

Experiment #4: Basic Electrical Circuits

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Purpose:

To construct some simple electrical circuits which illustrate the concepts of current, potential, and resistance, and to gain familiarity with the use of a multimeter and the facilities for computer-based measurement, analysis, and presentation.

Equipment:

Macintosh computer equipped with a PASCO 750 Science Workshop interface.
DataStudio software, MS Office Word and Excel
Breadboard (to assemble circuits)
Variety of Resistors (including a 270- Ω carbon resistor)
Voltage Sensor leads and Alligator Clips
Handheld Digital Multimeter (Radio Shack 22-194 or equiv.)
Banana Leads

Discussion:

I. Computer-Based Tools for Measurement and Analysis

HARDWARE: Basic manual measurements (and the reference standards) of electrical quantities (Voltage, Current and Resistance) are done using a Digital Multimeter. A PASCO Science Workshop 750 Interface (connected to a Macintosh computer) is then used for signal/power generation in addition to display and logging of Voltage measurement data. The interface box has four digital and three analog Input channels (labeled A, B and C – each capable of measuring +/- 5V), and one ± 5 V (up to 300 mA) variable output available on the front panel. This output is controlled by an internal (but software controlled) Function Generator, which can supply DC power or various waveforms

SOFTWARE: Control of the I/O channels is through a program called DataStudio, which has been loaded into your computer and is available via the DataStudio II Labs folder in Applications. The program can be used to take readings, automatically collect data, display and analyze the data, and graph the results. Finally, the Microsoft Word and Excel programs are available to prepare your lab reports on these computers

II. Elementary Theory of Electrical Circuits

CHARGE: The concept of charge (symbol q) is fundamental to all electrical phenomena. Charge is measured in units of a **coulomb (symbol C)**. There are two kinds of charges, positive and negative. The smallest charge known to exist freely is that on an electron, a negatively charged particle with a charge equal to -1.602×10^{-19} C. The proton has a positive charge exactly equal in magnitude to that of an electron. The magnitude of this elementary charge is usually represented by the symbol $e = 1.602 \times 10^{-19}$ C. In electrical circuits, positive charge usually indicates an absence of electrons, rather than mobility of the protons.

Supplementary Question 1:

How many electrons N does it take to make a charge of -1.0 C?

CURRENT: Moving charges constitute a **current (symbol I)**. A current is generated in a metal wire by causing the electrons to flow. Charges move quite freely in metals, but very poorly in insulating materials such as glass or wood. The rate at which charge moves across any given cross section of a wire is called the current. The direction of the current is the direction in which positive charges would move, which is opposite to the direction in which the actual negatively-charged electrons in a metal move. The **SI unit of current is an ampere (symbol A)**, related to the coulomb such that $1 A = 1 C/s$. That is, a current of $1 A$ means that a charge of $1 C$ is moving across any cross section of the wire per second. The ampere is one of five base units in the SI system (the others being the meter, second, kilogram, and mole) and is actually used to define the coulomb, rather than the other way around. Currents can be measured with a device called an ammeter, which must always be connected in series with the circuit branch of interest, so that the current flows through the meter. It should never be connected in parallel.

Supplementary Question 2:

A current of $1.2 A$ passes through a wire for 1.3 minutes. How much total charge q has been transported? How many electrons N have been transported? Please use the appropriate number of significant figures in your answer.

POTENTIAL: Charges are made to move from one place to another (such as along a wire) if there is a difference in electrical potential energy ΔU between one end of the wire and the other. Just as for a ball rolling downhill, charges move from regions of higher potential energy to lower potential energy.

In particular, a battery is capable of maintaining a difference in electrical potential energy between its terminals. A positive charge has a higher potential energy at the positive terminal of the battery than it does at the negative terminal. So if you connect a wire between the terminals of the battery, positive charges move from the positive terminal to the negative terminal along the wire. (Actually in a metal, the electrons, which are negatively charged, move from the negative to the positive terminal, but the effect is the same.) We have a current passing through the wire, from the positive to the negative terminal of the battery, through the wire.

The change in electrical potential energy ΔU of some amount of charge q moving from one point to another point along a wire is linearly proportional to q , just as the change in mechanical potential energy (namely $m g h$) of a body changing height is linearly proportional to the mass m of the body. If we divide out this charge from the potential energy, we get a quantity that only depends on the electrical circuit, which we call the electrical potential difference V between the two points in the circuit.

$$V \equiv \frac{\Delta U}{q} \tag{1}$$

Since potential energy has units of **joules (symbol J)** and charge has units of coulombs, the units of potential must be **joules per coulomb**, which carries the name **volt (symbol V)**, i.e., $1 V = 1 J/C$. So if a charge of $1 C$ moves from one terminal of a $1.5 V$ cell to the other, its potential energy changes by $1.5 J$. Potential differences are measured with a device called a voltmeter. One lead is connected to each of the two points between which you wish to measure the potential difference. This means that you must connect a voltmeter in parallel with the circuit elements of interest, never in series, in contrast to how an ammeter is used.

