

# Electricity and Electronics for Robotics

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## Lesson Information

Your advisor will share some of the information in this section with you during the club meeting. You can read this section after the meeting to review what you have learned.

We use electricity daily. Electricity makes light bulbs glow, makes heating elements of an electric stove hot, powers computers, televisions and refrigerators, causes electric motors to spin and is used for many other things. Robots are commonly powered by electricity. If you would like to build a robot, it would be a good idea to learn about electricity and electronics.

**Electricity is the flow of electric charge.** What does that mean? First we need to learn a little about electric charge. Our story starts with amber, which is fossilized resin from evergreen trees (pine, etc.). Ancient Greeks who lived more than 2,000 years ago were aware of a curious property of amber. When rubbed with wool, amber will attract light-weight materials such as a small piece of paper or a feather. Today we know that static electricity is the cause of the attraction. The amber becomes charged with an excess of electrons when rubbed with wool. That charge can attract other objects. The word electron comes from the Greek word for amber.

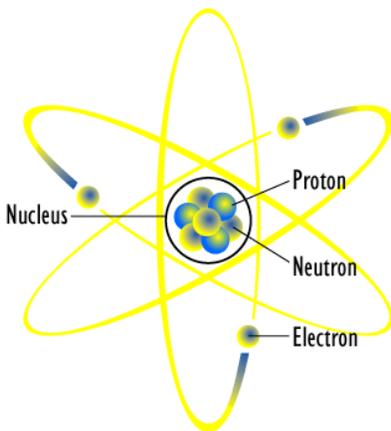


Figure 1 A Rutherford model of an atom

Perhaps you have learned about atoms in school. Atoms contain particles that have electric charge. Everything on Earth, all the stars in the night sky, the Sun and planets, everything is made from atoms. Atoms are the building blocks of matter. Atoms are composed of two major parts: the **nucleus** and **electrons** that orbit around the nucleus. The nucleus is composed of two kinds of particles: protons and neutrons. There is much more to atoms than just these parts, but this is all we need to know for now.

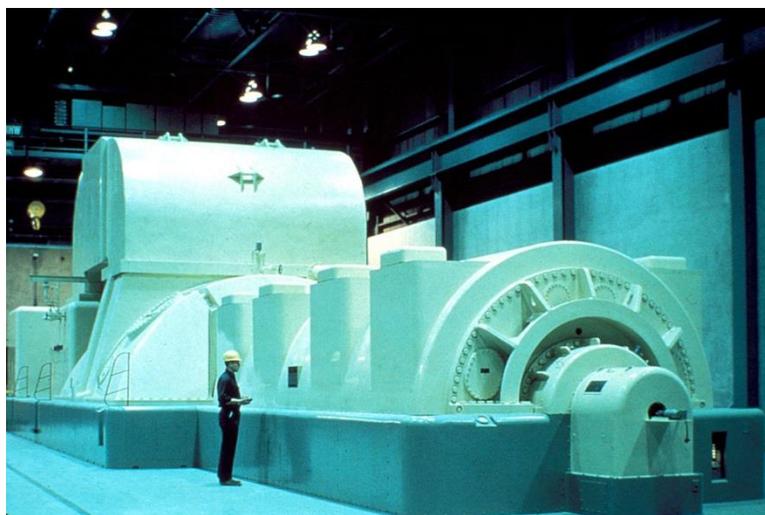
The protons in the nucleus are electrically charged and the electrons that orbit around the nucleus are also electrically charged. In most cases, when we talk about electricity, we are talking about the flow of electrons, not protons. The electric charge that flows through an electric wire is electrons.

Electrons are very small particles. In fact, they are so small that scientists believe they have no size at all. They have no dimensions of size. Scientists call this kind of particle a point particle. The properties of electrons allow them to move easily through a solid metal wire! However, a solid that allows the flow of electrons has to be made of particular kinds of atoms because **electrons can't flow through all kinds of solids**. I will have more to say about that later.

Since we can't see the electrons moving in the wire, it is helpful to compare the flow of electrons to the flow of water, something we can see. We can compare water flowing through a pipe with electrons flowing through a wire. That does not mean that flowing water is electricity, we only think about flowing water because we can see it and in some ways it can behave like electrons flowing through a wire. Flowing water helps us to visualize flowing electrons.

