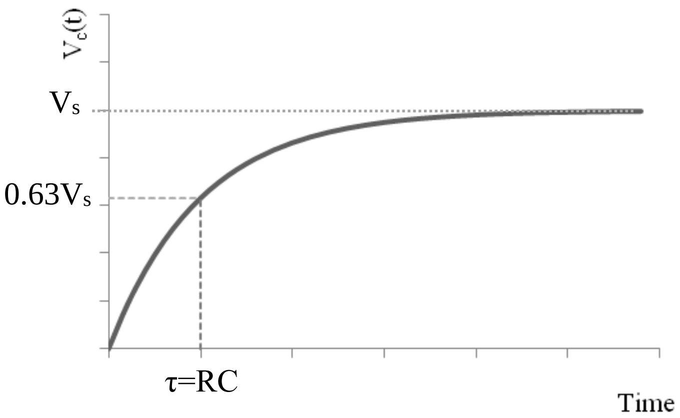


Figure 3. Charging of a capacitor

In a time equal to the time constant, the capacitor reaches a value of (1-1/e) of its maximum value or about 63% (see Fig. 3.). In the same time, the current will have decreased by a factor of 1/e of its initial value or to about 37%. This kind of decrease is called an exponential decay.

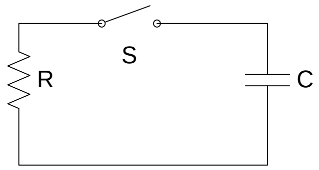


Figure 4.

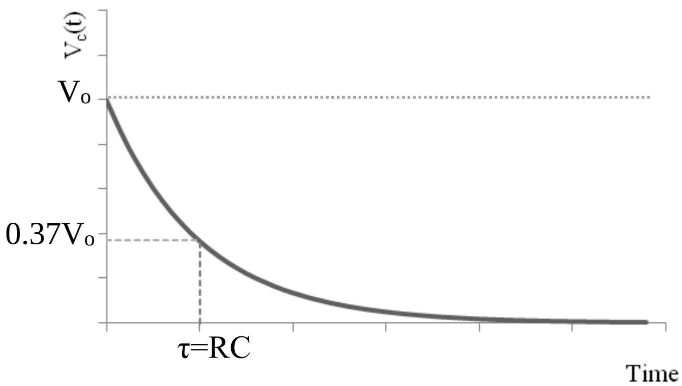


Figure 5. Discharging of a capacitor

Let us consider the situation in which we have a fully charged capacitor at time t=0s, which we then discharge using the circuit in Fig. 4. In this case it is found that the voltage of the capacitor decreases as

$$V_c(t) = V_0 e^{-(t/_{RC})} \quad (3)$$

and the current flowing in the circuit as a function of time is

$$I_c(t) = -I_0 e^{-(t/_{RC})} \quad (4)$$

where $I_o = V_o/R$ is the current at t=0s. The negative sign of the current indicates that it flows in the opposite direction as the one when we charged the capacitor. Notice that the voltage decreases as an exponential, and that it decreases to 1/e or about 37% of its initial value in a time equal to the time constant RC. The graph for the voltage as function of time is shown in Fig. 5.

Your Name: ________________________________

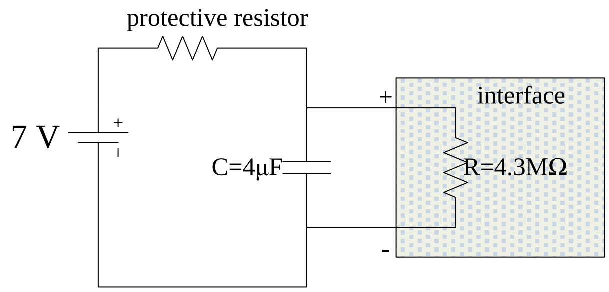
Lab Partner: ________________________________

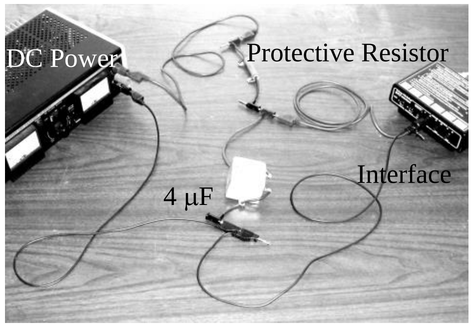
Experiment 7: RC Circuits Worksheet

Part I. Long Time Constant

You will be using the computer to measure the voltage as a function of time across the capacitor as it discharges through the computer interface.

Connect the 4.0 μF capacitor, the 1000Ω protective resistor, the power supply and the computer interface as shown.

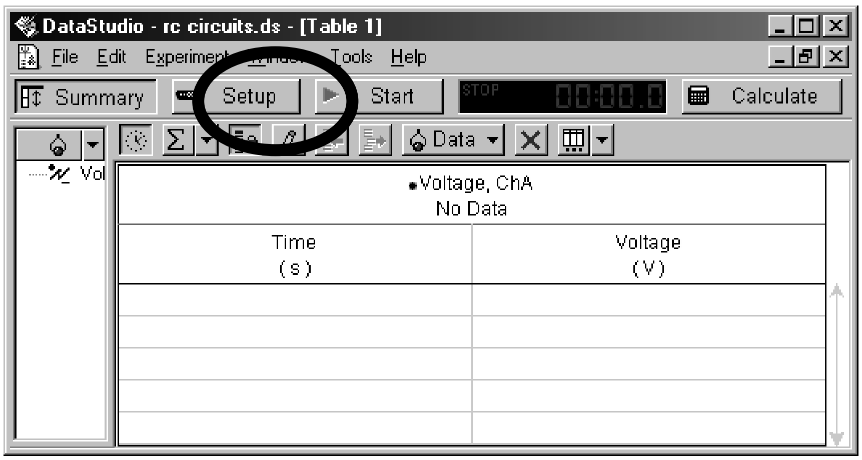




Long Time Constant Setup

Open the file titled "rc circuits.ds" on the computer at your lab station. Make sure that the interface is turned on. Turn the power supply voltage up to about V_o=7V. Allow the capacitor to charge.

Disconnect the protective resistor from the capacitor. Immediately after disconnecting the protective resistor, click on the START button in the Data Studio window on the computer.



The computer will begin measuring the voltage across the capacitor at three second intervals. Continue to measure the voltage for 60 seconds then press the stop button.

Copy the data from the computer display into your data table. You should have about twenty data points. Make a graph of the voltage across the capacitor verses the time. From the graph determine the time constant, τ, for the discharge of the 4μF capacitor through the interface. Compare the value of the time constant that you measure from the graph to the expected value, RC. Use $R = 4.3 \times 10^6\ \Omega$ for the internal resistance of the interface.

V_o= __________ R = __________ C = ___________

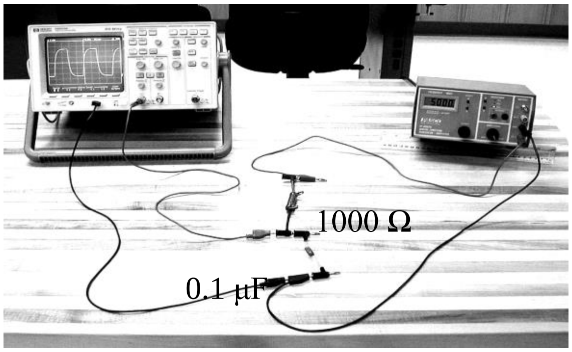
Time ( )	Voltage ( )

Time Constant		
Theoretical	**Experimental**	**% Discrepancy**

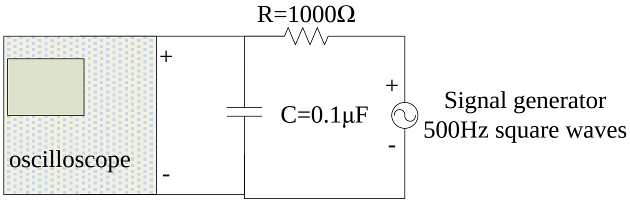
Question 1. Is the value of the time constant measured in the long time constant circuit consistent with the expected value?

Part II. Short Time Constant

Construct a short time constant RC circuit using a 1000 Ω resistor and a 0.1 μF capacitor. You will use the signal generator to alternately charge and discharge the capacitor many times per second. The oscilloscope is used to measure the voltage across the capacitor as it charges and discharges over time. Connect the signal generator, R=1000 Ω resistor, C_1=0.1 μF capacitor and the oscilloscope as shown.



