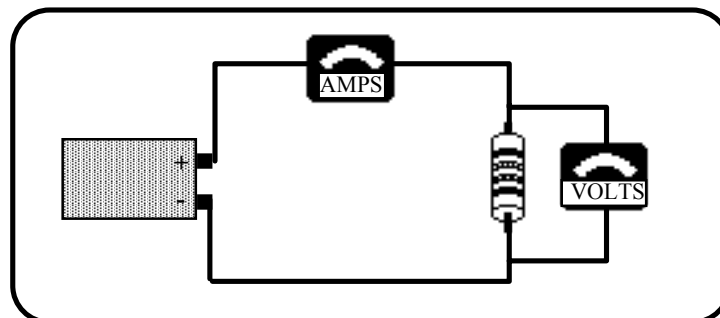


Name _____ Date _____ Partners _____

Lab 3 - OHM'S LAW AND KIRCHHOFF'S CIRCUIT RULES



OBJECTIVES

- To learn to apply the concept of potential difference (voltage) to explain the action of a battery in a circuit.
- To understand how potential difference (voltage) is distributed in different parts of series and parallel circuits.
- To understand the quantitative relationship between potential difference and current for a resistor (Ohm's law).
- To examine Kirchhoff's circuit rules.

OVERVIEW

In a previous lab you explored currents at different points in series and parallel circuits. You saw that in a series circuit, *the current is the same through all elements*. You also saw that in a parallel circuit, *the current divides among the branches so that the total current through the battery equals the sum of the currents in each branch*.

You have also observed that when two or more parallel branches are connected directly across a battery, making a change in one branch does not affect the current in the other branch(es), while changing one part of a series circuit changes the current in all parts of that series circuit.

In carrying out these observations of series and parallel circuits, you have seen that connecting light bulbs in series results in a larger resistance to current and therefore a smaller current, while a parallel connection results in a smaller resistance and larger current.

In this lab, you will first examine the role of the battery in causing a current in a circuit. You will then compare the potential differences (voltages) across different parts of series and parallel circuits.

Based on your previous observations, you probably associate a larger resistance connected to a battery with a smaller current, and a smaller resistance with a larger current. You will explore the quantitative relationship between the current through a *resistor* and the potential difference (voltage) across the resistor. This relationship is known as Ohm's law. You will then use Kirchoff's circuit rules to completely solve a DC circuit.

INVESTIGATION 1: BATTERIES AND VOLTAGES IN SERIES CIRCUITS

So far you have developed a current model and the concept of resistance to explain the relative brightness of bulbs in simple circuits. Your model says that when a battery is connected to a complete circuit, there is a current. For a given battery, the magnitude of the current depends on the total resistance of the circuit. In this investigation you will explore batteries and the potential differences (voltages) between various points in circuits.

In order to do this you will need the following items:

- two voltage probes
- 2 1.5 volt D batteries (must be very fresh, alkaline) and holders
- 6 wires with alligator clip leads
- 2 #14 bulbs in sockets
- contact switch

You have already seen what happens to the brightness of the bulb in circuit 1-1(a) if you add a second bulb in series as shown in circuit 1-1(b). The two bulbs are not as bright as the original bulb. We concluded that the resistance of the circuit is larger, resulting in less current through the bulbs.

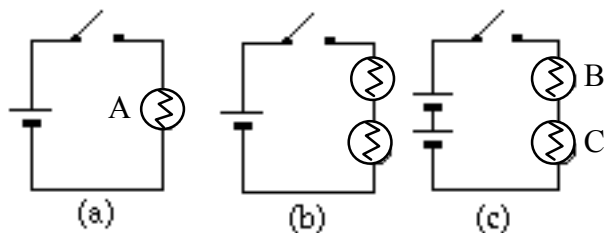


Figure 1-1: Series circuits with (a) one battery and one bulb, (b) one battery and two bulbs and (c) two batteries and two bulbs. (All batteries and all bulbs are identical.)

Prediction 1-1: What do you predict would happen to the brightness of the bulbs if you connected a second battery in series with the first at the same time you added the second bulb, as in Figure 1-1 (c)? How would the brightness of bulb A in circuit 1-1(a) compare to bulb B in circuit 1-1(c)? To bulb C?

Activity 1-1: Battery Action

1. Connect the circuit in Figure 1-1 (a), and observe the brightness of the bulb.
2. Now connect the circuit in 1-1 (c). (Be sure that the batteries are connected *in series*--the positive terminal of one must be connected to the negative terminal of the other.)

Question 1-1: What do you conclude about the current in the two bulb, two battery circuit as compared to the single bulb, single battery circuit?

