# Simple Circuits

**Introduction**

In this first of two exercises dealing with electrical circuitry, you will become familiar with the tools and terminology that is common to the world of electrical components and circuits. First, we describe three types of materials when working with electricity:

- **Conductors**: materials that allow electrical current to flow with relative ease; includes most metals (e.g. copper, aluminum, silver or gold).
- **Insulators**: materials that mostly or completely restrict the flow of electrical current; includes most plastics, wood, vacuum.
- **Semiconductors**: materials that conduct some electrical current, but have a high resistance compared to most metals.

Electric current ($I$) is the movement of charge from one place to another due to difference in electric potential or voltage ($V$). The ability to restrict the flow of charge through an object is characterized by its resistance ($R$).

If a voltage is applied across an object and the resulting current is large, then the resistance to the flow of charge is low and the resistance is small - this is true for conductors. If a voltage is applied across an object and the resulting current is small, then the resistance is high - this is true for insulators.

Resistors are devices that limit the flow of current and convert electrical energy into heat. We are all familiar with toasters, hair dryers, space heaters, electric ranges, and the myriad of everyday devices that utilize this property. Fuses and circuit breakers are other common examples of resistance-heated devices. A fuse operates by getting hot enough to melt and break a circuit when the current through it exceeds a specified value. Some circuit breakers perform the same function, but they use the heat produced in a resistance to trip a mechanical switch that can be reset and used again.

While resistance can be exploited, it also has an undesirable quality, like friction in machinery. Energy is lost in electric power transmission lines and converted into waste heat by the resistance of the copper wire of which they are made. This is one of the reasons why a substance whose resistance is close to zero (called a superconductor) is much sought after. Superconductivity has long been realized at temperatures near absolute zero, but keeping a transmission line hundreds of miles long that cold is obviously impractical; hence the great interest in the so-called "room temperature superconductor".

**Equipment**

- Simple Circuits Assembly Board
- Components (on plastic bases), including Resistors, Light Bulb, Light-Emitting Diode (LED)
- AA Alkaline Batteries
- Adjustable variable resistor (with knob)
- Fluke Model 73 Digital Multi-Meter (DMM)
- Wavetek Model DM2 Multi-Meter

**Background**

Electric charges are driven through a circuit by a potential difference ($V$), which is measured in volts. Common potential differences are typically high-power devices: electric utilities, thunderstorms, batteries, solar cells, eels, etc. However, low-powered devices such as microphones, tape recorder heads, and neurons are also sources of potential differences.

Current (I) is the rate at which charge flows through a cross sectional area:

$$I = \frac{dq}{dt}$$

As opposed to a bolt of lightning, the current within a circuit is confined to well-defined conducting paths consisting of wires and electrical components that can be described by the amount of resistance that they exhibit.

Mathematically, the resistance of an object is obtained from the ratio of the potential difference across the object to the current flowing through it

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

This relationship is known as Ohm's law, named after Georg Ohm, the German physicist who first described this relation. For many devices, the resistance of an object is constant over a large range of currents and voltages. Such circuit elements are known as *ohmic devices*.

In today's experiment, you will be investigating electric circuits and the electrical properties of various circuit elements.

**Procedure**

**Resistance**

The easiest way to measure resistance of an object is with a device called multimeter. As you might guess from the name, a multimeter allows you to measure serveral electrical properties, such as voltage, current, or resistance. Your kit contains a Fluke Model 73 DMM (Digital Multi-Meter) brand multimeter, which can be used to measure resistances ranging from tenths of an ohm (Ω) to 32MΩ (mega-ohms). The accuracy of the multimeter is about 1%.

The measurements are made with a set of probes that plug into the multimeter depending on what values you are trying to measure: for instance, on the Fluke model, there are plug-ins for measuring voltage (V) & resistance (Ω), and one for measuring current (with a 10 A threshold). The last plug-in, typically labeled "COM", stands for your source of ground.