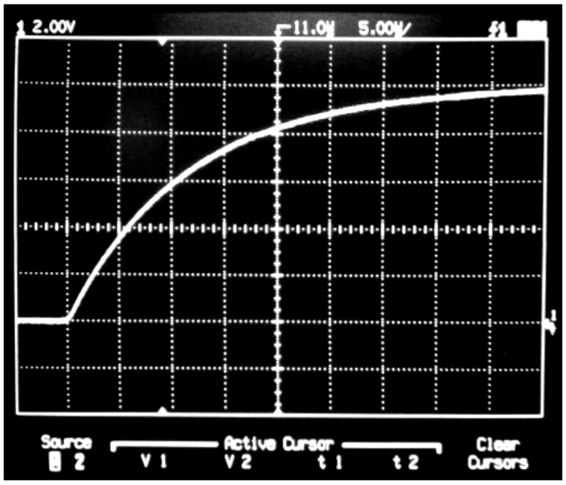
Short Time Constant Setup



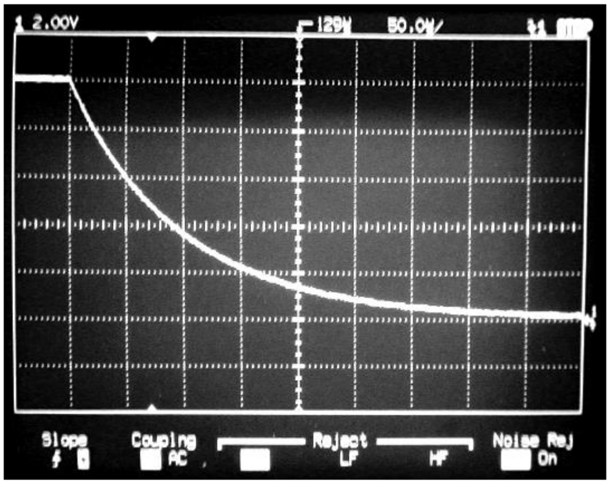
The signal generator should be set to make square waves at about 500 Hz. Turn the amplitude knob on the signal generator all the way up. Use the AUTO-SCALE button on the oscilloscope to get a first look at the voltage across the capacitor as a function of time.

After hitting the AUTO-SCALE button the display of the oscilloscope should look something like Fig. 6.

Turn the HORIZONTAL SCALE knob and adjust the horizontal and vertical position knob until the display looks like Fig.7a.



a) Charging of a capacitor



b) Discharging of a capacitor

Figure 7. Oscilloscope trace for slope coupling

Determine V_s by selecting V_{p-p} from your VOLTAGE functions.

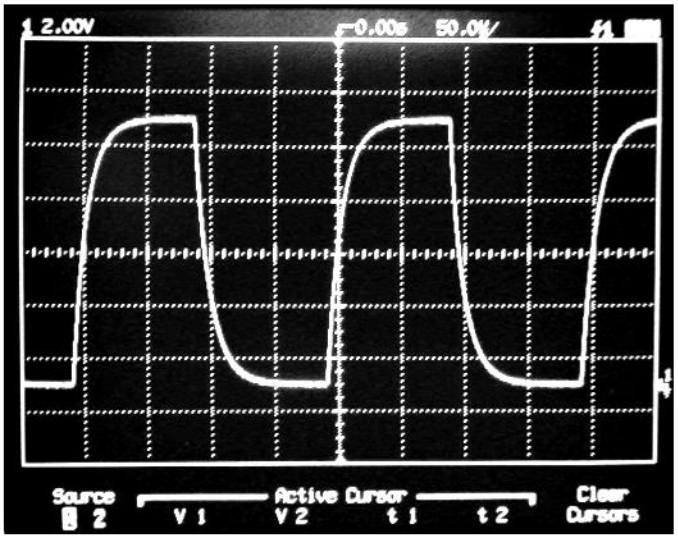


Figure 6: Charging/discharging RC circuit trace

For a charging capacitor, determine 63% of V_s and measure the time constant, τ_1. Record the measured time constant into your data table.

Compare the measured value to the expected value, $\tau = RC$.

Follow the same procedure to measure the time constant from the discharging portion of the trace (Fig. 7b). Remember that the time constant is at 37% of V_o for a discharging capacitor. Press the SLOPE COUPLING button on the oscilloscope and then the softkey under the slope option on the screen to display the discharging portion of the trace. The oscilloscope will look something like this:

Record measured time constant in your data table. Compare the measured value to the expected value, τ=RC.

Repeat both the charging and discharging measurements with the other 0.1 μF capacitor, C_2, to find the time constant for the second capacitor, τ_2.

R=___________ Printed C_1=______________ Measured C_1=__________

	Time Constant τ	**Expected τ**	**% Disc.**
Charging			
Discharging			

R=___________ Printed C_2=______________ Measured C_2=__________

	Time Constant τ	**Expected τ**	**% Disc.**
Charging			
Discharging			

Question 2. Are the time constants measured in the short time constant circuit consistent with the expected value?

Questions 3. Are there significant differences between the time constants measured while charging and those measured while discharging?

Part III. Capacitors in Series

Repeat the measurement of the charging time constant replacing the single capacitor with two 0.1 μF capacitors in series. You may have to adjust the horizontal scale in order to get a precise measurement. Record your result in your data table. Use the measured time constant for the two capacitors in series to obtain a measured value for the effective capacitance, C_{es}, of the two capacitors in series.

$$C_{es} = \tau_{es}/R$$

Compare the measured value of the effective capacitance to the expected value. The measured capacitance for the individual capacitors can be calculated by:

$$C_1 = \tau_1/R$$

$$C_2 = \tau_2/R$$

Where τ_1 and τ_2 are the time constants found in Part II.

Then use C_1 and C_2 to find the expected value of effective capacitance for two capacitors in series, C_s.

$$C_s = \frac{1}{\left(\frac{1}{C_1} + \frac{1}{C_2}\right)} \quad (5)$$

Compare the value of C_S to the measured value C_{es}.

Part IV. Capacitors in Parallel

Measure the charging time constant for two capacitors in parallel. Record you result in your data table.

Find the measured value for the effective capacitance of the two capacitors in parallel, C_{ep}.

$$C_{ep} = \tau_{ep}/R$$

Compare the value of C_{ep} with the expected value for two capacitors in parallel, C_p.

$$C_p = C_1 + C_2 \quad (6)$$

Use the same values for C_1 and C_2 that you used for the series comparison.

R = ____________________

	Time Const. τ	**C_{exp}**	**Theoretical C**	**% Disc.**
Series				
Parallel				

Question 4. Do you confirm the expected rules for adding capacitors in series and parallel?

EXPERIMENT 8 MAGNETIC FIELDS

OBJECTIVE

You will measure the magnetic field produced by a single current carrying coil and verify the behavior predicted by Biot-Savart Law, and you will verify the property of superposition for magnetic fields for two current carrying coils.

EQUIPMENT

Two 200-turn field coils with base, Low voltage AC/DC power supply, Magnetic field sensor, Computer with Science Workshop computer interface, Meter stick, lab stands, rubber bands.

THEORY

Magnetic fields exert forces on charged particles in motion, therefore charges in motion must cause magnetic fields. The magnetic field of a permanent magnet is due to the motion associated with electron spin. The magnetic field of an electromagnet is due to the motion of the charged particles in an electric current. In this experiment you will investigate the magnetic field of a current carrying coil of wire and compare the behavior of this field to the its expected behavior.

<u>The Magnetic Field Due to the Current in a Single Coil</u>

Biot-Savart Law allows us to determine the magnitude and direction of the magnetic field due to a length of current. Biot-Savart Law states that the magnetic field, $d\vec{\boldsymbol{B}}$, due to a single infinitesimal (very small) length of current is given by (exact formula to use depends on textbook used for your class):

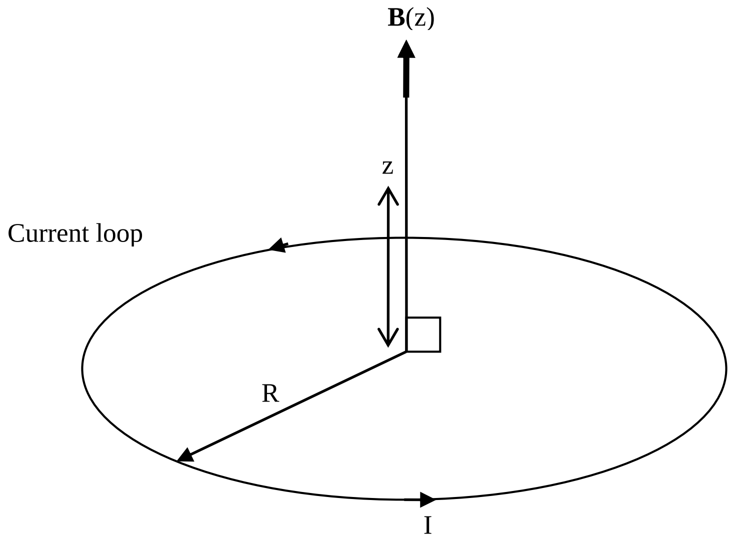
$$d\vec{\boldsymbol{B}} = \frac{\mu_0 I d\vec{\boldsymbol{l}} \times \vec{\boldsymbol{r}}}{4\pi r^3} = \frac{\mu_0 I d\vec{\boldsymbol{l}} \times \hat{\boldsymbol{r}}}{4\pi r^2} \quad (1)$$

Where μ_o (= $4\pi \times 10^{-7}$Tm/A) is the permeability constant, I is the current, $\vec{\boldsymbol{r}}$ is vector displacement that points from the length of current to the point of interest, $d\vec{\boldsymbol{l}}$ is a vector that has a magnitude equal to the length of the piece of current, and is directed along the direction of the current.

