Experiment I   Ohm's Law

I. References

Halliday, Resnick and Krane, Physics, Vol. 2, 4th Ed., Chapters 32, 33
Purcell, Electricity and Magnetism, Chapter 4

II. Equipment

Digital multimeters
Resistor board with 4, 5 10, and 20 ohm resisitors
6-volt battery
knife switch
10 V Power Supply
diode board with 4 diodes and 40 ohm resistor

III. Introduction

Sometimes, when an electric charge is moved between two points in space, work is done. The amount of work that is done is equal to the change in the potential energy of the charge. This difference in potential energy difference is given by the product of the difference in the electrical potential between the points and the magnitude of the electric charge. The difference in electrical potential has an SI unit of volts.

The rate at which charge passes through some surface with a finite area is called the electrical current passing through that area. It is measured in Ampères. One ampère of current is defined as one Coulomb of charge passing through a cross-sectional area per second. This is equivalent to about 6×10^{18} electrons passing per second. When a current of electrical charges is driven through some material system it is in most cases impeded by some sort of frictional drag. As a result, work must be done to move the charges against this retarding force, very much as air resistance must be worked against by the engine of a car. The current will only flow between two points in the material system if there is an electrical potential difference between those two points (providing the work). In many materials the current is directly proportional to the potential difference, i.e.

$$I = \frac{1}{R}V$$

where I is the current in ampères, V is the potential difference in volts and $1/R$ is the proportionality factor, measured in ohms. Usually this relationship is written $V=IR$ and is called Ohm's Law. Here the proportionality factor R is called the resistance and is measured in ohms. In many materials and devices the resistance does not change with the amount of voltage applied or the current passing through it, over a large range of both parameters, so it is a constant to a very good approximation. Materials with low resistance, in which electrons can move somewhat freely with little impedence, are conductors, whereas materials in which the electrons are more tightly bound and cannot move

freely are electrical insulators. Later this proportionality factor will be generalized in the concept of impedance.

Batteries produce an electrical potential difference through chemical reactions. If a connection is made between these two regions of the battery with some material, such as a wire or some other material that has finite resistance, a current will flow through the object and through the battery. The current is defined to be flowing from the side of the object that is connected to the region of the battery defined to have the more positive potential, through the object and to the side connected to the region of the battery with the more negative potential. The current flows from the positive to the negative potential. Inside the battery, the current flows from the more negative region to the more positive region. As a result, a battery can sometimes be referred to as a charge pump. Benjamin Franklin got us into this and you should think of him when you recall that electrons flow in the opposite direction to the current in the object, but in the same direction as the current in the battery.

Historically, a popular notion was that an electrical current needs to be pushed by some force, for example, through a piece of wire. The force was thought to be needed to overcome the resistance of the piece of wire to the flow of the current. This force was called the electromotive force (EMF), i.e. the force required to move the electric charges. To make the current flow required a battery, so the battery was thought to be the source of this electromotive force. But because the EMF is measured in volts, it is not a force but a potential difference. Part of this experiment is to measure the EMF of a battery, that is, the potential difference across its terminals.

When a current flows inside a battery it is also impeded by a small frictional force, so the battery has a small internal resistance which can also be measured, with some care. The purpose of this experiment is to measure the internal resistance of a battery and its EMF using a known set of carbon resistors and Ohm's Law. In Part II of this lab, you will measure the resistance of a diode, which is an electrical device that does not obey Ohm's law.

IV. Symbols

Many of the components used in electrical experiments have standard symbols. Those required in this experiment are shown in Fig. (I-1).
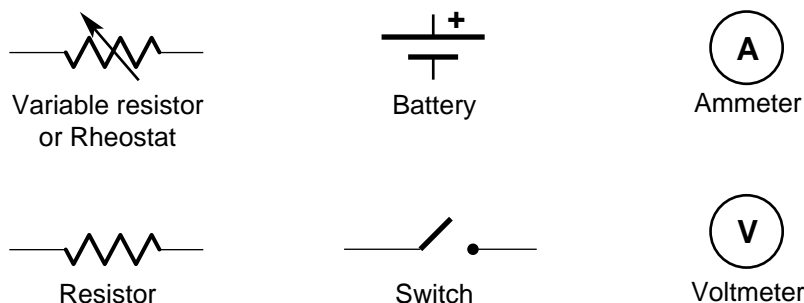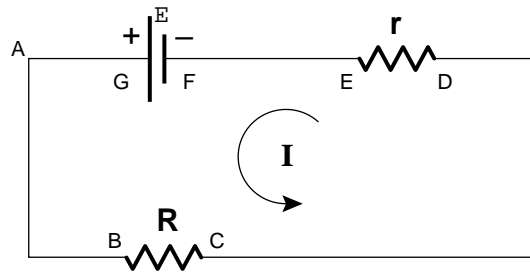