In this experiment, we will use ordinary alkaline cells (size AA) that produce a steady emf of about 1.5V. They are installed in holders that are equipped with a switch that must be operated manually by pushing a small red button. This allows positive charge to move from the end marked with a "+" sign to the end marked with a "-" sign along a path through any resistance that is connected across them.

- Begin by plugging one probe into the (V\Ω) port, and the other into the ground (COM) port. Rotate the dial to the Ω symbol to measure resistance.
- Quantities are measured by touching the tips of the leads to the points between which you wish to measure.
- Read the value in the digital display window, taking note of the symbol to the right of the number: Ω (ohms), kΩ (thousands of ohms) or MΩ (millions of ohms). For example, a reading of 16.501 kΩ indicates a total resistance of 16,501 Ω.
- If the "OL" indication appears, you have encountered an overload - the value of the resistance is greater than the limit of the meter (which is 32 MΩ) - or you may have a faulty multimeter, usually caused by an internal fuse that is blown.
- If the meter reading changes erratically while taking a measurement, it probably means that proper contact is not being made. Try holding the probes in place more firmly or use clips on the ends of the leads to ensure proper contact.

Use the following exercises to study the resistance of several objects, as well as to learn how to use the multimeter.

- Measure the resistance of both resistors and the light bulb in the kit provided, and record their values in your notebook. The resistors with the colored bands are produced with the guarantee that they are within 10% of their nominal values. Use the table in Appendix A to determine what the value of both resistors should be, and compare those values with what you actually measured. Calculate the percent difference between the measured and theoretical values of resistance for both resistors. If your measurements are not within 10% of the theoretical values, repeat your measurements.
- Now measure the resistance of an animate object - the human body. Recall that while the human body may be approximately two-thirds water, it does somewhat restrict the flow of electricity. Hold one lead in each hand by pinching the tip with dry fingertips and read the resistance of your body. Have no fear - you will not be electricuted!
- As you may well know, water is a relatively good conductor. In this step, you will see how the addition of water to the surface of an object can change its resistance value. Moisten your fingertips & re-measure your body's resistance. Does the value of resistance increase or decrease? Explain your reasoning.
- Next, measure the resistance of some unpainted metallic object, like a coin or the clip on a pen. Repeat this measurement for a piece of notebook paper. How do the resistance values of the two materials (metal and paper) compare? Is this consistent within the context of the definitions of conductors and insulators discussed earlier?

**Kirchhoff's Junction Rule**

Kirchoff's Junction Rule states that for any circuit with multiple paths through which current can flow, the current entering a junction equals the current leaving. Fundamentally, this is a statement of charge conservation. By convention, currents entering the junction are assigned positive values and those leaving negative values. Thus, the sum of all the currents entering and leaving a junction will be zero.

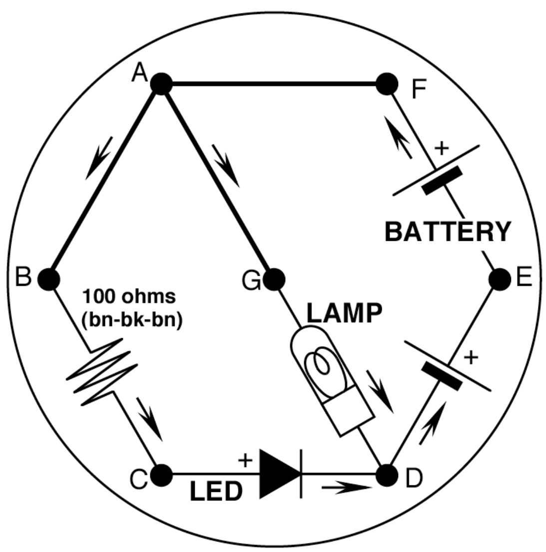


Figure 1: Schematic for Electrical Circuit

- Assemble the circuit shown in Figure 1 using two batteries, the light bulb, the LED, the 100 Ω resistor, and three conducting links.
- Once assembled, press the switches on both batteries simultaneously and verify that both the LED and the lamp are lit.