It is useful to note that, according to Biot-Savart Law, the magnetic field is proportional to the current independent of the specifics of the geometry.

We can use Biot-Savart Law to calculate the magnetic field along the axis of a loop of current as shown:

By symmetry, we know that the direction of the magnetic field on the axis is along the direction of the axis (the z-direction). We can determine whether the magnetic field is in the +z direction or the -z direction by the right hand rule. Imagine grabbing the loop of current with your right hand such that your right thumb points along the direction of the current. The magnetic field will go through the loop is the same direction that the fingers of your right hand go through the loop. Consequently, the magnetic field along the axis is in the +z direction. The right hand rule also shows us that the magnetic field is pointing down in the region of the plane of the loop outside of the loop.



From the Biot-Savart Law we can determine the magnitude of the magnetic field by integrating around the loop.

$$\vec{\boldsymbol{B}}(z) = \oint \frac{\mu_0 I d\vec{\boldsymbol{l}} \times \vec{\boldsymbol{r}}}{4\pi r^3} = \oint \frac{\mu_0 I d\vec{l} \times \hat{\boldsymbol{r}}}{4\pi r^2} \quad (2)$$

The resulting magnetic field magnitude is given by:

$$B(z) = \frac{\mu_0 I}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} \quad (3)$$

Where z is the position on the axis of the loop, R is the radius of the loop, I is the current in the loop and $\vec{\boldsymbol{B}}(\boldsymbol{z})$ is the magnetic field at the position z.

In our experiment we will be using a current carrying coil of wire with many turns. By the principle of superposition, we know that the net magnetic field due to all the turns of the coil is just the sum of the magnetic fields due to each individual loop of the coil. Consequently, the magnetic field along the axis of the coil is given by:

$$B(z) = \frac{\mu_0 N I}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} \quad (4)$$

Where N is the number of turns in the coil.

Note that in the special case z = 0cm which corresponds to the center of the coil, Eq. (4) reduces to:

$$B(z) = \frac{\mu_0 N I}{2R} \quad (5)$$

In Parts I & II of the procedure, you will verify experimentally that Eq. (4) and (5) describes the magnetic field of a current carrying coil.

Superposition - Multiple Coils

Magnetic fields exhibit the property of superposition. This means that when there are two or more sources of magnetic fields, the resulting magnetic field is the vector sum of individual magnetic fields that would be present with each one of the sources along. For instance, if there are two current carrying coils then magnetic field produced by the combination of coils is:

$$\vec{\boldsymbol{B}} = \vec{\boldsymbol{B}}_1 + \vec{\boldsymbol{B}}_2 \quad (6)$$

Where $\overrightarrow{\boldsymbol{B_1}}$ is the magnetic field of coil 1 alone and $\overrightarrow{\boldsymbol{B_2}}$ is the magnetic field of coil 2 alone. The magnetic fields are vectors so you must add them with vector addition.

In Part III of the procedure, you will verify the property of superposition for the magnetic fields from two current carrying coils.

The Magnetic Field Sensor - the Hall Effect

You will use a magnetic field sensor based on the Hall Effect to measure magnetic fields. The sensor uses the fact that the magnetic field exerts a force on charged particles in motion. Force exerted by magnetic field on a moving charge is perpendicular to both the direction of motion and the direction of the magnetic field. The magnitude of the magnetic force is proportional to the speed of the charge, the magnitude of the magnetic field and the cosine of the angle between the magnetic field direction and the direction of motion. The magnetic force is given by:

$$\vec{\boldsymbol{F}} = q\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}} \quad (7)$$

Where $\vec{\boldsymbol{B}}$ is the magnetic field, q is the charge, and $\vec{\boldsymbol{v}}$ is the velocity of the charge. The magnitude of the magnetic force is given by:

$$|\boldsymbol{F}| = |q|vB\sin\varphi \quad (8)$$

Where φ is the angle between the magnetic field and the velocity of the charge.

An electric current flows in the magnetic field sensor. The component of the magnetic field that is perpendicular to the direction of the current exerts a force on the moving charges in the current. Consequently, the charges are pushed toward one edge of the conductor carrying the current. The result is a buildup of excess charge on that side of the conductor. This buildup of charge produces an electric field and, as a consequence, an electric potential as well. This electric field will resist the additional build up of charge on the edge of the conductor. The electric field will increase until the resulting electric force on the charges in the current is equal and opposite of the magnetic force causing the buildup.

$$F_E = -F_B \quad (9)$$

or

$$q\vec{\boldsymbol{E}} = -q\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}} \quad (10)$$

dividing both sides by q:

$$\vec{\boldsymbol{E}} = -\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}$$

The resulting electric potential difference is given by:

$$\Delta V = -\int \vec{\boldsymbol{E}} \cdot d\vec{\boldsymbol{l}} \approx -\vec{\boldsymbol{E}} \cdot \Delta\vec{\boldsymbol{l}} \approx vB\Delta l \sin\varphi \cos\theta \qquad (11)$$

Where $\Delta\vec{\boldsymbol{l}}$ is the width of the conductor and θ is the angle between the electric field and the direction across the conductor.

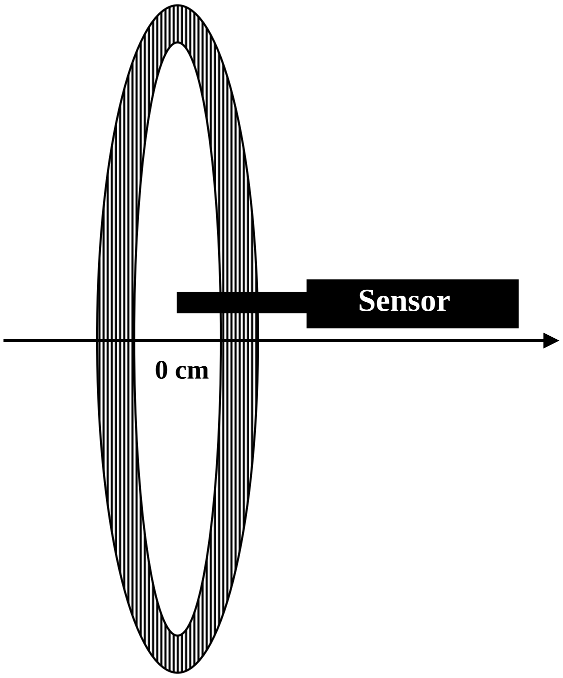
The voltage produced in the magnetic field sensor is proportional to the magnetic field.

$$V \propto B \qquad (12)$$

PROCEDURE AND ANALYSIS

Part I. The Magnetic Field at the Center of a Coil.

You will show that the magnetic field at the center of coil is proportional to the current in the coil according to Eq. (5). Set up the 200-turn field coil on the base at the 0 cm position as shown. Use a pair of wires to connect the field coil to the DC plugs on the Low Voltage AC/DC power supply. Make sure that you connect to the white plugs on the coil and not to the gray plug. Attach the magnetic field sensor to the computer interface. Your instructor will help you set the computer to make measurements from the magnetic field sensor.



Place the tip of the magnetic field sensor at the center of the coil as shown. Make sure that the sensor points along the axis of the coil. Set the radial axial switch on the sensor to axial. Set the range select switch on the sensor to 10x. While no current running through the coil, press the tare button. This will zero out the voltage measurement of the magnetic field sensor. You will be measuring the voltage output of the magnetic field sensor. The magnetic field sensor uses the Hall Effect to produce a voltage which is proportional to the component of the magnetic field along the direction of the sensor. The following table represents the relation between the magnetic field sensor voltage and the component of the magnetic field vector along the direction of the sensor:

Magnetic field sensor settings

Calibration Factor

Range select	(gauss)	(Tesla)
1x	100 gauss/volt	0.01 Tesla/volt
10x	10 gauss/volt	0.001 Tesla/volt
100x	1gauss/volt	0.0001 Tesla/volt

Turn on the low voltage power supply. Turn the DC voltage adjust all the way clockwise. Set the current in the Field Coil to 0.400 A by turning the DC current adjust knob on the power supply. Read the magnetic field sensor voltage off of the computer display. Measure and record the magnetic field sensor voltage as a function of the current in the coil. Increase the current in the coil in increments of 0.400 A. Use the magnetic field sensor calibration factor provided in the table to convert the magnetic field sensor voltage into magnetic field strength in Tesla and record the result.