**What makes electrons flow in a wire?** To help us understand the cause of electron flow, let us use the example of flowing water. What makes water flow through the pipes in your house? The water is under **pressure** and it is the pressure that forces the water to flow out of an open faucet. What causes the pressure? That depends on how water is delivered to your house. Suppose your house gets its water from a village supply. Maybe you have seen a village water tank like the one on the square in Burton. The tank of water sits high above the ground. Water is pumped into the tank from a well. Since the tank sits high above ground level at a high place in the village, the water in pipes below the tank becomes pressurized due to the force of gravity. In this case, it is the force of gravity that causes the water to become pressurized.

Scientists use the term **electromotive force (emf)** for the kind of force that causes electrons to flow in a



**Figure 2** A modern steam turbine generator. You can't see the spinning parts in this machine because they are inside the machine case.

wire. Emf is generated by various methods. The electricity delivered to your house from the electric company is created by spinning a generator, which is similar to an electric motor. The generator is commonly spun by a steam turbine and the steam is produced by heating water using burning coal or nuclear power. Another source of electricity that you are familiar with is a battery. In the case of electricity delivered to your house, the method of generation is mechanical (the spinning of a generator). In the case of a battery, the source of generation is chemical.

There are three important words or terms that you need to know before you can learn more about electricity and electronics: **electromotive force, current** and **resistance**. We have already said that emf is the force that causes electrons to flow in a wire. **Current** is the amount of electrons flowing in the wire. Emf and current are not equivalent. Suppose we have a pipe that is very large in diameter and is carrying water at a rate of 1,000 gallons a minute. However, the pressure on the water is very low and it falls straight to the ground from the open end of the pipe. That would be analogous to a large wire carrying a great amount of electrons but under a low emf. Compare this with the water from a garden hose with a spray head attached. The hole in the spray head is small and the water in the hose is under high pressure. The water coming out of the spray head travels 20 feet before it hits the ground because

it is under high pressure. However, the amount of water coming out of the hose is only 10 gallons a minute. That would be analogous to a small amount of electrons flowing through a small wire under high emf.

We have one word left to define: **resistance**. Usually it is not acceptable to define a word by using the same word, but perhaps you will forgive me for doing just that. **Resistance** is a measure of resistance to the flow of electrons. Let us think again about water in pipes. Suppose we have a tank of water that sits 10 feet above ground level. There are two pipes connected to the tank, one that is twice the diameter of the other pipe. If we fill the tank with water, then empty the tank by opening the larger pipe, fill it again and empty it using the smaller pipe, which pipe will empty the tank faster? The larger pipe will empty the tank faster because it has a lower **resistance** to the flow of water. Under the same emf, an electrical circuit of lower resistance will allow more current to flow than a circuit of higher resistance.

**Ohm's Law** is a mathematical formula that relates emf, current and resistance. It is an important law to know because you can use it to understand how electrons flow in electrical circuits. Here it is:

$$\text{Current} \approx \text{Emf}/\text{Resistance}$$

That is, current in a circuit is proportional to the emf divided by the resistance. We need to apply the proper units to convert the proportion to an equation. The current must be in the unit named **ampere (or amp)**, the emf in **volts** and the resistance in **ohms**. Here is the equation in three forms:

$$\text{Amps} = \text{Volts}/\text{Ohms}$$

$$\text{Volts} = \text{Amps} \times \text{Ohms}$$

$$\text{Ohms} = \text{Volts}/\text{Amps}$$

If we know two of the three terms we can calculate the third one using one of the above equations. For example, if we measure the volts and ohms of a circuit, then we can calculate the amps of current that will flow in the circuit using the first equation above.

If we apply one volt of emf to a circuit containing one ohm of resistance, then one amp of current will flow through that circuit. What would happen if we apply 2 volts to the same circuit? Then two amps of current would flow. What if we applied one volt to a circuit containing two ohms of resistance? Then one half an amp of current would flow. Therefore, we can see that an electrical engineer can design an electrical circuit to carry a specific amount of current depending on how much emf is applied and how much resistance the circuit contains. We will see later how this is done.