Note carefully that just as in the case of potential energy, only differences in potential are physically meaningful. If the potential at the negative terminal of a 1.5 V battery is arbitrarily called 0 V, the positive terminal would be at +1.5 V. However, with equal validity, you could say that the positive terminal is at -9000.0 V so that the negative terminal is at -9001.5 V. This simply means that you have set the zero of potential somewhere else. To keep things from getting confusing, it is conventional to choose some point in the circuit which we all agree to call 0 V. That point is called ground and serves as a reference point for all measurements of potential. For this reason, it is important that you always remember to connect the ground point of your circuit to the ground point of the interface box, so that the computer is using the correct reference point in making measurements. If you forget to connect it, all of your data will be garbage!

The word potential and voltage are used interchangeably.

In the lab, you will use sources of potential difference (also called voltage), such as batteries and power supplies, which can maintain the potential difference between their terminals at specific values. A power supply is available to you from the interface. It can provide voltages, which you can adjust on the computer to any value you like between -5 V and +5V. In this first experiment on electric circuits, you will use constant voltages, commonly called dc (“direct current”), which means that the voltage difference between the two terminals is held constant.

Supplemental Question 3:

Suppose that the negative terminal of a 1.5 V cell is designated as ground. What electrical potential energy ΔU would an electron have at the positive terminal? Also answer the same question for a proton instead of an electron.

RESISTANCE: If a potential difference V is applied across the leads of a sample and the resulting current flowing through it is I , then the resistance R of the sample is defined as

$$R = \frac{V}{I}. \quad (2)$$

The unit of resistance is the ohm (symbol Ω) which is evidently equal to 1 V/A. For example, if 4.0 V is applied across a device and a current of 40 mA (0.04 A) flows through it, the resistance of the device is 100 Ω .

In many important cases, if the voltage across a device is changed then the current changes proportionally, provided that the device’s temperature is kept constant. Under these conditions the resistance R of the sample is independent of the voltage and current, so that V and I are related according to

$$V = IR. \quad (3)$$

This is called Ohm’s law. You should be careful to distinguish Eq. (2), which is the definition of resistance and must thus hold for any device, from Eq. (3), which only holds for certain devices which are said to be ohmic. For a nonohmic device such as a diode, the resistance given by Eq. (2) varies with the potential applied across it. We will use simple ohmic devices called resistors in many of our labs, whose resistances are indicated by the color coding scheme tabulated on the top of the next page, as will be explained to you in the lab. Ohm’s law becomes very useful when applied to resistors in circuits and we will use it often.

Color	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

Note that for a given applied voltage V , the amount of current I which flows through a resistor is inversely proportional to its resistance, since $I = V/R$. For example, if I connect the same battery across first one resistor and then another with a different resistance, more current will flow through the smaller resistance. This explains why we give resistance its name: it is a measure of the opposition of the device to the flow of current. Conductors like metal wires have very low resistance. In fact, the copper wires we will use for connections in this lab have resistances which are so low (on the order of 0.001Ω) that we can neglect them (i.e., approximate their resistance as being zero) compared to the resistances of the various components in our circuits; we will also choose to neglect the small internal resistances of the batteries used in this lab. In contrast, insulators such as the ceramic wire holders on telephone poles have very high resistance and hence no significant current can flow through them, even with a large voltage applied across them.

Part 1—Measurement of a resistance

Resistances can be measured using what is called an ohmmeter, which is essentially a voltmeter plus a constant current source. A known current I is passed by the meter through the resistor attached to its connectors, the resulting potential difference V across the resistor is measured, and the meter then internally ratios V to I to determine the resistance in accordance with Eq. (2).

1. Choose a 270Ω resistor by its color code. Connect two leads from the two leads on the resistor to the 'A Ω ' and '-' sockets in the multimeter. Set the knob on the circular scale on your multimeter to the 2K position in the blue 'OHMS' section. Turn the multimeter on and see the display. Turn the knob to the 20K, and 200K positions, and then to the 200 position and see what happens. Explain what happens in your report.

Notice that this procedure may not work if the resistor is connected to other circuit elements: you may then be measuring the resistance of these other elements! To be safe, always remove a resistor from its circuit before you try to measure its resistance.

Part 2—Setting and measuring a voltage

The computer can set the output voltage of the interface box.