Figure I-1

V. Electrical Circuits

It is very common to connect devices together with good conductors in such a way that a closed loop is formed. In passing round this loop the current may be split any number of times at the junction of several conductors or inside some device. However each new channel for current flow that is created at these junctions must rejoin another channel or even several channels at some other point, so that all loops close. All loops that are created must be closed so that current can flow. These connected systems are called electrical circuits.

A. Kirchhoff's Rules

There are two very useful rules for understanding the behavior of electrical circuits.

Rule 1: In going round a closed loop the total change in potential must be zero.

Figure I-2

Applying this rule to Fig. (I-2) and assuming that the conductors joining the components have zero resistance, the potential differences between the lettered points in the circuit are given by:

$$V_A - V_B = \Delta V_{AB} = 0 \quad \Delta V_{BC} = IR$$
$$\Delta V_{CD} = 0 \quad \Delta V_{DE} = Ir$$
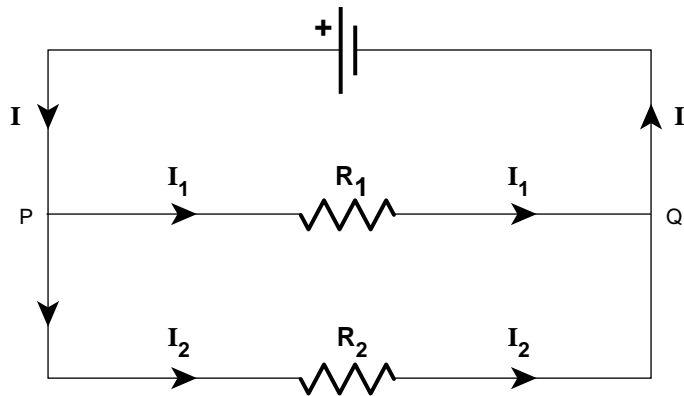$$\Delta V_{EF} = 0 \quad \Delta V_{FG} = -\varepsilon$$

Summing all the differences we get

$$\Delta V_{AA} = IR + Ir - \varepsilon = 0$$

which can be rewritten

$$\varepsilon = I(R + r) \ .$$

Rule 2: The flux of charge is conserved so that at any junction the current flowing into the junction is equal to the current flowing out of the junction.
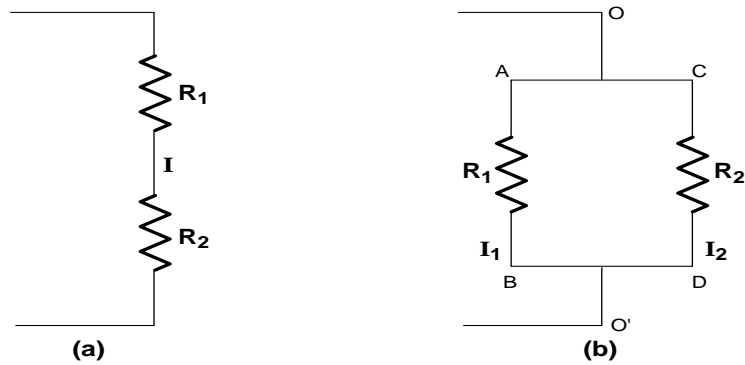
Figure I-3

When this rule is applied at the points P and Q of the circuit in Fig. (I-3), we get

At P: Current in $= I$ At Q: Current in $= I_1$ and I_2
             Current out $= I_1 + I_2$ Current out $= I$

Both points yield the equation $I = I_1 + I_2$.