We need to add one more word to our electrical vocabulary at this point: **watt**. Perhaps you know that the incandescent electric light bulbs in your house are rated by their wattage (I am assuming you might still have some of these old style light bulbs in your house). The watt is a measure of the rate of electrical consumption or electrical power. It is not enough for us to say how much current is flowing to understand the amount of power being consumed in an electrical circuit. We also need to consider the emf in the circuit as well. If we apply 100 volts of emf to a light bulb and we find that the current

flowing through the light bulb is one amp, then that light bulb consumes 100 watts of electrical power. It is a 100-watt light bulb. The formula for electrical power is as follows:

$$\text{Power} \approx \text{Emf} \times \text{Current}$$

Or

$$\text{Watts} = \text{Volts} \times \text{Amps}$$

In this case the unit for power is the watt, and volt for emf and amp for current. An electrical circuit with one amp of current flowing under an applied emf of one volt consumes one watt of electrical power.

It is important to know the wattage consumed by electronic components in a circuit. For example, if we apply two volts to a one ohm resistor, then two amps of current will flow through the resistor according to Ohm's Law. Now suppose that resistor is rated at one watt, which means it can't withstand more than one watt of power consumption without being damaged. In our example, four watts of electrical power are consumed by the resistor (2 volts x 2 amps). As a result, the resistor will become very hot and will be ruined. If we had used Ohm's Law to study this circuit before allowing current to flow, we would realize ahead of time that the resistor could not withstand the current flowing through it. Our design must be changed to prevent damage to the one watt resistor.

### Definition of amp

What exactly is one amp of current? Scientists define the amp as follows: one amp is the passage of one **coulomb** of charge past a point in a circuit during one second of time. Well, that only helps if we know the definition of coulomb. A coulomb is equal to the charge of  $6.241 \times 10^{18}$  electrons. At least that is how a scientist would give us the definition. That is a very large number of electrons! Scientists write the number as a power of ten. If we write out the number it is 6,241,000,000,000,000 electrons. If we had a method of counting the electrons as they passed by one point in a circuit, we would see that 6,241,000,000,000,000 electrons passed that point during one second of time if the current flowing in the circuit was one amp. Amazing!



### Two Kinds of Electrical Current

Two important kinds of electrical current are **alternating current (AC)** and **direct current (DC)**.

**Figure 3** The city lights of Prince George, British Columbia viewed in a motion blurred exposure. By moving the camera during the exposure, each city light is seen as a wavy line, not a dot. Using this method, we can see that the city lights are powered by alternating current. Each time the current changes direction, the lights stop glowing for a very short amount of time. In other words, the lights are flashing on and off 120 times each second. This flashing rate is too fast for humans to see with their eyes.

Alternating current changes direction of flow and direct current flows only in one direction. **The electricity that is delivered to your house is AC.** In the United States, the AC delivered by the electric companies is 60 cycles. That means the current cycles 60 times each second. One cycle is the flow of current in one direction followed by flow in the reverse direction. Therefore, 60 cycle AC changes direction of flow 120 times each second.

Most of the electrical appliances in your house run on AC (electric stove, refrigerator, kitchen mixer, hair drier, etc.). However, the electronic devices in your home operate with direct current (DC). **Batteries supply direct current.** Electronic devices that don't run on battery power, like a TV, convert the house AC to DC in an electrical circuit called a power supply.

### Direction of Current Flow

We need to go back to atoms for a minute to talk about another property of electrically charged particles, the protons and electrons. **Protons have an electrical charge that is positive (+)** while **electrons have an electrical charge that is negative (-)**. Opposite charges attract each other while like charges repel each other. The protons in the nucleus attract the electrons spinning around the nucleus of an atom because they have opposite charges (plus and minus). It is the attractive electrical force that keeps the electrons spinning around the nucleus of the atom, just as the force of gravity keeps the planets orbiting around the Sun.



Figure 4 battery

Have you ever taken a close look at a battery? The common types have a metal button on top. That is the positive end of the battery. If you look at the side of the battery it may have a plus sign near the top and a minus sign near the bottom. The top end is the positive charge end and the bottom is the negative charge end. When a battery is connected to an electrical circuit, electrons flow out of the bottom of the battery and return back to the top of the battery. The electrons flow toward the plus end of the battery because opposite charges attract each other (electron is minus, top of battery is plus).

Now here is the really confusing part. Scientists and engineers decided that when describing the direction of current flow, we should describe the direction of flow for positive charge. The direction of flow for positive charge is opposite the direction of flow for negative charge (electrons). Therefore, we must say that current flows from the positive end of the battery to the negative end, even though electrons flow in the

opposite direction. Confusing, isn't it?