Prediction 1-2: What do you predict about the brightness of bulb D in Figure 1-2 compared to bulb A in Figure 1-1 (a)?

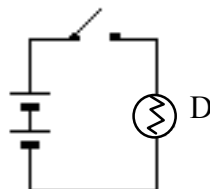


Figure 1-2: Series circuit with two batteries and one bulb.

3. Connect the circuit in Figure 1-2. *Only close the switch for a moment to observe the brightness of the bulb--otherwise, you will burn out the bulb.*

Question 1-2: How does increasing the number of batteries connected in series affect the current in a series circuit?

When a battery is fresh, the voltage marked on it is actually a measure of the *emf* (*electromotive force*) or *electric potential difference* between its terminals. *Voltage* is an informal term for emf or potential difference. We will use the two terms interchangeably.

Let's explore the potential differences of batteries and bulbs in series and parallel circuits to see if we can come up with rules for them as we did earlier for currents.

How do the potential differences of batteries add when the batteries are connected in series or parallel? Figure 1-3 shows a single battery, two batteries identical to it connected in series, and two batteries identical to it connected in parallel.

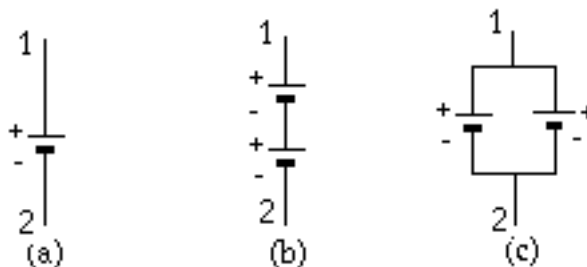


Figure 1-3: Identical batteries (a) single, (b) two connected in series and (c) two connected in parallel.

Prediction 1-3: If the potential difference between points 1 and 2 in Figure 1-3 (a) is known, predict the potential difference between points 1 and 2 in 1-3 (b) (series connection) and in 1-3 (c) (parallel connection). Explain your reasoning.

Activity 1-2: Batteries in Series and Parallel

You can measure potential differences with voltage probes connected as shown in Figure 1-4.

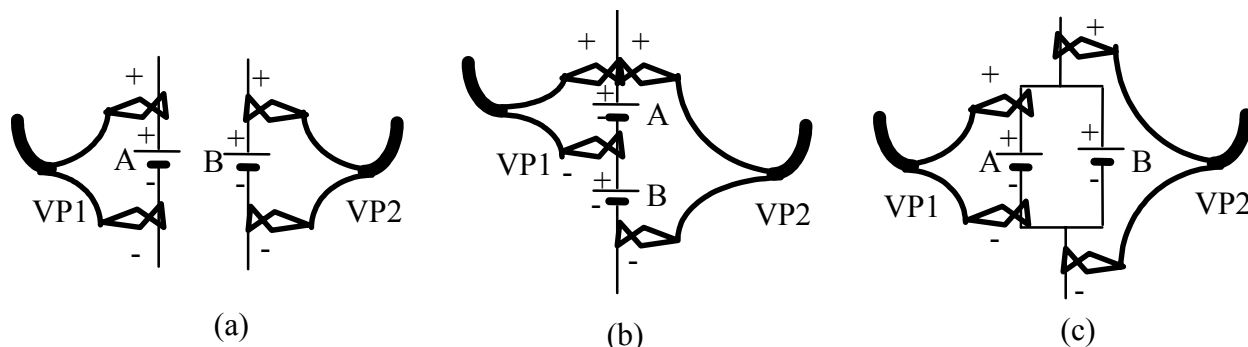


Figure 1-4: Voltage probes connected to measure the potential difference across (a) two single batteries, (b) a single battery and two batteries connected in series, and (c) a single battery and two batteries connected in parallel.

1. Open the experiment file **Batteries L3A1-2**.
2. Connect voltage probe 1 across a single battery (as in Figure 1-4(a)), and voltage probe 2 across the other identical battery.
3. Record the voltage measured for each battery below.
Voltage of battery A: _____ Voltage of battery B: _____
4. Now connect the batteries in series as in Figure 1-4(b), and connect probe 1 to measure the potential difference across battery A and probe 2 to measure the potential difference across the series combination of the two batteries. Record your measured values below.
Voltage of battery A: _____
Voltage of A and B in series: _____

Question 1-3: Do your measured values agree with your predictions? Explain any differences.

