OHM'S LAW

Introduction

When a potential difference is maintained between the contacts of an incandescent light bulb, the electric field forces charge to flow through the filament of the bulb. The filament resists the flow of charge, and the work done to force the charge through is converted to thermal energy, heating the filament to the point where it emits light. The flow of charge is described as a current and we would like to explore how the current through a particular material depends on the potential difference in various materials.

To examine this question adequately, we must first define quantitatively what is meant by "current" and "resistance," as well as considering the physical mechanism that accounts for the electrical resistance of a metal.

The Electric Current

The current passing through a wire is defined by how much charge passes through a cross-sectional area A of the wire per unit time, as shown in Fig. 1. You should convince yourself that conservation of charge implies that the current is the same no matter what surface across the wire is used in defining the current. When the current changes in time, however, it is useful to consider the rate of charge crossing the area at each given instant, so that the current I is defined more generally as

$$I = \frac{dQ}{dt} \qquad (1)$$

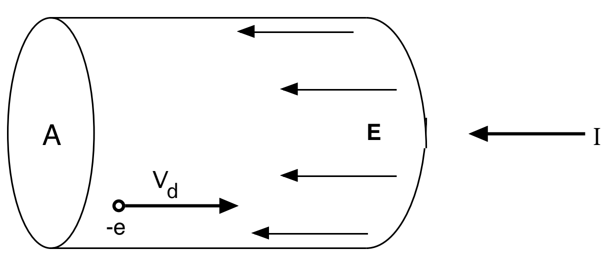


Figure 1 Electric Current in a Wire

where dQ is the charge passing through the area in some very brief time interval dt when the observation is made. In the one dimensional case, a positive sign would be assigned to I when positive charge flows from left to right across the surface, a negative sign when it flows in the opposite direction.

The unit of current is a coulomb per second, which is given the special name "ampere," so that 1 ampere = 1 coulomb / second or, in official SI symbols, 1 A = 1 C/s.

We are primarily concerned with the current in a metallic conductor. In these systems, the electrons at the higher available energies are reasonably free to migrate from one location to another around the background of positively charged ions of the metal. The electrons moving in this way behave in many respects as if free. The background ions are mostly arranged in an orderly way on lattice sites. But because of the vibrational motion of the ions, and because of impurities and other unavoidable irregularities in the periodicity of the lattice, the electrons are constantly being scattered by the lattice of ions, interchanging energy and momentum with the heavier background ions. This randomizes the electronic motion and keeps the free electrons in thermal equilibrium with the lattice. When an electric field **E** is applied along the conductor (see Fig. 1), the field imposes a force ($\mathbf{F} = -e\mathbf{E}$) on the electrons (where e is the absolute value of the electron charge, $e = 1.602 \times 10^{-19}$ C). Scattering by the lattice prevents the electrons from accelerating indefinitely, but instead transforms the extra kinetic energy that the electrons acquire from the field into vibrational energy of the lattice. The conductor can become hot (as in the case of an electric stove), or even incandescent (as does the filament of a light bulb). The combined effect of the scattering and the applied field on the electrons is that their average velocity shows a small overall drift velocity v_d (typically about 0.1 m/sec) in the direction opposite to that of the applied electric field **E.** This overall drift velocity of the electrons, superposed on their random thermal motion, is responsible for the electric current.

While the current in a metallic conductor is caused by the motion of electrons, there are systems such as a plasma (which is a gas of ions) in which the current can result from the motion of positively charged particles, as well as systems such as the electrolyte in a car battery in which the electric current results from positive and negative ions moving in opposite directions.

Benjamin Franklin made significant contributions to the understanding of electricity by proposing a "single fluid theory" in which electrification by friction resulted from transferring particles of an "electrical fluid" (or "charge" from the modern viewpoint) from one object to the other. Objects with a deficiency of this fluid were negatively charged, and those with an excess would be positively charged. But, lacking our present knowledge of electrical phenomena, Franklin assigned a negative charge to the amber that had been rubbed with fur. This unfortunate choice was seen eventually to require assigning a negative charge to the electron, complicating the lives of future generations of physics students in their efforts to understand which way the charge really flows in an electric circuit.