1. Make sure that the Science Workshop 750 Interface is connected to its power supply and the interface cable is connected to the computer. Also that it is ON as indicated by the green Power LED in lower left corner. (Power switch is on back panel)
2. Open the Mac OS Finder by clicking the leftmost icon (blue “smiley”) in the Dock. Click on Application icon in Finder Sidebar. Click on the *DataStudio II Labs* folder icon. Then OPEN the file “(Finder\Applications\DataStudio II Labs\Experiment 4)” by double-clicking its icon. The DataStudio program opens with a display which has 2 windows and a DataStudio menu bar along the top.

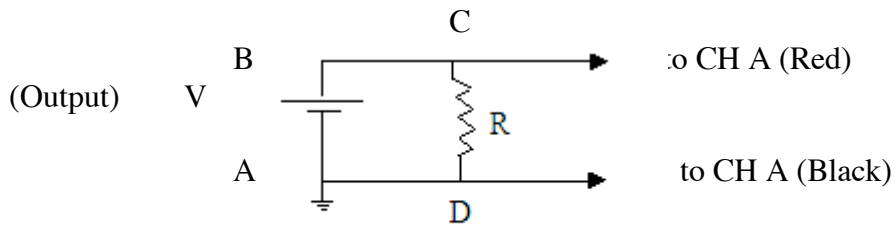
On the right are four digital meters. The top two monitor the output voltage and output current from the OUTPUT of the interface box. The two bottom digital meters display the input voltages from ANALOG CHANNEL A and ANALOG CHANNEL B of the interface. Any voltage that you want to measure can be given to either of these channels and the value will be shown on the corresponding meter.

Finally, there is a SIGNAL GENERATOR window to the left of the four digital meters, which allows you to program the output signal available at the OUTPUT of the interface.

3. In the Signal Generator window, check that *DC Voltage* is selected, and then set the DC voltage to 2 V by clicking on the up and down arrow buttons. You can also click on the numerical display of DC volts, and then type in a value that you want to set (e.g., 2.54 V). On the right, you will see three buttons. Check that the AUTO button is selected and that the OFF button is shaded. (AUTO means that the Signal Generator will automatically be turned on when the Experiment is started) The signal OUTPUT is now OFF.
4. Connect the OUTPUT of the interface to the voltage inputs (\pm) of the digital multimeter. Set the multimeter to the 20 V (DC) range and then switch it ON. Also connect the OUTPUT of the interface box to the ANALOG CHANNEL A inputs on the interface box. Both CHANNELs have round connectors with two leads coming out of them. Make sure that these connectors are properly plugged into the inputs of CHANNEL A and B (painted red stripes up). You can leave the CHANNEL B wires loose.
5. Go to the DataStudio menu bar and click on the Experiment menu. From that drop down menu click *Monitor Data*. The OUTPUT Volts meter and the CHANNEL A Voltage meter both show the same value of the output, which you selected on the signal generator. Change the output voltage of the Signal generator to 1.00 V (by clicking on the DC Voltage display on the Signal Generator Window), 1.5 V, -1.5 V etc., and see how the display changes. You can simultaneously monitor these voltage changes with the digital multimeter.
6. Similarly use the CHANNEL B to measure the output. Record Signal Generator setting, Digital Multimeter, Output Voltage, CH A and CH B at several settings of both positive and negative outputs. Using the Multimeter as a standard, compute and report errors in all readings using Excel.
7. Click STOP button (below Edit in DataStudio menu bar to stop reading and shut off Signal Generator.

8. Part 3— Verification of Ohm’s Law

1. Connect the circuit as shown below. The terminals of the battery represent the + and – terminals of the OUTPUT from the interface.



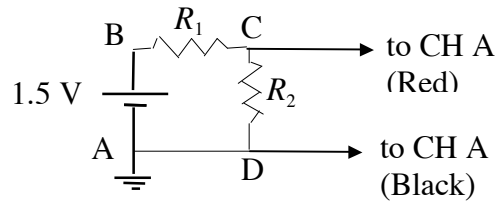
Choose a resistance $R = 100 \Omega$, or 270Ω by the color code. Note from the circuit that the voltage output from the interface is the same as the voltage across the resistor, and the current output from the interface is the same as the current through the resistor, since the circuit has only (one resistor in) a single loop.

2. Start the experiment by clicking on Experiment from the top drop down menu, and then click Monitor Data. Note the values of the CHANNEL A voltage V and the current output I from the interface. The ratio V/I gives the value of the resistance. Note this down.
3. Change the value of the voltage across the resistor using the SIGNAL GENERATOR window. Repeat step 2, for 5 different values of the voltage across the resistor. Draw a graph of the Voltage V vs. Current I . This should be a straight line passing through the origin. The slope gives the resistance in ohms.