5. Now connect the batteries in parallel as in Figure 1-4(c), and connect probe 1 to measure the potential difference across battery A and probe 2 to measure the potential difference across the parallel combination of the two batteries. Record your measured values below.
Voltage of battery A: _____
Voltage of A and B in parallel: _____

Question 1-4: Do your measured values agree with your predictions? Explain any differences.

Question 1-5: Make up a rule for finding the combined voltage of a number of batteries connected in series.

Question 1-6: Make up a rule for finding the combined voltage of a number of identical batteries connected in parallel.

What would happen if you wired two batteries of **unequal** voltage in parallel (don't do it)? In attempting to equalize the voltages, the stronger (higher-voltage) battery would charge up the weaker battery. This would severely drain the stronger battery, reducing its voltage, and temporarily add charge to the weaker battery, increasing its voltage. This could cause both batteries to overheat, and could be dangerous.

You can now explore the potential difference across different parts of a simple series circuit. Consider the circuit shown in Figure 1-5.

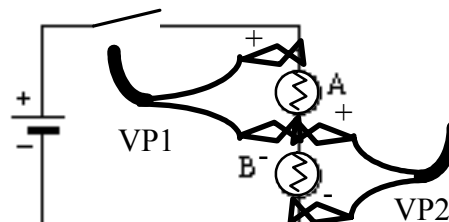


Figure 1-5: A series circuit with one battery and two bulbs. **Add a switch to the circuit to save the battery.**

Prediction 1-4: If bulbs A and B are identical, predict how the potential difference (voltage) across bulb A in Figure 1-5 will compare to the potential difference across the battery. How about bulb B?

Activity 1-3: Voltages in Series Circuits

1. Open the experiment file **Batteries L3A1-2**, if it is not already open.
2. Connect the voltage probes as in Figure 1-5 to measure the potential difference across bulb A and across bulb B. Record your measurements below.

Potential difference across bulb A: _____

Potential difference across bulb B: _____

Question 1-7: Formulate a rule for how potential differences across individual bulbs in a series connection combine to give the total potential difference across the series combination of the bulbs. How is this related to the potential difference of the battery?

INVESTIGATION 2: VOLTAGES IN PARALLEL CIRCUITS

You can also explore the potential differences across different parts of a simple *parallel* circuit.

You will need the following material:

- 2 voltage probes
- 1.5 V D cell battery (must be very fresh, alkaline) with holder
- 8 alligator clip leads
- 2 #14 bulbs with holders
- knife switch
- contact switch

Activity 2-1: Voltages in a Parallel Circuit

1. The experiment file **Batteries L3A1-2** should still be open showing two voltage graphs as a function of time.
2. Connect the circuit shown in Figure 2-1.

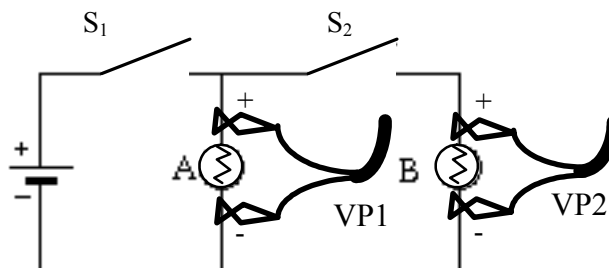


Figure 2-1: Voltage probes connected to measure the potential differences across bulbs A and B. **Add a switch to the left side of the circuit to save the battery.**

3. **Begin graphing**, and then close and open the switch S_2 as you've done before. Remember to open switch S_1 when not taking data.
4. **Print** out one set of graphs for your group.
5. Record your measurements using the **Digit Display**.

Switch S_2 open

Voltage across bulb A: _____ Voltage across bulb B: _____

Switch S_2 closed

Voltage across bulb A: _____ Voltage across bulb B: _____

Question 2-1: Did closing and opening switch S_2 significantly affect the voltage across bulb A (by more than several %)?

Question 2-2: Did closing and opening switch S_2 significantly affect the voltage across bulb B (by more than several %)?

Question 2-3: Based on your observations, formulate a rule for the potential differences across the different branches of a parallel circuit. How are these related to the voltage across the battery?

You have now observed several times in these activities that the voltage across an ideal battery doesn't change no matter what is connected to the battery (i.e. no matter how much current flows in the circuit). No battery is truly ideal (this is especially true for a less than fresh battery), so the voltage usually drops somewhat when the load on the battery is increased.

INVESTIGATION 3: MEASURING CURRENT, VOLTAGE AND RESISTANCE

The multimeters available to you can be used to measure current, voltage or resistance. All you need to do is choose the correct dial setting, connect the wire leads to the correct terminals on the meter and connect the meter correctly in the circuit. Figure 3-1 shows a simplified diagram of a multimeter. We will be using the multimeter to make DC (direct current) measurements, so make sure the multimeter is set to DC mode.