By convention, the direction of the electric current is taken to correspond to the flow of positive charges, in the direction of the applied electric field from the higher to the lower electrical potential, even when the actual charge carriers are negatively charged electrons which in reality must move in the opposite direction (see Figs. 1 and 2). Sometimes, for emphasis, the term "conventional current" is used to distinguish the current defined in this way from the actual motion of electrons. This seemingly artificial sign convention does not affect the validity of the equations based on it. The results are the same whether the current is taken to be that of positive charges flowing from a positive potential to a negative potential, or that of negative charge flowing from the negative potential to a positive potential. Indeed, close examination of the definition of current for the one-dimensional case, Eq. (1), shows that a flow of negative charge to the left produces a positive current, just as if positive charge really were flowing to the right.

The Electromotive Force (emf)

Maintaining a steady current in a wire requires a source of electrical energy, such as an electric battery or electric generator (Fig. 2). Chemical energy in the battery, or mechanical energy in the case of the generator, is converted into electrical energy by doing work on the charge passing through. The "electromotive force" (referred to typically as "emf") is the work done per unit charge by the battery or generator to move charge from lower to higher potential. The units of emf are volts (V). For a battery, the emf is also equal to the voltage across the battery terminals when nothing is connected to the

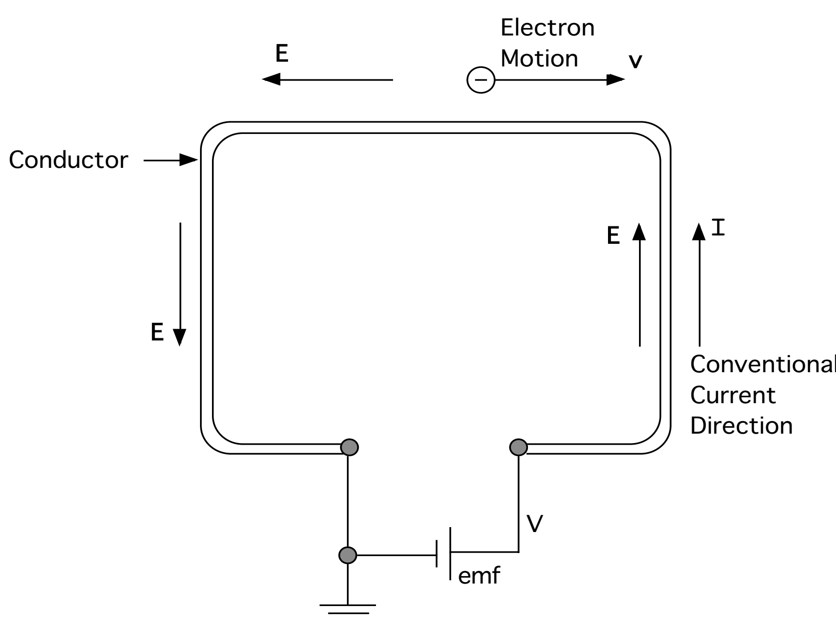


Figure 2 Electrical Circuit

battery terminals that allows any significant current to flow. Note that the customary term "electromotive force" is somewhat misleading, since the emf is not a force.

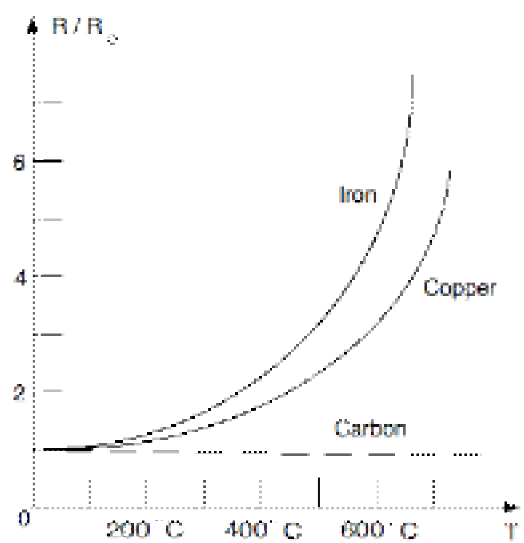
Resistance and Ohm's Law

Early in the nineteenth century George Ohm discovered that, as long as the temperature was kept constant, the magnitude of the current in a metal is proportional to the applied voltage (Fig. 3), a result now known as Ohm's law. Ohm defined the resistance R of a conductor as the proportionality constant in this law, given by the voltage divided by the current

$$R = V/I . \qquad (2)$$

The resistance of a particular resistor depends on the physical dimensions of the resistor material: length L and cross sectional area A(extrinsic values).