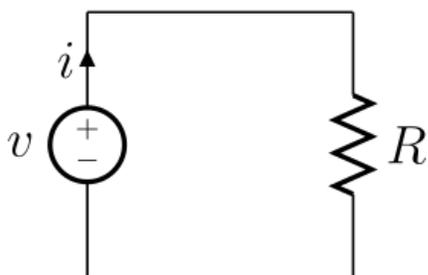


Figure 5 A simple electric circuit showing the direction of current flow. This is a closed circuit because there is a complete path for current to flow from the positive side of the voltage source to the negative side.

that Franklin's glass tubes really were positively charged, then Franklin was wrong about the direction of electrical "fluid" movement. If his glass tubes were positively charged, then that was achieved by the movement of electrons from the glass to the material he used to rub the glass. He thought the "fluid" was moving into the glass but it was really moving the other way. We can't blame Franklin for this error because he lived at a time when scientific knowledge was not advanced enough for him to understand the true direction of electrical movement in his experiments. The structure of the atom was not discovered until very late in the 19<sup>th</sup> and early 20<sup>th</sup> centuries. Benjamin Franklin did his electrical experiments in the late 1740s and early 1750s. Had Benjamin Franklin known that electrons are the particles that move in static electricity experiments, then it is likely that he would have assigned them as a positive charge. Then we would not have the confusion about the direction of current flow. If you would like to read more about Franklin's experiments, then I suggest you read a letter that Franklin wrote to Peter Collinson describing some of his experiments. The text of the letter is available at this web address: <http://www.revolutionary-war-and-beyond.com/benjamin-franklin-letter-to-peter-collinson-may-25-1747.html>

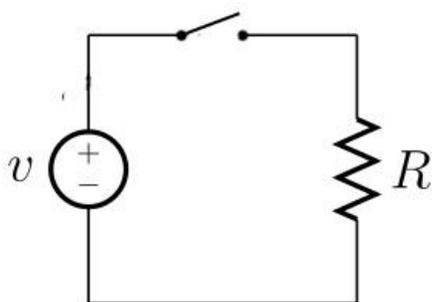


Figure 6 A switch has been added to this circuit and the switch is in the off position, creating an open circuit - no current can flow

This confusion has its roots back in the 18<sup>th</sup> century. Perhaps you know from your studies in school that the famous American, Benjamin Franklin, experimented with electricity. He is the one who first used the terms **positive charge** and **negative charge**. Franklin believed that electricity was a type of invisible fluid present in all materials. In static electricity experiments done by rubbing different materials together, Franklin believed that this electrical fluid moved out of materials like amber and into materials like glass. He said that the glass became positively charged. If we think of a positive charge as a process of gaining the electrical fluid, then we can understand why Franklin applied this term. If we assume

I have used the word **circuit** many times but have not defined it yet. A circuit is a path for electricity to follow as it flows. We can use the terms **open circuit** and **closed circuit**. **Electricity only flows in a closed circuit**. Suppose I have a light bulb with two wires attached to it. We can use the diagram in Figure 5 for our circuit, where **R** is the light bulb and **v** is the battery, or just look at Figure 7. The wires and bulb are the circuit, or path for electrical flow. The electricity flows from the battery through one wire to the bulb and returns through the second wire. But electrons don't flow in the circuit until one wire is connected to the top of a battery and the other wire to the bottom of the

battery. Once both wires are connected, the circuit is closed and current will flow.

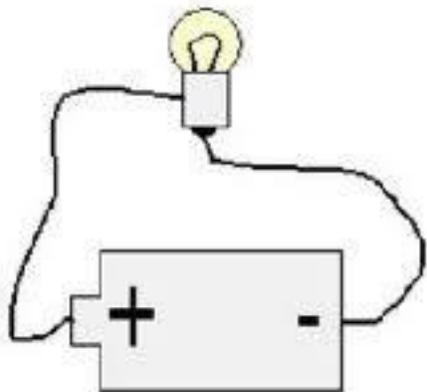


Figure 7 a closed circuit containing two wires, a battery and a light bulb.