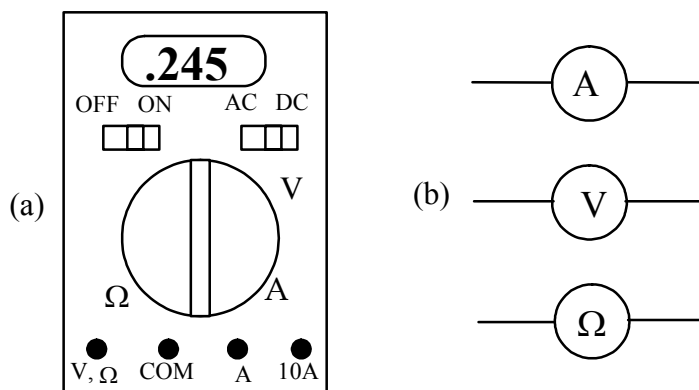


Figure 3-1 (a) Multimeter with voltage, current and resistance modes, and (b) symbols that will be used to indicate a multimeter used as an ammeter, voltmeter and ohmmeter respectively.

A current probe or a multimeter used to measure current are both connected in a circuit in the same way. Likewise, a voltage probe or a multimeter used to measure voltage are both connected in a circuit in the same way. The next two activities will remind you how to connect them. The activities will also show you that when meters are connected correctly, they don't interfere with the currents or voltages being measured.

You will need:

- digital multimeter
- two 1.5 V D batteries (must be very fresh alkaline) with holder
- 6 alligator clip leads
- 2 #14 bulbs and sockets
- 22 Ω and 75 Ω resistors

Activity 3-1: Measuring Current with a Multimeter

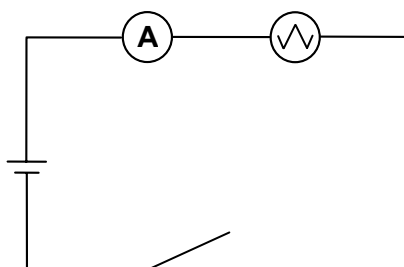


Figure 3-2: Connections to use a multimeter as an ammeter.

1. Set up the basic circuit in Figure 3-2, but without the ammeter (connect the bulb directly to the battery). Observe the brightness of the bulb.
2. Set the multimeter to measure current. **Important:** Use the **20-amp setting** and connect the probe to the **20-amp terminal** on the multimeter. When the multimeter is ready, connect it to the circuit as shown in Figure 3-2.

Was the brightness of the bulb significantly affected?

What current do you measure? _____

Question 3-1: When used correctly as an ammeter, the multimeter should measure the current through the bulb without significantly affecting that current. Does the multimeter appear to behave as if it is a large or small resistor? Explain based on your observations. What would be the resistance of a perfect ammeter?

Activity 3-2: Measuring Voltage with a Multimeter

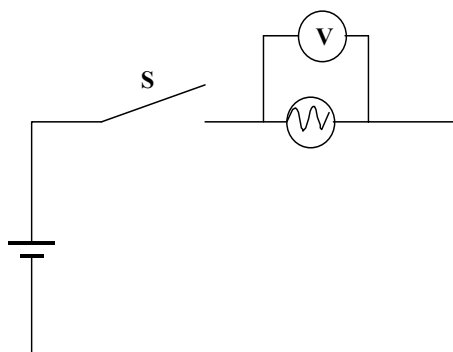


Figure 3-3: Connections to use a multimeter as a voltmeter.

1. Set up the basic circuit in Figure 3-3, but without the voltmeter. Observe the brightness of the bulb.
2. Set the multimeter to measure voltage. Important: Use the **volts** setting and connect the probe to the **voltage** terminal on the multimeter. When the multimeter is ready, connect it to the circuit as shown in Figure 3-3.

Was the brightness of the bulb significantly affected?

What voltage do you measure? _____

Note: The multimeters we are using have two attachments. One is the alligator clip-on probe and the other is a needle-like probe. You can screw off the clip-on probe to reveal the needle-like probe. Use whichever one you prefer, but make sure you screw the clip-on probe back on when finished.

Question 3-2: When used correctly as a voltmeter, the multimeter should measure the voltage across the bulb without significantly affecting that voltage. Does the multimeter appear to behave as if it is a large or small resistor? Explain based on your observations. What would be the resistance of a perfect voltmeter?