Since current is the flow of electric charge, the entire charge flow must pass through the multimeter in order to be measured. The circuit was designed so that Kirchhoff's junction rule can be checked conveniently at junction A.

To measure the currents flowing into and out of junction A:

- Remove the conducting link between F and A, and place the **Wavetek** multimeter (now acting as an ammeter, a current-measuring device) in this gap.
- Plug the end of one wire into COM port of the ammeter, and a second wire into the FUSED-200mA port of the ammeter.
- Plug the ammeter into the empty space where you removed the conducting link. Figure 2 illustrates this procedure for the current flowing in segment AF.
- Turn the dial on the multimeter to 200m (200 milliamperes = 200 x $10^{-3}$ amperes)
- Measure the current from (or to) point F. If you get a negative reading, e.g., -15.3, it means that the current is going into the COM terminal and out of the 200mA terminal. Record the current flowing through this segment in your notebook, and explain how you determined whether the current in this segment is flowing into or out of the junction at A.
- Repeat for the other two paths connected to junction A (AG & AB).

If Kirchoff's Junction Rule holds true, the sum of the currents flowing into and out of junction A should be zero. Determine whether this is the case within experimental error.

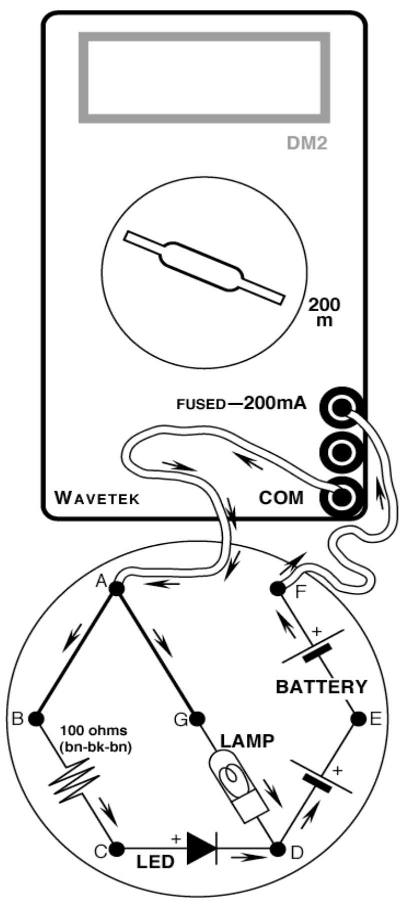


Figure 2: A multi-meter connected in series with the batteries permits the current flowing through the batteries to be measured.

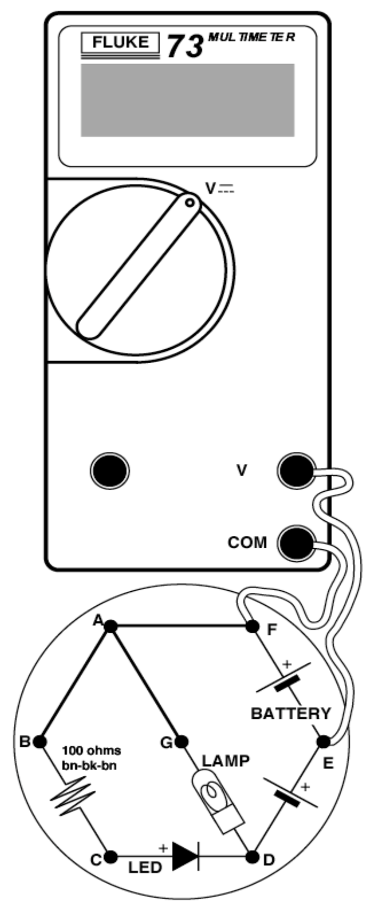


Figure 3: A multi-meter in parallel with the battery permits the potential difference across the battery to be measured.