Part 4---Measurement of the potential difference between two points in a circuit

1. Obtain a 270Ω carbon resistor and another resistor whose resistance lies between 100 and 1000Ω . Interpret the color-coding to determine their nominal resistances and their tolerances and write these down. Now use the handheld multimeter to measure their actual resistances as follows. Connect a resistor between the “–” and “ $A\Omega$ ” jacks; alligator clips attached to the ends of two leads would help here. Turn the dial into the blue Ohms range—the “ $2 \text{ k}\Omega$ ” scale should be appropriate. Now turn on the meter and write down the displayed resistance. Then disconnect the resistor and attach the other resistor and write down its value. Do you get the same answer if you interchange the two leads connected to the resistor, i.e., does the resistor have a preferred direction of current flow? (While you are at it, also write down what the ohmmeter reads for the open and short circuit conditions on the largest and smallest scales, respectively, so you can recognize the limits of the meter.) Compute the percent errors between the color-coded and actual resistances. Do they lie within the tolerances? (Even if they do not, you can still use these resistors.)
2. Connect the circuit shown below. Whenever you build complicated circuit like this, first construct the circuit before making any connections to the interface box. Specifically, first build the loop A-B-C-D on the breadboard by connecting the positive terminal of the power supply to either of the two resistors, call it R_1 ; then connect the other end of R_1 to the other resistor, call it R_2 ; finally, connect the free end of R_2 to the negative terminal of

the power supply to complete the loop. Now connect the appropriate points in the circuit to CH A on the interface box; an alligator clip might help for the connection to point C.



This is the simplest example of a “series” circuit: the two resistors are connected in series to the power supply, meaning that the same current I flows through the two resistors and from the power supply. Otherwise, if say the current through R_1 were smaller than that through R_2 , extra charges would have to be spontaneously created between the two resistors to provide the extra current, in violation of the law of charge conservation.

Now consider a positive charge q that starts at point A, the negative terminal of the power supply, and traverses the circuit along the clockwise path A-B-C-D-A. When it returns to the original point A, the change in its electrical potential energy must be zero. So the sum of the changes in energy as it goes through each leg A-B, B-C, C-D, and D-A must be zero. Let us look at each of these terms in turn:

- A-B Since the power supply maintains a potential difference of V between its terminals, with the positive terminal at the higher potential, the charge gains energy qV when it gets “pumped” from A to B, as though the power supply were a water pump.
- B-C Since the current is flowing from the positive terminal of the power supply to the negative terminal along the wire and since positive charges move from higher potential to lower potential, B must be at a higher potential than C. Specifically the potential difference V_1 across R_1 must be IR_1 according to Ohm’s law. So the change in energy of the positive charge for this leg is $-qV_1 = -qIR_1$. You can think of this as water flowing downhill through a pipe stuffed with cotton wool—the potential difference across the two ends of the wire is analogous to the pressure difference across the pipe, and the electric and water currents are analogous, as are the electric and fluid resistances.
- C-D Similarly the energy of the charge changes in this leg by $-qV_2 = -qIR_2$.
- D-A This is just a copper wire of negligible resistance so that the potential drop across it is almost zero. Hence the change in energy of the charge in this part of the loop is very nearly zero. It’s like a smooth, wide pipe through which water easily flows.

The total change in energy of the charge in going around the loop is thus $qV - qV_1 - qV_2 = 0$, or dividing through by q ,

$$V - V_1 - V_2 = 0. \tag{4}$$

More generally, in going around any closed loop the sum of the potential differences across all of the circuit elements is equal to zero. This is called Kirchoff’s Voltage or Loop Rule.

Equation (4) can be rewritten as $V = V_1 + V_2 = IR_1 + IR_2$ so that

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

is the current in the circuit in terms of known quantities. The potential drop across each resistor is then given by

$$V_1 = IR_1 = V \frac{R_1}{R_1 + R_2} \quad \text{and} \quad V_2 = IR_2 = V \frac{R_2}{R_1 + R_2}. \quad (6)$$

This circuit is often called a voltage divider since we see from this equation that the total voltage V of the power supply has been split between the two resistors in proportion to their resistances.

3. Connect CH A across the resistor R_2 (to the two ends of the resistor). Note the voltage displayed in CH A. This should be according to equation 6 above. Now similarly connect CH B across resistor R_1 , and note the voltage in the corresponding display. Check if this also obeys equation (6). Change the OUTPUT voltage from the interface and go through this procedure step 3 for 5 different voltages.

Supplemental Question 4:

Consider a 5.0 V battery connected in series with two resistances of 250 Ω and 340 Ω . Draw the circuit and calculate the current through and voltage across each resistor. Use your answers to check that Kirchhoff's Voltage Loop Rule holds.