Activity 3-3: Measuring Resistance with a Multimeter

Next we will investigate how you measure resistance with a multimeter. In earlier labs, you may have observed that light bulbs exhibit resistance that increases with the current through the bulb (i.e. with the temperature of the filament). To make the design and analysis of circuits as simple as possible, it is desirable to have circuit elements with resistances that do not change. For that reason, *resistors* are used in electric circuits. The resistance of a well-designed resistor doesn't vary with the amount of current passing through it (or with the temperature), and they are inexpensive to manufacture.

One type of resistor is a carbon resistor, and uses graphite suspended in a hard glue binder. It is usually surrounded by a plastic case with a color code painted on it.

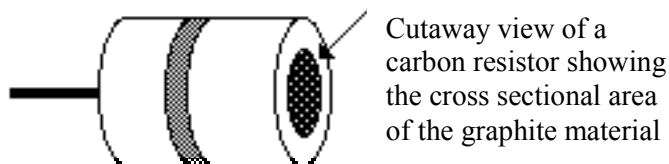


Figure 3-4: A Cutaway View of a Carbon Resistor

The color code on the resistor tells you the value of the resistance and the tolerance (guaranteed accuracy) of this value.

The first two stripes indicate the two digits of the resistance value. The third stripe indicates the power-of-ten multiplier. The following key shows the corresponding values:

black = 0	yellow = 4	grey = 8
brown = 1	green = 5	white = 9
red = 2	blue = 6	
orange = 3	violet = 7	

The fourth stripe tells the tolerance according to the following key:

red or none = $\pm 20\%$	gold = $\pm 5\%$
silver = $\pm 10\%$	brown = $\pm 1\%$

As an example, look at the resistor in Figure 3-5. Its two digits are 1 and 2 and the multiplier is 10^3 , so its value is 12×10^3 , or $12,000 \Omega$. The tolerance is $\pm 20\%$, so the value might actually be as large as $14,400 \Omega$ or as small as 9600Ω .

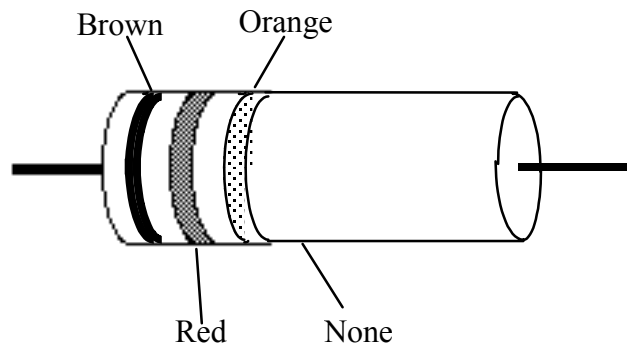


Figure 3-5: An example of a color-coded carbon resistor. The resistance of this resistor is $12 \times 10^3 \Omega \pm 20\%$.

The connection of the multimeter to measure resistance is shown in Figure 3-6. When the multimeter is in its ohmmeter mode, it connects a known voltage across the resistor, and measures the current through the resistor. Then resistance is calculated by the meter from $R = V/I$.

Note: Resistors must be isolated by disconnecting them from the circuit before measuring their resistances. This also prevents damage to the multimeter that may occur if a voltage is connected across its terminals while in the resistance mode.

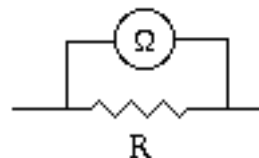


Figure 3-6: Connection of an ohmmeter to measure resistance.

1. Choose two different resistors and read their codes. Write down the resistances and tolerances. Then set up the multimeter as an ohmmeter and measure each.

Comment on the agreement:

2. Measure the equivalent resistor of the two resistors in series. Use alligator clip wires to connect the resistors. Calculate what the equivalent total resistance should be and compare with your measurement. (Look up in textbook if you don't know how to find equivalent resistance in series and parallel)

Discuss the agreement:

3. Do the same thing as in step 2 for the two resistors in parallel.

Discuss the agreement.

INVESTIGATION 4: OHM'S LAW

What is the relationship between current and potential difference? You have already seen that there is only a potential difference across a bulb or resistor when there is a current through the circuit element. The next question is how does the potential difference depend on the current? In order to explore this, you will need the following:

- current and voltage probes
- Hewlett Packard 6213A variable regulated DC power supply
- 10 alligator clip leads
- 10 Ω and 22 Ω resistors
- #14 bulb in a socket

Examine the circuit shown below. A variable DC power supply is like a variable battery. When you turn the dial, you change the voltage (potential difference) between its terminals. Therefore, this circuit allows you to measure the current through the resistor when different voltages are across it.