There is one additional term we should discuss in terms of circuits: **short circuit**. A short circuit is a kind of closed circuit, but a kind to be avoided in electronic circuits. If we take a wire and connect it to both the top and bottom ends of a battery, we create a short circuit. The wire by itself offers very little resistance to the flow of electricity and the result is an excess amount of electron flow. The wire will become very hot and may even melt! When we include the light bulb in the circuit, the light bulb adds enough resistance so that excessive amounts of current don't flow in the circuit.

### Conductors and Insulators

We can divide materials into categories with respect to how easily electrons flow through them. You may know that electric wires are made of metals because electricity flows easily through metals. The metal copper, made of copper atoms, is one metal that allows electrons to flow very easily. That is why electric wires are commonly made of copper. Metal made of silver atoms is even better at allowing electrons to flow. However, silver is very expensive and not worth the extra cost in making electric wires, except under unusual situations. Copper is moderately expensive compared to the metal aluminum. Metal of aluminum atoms is commonly used for very large wires partly because it is a cheaper metal. It does not conduct electricity as well as copper, but the cheaper price makes it a good choice for large wires.

Now I have used the word **conduct**. Materials, like metals, that allow electricity to pass through them easily are known as **conductors**. Materials that are very good at blocking the flow of electricity are known as **insulators**. Rubber and many plastics are good electrical insulators. That is why electric wire is commonly covered with some type of insulator, to protect people from getting electric shocks. You always want to protect yourself from electric shock when working with electricity. Now let us learn something about working safely with electricity.

### Electrical Safety

The standard voltage supplied by the electric receptacles in your house is 120 volts. That level of voltage can give you a strong electrical shock if you touch a bare metal wire. That is one reason why electric wires carrying 120 volts are always insulated in situations where you can touch the wire. In fact, an electrical shock of 120 volts may even be lethal to humans (that is, it may cause death). People who work with voltage at high levels, like 120 volts, must have a lot of training so that they know how to work safely. **In our robotic projects we will not use high voltage.** Common batteries supply only low voltage that is safe to work with. You may know that you can touch both ends of a common battery and not feel a thing. A standard AA battery supplies only 1.5 volts, which is completely harmless to humans and other living things. Even 9 volt batteries are safe to work with. Using batteries to power your electronic projects is a safe way to learn and is the way we will work in our club.

**A WORD OF CAUTION:** never open the case or cabinet containing an electrical device that runs on house voltage (for example, 120 volts). Many of these devices will have exposed metal surfaces on the inside that carry electricity. If you touch a metal surface inside that is energized, you will get an electric shock. You may even get an electric shock if the cord for the device is not plugged into an electrical receptacle. Some electrical devices contain components called capacitors which temporarily store electricity, even when the device is turned off and unplugged. That is why you need to have a lot of training to work on electrical devices that work with house voltage. It is much safer to start learning about electricity using batteries that supply low voltage (under 20 volts).

### Units of voltage and amperage

In our projects with robots, many of the circuits will carry small amounts of current or very low voltages. In these cases it is more convenient to use smaller units for voltage and current than the volt and amp. When current is small, we can use the unit milliamp. One amp is the same as 1,000 milliamps. One milliamp is  $1/1,000^{\text{th}}$  of an amp. Similarly, we can use the unit millivolt for emf. One volt is the same as 1,000 millivolts. One millivolt is  $1/1,000^{\text{th}}$  of a volt. It is common to abbreviate volt as V, amp as A, milliamp as mA, millivolt as mV. For example, 100 milliamps can be abbreviated as **100 mA**.

### Activity – static electricity

Benjamin Franklin used a glass tube to collect electric charges in his static electricity experiments. The electric charges were generated when Franklin rubbed the glass tube with various materials (his hand, silk cloth or leather). Other materials can be substituted for glass in static electricity experiments. In your experiment you will be using a PVC pipe. When PVC plastic is rubbed with wool, the PVC collects electrons from the wool and becomes negatively charged. If the charged PVC is placed near small pieces of paper, the pieces of paper will be attracted to the PVC.

Remember that there are two types of electric charge: **negative** and **positive**. Electrons are negatively charged and protons are positively charged. When an atom contains equal numbers of electrons and protons, it does not have a net electric charge. The negative charges balance the positive charges. When an electron escapes from an atom, the atom becomes positively charged because it has more protons than electrons. Like charges repel each other and different charges attract each other. When the negatively charged PVC is placed near the paper pieces, some of the electrons in the paper move to the side of the paper that is opposite the PVC (like charges repel each other). When that happens, the side of the paper facing the PVC becomes positively charged. Then the paper is attracted to the PVC because different charges attract each other (the PVC is negatively charged and the side of the paper facing the PVC is positively charged).