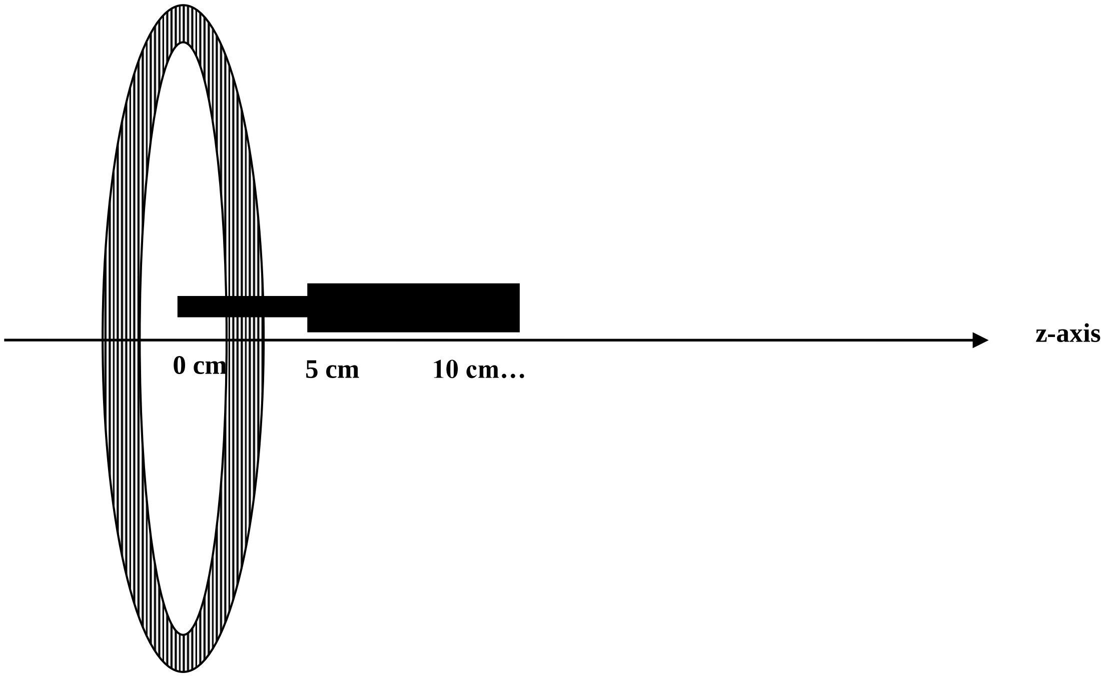
As the current in the coil increases, the magnetic field sensor voltage should increase. If the magnetic field sensor voltage decreases (becomes more negative), turn the coil current off, reverse the direction of the magnetic field sensor and re-zero (tare) the magnetic field sensor. Then continue with measurements as described above.

Make a graph of the B vs. I. Find the slope of the resulting line and compare it to the value that you would expect from Eq. (5). (Use 10.5 cm for the radius of the coil). Compute the percent discrepancy.

Part II. The Magnetic Field along the axis of a coil

In this part of the experiment you will show that the magnetic field of the coil varies along the axis of the coil according to Eq. (4).

Set the current in the coil to 1.00 A. You will leave the current at 1.00 A throughout this part of the experiment. You should check the current periodically as it might "drift" away from the constant setting. Record the coil current with your data.



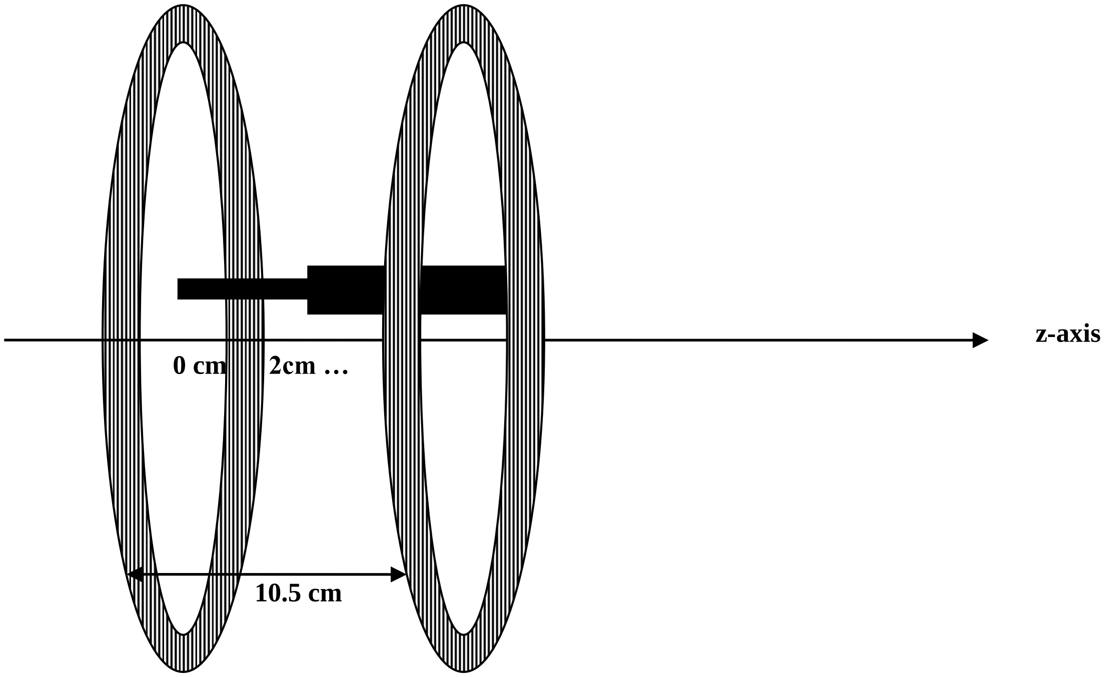
Begin with the sensor at the center of the coil as in Part I of the experiment. Measure and record the magnetic field sensor voltage at the center. Then move the magnetic field sensor away from the center along the axis of the coil. Be sure to keep the magnetic field sensor pointed along the axis of the coil. Make measurements of the magnetic field sensor voltage at 5.0 cm intervals out to 25 cm away from the coil. Record your measurements and convert the magnetic field sensor voltage into Tesla as in Part I.

Calculate the expected values of the magnetic field for each measurement along the axis of the coil using Eq. (4). Compare the expected value to the measured value. Calculate the percent discrepancy.

Make a graph of B vs. z for Part II.

Part III. Superposition - Two coaxial coils

Set up the second 200-turn field coil on the base as shown. Position the second coil such that it is 10.5 cm from the first coil along the axis. Make sure the two coils are parallel to each other.



A. Helmhotz coils

Connect the two coils in series to the low voltage DC power supply. Make sure that the current goes through both coils in the same direction. Set the current through the coils to 1.00 A. When two identical coils are set up this way at a distance of one coil radius they are called Helmholtz coils.

Measure the magnetic field sensor voltage long the axis of the two coils starting at the center of the first coil. Make measurements at 2.0 cm intervals in the region between the two coils and until the sensor is 14 cm from the center of the first coil. Then make an additional two measurements at 20 cm and 25 cm from the center of the first coil. Record your measurements and convert the voltages to Tesla.

B. Reversed polarity

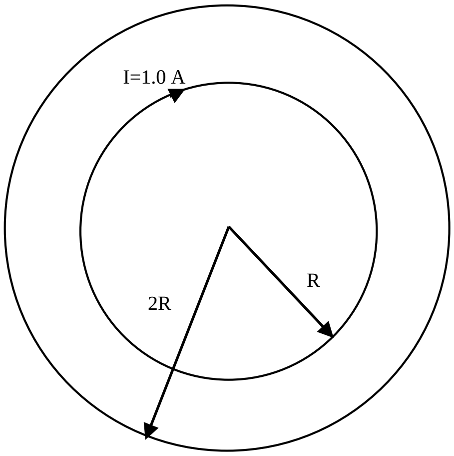
Turn off the current and reverse the wires on the first coils such that the current flows through the coils in opposite directions. Reset the current through the coils to 1.00 A, and repeat the measurements as in Part I. Notice that field is negative near the first coil now. Record your results and convert the sensor voltage measurements to Tesla.

Make a graph of B vs. z for Part III. Graph all of the data on the same axes.

Question 1. Does your graph from Part I show that the magnetic field strength is proportional to the current in the coil as expected? Explain.

Question 2. Is the slope of magnetic field strength vs. current graph from Part I. consistent with the expected value? Explain.

Question 3. The radius of one current carrying loop is twice that of another current carrying loop. The two loops are concentric and the current in the smaller of the two is 1.0 A in the clockwise direction. If the net magnetic field is zero at the center, what must be the direction and magnitude of the current in the outer loop?



Question 4. In Part II, does the magnetic field vary along the axis of the coil as expected? Explain.

Question 5. In the case of the Helmholtz coils, we expect that the magnetic field will be roughly constant in the region midway through the two coils. Are your results consistent with this expectation? Explain.

Question 6. In the case of the reversed polarity coils, why is there a place on the axis between two coils where the magnetic field goes to zero? On your graph, does the magnetic field go to zero where you would expect? Explain.