$$R = \rho L/A$$



Figuße Temperature Dependence of Resistance

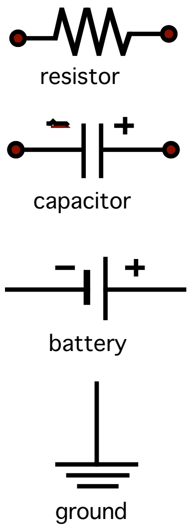
Aside from these dimensional quantities the resistance also depends on the intrinsic property of the material called the resistivity ρ. This resistivity, in turn, is temperature dependent.

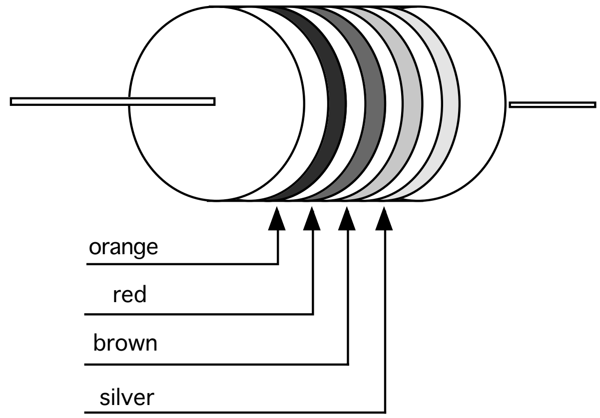
$$\rho = \rho_o(1+\alpha(T-T_o)$$

where a is the temperature coefficient, T_o is a reference temperature, usually 21°C and ρ_o is the resistivity at this temperature. The resistance of most conductive materials increases with temperature. Insulators, on the other hand, decrease their resistance with increased temperature.

Since vibrations of the ions around which the electrons move typically produce most of the scattering that impedes the response of the electrons to an applied field, and since the amplitude of these vibrations increases with temperature, the resistance of most solids increases with temperature (Fig. 3). Ohm's law can be explained best, however, by the quantum theory of solids.

Anything that has electrical resistance may be termed a resistor. In a circuit diagram, the symbol for a resistor is a zigzag line (see Fig. 4).





Color coding of a 320 Ω resistor with 10% tolerance. The leftmost two bands indicate the digits of an integer, the third band gives the power of ten by which the integer is multiplied , and the fourth band indicates the upper limit of the percentage standard deviation {or tolerance, + or - } of the manufacturing process.

Figure 4 Color Codes and Symbols for the Components of Electrical Circuits

Table 1 STANDARD RESISTOR COLOR CODE

Color	Digit	Tolerance + / -
Black	0	
Brown	1	
Red	2	
Orange	3	
Yellow	4	
Green	5	
Blue	6	
Violet	7	
Gray	8	
White	9	
Gold		5%
Silver		10%
None		20%

The resistors used in most applications are called "composition" resistors – small cylinders with wire leads at each end, constructed of powdered graphite in clay. Most resistors are color-coded with a series of bands on them, starting from closest to the edge as shown in Fig. 4 and Table 1. The last band, which is gold, silver, or simply absent, denotes the manufacturer's tolerance in achieving the indicated value of resistance. The band just before that indicates a power of ten multiplying the previously coded numbers. The remaining colors, starting from the edge, indicate a sequence of digits. An example of this coding scheme is shown and explained in Fig. 4.