### Task One

Now try this experiment yourself. Sprinkle some small pieces of paper on the table where you are working. Take the PVC pipe in your hand and then place it very close to the paper pieces, but do not touch the paper pieces with the pipe. Nothing should happen to the paper pieces. Now, still holding the PVC pipe in one hand, rub the pipe with a piece of wool held in your other hand. Rub the pipe

vigorously for a few seconds. Now place the pipe very near the paper pieces, but do not touch them. The paper pieces should jump up and stick to the pipe. If nothing happens, then you may need to rub the pipe again with the wool. The more you rub the pipe, the more it becomes negatively charged (up to a certain point).

### Task Two

For this task you will need to work with another group because you will need two PVC pipes. Remember that like charges repel each other. In this experiment you will see that if both PVC pipes are charged negatively (by rubbing with the wool), then they will repel each other. Place a bowl on your work table. Place one of the PVC pipes on top of the bowl. If the bowl is level, then the pipe should not roll off the bowl. If the pipe does roll off the bowl, you will need to find another location that is level or you can level your bowl by placing sheets of paper underneath one side. When you have a level bowl, rub both pipes with wool to charge them negatively. Carefully place one pipe on top of the bowl. Now, holding the other pipe in your hand, place it close to the pipe on the bowl but do not touch the two pipes together. The pipe on the bowl should start to roll away from the other pipe in your hand (like charges repel).

### Activity – series and parallel circuits (Activity A – Series/Parallel)

You will be working with a circuit board containing six light bulbs. Each light bulb has two wires and each wire is connected to a white terminal strip. The light bulbs are not electrically connected to each other or the batteries. You will be making connections to the light bulbs and batteries using wires with alligator clips.



Figure 8 battery holder

A battery holder is attached to the circuit board and it contains two AA size batteries (Figure 8). The batteries are side by side in the holder but are electrically connected in series as seen more clearly in Figure 9 (in Figure 8 notice on the right side of the holder that the (+) terminal of the bottom battery is connected to the (–) terminal of the top battery). When batteries are connected in series, the voltages of the batteries are added together. Each battery supplies 1.5 volts. Two batteries in series supply 3.0 volts.

There are three wires attached to the battery holder, two on the left end and one on the right end. This arrangement allows you to apply either 1.5 or 3.0 volts to the light bulbs, depending on which two of the three wires you use. You should always use the black wire of the battery holder as the minus terminal. For most of your experiments, you should use the red wire labeled 1.5 volts as the positive terminal. When experimenting with three light bulbs in series, 1.5 volts may not be enough to make the light bulbs glow. In that case,



Figure 9 two batteries in series

you can use the red wire labeled 3.0 volts. THREE VOLTS SHOULD BE USED ONLY IN THE SERIES CIRCUIT WITH THREE OR TWO LIGHT BULBS. IF YOU APPLY THREE VOLTS TO A SINGLE LIGHT BULB, IT MAY BURN OUT.

You will be recording some of your work in your Robotics Notebook on page 62. Turn to page 61 in your notebook and look at the drawing of a light bulb and battery. The battery is connected to the light bulb with two wires to create a SIMPLE CIRCUIT. The battery has two places where wires can be connected (plus and minus ends of the battery) and the light bulb has two places where wires are connected. The circuit will be closed and the light bulb will glow when all connections are made properly (a CLOSED CIRCUIT).

### **Task One**

Build a series circuit containing three light bulbs (use the light bulbs numbered 4, 5 and 6 on the circuit board). You will find a schematic (a kind of electrical wiring drawing) of a series circuit on page 61 of your notebook. In a series circuit the current flows through one light bulb, then the next and then the next and so on. After you connect the three light bulbs together ask your advisor to check your circuit. Then connect the battery wires to your circuit while your advisor watches. Use the black battery wire and the red battery wire marked 1.5 volts. If the light bulbs do not glow, then use the red battery wire marked 3.0 volts instead. You should be observing the brightness of the light bulbs in your experiments and recording your observations in your notebook. How bright are the light bulbs? Are they bright, medium, dim, just barely glowing or not glowing? Make a drawing of your circuit in the Step 1 box on page 62 of your notebook.