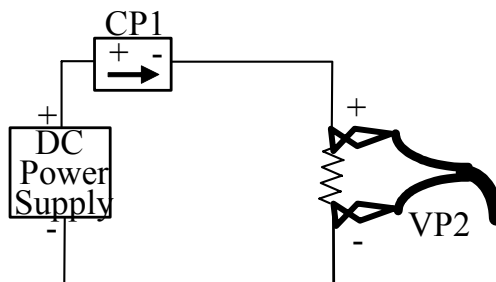


Figure 4-1: Circuit with a variable power supply to explore the relationship between current and potential difference for a resistor.

Prediction 4-1: What will happen to the current through the resistor as you turn the dial on the power supply and increase the applied voltage from zero? What about the voltage across the resistor?

Prediction 4-2: What will be the mathematical relationship between the *voltage across the resistor* and the *current through the resistor*?

Activity 4-1: Current and Potential Difference for a Resistor

1. Open the experiment file **Ohm's Law L3A4-1**.
2. Connect the circuit in Figure 4-1. Use a resistor of $10\ \Omega$. Note that the current probe is connected to measure the current through the resistor, and the voltage probe is connected to measure the potential difference across the resistor.
Your instructor will show you how to operate the power supply.
3. **Begin graphing** current and voltage with the power supply set to zero voltage, and graph as you turn the dial and increase the voltage slowly to about 3 volts.

Warning: Do not exceed 3 volts!
--

Question 4-1: What happened to the current in the circuit and the voltage across the resistor as the power supply voltage was increased? Did these agree with your prediction?

4. If it's not visible already, bring up the display for current CP1 versus voltage VP2. Notice that voltage is graphed on the horizontal axis, since it is the independent variable in our experiment. Use the **fit routine** to see if the relationship between voltage and current for a resistor is a proportional one. Write down the slope, and use it to calculate R.

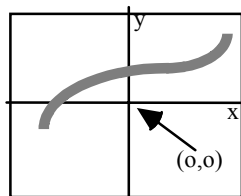
Slope = _____ Calculated R = _____

Question 4-2: Did you find that the relationship between voltage and current for a resistor is a proportional one? How did you calculate R from the slope? Now remove the resistor from the circuit and measure R directly with a multimeter. Does this agree with your calculated R (find percentage difference)?

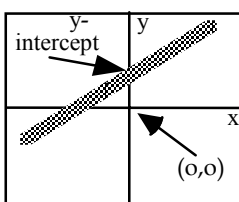
Measured R = _____

Agreement: _____

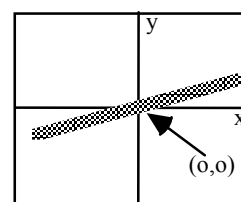
Reminder: We are interested in the nature of the mathematical relationship between the voltage across the resistor and the current through the resistor. This can be determined from the graph by drawing a smooth curve that fits the plotted data points. Some definitions of possible mathematical relationships are shown below. In these examples, y might be the voltage reading and x the current.



y is a function of x which increases as x increases.



y is a *linear* function of x which increases as x increases according to the mathematical relationship $y=mx+b$, where b is a constant called the *y-intercept*.



y is *proportional to* x . This is a special case of a linear relationship where $y = mx$, and b , the *y-intercept*, is zero.

These graphs show the differences between these three types of mathematical relationship. y can increase as x increases, and the relationship doesn't have to be *linear* or *proportional*. Proportionality refers only to the special linear relationship where the *y-intercept* is zero, as shown in the example graph on the right.

5. On the same graph, repeat steps 2 and 3 for: (a) a resistor 22Ω and (b) a light bulb. Be sure to increase the voltage **very slowly** for the light bulb, especially in the beginning. There should now be three sets of data on the I vs. V graph.

6. **Print** out one set of graphs for your group.

Question 4-3: For the second resistor, use the fit routine or the slope tool to find:

Slope = _____

Calculated R = _____

7. Measure R directly with the multimeter, and find the percentage difference. R_{measured} _____

Percentage difference in two values of R _____

The relationship between potential difference and current that you have observed for a resistor is known as Ohm's law. To put this law in its normal form, we must now define the quantity known as *resistance*. Resistance is defined as the slope of a voltage vs. current graph. (Recall that we have graphed current vs. voltage instead.)

If potential difference is measured in volts and current is measured in amperes, then the unit of resistance is the ohm, which is usually represented by the Greek letter "omega" (Ω)

Question 4-4: Based on your data for the light bulb, does it have a larger resistance for low current (cooler bulb) or high current (hotter bulb)? Use Data Studio to find the slope (and calculate R) for a low current and a high current.