Your Name: ______________________________
Lab Partner: ______________________________
Instructor Signature: ______

Experiment 8: Magnetic Fields Worksheet

Section I: The magnetic field at the center of a current carrying coil.
Field Coil Radius, R=_______ Number of turns in Field Coil, N=______

Field Coil Current (A)	Sensor Voltage ( )	B Field ( )	Expected B Field ( )	% Disc.
0.40				
0.80				
1.20				
1.60				
2.00				

Section II: The magnetic field along the axis of a current carrying coil.
Field Coil Current = 1.00A

Position on Axis z (m)	Sensor Voltage ( )	B Field ( )	Expected B Field ( )	% Disc.
0.000				
0.050				
0.100				
0.150				
0.200				
0.250				

Section III: Superposition – two coaxial coils
Field Coil Current = 1.00A Coil Seperation = ________________________

Position on Axis z (m)	Helmholtz Coils		Reversed Polarity	
	Sensor Voltage ( )	B Field ( )	Sensor Voltage ( )	B Field ( )
0.000				
0.020				
0.040				
0.060				
0.080				
0.100				
0.120				
0.140				
0.200				
0.250				

EXPERIMENT 9 INDUCTION AND TRANSFORMERS

OBJECTIVE

To become familiar with transformers and the principle of magnetic induction.

EQUIPMENT

DC power supply, signal generator, DVM, 800-turn coil, 200-turn coil, transformer core, bar magnets, 3400 turn coil, light bulb.

THEORY

Electromagnetic Induction

Electromagnetic induction is the effect that occurs when magnetic flux (Fig. 1), or flow of magnetic field, through a loop of wire is altered in any of the following ways:

1. Change in the magnetic field strength.
2. Change in the size of the loop.
3. Change in the orientation of the loop with respect to the magnetic field direction.

From this description, you can see that the magnetic flux can be described by

$$\Phi = \int \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} \quad (1)$$

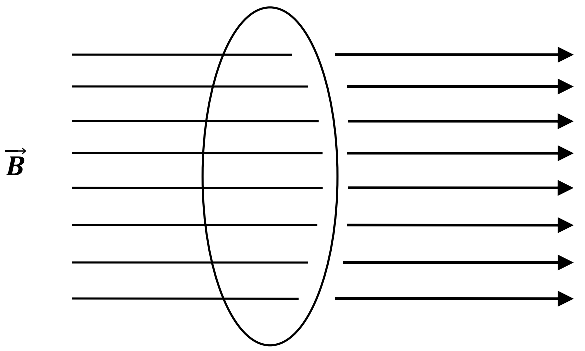


Figure 1.

For a coil consisting of N identical loops, the total flux is given by

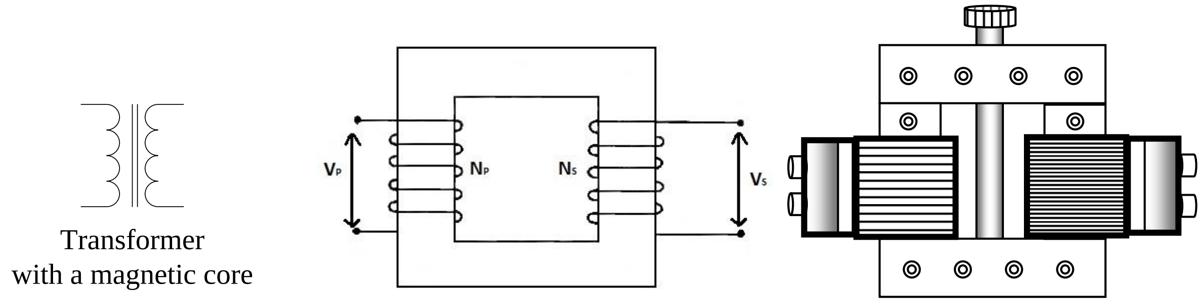
$$\Phi = N\int \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} \quad (2)$$

The term induction refers to the fact that an electromotive force ($\mathscr{Emf}$) can be "induced" in the coil by the change in magnetic flux, which means that the $\mathscr{Emf}$ is caused to appear by indirect means. The $\mathscr{Emf}$ is related to the changing magnetic flux.

$$\mathscr{Emf} = -\frac{d\Phi}{dt} = -N\frac{d\int \vec{\boldsymbol{B}}\cdot d\vec{\boldsymbol{A}}}{dt} \quad (3)$$

This results in a current flowing through the coil during the time that the magnetic flux is changing in the loop. It should be noted that the negative sign in the induction formula indicates that the induced current generates its own magnetic flux through the loop, and that induced magnetic flux opposes the very change that caused it to appear. This is expected, since conservation of energy prohibits the magnetic field caused by the induced current from increasing the overall magnetic field energy.

<u>Transformers</u>



a.)Electrical symbol b.) Basic transformer c.)Classroom transformer

Figure 2.

The transformer (Fig. 2) uses electromagnetic induction to induce an alternating current in a secondary, isolated coil of wire that is different from the alternating current in a primary coil of wire, caused by ordinary means. Recall that any current in a wire causes a magnetic field to surround the wire. When the primary coil is installed on the transformer core, each individual turn of wire in the primary coil causes a magnetic field to be present in the transformer core. The transformer core is a very good conduit for the magnetic field compared to the surrounding air, so nearly all of the magnetic field will be contained in the transformer core. In order for a current to be induced in the secondary coil, the magnetic field must change. The geometry of the primary and secondary coils, including the number of turns in each is fixed. The coils fit tightly around the transformer core as well so neither the coil sizes nor their orientation can be changed. We will use the signal generator to create a high frequency sine wave (AC) current in the primary coil, so the magnetic field in the transformer core will change, varying the magnetic flux through the secondary coil thus inducing an AC current of the same frequency in the secondary coil. Since each turn in the secondary coil produces an $\mathcal{E}mf$, the secondary voltage is related to the primary voltage as the number of turns in each coil.

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad (4)$$

This assumes that the power produced in the secondary coil is equal to the power going in to the primary coll. With resistive losses, this impossible, but is used as a reasonable approximation. We say that the transformer "steps the voltage up" if the secondary coil voltage is greater than the primary, and that the transformer "steps the voltage down" if the secondary coil voltage is less than the primary.

Your Name: ________________________________

Lab Partner: ________________________________

Experiment 9: Induction and Transformers Worksheet

Part I. Electromagnetic Induction

A 3400 turn coil is connected to an DVM. First, a magnet is moved around the coil. Then a current carrying loop is moved around the coil. Observing the induced voltages in the 3400 turn coil due to the movement of these two magnetic sources is the objective of this portion of the procedure.

Using the 3400 turn induction coil connected to the DVM and a bar magnet, perform the following test, recording the voltage of each $\mathscr{E}mf$ induced in the large coil. Explain each $\mathscr{E}mf$ in terms of the causes noted in the theory section above.

P1	**Connect the 3400 turn coil to the voltmeter and use a bar magnet**	**Voltage Present (Y/N)**	**Reason**
1	Hold the bar magnet by one end close to the outside of the coil, but not moving		
2	Hold the bar magnet by one end close to the outside of the coil and move it side to side		
3	Hold the bar magnet by one end close to the outside of the coil; move the coil around		
4	Hold the bar magnet by one end inside the coil but not moving		
5	Hold the bar magnet by one end inside of the coil and move it around		
6	Hold the bar magnet by one end and move it into and out of the coil		
7	Hold the bar magnet by one end inside of the coil; move the coil side to side		

Connect the 800 turn coil to the power supply, with a potential of about 5V across the coil. Use the magnetic field from this coil to induce $\mathscr{Emf}$ s in the large coil.

P2	Connect the 800 Turn coil to the power supply with a potential of 5V across the coil	Voltage Present (Y/N)	Reason
1	Hold the current carrying coil close to the large coil, but not moving		
2	Hold the current carrying coil close to the large coil, move the large coil side to side rapidly		
3	Hold the current carrying coil close to the large coil, move the current carrying coil side to side rapidly		

Part II. Transformers

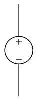
Set the signal generator to produce a 2Hz sine wave. Turn the amplitude all the way down.

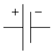
Question 1. Plug the 800 turn coil into the signal generator and the light bulb into the 200 turn coil. Turn up the amplitude until you can just barely see the light. What is happening to the light bulb? Why?

Question 2. Switch the coils so the 200 turn coil is plugged into the signal generator and the 800 turn coil is plugged into the light bulb. What is the light bulb doing now? Why? How does this differ from the previous case?

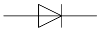
Question 3. Leaving the 800 turn coil plugged into the light bulb, unplug the 200 turn coil from the signal generator and plug it into the power supply with it set to 5V. Does the light bulb light up? Why or why not?