**Kirchhoff's Loop Rule**

Kirchoff's Loop Rule states that the sum of all potential differences across the circuit elements in any closed loop must equal zero. In essence, this is a statement of energy conservation. As an example, consider the circuit shown in Figure 1. It contains three closed loops, one of which is AGDCBA. In this case, Kirchoff's Loop Rule requires that:

$$V_{AG} + V_{GD} + V_{DC} + V_{CB} + V_{BA} = 0$$

The notation of $V_{AG}$ indicates the difference in voltage from point A to G.

*An important distinction to note: you can refer to a current through a single point, but voltage here refers to the potential difference between two points. Often one point in a circuit is connected to ground, and the voltage at ground is defined as zero volts. Then one speaks of the voltage at various points in the circuit, meaning the voltage difference between a point and ground.

- Use the Fluke multimeter with the black lead plugged into the "COM" port and the red lead plugged into the "V\Ω " port; turn the dial to the DC voltage position, noted by the symbol $\overset{-}{\underset{...}{V}}$ (alternatively, the symbol V~ refers to AC voltage).
- You will not need to break the circuit to measure potential difference - simply attach (or just touch) the leads across (in parallel with) the circuit element being considered (see Figure 3). If a negative sign appears in the display, it means that the black lead is touching a point at higher potential than the red lead; no sign means that the red lead is at a higher potential.
- Choose any closed path and measure the magnitudes and polarities of the potential differences across each element around the path. Use the diagram as a roadmap to follow each loop as you go. Be sure to re-draw Figure 1 in your lab notebook, and state which loop you are using.
- Determine whether your measurements confirm Kirchoff's Loop Rule.
- Now unplug one of the batteries, turn it around and reinsert it. Describe the effects of this action on the light bulb, the LED, and the sum of the potentials around the loop. Clearly explain reason for any differences that you observe.

**Ohmic Devices**

Recall that ohmic devices are ones that have a constant resistance that is independent of the voltage applied or the current passing through it. While many devices are ohmic, there are many non-ohmic circuit elements. For these devices, the resistance of an object is not constant, and can vary with applied voltage.

In this exercise, you will determine whether two circuit elements (a 22-Ω resistor and a light bulb) behave according to Ohm's Law.

- Assemble the circuit shown in Figure 4 below, with the voltmeter connected in parallel and the ammeter connected in series. For simplicity, the meters are represented in schematic form, which is a circle with a letter that designates the type of meter in it: A "V" represents the **Fluke** voltmeter and an "A" represents the **Wavetek** ammeter.
- The combination of the two batteries and the variable resistor is called a voltage divider, which allows for continuous variation of the applied voltage via an adjustable knob. Begin with the applied voltage set to zero by turning the knob on the variable resistor fully counterclockwise.
- While pressing the switches (red buttons) of both batteries simultaneously, increase the voltage by turning the knob on the variable resistor until you observe a current value of ≅ 5 mA. Touch the leads of the volt meter first across the resistor and then across the light bulb. Record the exact values for the current through and the voltage across both the light bulb ($V_{LB}$) and the resistor ($V_R$)
- Increase the current in steps of 5 mA until you reach a final current of ≅ 25 mA, recording the current and voltage values each time.
- Use Excel to produce a plot of $V_R$ and $V_{LB}$ as a function of $I$ on the same graph.