Low current = _____ slope = _____ R= _____

High current = _____ slope = _____ R= _____

Question 4-5: Does a proportional or linear fit seem more reasonable for the resistor? Explain. What about for the light bulb? Explain.

INVESTIGATION 5: KIRCHHOFF'S CIRCUIT RULES

Suppose you want to calculate the currents in various branches of a circuit that has many components wired together in a complex array. The rules for combining resistors are very convenient in circuits made up only of resistors that are connected in series or parallel. But, while it may be possible in some cases to simplify parts of a circuit with the series and parallel rules, complete simplification to an equivalent resistance is often impossible, especially when components other than resistors are included. The application of Kirchhoff's Circuit Rules can help you to understand the most complex circuits.

Before summarizing these rules, we need to define the terms *junction* and *branch*. Figure 5-1 illustrates the definitions of these two terms for an arbitrary circuit. A junction in a circuit is a place where two or more wires are connected together. A branch is a portion of the circuit in which the current is the same through every circuit element. (That is, the circuit elements within the branch are all connected in series with each other.)

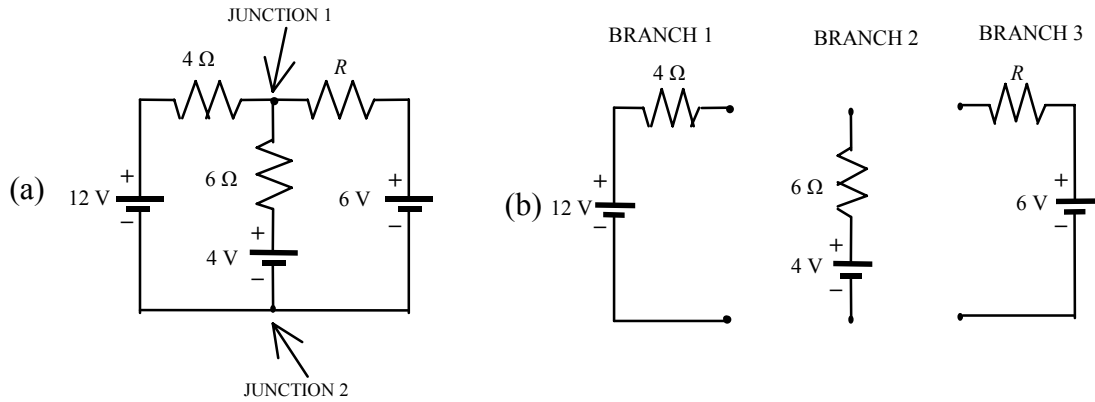


Figure 5-1: An arbitrary circuit used to illustrate junctions and branches.

Kirchhoff's rules can be summarized as follows:

1. *Junction Rule (based on charge conservation)*: The sum of all the currents entering any junction of the circuit must equal the sum of the currents leaving.
2. *Loop Rule (based on energy conservation)*: Around any closed loop in a circuit, the sum of all changes in potential (emfs and potential drops across resistors and other circuit elements) must equal zero.

You have probably already learned how to apply Kirchhoff's rules in class, but if not, here is a quick summary:

1. Assign a current symbol to each branch of the circuit, and label the current in each branch I_1 , I_2 , I_3 , etc.
2. *Arbitrarily* assign a direction to each current. The direction chosen for the current in each branch is arbitrary. If you choose the right direction, the current will eventually come out positive. If you choose the wrong direction, the current will eventually come out negative, indicating that you originally chose the wrong direction. Remember that the current is the same everywhere in a branch.
3. Apply the *Loop Rule* to each of the loops.
 - (a) Let the voltage drop across each resistor be the product of the resistance and the net current through the resistor. (However, make the sign positive if you are traversing a resistor in the direction opposite that of the current).
 - (b) Assign a positive potential difference when the loop traverses from the $-$ to the $+$ terminal of a battery. (If you are going across a battery in the opposite direction, assign a negative potential difference.)
4. Find each of the junctions and apply the *Junction Rule* to it.

Consider the circuit in Figure 5-2.

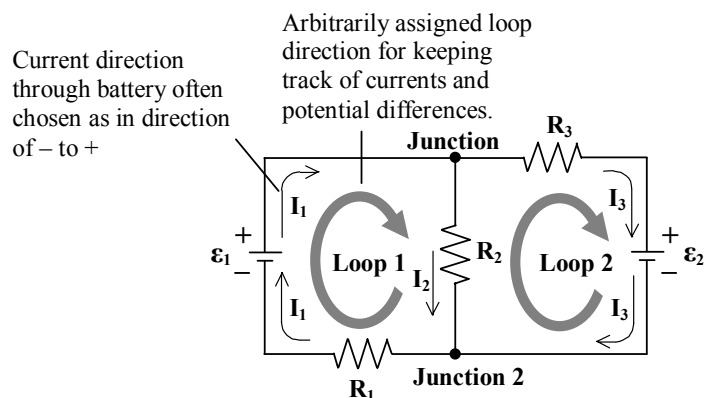


Figure 5-2: A complex circuit in which loops 1 and 2 share the resistor R_2 .