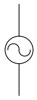
APPENDIX A: Electrical Symbols

 DC Direct current source

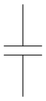
 Battery

 Resistor

 Doide

 AC Alternating current source (Signal generator)

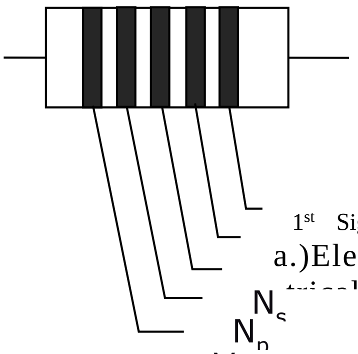
 Ground

 Capacitor

 Switch

Color	**1st & 2nd Significant Figures**	**Multiplier**	**Tolerance**	**Failure Rate (%Failure/1000hrs)**
Black	0	1		
Brown	1	10	± 1%	1.0
Red	2	100	± 2%	0.1
Orange	3	1000	± 3%	0.01
Yellow	4	10000	± 4%	0.001
Green	5	100000		
Blue	6	1000000		
Violet	7	10000000		
Gray	8	100000000		
White	9	1000000000		
Gold		.1	± 5%	
Silver		.01	± 10%	
No color			± 20%	

2nd Significant Figure



1st Significant

a.)Elec

N_s

N_p

APPENDIX B: Sources and Meters

DC Regulated Power Supply

Low Voltage Power Supply

Care should always be taken when working with electrical components. Always turn off power sources when assembling/dismantling circuits.

Multiplier

Tolerance

Voltage range:

OVERLOAD

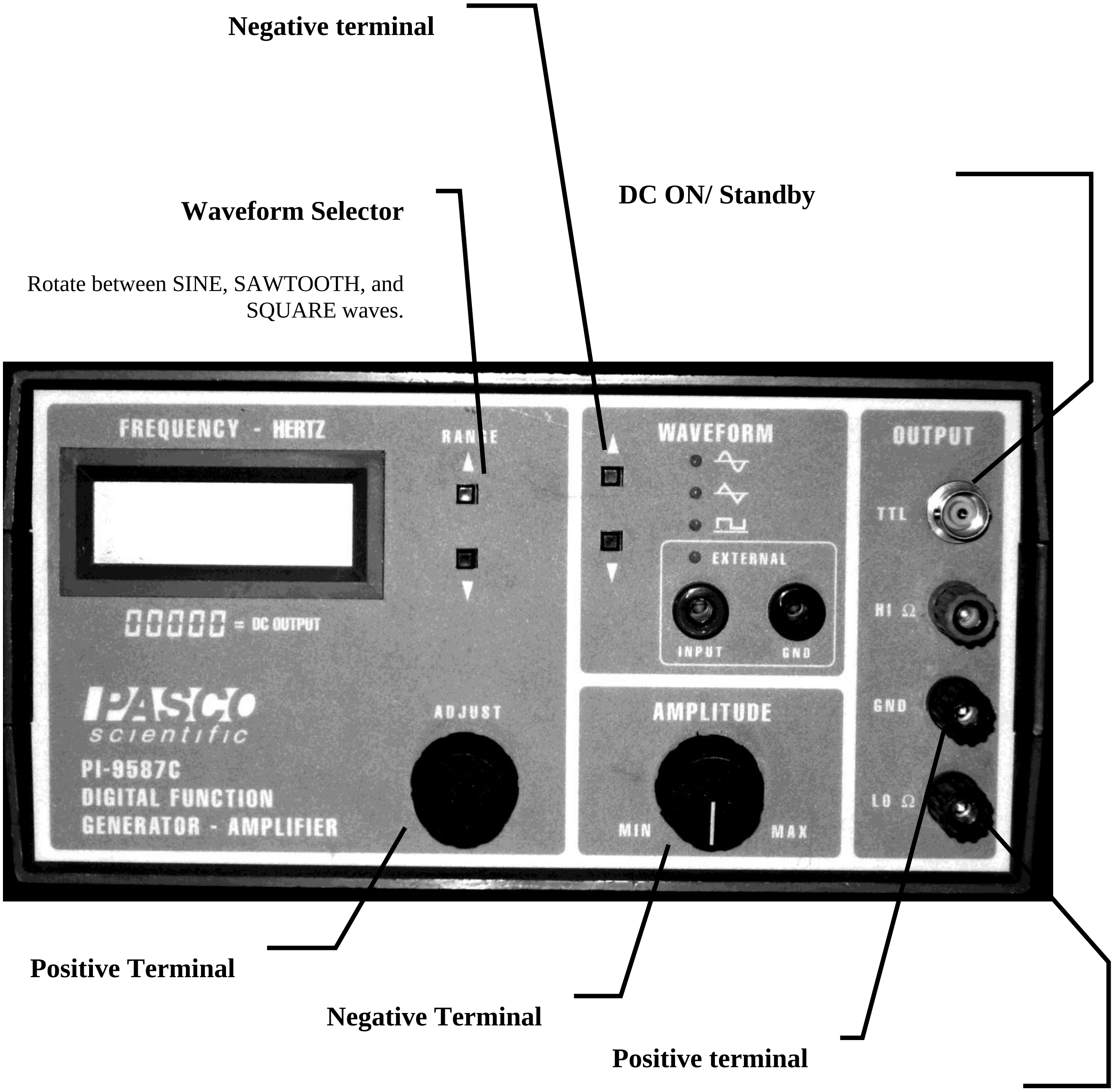
Failure Rate

Press when OVERLOAD indicator lights

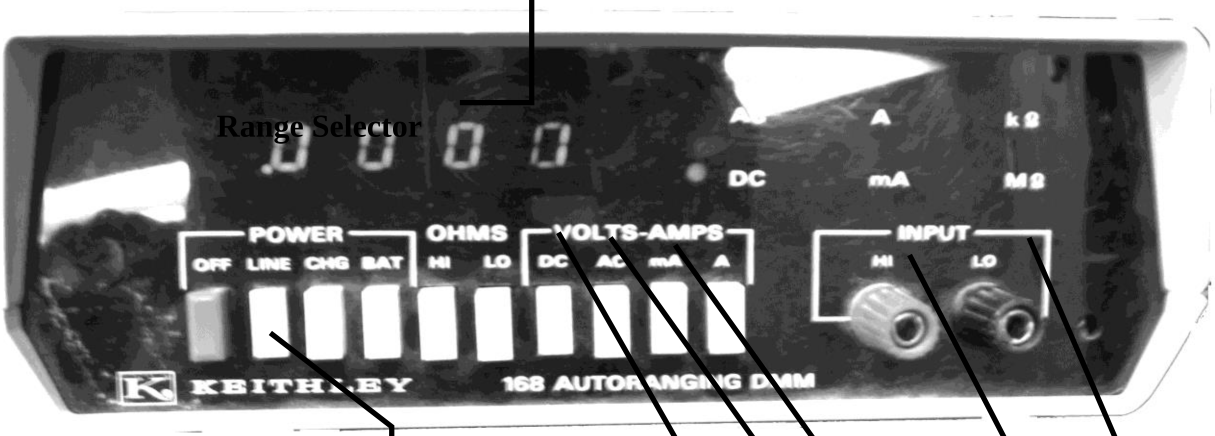
Voltage control:

Resistor Color Band System

Signal Generator (AC Power Source)