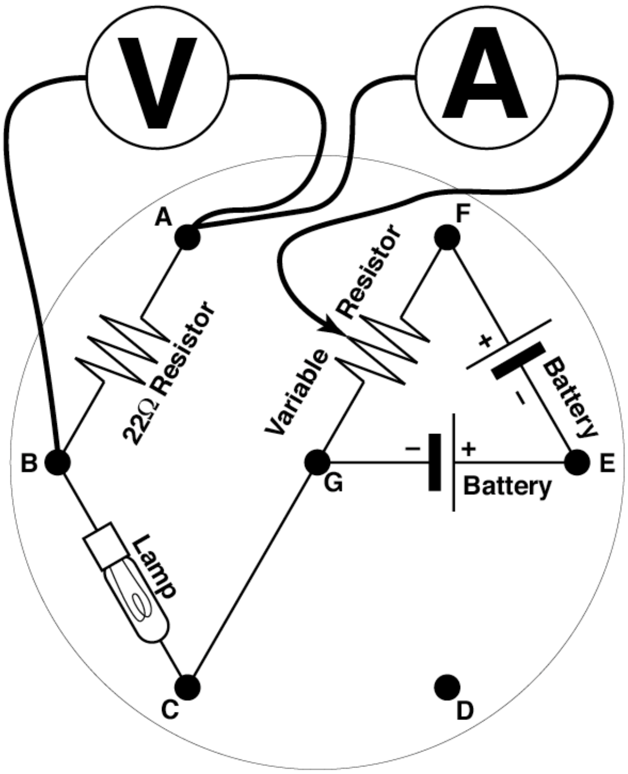


Figure 4: Simple Circuit Diagram

Regarding the recent data set, consider the following questions:

- Assume that the resistance for both the light bulb & the 22-Ω resistor are constant between ~ 5 mA to 10 mA. Extrapolate your data, and calculate what the voltage values for both objects would be at ~ 15, 20 and 25 mA if these were both ohmic devices.
- Compare the ohmic predictions in the previous step to the voltage data that you collected for both the resistor and the light bulb. Are either of these devices ohmic based on your measurements?

## Concluding Questions

When responding to the questions/exercises below, your responses need to be complete and coherent. Full credit will only be awarded for correct answers that are accompanied by an explanation and/or justification. Include enough of the question/exercise in your response that it is clear to your teaching assistant to which problem you are responding.

1. Given the following three materials: graphite from a mechanical pencil, an aluminum pie tin, and a Styrofoam coffee cup, list the materials in order of increasing resistance. Explain your reasoning.

2. If a 5V battery were connected to each of the three materials in the previous exercise and a complete circuit was formed, list the objects in order of increasing amount of current flow through the materials. Explain your reasoning. What does this suggest about the relationship between resistance and current?

3. The circuit diagrammed in Figure 4 illustrates how you measured voltages and currents to test Ohm's law. What must be true about the resistance in a voltmeter if the current passing through the 22-Ω resistor was the same regardless of whether the voltmeter was connected across the resistor? Explain your reasoning.

### Appendix 1: Resistor Color Code

| Color | Numerical Value | Uncertainty |
|---|---|---|
| Black (BK) | 0 | --- |
| Brown (BN) | 1 | --- |
| Red (RD) | 2 | --- |
| Orange (OR) | 3 | --- |
| Yellow (YO) | 4 | --- |
| Green (GN) | 5 | --- |
| Blue (BU) | 6 | --- |
| Violet (VI) | 7 | --- |
| Grey (GY) | 8 | --- |
| White (WH) | 9 | --- |
| Gold (GD) | --- | 5% |
| Silver (SL) | --- | 10% |
| none | --- | 20% |

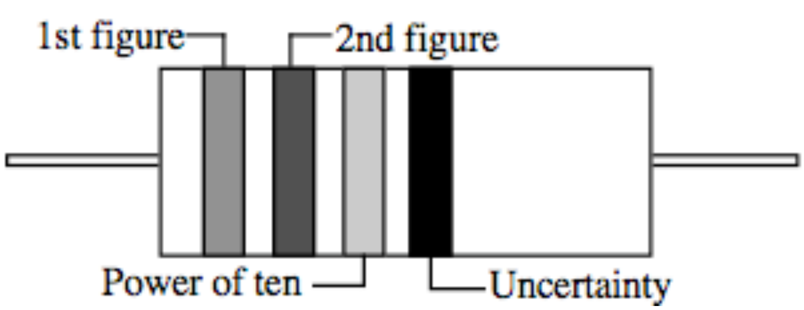


Figure 5: Determining the Value of a Resistor

Example: If the first three bands on the resistor have the colors brown, black, red from left to right, then the first figure is 1. The second figure is 0, and the power of ten is 2. Thus, this resistor has a resistance of $10 \times 10^2 = 1000\Omega$.