VI. Computing the Effective Resistance of Networks of Resistors

**Figure I-4:**   (a) Series connection.   (b) Parallel connection

Series connection	Parallel connection
Since current represents flow of charge and therefore must be conserved, the current in R_1 must be the same as the current in R_2. Hence $V_1 = IR_1$ $V_2 = IR_2$ therefore $V_1 + V_2 = I(R_1 + R_2)$ which is equivalent to writing $V = IR$ where $V = V_1 + V_2$ and $R = R_1 + R_2$ i.e. two resistors connected in series are equivalent to one resistor whose value is equal to their sum. Generalizing, $R = \sum_i R_i$	The potential difference V between O and O' must be the same whether we go along $OABO'$ or $OCDO'$. Also conservation of current requires that $I = I_1 + I_2$ $I_1 = \dfrac{V}{R_1} \quad I_2 = \dfrac{V}{R_2}$ therefore $I = V\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)$ which is equivalent to writing $V = IR$ where $R = \dfrac{R_1 R_2}{R_1 + R_2}$ i.e. two resistors are connected in parallel are equivalent to one whose reciprocal is equal to the sum of their reciprocals. Generalizing, $\dfrac{1}{R} = \sum_i \dfrac{1}{R_i}$

VII. Experiment

A. Internal Resistance and EMF of a Battery

The purpose of this experiment is to measure the EMF and internal resistance of the battery. The experiment is simple but the determination of the uncertainties on these two quantities is a bit subtle.

Connect up the circuit shown in Fig. (I-5) (the resistances of the meters are not shown).
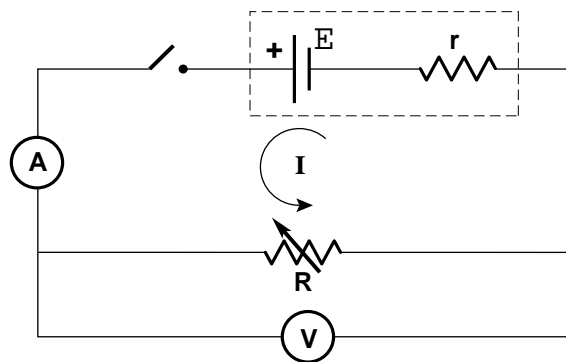
Figure I-5

Here A is a digital ammeter and V a digital voltmeter. The variable resistance R can be achieved by choosing various combinations of resistances on the resistor board. It is important to note that the insertion of A introduces a small series resistance into the circuit and the insertion of V introduces a large resistance in parallel to R. You can measure the resistance of the ammeter with the digital multimeter operating as an ohmmeter. Consult the manual for the meter to determine the resistance meter when it is acting as a voltmeter. S is a switch that is normally open and should only be closed when you are taking a measurement. This helps avoid exhausting the battery. The internal resistance of the battery is denoted as r.

To perform the experiment, proceed as follows:

1. Measure V and I for various values of R. If the resistances of the meters, which are not shown, are neglected, then the equations describing the circuit are

$$V = IR \quad \varepsilon = I(R + r)$$

which can be combined and rewritten as

$$V = \varepsilon - rI .$$

As you are making these measurements, periodically measure the battery EMF with the switch open using the voltmeter to be sure that it remains constant. If it isn't consult with your instructor.

2. Put the data into Excel, plot V vs I, and fit the data to a straight line and determine the slope and offset $-r$ and ε along with their uncertainties. Compare your deduced EMF ε with your direct measurements of the battery output voltage.

Be sure to consider the uncertainties associated with the meter readings in specifying the uncertainties in your measurements. Consult a copy of the manual that comes with the meters to determine the uncertainties. Consider what component of the meter uncertainty is random (*i.e.*, varies from measurement to measurement) and what component is systematic (such as an overall scale uncertainty) and how they affect your determination of r and ε. The random uncertainties should be used in the linear fit, and the systematic uncertainties should be accounted for after you have extracted the fit parameters.

Ideally, you would choose meter scales that will give you the best resolution for your measurements, but you might want to consider whether the systematic errors will be easier to handle if you use the same scale for all readings. Add your fitted result to your plot. Do your results depend on which direction current is flowing through the resistor?

3. Now include the resistances of the meters in your analysis by including their effects in the circuit equations. Determine whether an appreciable error has been made in the determination of either ε or r by neglecting the resistances of the meters.