Digital Voltmeter



Trigger Input

Amplitude Adjust

Frequency Adjust

Measures DC

Measures Resistance

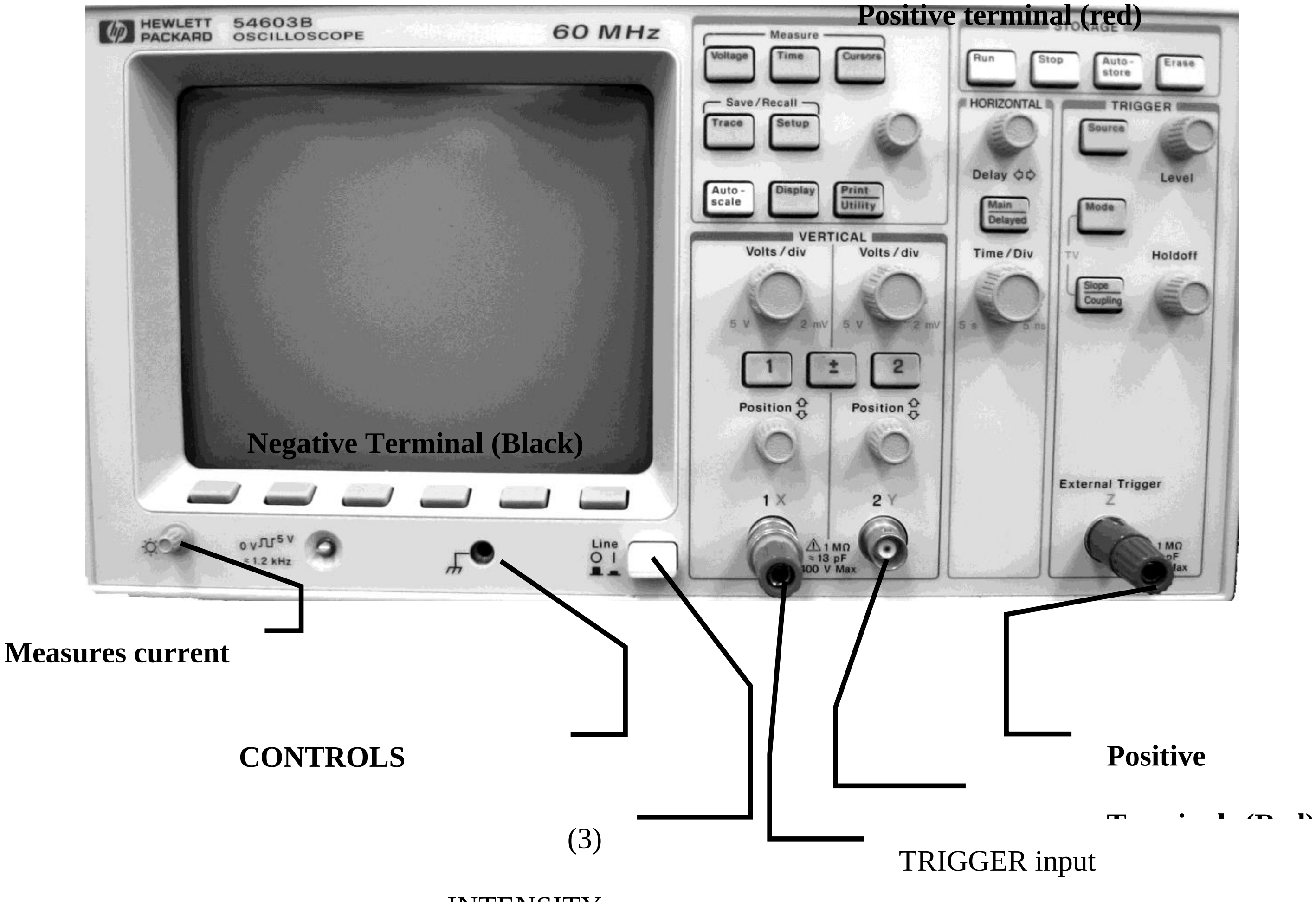
LINE: power on

Analog Ammeters, Galvanometers, Voltmeters

All meters that look like this work in the same matter. Some do not print all three scales; it will be assumed that the user will know that the printed value on the plug is the top of the range.

Measures AC VOLTS **Negative terminal (black)**

APPENDIX C: The Oscilloscope



(1) LINE is your power on/off button. You should see a horizontal beam on the display after a few seconds. This beam traces out the pattern of voltage changes over time, so we call this pattern the oscilloscope TRACE.

(2) COMMON GROUND looks like a rake and leads to the ground wire. This is used as the negative terminal on the oscilloscope. The ground connection defines zero voltage for the oscilloscope. Since input voltage is interpreted as signal strength, it is essential for the instruments to agree on where 0 Volts lies. This is similar to defining zero height when calculating gravitational potential energy values.

(3) INTENSITY control, labeled by an icon that looks like the sun. Turn it to adjust the brightness. Check this adjustment each time you use the oscilloscope.

(4) SOFT KEYS are enabled by the buttons on the face of the oscilloscope and will be used to make adjustments and record event times and signal strengths. The options on the soft keys change as different control buttons are used.

Inputs

You may display up to two signal sources on the screen, one from CHANNEL 1 and one from CHANNEL 2. To trigger an input signal, you must also plug into the TRIGGER input. The CHANNEL SWITCH (button 1 and 2) selects what is shown on the display from the inputs to CHANNEL 1, CHANNEL 2, or both. In this experiment, we will only have inputs to one channel at a time, so make sure to select the channel of your signal input.

Controls

1. VERTICAL: (SENSITIVITY) for CHANNEL 1 and CHANNEL 2
   The sensitivity controls are two copies of the same controls, one for each channel. The sensitivity is the vertical magnification of the input signal, so you can see very strong or very weak signals equally well. The values are labeled VOLTS/ DIV, from 2 millivolts per division to 5 volts per division. We usually want to adjust the sensitivity so the trace is as large as possible, but completely visible on the screen.
2. HORIZONTAL: (SWEEP RATE)
   The sweep rate is the rate at which time is displayed on the screen, which is to say the speed of the trace sweeping horizontally across the screen. Turning the sweep rate knob counterclockwise slows the trace; clockwise speeds the trace up. The sweep rate value is labeled TIME/DIV, from 5 nanoseconds per division to 5 seconds per division. The display screen has a grid of horizontal and vertical lines, with one division being the distance from one line to the next. For example, if the sweep rate is set at 20ms/div, a sine wave that repeats itself every 3.0 divisions has a period of (20 ms/div)(3.0 div) = 60 ms. For periodic signals, we usually want to adjust the sweep rate so a little more than one complete period is visible on the screen.
3. TRIGGER (synchronizing)

   The TRIGGER controls allow repeating signals to be synchronized so that a periodic signal can be displayed. We will connect the signal generator directly to the EXTERNAL TRIGGER function; with each wave pulse the signal generator sends to the speaker, a simultaneous signal is sent to the oscilloscope's TRIGGER, telling the oscilloscope to start the trace. In our speed of sound experiment, we will employ the TRIGGER function to overlay each successive pulse exactly on top of the previous pulse. In this way, we see the collection of pulses as a static pattern. Without the TRIGGER function, the patterns are randomly aligned, and the pattern drifts across the screen; with the TRIGGER, the pattern is stable. The TRIGGER LINE function can generate a signal from the 60 Hz power supply that runs the oscilloscope.

4. GENERAL
   Under MEASURE:
   (a) VOLTAGE menu gives choices for: Source (channel 1 or 2); Voltage measurements (peak-to-peak, average, rms, max, min, top, base); and clear. We will use this menu to measure the strength of various signal inputs.
   (b) TIME menu gives choices for: Source (Channel 1 or 2); Time measurements; and clear, which removes the displayed reading. We will use this menu to measure the period and frequency of some sound waves, and to measure time delays.
   (c) CURSOR menu is used to get an accurate measurement of either the time or the voltage

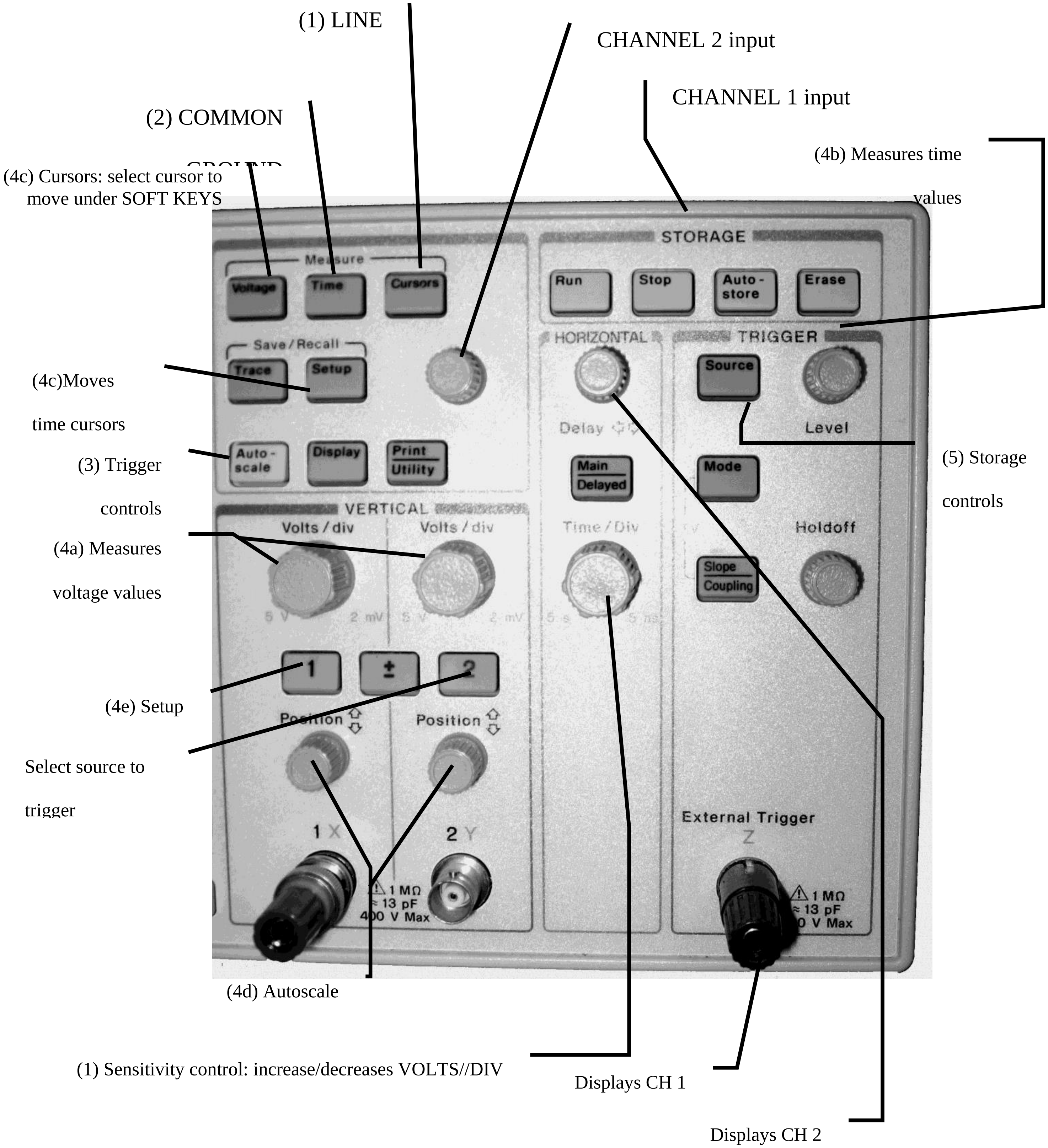
of a signal. Cursor SOFTKEYS are enabled by selecting CURSORS. The position control in the same area moves the cursors to the extremes of an area of interest. The value of each cursor position is displayed. Typically, the difference between cursor values gives the value we want. The knob below the cursor button is the CURSOR CONTROL KNOB.