To compute the power expended in moving a current flowing in a resistor, we note that the work the electric field does on a charge dq that "falls" through a potential difference V is $V\,dq$. Hence, the work done per second is

$$P = V(dq/dt) = V\,I = R\,I^2 \tag{3}$$

and is in units of volt-amperes or watts. The units of volts and amperes have been defined in a way that relates electrical and mechanical quantities, because a volt is an amount of work per coulomb, so that

$$\begin{aligned} &1\ \text{V·C} = 1\ \text{joule} \\ &= 1\ \text{watt-second} = 1\ \text{newton-meter} \end{aligned}$$

Equipment The plug-in boards we will use in this experiment allow you to assemble a circuit from component parts. In this lab we will assemble a simple circuit with a power source (EMF) and a single resistor. We will include in the circuit a means of measuring the voltage of the EMF and the corresponding current that this EMF drives through the resistance as we vary the EMF. We will do this experiment for each one of three resistances with values of 1K Ω, 470 Ω and 100 Ω, and with a light bulb and a light emitting diode (LED). To prepare for the lab you should calculate the voltage and currents through resistances of the values above for a supply voltage of 6 volts maximum. The resistances you will use are rated for 2.0 watts. Check to make sure this wattage is not exceeded for any of resistances you will be using BEFORE you power up the circuit for real.

The Science Workshop 750 Interface will provide a variable voltage power source. The voltage output leads can be located on the right front panel of the 750 Interface box. Connect the positive and negative terminals to the appropriate sockets on the plug-in board. Construct a simple circuit using the 100 Ω resistor as shown in Figure 5. The multimeter, a separate unit will be used as an Ammeter the measure the current in the circuit.

Warning: You should not attempt to measure the current directly from the power source. Do not connect the leads of the multimeter across the power supply terminals or any leads coming from the power supply while the multimeter is in the ammeter mode. It will blow a fuse in the multimeter and cause it to malfunction. If you have any doubts about your connection, have your Lab Instructor look over your connections before you turn on the power.

To measure the current the circuit must be broken and an Ammeter inserted as shown in Figure 5. Set the multimeter settings to measure milliamperes (300 mA scale). The positive