B. Devices that do not Obey Ohm's Law.

The resistors used above are likely made of carbon, which is a pretty good conductor and, although its resistance has some dependence on temperature, the resistors obey Ohm's Law. A general class of materials that do not obey Ohm's law all that well are semiconductors, of which silicon is one example. Such materials typically have a resistance that changes dramatically with temperature, with incident light, applied voltage, or with a small addition of impurities. A complete description of the properties of semiconductors requires application of the principles of quantum mechanics. A qualitative description of the behavior of semiconductors can be found in chapter 32 of Halliday, Resnick and Krane, or Chapter 31 of Tipler. Here we will just focus on measuring the characteristics of a common electrical device made of semiconductor material, called a diode.

A diode consists of a junction of two semiconductor materials, called "n-type" and "p-type", in which the degree of mobility of the electrons is different. When the materials are brought together, electrons will drift from one material to the other, and the equilibrium condition results in a small potential difference at the junction. Current will not flow through the diode until this potential "barrier" is overcome, but once a sufficient amount of voltage is applied, electrons flow very freely across the junction. Current will not flow across the junction in the other direction, however, except for a small amount of "leakage" through the junction. However, if too much voltage is applied in the "reverse" direction, the junction fails. The voltage at which this happens is called the "breakdown voltage". The symbol for a diode is
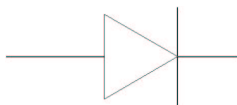

where the tip of the triangle indicates the direction that current is expected to flow if the vertical line is at a more negative potential than the base of the triangle. The stripe on the diodes that you are using indicates the end corresponding to the tip of the triangle. The characteristics of the diode whose behavior you are studying are shown in figure I-6 and in the table below.
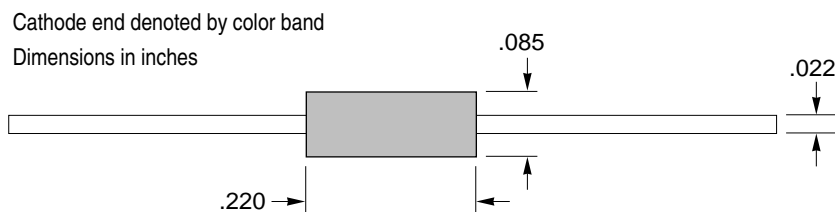
Figure I-6: The 1N914 Switching Diode

Peak Reverse Voltage	75 V
Average Forward Rectified Current	75 mA
Peak Surge Current, 1 Second	500 mA
Continuous Power Dissipation at 25°C	250 mW
Operating Temperature Range	-65 to 175°C
Reverse Breakdown Voltage	100 V
Static Reverse Current	25 nA
Static Forward Voltage	1 V at 10 mA
Capacitance	4 pF
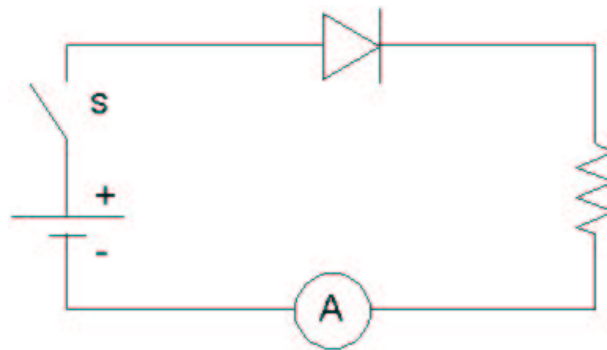
Figure I-7

Set up the circuit in figure I-7. The "load resistor", R_L, is used to limit the total amount of current flowing through the diode so that it does not burn up. Use a 40Ω resistor for R_L. V_0 is a power supply. Measure the voltage across the load resistor, the voltage across the diode, the input voltage, and the current through the loop for various input voltages between ±10 V (you will need to move around the voltmeter). Verify that Kirchoff's laws are satisfied by calculating the load resistance and the input voltage and comparing to your measurements. Plot the current through the loop as a function of voltage across the diode. Take enough data that you can clear see the "non-Ohmic" behavior of the diode. This type of plot is often referred to as the I-V characteristics for the device. Calculate the effective resistance of the diode as a function of the voltage across it. Describe your results.