(d) AUTOSCALE: When pressed, the oscilloscope will select a vertical and horizontal scale.

(e) SETUP menu allows you to start all over again. Start over by pressing SETUP and then DEFAULT SETUP on the SOFT KEYS. This is the setup of the oscilloscope when it is first turned on.

5. STORAGE

   To freeze a trace, you may depress the STOP button. RUN will allow it to run again. AUTOSTORE stores information while ERASE deletes information.


(1) LINE
CHANNEL 2 input
CHANNEL 1 input
(2) COMMON
(4c) Cursors: select cursor to move under SOFT KEYS
(4b) Measures time values
(4c)Moves time cursors
(3) Trigger controls
(4a) Measures voltage values
(4e) Setup
Select source to trigger
(5) Storage controls
(4d) Autoscale
(1) Sensitivity control: increase/decreases VOLTS//DIV
Displays CH 1
Displays CH 2
Measure
Voltage
Time
Cursors
Save/Recall
Trace
Setup
Auto-scale
Display
Print Utility
STORAGE
Run
Stop
Auto-store
Erase
HORIZONTAL
TRIGGER
Source
Level
Delay
Main Delayed
Mode
VERTICAL
Volts/div
Volts/div
Time/Div
Holdoff
Slope Coupling
Position
Position
1 X
2 Y
External Trigger
Z
1 MΩ
≈ 13 pF
400 V Max

APPENDIX D: Units

Basic Units	Symbol	Name of unit	Unit
Length	l, w, h, d, s, x, y, z	meter	m
Mass	M, m	gram	g
Time	T	second	s
Temperature	t	Kelvin	K
Amount of substance	N, n	mole	mol
Electric current	I	Ampere	A
Light intensity	I_V	candela	cd
Angle	Θ, Φ, φ, α, β	degree, radian	º, rad

Derived Units Name					In terms of base units
Momentum	p		kg*m/s		
Angular momentum	L		kg*m^2/s		
Torque	τ		N*m	=	kg*m^2/s^2
Force	F	Newton	N	=	kg*m/s^2
Energy (work, heat)	E, W, U, K, Q	Joule	J	=N*m=	kg*m^2/s^2
Entropy	S		J/K	=	kg*m^2/(s^2*K)
Power (work rate)	P	Watt	W	=J/s=	kg*m^2/s^3
Frequency	f, υ	Hertz	Hz	=s^{-1}=	1/s
Period	T		s		
Pressure, stress	p	Pascal	Pa	=N/m^2=	kg/(m*s^2)
Electric charge	q	coulomb	C	=	A*s
Resistance	R	ohm	Ω	=V/A=	kg*m^2/(A^2*s^3)
Electric capacitance	C	farad	F	=C/V=	A^2*s^4/(kg*m^2)
Electric inductance	I	Henry	H	=Wb/A=	kg*m^2/(A^2* s^2)
Electric field	E		V/m	=	kg*m/(A*s^3)
Electric potential (Emf)	V, E	volt	V	=W/A=	kg* m^2/(A* s^3)
Electric flux	Φ_e		V*m	=	kg*m^3/(A* s^3)
Magnetic flux density	B (B=μH)	Tesla	T	=Wb/m2=	kg/(A* s^2)
Magnetic field intensity	H		A/m		
Magnetic flux	Φ_m	Weber	Wb	=V/s=	kg* m^2/(A* s^2)
Permeability	μ		H/m	=	kg*m/(A^2* s^2)
Resistivity	ρ		Ω*m	=	kg*m^3/(A^2* s^3)

Metric Prefixes

Prefix	Symbol	Fraction	Decimal	Scientific Notation
femto	f	1/1,000,000,000,000,000	0.000000000000001	1 x 10^{-15}
pico	p	1/1,000,000,000,000	0.000000000001	1 x 10^{-12}
nano	n	1/1,000,000,000	0.000000001	1 x 10^{-09}
micro	μ	1/1,000,000	0.000001	1 x 10^{-06}
milli	m	1/1,000	0.001	1 x 10^{-03}
centi	c	1/100	0.01	1 x 10^{-02}
kilo	k	1,000	1,000	1 x 10^{+03}
Mega	M	1,000,000	1,000,000	1 x 10^{+06}
Giga	G	1,000,000,000	1,000,000,000	1 x 10^{+09}
Tera	T	1,000,000,000,000	1,000,000,000,000	1 x 10^{+12}
Peta	P	1,000,000,000,000,000	1,000,000,000,000,000	1 x 10^{+15}

APPENDIX E: Fundamental Physical Constants

Atomic mass constant	m_u	=	1.660538×10^{-27} kg = 9.31494×10^{2} MeV/c^2
u=10^{-3} kg/(mol*N_A)		=	1/12 m (^{12}C)=1u
Avogadro's constant	N_A	=	6.022142×10^{23} mol^{-1}
Bohr magneton (eħ/2m_e)	μ_B	=	9.27401×10^{-24} J/T
Bohr radius ($4\pi\varepsilon_0\hbar^2/m_e e^2$)	a_0	=	0.529177×10^{-10} m
Boltzmann constant (R/N_A)	k_B	=	$1.3806503 \times 10^{-23}$ J/K
Classical electron radius ($\alpha^2 a_0$)	r_e	=	2.817940×10^{-15} m
Compton wavelength ($h/m_e c$)	λ_c	=	2.426310×10^{-12} m
Electron g-factor	g_e	=	-2.002319
Electron rest mass	m_e	=	9.109382×10^{-31} kg = 0.510998 MeV/c^2
Elementary charge	e	=	1.602176×10^{-19}C
Faraday's constant	F	=	9.648531×10^{4} C/mol
Gravitational constant	G	=	6.673×10^{-11} $m^3/(kg*s^2)$
Molar gas constant	R	=	8.314472 J/(mol*K)
Molar volume of ideal gas (RT/p) T=273.15K, p=101.325kPa	V_m	=	2.2414×10^{-2} m^3/mol
Muon rest mass	m_μ	=	1.883531×10^{-28}kg = 1.05658 MeV/c^2
Nuclear magneton (eħ/2m_p)	μ_N	=	5.050783×10^{-27}J/T
Neutron rest mass	m_n	=	1.674927×10^{-27} kg = 9.39565 MeV/c^2
Pi	π	=	3.1415926536…
Permeability of free space	μ_0	=	$4 \pi \times 10^{-7}$ N/A^2
Permittivity of ($1/\mu_0 c^2$)	ε_0	=	8.85×10^{-12} F/m
Planck constant	h	=	4.135667×10^{-15} eV*s = 6.626069 MeV/c^2
Planck mass [$(\hbar c/G)^{1/2}$]	m_p	=	2.1767×10^{-8} kg
Planck length [$(\hbar/Gc^3)^{1/2}$]	l_p	=	1.6160×10^{-35} m
Planck time[$(\hbar G/c^5)^{1/2}$]	t_p	=	5.3906×10^{-44} s
Proton rest mass	m_p	=	1.672621×10^{-27} kg = 9.38272×10^{-2} MeV/c^2
Speed of light in vacuum	c	=	2.99792458×10^{8} m/s
Speed of sound (estimate in air)	s	=	343 m/s
Standard acceleration of gravity	g_n	=	9.80665 m/s^2
Standard atmosphere		=	1.01325×10^{5} Pa = 760mm Hg (Torr)
Stefan-Boltzmann constant [$(\pi^2/60)k^4/\hbar^3 c^2$]	σ	=	5.670400×10^{-8} W/(m^2*K^4)
Tau rest mass	m_τ	=	3.16788×10^{-27} kg = 1.77705×10^{3} MeV/c^2
Earth mass		=	5.97×10^{24} kg
Earth radius (mean)		=	6.38×10^{3} km
Moon mass		=	7.35×10^{22} kg
Moon radius (mean)		=	1.74×10^{3} km
Sun mass		=	1.99×10^{30} kg
Sun radius (mean)		=	6.96×10^{5} km
Earth-sun distance (mean)		=	1.496×10^{8} km
Earth-moon distance (mean)		=	3.84×10^{5} km