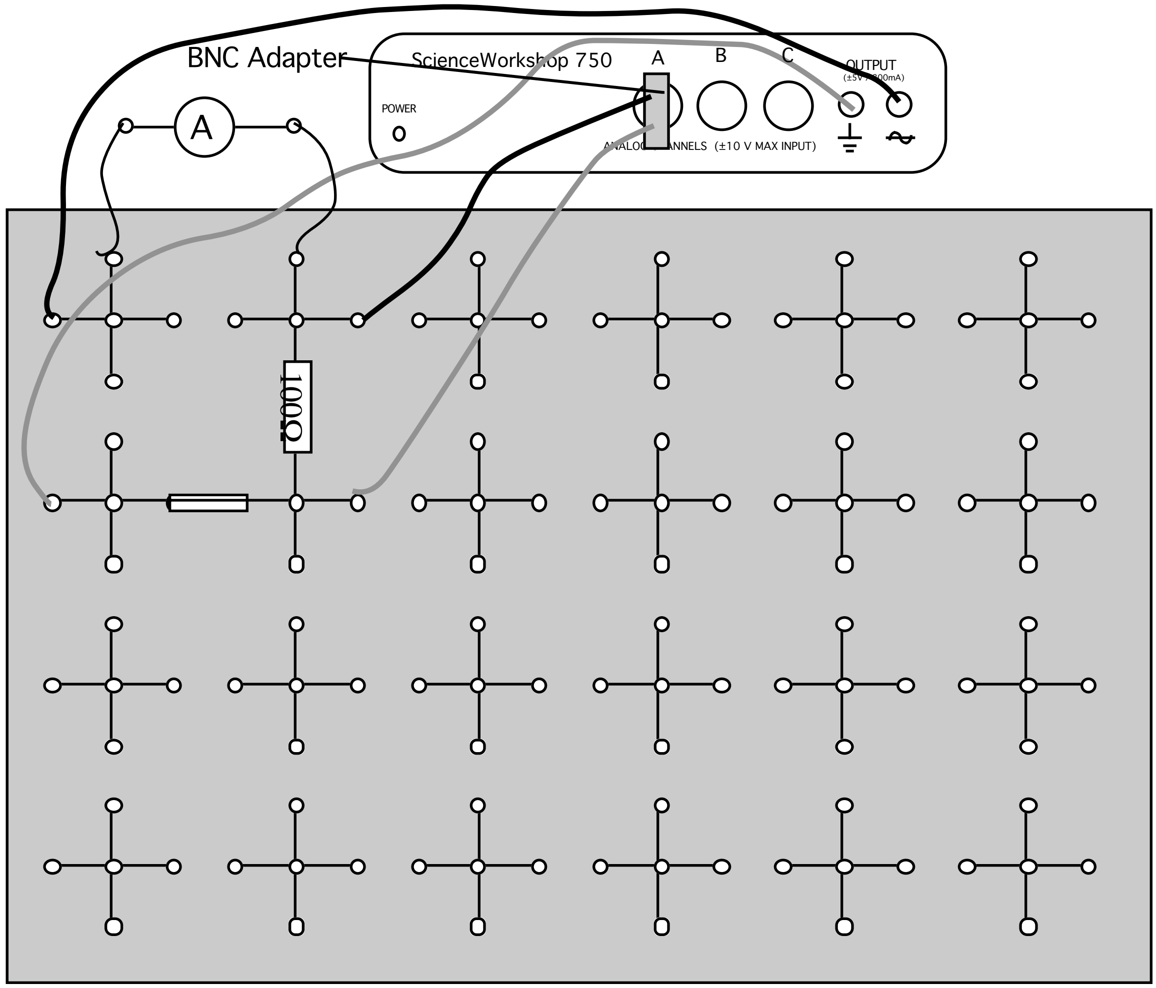


Figure 5
Test Cicuit

lead of the ammeter should go to the socket at higher potential (+) and the common lead should connect to the socket at lower potential (-) in order to read a positive current.

The voltage will be measured using the Science Workshop 750 Interface and the Data Studio program. Connect the voltage leads to input A on the 750 Interface box through the BNC adapter. Apply the leads to the ends of the circuit element to be tested, as shown in Figure 5 for the case of a resistor. Load up the Data Studio software and click on the option to create a new experiment. Choose the voltage sensor option from the sensor menu. Display the voltage by dragging the "3.14 Digits" display option in the lower left window onto the desktop. You may drag the lower right corner of the digital display to make the digits larger and easier to read. Locate the signal generator control box just below the sensor menu, and click on it to activate the output voltage. The default setting for the voltage supply is for a sine wave function. Change the "sine wave function" option in the control panel for the voltage supply to "D.C.". Note the D.C. voltage icon box that appears in the picture of the 750 Interface box.

To start recording readings, hit the "start" button in the control bar near the top of the screen. Increment the voltage output with the + or - buttons. Using the 100-Ω resistor measure both the current and voltage for voltages from -5 volts to 5volts in one volt increments. It would appear that the voltmeter is a redundancy since the voltage source is supplying a specified voltage. Note if the voltmeter reading matches the power supply output voltage. Note any discrepancies. Can you offer an explanation?

Make a table of the results and plot your data in your lab notebook. Repeat the experiment for the 470-Ω and 1-kΩ resistances. Note any changes in the data from one circuit element to the next. Obtain a slope from your graph and compare that number to the labeled resistance. Then do the same experiment using the small light bulb. Comment in your conclusion about any difference observed between the resistor data and the light bulb data.

If available and time permits, try to repeat the measurements using an LED (Light Emitting Diode).

Questions

The following list of questions is intended to help you prepare for this laboratory session. If you have read and understood this write-up, you should be able to answer most of these questions. Some of these questions may be asked in the quiz preceding the lab.

• What is an electric current?

• State Ohm's Law.

• Which way does the current flow when the applied electric field is from left to right along a wire? Which way do the electrons flow?

• How does the resistance of a metal usually vary with temperature? Why?

• What is the symbol for a resistor in a circuit diagram?

• What is an emf?

• By what factor does the power increase when the current through a resistance is doubled?

• What is meant by the term ohmic material?

• Why must the voltage be read directly across the material being tested rather than using the voltage reading of the source?

• Why must the Ammeter interrupt the circuit and not be placed in parallel with the element through which the current is being measured?