### **Task Two**

Keep your series circuit on the circuit board but disconnect it from the battery holder. Now add a parallel circuit to your circuit board using the remaining three light bulbs (the ones numbered 1, 2 and 3 on the circuit board). Look at the schematic drawing of a parallel circuit on page 61 of your notebook. This should help you build the circuit properly. After you connect the three light bulbs together ask your advisor to check your circuit. Then connect the battery wires to your circuit while your advisor watches. Use the black battery wire and the red battery wire marked 1.5 volts. Observe the brightness of the light bulbs and record your observations in your notebook. How does the brightness of the light bulbs in the parallel circuit compare with those of the series circuit? Make a drawing of your circuit in the Step 2 box on page 62 of your notebook.

### **Task Three**

In this task your advisor will help you use a meter to measure voltage, amperage and resistance in your circuits. You will measure the voltage drop across each of the three light bulbs in the series circuit, the total voltage drop in both the series and parallel circuits and the amperage flow for each circuit. When you are done with these measurements, disconnect the battery from the light bulbs. **You must not try**

**to measure resistance with your meter if electric current is flowing through your circuits as this may damage the meter.** With the battery disconnected, measure the resistance of one light bulb with the meter. Record your data in the tables below.

Series circuit data

Bulb number	Voltage drop (volts)	Current (milliamps)
4		Don't measure this
5		Don't measure this
6		Don't measure this
4, 5 and 6 (total)		

Parallel circuit data

Bulb number	Voltage drop (volts)	Current (milliamps)
1	Don't measure this	
2	Don't measure this	
3	Don't measure this	
1, 2 and 3 (total)		

Enter your measured resistance of one light bulb in the space below.

<b>Measured resistance of one light bulb =</b>
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After you have recorded your meter readings in the tables above, you may notice some interesting things about your measurements. For example, how does the voltage drop of each bulb in the series circuit compare to the total voltage drop of the circuit? How does the current through each bulb of the parallel circuit compare to the total current in the parallel circuit? How does the total current in the parallel circuit compare to the total current in the series circuit? Do these measurements help you understand what you observed in tasks one and two as regards the brightness of the bulbs? Write your thoughts and analysis in the space below.

#### Task Four

Now you will discover what happens to the brightness of light bulbs in each circuit as you subtract one light bulb at a time. For these experiments use only the 1.5 volt red wire from the battery holder. For example, change the wiring of your series circuit so the current flows through two light bulbs instead of three and then change it again so that current flows through only one light bulb. What happens to the brightness of the light bulbs? Write your answers in the bottom box on page 62 of the notebook. Do the same thing with the parallel circuit and write your answers in the bottom box.

#### Analyzing the results of your experiments using Ohm's Law – Your homework assignment

When any substance is heated to a high temperature, it will emit light. The part of the light bulb that produces light is called the filament. The filament is a very thin wire made from the metal tungsten. When electrical current flows through the filament, it gets very hot and emits light.

Resistance in metal wire conductors increases with temperature. When you measured the resistance of the light bulb, you measured the "cold" resistance of the tungsten filament. There is no way to use your meter to directly measure the resistance of the filament at its operating temperature (remember we said you would damage the meter if you tried to make the measurement with current flowing through the circuit).

While we can't measure the resistance of the hot filament, we can calculate it using Ohm's Law. Here is the law in the form used to calculate resistance:

$$\text{Resistance} = \text{Voltage}/\text{Current}$$

You have measured the voltage drop across the light bulbs and measured the current. Let us take an example from the parallel circuit. The voltage applied to a light bulb was about 1.5 volts. Suppose the current measured for one bulb was 0.100 amps (your measurements probably won't match these numbers). Now let us use Ohm's Law to calculate the hot resistance of the filament:

$$\text{Resistance} = 1.5 \text{ volts}/0.100 \text{ amps} = 15 \text{ ohms}$$

In this example the hot resistance of the filament is 15 ohms. This should be substantially more resistance than the resistance you measured for the cold filament. In the space below, calculate the hot resistance of a filament using the data for one light bulb from your tables. How does your calculated resistance for a hot filament compare to your measured resistance of a cold filament?