In Figure 5-2 the directions for the loops through the circuits and for the three currents are assigned arbitrarily. If we assume that the internal resistances of the batteries are negligible (i.e. that the batteries are ideal), then by applying the *Loop Rule* we find that

$$\text{Loop 1} \quad \mathcal{E}_1 - I_2 R_2 - I_1 R_1 = 0 \quad (1)$$

$$\text{Loop 2} \quad -\mathcal{E}_2 + I_2 R_2 - I_3 R_3 = 0 \quad (2)$$

By applying the *Junction Rule* to junction 1 or 2, we find that

$$I_1 = I_2 + I_3 \quad (3)$$

It may trouble you that the current directions and directions that the loops are traversed have been chosen arbitrarily. You can explore this assertion by changing these choices, and analyzing the circuit again.

In order to do the following activity you'll need a couple of resistors and a multimeter as follows:

- 2 resistors (rated values of 39 Ω and 75 Ω , both $\pm 5\%$)
- digital multimeter
- 6 V battery
- 1.5 V D battery (very fresh, alkaline) and holder
- 200 Ω potentiometer (will be set to 100 Ω)
- 8 alligator clip lead wires

1. Measure the actual values of the two fixed resistors and the two battery voltages with your multimeter. List the results below.

Measured voltage (emf) of the 6 V battery \mathcal{E}_1 : _____

Measured voltage (emf) of the 1.5 V battery \mathcal{E}_2 : _____

Measured resistance of the 75 Ω resistor R_1 : _____

Measured resistance of the 39 Ω resistor R_3 : _____

2. Carefully rewrite Equations (1), (2) and (3) with the appropriate *measured* (not rated) values for emf and resistances substituted into them. Use 100 Ω for the value of R_2 in your equations. You will be setting a variable resistor to that value soon.
3. In the pre-lab assignment you solved these three equations for the three unknown currents, I_1 , I_2 and I_3 in amps.

Calculated values: I_1 _____ I_2 _____ I_3 _____

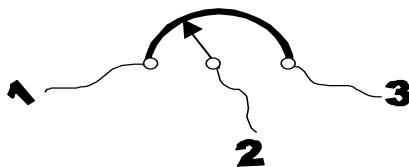


Figure 5-3: Schematic of a potentiometer. As the dial is rotated, the amount of resistive material between terminals 1 and 2, and between 2 and 3, changes. Thus it is a variable resistor.

Activity 5-1: Testing Kirchoff's Rules with a Real Circuit

1. Using the resistance mode of the multimeter measure the resistance between the center wire on the variable resistor and one of the other wires. You may need to use the needle-like probes here and have an extra pair of hands.

Question 5-1: What happens to the resistance reading as you rotate the dial on the variable resistor clockwise? Counterclockwise?

2. Set the variable resistor so that there is $100\ \Omega$ between the center wire and one of the other wires.
3. Wire up the circuit pictured in Figure 5-2 using the variable resistor set at $100\ \Omega$ as R_2 . Spread the wires and circuit elements out on the table so that the circuit looks as much like Figure 5-2 as possible. It will be a big mess!
4. Use the multimeter to measure the current in each branch of the circuit (you will actually measure voltages; see Note below), and enter your data in Table 5-1. Compare the measured values to those calculated in the pre-lab by computing the % difference in each case.

Note: The most accurate and easiest way to measure the currents with the digital multimeter is to measure the voltage across a resistor of known value, and then use Ohm's Law to calculate I from V and R .

Pay careful attention to the + and - connections of the voltmeter, so that you are checking not only the magnitude of the current, but also its direction.

Table 5-1 Results from test of Kirchhoff's Circuit Rules

	R measured w/ multimeter (ohms)	V measured w/ multimeter (volts)	Measured $I=V/R$ (amps)	Theoretical I (amps) (pre-lab)	% Difference
R1					
R2					
R3					

Question 5-2: How well do your measured currents agree with the theoretical values? Discuss possible errors in both your theoretical and measured currents. Were the directions of the currents confirmed?

Question 5-3: If the currents were less than expected, could this be explained by the conditions under which you measured the battery voltages?

